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Optimization of Core Loss for Power Transformer Using Taguchi Method

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Abstract

This article focuses on the optimization of process parameters such as core area, core material and voltage for the design of power transformer. It employs Taguchi orthogonal array technique for designing the experiments and its analysis. Utility transformers are usually specified with the losses associated at design stage. The area of the core cross-section applied voltage, as well as the core material all has impact core loss deterioration. The impact of such variables influencing core loss is investigated by executing the model. A small proportion of core as well as the coil assembly experiments is simulated using the Taguchi approach with the orthogonal array. In this study, the core as well as the coil assembly of an 8MVA, 33/11KV, 3 Phase Transformer is modelled in ANSYS MAXWELL software. MINITAB software is used to assess the program's anticipated core loss in order to discover the optimal arrangement for three control variables.

Keywords: Electrical Losses, Power transformer, flux density, MINITAB, Maxwell's ANOVA analysis

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1. Introduction

In transformer, during its operation of transforming energy from one voltage level to another, the transformer consumes power in its magnetic circuit to maintain the magnetic field and electric circuit as resistive loss. These losses are generally referred as No-load loss (without load) and load loss. Thus, the load loss depends on the load whereas the No load loss does not depend on the load [1]. The No load loss is present irrespective of the load, as long as the transformer is energized. It is thus necessary to keep this loss to a minimum without increase in cost as this loss contributes to generation of heat and to the cost of energy, utilities specify a maximum limit for the core loss. The No load loss has core loss as its primary component with some stray loss. The stray loss occurs in the steel carpentry used to keep the core and winding intact [2].

The Hysteresis loss can be minimized by using superior grade of core material. Different grades of steel were used earlier but now CRGO silicon steel is commonly used by the manufacturers [3]. This material is commercially available in different grades having different magnetic characteristics. Specific core loss, which is the core loss per kg weight of material, is an important property, as this will determine the final core loss of the transformer, after its assembly. Lower the specific core loss, higher will be the cost [4],[5]

As Eddy current loss can be reduced by proper assembly of the core laminations, minimizing Hysteresis loss will effectively reduce the overall core loss. The core material and its dimensions are generally selected based on the requirement and analytical calculations. Based on the calculation, core and winding assembly is built and the core loss is measured and verified before proceeding to final manufacture. Assembly of core and winding for each design is expensive and time-consuming. To save time and cost, the core and winding assembly can be simulated in computer and the loss can be determined quickly and accurately [6],[7]

A static device that converts AC power at one level to another desired level by magnetic induction is called a transformer. The two electric circuits in a transformer are isolated and they do not have any electrical contact. Power transformer is a type of transformer that helps transfer power from generator to consumer. Power transformers help in stepping up and stepping down the voltages at different levels at desired voltages. The major parameters that affect the core loss are identified and simulations are carried out by changing these parameters. To reduce the number of simulations, Taguchi approach is adopted. Results are analyzed to select an optimum combination of the parameters which give the minimum core loss at lesser cost are investigated [8],[9].

Depending upon the range, power transformers are classified as generator transformers, station transformers, transmission and auto transformers. Generator transformers are connected directly to the output of the generator in generating stations, with large ratios like 22kV/400kV or 22kV/765kV. Station transformers generally supplies power to the auxiliary system for starting up the boiler/Turbine generator unit. The functionality of a transformer is determined by the flux connections in between the primary and secondary windings. Some minimal-loss CRGO steel is frequently used as the core to link the magnetic flux between both of the windings. To minimize saturation, thus the maximum operational magnetic flux density is commonly stated as the 1.6T. The core loss is caused by the alternating current's hysteresis effect on the core [10],[12]. Since the transformer has no moving parts, there are no mechanical losses such as wind age and frictional losses. So, transformer consists of only electrical losses like copper loss and iron loss (Load loss and No-load loss). Eddy current loss and hysteresis loss make up the No load losses. The back magnetism in the transformer core when the core is subjected to an alternating current is called as hysteresis loss. This can be reduced by using material such as silicon steel with minimum area or air-cooled transformers [13]. The losses in the core occur whenever a transformer is powered on regardless of load, it must be minimized. The dimensions in the core might theoretically be approximated to ensure that the flux density stays within the specified limits. Thus, the core loss is governed by the characteristics, weight, and structure of the core material. The author establishing core loss early in the design process is crucial for saving money on trial expenditures [14] [15].

