

Computer simulation of induction heating process for system powered from series inverter

Abstract. The paper presents a simulation analysis of the induction heating of steel load for inductor-charge system supplied by voltage inverter with series resonance. The simulation was based on the coupled analysis of AC electromagnetic field and transient temperature field, including the influence of the heated load temperature variation on the supplying inverter, especially on its output frequency. For two heating systems different with respect to size of the inductor-load air gap, the simulation results were compared with results received for simulation not respecting load-inverter interaction.

Streszczenie. W pracy przedstawiono analizę symulacyjną procesu nagrzewania wsadów stalowych, przy zasilaniu z napięciowego generatora rezonansowego o rezonansie szeregowym. Symulację oparto o sprzężoną analizę pola elektromagnetycznego AC z niestalonym polem temperatury, z uwzględnieniem zmieniających się z temperaturą wsadu parametrów zasilania układu wzbudnik-wsad, w tym częstotliwości prądu zasilającego. Dla dwóch układów grzejnych różniących się wielkością szczeliny powietrznej wzbudnik-wsad zestawiono wyniki symulacji z wynikami dla symulacji nie uwzględniających wzajemnego oddziaływania obciążenia i źródła. (Symulacja komputerowa procesu indukcyjnego nagrzewania w układzie zasilanym z rezonansowego falownika szeregowego).

Keywords: induction heating, inverter for induction heating, series inverter.

Słowa kluczowe: nagrzewanie indukcyjne, falowniki do nagrzewania indukcyjnego, falowniki szeregowo.

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Introduction

Induction heating is currently the dominant technology of industrial heating of metal loads before heat treating or plastic processing. For development of this technology or design induction furnace equipments the computer simulation calculations are used. Depending on the task, these are calculation of electromagnetic field, temperature ϑ field, strain, metal or air flow and computation of electronics control systems or power supply. These different types of computer simulations are often performed in an autonomous, separate way and so e.g. the electromagnetic and thermal field calculations are disconnected from circuit power electronic calculations or control systems calculations. For example, are rare cases [1] in which the induction heating system as control object is simulated by field methods or power electronics system is calculated with take into account that its parameters depend on the charge temperature and shape. This also applies to simulate the electromagnetic field of the inductor – charge system (ICS), which is usually performed almost in separation from the power source, which is treated as a supply voltage or current source with constant amplitude and frequency value. Rather seldom [2], [3] were presented the examples of co- simulation the induction heating system and the power supply. The modern power sources for induction heating are today mainly resonant voltage or current inverter, as shown schematically in Figure 1.

In the inverter for induction heating the ICS is an essential part of the resonant circuit. In such case the changes of the electrical parameters of the heating system, caused its heating or moving, often cause significant changes in the output inverter signal, which (in the other side) acts on the heating process. Taking into account the mentioned interaction of the source and the ICS is therefore so important, from the simulation accuracy point of view. Competent simulation of this interaction can be useful both for the credibility of simulation results as for developing of inverter-load matching systems.

The paper presents a methodology for computer simulation the coupled magneto-thermal problem of inductor-charge system which is fed by voltage signal of varying frequency and amplitude. This changing are caused by temperature field variation of the heating charge which electro-thermal material parameters are temperature dependent. It is

presented on the selected examples of induction heating the cylindrical ICS with cooperation with series inverter.

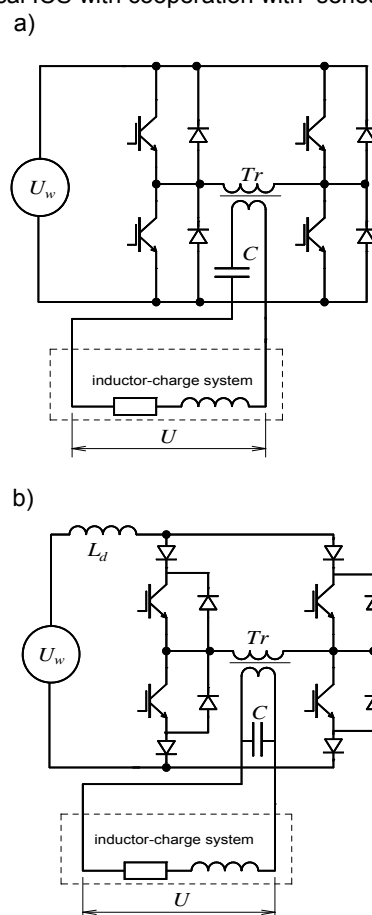


Fig.1. Typical transistor inverters for induction heating applications: a) voltage-fed, b) current-fed.

