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Voltage feed welding transformer at no-load

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Abstract: – The aim of the proposed paper is to present the simplified model of welding transformer supplied by voltage frequency inverter. The model is used to simulate welding transformer behavior at no-load. Special attention is paid to the magnetic behavior of transformer core and produced iron losses. The hysteresis loop and voltage frequency inverter duty cycle is also taken into account. The results show that such a model could be used as an useful tool in design of welding transformer.

Key-words: welding transformer, spot welding, iron losses, hysteresis loop

1 Introduction

Spot welding was developed from fusion welding based on resistive heating of material. Resistance welding generates heat by applying electrical current through a relatively low conducting metal-typically steel. The current and the resistance of the steel generate the heat, which allows the material to be welded. The quality of spot weld is dependent on weld time period, electrode pressure on overlapping metal, current value passing through metal, shape of electrodes, etc... The over heat deformation of material is also very important and is obtained by minimizing heat dissipation when the weld is formed very quickly (1/10 s). This requires very large electrical currents because the product of time and applied power (energy) must be constant. The required spot welding quality is achieved with control of welding transformer (Fig. 1) working cycle by frequency converter. In this case beside spot welding, the transformer could be used for the seam welding.
The magnetic core of welding transformer is build of two C cores.

2 Simplified welding transformer model

The Fig. 2 shows the equivalent no-load transformer circuit. No-load current i_p entering the primary side covers the iron losses (i_{fe}), primary winding losses and energy needed to magnetize the core (i_m).

Equivalent transformer circuit from Fig. 2 is further simplified. Resistance R_{fe} representing all iron losses can be connected in parallel to source, because the

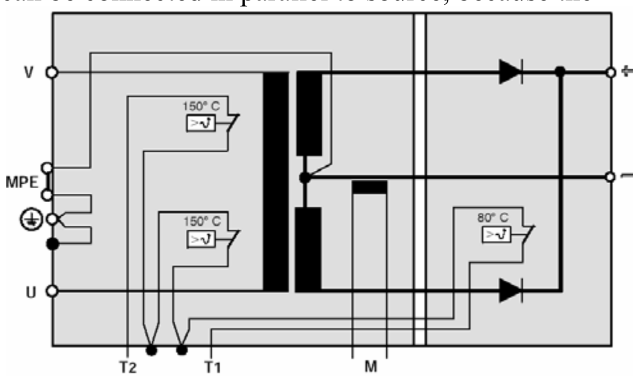

Fig. 1. Welding transformer block diagram.

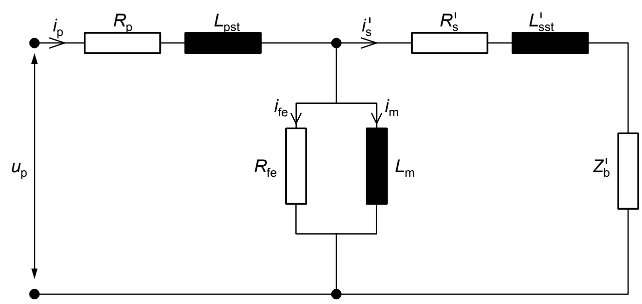

Fig. 2. Equivalent no-load transformers circuit.

voltage drop on primary windings can be neglected. Doing this the next simplified equivalent circuit is formed (Fig. 3) [1-6].

3 Dynamic model for welding transformer

Following the voltage Kirchoff`s law for internal loop L on Fig. 3 the following expression is written:

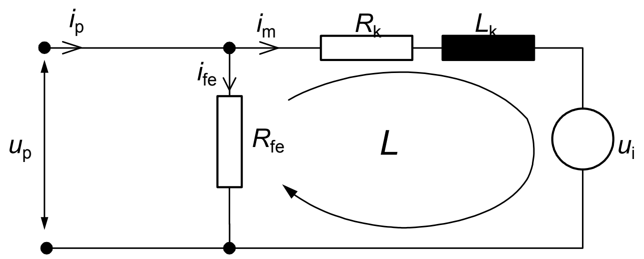

Fig. 3. Simplified equivalent transformer circuit for the presented model.

