

# Approximate Computation of Inductors with Variable Coil Turn Space Factor for Through-Heaters using MATLAB

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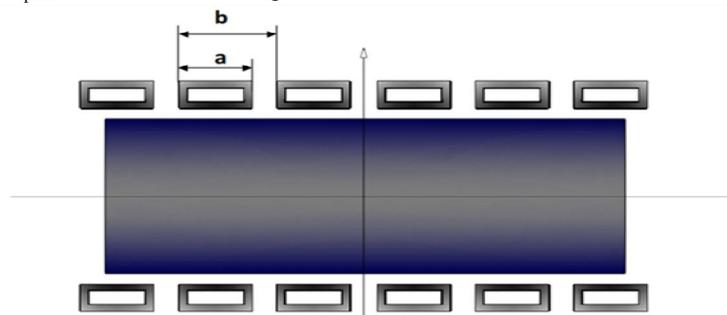
## ABSTRACT

*The paper presents an approximate computation of inductors with variable coil turn space factor for through-heaters using Matlab GUI (Graphical User Interface), that calculates the electric parameters of the inductor and goes step by step with the computation finding the geometry of the inductor for a given workpiece. We develop a Matlab GUI that requires certain input values in order to compute the requested output variable. The paper discuss an approximate computation of inductors with variable coil turn space factor for through-heaters having given a cylindrical billet as workpiece, but the same principle can be applied to other shapes of workpiece.*

**Keywords:-** induction heating, Matlab, electric computation of the inductor, geometry computation of through-heaters.

## 1. INTRODUCTION

Uniform distribution of the temperature, inside the billet, was and will remain an important topic in all kinds of mass heating. A considerable time reduction of heating, and thus reduce the length of the inductor can be done by using an inductor with variable coil turn space factor  $k_{space}$  [1], and making it bigger at the end of unloading area. The coil turn space factor is equal with:  $k_{space}=a/b$  as shown in Figure 1.

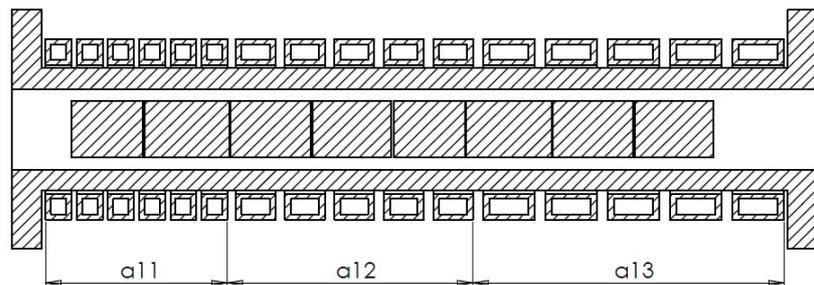


**Figure 1** Coil turn space factor  $k_{space}$

Due to the fact that through all the coils is passing the same current, the magnetic field intensity and hence the specific power will have the maximum at the beginning of the inductor, which is ensuring a fast increasing of temperature. Billet surface temperature reaches a final value within 10-30% of the total heating time, which happens on the sector of 10-30% from the total length of the inductor, and further on the temperature of the billet is almost unchangeable, fact that is ensuring a faster heating of deeper layers. Such a heating process is called accelerated heating [2]. Induction heating is highly used to heat metal mostly for hot forming by forging, upsetting, rolling, extrusion and other methods. Billets are heated either in cut lengths or continuously and are forged in presses, or upsetters, or are extruded. Steel components by far represent the majority of hot-formed billets, although other materials including titanium, aluminum, copper, brass, bronze and nickel are also induction heated for forming. The initial temperature of the billet prior to induction heating may be uniform (at ambient temperature) or nonuniform. It is typically required to raise the temperature of the billet to a specified level and degree of heat uniformity. The uniformity requirement may include maximum tolerable temperature differences like: surface-to-core, end-to-end and side-to-side. For this kind of applications, as billet-heating, the powers start from hundreds to thousands of kilowatts and frequencies go from typically in the line frequency (50 to 60 Hz) to 3 kHz range, that is the most commonly used for induction heating of large billets.

