Power, Energy and Electrical Engineering
M. Deng (Ed.)

doi:10.3233/ATDE240306

Design of the Cruciform Core for a Three-Phase Distribution Transformer with the Aim of Reducing Technical Losses and Stabilizing the Electrical System

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Abstract. The primary objective of this research is to design a three-phase distribution transformer that reduces technical losses within the electrical distribution system. These losses translate into costs associated with energy dissipation. While it's impossible to eliminate these losses entirely, the aim is to optimize system efficiency. The focus is on the 220 V secondary voltage level. The research resulted in a transformer with losses of 4.6882 W, which complies with IEEE standards. The design features a cruciform morphology, operates at 13.2 kV, and has a total surface area of 9660 mm2. The core material is mu-metal, and the coil material is copper. The applied design methodology includes a 2^4 factorial design, and simulation is performed using ANSYS Maxwell, evaluating sixteen combinations. The design with the lowest power loss is selected as the optimal choice, effectively reducing technical losses in the electrical system.

Keywords. three-phase distribution transformer, technical losses, Electrical distribution system, Efficiency, Cruciform morphology.

1. Introduction

In a world of constant evolution, Peru is striving to maintain economic and technological growth. To achieve sustainable economic development and technological advancements, innovation within the electricity subsector and the reinforcement of traditional electrical systems are essential. This entails a gradual expansion of the electrical networks, enhancing existing technology, and integrating new technologies.[1] "Energy should be inexpensive, plentiful, cost-effective, readily available, easy to transport, and storable." That ideology forms the primary foundation of the research since it aims to enhance the performance of the fundamental static machine within the electrical system. Various methods, such as spectroscopy applied to transformers, provide a tool for measuring

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losses, and the frequency sweep response analysis method (SFRA) is a diagnostic technique for detecting deformations, displacements, and other electrical and mechanical faults in power transformers' windings. [2] Distribution transformers are exposed to operating conditions different from their design specifications due to the presence of harmonic currents and nonlinear devices.[3] This doesn't contribute to the reliable operation of the system, as it necessitates that voltage and current magnitudes, angles, and power flow stay within the allowable ranges.[4] It is essential to investigate the operation of transformers and estimate their service life. Methods such as calculating operational conditions based on monthly billing data are used to identify overloaded transformers and assess their estimated service life based on temperature increases. The primary focus is on thermal behavior to ensure optimal performance. [5] Another approach that is increasingly being used in substation solutions worldwide is based on the concept of open-core design. It offers significant advantages in terms of transformer performance and reliability. This approach details losses in the open core and a measurement-based method for calculating total losses and verifying the magnitude of all components in the flux density vector. [6]

The study aims to emphasize the reduction of losses in the transformer, especially the losses occurring in its core. The failure analysis of silicon steel sheet in distribution transformers presents a model based on the microstructure and magnetic properties of this diagnostic material, used in the core of single-phase distribution transformers. These diagnostics and supplementary studies assess the lifespan of these devices, comparing the quality of materials manufactured using "non-conventional methods" when fault conditions occur. This contributes to the knowledge and experience in electric power distribution systems.[7] Another critical point of the electric field at the corners of the windings requires shielding through equipotential rings.[8] The distribution transformer is the most vital component of the electrical system. Transformer failure leads to revenue loss and impacts the reliability of power supply to consumers. It can result in extended unavailability of the transformer.[9] Many energy utility companies may encounter issues with data quality in records regarding which feeder a distribution transformer is connected to. This impacts the operation and maintenance of the smart grid infrastructure, outage management, line loss management, and workforce safety.[10] Undoubtedly, the issue of losses is the result of inefficiencies within the distribution system, which can be further subdivided into technical-commercial losses. However, when focusing on the distribution transformer, the emphasis is placed on technical losses, which are typical in electrical machines. Therefore, it is essential to contribute to the control of these losses and maximize their reduction within the electrical system.

2. Methodology

The proposed design consists of 8 stages for the core design of a three-phase distribution transformer to reduce technical losses. In the first stage, combinations of variable treatments; secondly, study of the applicable formulas; and thirdly, design of plans for construction.

2.1. This Stage Involves Combinations of Variable Treatment and the Study of Applicable Formulas

This stage integrates the choice of material (M-4 Steel and Mu_Metal), morphology (rectangular and cruciform), coil material (copper and silver), voltage level (10 kV and 13.2 kV).