Induction heating as coupled magneto-thermal problem

From a theoretical point of view, the analysis of the electromagnetic field of ICS is based on Maxwell's equations defining the magnetic field:

$$(1) \quad \text{rot } \mathbf{H} = \mathbf{J}, \quad \text{div } \mathbf{B} = 0, \quad \mathbf{B} = \mu \cdot \mathbf{H}$$

and electric field:

$$(2) \quad \text{rot } \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}, \quad \text{div } \mathbf{J} = 0, \quad \mathbf{J} = \frac{\mathbf{E}}{\gamma}$$

where: \mathbf{H} , \mathbf{E} – vector of magnetic and electric field strength, \mathbf{B} – vector of magnetic density, \mathbf{J} – vector of current density, μ – magnetic permeability, γ – electrical conductivity.

The solution of these equations can be performed in various ways with different types of simplifying assumptions. For induction heating applications is, for example, assumed that the displacement current can be skipped in considerations or (excluding special installations for heating of charges with low resistivity [4]) current induced by charge moving can be neglected too. The issue of magnetic non-linearity of charges, occurring for ferromagnetic material (which are the main induction heated product range) leads clearly to the need of electromagnetic phenomena analysis in the time domain. Taking into account the practical point of view they are often simplified (especially for coupled magneto-thermal calculations) for analysis in time-harmonic domain carried out in the field of complex numbers. In order to reduce the number of variables, the electromagnetic analysis often used the vector potential: magnetic \mathbf{A} or electrical \mathbf{T} . The calculation of the temperature field in the charge is accomplished by solving Fourier-Kirchhoff equation

$$(3) \quad \text{div}[(-\lambda)\text{grad } \vartheta] + \rho c \frac{\partial \vartheta}{\partial t} = p_v$$

where: λ – thermal conductivity, ρ – density, c – specific heat, p_v – volumetric heat source power density,

with the existing boundary and initial conditions taken into consideration.

The temperature dependent electrical parameter of the material occurring in equations (1) and (2) and the volumetric heat flux density p_v in equation (3) which resulting action of the electromagnetic field, makes clear the need for the interconnection of the electromagnetic and thermal calculations. In computer simulation process this connection (coupling) may be realized in different ways. The basic method called "strong coupling" is based on describing the functional correlations of both fields and solving them simultaneously. The scale of difficulties of such approach makes that it is now being used to analyze a very simple cases, such as 1D. "Weak" coupling is a commonly used iterative method combining electromagnetic and thermal calculations. For cases in which there is a high uniformity of temperature field and the temperature has relatively small increments, the "one-way" called coupling can be used in which the transfer of heat sources from electromagnetic to thermal calculations is made only.

Computer implementation of coupled electro-magneto-thermal calculations

Numerical simulation of the electromagnetic or thermal field, in 2D and 3D systems, can be realized now by commercial packages for such calculation [5], [6]. The use of commercial packages, depending on your needs supplemented with own procedures and cooperating programs, seems the most effective way of carrying out scientific research in areas which required computational analysis of magneto-thermal phenomena such as induction heating. This study was based on a commercial software

Flux[®] of French company Cedrat. In this package the coupled magneto-thermal calculations in 2D and 3D domain can be carry out. Such calculations (module Steady AC Magnetic coupled to Transient Thermal) are based on the use of "weak" coupling, connecting iterative the time-harmonic magnetic analysis (module Steady AC Magnetic - using complex numbers) with transient temperature field analysis (module Transient Thermal) as shown schematically in Figure 2.

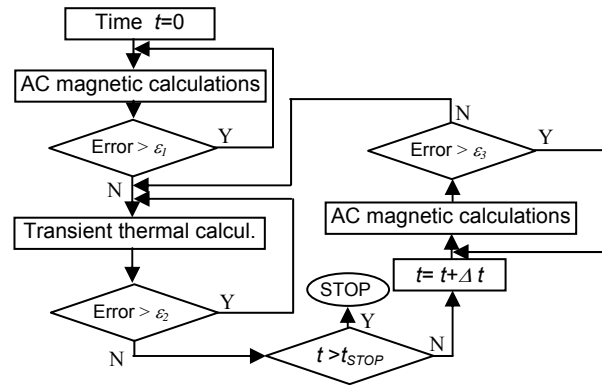


Fig.2. A general algorithm for coupled calculations in Flux[®] package.

