ГОДИШНИК на Минно-геоложкия университет "Св. Иван Рилски", Том 53, Св.III, Механизация, електрификация и автоматизация на мините, 2010
ANNUAL of the University of Mining and Geology "St. Ivan Rilski", Vol. 53, Part III, Mechanization, electrification and automation in mines, 2010

CALCULATION OF INDUCTION DEVICE WITH SIMULATION METHODS

Goce Stefanov [1], Ljupco Karadzinov[2] Natasa Mojsoska [1]

[1] *University Goce Delcev, R. Macedonia, goce.stefanov@ugd.edu.mk, natasa.mojsoska@ugd.edu.mk*

[2] *University Sts. Cyril and Methodius, R. Macedonia, L.Karadzinov@ukim.edu.mk*

ABSTRACT. In this paper is given a procedure for practical calculation of induction device for melting of the metal with a small capacity. Used to simulations programs ELTA, PowerSim and SemeSemikron. With simulation program ELTA, for object of investigation work piece metal are defining the parameters of the induction device. And by simulation programs PowerSim and SemeSemikron the power converter is optimized. The induction device is intended for melting 5kg copper.

ИЗЧИСЛЯВАНЕ НА ИНДУКЦИОННИ НАГРЕВАТЕЛИ СЪС СИМУЛАЦИОНИ МЕТОДИ

Гоце Стефанов [1], Люпчо Караджинов[2], Наташа Мойсоска[1]

[1] *Университет Гоце Делчев-Щип, e-mail goce.stefanov@ugd.edu.mk, natasa.mojsoska@ugd.edu.mk,*

[2] *Университет Св.Кирил и Методий-Скопие, Гоце Делчев-Щип, e-mail L.Karadzinov@ukim.edu.mk*

РЕЗЮМЕ. В този доклад се дава процедура за практическото изчисляване на индукция устройство за топене на метал *с малък капацитет*. Използва се симулации програми ELTA, PowerSim и SemeSemikron. С симулационна програма ELTA, за предмета на разследването металообработване парче се определят параметрите на индукция устройство. А от симулационни програми PowerSim и SemeSemikron конвертор е оптимизиран. Устройство е предназначено за топене 5 кг. мед.

1. Introduction

The induction device is intended for induction heating of metallic materials. The procedure for calculating the induction device cover a procedure for calculating of the parameters of the work piece which is subject to induction heating and procedure for optimization of the power converter that will manage with induction device. In the paper is given the calculations of the induction device for melting of the 5kg copper.

The procedure for calculation of the parameter of the work piece which is subject of the induction heating, in this paper, is based of the simulation program.

Also, the optimization of the power converter that manage with the induction device is based of the simulations programs.

In the power electronic from interest is the work of electronic components as switches. The electronic components as switches in the electronic circuits of power electronics manage by conversion of electrical energy from one to another shape, [1]. Major efforts for designing of the circuits in power electronics is the reducing of the price and the size of used parts. High working frequency enables reducing of the size of the used inductance L and capacitor C. So, increasing the working frequency allows reducing of the values of inductance L and capacitance C for same impedance of the circuit, [4], [7]. But on the other hand the increasing of the working frequency reduces the stability of power converter and increases power switching losses, [7]. Therefore is required designing the power converters with circuits that enable operation of high frequencies with less power losses. Here are used circuits that allow switching of the power switches at zero voltage ZVS and zero current ZCS. The resonant circuits, as output load of the power converters are circuits that allow work on switches with ZVS and ZCS. And because of that the operation of the power converter with resonant load is of great interest. At working processes with output load in the mode on induction device, the dynamics of process affects of the parameters of resonant circuit. In such loads, the output power of the converter not only depend on the effective value of voltage, but and from the frequency. The dynamic of work of the induction device affects of the values of inductance L and resistance R of resonant tank. Because the frequency of resonant system is determined by L and R on the circuit, with change of L and R of the circuit, the frequency of resonant tank is changing. In such modes of operation is necessary regulation of the output power, [8].

2. Calculation of the induction device

In the design of the induction device are used simulation programs:

- *Elda,* [2], for defining of the parameters of the induction device.
- P*owerSim*, [3], for modeling of power converter against defined power of the induction device obtained from Elda simulation program
- *Semesiel,* [6], for optimization of the power losses of converter.