Table 1. Combination of Materials Used in the Designs

Three-phase transformer core.				Technical losses.	Rep
Material	Morphology	Winding	Voltage level.	Level of generated losses.	Loss level
g	m^2	Ω/m	V	W	
Acero M4	Traditional	Silver	10 kV	D1A1B1C1	1
			13.2 kV	D1A1B1C2	2
		Copper	10 kV	D1A1B2C1	3
			13.2 kV	D1A1B2C2	4
	Cross-sectional	Silver	10 kV	D1A2B1C1	5
			13.2 kV	D1A2B1C2	6
		Copper	10 kV	D1A2B2C1	7
			13.2 kV	D1A2B2C2	8
Mu_Metal	Traditional	Silver	10 kV	D2A1B1C1	9
			13.2 kV	D2A1B1C2	10
		Copper	10 kV	D2A1B2C1	11
			13.2 kV	D2A1B2C2	12
	Cross-sectional	Silver	10 kV	D2A2B1C1	13
			13.2 kV	D2A2B1C2	14
		Copper	10 kV	D2A2B2C1	15
			13.2 kV	D2A2B2C2	16

Table I displays 16 combinations that will be evaluated through the proposed design. This design will be developed using ANSYS software, and factorial analysis will be conducted with the assistance of MINITAB software. This complements the study with the empirical data collection technique, which "allows direct contact observation with the object of study and the collection of testimonies to compare theory with practice in the search for truth" (35). Espinoza mentions four possible techniques: observation, interview, questionnaire, and interview, of which this research utilized observation.

2.2. Study of the Applicable Formulas

- The main characteristics of the distribution transformer to be designed.

Table 2. Characteristics of Voltage Level 1 And 2

Primary voltage		
S	150	kVA
VP	13.2	kV
VS	220	V
F	60	Hz
T	65	°C
# Taps	+/- 2	
Secondary voltage		
S	150	kVA
VP	13.2	kV
VS	220	V
F	60	Hz
T	65	°C
# Taps	+/- 2	

- Current and voltage calculations

$$Ipa = S/Vp = 150\ kVA\ 10\ kV = 15A \quad (1)$$

$$Ipb = S/Vp = 150\ kVA\ 13.2\ kV = 11.36A \quad (2)$$

$$Ipa1 = S/Vp1 = 150\ kVA\ 10.5\ kV = 14.286\ A \quad (3)$$
$$Ipb1 = S/Vp1 = 150\ kVA\ 14.7\ kV = 10.204\ A \quad (4)$$

$$Ipa5 = S/Vp5 = 150\ kVA\ 9.5\ kV = 15.789\ A \quad (5)$$
$$Ipb5 = S/Vp5 = 150\ kVA\ 11.7kV = 12.821\ A \quad (6)$$

$$Ips = S/Vs = 150\ kVA\ 0.220\ kV = 681.818\ A \quad (7)$$

- Calculation of the number of turns, conductor's cross-sectional area, and core's cross-sectional area.

Number of turns
$Vt = V/vueltas = 15.307\ V/vuelta$
$N2 = V2/Vt = 220/15.307 = 14.372\ espiras = 14\ espira$

$N1a = V2\ Vt = 10kV\ 15.714\ V/vuelta = 636.375\ espiras = 636\ espira$
$N1b = V2\ Vt = 13.2kV\ 15.714\ V/vuelta = 840.015\ espiras = 840\ espira$

$N1a(tp1) = V2\ (tp1)\ Vt = 10.5\ kV\ 15.714 = 668.19\ espiras = 668\ espira$
$N1b\ (tp1) = V2\ (tp1)\ Vt = 14.7\ kV\ 15.714 = 935.472\ espiras = 935\ espira$
Conductor gauge
$Aacond = Iap/\rho = 5.26\ mm2\ 10\ AW$
$Abcond = Ibp/\rho = 4.274\ mm2\ 10\ AW$

Low-voltage (secondary):

$Acond = Ip5$ ρ = 227.27 $mm2$ 450 $Kcmi$

- Calculation of the core's cross-sectional area and its geometric dimensions.

