

Investigation of the thermal impact of stray losses at the high-current LV exit region on the transformer tank wall in GSU transformers

Part I



ABSTRACT

In high-power Generator Step-Up (GSU) transformers, the high currents carried in the low-voltage (LV) exit region generate intense leakage magnetic flux, which induces stray losses on the tank wall and structural components. Even when total load losses remain within acceptable limits, local stray loss

density in compact designs may lead to significant temperature rise and long-term thermal reliability risks.

In this study, stray losses occurring on the tank surface due to leakage flux at the LV exit region of a 730 MVA GSU transformer are investigated under three different design scenarios. The results show

that, without altering the compact structural configuration, appropriate material selection and magnetic shunt modification can significantly reduce local loss density and improve thermal performance.

KEYWORDS:

stray losses, transformer tank, GSU transformers

Maintaining thermally safe operating limits under continuous full-load conditions is a fundamental design requirement

1. Introduction

Generator Step-Up (GSU) transformers increase the generator output voltage to transmission level in power plants and serve as the primary power transfer link between the generating unit and the transmission grid. Failures occurring in these units may result in unplanned outages, prolonged service interruptions, and significant generation losses [1–3]. Their operational lifetime typically spans long periods of 30–40 years. Therefore, transformer design must consider not only short-term performance criteria but also long-term aging behavior. Due to continuous operation under high current levels, GSU transformers are subjected to significant electromagnetic forces and thermal stresses [4]. These stresses arise not only under nominal operating conditions but also during load variations, transient operating regimes, and system disturbances. Moreover, the high currents flowing through these conductors increase the leakage magnetic flux density, leading to additional losses in conductive metallic parts [4].

Maintaining thermally safe operating limits under continuous full-load conditions

is a fundamental design requirement. Since temperature rise directly affects insulation aging rate, not only total losses but also local loss density and hot-spot formation must be thoroughly evaluated [5].

For this reason, it is critically important to control the local temperature, particularly in regions continuously exposed to high current.

If certain temperature thresholds are exceeded, thermal degradation of the oil may occur, resulting in a reduction in insulation performance [6,7]. Therefore, limiting the local temperature rises occurring in these regions is of critical importance. Otherwise, the increase in local thermal loading may lead to accelerated aging of the oil and a decrease in insulation performance [8,9].

Although stray losses and magnetic shunt applications have been extensively investigated in the literature, the relationship between the local temperature rises occurring on the tank wall due to leakage fluxes originating from high-current-carrying conductors and the

design parameters has been addressed in a limited manner [10].

In this study, the thermal impact due to loss generation in the tank cover region caused by high-current-carrying terminal conductors in a 730 MVA GSU transformer is investigated.

Within the scope of this study, three different design scenarios are considered in order to evaluate the effect of leakage-flux-induced local losses on the tank design. In the first scenario, a compact tank structure using magnetic structural material is examined. In the second scenario, while maintaining the same geometric structure, the effect of non-magnetic stainless-steel material on the leakage flux distribution is analyzed. In the third scenario, the magnetic shunt design is revised with the aim of reducing local losses.

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2. Theoretical background

In this section, stray loss formation is addressed within the framework of electromagnetic field theory and the theoretical basic relationship between structural material, magnetic shunt thickness, and stray losses is established. In addition, the thermal effect of the losses is explained in terms of radiation and convection principles.

2.1. Effect of structural material and magnetic shunt thickness on stray loss

For magnetic steel plates, although the relative permeability is high in the saturation region, the skin depth is low. At 50 Hz, the skin depth for a typical magnetic

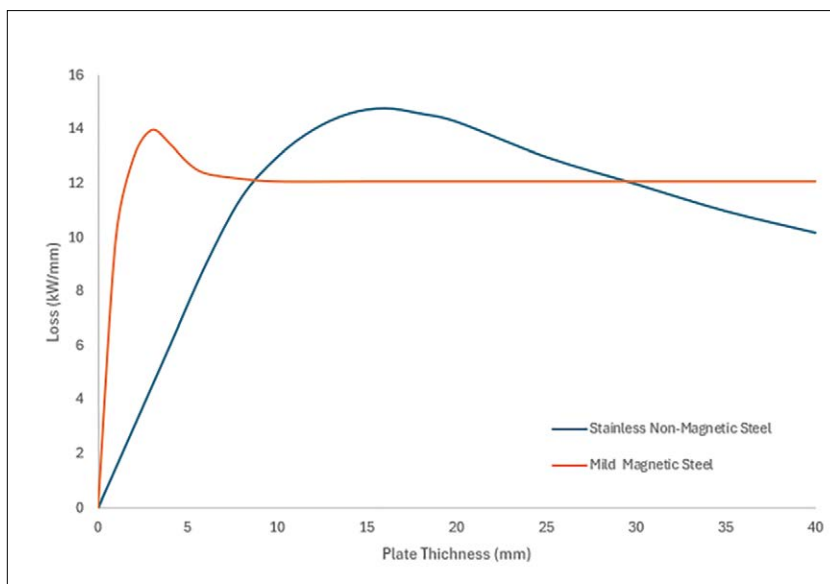


Figure 1. Effect of Plate Thickness on Loss Characteristics in Different Steel Types

