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Performance and Economic Evaluation of Power Transformer

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Abstract

This study presents a comprehensive performance and economic evaluation of a three-phase 132/33 kV delta/star power transformer using an enhanced Finite Element Method (FEM) integrated with ANSYS Maxwell software. The transformer model, developed based on operational data from the Gudum substation in Bauchi, Nigeria, was designed to assess electromagnetic and thermal characteristics under no-load, full-load, and short-circuit conditions. The FEM simulation incorporated detailed geometric configuration, material properties (M125-027S laminated steel core and copper windings), optimized meshing, and coupling with external electrical circuits. Key performance indicators—including magnetic flux density, core and copper losses, voltage and current outputs, and efficiency—were evaluated under varying load scenarios. The model exhibited peak efficiency of 80.84% at 97.10% loading, and simulated load currents demonstrated loss reductions between 8.46% and 11.05% relative to empirical measurements, validating the model's reliability. Furthermore, a life cycle cost (LCC) analysis was conducted using present-

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value cash flow techniques over a projected 22-year operational period. The total LCC was estimated at ₦2,777,811,381, with no-load and load losses accounting for ₦534.2 million and ₦1.88 billion, respectively. These findings underscore the substantial economic implications of design and material decisions in transformer manufacturing and operation. The study emphasizes the value of advanced FEM-based tools in optimizing transformer performance and cost-efficiency, offering strategic guidance for procurement, maintenance planning, and long-term infrastructure investment in power systems.

Keywords: ANSYS; Finite Element Method; Life Cycle Cost; Transformer; Losses; Efficiency.

INTRODUCTION

A transformer is a static device that transfers electrical energy between two or more stationary circuits through a common magnetic circuit. They vary in size and operation, with smaller ones being air-cooled and larger ones being oil-cooled. These machines are tailored to specific applications, and can be grain, non-grain, or hi-bi oriented to improve efficiency.

ANSYS, a software used for electromagnetism analysis, was used to create a Finite Element (FE) model based on transformer parameters from Gudum substation in Bauchi. The model included nodes, elements, material properties, real constants, boundary conditions, and other features to estimate the performance of a three-phase 132/33kV delta/star power transformer. The model was coupled to an external circuit to represent the transformer under no load, full load, and short circuit conditions. Solutions were based on no load and load analysis.

This study analyzes the life cycle cost of transformers, dividing it into initial, operating, maintenance, and scrap costs. It calculates these costs based on the transformer's name plate rating. For instance, 40/30 MVA transformers, key factors impacting the full life cycle cost are analyzed to achieve high quality, reliability, and economically optimal equipment procurement.

Power transformers are crucial in power systems, requiring minimal losses and high performance to ensure optimal efficiency. Improper performance evaluation can lead to saturation and increased losses, requiring careful design (Anionovo, 2024). Hence, the

development and application of Finite Element Method to complex engineering analysis of this nature like, electromagnetic was carried out by (Nivashini, 2020). This research presents an enhanced finite element model application for power transformer performance and economic evaluation, highlighting the benefits of a 3D model for accurate results.

METHODS

Materials

The material includes the Personal Computer, Name Plate Rating of the Transformer, Ansys Maxwell electronics, Data from TCN.

The flow chat in Figure 1 shows the step by step method in developing the physical model of the power transformer and its output results.

Table 1: Name Plate Rating of the Proposed Transformer

Parameter	Value
Power. (MVA)	30
Primary Voltage, (kV)	132
Secondary Voltage.(kV)	33
Circumscribing circle diameter, d (mm)	701.23
Frequency, (Hz)	50
Distance between adjacent limbs D (mm)	1764.1
Connection Type	Ynd11
Connection	Star/Delta
Current density, (A/mm^2)	2.3
Turns per phase	862/317
Primary cross sectional area (A_p) (mm^2)	57.05
Secondary cross sectional area (A_s), (mm^2)	131.75
Coil diameter inside, (mm)	795.23/721.23
Coil diameter outside, (mm)	895.23/751.23
Mean diameter turn winding,(mm)	845.23/736.23
Length of mean turn winding, (mm)	2656.4/2313.9
Level of maximum turn, (mm)	1476/1384
Primary Resistance (r_p), (Ω)	8.4299
Secondary Resistance (r_s), (Ω)	1.1703
pu Resistance	0.0294
pu Reactance	5.62
Pu Impedance	0.0634

