Determining of the Electrical Parameters of a Hardening Inductor

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Abstract: This paper presents a method of determining the electrical parameters that characterize the functioning of the supplying system of a hardening inductor: high frequency supplying transformer, short network and inductor-work piece system. The method combines geometrical issues, especially for the inductor-work piece system and measured results of the electrical parameters of the installation.

Key-Words: Hardening inductor, inductor-work piece system, electro thermal installation.

1. Introduction

Hardening treatment is a controlled heating and cooling process of metals in order to alter their physical and mechanical properties without changing the product shape. This process improves product performance by increasing strength or other desirable characteristics.

Steels are particularly suitable for heat treatment, since they respond well to heat treatment.

Induction heating treatment has the purpose to increase the steel hardness in a superficial layer, without changing the moldable properties in deeper layers. This process consists in heating the superficial layer using high frequency eddy currents. So, the piece is introduced into the hardening inductor, followed by cooling using air, water or oil.

Heating duration (usually second) depends on the applied power on the surface unit that has values between 2-10 KW/cm² [3].

There are many advantages in heating with high frequency eddy currents: the hardening time is reduced, the heating depth of penetration is controlled, and thermally regime can be also controlled in case of various shapes of workpieces.

The main goal of this paper is determining the electrical parameters of a hardening inductor. The electrical scheme that contains this inductor is presented in figure 1. The authors use a measurement set of electrical parameters established during the functioning of the installation [5], [6] and [8].

2. Technical characteristics of the electro thermal installation

The hardening electro thermal installation presented in figure 1 is composed by a converter CTC100K15 [4] and an inductor designed for hardening the materials. CTC100K15 has the following electric characteristics:
- supplying voltage 3×400V, 50Hz;
- rated current 27A;
- control voltage 24Vdc;
- consumed power at high frequency 15kW;
- voltage at medium frequency 500Vac [4].

The electro thermal installation is supplied from the three phase low voltage on 0.4kV, through a general distribution board equipped with an automat circuit breaker with thermal protection with Ir=40A, electromagnetic protection with lem=5It, differential protection with Id = 300 mA and overvoltage at 50Hz protection at U ≥ 260 - 280V. The power system voltage at 6kV is generated by a power transformer 6/0.4 kV, 400 kVA, Δ/Y connection.

The on/off switching of the installation is made with three static contactors WG480-D50Z (Solid state relay-SSR). Input characteristics are [4]:
- dielectric strength: 1500Vac;
- insulation resistance: 10³-10⁶MΩ;
- stray capacitance: 1-10pF.

In the electric scheme are introduced two diode bridge rectifiers KBPC 3508 with the following electric characteristics:
- maximum recurrent peak reverse voltage 800V;
- maximum RMS bridge input voltage 560V;
- maximum average forward rectified output current 35A;
- peak forward surge current 8.3ms single-half sine-wave superimposed on rated load 400A;
- maximum forward voltage drop per element 1.2V;
- maximum reverse current at rated dc blocking voltage per element 1μA.

In order to control the frequency in the melting and hardening process, it is using an inverter with four IGBT transistors: FF150R12KS4 with the following characteristics [4]:
- collector-emitter breakdown voltage 1200V;
- collector-emitter saturation voltage 3,2V;
- continuous collector current Icmax=225A;
- gate-emitter leakage current 400nA;
- power disipation 1,25kW.
The hardening inductor is supplied from two high frequency toroidal transformers [4]:

- T1: 660/500V, 40kVA, 70-100 kHz;
- T2: 150 kVA, 70-120 kHz with primary winding voltage of 500V and variable transformation ratio of 3:1, 5:1, 6:1, 10:1.

The electro thermal installation contains three coil shape inductors for hardening process.

The measurement set was made using a single turn copper inductor (fig. 2) and a steel piece (OLC45). T2 transformer had the transformation ratio 5:1 and the consumed power at high frequency was 15kW.

3. Determining of the electrical parameters

The electrical parameters of the inductor-work piece system are the resistance R and reactance X (fig. 3). The parameters of the transformers T1 and T2 are noted with Rp1, Xp1, Rs1, Xs1, respectively Rp2, Xp2, Rs2, Xs2.

The determining of the electrical parameters of the inductor-work piece system is made taking into consideration the hot state moment when the piece temperature exceeds the Curie temperature. At this time the relative magnetic permeability is $\mu_r = 1$.

