ESTIMATION OF THE PARAMETERS OF ELECTROMAGNETIC FIELD AT INDUCTION DEVICE BY THE AID OF COMPUTER SIMULATION

Goce Stefanov[1], Vasilija Sarac[2],

[1,2]University Goce Delecev-Stip, Faculty of Electrical Engineering,
22 Oktomvri b.b., 2420, Radovis, Macedonia, e-mail: goce.stefanov@ugd.edu.mk

Abstract : *In the paper is presented a method for estimation of parameters of electromagnetic field at induction device with computer simulations. Also in the paper is made a comparison of the results to the estimation the parameters of the electromagnetic field produced by simulations, with theoretical results. Simulation is made in ELTA program, product of the Fluxcontrol.*

Keywords: estimation, electromagnetic field, induction device, simulations.

Introduction

Induction heat treatment for metals is a complex combination of electromagnetic, heat transfer, and metallurgical phenomena involving many factors, [1], [2]. With the simulation program used in this paper, [3], for the object of investigation induction device, field strength, current density, power, inductance, impedance, current and $\cos\varphi$ will be estimated. Simulation is made in ELTA program, product of the Fluxcontrol [3]. Estimation of parameters of the electromagnetic field at induction device is important for the design of the power converter which is controlling induction device for metal heating.

The process of induction heating of metals is complex one and its dynamic affects the parameters of the electromagnetic field in the induction device. The features involved in the design and operation of modern induction heating process are greatly dependent upon used output load. Such output load for a power converter burden is a serial resonant circuit, when power converter is supplying induction furnace. The mode of operation of the induction furnace changes the inductance and resistance of resonant circuit and this affects the voltage, current and power of the converter. So the design of the converter with such load requires knowledge of the process dynamic. On Fig. 1 is presented equivalent diagram of the induction device.
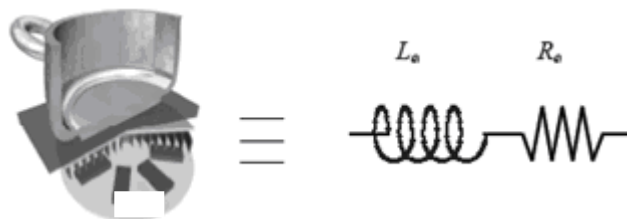
Fig.1. Equivalent circuit of the induction device

In general case the calculation of the parameters of the electromagnetic field at induction device is based on the calculation of Maxswell's equations for defined medium and geometry. Solving of Maxswell's equations in general and special case is a complex

task. Computer simulation makes the problem of designing the induction device easy and simple, [3], [4].

Basic electromagnetic phenomena in induction heating

The main components of an induction heating system are: induction coil, converter, load-matching station, quenching system (for heat treating applications), and the work piece itself, [1], [2]. Induction coils or inductors are usually designed for specific applications, therefore they are found in a wide variety of shapes and sizes. On Fig. 2 is given a simple system of inductor and cylindrical work piece.
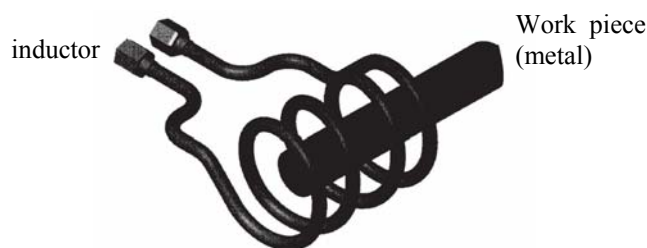

