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Comparative Geometric Analysis of Power Transformer Cores: CRGO Vs. Amorphous Metal Alloys (Focuses on the Physical Size Difference)

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Abstract- The use of transformers is vital in an electrical power system as they are expensive to acquire and maintain, which influences their lifecycle. This paper discusses the effect of material selection on the diameter of the core after giving a comparative study of the core geometry. Using MATLAB based mathematical modeling, the author analyzed the relationship between flux density, volt per turn of the two types of metals producing energy in the core. The benchmark of the simulation was set to be 100 kVA distribution transformer. The findings of the research showed that while Amorphous metals significantly decrease the loss of energy in the core, they're bigger in diameters (14-20% more than CRGO) because they have lower limits of magnetic saturation and stacking factors of the core.

Keywords: power transformer design, core material, CRGO steel, amorphous metal, core diameter, stacking factor

I. INTRODUCTION

The power transformer is an indispensable component of the AC power system. While statically efficient, transformers incur energy losses—specifically no-load (core) and load (winding) losses—throughout their operational life, which typically spans 25 to 30 years. With rising energy costs and stringent regulatory norms like the Bureau of Energy Efficiency (BEE) Star Rating plans, the focus of transformer design has shifted toward a dual-objective: reducing core losses while controlling size (core diameter and weight).

Transformer design is a complex, multi-variable engineering problem involving electromagnetic and mechanical constraints. Traditional design methods often overlook the volumetric penalty associated with high-efficiency materials. This paper proposes an optimization framework that:

1. Analyzes the impact of the K constant (Volts per turn) on core geometry.
2. Quantifies the increase in core cross-section and diameter when transitioning from CRGO to Amorphous alloys based on their respective saturation flux densities and stacking factors.

II. TRANSFORMER CORE MATERIALS

The material used for the magnetic core is the most significant when it comes to evaluating no-load losses. This paper compares the two most widely used materials:

A. Cold-Rolled Grain-Oriented (CRGO) Steel

CRGO (Grade M4) is a conventional material in the industry. It has very good saturation flux density (1.9 T) and permeability in the direction of rolling. However, the specific losses are moderate, and performance starts suffering when the flux deviates from the direction of the grains.

B. Amorphous Metal

Amorphous alloys (like Metglas®) differ from CRGO in the cell structure. Rapid cooling during production prevents the formation of crystals, resulting in a random arrangement of the atoms. This means that there are no grain boundaries, which leads to a 60-70% reduction of hysteresis loss as compared to CRGO material . The only disadvantage of this material is that its saturation flux density (1.56 T) and stacking factor are lower than CRGO materials, creating the necessity to use larger dimensions for the physical core.

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III. MATHEMATICAL MODELLING

A robust mathematical model is essential for the optimization loop. The study models a three-phase, core-type distribution transformer with concentric windings.

A. Core Design

The net iron area (Ai) is derived from the EMF equation:

$E_t = 4.44 \cdot f \cdot B_m \cdot A_i$ ……(1)

Where E_t is the EMF per turn, f is frequency, and B_m is the maximum flux density. The initial estimate E_t for is based on the rating (in kVA):

$E_t = K . \sqrt{Q}$ ……(2)

Where K is an empirical constant (0.45 for distribution transformers). To maximize the fill factor within the circumscribing circle of diameter D_c, a multi-stepped core is utilized. For a 4-step core, the gross area (A_g) related to by:

$A_i \approx K_s . 0.625 . (D_c)^2$ …..(3)

Where K_s is the stacking factor (0.97 for CRGO, 0.85 for Amorphous).

B. Core Loss Calculation

1. No-Load Loss (P_i): Calculated based on the weight of the limbs and yokes, multiplied by the specific loss (W/Kg) of the chosen material at the operating B_m, adjusted by a building factor ($K_b \approx 1.25$).

$P_i = (W_{core} \cdot Sp_{loss}) \cdot K_b$ ……(4)

IV. OPTIMIZATION METHODOLOGY: (TURN-WISE ITERATIVE OPTIMIZATION FOR CORE GEOMETRY)

The design optimization follows a systematic computational approach to determine the influence of the voltage-per-turn, constant (K) and flux density (B_m) on the transformer's physical core dimensions. The methodology is divided into the following five phases:

A. Definition of Design Space and Constants

The optimization process begins by defining the transformer's rated capacity (S in kVA) and the low-voltage (LV) line voltage (V_L). The phase voltage ($V_{ph} = V_L/\sqrt{3}$) is established as the primary reference. To ensure the design remains within industry standards, a range for the K constant (typically 0.45 to 0.60) and magnetic flux density B_m (1.4 to 1.6 T and 1.2 to 1.45) is predefined for CRGO and Amorphous core.

B. Derivation of Discrete Turn Constraints

Unlike traditional methods that treat turns as a continuous variable, this methodology employs Discrete Turn-wise Increment. The boundary values for the number of turns (N_{min} and N_{max}) are derived from the K constant limits using the EMF equation:

As per Eq.(2) $E_t = K . \sqrt{Q}$

$N = V_{ph} / E_t$ …..(5)

By converting the range of K(0.45-0.6) for Distribution transformer into a range of integer turns, the algorithm ensures that the resulting design is physically manufactural.