steel is on the order of a few millimeters. Therefore, eddy currents concentrate within the surface layer, and once the plate thickness exceeds several skin depths, the loss value stabilizes. This behavior is consistent with eddy current theory and indicates that increasing the plate thickness does not reduce the losses beyond a certain thickness.

In non-magnetic stainless steel, the relative permeability is approximately 1, and the skin effect is significantly larger. In this case, the magnetic field penetrates a larger volume within the plate, and the loss distribution exhibits a different characteristic. Although the loss value again reaches saturation with increasing thickness, it occurs at a different order of magnitude compared to magnetic steel [11].

For the investigated transformer, the side tank wall thickness is 12 mm. As shown in Figure 1, non-magnetic materials may exhibit higher losses in the thick-

At 50 Hz, the skin depth for a typical magnetic steel is on the order of a few millimeters

ness range of approximately 10–30 mm. Accordingly, a thickness of 12 mm falls within this intermediate region, where the use of non-magnetic material may lead to increased losses. However, due to the larger skin depth in non-magnetic materials, eddy currents are distributed over a larger volume, resulting in lower current density. Therefore, a detailed analysis is required to accurately assess the actual loss behavior.

The magnetic permeability of magnetic materials (μ) is high and increasing the thickness leads to a higher concentration of leakage flux within the material. This condition reduces the magnetic

field strength at the tank surface. Since the surface loss is proportional to H^2 , an increase in magnetic shunt thickness directly results in a reduction of local losses. The objective of this approach is to control the magnetic field distribution without modifying the structural geometry. To avoid increasing the weight and volume of the active part, it is aimed to achieve lower losses at the same thickness by changing the material [12,13].

The specific core loss of the 0,3 mm M-5 magnetic shunt material used in this study is 1,39 W/kg at 1,7 T, as shown in Table 1 [14].

Table 1. Magnetic Shunt Loss

Thickness (mm)	Grade	Assumed Density kg/dm ³	Core Loss 1,5T (W/kg)	Core Loss 1,7T (W/kg)	Min. Flux Density @800A/m (T)
0,23	M-0H	7,65	0,67	1	1,87
	M-3		0,79	1,18	1,8
0,27	M-0H		0,73	1,03	1,88
	M-1H		0,77	1,09	1,88
	M-3		0,83	1,21	1,8
	M-4		0,89	1,27	1,8
0,3	M-0H		0,76	1,05	1,88
	M-1H		0,8	1,11	1,88
	M-2H		0,85	1,17	1,88
	M-4		0,9	1,32	1,8
	M-5		0,97	1,39	1,8
0,35	M-1H		0,87	1,16	1,88
	M-2H		0,9	1,22	1,88
	M-3H		0,96	1,28	1,88
	M-5	1,01	1,45	1,8	
	M-6	1,11	1,57	1,8	

In this study, structural material selection and the effect of the magnetic shunt stand out in determining leakage flux

As a result, in this study, structural material selection and the effect of the magnetic shunt stand out in determining leakage flux. The effect of these parameters is directly related to the loss density and the associated temperature rise through the electromagnetic field distribution.

2.2. Stray loss theory for electromagnetic analysis

The distribution of the magnetic field generated by high-current low-voltage winding conductors depends on conductor geometry, phase arrangement, the distance to the tank surface, and the magnetic properties of the material used [4]. This time-varying magnetic field induces eddy currents on conductive metal surfaces, leading to Joule losses. The magnitude of these losses varies depending on both the field density and the electrical conductivity and magnetic permeability of the material [13]. The magnetic structural material used for the tank wall corresponds to structural carbon steel (ST37), which is modeled using a nonlinear B-H characteristic typical for magnetic structural steels. In Case 2, the structural material is replaced with non-magnetic AISI 304 stainless steel. In the electromagnetic model, the material properties such as electrical conductivity and magnetic permeability are defined according to typical literature data for these materials. Therefore, the analysis process, which begins with electromagnetic field equations, requires a coupled solution approach by combining them with thermal field equations.

