Fast Calculation of Copper Losses in Flush-Butt Welding Transformer

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Power toroidal transformers for flush-butt welding gas pipelines are considered. They have primary windings with several sections connected in parallel and made of litz. The paper proposes an original equivalent circuit of the multiwinding transformer based on the classical theory of transformers. The proposed equivalent circuit allowed us to use FEA magnetostatic formulation for the calculation of the copper losses in primary litz windings with several sections connected in parallel. The results of the copper losses calculation are confirmed experimentally

***Index Terms*—flush-butt welding, multiwinding transformer, equivalent circuit, litz, leakage fluxes, mutual inductance of leakage fluxes.**

I. INTRODUCTION

Special complexes for flash-butt welding gas pipelines are being developed in Russia. One of the important problems of developing such systems is the design of two-winding welding power toroidal transformers which are installed inside the pipe. Their power consumptions can be up to 1 MVA, rated uninterrupted currents in primary windings can be up to 1500 A. Secondary windings have only one turn. Primary windings can have several sections connected in parallel and made of copper stranded wires (litz). To calculate the losses in them it is necessary to take into account the distribution of the primary current between their parallel sections. Due to litz we have no skin–effect in each parallel section but the currents in them are not the same as they have different magnetic flux linkages. Therefore, it is necessary to find the uneven current distribution between sections when the current distribution within a section is uniform. This circumstance limits the use of FEA AC magnetic field formulation. In this paper we propose to consider each section of the primary winding as a separate winding, so the transformer becomes multiwinding one. We use an original equivalent circuit of the multiwinding transformer which differs from the well-known circuits [1-5] by two features: firstly, all windings are not conductively coupled, and secondly, the circuit parameters have the clear physical sense. This approach was used for design of welding three-winding transformers [6]. The circuit parameters can be easily evaluated by FEA of magnetostatic formulation. All inductances in the circuit are always positive, therefore, the circuit is suitable for the standard simulation programs.

II. EQUIVALENT CIRCUIT OF THE MULTIWINDING TRANSFORMER

Let us have a transformer with n primary windings and one secondary winding. The primary windings may be arbitrarily connected. The numbers of primary windings are *11, 12, ..., 1n*, the secondary winding has number *2*. Thus the transformer has *(n+1)* windings. Neglecting the inrush current we can get:

$$i_2 = i_{21} + \ldots + i_{2n} = -\left(i_{11}k_{21} + \ldots + i_{1n}k_{2n}\right) \tag{1}$$

where $i_{11}, i_{12} \ldots i_{1n}$ are instantaneous magnitude of the currents in the primary windings, i_2 is instantaneous magnitude of the current in the secondary winding, $k_{21} = w_{11} / w_2$, …, $k_{2n} = w_{1n} / w_2$ are transformation ratios , $w_{11}, w_{12} \ldots w_{1n}$ are the numbers of turns in each of the primary winding, $w_2 = 1$.

From this equation it follows that the secondary current in the transformer is sum of several components, each of them is determined by the current in the primary winding of a two-winding transformer and the transformation ratio of this transformer. Since the secondary current in the multiwinding transformer can be obtained by adding the secondary currents of n two-winding transformers, it is useful to replace it with n two-winding transformers. Each of these two-winding transformers has a secondary winding, which coincides with the secondary winding of multiwinding transformer, and one of its primary windings, so we have two-winding transformers with windings *11* and *2, 12* and *2,…, 1n* and *2* (further transformers *11-2, 12-2…1n-2*). The mutual impact of two-winding transformers is modelled as a change of EMF on the terminals of their primary windings by magnetic leakage fields and voltage drop of the primary windings of two-winding transformers. Therefore, we have n- equations:

$$\begin{aligned} u_{1i} &= L_{1i-2}\frac{di_{1i}}{dt} + L'_L\frac{di_{1i}}{dt} + r'_L i_{1i} + r_{1i-2}i_{1i} + \\ &+ \sum_{\substack{j=1 \\ i\neq j}}^{n} M_{1i-2,1j-2}\frac{di_{1j}}{dt} + \sum_{\substack{j=1 \\ i\neq j}}^{n}\left(r_2 + r_L\right)i_{1j}k_{1i,2}k_{1j,2} \end{aligned} \tag{2}$$

where i varies from *1* to n, , u_{1i} is the voltage on terminals *1i*, L_{1i-2} *i*s the leakage inductance of transformer *1i-2*, r_{1i-2} is the real resistance of transformer *1i-2*, the L'_L is the load inductance (referred to winding *1i*), r'_L is the load real resistance (referred to winding *1i*), $k_{1i,2} = w_{1i} / w_2$, $k_{1j,2} = w_{1j} / w_2$. The mutual inductance of the leakage fluxes of transformers *1i-2* and *1j-2:*

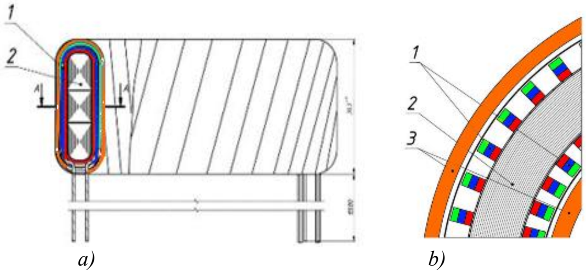
$$M_{1i-2,1j-2} = \frac{L_{1i-2} + L_{1j-2} - L_{1i-1j}}{2k_{1i,2}k_{1j,2}}, \tag{3}$$

Where $L_{1i\text{-}1j}$ is the leakage inductance of transformer L_i-L_j.