C. Iterative Computational Framework

The core of the methodology involves a nested iterative loop:

- *Outer Loop (Turn-wise Increment):* The algorithm iterates through every integer value of turns (N) within the calculated design space. This provides a granular look at how a single turn addition/subtraction affects the overall geometry.
- *Inner Loop (Flux Density Sweep):* For every discrete turn value, the flux density (B_m) is swept from 1.4 to 1.7 T for CRGO and 1.2 to 1.45 Tesla for Amorphous in increments of 0.02. This allows for the observation of core saturation effects and material utilization.

D. Geometric Modeling of the Core

For each iteration, the Net Iron Area (A_i) and the resultant Core Diameter (D_C) are calculated. The mathematical model accounts for the stacking factor ($K_s \approx 0.97$) for CRGO and 0.85 for Amorphous core to relate the net area to the physical diameter:

- *Net Iron Area (A_i):*

$A_i = E_t / 4.44 \cdot f \cdot B_m$ ……(6)

- *Physical Core Diameter (D_c):*

$D_c = \sqrt{(4.A_i/\Pi)}$/stacking factor * 1000 mm ……(7)

E. Evaluation and Convergence

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The results are tabulated to generate a sensitivity matrix. This matrix allows the designer to perform a Trade-off Analysis:

- *Mass Optimization:* Selecting a higher B_m to reduce D_c.

- *Efficiency Optimization:* Selecting a lower B_m to reduce iron losses while observing the increase in D_c. The optimal design point is converged upon by selecting the turn count that yields a Core Diameter satisfying both the window space constraints and the cooling requirements.

Table 1: Transformer Specifications

Parameter	Value
Power Rating	100 KVA
Number of Phases	3
Frequency	50 Hz
High Voltage (HV)	11000 V (Delta connected)
Low Voltage (LV)	433 V (Star Connected)
Cooling Type	ONAN (Oil Natural, Air Natural)
Core Type	3-Limb, Stepped Core
Winding Type	Concentric, Cylindrical

Table 2: Material Parameters Taken

Parameter	CRGO M4 Steel	Amorphous Metal	Unit
Material Properties			
Stacking Factor (K_s)	0.97	0.85	-
Highest Flux Density limit	~1.7	~1.45	T
Lowest Flux Density limit	~1.4	~1.2	T
K ranges	0.45-0.6	0.45-0.6	-

V. RESULTS AND DISCUSSION

In the case of both CRGO and Amorphous core, some optimizations were made to acquire minimum core diameter at maximum flux density. A 100 kVA transformer design process was modeled by means of a MATLAB-based iterative scheme. The comparative analysis was done for Cold Rolled Grain Oriented Steel and Amorphous Metal Alloys (AMDT) with different values of Volts per Turn obtained according to K constant.

Key Findings from optimization:

- Core Diameter: For constant numbers of turns (e.g., N=42 and K=0.595), Amorphous core is always correlated with larger diameter. The core diameter was calculated to be 161 mm for CRGO at the flux density of 1.4 T while the diameter of Amorphous core was equal to 184 mm (approximately 14.29% bigger).
- Flux Density Sensitivity: The geometry of CRGO core geometry remains unchanged at 1.7 T; on the other hand, the results for Amorphous core can be obtained only at 1.45 T because of its lower value of saturation induction.
- Stacking Factor Impact: The smaller stacking factor for Amorphous alloy (0.85 comparing to 0.97 for CRGO) leads to bigger value of gross area required (thus increasing the total area of the core in order to keep the same total area).

A. *DISCUSSION*

The comparative investigation indicates a considerable "Geometric Penalty" when employing Amorphous metallic compounds. Two key physical factors resulting in this disparity are:

1. Magnetic Saturation: Amorphous composites possess a lower saturation magnetic flux density (about 1.56 T) than CRGO (approximately 1.9 T). In order not to encounter core saturation and excessive magnetizing currents, Amorphous cores should function at lower flux densities (about 1.3 T to 1.4 T). According to the general equation of the transformer operation ($Ai = Et / 4.44 \cdot f \cdot Bm$), lower Bm values imply that it is necessary to increase the value of net iron area (Ai), which influences the increase of core size.

2. Lamination Thickness and Stacking Factor: In this way, CRGO lamination is noticeably thicker (0.23-0.30 mm) than Amorphous ribbons (around 0.025 mm). This results in a lower stacking factor ($K_s \approx 0.82$-0.86). As shown in the simulation code, the diameter D_c is inversely proportional to K_s. The smaller laminations create a higher number of air gaps and thus make it necessary to introduce more bulky physical constructions.
3. Design Trade-offs: The amorphous core has a bigger structure and therefore consumes more copper and fills larger tanks, but it has been found that its energy losses are reduced by 70-80% compared to CRGO transformer. Hence, the designer needs to weigh the higher costs and sizes of amorphous transformers against energy efficiency.

VI. CONCLUSION

This research performs a numerical geometric analysis of CRGO and Amorphous metal transformer cores. From the simulation:

- Amorphous cores achieve a larger physical size, as core diameter increases by around 14.29% for an equivalent power rating when compared to CRGO.
- Stacking Factor is an important distinguishing parameter, as the small thickness of the Amorphous ribbons increases the net volume of the cores.
- CRGO is the best option when there are volume limitation issues in either initial material volume (copper and oil) or material volume itself.
- On the other hand, Amorphous alloys represent a necessary compromise when it comes to geometrical design formulation of transformers as it provides the desired magnetic properties.

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