Fig. 2. Simple system of inductor and work piece

An alternating voltage applied to an induction coil (e.g., solenoid coil) will result in an alternating current in the coil circuit. An alternating coil current will produce in its surrounding a time-variable magnetic field that has the same frequency as the coil current. This magnetic field induces eddy currents in the work piece located inside the coil. Eddy currents will also be induced in other electrically conductive objects that are located near the coil. Induced currents have the same frequency as the coil current; however, their direction is opposite to the direction of the coil current. These currents produce heat by the Joule effect (I^2R). A conventional induction heating system that consists of a cylindrical load surrounded by a multi turn induction coil is presented on Fig. 3. Due to several electromagnetic phenomena, the current distribution within an inductor and work piece is not uniform. This heat source non uniformity causes a non uniform temperature profile in the work piece. Non uniform current distribution can be caused by several electromagnetic phenomena, including the skin effect, the proximity effect, and the ring effect. These effects play an important role in understanding the induction heating phenomena.
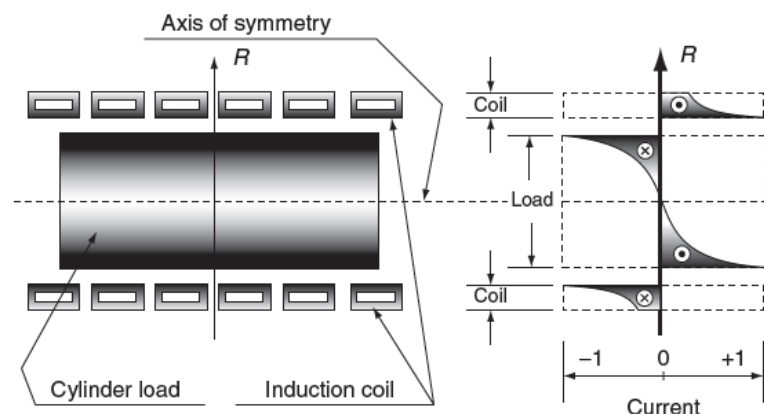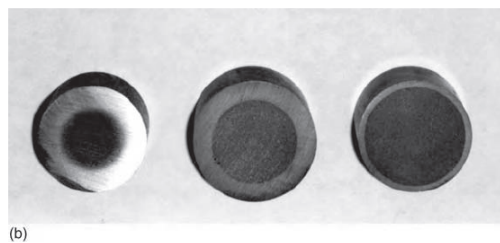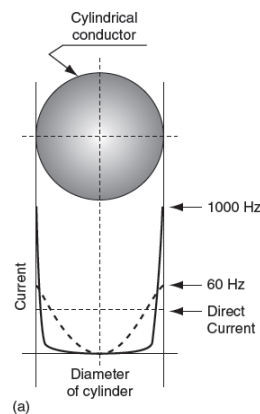

Fig. 3. Current distribution in coil–work piece induction heating system.

Skin effect

As one may know from the basics of electricity, when a direct current (DC) flows through a conductor that stands alone (bus bar or cable), the current distribution within the conductor's cross section is uniform, [1]. However, when an AC current flows through the same conductor, the current distribution is not uniform. The maximum value of the current density will always be located on the surface of the conductor; current density will decrease from the surface of the conductor toward its center. This phenomenon of non uniform current distribution within the conductor cross section is called the skin effect. The skin effect always occurs when there is an AC current. Therefore, the skin effect will also be found in the work piece located inside the induction coil (Fig. 3). This is one of the major factors that cause the concentration of eddy current in the surface layer (skin) of the work piece. Due to the circumferential nature of the eddy current induced in the work piece, there is no current flow in its center. As a result of the skin effect, approximately 86% of the power will be concentrated in a surface layer of the conductor. This layer is called the reference (or penetration) depth (δ). The degree of skin effect depends on the frequency and material properties (electrical resistance and relative magnetic permeability) of the conductor. There will be a pronounced skin effect when a high frequency is applied or when the radius of the work piece is relatively large (Fig. 4).

Fig. 4. Skin effect. (a) Current distribution as function of frequency. (b) Variation in depth of skin effect results in different hardness patterns

The distribution of the current density along the work piece thickness (radius) can be calculated by the equation

$$J_R = J_o e^{-\frac{y}{\delta}} \tag{1}$$

where J_R is current density at distance R from the surface, A/m^2; J_o is current density at the work piece surface, A/m^2; y is the distance from the surface toward the core, m; and δ is penetration depth, m.