The Flux[®] module for coupled magneto-thermal calculations is a very convenient tool for the implementation for induction heating simulation. In a relatively easy way it allows to build the discrete geometric and then the physical model for both the electromagnetic and thermal phenomena. Using this module carries unfortunately also very important limitations. Electromagnetic calculations must be carried out with the use of the description of time-harmonic fields using complex numbers. It is not possible to use, especially important when ferromagnetic charge is heated, the transient field description. Using such description although dramatically increases the cost of computer calculations, but in some specific cases, it may be indispensable. From induction heating practice point of view, the much more restriction of this module, however, is the need to perform calculations for a fixed frequency of power source. In such case even the most basic type of mutual interaction between the source and the load is not taking into account.

These problems can be solved by using of the Multiphysics module. It allows to combine the work of Flux[®] program with work of other programs (including another calculation process realized by Flux[®] program too) thanks communication based on the exchange of disk files. This type of connection seems to be inefficient, but in practice, taking into account the calculation time of every separate process it is very useful and usually a not noticeable increase in the total computation time. This solution offers great opportunities for development. It allows to use of commercial software for a very special purpose. This commercial software can be used in the parts of the considered problem which it is able to solve without closing the users their own creative activities. With this approach, the use of commercial software requires, of course, much greater knowledge of programming. If Multiphysics module is used the work of Flux[®] software can be controlled by the Python files. The idea of working with Multiphysics module, which using the two projects (Magnetic AC and Transient Thermal) carried out simultaneously by two Flux[®] processes was presented in [7], as shown in Fig. 3

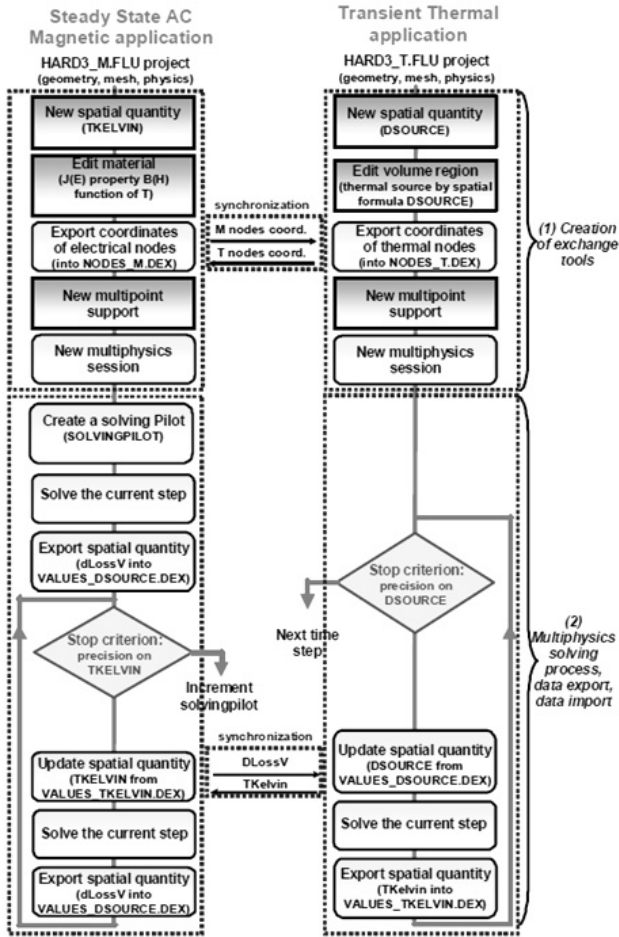


Fig.3. The principle of the exchange of data between running programs using Multiphysics module [7].

The computer simulation of ICS taking into account frequency variation

The computer analysis of ICS taking into account the frequency variation caused by variation of charge temperature was carried out. This co-simulation analysis were made for the two cylindrical systems, which arbitrarily considered to be representative of the heat treatment (e.g. hardening) Fig. 4a and heating before plastic working (e.g. forging) Fig.4b.

The main difference between the considered ICS was limited to the number of inductor coils (Fig. 4a - one turn, Fig. 4b - ten turns) and especial for the size of air gap between the inductor and the charge (1mm and 15mm respectively).