$$N_p S_m \frac{dB(t)}{dt} = u_p - R_k i_m - L_k \frac{di_m}{dt}, \qquad (1)$$

R_k is the sum of primary resistance R_p and reduced secondary resistance $R_s^{'}$, meanwhile L_k is the sum of primary leakage inductance L_{pst} and reduced secondary leakage inductance $L_{sst}^{'}$. Differential equitation presented by (eq. 1) describes the magnetic behavior of welding transformer at no-load. In this (Fig. 3) simplified transformer circuit only the current i_m with primary turns N_P generates the magnetic flux passing through transformer's core. Using Ampere's law for used core considering two air gaps and operating no-load condition in welding transformer the current i_m can be calculated as:

$$i_m = \frac{1}{N_p}\left(l_s H(B) + \frac{B(t)}{\mu_0} 2\delta_r \right) \qquad (2)$$

l_s – medium core length without air gap thickness,
δ_r – air gap thickness,
N_p – primary winding turns,

The relationship between H and B in (eq. 2) is in form of magnetization curve. Polynomial approximation of magnetization curve is used due to simplicity of the model and good magnetization curve fitting with measured one. The polynomial (eq. 4) represents the base magnetization curve with no losses. The losses are further added in the form of resistance R_{fe}.

$$H(B) = a_1 B(t) + a_2 B(t)^{15} + a_3 B(t)^{19} \qquad (3)$$

a_1, a_2, a_3 – fitting coefficients.

To achieve the best polynomial fitting with measured curve delivered by laminated steel manufacturer the fitting coefficients values (Table 1) were obtained by optimization technique.

Coefficients	Values
a_1	50
a_2	0.2181
a_3	0.1353

Table 1. Polynomial fitting coefficients.

The differential susceptibility is:

$$\frac{dH(B)}{dB(t)} = a_1 + 15 a_2 B(t)^{14} + 19 a_3 B(t)^{18} \qquad (4)$$

Inserting (eq. 4) in to time differentiated (eq. 2) leads to:

$$\frac{di_m}{dt} = \frac{1}{N_p}\left[l_{sr}\left(a_1 + 15 a_2 B(t)^{14} + 19 a_3 B(t)^{18}\right) + \frac{2\delta_r}{\mu_0} \right] \cdot \cdot \frac{dB(t)}{dt} \qquad (5)$$

The (eq. 5) and (eq. 3) are inserted in (eq. 1) and the final differential model equation is written, where the independent input variable is source voltage u_p (Fig. 4):

$$\frac{dB(t)}{dt} = \frac{\left(u_p - R_p \left(\frac{1}{N_p} \left(l_{sr} a_1 B + a_2 B_t^{15} + a_3 B_t^{19} + \frac{B_t}{\mu_0} 2\delta_r \right)\right)\right)}{N_p S_m + \frac{L_{pst}}{N_p}\left(l_{sr}\left(a_1 + a_2 15 B(t)^{14} + a_3 19 B(t)^{18}\right) + \frac{2\delta_r}{\mu_0} \right)} \qquad (6)$$

4 Iron Losses

The iron losess in welding transformer core are mainly composed of eddy current losses and hysteresis losses. Eddy current losses can be calculated using:

$$P_e = p_{es} C_e m_c \left(\frac{f}{f_{50}}\right)^k \left(\frac{B}{B_{1.5}}\right)^m \left(\frac{d}{d_{0.3}}\right)^p, \qquad (7)$$

p_{es} are specific eddy current losses at 50 Hz and 1.5 T given by lamination steel manufacturer, C_e voltage pulse shape factor, m_c transformer weight, f applied frequency, f_{50} basic frequency (50 Hz), B applied magnetic flux density, B_{50} basic magnetic flux density (1.5 T), d thickness of lamination, $d_{0.3}$ basic thickness

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(0.3 mm) and k, m, p are material dependant exponents.
For hysteresis losses calculation stands:

$$P_{\mathrm{h}} = p_{\mathrm{hs}} C_{\mathrm{h}} m_{\mathrm{c}} \left(\frac{f}{f_{50}}\right)\left(\frac{B}{B_{1.5}}\right)^{n}, \qquad (8)$$

p_{hs} are specific hysteresis losses at 50 Hz and 1.5 T given by lamination steel manufacturer, C_{h} voltage pulse shape factor and n is material dependant exponent.
The total iron losses can be found using:

$$P_{\mathrm{fe}} = P_{\mathrm{e}} + P_{\mathrm{h}}\,. \qquad (9)$$

In table 2 there are presented all used parameter values for iron losses calculation and the results of computation.

p_{es} [W/kg]	C_{e}	m_{c} [kg]	f [Hz]	B [T]
0.4	1.4	3.2	1000	1
d [mm]	k	m	p	p_{hs} [W/kg]
0.1	2	1.8	1.6	0.8
C_{h}	n	P_{e} [W]	P_{h} [W]	P_{fe} [W]
1.4	1.8	62	35	97

Table 2 Values of used parameters and iron losses results.

