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An algorithm for fast calculation of short circuit forces in high current busbars of electric arc furnace transformers based on method of images☆

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ABSTRACT

This paper proposes an algorithm for the calculation of short circuit forces on the high current busbars of electric arc furnace (EAF) transformers based on the method of images using an analytical solution for the electromagnetic force between two adjacent current carrying rectangular conductor. The theory of images is used to account for the impact of the tank walls on the short circuit forces on the busbars. The proposed method uses an iterative algorithm and increases the number of image layers to achieve the desired accuracy. A 30 MVA EAF transformer is investigated as a case study and the results are compared to 2D finite element analysis (FEA). ANSYS software is used for the FEA. The proposed algorithm converges very fast, so that only in its first iteration, the convergence error is less than 0.2%. The comparisons show that the short circuit force calculations using the proposed method, conform to the 2D FEA results. However, the short-circuit calculation time using the proposed method is about 20 times faster than the 2D FEA with the same relative error. Therefore it can be used as a faster alternative for the FEA. The proposed method is characterized by fast convergence, simple calculations and high precision.

1. Introduction

Nowadays, electric arc furnace (EAF) transformers are widely used in smelting industries. The proper design and sufficient production technology of the EAF transformers are fundamental for a high efficiency of the plant operation. Furnace transformers are one of the most valuable apparatuses in electric systems of smelting industries. Any failure will lead to high costs for the repair or replacement and may often lead to very high costs due to temporary loss of the power delivery capability. Therefore, EAF transformers are highly protected against various causes of failure. This type of transformer must have the capability to withstand the extremely high levels of electromagnetic forces due to short circuit faults. One of the important structural parts of a furnace transformer are high current low voltage output busbars. A typical EAF transformer with low voltage busbars is shown in Fig. 1. These busbars are used to transfer the high currents from the low voltage windings disks to the EAF through high current cables. Because of the very high currents in these busbars (e.g. 100 kA) special attention and design considerations are required [1–5]. Also, due to the low short circuit impedance at the low voltage side, the short circuit currents are very high and as a result the electromagnetic forces in busbars are critically high. Different numerical and analytical analysis of general purpose power transformers has been well studied in many publications [6–12].

The electromagnetic analysis of EAF transformers has been investigated in [7–24]. In [13] and [14], the current distribution in low voltage windings of EAF transformers has been discussed. The electromagnetic forces in high current busbars are investigated in [15] and [16]. In [15], the electromagnetic forces are calculated using 2D finite element analysis (FEA). The short circuit forces of busbars with multiple sub-conductors are calculated based on a correction factor method in [16]. The method of images is a well-known technique which has many applications in electromagnetics and has been widely used in different studies [2,7,18,21–23]. Specially, this method can be used for the calculation of different field parameters in power transformers, e.g. leakage field, short circuit forces, eddy current losses, etc. In [7] and [23], the method images is used for the calculation of the leakage field and the electromagnetic forces on the windings of power transformers and the results are compared to 2D FEA. The error associated with the use of the method of images in very low frequencies [22] (e.g. 50/60 Hz which

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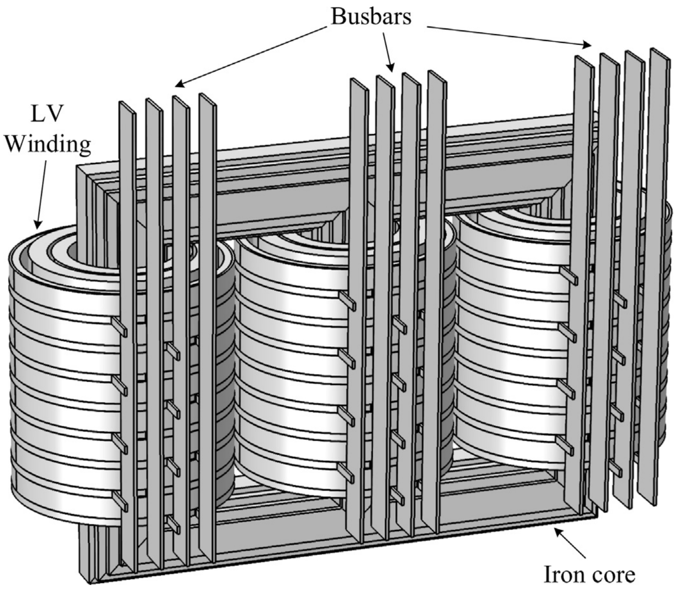

Fig. 1. A typical electric arc furnace (EAF) transformer with high-current low-voltage output busbars.

our study deals with) or very high frequencies analysis of electrical devices [18] are very low. However, The theory of images in its simple form cannot be used for medium frequencies anaylsis, and may lead to significant error and, the location and magnitudes of the images should be modified so that the boundary conditions in medium frequencies could be satisfied with the images [2]. In [17], the magnetic effects of induced eddy currents in thin conducting sheets and the transient electromagnetic forces are studied by means of moving current images and by using an electrical circuit analogy.