Penetration depth is described as:

$$\delta = 503\sqrt{\frac{\rho}{\mu f}} \ [m] \tag{2}$$

where ρ is the electrical resistance of the metal, Ωm; μ is the relative magnetic permeability; and f is the frequency , Hz (cycles per second).

Mathematically speaking, the penetration depth δ in (1) is the distance from the surface of the conductor toward its core at which the current decreases exponentially to 1/exp its value at the surface. The power density at this distance will decrease to $1/\exp^2$ its value at the surface. Fig. 5 shows the percentage reduction of current density and power density from the surface toward the core. As one can see from Fig. 5, at one penetration depth from the surface ($Y = \delta$), the current will equal 37% of its surface value. However, the power density will equal 14% of its surface value. From this we can conclude that 63% of the current and 86% of the power in the work piece within a surface layer of thickness δ, will be concentrated.
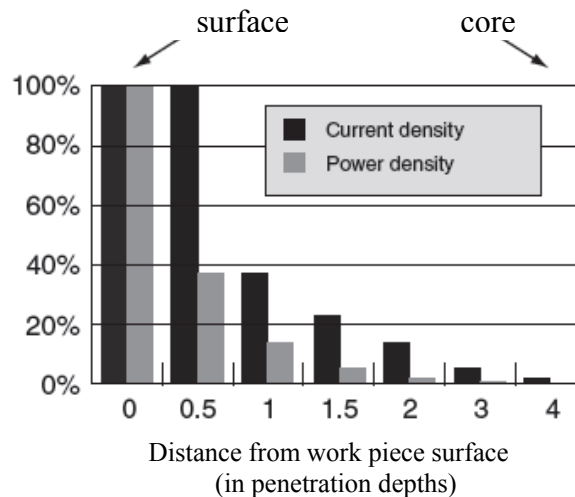

Fig. 5. Current density and power density distribution due to the skin effect.

Computer simulation

Computer simulation is used for estimation of the parameters of the induction device for defined work piece, [3]. Also computer simulation will confirm the above mentioned points:

-The distribution of the field, current and temperature is non uniform.

-The density of the field and current is greatest on the surface of the work piece.

-The process of the induction heating is a dynamic one and it affects on the impedance of the resonant circuit.

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 is defined with following operating conditions: metal steel with cylindrical shape and length of 0.35m, internal diameter of 0.03m, external diameter of 0.08m. Maximum temperature is 900ºC while time cycle is 600s. Switching frequency of 10 kHz was assumed for the calculation of maximum power. Also is selected serial resonant converter for the power supply of the induction device.

For the above defined working conditions in ELTA simulation program is estimated the dynamics of the parameters of electromagnetic field: δ - penetration depth, J - current density, H - field strength and P - heat sources density

On Fig. 6 is present the distribution of the current density in dependence of the distance from surface for a certain time moment t=0s.
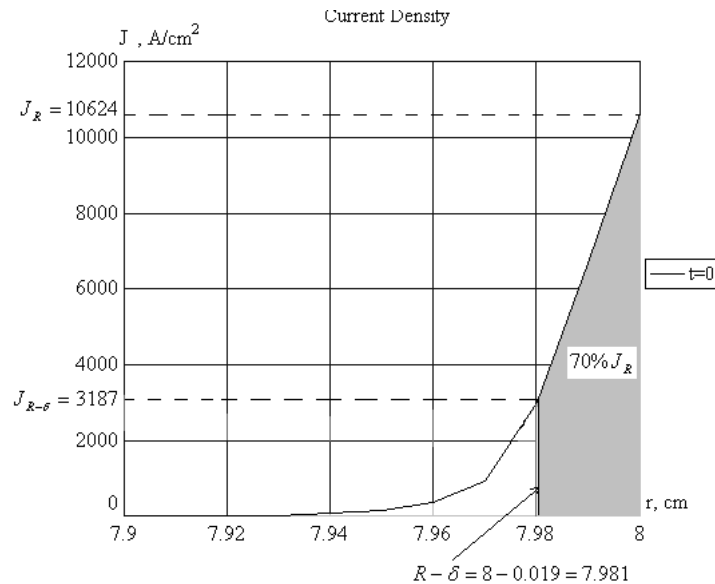