$A = v$×108/(4.44×f×N×B) = (10×10^3×10^8)/ (4.44×60×636×16×10^3) = 368.88 $cm2$

For transformers with M-4 grade electrical steel in the wound core structure, the stacking factor (fe) is between 0.93 and 0.96, while in the stacked core, the stacking factor (fe) is between 0.90 and 0.93. For our analysis, we will use (fe) = 0.95.

Af = A fe = 368.88 $cm2$ 0.95 = 388.29 $cm2$

Cross-sectional area

It is considered that the width of the sheet is 25 cm and is designed in the core of the steel sheet, so its thickness (2D) can be calculated based on the physical area (Af).

2 $D = Af$ C = 388.29 $cm2$ 25 cm = 15.5316 cm

The width-to-thickness ratio C / 2D is verified to be 1.69 times. The number of layers or thickness (2D) to form the core stack is determined based on the thickness of the sheet to be used, as previously mentioned, which will be M4-grade electrical steel with a thickness of 0.28 mm, and then the winding needs to be carried out.

$\#Lam$ = 2 D /(Espesor de láminas) = 155.316 mm /0.28 mm = 554.7 lam

- Calculation of the overall size of the coil and the width of the central arc window.

Sizing of Low-voltage coil.

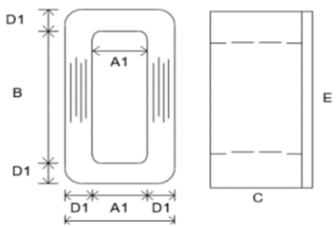

Figure 1. Transformer core dimensions.

$Acond(AL) = Acond(cobre)$ × 1.6 = 226.4 $mm2$

Height of the low-voltage coil.
hs = B − 2 × (da + 3.7) = 44.364 − 2 × (0.8 + 3.17) = 42.13 cm = 421.3 mm

Radial thickness of the low-voltage coil.
Dbt = 14 × (0.54 + 0.13) = 9.38 mm

In addition to that, a 5% tolerance is applied

Dbt = 9.38 × 1.05 = 9.849 mm

The length of the mean turn of the secondary winding is determined by the following expression
$Ivms$ = 2 × (25 + 15.53) + π × (2(0.32) + 9.849) $Ivms$ = 91.549 cm

The total length of the conductor.
$LtBT$ = 14 × 91.549 = 12.82 m
In addition to that, a 10% tolerance is applied is 13.26 m

Sizing of high-voltage coil.

For the high-voltage winding calculation, a 14 AWG gauge conductor is required. For the 15kV insulation class, conductors with double varnish insulation are needed. The wire with double varnish is chosen from the product datasheet of Magneto.

hp = B − 2 × (da + rc)
hp = 44.364 − 2(1.55 + 0.137) = 40.99 = 409.9 mm

The effective height of the winding
$espiras/capas$ = 403.9 2.59 = 158.26 = 158 $espiras\ por\ capa$

The required capacity will be obtained by dividing the total number of turns by the number of turns per layer.
#espiras/(#espiras/capa) = 636/158 = 4.025 $capa$

The length of the mean turn of the primary winding.
$Ivmp$ = 2 × (C + 2D) + π × (2 × (dcasq + Dbt + daisLAT − BT) + dAT)
$Ivmp$ = 2 × (25 + 15.53) + π × (2 × (0.32 + 0.97 + 0.69) + 1.672) $Ivmp$ = 97.24 cm

The total length of the conductor.
$LtAT$ = 668 × 97.24 = 649.56 m

Determine the width and weight of the central window of each arch.

= (#capas) × (espesor/capa × BT) + (#capas) × (espesor/capas × AT) Espesor de la bobina = (7 × 0.535) + (4 × 2.59) × 1,05 Espesor de la bobina = 14.81

A1 = 14.81 + 2,5 = 17 mm = 17.31 cm
A2 = 2 × 14.81 + 6 mm = 35.62 mm = 3.562 cm

The average length of the arch.
$Lm1$ = 2 × (A1 + B) + π × (D)
$Lm1$ = 2 × (2,5 + 44,36) + π × (7,4) = 116,9 cm

The weight of the small arch.
$P1$ = (25 × 7,394 × 116,96) × Pe = (21 620,056) × 7,65 $P1$ = 165,4 Kg

The total weight of the core will be the sum of the weight of each arch.
$Pt = 165{,}4\ Kg \times 2 = 330.8\ kg$

Determining the theoretical losses.