To analyze the performance of transformers and other electromagnetic equipment, Finite Element Techniques are commonly employed. One of the software programmers used to examine transformers is ANSYS Maxwell [16],[17]. The power transformer's no-load loss was calculated in ANSYS Maxwell using 3D and 2D models, with the 3D model producing the most accurate results. ANSYS was used to perform static, harmonic, as well as transient testing analysis on a three-phase distribution transformer [18],[19].

The Taguchi technique is utilized to improve industrial processes or goods. The author used Taguchi technique to improve the core annealing process (8 MVA 33/11kV transformer core and coil assembly combination is modelled in this work, and core loss is calculated [20]. A series of experimental simulations was designed using variables such as core cross-sectional area, applied voltage as well as the core material; all of these factors have an impact on core loss. The Taguchi Method is used to determine the best combination of these factors.

The section 2 deals about the design and analysis transformer core and winding. The requirements as per standard in transformer are discussed in section 3. The section 4 describes about the proposed transformer design. The results and discussion are carried out in section 5. The proposed work concluded in chapter 6.

2. Design and analysis of transformer core and winding

The core loss varies according to the core material, type of construction as well as the excitation. The core loss includes a set of Hysteresis loss and the Eddy current loss. When electrical transformer is energized, an alternating voltage is induced which causes current to circulate in the core. This circulating current causes heat loss, which is the Eddy current loss. This loss can be minimized by using laminated steel, which increases the resistance to the circulating current.

2.1 Requirement of accessories

The transformer shall conform to IS2026/IEC60076.The transformer and all the accessories shall conform to the following standards as depicted in table 1.

Table 1. Transformer standards

Indian Standard	Subject covered
IS2026	Requirements for Transformers
IS335	Specification for oil used in transformer
IS3347, IS2099	Design, manufacture and testing of Bushings for application in Transformers
IS8468	Tap changers – on load
IS3639	Requirements for external components used in Power Transformer

2.2 Technical requirements

Fresh filled oil is used in the transformer and all the parts assembled in the transformer. The oil used is in accordance with the IS335-1993. The oil should not have any moisture content in it and should be uniform in texture as described in table 2.

Table 2. Important characteristics of the transformer coil

S.No	Parameters	Acceptance norms
1.	Di electric strength	>42.42 KVpeak
2.	Loss Factor At 90 DegC	<0.01
3.	Resistivity at 27 DegC	>1500*(10)^12 ohm-cm
4.	Flash Point– Marton	>140°C
5.	IFT	>0.04N/m at 27°C
6.	Total acidity content	<0.03mg KOH/gm
7.	Moisture	<35 parts per million

The transformer will be assembled as per the IS group symbol DY11.The transformer is required to perform for continuous operation at a frequency of 50Hz. And a variation of $\pm$ 3% is allowed while the temperature does not exceed the maximum temperature rise. The tolerance for parameter is depicted in table 3.

Table 3. Tolerances

S. No	Parameter	Acceptance norm
1.	Primary to secondary voltage ratio	Should be within $\pm$ 0.5%
2.	Percentage impedance (principal tapping)	As per IS2026
3.	Open circuit current	To be within +30% of the declared open circuit current

Percentage impedance should be 8.35% of the total voltage at normal transformation ratio and at normal rating according to the IS. The impedance on the principal tapping should be 10 percent greater than the impedance value measured on any other tappings. The transformer should be appropriate for installation at any place which has the required ambient temperature and the maximum temperature limits as mentioned in table 4.

Table 4. Allowable temperature

1.	The Temperature of the ambient	Maximum of 50 °C
2.	Temperature rise of the oil, measured by thermometer	40 °C
3.	Temperature Rise of the winding, calculated by Measurement of resistance	50 °C

Under normal operating condition with nominal voltage and frequency, the magnetic flux density inside the core or metallic parts shall not exceed 1.6 weber per square meter. The core laminations have to be assembled without any air gaps to limit the core loss to be within the limits. Electrolytic copper material insulated with paper shall be used for the primary and secondary windings. The windings should be insulated with paper insulation and neutral points should withstand the specified voltage as per the relevant standard. The current density in either of the two windings, under normal operating conditions at full load, shall be limited to 2.5 A/mm^2. New Transformer oil conforming to relevant standard shall be filled under vacuum to prevent air bubbles, which may cause partial discharges leading to breakdown of insulation system. The core and coil assembly should be properly dried in vacuum at high temperature to drive out the moisture.