Defining the working conditions:
•*Maximum output power (Smax):* Maximum output power of 12000VA .
•object of investigation work piece with:
-cylindrical geometry
-metal copper
-weight 5kg
-maximum temperature is 1083ºC
-time cycle is 3600s
•*Switching frequency (fsw):* A switching frequency of 6 kHz is used for design of maximum power.

$$f_{sw} = \frac{1}{2\pi\sqrt{L_e C}} \quad (1)$$

•Typical value for the power factor for the induction cooker is 0.5, equation (2), [8].

$$FP = \frac{R_e}{\sqrt{R_e^{\,2} + (2\pi f_{sw} L_e)^2}} = 0.5 \quad (2)$$

•Also, IGBT devices and full bridge converter are used.

A. *Simulation*

Elda simulation programs, [2]. Induction heating is a complex combination of electromagnetic, heat transfer, and metallurgical phenomena. Heat transfer and electromagnetic are closely interrelated because the physical properties of heat treated materials depend strongly on both magnetic field intensity and temperature. In general, the transient (time-dependent) heat transfer process in a metal work piece can be described by the Fourier equation

$$C\gamma \frac{\partial T}{\partial t} + div(-\lambda gradT) = Q \quad (3)$$

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 current s 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. Computer simulation are based on numerical method, Finite Differences Method and Finite Element Method. By numerical methods the problems of distribution of the electromagnetic field and heat transfer in metals is reduced for finding approximate solutions of partial differential equations. In the paper is used ELTA simulation program for estimation of the electromagnetic field and head transfer for work piece metal with cylindrical geometry.

In Elda simulation program toward defined working piece of copper the geometry of the system inductor, graphite crucible , work piece is defined:
Input data

Work piece:
Shape: Cylinder. Length: 15cm, finite system length.

Layers:
1. Copper, R_{int}=0cm, R_{ext}=3.75cm, T=20ºC
2. Graphite, R_{int}=3.75cm, R_{ext}=5.25m, T=20ºC

Inductor:
R=5.75cm
Tube profile: ring, D=0.8cm, d=0.2cm,
Inductor length: 16.5cm
Number of turns: 14
Resistivity: $2x10^{-006}\,\Omega cm$

Processing stages:
$f = 6kHz$, $U = 30V$
Time cycle 3600s.

Magnetic flux Φi of the inductor flows around all its turns as one stream (Fig. 1). Inside of the inductor it consists of a leakage flux Φs in the gap between the coil and work piece and flux Φw inside of the work piece.

$$\phi_i = \phi_s + \phi_w \quad (4)$$

Main assumptions for Total Flux Method are:

1. Magnetic flux distribution inside of the coil (area A) is the same as in a piece of an infinitely long system;
2. Magnetic flux pattern outside of the coil (areas B) is approximately the same as for an empty coil.

Under these assumptions it is possible to calculate magnetic resistances of different parts of the system and compose a magnetic substitution circuit. In the Fig. 1 is given equivalent magnetic circuit.

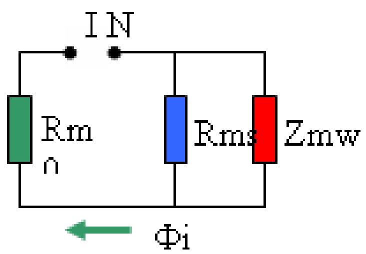


Fig. 1. Equivalent magnetic circuit

Magnetic impedance of the work piece Zmw may be found from analytical or numerical solution of 1D or 2D electromagnetic or coupled electromagnetic plus thermal problem. Magnetic impedance (reluctance) Rms of the gap may be calculated for uniform distribution of magnetic field in the gap, which follows from assumption1. Finally, reluctance of the back path of magnetic flux (areas B, Fig. 1) may be found using Nagaoka correction coefficient for inductance of empty coil. Magnetic flux generated by the coil ampere-turns IN may be calculated directly from the circuit of Fig. 1.

In ELTA program for define work piece are obtain temperature distribution and heat transfer, (3).

In the Fig. 2 is shown the temperature distribution for different distance from the surface of the work piece to its center.