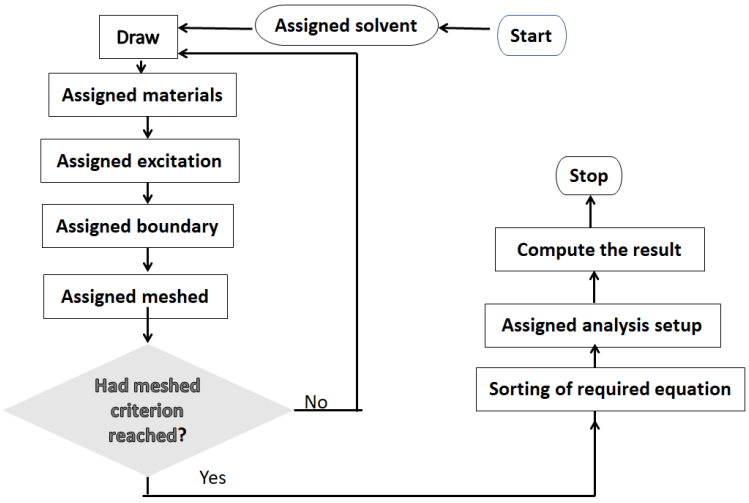


Figure 1: Flow chart of FEA

Analysis of electromagnetic and thermal model of transformer

In the following subsections, analysis of electromagnetic and thermal models was carried out in ANSYS MAXWELL based on the name plate rating, where magnetic flux density distribution, magnetic losses, input/output voltage, input/output current, and ohmic losses were obtained. The step-by-step method for achieving the analysis of above mention models was as follows;

i. Maxwell 3D> Simulation> Validation Check: To make sure there are no any errors with your simulation.

ii. M**axwell 3D> Analyze all**: To check the status of the simulation in the progress window and know it has finished completely

iii. **View> Set Solution Context**> **Maxwell 3D> Fields> Fields>B> Mag_B**: To view the magnetic fields, select a time step at which you want to view the fields, by selecting check the option "Plot on the surface only", and select Done. *Save a screen capture of this visualization.*

For fun, select **Maxwell 3D> Fields> Animate** and press OK to see an animation of the magnetic fields.

iv. **Maxwell 3D> Fields> Plot Mesh:** To see the mesh on the other objects as well. *Save screenshots of a couple different views of the underlying mesh.*

To view the voltage, current, core loss and copper loss induced in the coils as well as the core.

v. **Maxwell 3D> Results> Solution Context> Fields> Fields>E>Mag_E:** To view the electrostatic fields, select a time step at which you want to view the fields, by selecting check the option "Plot on the surface only", and select Done. *Save a screen capture of this visualization.*

Set the following values in the subsequent window:

i. **Category**: Winding, **ii**. **Quantity**: Flux Linkage (PhaseA_Winding) and (using the CNTL key) Induced Voltage (PhaseA_Winding). Then select **New Report**. *Save a screen capture of the plot.*

ii. **Category**: Loss, **ii**. **Quantity**: Core loss (Core) and (using the CNTL key) Stranded loss (Core). Then select **New Report**. *Save a screen capture of the plot.*

iii. **Category**: Force, **ii**. **Quantity**: Force_x (Radial_ Force) and (using the CNTL key) Force_y (Axial_Force). Then select **New Report**. *Save a screen capture of the plot.*

iv. **Category**: Tempareture, **ii**. **Quantity**: Temperature rise (Winding) and (using the CNTL key) Heat transfer (Winding). Then select **New Report**. *Save a screen capture of the plot.*