The transformer tank is to be provided with a valve for filling the oil and another valve for taking the oil for testing purpose. For allowing oil expansion during operation, a conservator tank need to be fixed on top of the tank.

One Tap changer used to control the voltage shall be designed and manufactured in accordance with the relevant product standard. It shall be on load type to facilitate operation under the load. Provision for Voltage variation at the high voltage side has to be provided with as many steps as required. The tap changer shall be operable from a remote location and also at the transformer location. The following features shall be built into the controls. At any time, operation shall be possible either from local or remote location. Suitable interlocks shall be provided to avoid simultaneous operation of both. Only one step shall be possible, either from remote or local operation. When it is in manual operating mode, electric drive should be disabled. The recommended air clearance is given in Table 5.

Table 5. Recommended minimum air clearance

Highest System Voltage, KVRMS	Test Voltage, dry Power Frequency (kVRMS)/Impulse KV peak	Air Clearances, in mm	
		Ph to Ph	Ph to ground,
12	28 / 75	280	205
36	70 / 170	350	320

2.3 Effect of transformer core area

The area of cross-section of the transformer core is given by

$$A = \frac{\pi d^2}{4} \quad (1)$$

Where, d represents the Core diameter.

Induced Voltage per turn is defined by,

$$Et = 4.44 * \psi * f = 4.44 * A * B * f \quad (2)$$

$$= 4.44 * \pi * d2 * B * f / 4 \quad (3)$$

Where, B= Maximum magnetic flux density

f = Frequency of applied voltage

The voltage per turn is thus proportional to d^2. As a result, as the diameter of the transformer core grows, so does the voltage per turn. If the voltage across the winding of transformer is V, then $V = E_t * N$ where N denotes the number of turns in winding.

To produce a greater induced voltage for a given applied voltage, either the number of turns or the diameter size of the core must be increased. However, increasing the diameter size of the core increases the weight, which raises the cost and causes core loss. The number of rotations required to get the same induced voltage may be lowered by increasing the diameter of the core. The resistance is reduced as the number of spins is reduced, and therefore the loss in the copper is reduced. The copper loss increases with load, whereas the core loss remains constant independent of load. It is critical to limit core loss, which occurs during the transformer's full operating life. The weight of the core and hence the core loss will be minimized if the diameter of the core is lowered. However, the induced voltage decreases as well. To make up for this, the number of turns must be increased. This will result in a greater loss of copper. As a result, the diameter and number of turns must be tuned to achieve the necessary core and copper loss.

Selection of transformer core material

The core loss consists of two components namely Hysteresis and eddy current loss. The Hysteresis loss is solely based on the characteristics of the material. To minimize the core loss, generally Cold Rolled Grain Oriented (CRGO) steel is used widely in power Transformers, as it has many important properties. The major properties are;

- High permeability – this allows magnetic flux to flow through the core and reduces the leakage flux
- High Resistivity – to reduce the eddy current flow in the core, thus reducing the eddy current loss
- High stacking factor – this offers high resistance path to the eddy current.

Different grades of CRGO steel are commercially available with varying specific core loss. Depending on the requirement and cost, appropriate grade CRGO steel is selected for core assembly.

Selection of core dimension

The induced voltage is proportional to the maximum flux in the core which links the winding. The core materials exhibit different B-H characteristics. (B is flux density in Tesla and H is ampere turn per meter length of the flux path. It has the core magnetic flux density that depends on the cross-sectional area of the core. CRGO steel's maximum flux density, without going into saturation is about 1.9 T. (1T = 1 W/sq-m) Normally, utilities specify that maximum flux density should not exceed about 1.6 T. As the operating flux density is fixed by the utilities, the maximum flux in the core is proportional to the area of cross section of the core.