The value of resistance R_{fe}, representing hysteresis and eddy current losses, depends on used laminated steel (quality, thickness…) and inverter duty cycle k_{d}. To calculate R_{fe} (eq. 11) for different inverter duty cycle k_{d} the reference value $R_{\mathrm{fe\text{-}ref}}$ (eq. 11) is calculated for 30% reference duty cycle $k_{\mathrm{d\text{-}ref}}$. These data are provided from manufacturer for losses on unit volume of used steel (Table 2).

$$R_{\mathrm{fe\_ref}} = \frac{2u_{\mathrm{ap}}k_{\mathrm{d\_ref}}}{P_{\mathrm{fe}}} = \frac{(2\cdot 560\cdot 0{,}3)^2}{97} = 1336\Omega \qquad (10)$$

$$R_{\mathrm{fe}} = R_{\mathrm{fe\_ref}}\left(\frac{k_{\mathrm{d\_ref}}}{k_{\mathrm{d}}}\right)^2 \qquad (11)$$

5 Results

The dynamic model equitation (eq. 6) is numerically solved using Runge-Kutta method. To get the hysteresis loop the calculation of magnetic field is done using:

$$H_{\mathrm{t}}(t) = \frac{i_{\mathrm{p}}N_{\mathrm{p}} - \dfrac{B(t)}{\mu_0}2\delta}{l_{\mathrm{sr}}}, \qquad (12)$$

i_{p} is total no-load current:

$$i_{\mathrm{p}} = \frac{u_p}{R_{fe}} + i_{\mathrm{m}}\,. \qquad (13)$$

Welding transformer is voltage supplied from frequency inverter. Measurements and simulation results for supply voltage with 30% inverter duty cycle are shown on Fig. 4 and 5.

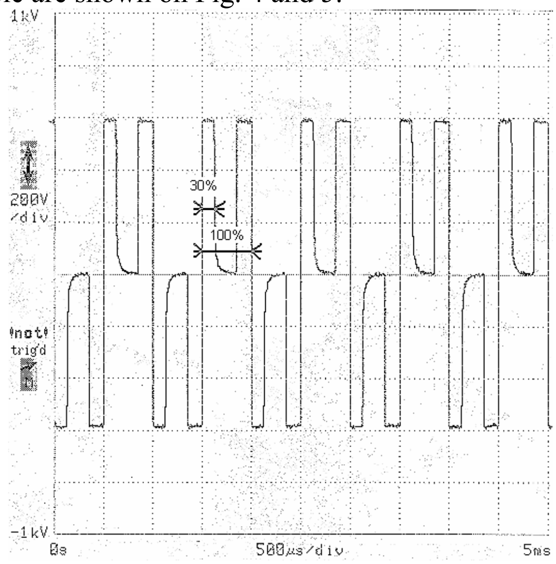

Fig. 4. Measured results for supply voltage with 30% inverter duty cycle.

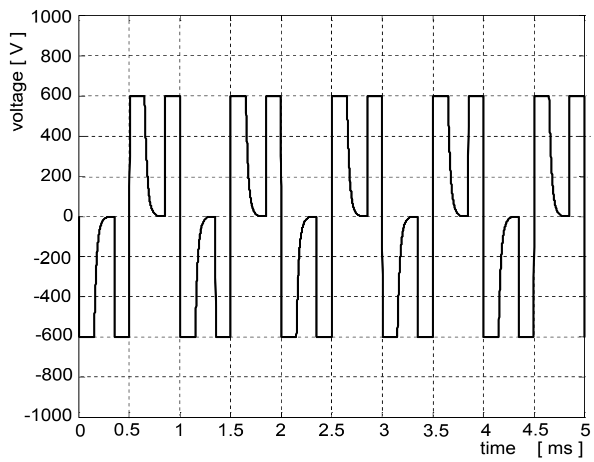

Figure 5 Simulated results for supply voltage with 30% inverter duty cycle.

Measured and modeled hysteresis loop for 30% inverter duty cycle are shown on Fig. 6 and 7.
The same analyze was done for supply voltage with 60% inverter duty cycle. The results for measured and modeled hysteresis loop are shown on Fig. 8 and 9.