Analysis of life cycle cost of power transformer

The life cycle cost (LCC) of a vehicle was analyzed using Excel software, including no load cost, load loss cost, installation and commissioning costs, auxiliary loss cost, maintenance costs, and oil condition monitoring costs (Ravindran, 2018). These include Cost computation of no-load losses, load loss, installation and commissioning time, space required, auxiliary losses e.g (radiator cooling fans and oil pumps), recommended spares for 5 year maintenance, oil condition monitoring, top ups and replacement, time for which transformer can be operated at full load after cooling system failure, maximum flux density at rated voltage and frequency, over flux withstand capability, and summation of all the cost computation to yield life cycle cost of power transformer.

RESULTS

Figures 2 and 3 shows the proposed developed and mesh model of the power transformer.

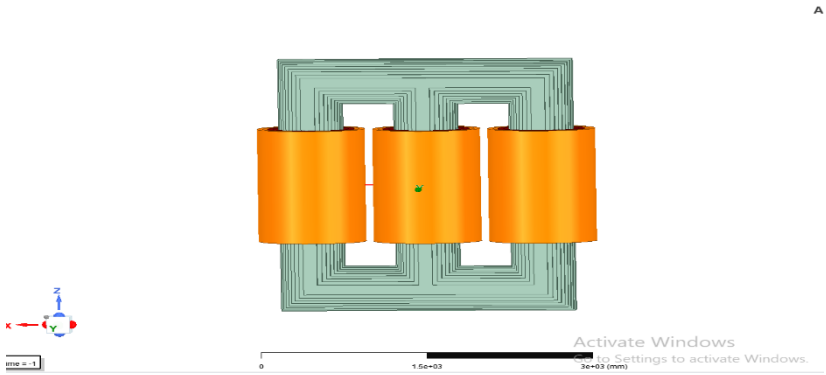


Figure 2: Transformer Model

Figure 3 is the front half 3D cross section of the transformer model in mesh form with triangular element.

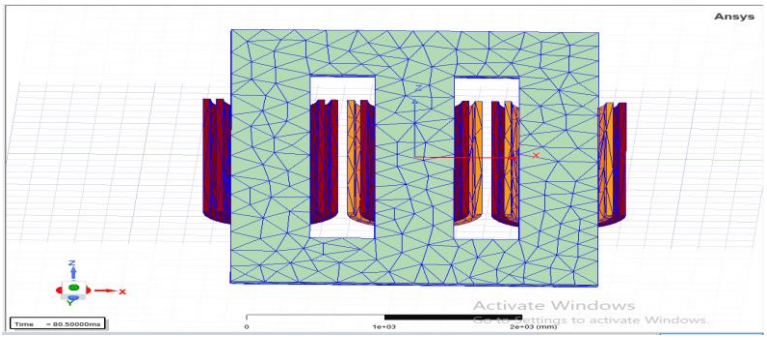


Figure 3: Front View of Half 3D Mesh Model

Table 2: Hourly loading Reading of TELK T3 Power Transformer

Voltage	Current	Power	Winding temp	Oil Temp	Tapped Position
31	270	13.5	30	48	5
30	244	12.2	30	48	5
31	230	11.5	30	48	5
29	234	11.7	30	48	5
30	282	14.1	30	48	5
28	344	17.2	30	48	5
31	156	7.8	30	48	5
31	164	8.2	30	48	5
32	138	6.9	30	48	5

31	92	4.6	30	50	5
30	140	7.0	30	50	5
32	198	9.9	30	52	5
30	220	11.0	30	52	5
28	226	11.3	30	52	5
28	274	13.7	30	52	5
29	444	22.2	30	52	5
29	466	23.3	30	50	5
28	382	19.1	30	50	5
34	176	8.8	30	50	5
32	158	7.9	30	48	5
34	158	7.9	30	48	5
32	146	7.3	30	48	5
31	220	11.0	30	48	5
32	274	13.7	30	48	5