The measurement set contains the followings:
- functioning frequency is $f = 91$kHz;
- current in primary winding of T1 is $I_1 = 46$A;
- voltage in primary winding of T1 is $U_1 = 442$V;
- power factor measured at the supplying source is $\cos \varphi = 0.66$ [7]
- supplying active power is $P = 15$kW.

This paragraph contains also the variation of the most representative electrical parameters measured at the supplying source (figures 5-10) [7].

The single turn inductor has the following characteristics:
- electrical resistivity $\rho_1 = 10 \cdot 10^{-8}$ $\Omega m$ [3];
- diameter $d_1 = 30 \cdot 10^{-3}$ $m$;
- height $h_1 = 7.8 \cdot 10^{-3}$ $m$.

The workpiece has the following characteristics:
- electrical resistivity $\rho_2 = 130 \cdot 10^{-8}$ $\Omega m$ [3];
- diameter $d_2 = 20 \cdot 10^{-3}$ $m$;
- height $h_2 = 7.8 \cdot 10^{-3}$ $m$.

3.1. Determining the inductor-work piece system parameters

The heating depth of penetration can be calculated for the both components of the inductor-work piece system...
with the following relation [1], [2], [3]:

\[ \delta = 503 \frac{\rho}{\mu_0 f} \]  

(1)

From relation (1) there are resulting the followings:

\[ \delta_1 = 0.52 \cdot 10^{-7} m \]
\[ \delta_2 = 1.9 \cdot 10^{-3} m \]

The electrical resistance and reactance of the inductor are calculated with the relations [1]:

\[ R_1 = \rho_1 \cdot \frac{\pi \cdot d_1}{h_1 \cdot \delta_1} \cdot N^2 \cdot K_{R1} \]  

(2)
\[ X_1 = R_1 \cdot \frac{K_{X1}}{K_{R1}} \]  

(3)

where \( g = 1 \) (the inductor section is a square) \( N = 1 \) (the turns number of the inductor). \( K_{R1} = 0.94 \) and \( K_{X1} = 0.98 \) are functions that in case of the inductors can be expressed by hyperbolic functions [1], [2], [3].

After the calculation, there are resulting the inductor parameters:

\[ R_1 = 2.15 \cdot 10^{-3} \Omega, \quad X_1 = 2.24 \cdot 10^{-3} \Omega \]

The electrical resistance and reactance of the piece are calculated with the relations [1]:

\[ R_2 = \rho_2 \cdot \frac{\pi \cdot d_2}{h_2 \cdot \delta_2} \cdot K_{R2} \]  

(4)
\[ X_2 = \rho_2 \cdot \frac{\pi \cdot d_2}{h_2 \cdot \delta_2} \cdot K_{X2} \]  

(5)

\( K_{R2} = 0.95 \) and \( K_{X2} = 0.98 \) are functions that in case of the cylindrical pieces can be expressed by Bessel functions [1], [2], [3].

The parameters for the steel piece are:

\[ R_2 = 5.23 \cdot 10^{-3} \Omega, \quad X_2 = 5.4 \cdot 10^{-3} \Omega \]

The leakage inductivity for the inductor and the piece can be determined using the following relations [1]:

\[ L_1 = \mu_0 \cdot \frac{\pi \cdot d_{1m}^2}{4h_1} \cdot N^2 \cdot \alpha_1 \]  

(6)
\[ L_2 = \mu_0 \cdot \frac{\pi \cdot d_{2m}^2}{4h_2} \cdot \alpha_2 \]  

(7)

where

\[ d_{1m} = d_1 + \delta_1 \]
\[ d_{2m} = d_2 - \delta_2 \]  

(8)

The mutual inductivity is:

\[ M = N \cdot L_2 \cdot \frac{\alpha_M}{\alpha_2} \]  

(9)

The parameters \( \alpha_1, \alpha_2, \alpha_M \) are functions that depend on the material dimensions [1], [2], [3].

In case of small height inductors, \( \alpha_2 = \alpha_M [2] \).