High-current LV leads generate strong leakage magnetic fields that may induce proximity currents in nearby conductive structures. These currents contribute to circulating currents and structural eddy losses in the tank wall and turret region. In the present study, these effects are inherently captured in the electromagnetic FEM model, since the eddy current distribution is solved directly from the magnetic field generated by the current-

carrying conductors. Therefore, proximity-induced effects are implicitly included in the loss calculations.

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The electromagnetic field distribution is defined by Maxwell's equations. In differential form, the field equations can be written as follows:

$$\begin{aligned}\nabla \times E &= -\frac{\partial B}{\partial t} \\ \nabla \times H &= J + \frac{\partial D}{\partial t} \\ \nabla \cdot B &= 0 \\ \nabla \cdot D &= \rho\end{aligned}$$

Where;

- H: magnetic field strength (A/m)
- E: electric field strength (V/m)
- B: flux density (Wb/m²)
- J: current density (A/m²)
- D: electric flux density (C/m²)
- ρ : volume charge density (C/m³)

The fundamental constitutive relations are as follows:

$$\begin{aligned}J &= \sigma E \\ B &= \mu H \\ D &= \epsilon E\end{aligned}$$

Where;

- μ : permeability of material (henrys/m)
- ϵ : permittivity of material (farads/m)
- σ : conductivity (S/m)

The ratio of the conduction current density (J) to the displacement current density ($\partial D/\partial t$) is given by $\sigma/(j\omega\epsilon)$. This ratio is quite large even for a weak metallic conductor at very high frequencies. Since the analysis carried out in this study is performed at low frequency, the displacement current density is neglected in the analysis of eddy currents in the conductive parts of transformers (copper, aluminum, steel, etc.).

Therefore, Maxwell's equation simplifies to the following form:

$$\nabla \times H = J$$

By using Ampère's law and Faraday's law together, the diffusion equation of the magnetic field for a conductive medium is obtained. In power-frequency transformers and in highly conductive metals, the principle of charge conservation gives the point form of the continuity equation.

The analytical expression is included only to illustrate the theoretical dependence of the surface loss density on the magnetic field intensity

In the present analysis of eddy currents within the conductor, in the absence of free electric charges, we obtain the following expression:

$$\nabla \cdot J = 0$$

When the expressions for E and H given above are considered together, the following is obtained:

$$\nabla^2 H = \mu \sigma \frac{\partial H}{\partial t}$$

Assuming that in the time-harmonic regime the field varies as $H = \hat{H}e^{j\omega t}$ the equation is reduced to the following form in the frequency domain:

$$\nabla^2 H = j\omega\mu\sigma H$$

When a structural element of the infinite half-space type is considered and it is assumed that the magnetic field varies only in the z-direction normal to the surface, the equation becomes one-dimensional:

$$\frac{d^2 H_y}{dz^2} = j\omega\mu\sigma H_y$$

The solution of this differential equation shows that the field decays exponentially within the conductive material:

$$H_y = H_0 e^{-kz}$$

Here, the propagation constant is defined as follows:

$$k = \sqrt{j\omega\mu\sigma} = (1+j)\sqrt{\frac{\omega\mu\sigma}{2}}$$

Using this expression, the penetration skin depth is obtained as follows:

$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}}$$

The current density induced by the magnetic field is determined by taking the curl of the field:

$$J = \nabla \times H$$

The time-averaged power density generated at the conductor surface is calculated using the real part of the complex Poynting vector:

$$P = \frac{1}{2} \text{Re} (E \times H^*)$$

Using this relation, the eddy loss per unit surface area is obtained as follows:

$$P = \frac{1}{2} \frac{H_0^2}{\sigma\delta}$$

Equivalently, the loss density can also be expressed in the following form:

$$P = \sqrt{\frac{\omega\mu}{8\sigma}} H_0^2$$

Finally, the total stray loss of the tank or a structural component is determined by integrating over the surface:

$$P_{\text{total}} = \sqrt{\frac{\omega\mu}{8\sigma}} \int_{\text{Surface}} H_0^2 ds$$

These relations represent analytical approximations derived for idealized conductive plates. In practical transformer structures, the leakage magnetic field distribution is three-dimensional and influenced by geometry and structural components. Therefore, the actual stray losses are calculated using a 3D

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electromagnetic FEM solution, while these relations are presented only to illustrate the theoretical dependence of loss density on the magnetic field intensity.

The theoretical framework quantitatively defines the eddy losses generated in structural components by the leakage magnetic field originating from high-current low-voltage winding conductors directly in terms of the magnetic field strength. As seen from the derived expressions, the surface loss density is proportional to H_0^2 , and therefore even small variations in the leakage field distribution may lead to significant increases in loss density.