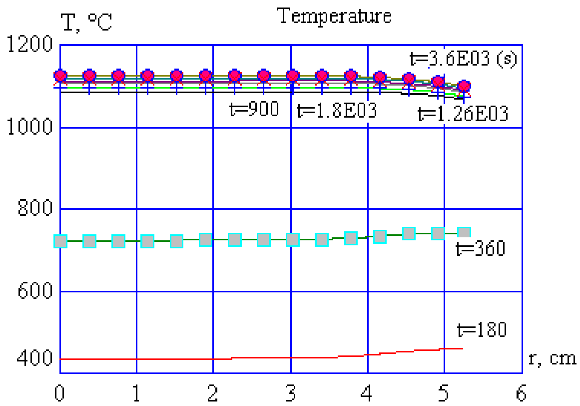


Fig. 2. Temperature distribution on the work piece

As a parameter appears the time for which work piece is exposed on heating. From the diagram it is obvious that after $t = 900s$ temperature in the work piece from surface to its center is 1083 º C. So after $t = 900s$ we can say that the metal is melted. In the Fig. 3 is given temperature distribution of the work piece of induction furnace.

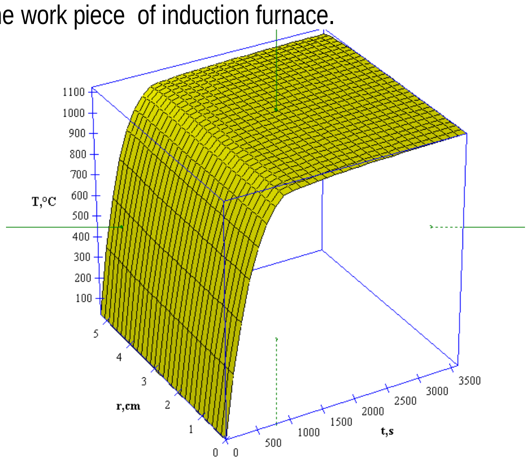


Fig. 3. Temperature distribution of the work piece

From the Fig. 3 it is obvious that after a time of 900 seconds all points of work piece reach a temperature of 1083 ºC.

Also, in Elda simulation program are obtain wave forms of the magnitudes of the system inductor work piece. In the Fig. 4 are present the power, the current, the voltage, and the impedance of the power converter.