The core should preferably have a circular cross section to prevent flux leakage in the air. As discussed earlier, core is built of sheets (laminations) of small thickness, to reduce eddy current loss. It is not practically feasible to cut each lamination to the required size to obtain a perfect circular cross section. Manufacturer typically get groups or packets of laminations, each group having the same dimensions. Such groups are assembled together to get cross section close to circular shape. Hysteresis loss is reduced by choosing appropriate core material considering the cost and reliability of the transformer.

2.4 Winding design

The winding type of a transformer is selected to meet the necessary electrical properties as well as suitable mechanical strength. There are instances when more than one form of winding is appropriate. The winding will be employed in this example since it is straightforward to manufacture. There are two kinds of windings that are often used: i. Disc winding ii. Cylindrical winding

Cylindrical winding

The conductor used in the winding are either circular or rectangular in cross section. Rectangular conductor is widely used to have less inductance. The conductors are wound around the core in multiple layers to accommodate the required number of turns, within the core window. Each layer can have one or more conductors in parallel, depending on the current rating. If multilayer winding is used, oil duct is provided between the layers to improve the cooling.

Ratings of the high voltage range are of 6.6 kV, 11 kV, and 33 kV with power ratings up to 600 kVA are the most common applications for cylindrical windings with circular conductor. Low voltage ratings of 0.415 kV and 6.6 kV with power ratings up to 750 kVA are the most common applications for cylindrical windings with rectangular conductor.

Disc winding

Disc windings are often found in high-capacity voltage transformers with current ratings of 12 to 600 A. This winding is made up of a single layer disc coil coiled in series and parallel with rectangular conductor. Coils are spirally coiled in a radial way from the center outwards. The horizontal duct is formed by each coil resting on pressboard spacers. The width of a radial oil duct is determined by the voltage difference between nearby coils, the particular thermal load, and the transformer cooling method. The number of coils should be set such that the required winding height is achieved with a standard conductor size. Normally, 60 to 80 coils are used in windings built for voltages ranging from 33 to 110 kV. Table 6 shows the fundamental technical parameter specification for transformer modelling:

Table 6. Fundamental technical parameters

Parameter Specification	Unit	Specified Range Value
No of phases		3
Nominal rating of transformer	MVA	8
Nominal primary voltage	V	33000
Nominal Secondary voltage	V	11000
Winding connection	----	Delta/star
No-Load loss	KW	5
Load loss at 75 degC	KW	41.8
Frequency	Hz	50
Maximum current density	A/sq.mm	2.5
Impedance voltage	percent	8.35
Maximum flux density	T	1.6

3. Requirements as per standard in transformer

The major relevant requirements for power transformer are reproduced below.[6]

All the three-phase and single-phase transformers (including the autotransformers) should adhere to these standards. Few small transformers and special transformers of a particular category are not covered viz.,

a) Transformers both 1and 3 phase

b) Voltage transformer;

c) Current transformer

d) Transformer used in rail locomotive

e) High voltage transformer for testing purpose

3.1 Service conditions

Transformer has to work satisfactorily under normal environment and weather condition. Transformer will normally be installed at an altitude of less than 1000 m. The air surrounding the transformer will be between – 5° C and 50 ° C. If cooling water is used, then its temperature shall not exceed 30 ° C. More requirements for different type of cooling are mentioned in relevant Indian and International standards. For small power transformers used in distribution stations natural air cooling is used along with natural air flow surrounding the transformer. For higher rated power transformers used in generating stations forced air flow is typically used with forced oil by means of pumps. Temperature indicators and alarms are also used in such critical transformers to ensure that the temperature of oil does not go beyond the flash point of the oil, which may result in fire. Relays are provided to act in case of any gas released in oil due to high temperatures. When the transformer is in work, tolerances of few rated quantities need to be applied accordingly. The given table below shows the referred standards for the manufacturers guarantee.

3.2 Type of tests

Routine tests

Routine tests are conducted on each and every tranformer. The tests to be conducted as routine tests are mentioned in the relevant standard. These tested are designed to ensure that the manufactured transformer conforms to the prototype transfomer which was subjecetd to all the type and special tests. These tests are generally simple in nature and will make sure that there are no deviations in the quality of raw materials, manufacturing process and the assembly process.