The electromagnetic solution is obtained using a full volumetric eddy-current formulation in the FEM model. The tank wall and structural components are modeled explicitly as conductive regions, and the losses are calculated directly from the induced current density distribution within the material. Therefore, a surface impedance boundary condition was not used in the simulations. The analytical expression presented in the manuscript is included only to illustrate the theoretical dependence of the surface loss density on the magnetic field intensity.

2.3. Radiation and convection theory for thermal analysis

The stray losses obtained from the electromagnetic analysis appear as volumetric or surface heat generation terms in the transformer tank and bushing transition regions. In order to accurately

determine the temperature distribution caused by these losses, the heat transfer mechanisms must be modeled in a conjugate manner [4]. In a 730 MVA class GSU transformer, since the surface areas are large, the temperature differences are significant, and the operation is continuously close to full load, radiation and natural convection are effective together at the outer surface, while heat conduction is dominant in solid regions. Therefore, the thermal model is established based on three fundamental mechanisms which are radiation, natural convection and conduction.

The local heat flux emitted by radiation at the outer surface is defined by the Stefan-Boltzmann law. The radiation heat flux per unit surface area along the height (z) is expressed as follows.

$$q''(z) = \frac{q}{A} = \varepsilon\sigma(T_s^4 - T_{\text{air}}^4)$$

Where,

T_s : represents the surface temperature (°C)
 T_{air} : the ambient air temperature (°C)
 ε : the surface emissivity
 σ : the Stefan-Boltzmann constant
 A : is the surface on which radiation occurs (m²)

Since the radiation term depends on the fourth power of temperature, radiative heat transfer increases nonlinearly with increasing temperature in high-power transformers. This effect becomes more pronounced at local hot spots occurring around the tank cover and bushing regions.

Heat transfer by natural convection depends on the temperature difference

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Since the radiation term depends on the fourth power of temperature, radiative heat transfer increases nonlinearly with increasing temperature in high-power transformers

between the surface and the surrounding air. The local convective heat flux as a function of height is expressed as follows:

$$q''(z) = \frac{q}{A} = h(z)(T_s - T_{air})$$

It is defined as follows:

$h(z)$ represents the local heat transfer coefficient (W/m^2K) and varies with height along the vertical surface. The local heat transfer coefficient is calculated based on the Nusselt number as follows:

$$h(z) = \frac{Nu_z k_{air}}{z}$$

Under the assumption of uniform heat flux, the correlation used for the local Nusselt number is given as follows:

$$Nu_z = \left[\frac{4Pr^2 Gr^*}{36+45Pr} \right]^{1/5}$$

The Prandtl number (Pr) represents the ratio of momentum diffusivity to thermal diffusivity and is defined as follows:

$$Pr = \frac{\nu}{\alpha}$$

Where,

ν : kinematic viscosity of the fluid (m^2/s)
 α : thermal diffusivity of the fluid (m^2/s)

The modified Grashof number is defined as follows:

$$Gr^* = \frac{g\beta q'' z^4}{k_{air} \nu^2}$$

In this expression, g represents gravitational acceleration, β the volumetric expansion coefficient, ν the kinematic vis-

cosity, and k_{air} the thermal conductivity of air. These correlations are valid within the range $10^5 \leq Gr^* \leq 10^{10}$. Considering the temperature differences occurring in high-power GSU transformer tanks, this range is typically satisfied.

For the outer surface, the total heat flux can be written as the superposition of radiation and natural convection:

$$q_{total}''(z) = \epsilon\sigma(T_s^4 - T_{air}^4) + h(z)(T_s - T_{air})$$

This expression is balanced by the surface loss density obtained from the electromagnetic analysis. In other words, under steady-state conditions, the loss density generated at the surface must be equal to the total heat flux dissipated to the surroundings.

The total conduction heat is given as follows:

$$Q = kA \frac{\Delta T}{L}$$

Where,

k : represents the thermal conductivity of the material (W/mK)
 A : the heat transfer area
 ΔT : the temperature difference between a cold surface and a hot surface
 L : material thickness (m)

As a result, the loss density generated by the leakage magnetic field originating from high-current conductors appears in the thermal model as a heat generation term, while radiation and natural convection boundary conditions are

applied at the outer surface to determine the temperature distribution. This approach demonstrates that in 730 MVA GSU transformers, not only the electromagnetic loss distribution, but also local temperature rises and insulation lifetime are determined. The conjugate analysis of electromagnetic and thermal fields is therefore essential for reliable performance evaluation in high-power transformer design.

The second part of this article will be published in an upcoming edition of Transformer Magazine.

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The conjugate analysis of electromagnetic and thermal fields is essential for reliable performance evaluation in high-power transformer design

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