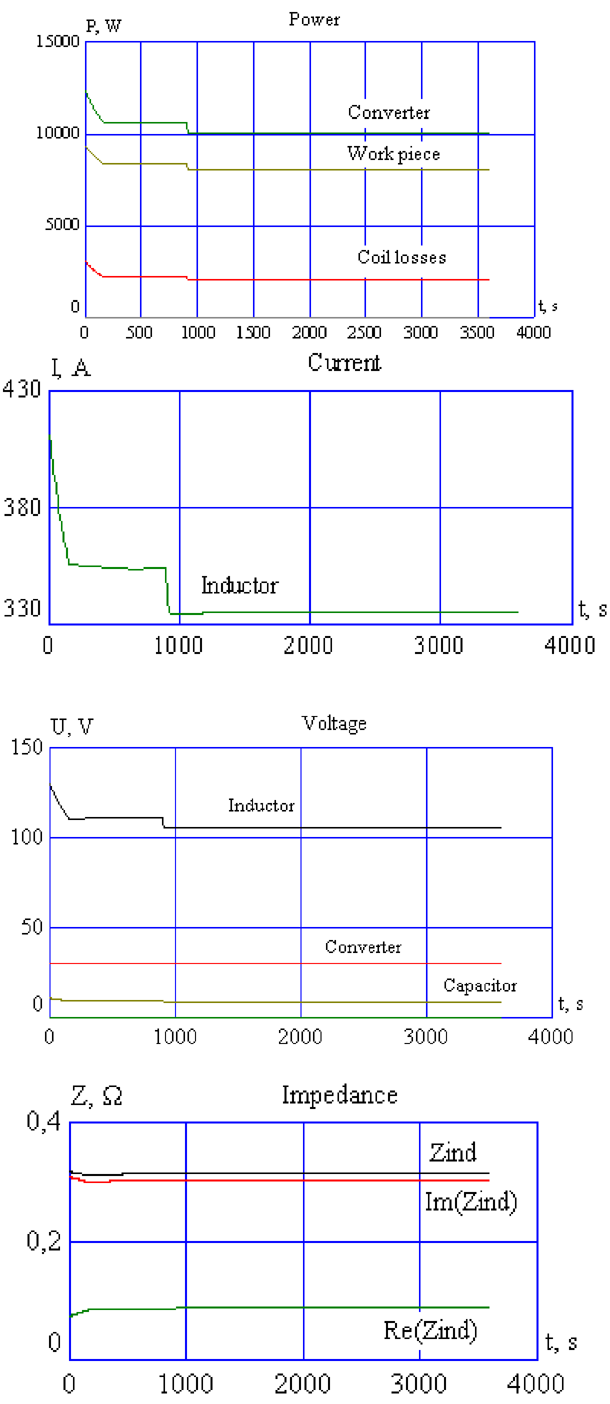


Fig. 4. Power, current, voltage and impedance

In the Fig. 5 are given the current density, the efficiency , the inductance and cosφ for the work piece copper.

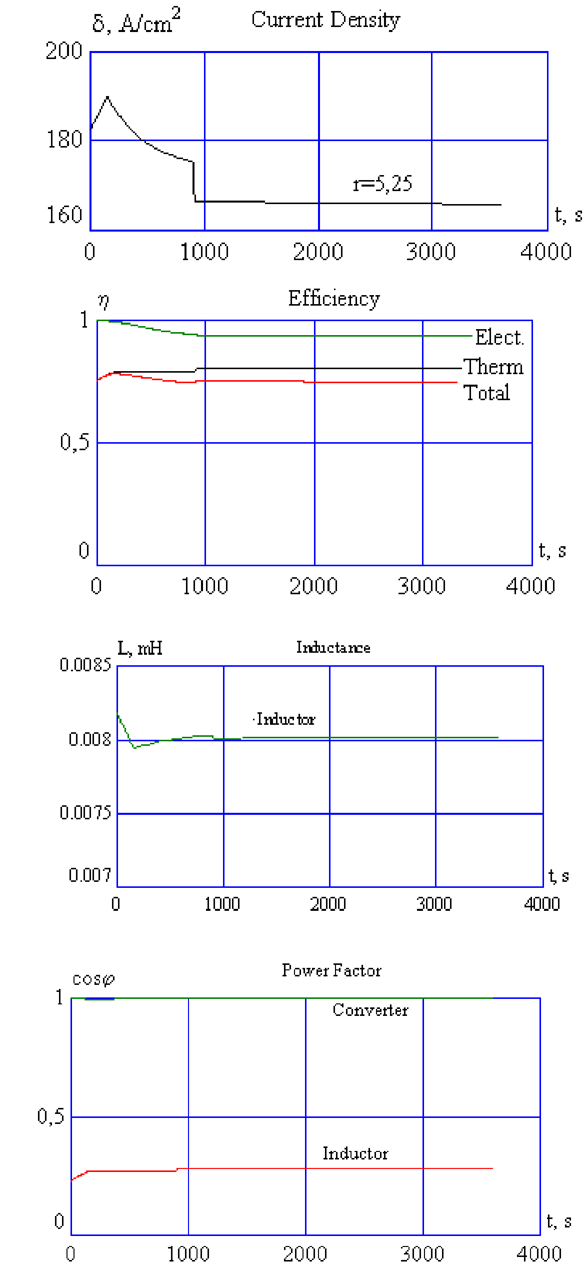


Fig. 5. Current density, efficiency, inductance, cosφ

In the table 1 are present values of the parameters L, R and magnitudes Iin (inductor current), P (power converter) of the system inductor work piece.