**2. COMPUTATION**

Two of the most common billet-heating are progressive multistage horizontal heating and static heating. Progressive multistage horizontal heating goes especially for small and medium size billets (usually less than 150 mm in diameter). The billet is progressively heated at predetermined positions inside of the induction heater. When heating large steel diameter (200 to 300 mm and larger), it is usually proper to use a static heating with a vertical coil arrangement or a combination of progressive multistage horizontal method for preheating and the static vertical method for final heating [3]. Billet-heating in inductors with variable coil space turn factor is done usually with two or more billets, which are moved through a single coil or multicoil. In practice the coil turn space factor, implicitly the multicoil number, doesn't exceed the number four. In most of the cases the limit is three and in some cases even at two different coils turn space factor for the whole inductor [4]. We'll consider the case of three different coil turn space factor as shown in Figure 2.



**Figure 2** 2D drawing of considered inductor with the sectors lengths of the three different coil turn space factor

To make an approximate computation of inductors with variable turn space factor for through-heaters, for above given billet geometry and electric parameters, we used the following equations to find out the geometry of the inductor:

$$a_{21} = (0,2\dots0,3)a_2 = a_{22} \tag{1}$$

$$a_{23} = (0,4\dots0,6)a_2 \tag{2}$$

$$a_{11} = a_{21} + \Delta a \tag{3}$$

$$a_{12} = a_{22} \tag{4}$$

$$a_{13} = a_{23} + \Delta a \tag{5}$$

$$\Delta a = (a_1 - a_2) / 2 \tag{6}$$

where,  $a_{21}, a_{22}, a_{23}$  – are the sectors lengths that is separating the billets loading measured in meters [m] and  $a_{11}, a_{12}, a_{13}$  – are the inductors sectors lengths for the three different coil turn space factor measured in meters [m]. After the computation of the sectors lengths of the billet loading and of the inductor, we can compute the heating time for each sector of the billet loading.

For the first sector:

$$t_1 = a_{21}t_k / a_2 \quad [s] \tag{7}$$

The time for the second sector:

$$t_2 = (a_{21} + a_{22})t_k / a_2 \quad [s] \tag{8}$$

and

$$t_3 = t_k \quad [s] \tag{9}$$

where,  $t_k$  – is the heating time measured in seconds [s]. Magnetic field intensity on each sector of the billet loading can be approximately computed, if we consider that the outer magnetic field of the inductor  $H_A$  is equal with zero.

In this case the current on each sector of the billet loading will be:

$$I_{21} = a_{21}H_{e1} \quad [A] \tag{10}$$

$$I_{22} = a_{22}H_{e2} \quad [A] \tag{11}$$

$$I_{23} = a_{23}H_{e3} \quad [A] \tag{12}$$

where,  $H_{e1}$ ,  $H_{e2}$ ,  $H_{e3}$  – are the values of the magnetic field intensity on each sector, and they will be computed knowing the total power on each sector and also their resistance. The resistance and the reactance of the first sector, measured in ohms  $[\Omega]$ , will be computed with the formulas:

$$r_{21} = \pi D_2 \cdot 3,6 \cdot 10^{-6} \sqrt{f / a_{21}} \quad (13)$$

$$x_{21M} = 0,298 \cdot r_{21} \quad (14)$$

The total power and the reactive power will be computed with the formulas:

$$P_{21} = p_1 \pi D_2 a_{21} = I_{21}^2 r_{21} = (a_{21} H_{e1})^2 r_{21} \quad [W] \quad (15)$$

$$P_{21r} = 0,298 \cdot P_{21} \quad [Var] \quad (16)$$

And from above relations (15) and (16), the magnetic field intensity will be:

$$H_{e1} = \frac{1}{a_{21}} \sqrt{\frac{P_{21}}{r_{21}}} \quad [A / m] \quad (17)$$

For the sectors two we'll use the relations:

$$r_{22} = \pi \rho_2 m_2^2 A / a_{22} \quad [\Omega] \quad (18)$$

$$x_{22M} = r_{22} B / A \quad [\Omega] \quad (19)$$

$$P_{22} = p_2 \pi D_2 a_{22} = I_{22}^2 r_{22} = (a_{22} H_{e2})^2 r_{22} \quad [W] \quad (20)$$

$$P_{22r} = 0,298 \cdot P_{22} \quad [Var] \quad (21)$$

$$H_{e2} = \frac{1}{a_{22}} \sqrt{\frac{P_{22}}{r_{22}}} \quad [A / m] \quad (22)$$

The same algorithm of relations will be used also for sector three, as per sector two relations.