Type tests

Type tests are conducted on one proto type transformer. As the facilities required for conducting the tests are expensive, they are usually conducted in Third party test laboratories. These tests will assure the end users that the transformer is designed, manufactured and assembled correctly.

Special tests

In addition to type tests, some special tests are specified in the standard. The tests to be conducted depend on the product and its application. Some tests like capacitance of bushing, are conducted as finger prints. The result obtained on the new transformer will be used as a reference and compared with the values obtained during the operation of the equipment, at a predetermined interval to estimate the healthiness of the component / equipment. These tests also act as diagnostic tests. As the transformer is the heart of any sub station, its healthiness has to be monitored at regular intervals to improve of the reliability of the power supply. For eg. Frequency response analysis (FRA) is conducted to obtain the finger print of the windings to be used as a reference for monitoring of any movement of winding during transport or after installation due to short circuit.

3.3 Cooling methods used for oil immersed transformer

Based on the current and power rating of the transformer, cooling methods are adopted. Dry type transformer employs air as cooling medium and oil immersed type uses mineral oil as cooling medium. Type of cooling used in the 8000 KVA transformer is ONAN – Oil Natural and Air Natural type of cooling is adopted, to dissipate the heat generated in the winding and core. Mineral oil is used as the cooling medium. The oil also acts as an insulating medium, to insulate the high voltage winding from the tank. The oil needs to fulfil various requirements to function as a cooling and insulating medium. The requirements for use in Transformer are specified in IS 335.

3.4 Selection of transformer core material

The core loss consists of two components namely Hysteresis and eddy current loss. The Hysteresis loss is solely based on the characteristics of the material. The magnetic field intensity increases with the ampere turns. But when the ampere turns decreases, the field intensity does not follow the same path. i.e. the magnetic field intensity will have some residue, even after the current becomes zero. Such Hysteresis nature of the magnetic material causes Hysteresis loss. As Hysteresis loss is a property of the material, suitable material has to be selected based on the requirement of the core loss.

When there is an alternating flux in the core, due to the alternating applied voltage, a voltage is induced in the core itself, as it is a conducting material. This induced voltage in the core causes circulating current in the core material. This current leads to power loss, and it is called Eddy current loss. This Eddy current loss is reduced by reducing the current magnitude. This is achieved in practice, by using thin sheets (typical thickness of 0.2 mm) and then stacking together to get the required core diameter**.**

3.5 Characteristics of CRGO steel

To minimize the core loss, generally Cold Rolled Grain Oriented (CRGO) steel is used widely in power Transformers, as it has many important properties. The major properties are;

- High permeability – this allows magnetic flux to flow through the core and reduces the leakage flux
- High Resistivity – to reduce the eddy current flow in the core, thus reducing the eddy current loss
- High stacking factor – this offers high resistance path to the eddy current.

Different grades of CRGO steel are commercially available with varying specific core loss. Depending on the requirement and cost, appropriate grade CRGO steel is selected for core assembly.

3.6 Selection of core dimension

The induced voltage in the winding is proportional to the maximum flux in the core which links the winding. The core materials exhibit different B-H characteristics. (B is flux density in Tesla and H is ampere turn per meter length of the flux path has the flux density in the core depends on the area of cross section of the corer. The maximum flux density of CRGO steel, without going into saturation is about 1.9 T. (1 T = 1 Weber/sq,m) Normally, utilities specify that maximum flux density should not exceed about 1.6 T. As the operating flux density is fixed by the utilities, the maximum flux in the core is proportional to the area of cross section of the core. To ensure that there is no flux leakage in air, the core ideally should have circular cross section. As discussed earlier, core is built of sheets (laminations) of small thickness, to reduce eddy current loss. It is not practically feasible to cut each lamination to the required size to obtain a perfect circular cross section. Manufacturer typically get groups or packets of laminations, each group having the same dimensions. Such groups are assembled together to get cross section close to circular shape.