$P1 = Vfe1 \times Pe$
$P1 = (25 \times 7{,}394 \times 116{,}96) \times Pe = (21\ 620{,}056) \times 7{,}65\ P1 = 165{,}4\ Kg$

$Pt = 165{,}4\ Kg \times 2 = 330.8\ kg$
$fPh\ (1.7\ tesla) = 1.52\ W\ kg/\ a\ una\ frecuencia\ de\ 60\ Hz\ Ph = fPh \times pt$

$Ph = 1.52\ W\ kg/ \times 330.8\ kg = 502.8W$

Percentage of losses based on the calculated values

150 kw = 100%
502 W = x%

$x = 100 \times 502.78\ 150000\ Ph = 0.3352\%$

Removal of core vertices

a) At the first voltage level, which is 10 kV, in this initial model, a total area of 8694 mm2 is extracted from each outer core vertex.
b) At the second voltage level, which is 13.2 kV, in this initial model, a total area of 9660 mm2 is extracted from each outer core vertex.

- Design of plans for construction

For modeling the core of a three-phase distribution transformer in the ANSYS Maxwell simulator, the following characteristics are considered: a comparison between materials M-4 Steel and Mu_Metal, a comparison between rectangular and cruciform cross-sectional morphology, a comparison between copper and silver as coil materials, and the evaluation of voltage levels at 10 kV and 13.2 kV. Based on this comparison, the design determined to have the lowest losses according to the conducted tests is the cruciform morphology, utilizing Mu-Metal as the ferromagnetic material, a copper winding, and a voltage level of 13.2 kV.

The dimensions for the 13.2 kV voltage level

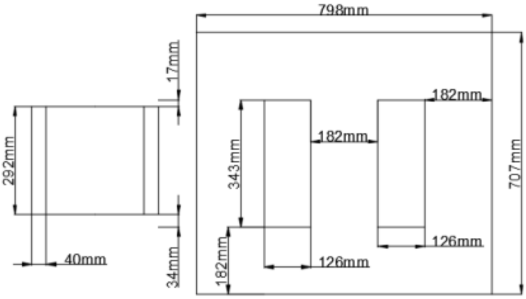

Figure 2. Designation of the parts of the arches.

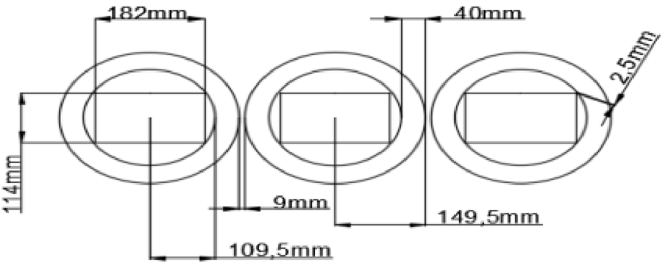

Figure 3. Designation of the parts of the arches.

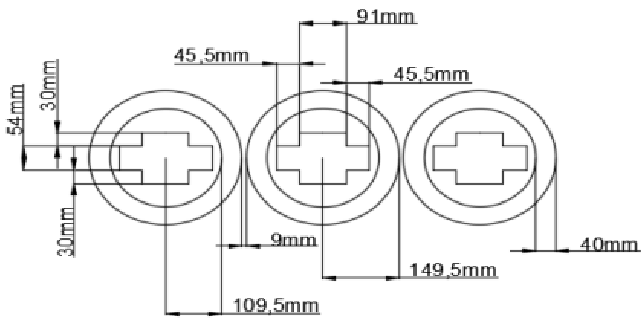

Figure 4. Designation of the parts of the arches

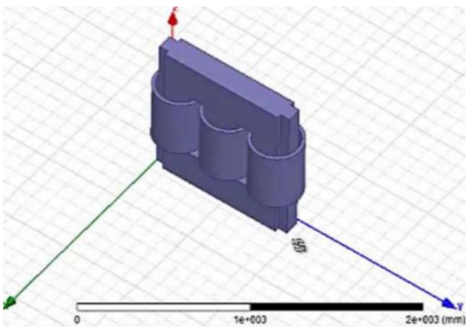

Figure 5. Cruciform core design.