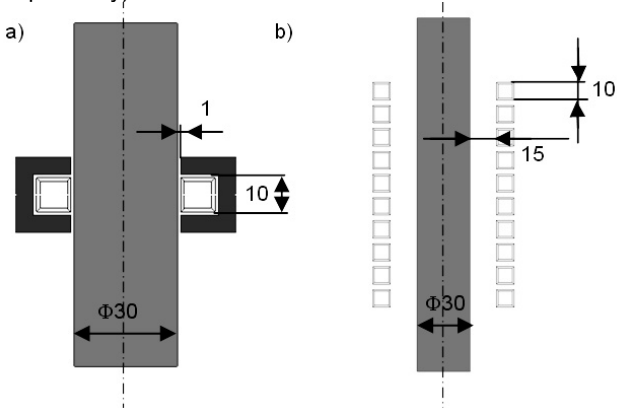


Fig.4. Considered ICS for heating before: a) heat treatment, b) plastic working.

It was assumed that ICS is supplied by a series resonance inverter, as shown in Fig. 5.

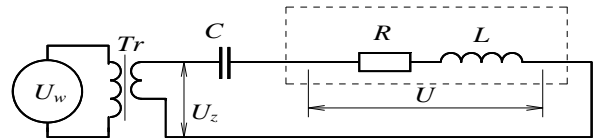


Fig.5. Scheme of assumed supply system.

As presented in [3], [8] for ICS with a quality factor $Q = \omega L/R > 4$ and typical dead time t_d of switching transistors smaller than a few to several percent of the oscillation period T , the current output of this inverter dominated by the first harmonic of the error of values RSM less than 2-3 percents. This is not for inverter output voltage which is rather close to square wave but taking into account that ICS is supplied by transformer the sine wave source U_z for the first harmonic of secondary side of matching transformer was assumed, Fig. 5. The discussion also omitted dead time, assuming that working frequency is equal to the series resonant frequency.

Using Multiphysics module and appropriate modifying presented in [7] Python control file, the connection of AC electromagnetic and transient thermal calculations of Flux program were realized. The synchronization operation was based on disk files indicating the completion status of each type of calculation. Electromagnetic calculations are waiting for finish thermal calculation and vice versa. This approach is paid for, mentioned above, the slowdown associated with the exchange of data across the disk, but does not limit it in any way of multicore or multiprocessor work every type of calculations.

In the Python control file was introduced the procedures for changing the resonance frequency f and the voltage U (which supplied ICS, Fig.5) caused by changing (with charge temperature) the values of the equivalent resistance R and inductance L of ICS. It was assumed that RSM value of the matching transformer output voltage U_z and resonant capacitance C are constant.

Sample simulations for ICS presented in Fig. 4a were carried out for ferromagnetic steel charge of resistivity $\rho = 0.25 \cdot 10^{-6} (1 + 4 \cdot 10^{-3} \cdot \theta)$, for capacitance $C = 0.426 \text{ mF}$ (such value for "cold" state of charge yields the resonant frequency $f = 30 \text{ kHz}$) and for output RSM voltage of the matching transformer $U_z = 9 \text{ V}$ (such value for initial "cold" state of the process gives the effective RSM voltage on ICS $U = 15 \text{ V}$). The received time curve of charge surface temperature (in the middle of the inductor) is presented in Fig. 6a. In Fig.6b the waveforms of frequency f , RSM value of ICS voltage U at power P_c of charge were presented. These figures also shows the waveforms of charge surface temperature and ICS power, obtained for simplifying simulation assuming the constancy value (as for initial "cold" state) of supply frequency f . Such assumption is typical for magneto-thermal coupling simulations which join magnetic AC and transient thermal simulations in way presented in Fig.2. In this simplifying simulation the supply circuit (Fig.5) with $U_z = \text{const}$ was taken into account. For comparative purposes in Fig.6a the surface temperature of charge received for simulation in which was assumed not only constant frequency but also the voltage U on inductor was presented too.

For the same type of charge material, the simulations of heating process in system from Fig.4.b were carried out. The simulations were made for the RSM output voltage of the matching transformer $U_z = 49.6 \text{ V}$ (at the initial "cold" state of the process its gives the voltage on ICS, $U = 280 \text{ V}$),

and the resonant capacitance $C = 13.96 \mu\text{F}$ (in "cold" state it gives, as before, the resonant frequency $f=30\text{kHz}$). In Fig.7a the obtained waveforms of charge temperature, at its axis and surface (in the middle of the inductor) were presented.