3.7 Core Loss

When an ac voltage is applied to the transformer primary winding, an alternating magnetic flux is created in the transformer core. Due to this alternating flux, power is lost in the core. This electrical power loss is converted to heat and the core gets heated. This heat raises the temperature of the oil, leading to deterioration of the insulation of the paper used to insulate the winding turns. Hence, this loss needs to be reduced to increase the life of the insulation and efficiency of the transformer. Eddy current loss and Hysteresis loss make up the core loss. Instead of solid core material, laminated steel is used to break the continuous path for the eddy current. Laminated steel is also insulated and stacked to offer a very high resistance to the eddy current. Hysteresis loss is reduced by choosing appropriate core material considering the cost and reliability of the transformer.

4. Proposed transformer design

A core and coil assembly are used to represent the 8 MVA transformer. Thus, the number of turns present in the primary as well as secondary are approximated with the EMF/turn assumed to be 38.733(No. of turns = Induced voltage/EMF per turn). Coil assemblies are used to represent the primary and secondary windings. Figure 1 depicts the simulated model.

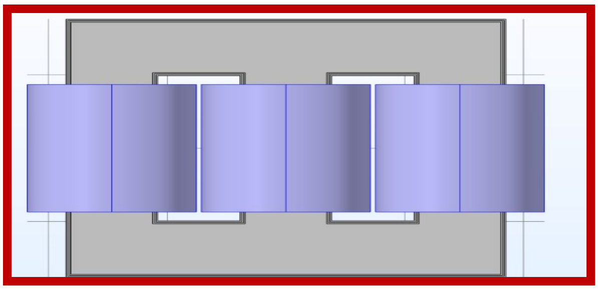

Figure 1. Core and coil assembly

The Taguchi technique applies an alternate Experiment Design to significantly minimize the total experiments required to get the desired output result. The Taguchi technique to experiment design is employed here to simulate the fewest number of transformer models feasible in order to get the lowest losses in core. As shown below, a L_9an orthogonal array is made up of three variables, each with three levels:

a) The no. of parameter specification in levels and variables are depicted in table 7.

1. The primary winding is excited, or voltage is delivered to it (-0.6 %, nominal, +0.6%)

V1 =– 46439; V2 = 46672: V3 = 46886

2. Three levels present in the cross-sectional area, measured in square millimetres (-6%, Nominal, +6%)

3. A1 = 133583 $mm^{2:}$ A2 = 140615 mm^2: A3 = 147646 mm^2 (384.3x384.3 mm)

4. G1, G2, and G3 are the three grades of core material.

Three separate CRGO material grades with distinct core loss characteristics are selected.

Table 7. Variables with their levels

Variable parameters	**Ranging of Level 1**	**Ranging of Level 2**	**Ranging of Level 3**
Applied Voltage, V	46439	46672	46886
Cross-Sectional Area of Core, mm^2	147646	140615	133583
Grading which is present in the core material	Grade 1	Grade 2	Grade 3

5. Results and its discussions

A collection of nine Transformers simulations were performed with the settings listed in Table 8. Figure 2 depicts the applied voltage to the three windings.

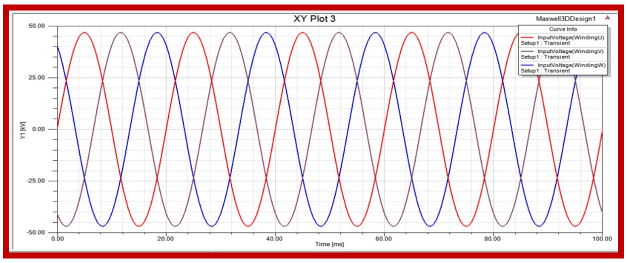

Figure 2. Voltage applied to the windings

Figure 3 depicts the magnetic flux distribution mostly in the core. Because of the interaction between the three phases, the flow (flux) distribution is not uniform, resulting in a 120-degree phase difference.

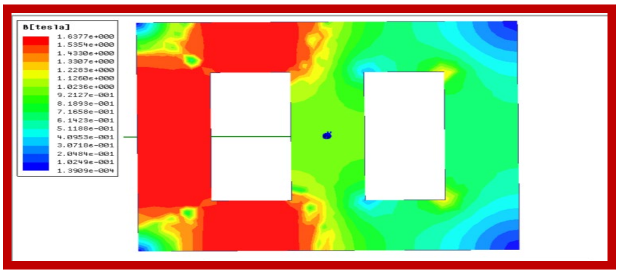

Figure 3. Standard magnetic field representation in the core material

Table only shows an orthogonal array with the program's average core loss and the estimated S/N ratio.