**Fig. 6**. Current density of the work piece in dependence of the distance from the surface

On Figures 7 and 8 are present the distributions of electromagnetic field in dependence of the distance from the surface for t=0s and the dynamic characteristic of electromagnetic field for the work piece consequently. On Fig. 9 is present the distribution of the heat sources density.
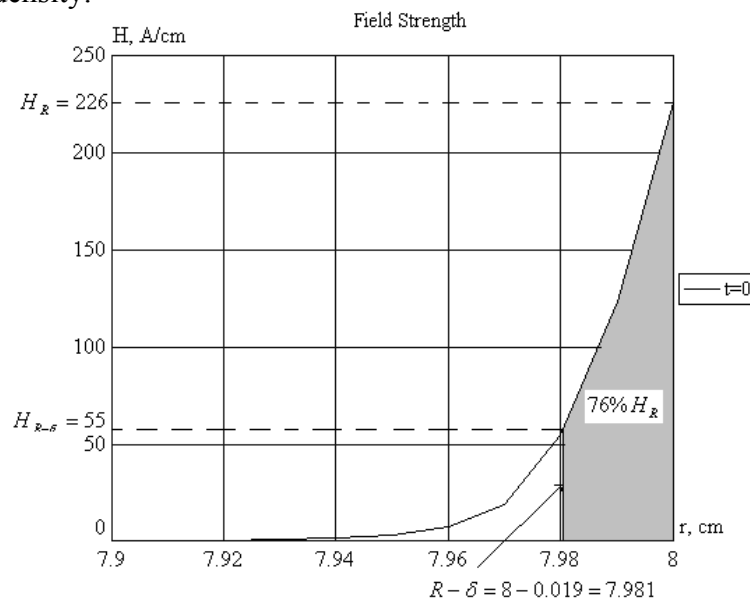
Fig. 7. Field strength versus distance on surface of the work piece
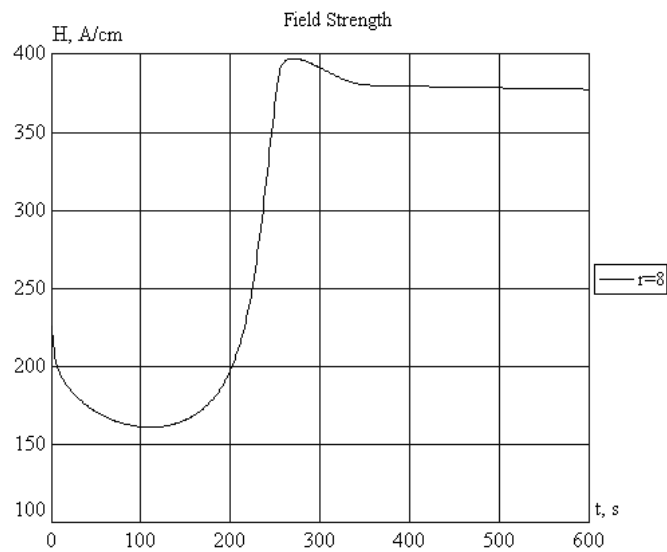
Fig. 8. Field strength versus time on the surface of the work piece
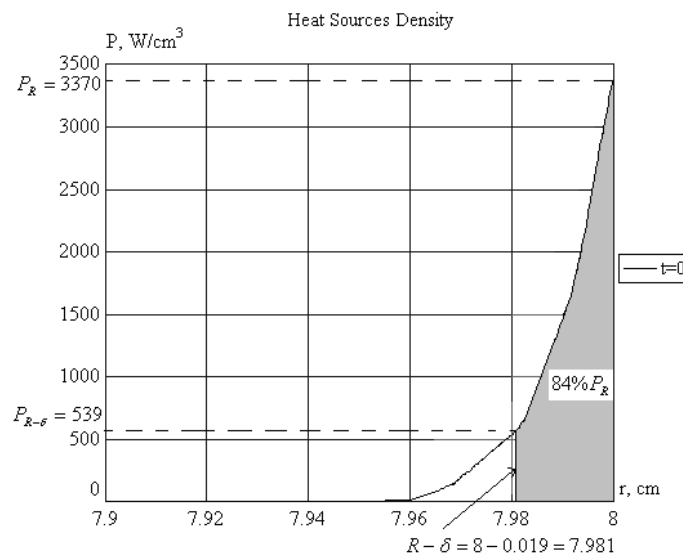
Fig. 9. Heat sources density