Table 1

	L(μH)	R(Zind)	C(μF)	Iin(A)	P(kW)
min	7.9	0.073	86	335	10.6
max	8.2	0.089	88	410	12.2

The analysis of the Fig. 3, 4, 5 and table 1 shows that the power converter must operate under the following conditions:

•Required maximum power on the converter is 12kW.
•Maximum output current of the converter is 410A.
•Output voltage of the converter is 30V.
•The change of the temperature of the work piece from 20 to 1083 º C produces change on the inductance for 2.7%.
•The capacitance of the resonant circuit for compensate on the inductance is 86μF.
•The change of the inductance produces change of power of the converter for 13%.
• When the inductance is minimum, the power and the current have a minimum value and vice versa.
•When the resistance is minimum, the power and the current have a maximum value and vice versa.
•$|Z_{ind}| = \sqrt{R_e^2 + I_m^2}$ is a module of the impedance of the inductor.
•The change of the power of the converter shows that in such variable loads is necessary to build a system for maintaining constant output power.

PowerSim simulation program. For defined power, current and frequency on the induction device obtained in Elda simulation program by the PowerSim simulation program are designed power converter with using simulation circuit in Fig. 6.

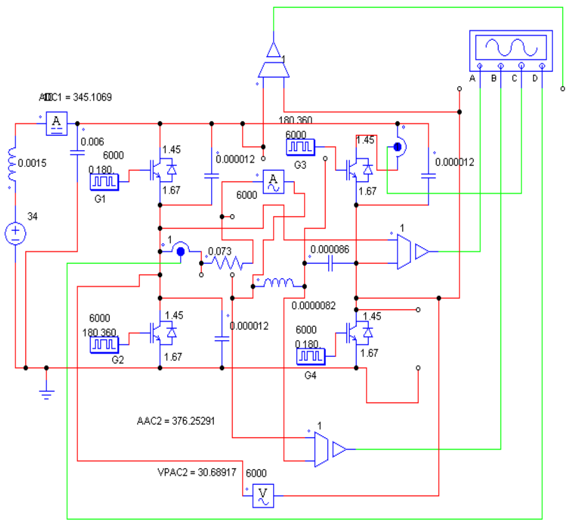


Fig. 6. Simulating circuit in the PowerSim program

The circuit for simulation of the Fig. 6 is tested for the minimum (1) and maximum (2) values of magnitudite obtained by ELTA program, table 2.

Table 2

test	L(μH)	R(Zind)	C(μF)
(1)	8.2	0.073	86
(2)	7.9	0.089	88

The results are presented in the table 3.

Table 3

	I_{DC} (A)	U_{DC} (V)	P_{DC} (kW)	U_o (V)	I_o (A)	S_o (kVA)	cosψ (º)	η (%)
(1)	360	34	12.2	30.7	391	12	0.99	98
(2)	300	34	10.2	30.5	323	9.9	0.99	96

In the table 3 the sizes are:

- $U_o = \sqrt{\frac{1}{T}\int_0^T u_{out}^2(t)dt}$
- Ψ is phase angle among Uo and Io
- $P_{conv} = S_o \cos\psi$
- $\eta = \frac{S_o \cos\psi}{P_{DC}} 100\%$ is efficiency on the full bridge converter

In the Fig. 7 is given the wave shapes of output voltage and output current of the converter.

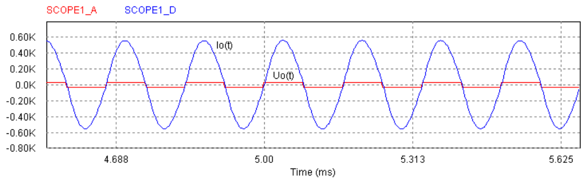


Fig. 7. Output voltage and output current

SemeSiel simulation program. In the simulation program Semesiel the converter is optimized in term of the switching losses, table 4 and the temperature losses, table 5 and Fig. 8

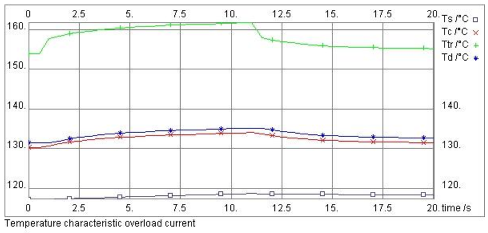
Table 4

	SKM200GB12T4		SKM300GB066D		SKM400GB066D	
	rated current	overload	rated current	overload	rated current	overload
$P_{cond\ tr}$	153 W	181 W	99 W	113 W	91 W	103 W
$P_{sw\ tr}$	16 W	18 W	9.8 W	11 W	8.97 W	9.98 W
P_{tr}	169 W	199 W	109 W	124 W	100 W	113 W
$P_{cond\ d}$	0.00 W	0.00 W	0.0 W	0.00 W	0.00 W	0.00 W
$P_{sw\ d}$	4.3 W	4.69 W	3.2W	3.41 W	3.4 W	3.64 W
P_d	4.3 W	4.69 W	3.2W	3.41 W	3.4 W	3.64 W
P_{tot}	692 W	813 W	450 W	511 W	413 W	466 W