3. Results

3.1. Integration of Values for the H-B Curve for M-4 Steel

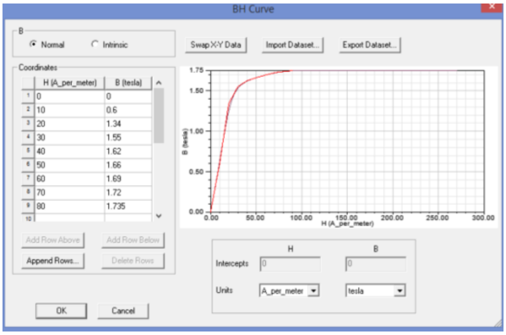

Figure 6. Designation of the parts of the arches.

3.2. Integration of Values for the H-B Curve for Mu_Metal.

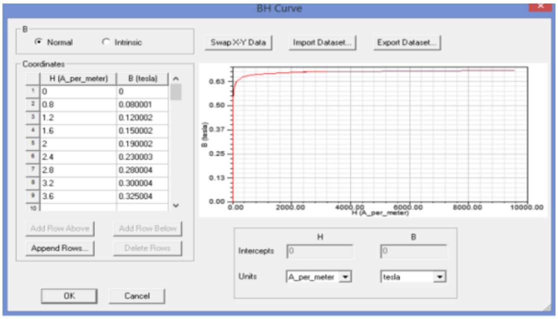

Figure 7. Designation of the parts of the arches

3.3. Maximum and Minimum Results of the Combinations in the Cruciform Morphology

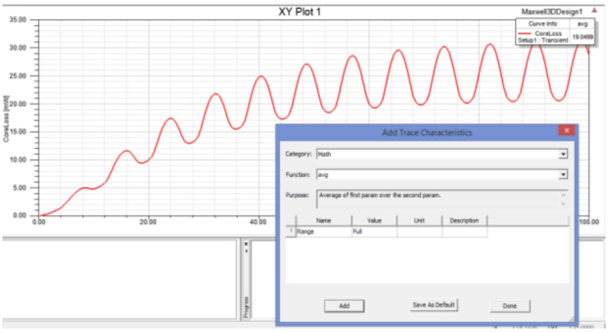

Figure 8. Designation of the parts of the arches.

The third combination features the cruciform morphology, M-4 Steel, silver coil conductor at 10 kV voltage, which exhibits a loss of 19.0499 W.

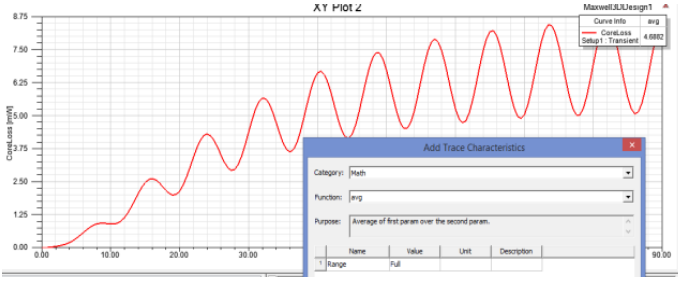

Figure 9. Designation of the parts of the arches

The sixteenth combination features the cruciform morphology, Mu-metal, copper coil conductor at 13.2 kV voltage, which exhibits a loss of 4.6882 W

3.4. Statistical Analysis of the Combinations

Having obtained the results according to the variables specified in Table 15 with their designated levels, we perform the analysis using Minitab software for the results of the 16 combinations.

Table 3. Factorial Design

Letter	Factor	Low (-1)	High (1)
A	Core Material	Steel M-4	Mu_Metal
B	Core Shape	Rectangular Section	Cruciform Section
C	Coil Material	Silver	Copper
D	Voltage Level	10 kV	13.2 kV

- Factorial regression for losses (W) vs. A, B, C, D.