After the calculation,

\[ L_1 = 435.6 \cdot 10^{-10} H \]
\[ L_2 = M = 205.08 \cdot 10^{-10} H \]

The transformation ratio of the inductor-work piece system is calculated with the following relation [1], [2]:

\[ p^2 = N^2 \cdot \frac{(\alpha_M / \alpha_2)^2}{1 + (R_2 / \omega L_2)^2} = 0.846 \]  

(10)

The electrical impedance of the inductor-work piece system is:

\[ Z = R_1 + R_2 + j(X_1 + X'_a + X'_2) = R + jX \]  

(11)

where

\[ R_2 = p^2 \cdot R_2 \]  

is the electrical resistance of the inductor-work piece system.
\[ X'_a = \omega L_1 - p^2 \omega L_2 \]  

is the reactance of the air between inductor and piece.
\[ X'_2 = p^2 X_2 \]  

is the reactance of the inductor-work piece system.

The authors obtained the following results:

\[ R = 6.5 \cdot 10^{-3} \Omega \]
\[ X = 23.7 \cdot 10^{-3} \Omega \]
\[ Z = \sqrt{R^2 + X^2} = 24.6 \cdot 10^{-3} \Omega \]

### 3.2. Determining the electrical parameters of the HF transformer

The following calculation has the purpose to obtain the electrical parameters of the HF transformer windings. They can be made using the figure 3.

HF transformer T1 has the transformation ratio \( k_1 = 1.32 \) (figure 1). There can be calculated the voltage and current in the secondary winding of T1:

\[ I_2 = k_1 \cdot I_1 = 60.7 A \]
\[ U_2 = \frac{U_1}{k_1} = 334.8 V \]

The HF transformer T2 has the transformation ratio \( k_2 = 5 \). There can be calculated the voltage and current in the secondary winding of T2:

\[ I_2 = k_2 \cdot I_1 = 303.5 A \]
\[ U_2 = \frac{U_1}{k_2} = 66.96 V \]

The electrical parameters of the inductor-work piece system reported at the primary winding of T2 are:

\[ R_{p2e} = R_{p2} + \frac{R_{2eR}}{k_2^2} \]  

(12)
\[ X_{p2e} = X_{p2} + \frac{X_{2e}}{k_2^2} \]  

(13)

The impedance of the inductor-work piece system reported at the primary winding of T2 is:
\[ Z_{p2e} = \frac{U_2}{I_2} = 5.51 \Omega \]
\[ Z_{p2e} = \sqrt{R_{p2e}^2 + X_{p2e}^2} \]  
(14)

The electrical parameters of the system supplied by the secondary winding of T2 are:
\[ R_{sR} = R + R_{s2} \]
\[ X_{sR} = X + X_{s2} \]  
(15)
The impedance is:
\[ Z_{s2e} = \sqrt{R_{s2e}^2 + X_{s2e}^2} = \frac{U}{I} = 0.22 \Omega \]
\[ \cos \varphi = \frac{15kW}{20.3kVA} = 0.73 \]
\[ \cos \varphi = \frac{R_{s2R}}{Z_{s2e}} \]  
(16)
\[ R_{s2R} = 0.16 \Omega \]
The resistance in the secondary winding of T2 is:
\[ R_{s2} = R_{s2R} - R = 0.153 \Omega \]
\[ X_{s2} = X_{s2X} - X \]
\[ X_{s2X} = \sqrt{Z_{s2e}^2 - R_{s2R}^2} = 0.15 \Omega \]
The reactance in the secondary winding of T2 is:
\[ X_{s2} = 0.126 \Omega \]
\[ R_{p2e} = R_{p2} + \frac{0.16}{25} \]
\[ X_{p2e} = X_{p2} + \frac{0.15}{25} \]

Power factor measured at the supplying source is \( \cos \varphi_m = 0.66 \) (fig. 9).
\[ R_{p2e} = \cos \varphi_m \cdot Z_{p2e} = 3.63 \Omega \]
The resistance in the primary winding of T2 is:
\[ R_{p2} = 3.62 \Omega \]
\[ X_{p2e} = \sqrt{Z_{p2e}^2 - R_{p2}^2} = 4.14 \Omega \]
The reactance in the primary winding of T2 is:
\[ X_{p2} = X_{p2e} - \frac{0.15}{25} = 4.13 \Omega \]

3.3. Measurements with power quality analyzer.

As it was depicted at the beginning of this chapter, the authors used a measurement set of electrical parameters made during the functioning of the electro thermal installation with HF transformation ratio 5:1 and consumed power at high frequency 15kW.

The measurements were made using a three phase power quality analyzer, CA 8334B. In order to recover the recordings, the transients, the alarms and the screen copies, there was used the QualiStar View software [9].