In Table I are presented values of the parameters obtained from the analysis of the Figures 6, 7, 8 and 9, on the surface of the work piece, i.e. $R = 8cm$

Table I. Values of the parameters of electromagnetic field obtain by ELTA program

	T (°C)	$H(\dfrac{A}{cm})$	$\rho(\mu\Omega m)$	μ^*	$\delta(mm)$	$X(T)$
0.4%steel 2Tanneal	20	226	0.15999	112	0.19	0.08

*Magnetic permeability is a function of temperature and electromagnetic field $\mu = f(T,H)$. Magnetic permeability from Table I is calculated from the equitation:

$$\mu = 1 + [\mu(H) - 1] * [1 - X(T)] \qquad (3)$$

In the table II are presented values on the current density, the heat sources density and the field strength on the surface of the work piece and on the border of the penetration depth.

Table II. Current density, heat sources density and field strength on surfaces of work piece and on penetration depth

	$J\ (\frac{A}{cm^2})$	$\frac{J_{R-\delta}}{J_R}$ (%)	$P(\frac{W}{cm^3})$	$\frac{P_{R-\delta}}{P_R}$ (%)	$H(\frac{A}{cm})$	$\frac{H_{R-\delta}}{H_R}$ (%)
$R = 8cm$	10624	30	3370	16	226	24
$R - \delta = 7.981cm$	3187		539		55	

From the Fig. 6, 7, 8, 9 and Tables I and II following conclusions can be drawn:
- The current density, electromagnetic field and the head sources density are more concentrated of the surface of the work piece.
- 70% from the current density J is concentrated in a surface layer of thickness δ.
- 84% from the heat sources density is concentrated in a surface layer of thickness δ.
- 76% from the electromagnetic field strength is concentrated in a surface layer of thickness δ.
- From the time of 220s up to 260s value of electromagnetic field rise fast from 220 A/cm up to 390 A/cm, (Fig.8). The rapid increase on the field strength indicates that, that region of the metal has reached the Kyri temperature.

Results from ELTA simulation are compared with calculation data [1]. This comparison is presented in Table III

Table III. Comparison of parameters from ELTA program with calculated values

| ELTA		CALCULATION		ERROR	
$\frac{J_{R-\delta}}{J_R}$ (%)	$\frac{P_{R-\delta}}{P_R}$ (%)	$\frac{J_{R-\delta}}{J_R}$ (%)	$\frac{P_{R-\delta}}{P_R}$ (%)	γ_J (%)[*]	γ_P (%)
30	16	37	14	18.9	14.2

