3D model for calculating the impedance of the transformer of the inverter power source of the resistance welding machine

L Sakhno¹ *, O Sakhno², M Krylov¹ and D Likhachev³

¹Institute of Energy and Transport Systems, Peter the Great Saint-Petersburg Polytechnic University, Saint-Petersburg, 195251, Russia
²Institute of Applied Mathematics and Mechanics, Peter the Great Saint-Petersburg Polytechnic University, 195251, Russia
³LLA”Ranta”, 194292, Russia

* E-mail: sahno_li@spbstu.ru

Abstract. 3D model for calculating the short circuit impedance and inductance of the secondary windings bars of a welding transformer are given. An example of calculating these parameters for a transformer with a rated current of 7 kA in the frequency range from 0 up to 1000 Hz are considered. The accuracy of these parameters and calculation time are discussed. The results of transformer impedance calculations using 2D and 3D models are compared. The inductance of the transformer bars is about 70% of the transformer short-circuit resistance.

1. Introduction

This paper discusses welding transformers of inverter power sources for resistance spot welding machines [1-3]. Such a source consists of a three-phase network rectifier, a capacitive filter, an input H-bridge inverter, welding transformer and a full-wave centre tapped output rectifier that consists of two diodes. Power sources with a frequency not more 1000 Hz are most widely used. It is known that the short-circuit impedance of the welding transformer significantly affects the welding current and the power consumption of the source, therefore great attention is paid to the calculation of this parameter [3-7]. In addition, these transformers have massive secondary winding bars. They are used for attaching two powerful diodes of the output rectifier. For example, the diameter of diode DCH-143-1000-18 is 60 mm. The distance between bars are rather big in comparing with the distance between the coils of primary and secondary windings. From the experience of designing and operating inverter power sources, it follows that the inductance of the bars of the secondary winding can be up to 100% of the inductance of the transformer short circuit. At the present time designers are working on developing secondary windings bars with minimum values of its inductances. Large welding currents (tens of kiloampere) and increased frequency lead to a significant manifestation of skin effect and proximity effect in the transformer windings. These effects affect the transformer short circuit impedance. To calculate the impedance, both analytical and numerical methods are used. These methods are based on the 2 D model of the transformer [8-10]. Special empirical coefficients are often used to take into account the real three-dimensional magnetic leakage field of a transformer [8, 9]. 3D model is used only for a magnetostatic transformer field calculation [9–15].

One way to increase the accuracy of the short circuit impedance calculation is to find the transformer’s AC 3D leakage magnetic field. In this regard, the purpose of this work is to develop a
3D AC model of the transformer (with its bars). The development of a 3D AC model of a transformer consists of studying the accuracy and timing of the solution. In addition, it is necessary to compare the results of transformer impedance calculation using 2D and 3D models and give recommendations on the efficiency of using a 2D model. An example of calculating the short-circuit impedance of a transformer with a rated current of 7 kA in the frequency range from 500 Hz to 1000 Hz is given.

2. Methods
The 3D model of the transformer was built in the Solidworks program taking into account the real dimensions of the transformer under study, and exported to the Maxwell 3D program [16]. Magnetic permeability of the magnetic core is accepted $1000 \mu_0$ ($\mu_0 = 4\pi 10^{-7}$ Hn/m), outside the magnetic core the magnetic permeability is equal $\mu_0$. All windings have electrical conductivity of copper (58 - 10$^8$ S/m). The computational domain is bounded by planes on which the tangential component of the field strength is assumed to be zero. The position of these planes was found by numerical experiment. During this experiment the distance from the transformer to these planes was sequentially doubled and the impedance values were calculated for each distance. When the difference between the successive values of impedances did not exceed 1%, the position of these planes is considered to be established and is used for all calculations. A similar procedure is used when choosing sizes of finite elements. Inside the conductive regions, the sizes of the finite elements are no more than a quarter of the equivalent penetration depth. The initial data for calculating the leakage magnetic field are MMF of the primary and secondary windings ($I_1 w_1$ is MMF of the primary winding, $I_1$ is the current in the primary winding, $w_1$ is the number of turns of the primary winding, $I_2 w_2$ is MMF of the secondary winding, $I_2$ is the current in the secondary winding, $w_2$ is the number of turns of the secondary winding) which are equal in magnitude and opposite in sign $I_1 w_1 = -I_2 w_2$ (opposition mode). The MMF value of any winding can be set arbitrarily. According to the results of the field calculation, the magnetic field energy $W_\mu$ and the total losses $P_\Sigma$ in the primary and secondary windings are found. The leakage inductance referred to the primary winding can be found using the energy of a magnetic field:

$$L = \frac{2W_\mu}{I_1^2} \tag{1}$$

where $I_1$ is RMS of primary winding.

The active resistance referred to the primary winding is:

$$R_{SC} = \frac{P_\Sigma}{I_1} \tag{2}$$

The impedance of the transformer short circuit, referred to the primary winding:

$$Z_{SC} = R_{SC} + j\omega L_{SC} \tag{3}$$

where $\omega = 2\pi f$, $f$ is frequency, $j = \sqrt{-1}$.

3. Results and discussion
Transformer VT-3 was chosen for the study [3]. A rated current of this transformer is 7 kA. This transformer has two series-connected primary coil, made of rectangular wire. The number of turn of primary winding is 36. The two coils of the secondary winding are made of copper tubes through which the cooling water passes. In figure 1a the cross section passing through the vertical axis of the transformer is shown. 3D model of this transformer is shown in figure 1b. For most of the period, the
welding current passes through only one coil of the secondary winding, therefore this mode is regarded as nominal [3]. Two models of the transformer are considered: without the bars of the secondary winding (Figure 1b) and with the bars of the secondary winding (Figure 2). The design of the bars is not real but allows to estimate their value in shot circuit impedance of transformer. Calculations are made for these two models for both DC and AC magnetic at three frequencies of 500, 750, and 1000 Hz. Calculation time for a magnetostatic problem on a PC with system properties: Intel (R) Core i3-2120; 3.3GHz, 4 GB of RAM, was about 5 hours. The calculation was made for the whole model without using the properties of symmetry. The results for model in Figure 1b is given in Table 1. In this table all parameters are referred to the primary winding.

![Figure 1. 3 D model of transformer transformer VT-3.](image1)

![Figure 2. Transformer design with bars (view from above).](image2)

| $f$, kHz | $R_{SC}$, mOhm | $L_{SC}$, $\mu$H | Inductance of the second winding bars, $\mu$H | Short circuit impedance, Ohm |
|---------|----------------|-----------------|---------------------------------|-----------------------------|
| 0       | 170            | 56.6            | 42.4                            | -                           |
| 0.5     | 201            | 52.8            | 37.2                            | 201+ j165                   |
| 0.75    | 220            | 52.2            | 37.6                            | 220+ j245                   |
| 1       | 240            | 51.8            | 37.1                            | 240+ j325                   |

From Table 1 it can be seen that the leakage inductance decreases and the resistance increases with increasing frequency. The results are consistent with electromagnetic field theory. The transformer
bars make up 70% of the transformer short-circuit resistance, therefore it is very important to calculate these parameters with high accuracy.

Impedances calculated using a two-dimensional model differ from these parameters calculated with a three-dimensional model without bars by no more than 2%. On the one hand, these results confirm the correctness of the 3D model, and on the other hand, they show a high accuracy of calculating the impedance of a transformer using a 2D model. It is reasonable to use this model for multivariate calculations, which are necessary for finding the optimal transformer design. 3D model is effective in performing an exact calculation for the found optimal variant.

4. Conclusions
3D model of a welding transformer for calculating the transformer impedance has been developed. The influence of the position of the planes limiting the computational domain and the sizes of finite elements on the accuracy of calculating the transformer impedance has been investigated. The difference between the transformer impedances calculated using 2D and 3D does not exceed 2%. The inductance of the transformer bars is 70% of the transformer short-circuit resistance. The 2D model of the transformer is expediently used for the multivariate calculations that are necessary to find the optimal design of the transformer. 3D model is effective in performing an exact calculation for the found optimal variant.

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