CA 8334B can measure and compute the following electrical parameters: electrical network frequency, RMS values for line and phase voltages and currents, crest factor and THD generated by line and phase voltages and currents, active, reactive and apparent powers, power factor and displacement power factor. All these electrical parameters have graphical representations selecting different channels [9].

![Fig. 4. CA 8334B power quality analyzer.](image)

Measurement for RMS voltage and currents are computed according to the following relations [9], [10]:
\[ V_{rms}(i) = \sqrt{\frac{1}{N} \sum_{n=0}^{N-1} V(i,n)^2} \]  
(17)
where: \( V_{rms} \) - RMS phase voltage;
\[ U_{rms}(i) = \sqrt{\frac{1}{N} \sum_{n=0}^{N-1} U(i,n)^2} \]  
(18)
where: \( U_{rms} \) - RMS line voltage;
\[ A_{rms}(i) = \sqrt{\frac{1}{N} \sum_{n=0}^{N-1} A(i,n)^2} \]  
(19)
where: \( A_{rms} \) - effective phase current;

In relations (1) – (3) \( N \) represents the number of samples for one period of the input signal and \( i \) represents the number of the phase.

The three phase electric powers are computing with relations [9]:
\[ P(i) = \frac{1}{N} \sum_{n=0}^{N-1} V(i,n) \cdot A(i,n) \]  
(20)
\[ S(i) = V_{rms}(i) \cdot A_{rms}(i) \]  
(21)
\[ Q(i) = \frac{1}{N} \sum_{n=0}^{N-1} V(i,n) \cdot A(i,n) \cdot \cos \varphi \]  
(22)
\[ \text{or} \]
\[ Q(i) = \sqrt{S(i)^2 - P(i)^2} \]
where: \( P(i) \) is the active power, \( Q(i) \) is the reactive power and \( S(i) \) is the aparrent power on the \( i \) phase.

The power factor is computed based on electric powers using the relation [9]:
\[ PF(i) = \frac{P(i)}{S(i)} \]  
(23)
4. Conclusions

Using a measurement set of electrical parameters made during the functioning of electro thermal installation described in the second paragraph, the authors determined the electrical parameters of the hardening inductor attached to the electro thermal installation.

The inductor is a single turn copper inductor cooled by water with the following dimensions:
- diameter $d_1 = 30 \cdot 10^{-3} m$
- height $h_1 = 7.8 \cdot 10^{-3} m$

The piece (OLC45) has the following dimensions:
- diameter $d_2 = 20 \cdot 10^{-3} m$
- height $h_2 = 7.8 \cdot 10^{-3} m$

Determining of the electrical impedance of the inductor-work piece system was made when it was reached the Curie temperature.

The inductor parameters are:
- $R_1 = 2.15 \cdot 10^{-3} \Omega$
- $X_1 = 2.24 \cdot 10^{-3} \Omega$

The parameters for the steel piece are:
- $R_2 = 5.23 \cdot 10^{-3} \Omega$
- $X_2 = 5.4 \cdot 10^{-3} \Omega$
The electrical parameters of the inductor-work piece system are:

\[ R = 6.5 \cdot 10^{-3} \, \Omega \]
\[ X = 23.7 \cdot 10^{-3} \, \Omega \]
\[ Z = \sqrt{R^2 + X^2} = 24.6 \cdot 10^{-3} \, \Omega \]

Following HF electric equivalent scheme (figure 3), and taking into consideration the measurement set of the electrical parameters:
- functioning frequency is \( f = 91 \text{kHz} \),
- current in primary winding of \( T_1 \) is \( I_1 = 46 \text{A} \),
- voltage in primary winding of \( T_1 \) is \( U_1 = 442 \text{V} \),
- power factor measured at the supplying source is \( \cos \phi = 0.66 \),

there were obtained the following results:
- resistance in the primary winding of transformer \( T_2 \) is \( R_{p2} = 3.62 \, \Omega \);
- reactance in the primary winding of transformer \( T_2 \) is \( X_{p2} = 4.13 \, \Omega \);
- resistance in the secondary winding of transformer \( T_2 \) is \( R_{s2} = 0.153 \, \Omega \);
- resistance in the secondary winding of transformer \( T_2 \) is \( X_{s2} = 0.126 \, \Omega \).

References: