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Analysis of slots in horizontal plates of T-beams in shell-form power transformers

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ABSTRACT

A systematic analysis of the use of slots to reduce stray losses in the horizontal plates of the T-beams in shell-form power transformers is presented. In the paper, the horizontal plate of T-beams is modeled as a rectangular stainless steel plate subjected to a perpendicular uniform magnetic field generated by a Merritt coil. The results are compared with the values given by an analytical formula for calculating the losses in a stainless steel plate without slots. The following important design alternatives are analyzed and discussed: (1) plates with rounded slots; (2) plates with unrounded slots; (3) effect of width and length of one slot; (4) effect of the distance between slots; (5) effect of number of slots. It has been found that substantial loss reduction can be obtained when drilling a few slots. Measurements of flux densities were done for seven shell-form power transformers. Using the measurements we calculated the losses in the plates using formula. Using the results of the design alternatives the efficiency of the use of slots in plates of real T-beams was demonstrated. Finally, a structural analysis was made to study the impact of slots in an experimental slotted T-beam.

1. Introduction

Magnetic and non-magnetic metal plates are used in the manufacturing of distribution and power transformers. These plates offer reinforcement, support and magnetic shielding. The plates are subjected to stray fields, which induce eddy currents in them. Consequently, the associated losses cause localized heating [1–7,14–16]. One of the existing techniques for reducing eddy losses in metal plates is drilling slots on them. This produces an effective increase of the resistance by the elongation of the eddy current path. In core-form power transformers; tie plates are present on both sides of each leg of the core. These plates are made of stainless steel and are subjected to stray fields. Hence, the tie plates are frequently slotted to reduce stray losses [8–12]. Other elements of the transformers are slotted to reduce losses [1,13].

In shell-form power transformers, the T-beams, the entire iron core, and the supports of the end tank serve to mechanically support the pancake coils as shown in Fig. 1. The horizontal plates of T-beams are usually made of stainless steel and the vertical plates are usually made of carbon steel. Transformer manufacturers normally use carbon steel, which is cheaper than the stainless steel and it has excellent mechanical properties [17,18]. In order to reduce eddy currents induced in the horizontal plates, magnetic shunts are placed on them [19]. The magnetic shunts are composed of packets of grain-oriented silicon steel sheets. The shunts and the horizontal plates are separated by a distance of about 3 mm. In this small space, there exists a weak flux density of less than 15 mT, which is a value similar to the induction found on the walls of the tank of power transformers protected with magnetic shunts [20]. This flux hits the horizontal plates inducing high eddy currents. Because plates of shell-form power transformers are large (3.75 m^2 for a single-phase 300 MVA shell-form transformer) considerable losses and heating are produced in them. The vertical plates of T-beams are strongly shielding by the iron core. They do not need magnetic shunts.

To the best of authors' knowledge, no general way to reduce stray losses in the horizontal plates of the T-beams in shell-form power transformers has previously been presented.

In this paper authors assume that the stray flux enters perpendicularly the horizontal plates of stainless steel of the T-beams, see Fig. 2. This is a realistic assumption because there is a large difference between the permeability of grain-oriented silicon steel and the adjacent air. This forces the field to enter the grain-oriented silicon steel at 90° [21]. The authors note that in the region surrounding

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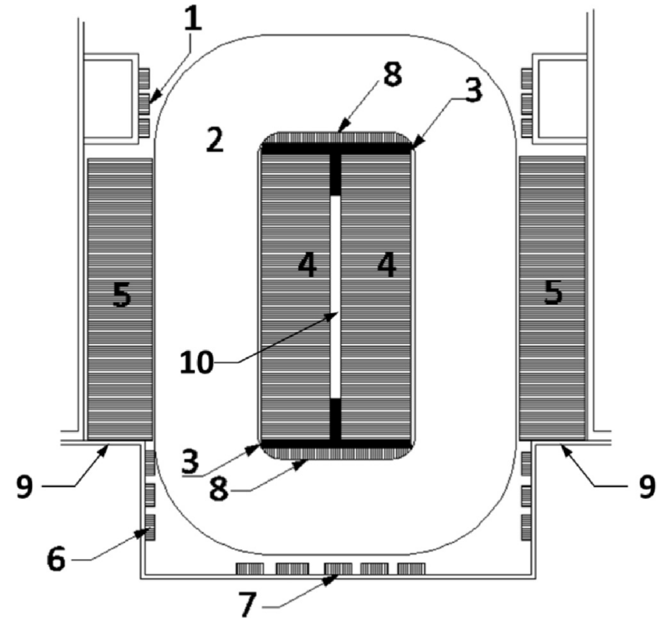

Fig. 1. Shell-form power transformer. 1: Side frame magnetic shunts, 2: pancake coils, 3: T-beams, 4: tongue iron, 5: leg iron, 6: end tank magnetic shunts, 7: tank bottom shunts, 8: T-beams magnetic shunts, 9: supports of the end tank, 10: supports between T-beams.

the plates and the shunts the velocity of transformer oil is around 10 cm/s [22,23]. This is so because there are no major cooling ducts for oil circulation in the region. Therefore, substantial temperature rise in this area is commonly found.

The main contribution of this paper is to present a comprehensive and systematic analysis of the effects of slots on the horizontal plates of the T-beams to reduce losses. Authors show that drilling slots effectively reduces the losses in the plates. It is shown that the number and length of slots have a significant influence on the losses while the position and width of the slots is less important. Other contribution of this paper is the validation of two available analytical formulas with finite elements simulations. The formulas are those used to compute the magnetic field at the center of a Merritt coil and the formula to compute the losses produced by a perpendicular magnetic field incident on a metallic plate.

2. Analytical formulation and validation

An existing analytical formula is used to calculate the power losses in a rectangular plate of stainless steel. Finite elements (FE) simulations are used to validate the results obtained with the analytical formula.

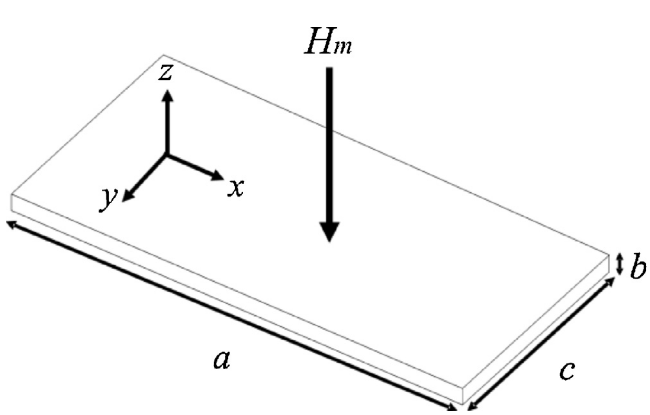

Fig. 2. Magnetic field perpendicular to a plate of stainless steel.

2.1. Analytical formula

Consider a rectangular plate of stainless steel which has thickness b in z direction, length a in x direction and width c in y direction as shown in Fig. 2. The plate of stainless steel is placed in free space and is subjected to a uniform field strength $H_m = B_m/\mu_o$, which enters perpendicularly on the xy plane of the plate. To calculate the stray losses in the plate in the steady state condition, authors use the formula for double sided excitation (both sides of the metallic plate have the same magnitude of magnetic excitation) of given by:

$$P_e = \frac{ac(a^2+c^2)\omega B_m^2}{48\mu\delta\left|1+(\mu_o(a+c))/(\sqrt{2}\pi\mu\delta)\tanh\gamma b\angle 45^\circ\right|^2} \times \left[\frac{\sinh(2b/\delta)+\sin(2b/\delta)}{\cosh(2b/\delta)+\cos(2b/\delta)}\right] \quad (1)$$

where:

P_e = stray loss in the plate
B_m = peak value of flux density
ω = angular frequency
μ = permeability of the plate
μ_o = permeability of vacuum = $4\pi \times 10^{-7}$
δ = skin effect factor $= \sqrt{\frac{2}{\omega\mu\sigma}}$
σ = conductivity of the plate
γ = propagation constant $= \sqrt{j\omega\mu\sigma} = \frac{(1+j)}{\delta}$

The above formula can be derived for a rectangular metallic plate under the action of uniform normal field excitation on its surface by considering the Maxwell's diffusion equation in terms of the normal component and then determining tangential components of the magnetic field from the continuity equation. The reaction field due to eddy currents is also considered. Details of the theory and the corresponding derivation of the formula will be reported separately. For the analysis of the stray losses in the horizontal plates of the T-beams, a small rectangular stainless steel plate is used with the following dimensions and properties: a = 800 mm, b = 19.05 mm, c = 400 mm, δ (60 Hz) = 61.95 mm, $\mu = 4\pi \times 10^{-7}$ H/m and $\sigma = 1.1 \times 10^6$ S/m. Authors assume that a peak value of flux density B_m = 5 mT. Substituting all these values in (1) a loss of 103 W is obtained.

2.2. Validation

A FE simulation was carried out to validate the analytical calculations. A uniform magnetic field was applied perpendicular to a plate. Authors utilized ANSYS Maxwell v15® software for this purpose. To generate a uniform flux density B_m = 5 mT, a four-turn Merritt coil was used [24,25]. This Merritt coil consists of square copper coils with the following physical properties: relative permeability μ_r = 1 and conductivity $\sigma = 5.8 \times 10^7$ S/m. These coils are electrically connected in series. To obtain a uniform field distribution at the center of the Merritt coil the dimensions were chosen to satisfy the following dimensionless relations [24,25]:

$$\frac{e}{d} = 0.128106 \quad (2)$$

$$\frac{g}{d} = 0.505492 \quad (3)$$