In this paper, an algorithm for fast and accurate calculation of the short circuit forces on high-current busbars of EAF transformers is presented. The proposed algorithm applies the theory of images to an analytical solution for the electromagnetic force between adjacent rectangular busbars, to account for the impact of the transformer tanks walls on the short-circuit forces. The analytical solution for the electromagnetic force is verified using 2D FEA. A 30 MVA EAF transformer is investigated as a case study and the results are compared to the corresponding 2D FEA to verify the accuracy of the analytical method. The comparisons show that the proposed algorithm completely conform to the 2D FEA with a much lower calculation time. Also, the short circuit calculations show that the short circuit forces on the high current busbars are of a great strength and therefore, should be considered as an important design measure in EAF transformers.

2. Analytical calculation of the magnetic field of a single busbar

In order to find an analytical solution for the electromagnetic force between two rectangular busbars, magnetic field distribution of a single rectangular conductor is required. The derivation of the electromagnetic force is described in Section 3. The magnetic field of a single rectangular conductor can be calculated analytically by assuming a uniform current density inside the conductor. The cross section of a typical rectangular conductor with the dimensions of $a \times b$ [m] and a uniform current density J [A/m^2] perpendicular to x–y plane is shown in Fig. 2. By applying the Biot–Savart law [6] and integrating the magnetic field of the current elements $Jdxdy$ over the cross section of the conductor S_c, the total magnetic field

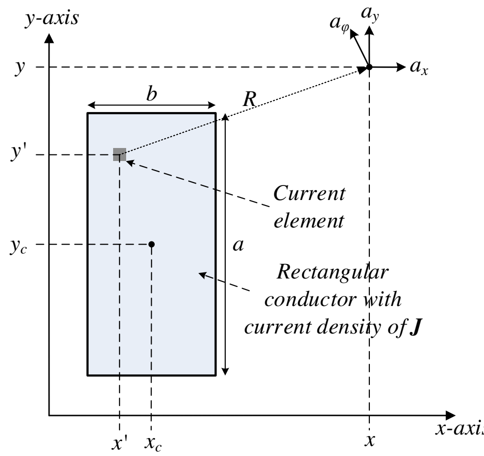

Fig. 2. The definition of parameters used for the calculation of magnetic field of rectangular conductor with a uniform current density of J [A/m^2].

of a rectangular conductor can be calculated using the following equation:

$$H = \iint_{S_c} \frac{J\, a_\phi}{2\pi\, ||R||} dx'\, dy' \quad (1)$$

where H [A/m] is the magnetic field vector at point (x, y), (x', y') are the current elements coordinates, J [A/m^2] is the current density of the conductor, R [m] is the vector from (x', y') to (x, y), a_ϕ is the unit vector perpendicular to R vector. By converting R and a_ϕ into Cartesian form, (1) can be rewritten as follows:

$$H = \frac{J}{2\pi} \int_{y_c-\frac{a}{2}}^{y_c+\frac{a}{2}} \int_{x_c-\frac{b}{2}}^{x_c+\frac{b}{2}} \frac{-(y-y')a_x + (x-x')a_y}{(x-x')^2 + (y-y')^2} dx'\, dy' \quad (2)$$

where (x_c, y_c) are the coordinates of the center of the busbar, (x, y) are the coordinates of an arbitrary point at which the magnetic field is desired and a_x and a_y are unit vectors along x and y axes respectively. By assuming that the center of the conductor is located at the origin of the x–y coordinate system ($x_c = 0$ and $y_c = 0$), the components of the magnetic field, H_x and H_y can be calculated as the following set equations:

$$\begin{aligned} H_x = -\frac{J}{8\pi} \Bigg[&(4x+2a)\left(\tan^{-1}\left(\frac{b+2x}{a+2y}\right) + \tan^{-1}\left(\frac{b-2x}{a+2y}\right)\right) \\ &+(4y-2a)\left(\tan^{-1}\left(\frac{b+2x}{a-2y}\right) + \tan^{-1}\left(\frac{b-2x}{a-2y}\right)\right) \\ &+(2x+b)\ln\left(\frac{(b+2x)^2+(a+2y)^2}{(b+2x)^2+(a-2y)^2}\right) \\ &+(2x-b)\ln\left(\frac{(b-2x)^2+(a-2y)^2}{(b-2x)^2+(a+2y)^2}\right)\Bigg] \end{aligned} \quad (3)$$

$$\begin{aligned} H_y = \frac{J}{8\pi} \Bigg[&(4x+2b)\left(\tan^{-1}\left(\frac{a+2y}{b+2x}\right) + \tan^{-1}\left(\frac{a-2y}{b+2x}\right)\right) \\ &+(4x-2b)\left(\tan^{-1}\left(\frac{a-2y}{b-2x}\right) + \tan^{-1}\left(\frac{a+2y}{b-2x}\right)\right) \\ &+(2y+a)\ln\left(\frac{(b+2x)^2+(a+2y)^2}{(b-2x)^2+(a+2y)^2}\right) \\ &+(2y-a)\ln\left(\frac{(b-2x)^2+(a-2y)^2}{(b+2x)^2+(a-2y)^2}\right)\Bigg] \end{aligned} \quad (4)$$

Eqs. (3) and (4), provide the analytical solutions for magnetic field components of a single rectangular busbar for the entire space.