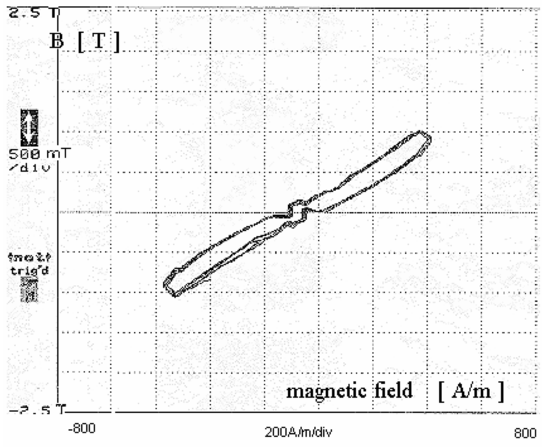

Fig. 6. Measured hysteresis loop for 30% inverter duty cycle.

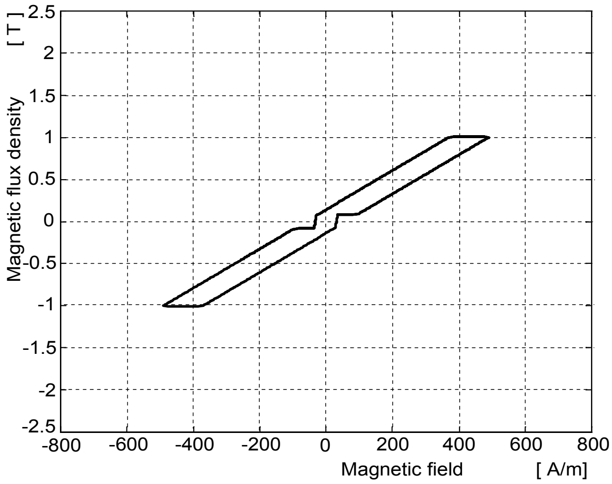

Fig. 7. Modeled hysteresis loop for 30% inverter duty cycle.

6 Conclusion

The paper describes a simple model and procedure for iron losses calculation in laminations of welding transformer at no-load. The transformer model is fed by voltage source from frequency inverter with regulated duty cycle. As it is shown in the paper, the presented model can be used also for hysteresis loops calculation dependant on frequency inverter duty cycle. The main characteristics of the model are, beside its simplicity, its dynamic behavior and applicability to any magnetization characteristics. Comparison of measured and calculated results confirms the model as a useful tool in design of welding transformer.

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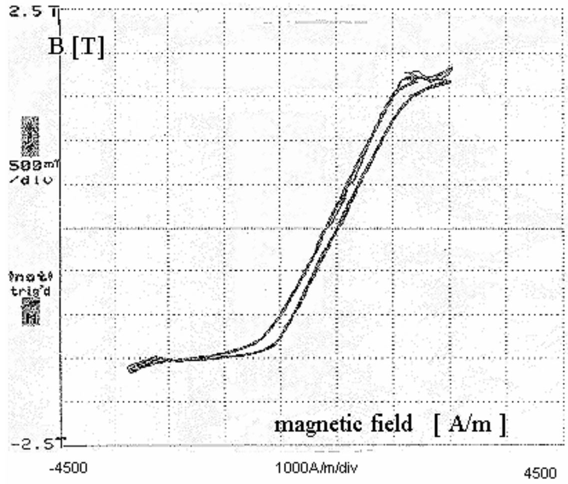

Fig. 8. Measured hysteresis loop for 60% inverter duty cycle.

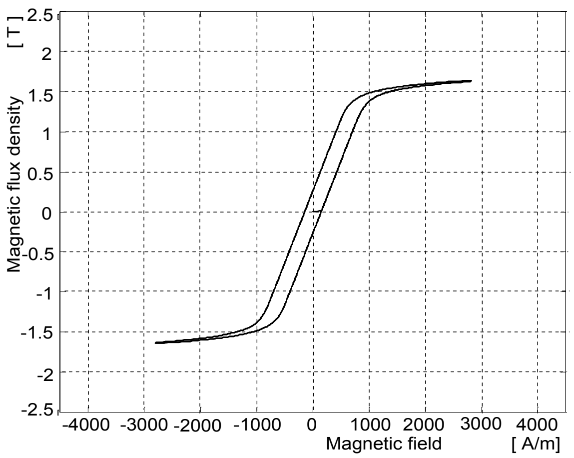

Fig. 9. Modeled hysteresis loop for 60% inverter duty cycle.

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