The average intensity of the magnetic field, for the whole length of the sector will be:

$$H_e = \frac{a_{21} H_{e1} + a_{22} H_{e2} + a_{23} H_{e3}}{a_2} \quad [A / m] \quad (23)$$

and

$$P_2 = P_{21} + P_{22} + P_{23} \quad [W] \quad (24)$$

$$P_{2r} = P_{21r} + P_{22r} + P_{23r} \quad [Var] \quad (25)$$

In the final part, after we calculate the number of the coil turns against the resulted voltage:

$$\omega = U_i / U_i' \quad (26)$$

and we'll compute the average number of coil turns for the total length of the inductor.

$$\omega' = \omega / a_1 \quad [turns / m] \quad (27)$$

The sectors are connected in series and the current in the windings of all sectors is the same. So, unless we don't take in account the magnetomotive voltage outside the inductor, we can determine the number of windings per unit length of each sector, proportionally with the magnetic field intensity corresponding on each sector. In this way:

$$\omega_1' = \omega' H_{e1} / H_e \quad (28)$$

$$\omega_2' = \omega' H_{e2} / H_e \quad (29)$$

$$\omega_3' = \omega' H_{e3} / H_e \quad (30)$$

where,  $\omega_1'$ ,  $\omega_2'$ ,  $\omega_3'$  – represent the number of windings per unit length of each sector,

A check is needed to see the allocation of windings:

$$\omega = a_{11} \omega_1' + a_{12} \omega_2' + a_{13} \omega_3' \quad (31)$$

where,  $\omega$  – is the number of the windings of the inductor, determined at equation (26). If the number of windings, from equation (31), is bigger compared with the number of windings from equation (26), then the number of windings from equation (29) and (30) needs to be decreased.

### 3. RESULTS AND DISCUSSIONS

Based on the above summarized relations, with the help of Matlab GUI (Graphical User Interface), we developed some interfaces that compute the needed parameters. A certain input values are needed in order to have the output values.

As an example in our computation, we'll choose a billet with the further given input values: billet diameter  $D_2=0.07\text{m}$ , length of the billet  $a_2=0.15\text{m}$ , frequency  $f=1900\text{ Hz}$ , delivery time of billet  $t_0=25\text{s}$ , temperature gradient  $T=100^\circ\text{C}$ , voltage  $U_i=750\text{V}$ . The GUI interface for computation of heating time can be seen in Figure 3. After the requested input values are given, we press "Compute" button and the result will be shown [5]-[7].

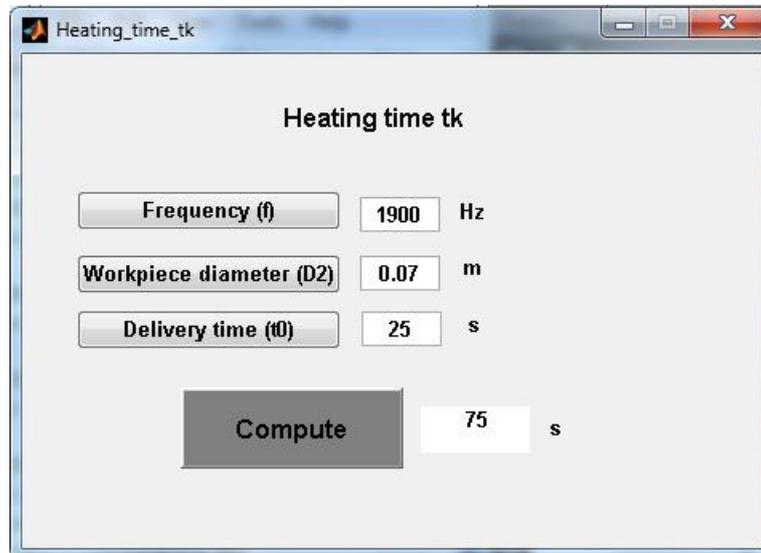


Figure 3 Computation of heating time  $t_k$  for given data  $f=1900\text{Hz}$ ,  $D_2=0.07\text{m}$  and  $t_0=25\text{s}$