Table 8. Total average loss using taguchi L_9 array

Applied Voltage	**Core Sectional area**	**Core Material Components**	**Average losses core material** kw (y)	**y^2**	**Ratio of S/N**
Voltage1	Area1	Grade1	4.505	21.31	-14.07
Voltage1	Area2	Grade2	4.962	25.62	-14.92
Voltage1	Area3	Grade3	5.452	28.73	-15.74
Voltage2	Area1	Grade2	4.898	25.04	-14.81
Voltage2	Area2	Grade3	5.533	31.63	-15.87
Voltage2	Area3	Grade1	4.568	21.86	-14.21
Voltage3	Area1	Grade3	5.427	28.43	-15.68
Voltage3	Area2	Grade1	4.589	22.06	-14.22
Voltage3	Area3	Grade2	5.535	31.62	-15.87

MINITAB 19 is used to examine the data for all models. Minitab is statistical analysis software, and it is utilized, and the ANOVA analysis was used in this study. To compute the S/N Ratio, the expression "smaller is better" is employed. Thus, the conclusion is utilized to obtain the most effective integration of core sectional area, voltage, as well as the core material for minimum core loss.

$$\frac{S}{N} = -10 * \log_{10}(y^2) \quad (4)$$

Where, y represents the overall average core loss expressed in kW.

The MINITAB software output analysis, including mean S/N ratio, mean core loss, as well as variance analysis (ANOVA), is shown below. The average mean core loss for each parameter as well as the level is shown in Table 9 and Figure 4.For example, at level 1, the total mean core loss for each core sectional area is calculated by averaging the core losses from studies 1, 4, and 7. The mean core loss for core material at level 2 is calculated by averaging the results of experiments Nos. 2, 4, and 9.

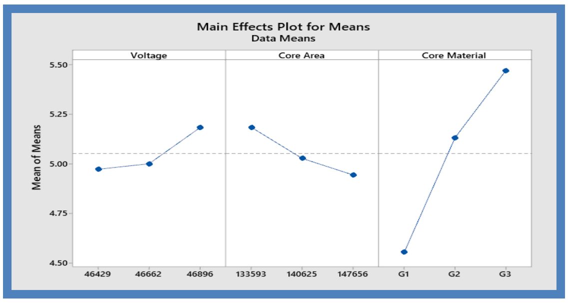

Figure 4. Impact of the three factors on core sectional loss

Table 9. The average losses in core expressed in kW

Level Range	Applied Voltage	Core Sectional area	Core Material Components
1	4.972	4.945	4.553
2	5.002	5.029	5.133
3	5.184	5.184	5.471
Delta	0.211	0.242	0.917
Rank	3.1	2.1	1.2

Table 10 and Figure 5 show the mean S/N ratio of core loss for each parameter and component level. The mean S/N ratio of core loss for the core sectional area at level 2, for example, is calculated by averaging the S/N ratios from studies 2, 5, and 8. As a result, the mean S/N ratio of core loss for core material at level 3 is calculated by adding the means of investigations Nos. 3, 5, and 7.

Table 10. Ratio of S/N (signal-to-noise)

Level Range	**Applied Voltage**	**Core Sectional area**	**Core Material Components**
1	-13.92	-13.85	-13.18
2	-13.94	-14.01	-14.18
3	-14.27	-14.27	-14.77
Delta	0.37	0.42	1.58
Rank	3.1	2.1	1.1