Table 4. Factorial Design

Fuente	**GL**	**SC Ajust.**	**MC Ajust.**	**Valor F**	**Valor p**
Modelo	8	429.028	53.629	745300.13	0
Lineal	4	404.258	101.065	1404540.95	0
A	1	164.006	164.006	2279263.11	0
2B	1	0.006	0.006	89.00	0
C	1	0.000	0.000	2.18	0.183
D	1	240.246	240.246	3338809.51	0

Interacción de 2 términos	3	24.707	8.236	114456.61	0
A*B	1	0.009	0.009	119.88	0
A*D	1	24.606	24.606	341958.20	0
B*D	1	0.093	0.093	1291.75	0
Interacción de 3 términos	1	0.062	0.062	867.38	0
A*B*D	1	0.062	0.062	867.38	0
ERROR	7	0.001	0.000		0
TOTAL	15	429.029			0

Interpretation:
Significance level: 0.05
P-value < significance level (α = 0.05)
The combinations shown in the analysis of variance are significant, except for factor C, which is not significant. Combinations that include factor C are also insignificant, and therefore, those combinations are excluded.

- Factorial regression for losses (W) vs. A, B, C, D.

Table 5. Factorial Design for Losses

S	R-cuad	.R-cuad. (ajustado)	R-cuad. (pred)
0.0084827	100.00%	100.00%	100.00%

Interpretation:
S: Standard deviation or variance

R-SQ: Coefficients of determination
It should be close to 1 or 100%
Indicates how well the model replicates the results
In this case, it is 100% (high), which means that the inserted data is of good quality.

R-SQ (Adjusted)
It should be close to 1 or 100%
Related to the sample size and the number of factors
In our case, it is 100% (high) because we have a large sample.

R-SQ (Pred)
It should be close to 1 or 100%
Indicates the predictive power of the model
In the Pareto diagram, all components are significant.
In our case, it is 100% (high), and all components are significant.

- Standardized Effects Normal Plot

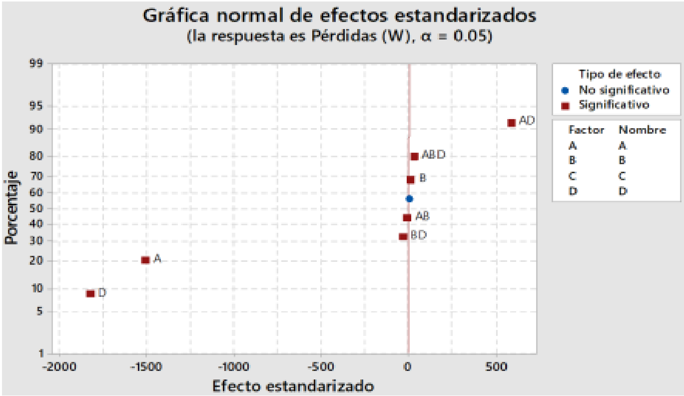

Figure 10. Designation of the parts of the arches.

Interpretation:

This table confirms in the analysis of variance that all factors are significant or influential in the response. Factor C is not significant. The average result (losses in watts) is 4.6947 W with a desirability of 0.99955. In the cube graph, the optimal result is achieved when all variables are at a high level.

- **Factorial regression for losses (W) vs. A, B, C, D.**

LOSS (W) = 10.5513 - 3.20162 A + 0.02001 B - 0.00313 C - 3.87497 D - 0.02322 A*B + 1.24011 A*D - 0.07622 B*D + 0.06246 A*B*D

4. Discussion

The analysis of failure in the silicon steel sheet in distribution transformers. The effect of the setback area of the transformers contributes to material and design aspects. Through this study, some tests excluding failed transformers[7] were conducted. As a result of this study, two possible materials for the design were identified: Acero M-4 and Mu_Metal, with Mu_Metal being determined as the more stable choice.

Early estimation of the loss of the useful life of distribution transformers (9) is mentioned, with the scientific article comparing transformers at risk to those that have failed. The study includes important characteristics considered in the research, such as the estimation of losses using monthly billing data (9). Regarding the estimation of monthly losses, a more in-depth analysis has not been conducted yet, but a figure of 4 W in losses is established.

5. Conclusions

The design that was determined to have the lowest losses according to the tests is the one with cruciform morphology, made of Mu_metal, with a copper winding and a voltage level of 13.2 kV. The winding with the highest efficiency is the copper winding. Despite silver having higher conductivity compared to copper, the combination of factors makes copper efficient, especially with a purity level of 99.9%. It was determined, according to the surface graph, that in the Losses vs. D*A graph, the minimum average loss value of 4.6882 W is within the range specified by IEEE C57-12-2015, which sets an allowable +/- 3.0% loss at its rated power.

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