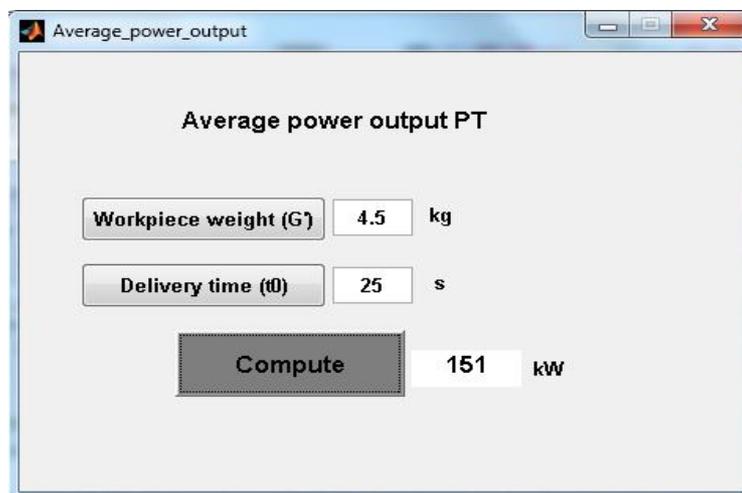


Figure 4 Computation of average power output  $P_T$  for given data  $G'=4.5\text{kg}$  and  $t_0=25\text{s}$

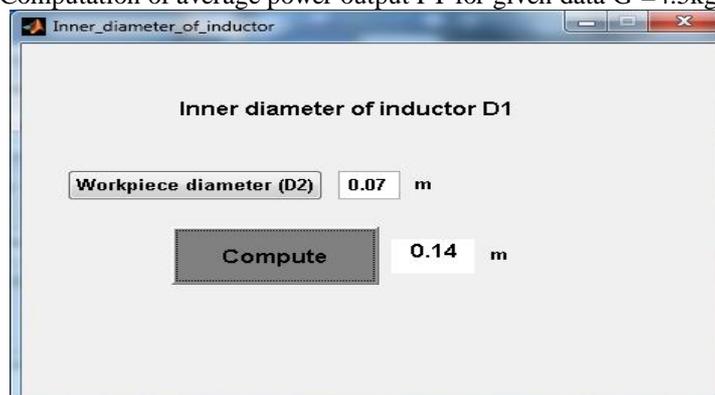
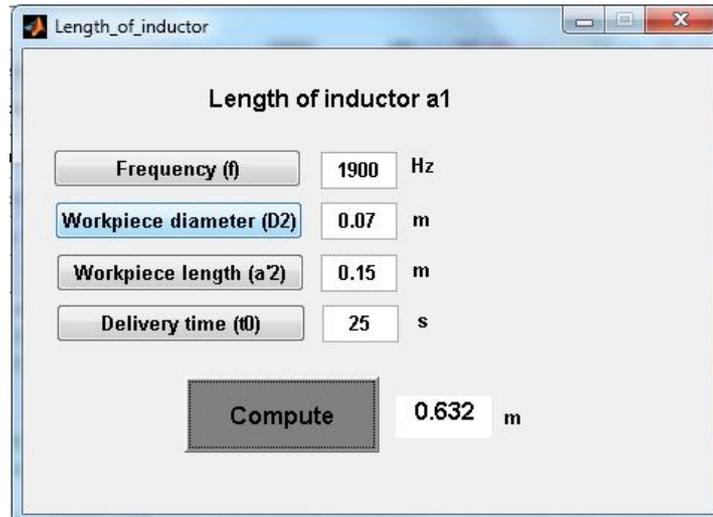
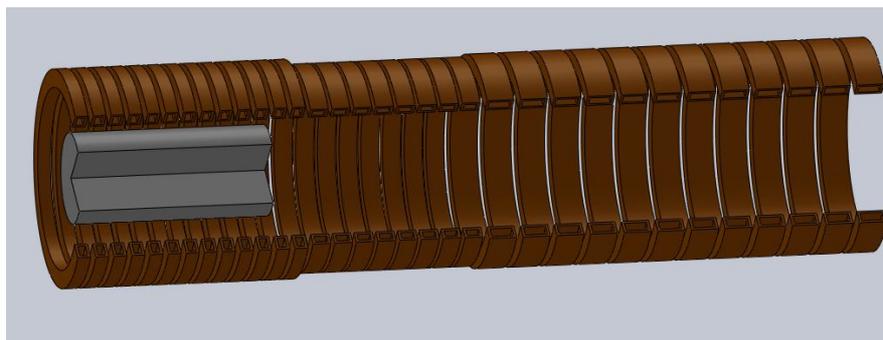