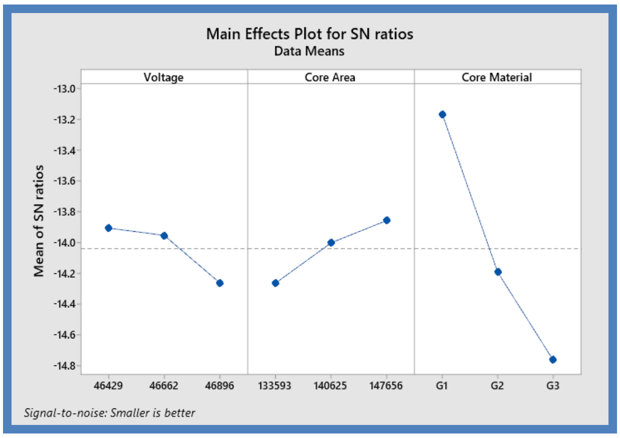

Figure 5. Effect of various forms of the three components on the S/N Ratio

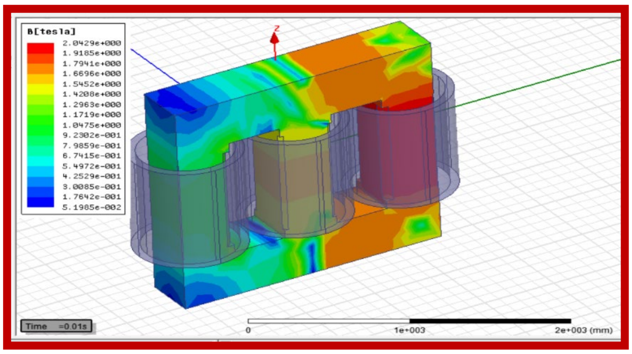

Figure. 6. Flux density plot at 5 ms

Table 11 displays the MINITAB result for the variance analysis of (ANOVA). It demonstrates how much variance each and every variable produces in comparison to the overall variation seen in the outcome. The final column of Table 6 indicates each variable's % contribution to the core loss. Thus, the flux density plot of the proposed transformer design is illustrated in figure 6.

Table 11. Variance evaluation analysis

Source Reference	DF type Range	Adjoint SS Value	Adjoint MS Value	F-type Range Value	P-type Range b Value	(%) Level
Applied Voltage	2.1	0.0780	0.0390	0.88	0.528	5.34%
Core Sectional area	2.2	0.0897	0.0448	1.04	0.495	6.18%
Core Material Components	2	1.2878	0.6439	14.23	0.063	88.4%
Error Impedance	2.3	0.0874	0.0437			
Overall Range	8.1	1.5431				

Figure 7 depicts the impact of each and every parameter on the mean core loss. According to what should be observed, thus the core material components contribute the most (88.46%), preceded by the core area (6.19%). The voltage has the lowest contribution of 5.35%.

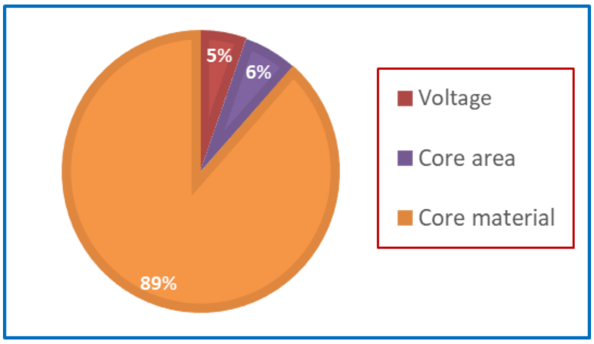

Figure 7. Variables percentage proportion to core loss

The core material has a significant effect on core loss, whereas the voltage level has the minimum range. Theoretically, at around 95% assurance rate, then the overall (%) percentage to the value of mean core loss of the transformers through Core sectional area, Voltage, as well as the core Material are 5.34%, 6.18% and 88.45% accordingly. Taguchi's optimization method yielded a minimal core loss of 4.5062 kW. The best optimum condition of research variables is (V1A1G1), which might behave applied voltage range of 4641 V, core sectional area 133594 mm^2, but also core material grade G1. Thus, the Core loss grows with rising voltage while decreasing with increasing core area. The proposed work is concluded in section 6.

6. Conclusion

The core loss was calculated using ANSYS Maxwell software and a three-phase power transformer rated at 8MVA and 33/11 kV. With different combinations of these parameters, the impact of core material cross-sectional area, applied voltage, as well as core material on core loss was investigated. Taguchi L_9array in orthogonal was utilized to reduce the amount of simulation cases, and thus it has been established from of the variance analysis (ANOVA) and ratio of the S/N ratio that the least core loss as estimated by employing Taguchi's optimization approach. At 46662 V (33000*2) nominal voltage, 147656 mm^2 core area sectional, as well as core material grade Grade1, the overall core loss is 4.568 kW, which is lower than the necessary value.

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