[*]The error is calculate by equation

$$\gamma_J = \frac{\left|(\frac{J_{R-\delta}}{J_R})_{ELTA} - (\frac{J_{R-\delta}}{J_R})_{CALC}\right|}{(\frac{J_{R-\delta}}{J_R})_{CALC}}\ 100\% \qquad (4)$$
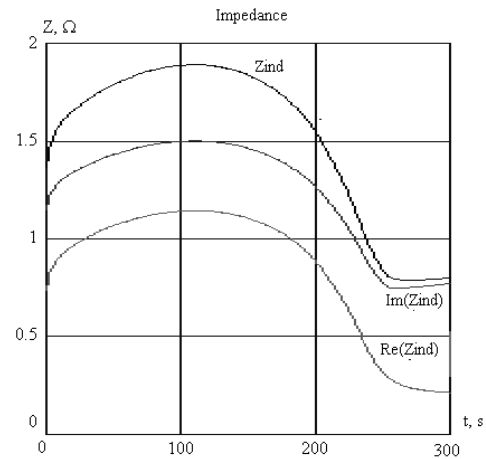
From Table III it can be concluded:
- The result of ELTA simulation is giving error of 18.9% regarding the estimation of the distribution of current density with respect to penetration depth δ compared by results of the calculation.
- ELTA simulation program is giving satisfactory results in estimation of distribution of heat sources density in dependence of penetration depth δ compared to calculation results.

For the above defined working conditions in ELTA simulation program, dynamic of following parameters of the induction device is estimated: L – inductance, Z – impedance, $\cos\varphi$ – power factor, I – current and S – power. From Figures 10 up to 14 are presented dynamic distributions of the inductance, the impedance, the power factor, the current, and the power of the induction device consequently.
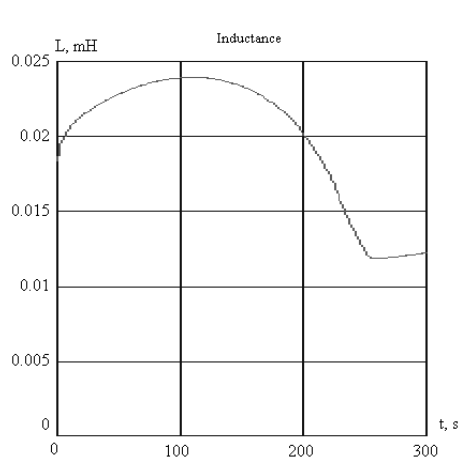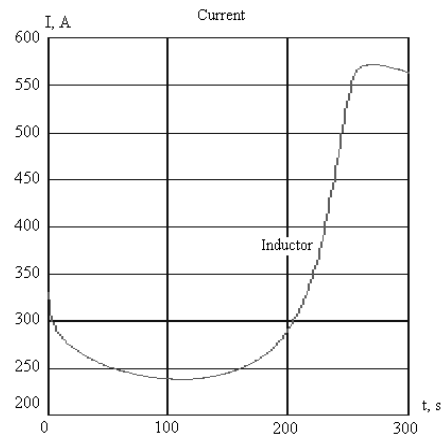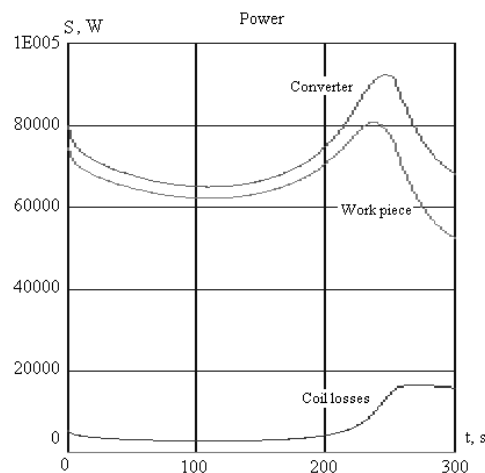
Fig. 10. Inductance of the induction device