Figure 5 Computation of inner diameter of inductor  $D_1$  for given data  $D_2=0.07\text{m}$



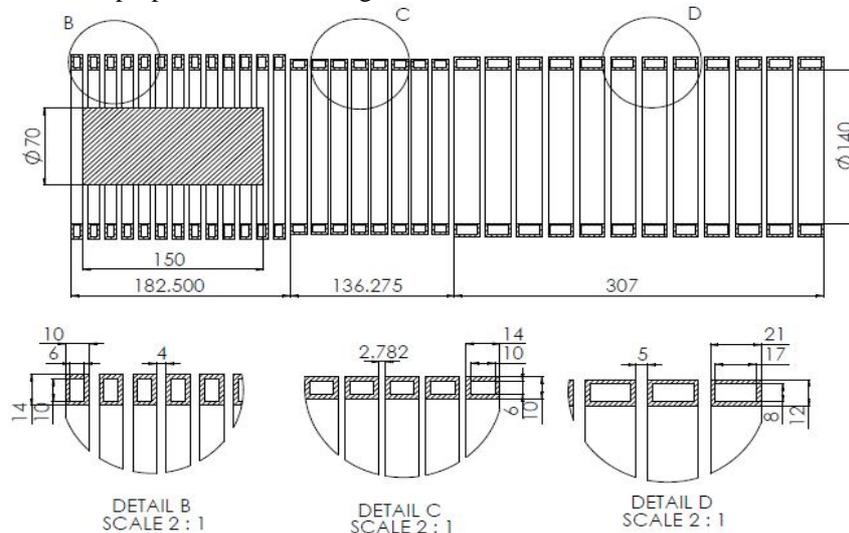
**Figure 6** Computation of length of inductor a1 for given data  $f=1900\text{Hz}$ ,  $D2=0.07\text{m}$ ,  $a^2=0.15\text{m}$  and  $t0=25\text{s}$

A certain output parameters were presented in Figure 4, Figure 5 and Figure 6, with the related GUI interface and pointed out the input values needed to compute the requested parameters. We cannot plot the whole GUI interfaces developed for our proposed objective, that of making an approximate computation of inductors with variable coil turn space factor for through-heater, but following presented relations we reached out the geometry of the inductor and its electric parameters.



**Figure 7** 3D model of computed inductor along with the 3D model of given billet

Figure 7 and Figure 8 are showing the resulted 3D and 2D geometry of the inductor, computed for induction heating of suggested billet. Having the approximate computation of the inductor with the three different coil turn space factor and also its electric parameters, a proper further checking will be a simulation of billet induction heating.



**Figure 8** 2D drawing of computed inductor along with the 2D drawing of given billet

#### **4. CONCLUSIONS**

Temperature uniformity inside the billet is a request in almost all mass induction heating. The paper presents an approximate computation of an inductor with variable coil turn space factor that starts from the billet data and the frequency and voltage of the installation. The method Matlab GUI has the advantage of flexibility and fast results output. Another aspect that needs to be considered is that Matlab GUI method is very easy to use, no need to go in details. All the equations are done in background; you just get the results. After the computation of the inductor for proposed billet, a linked simulation of billet induction heating will give further information for designing the proper through-heater.

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