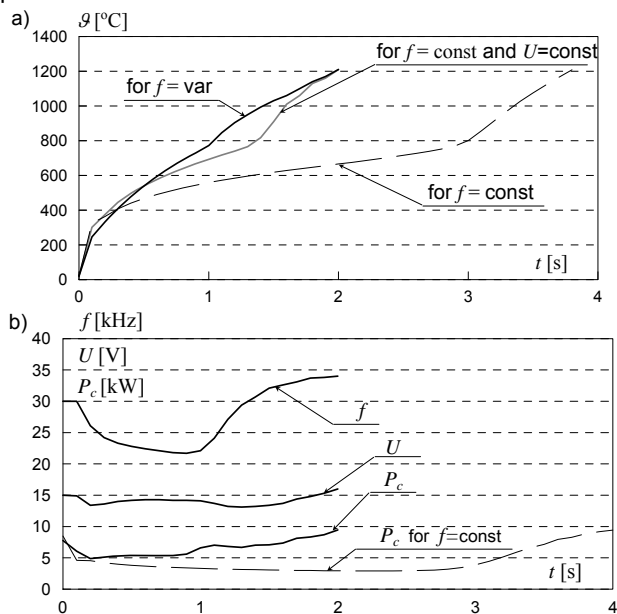


Fig.6. Waveforms a) temperature and b) the frequency f , voltage U , power in the charge P_c during heating of ICS from Fig.4a.

The Fig. 7b shows time curves of the frequency f , ICS voltage U and power P_c in charge.

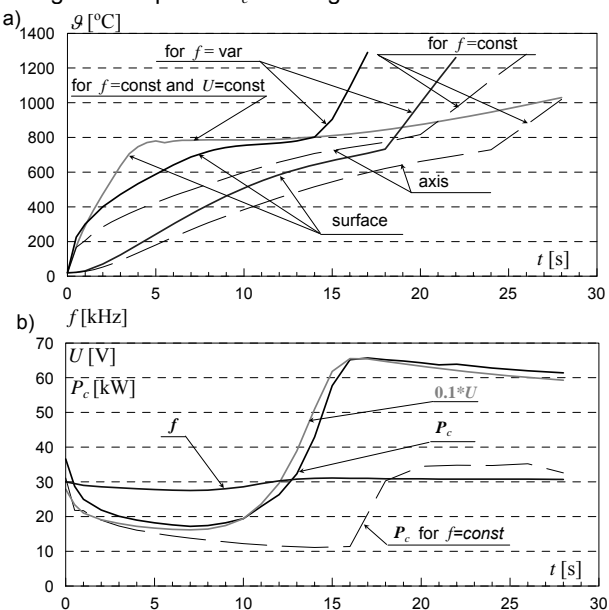


Fig.7. Waveforms a) temperature and b) the frequency f , voltage U , power in the charge P_c during heating of ICS from Fig.4b.

The figures also show the waveforms of these temperatures and power in the charge, obtained for simulation assuming constant frequency (as for initial "cold"

state). As before for comparative purposes in Fig.7a the surface temperature of charge received for simulation in which was assumed not only constant frequency but also the voltage U on inductor, was presented too.

Conclusions

The paper presents the simulation results for examples of induction heating the steel charges before heat treatment (Fig.4a) and plastic working (Fig.4b) in the system supplying by series resonance inverter. The main emphasis was put on the need to take into account in the simulations, the issues of frequency variation caused by charge temperature increasing.

The simulations results presented in Fig.6 and Fig.7 allow to make a number of comments and requests for such simulation process:

- disregarding the interaction of load and power supply resonance series inverter can lead to significant errors in the calculations,
- disregarding the working frequency variation can lead to significant errors both in ICS with "small" (as for heat treatment) and "big" (as for plastic processing) air gap, although the magnitude of frequency change for these processes is significant different,
- in ICS with "big" air gap the taking into account (in simplified simulation assuming $f = \text{const}$) that voltage on the inductor is changing during heating process (for $U_c = \text{const}$, Fig.5) improves significantly simulation results, but it do not remove the error caused by disregarding the phenomenon of frequency changing.

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