The equivalent circuit, corresponding to (2), contains as many branches as primary winding contains. In each branch there is a leakage inductance and real resistance of a two-winding transformer (short-circuit impedance). Leakage inductances are inductively linked. In addition, this branch has a dependent voltage sources. They take into account the change of the voltage at the terminals of the winding *1i* due to a primary winding voltage drop of the other two-winding transformers. For calculation of coefficients in (2) we need calculation of the magnetic leakage fields in two-winding transformers. They have been modeled by 3D or 2D model, both of magnetostatic formulation.

III. THE APPLICATION OF THE EQUIVALENT CIRCUIT TO CALCULATION OF COPPER LOSSES IN WELDING TRANSFORMER

Figure *1a* shows primary winding *1* and toroidal core *2* of the welding transformer. The cross section of the transformer by the plane *AA* is shown in Fig.1b. In this figure, we can see primary winding 1 with three parallel-connected sections (windings) *11* (red), *12* (blue), *13* (green), secondary winding 3 and magnetic core 2. Secondary winding is a copper body, covering the magnetic core and the primary winding. Its thickness is 16 mm. Each section of the primary winding is a coil made of litz with rectangular cross section 20x9 mm^2. The external diameter of primary winding is 843 *mm* , the external diameter of the secondary winding is 890 *mm*. The primary winding has 52 turns, the secondary winding has one turn, $k_{11,2}=k_{12,2}=k_{13,2}=52$.



a) b)

Fig.1. Design of transformer

The transformer is supplied by sinusoidal voltage $U_1=380\ V$, frequency is $f=50\ Hz$. The rated uninterrupted current is *1442 A*. The first task is to find currents in the sections of the primary winding when the transformer is short-circuited. Then we can find copper losses in the sections taking into account their real resistances. The equation (2) for the complex currents and voltages of this transformer can be written:

$$\begin{cases} U_1 = z_{11-2} I_{11} + \left(j\omega M_{11-2,12-2} + r_2'\right) I_{12} + \left(j\omega M_{11-2,13-2} + r_2'\right) I_{13} \\ U_1 = \left(j\omega M_{12-2,11-2} + r_2'\right) I_{11} + z_{12-2} I_{12} + \left(j\omega M_{12-2,13-2} + r_2'\right) I_{13} \\ U_1 = \left(j\omega M_{13-2,11-2} + r_2'\right) I_{11} + \left(j\omega M_{13-2,12-2} + r_2'\right) I_{12} + z_{13-2} I_{13} \end{cases}$$

where $j=\sqrt{-1}$, $r_2'=52^2 r_2$, r_2 is the real resistance of the second winding, $z_{11-2}=r_{11-2}+j\omega L_{11-2}$, $z_{12-2}=r_{12-2}+j\omega L_{12-2}$, $z_{13-2}=r_{13-2}+j\omega L_{13-2}$, $\omega=2\pi f$. The equivalent circuit corresponding to these equations is shown in Fig.2. The DC resistance of each section of the primary winding is *0.006 Ω*. All inductances and mutual inductances in (2) we found from 2D FEA calculations of magnetostatic fields of two-winding transformers. The real resistance of the secondary winding $r_2=0.67\mu\Omega$ we found from 2D FEA calculations of quasi-magnetostatic field of transformer in Fig.1b. The inductive resistances are given in the table in Ohms.

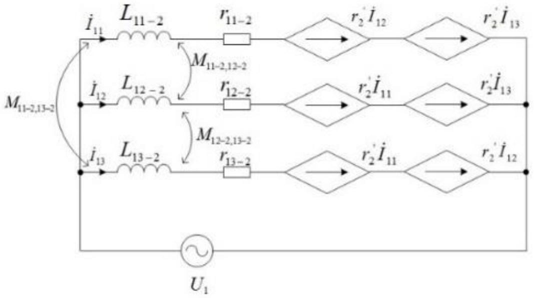


Fig.2. Equivalent circuit of transformer

ωL_{12-2}	ωL_{12-2}	ωL_{13-2}	$\omega M_{11-2,\ 12-2}$	$\omega M_{13-2,\ 12-2}$	$\omega M_{11-2,\ 13-2}$
0.021	0.016	0.0086	0.0152	0.00952	0.0095

The calculations showed that the currents in the sections of the primary winding are not the same. The maximum current (about 50%) are in the section 13 located next to the secondary winding. Minimum current (about 24%) is in the section 11 located near the core. These results are confirmed by measurements with clamp-on ammeter. Copper losses at the rated uninterrupted current in the primary winding are *4676 W*. This value is 12% more than when primary current is uniformly distributed between the sections. Copper losses in the secondary winding are greater than in the primary winding due to skin effect and they are about *14732 W*. These results were used in the design of the transformer and were confirmed by short – circuit test.

IV. CONCLUSION

The proposed equivalent circuit allowed us to use magnetostatic formulation for the calculation of the copper losses in transformer windings which have several sections connected in parallel and made of litz.

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