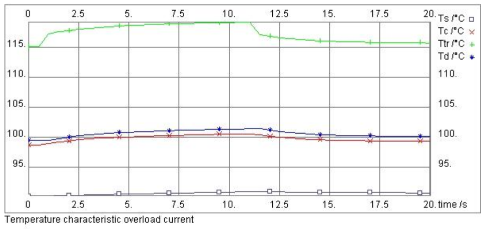
Table 5

	SKM200GB12T4		SKM300GB066D		SKM400GB066D	
T_h	117 °C	119 °C	90 °C	91 °C	86 °C	87 °C
T_c	130 °C	134 °C	99 °C	101 °C	94 °C	96 °C
T_{tr}	154 °C	162 °C	115 °C	119 °C	106 °C	109 °C
T_d	131 °C	135 °C	100 °C	101 °C	95 °C	96 °C

SKM200GB12T4



SKM300GB066D



SKM400GB066D

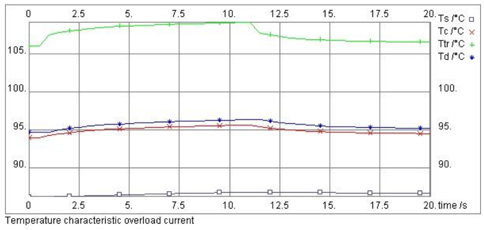


Fig. 8. Temperature losses for 3 different IGBT

B.Analysis of results

- The mode of the induction heating has changing dynamic which affects of the parameters on the resonant circuit, Fig. 4 and 5, and table 1.
- The full bridge converter satisfies the requirements for power and current defined in the table 1.
- Configuration of the full bridge converter with IGBT transistors SKM400GB066D has best features in term of power losses and the temperature losses, table 4 and 5.
- Because the mode of inductiion device has a variable dynamic, the converter which operates with such device in applications where is required constant output power must monitore and regulate the output power with adequate methods of management.
- The frequent and phase control are methods of management on these converters.

3. Conclusion

In the paper is presented method for calculation of induction furnace with computer simulation programs. By computer simulation solving of problems on distribution of the electromagnetic field and the heat transfer in metals is easy and simple.

In the paper is used ELTA simulation program for estimation of the electromagnetic field and the head transfer for work piece metal with cylindrical geometry.

For the defined power, current and frequency on the induction device obtained in ELDA simulation program by the PowerSim simulation program are designed power converter.

By the simulation program Semesiel converter is optimized in term of the switching and the temperature losses.

References

Ericison R.W.2000. *Fundamentals of Power Electronics*, Kluwer.

ELDA 4.1*, 2009.Fluxcontrol, simulation program*.

WWW.PowerSim.com, *simulation program for power electronic 8.0.5*

Stefanov G. Dambov R. 19-20.10.2009. *Fundemental principes of working in resonant converter for induction heating,* MGU International Scientific Conference, Sofia, VOL.52, pp. 23-27.

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

WWW.semikron.com, *simulation program semesiel for power electronic*

Viriya P. Yongyuth N. and Matsuse K. 2008. *Analysis of Two Continuous Control Regions of Conventional Phase Shift and Transition Phase Shift for Induction Heating Inverter under ZVS and NON-ZVS Operation,* IEEE.

Yan Y. Regan Z. June 2004. *Digital Phase Control for Resonant Inverters,* IEEE power electronics letters, VOL. 2, No. 2.

Marius Orban, Maria Orban, Kuril Ianakiev, Evtim Kartzelin, Static converters and their application, St. "Ivan Rilski", Publishing house, University of mining and geology, Sofia, 2002,

Recommended for publication of Editorial board