Fig. 11. Impedance of the induction device
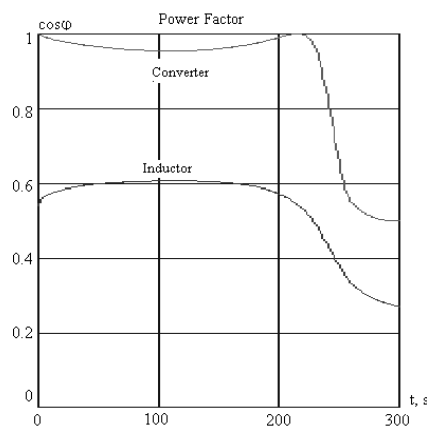
Fig. 12. Power factor of the induction device

Fig. 13. Current of the induction device

Fig. 14. Power at induction device

From the analysis of Figures 10, 11, 12, 13 and 14 it can be concluded that:
- Process of induction heating is a dynamical one, meaning relative permeability μ is a function of electromagnetic field strength H and temperature –T (up to Kyrie temperature), and this consequently changes the inductance of the induction device for 50 % (Fig.10) .

- The change of the inductance causes the change of the power of the converter for 25%, (Fig. 14).
- Required maximum power of the converter is 93kW.
- The change of the inductance causes the change of the current of the converter for 58%, (Fig. 13).
- Maximum output current of the converter is 568A.
- Fig. 12 shows that power factor of the inductor is below 0.6.

Conclusion

In this paper is given analysis of parameter estimation of electromagnetic field during the process of induction heating of the metals by aid of computer simulation. The results of the estimation of current density distribution and heat source density in the work piece show reasonable agreement with the theoretical results. Computer simulation offers possibility values of power, current and impedance of the power converter to be determined as well. Therefore computer simulation makes the problem of designing induction device easy and simple compared to the analytical calculations considering the fact that dynamic change of inductance of induction device causes the dynamic change of power of the converter. These dynamic changes of the parameters during the process of induction heating followed by change of the power of the converter can be calculated on fast and effective way by the aid of computer simulation. From the analysis of dynamic parameters of electromagnetic filed in induction device following can be concluded:

1. Computer simulation in ELTA simulation program gives an opportunity for estimation of parameters of electromagnetic field at induction devices.

2. The simulations results proved that distribution of the current density, the heat sources density and electromagnetic field is the largest on the surface of the work piece. This is consistent with the theoretical results for the skin effect.

3. Computer simulation shows that electromagnetic field in the work piece metal is a complex function of the distance from the surface, the temperature and the time. Above mentioned points make the process of an induction heating of the metals dynamic one.

4. Consequently this dynamics of the process of induction heating of the metals defines the mode of operation of the power converter which is controlling the induction device.

5. Estimation of the parameters of power, current, inductance and impedance of induction device is important for the construction of power converter.

6. Since the process of the induction heating is a dynamical process , caused by a change of a inductance, impedance and consequently the current and power of the induction devices , there is a need in some applications constant power to be maintained, and therefore there should be built systems for automatic regulation of output power of the converter.

7. Results from simulation of distribution of current density and heat source density at inductor and work piece show reasonable agreement compared to computation results, (proved by computation of the errors for current density distribution of 18.9 % and heat source density of 14.2 %). During evaluation of the errors, it should be taken into consideration that ELTA simulation program has the accuracy of $\pm$ 10 %.

References
[1] G.E.Totten, *Steel Head Treatment,* Portland State University, Oregon USA, Second Edition 2006.
[2] V.Rudnev, D.Loveless, R.Cook, M.Black, *Handbook of induction Heating,* Madison Heights, Michigan, USA, 2003.
[3] Simulation programs *ELTA 4.1,*Fluxcontrol 2009.
[4] G.Stefanov, *Computer simulation on the topologies of resonant converters used in induction cookers,* International Scientific Conference "CONFERENG 2009" Tg-Jiu, Romania, ISSUE 2/2009,161-170.
[5] G.Stefanov, R. Dambov, *Fundemental principes of working in resonant converter for induction heating,* MGU International Scientific Conference, Sofia, VOL. 52, pp. 23-27, 19-20.10.2009.