Figure 4 shows the daily load curve of T3 TELK transformer with maximum loading of 97.10%

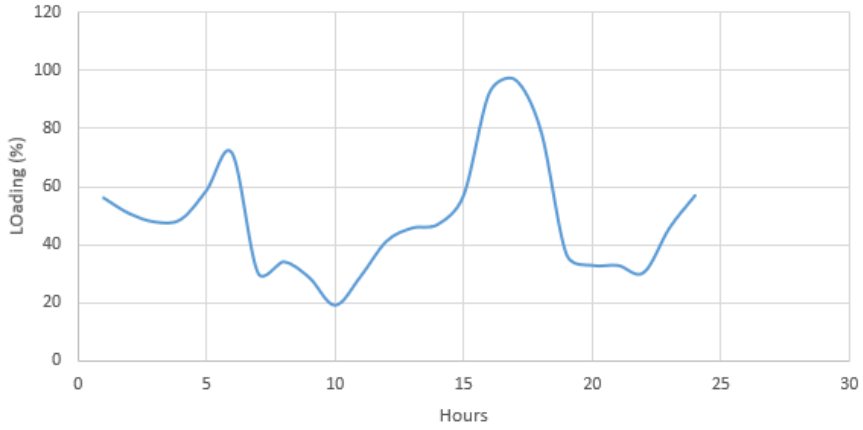


Figure 4: Daily Load Curve

Resistance values are calculated based on the impedance triangle. When Power Factor is 0.8, angle of α becomes 36.8^0, and secondary winding resistance will change, and there will be an inductance value (L) for secondary winding excitation parameters. All parameters are calculated for different loading conditions. The load parameter solution obtained using Orgive was presented in Table 3.

Table 3: Load Parameters of the T3 TELK Transformer at Different Loading Conditions

S/No	%Loading	Resistance(Ω)	Reactance(Ω)	Inductance(H)	Impedance(Ω)
1	19.17	454.46	340.84	1.0849	568.075
2	28.72	302.82	227.11	0.723	378.52
3	29.17	298.66	223.99	0.713	373.52
4	30.43	286.30	214.72	0.68	357.87
5	30.43	286.30	214.72	0.68	357.87
6	32.93	264.56	198.42	0.632	330.70
7	32.93	264.56	198.42	0.632	330.70
8	34.17	254.96	191.22	0.609	318.70
9	36.67	237.58	178.18	0.567	296.97
10	41.27	211.096	158.32	0.5039	263.87
11	45.83	190.09	142.57	0.4538	237.62
12	45.83	190.09	142.57	0.4538	237.62
13	47.10	184.97	138.73	0.4415	231.21
14	47.93	181.77	136.33	0.43	227.21
15	48.77	178.63	133.97	0.426	223.29
16	50.83	171.39	128.51	0.41	214.24
17	56.27	154.82	116.118	0.37	193.53
18	57.10	152.57	114.43	0.36	190.72
19	57.10	152.57	114.43	0.36	190.72
20	58.77	148.42	111.31	0.35	185.52
21	71.67	121.56	91.17	0.29	151.95
22	79.53	109.54	82.16	0.2615	136.93
23	92.50	94.18	70.63	0.2248	117.73
24	97.10	89.72	67.29	0.2142	112.15

Table 4 shows the simulated results using FEM for the input voltage, output voltage, input current and output current of T3 TELK transformer at different loading conditions in a day.

Table 4: Simulated Result of T3 TELK Transformer at Different Load Condition

Loading	Secondary Voltage	Secondary Current	Primary Voltage	Primary Current
56.27	38.74	191.b	106.38	134.15
50.83	38.78	173.38	106.38	135.85
47.93	38.80	164.24	106.39	141.43
48.77	38.74	166.57	106.39	142.32
58.77	38.68	200.20	106.39	132.16
71.67	38.60	243.81	106.39	148.09
30.43	38.85	104.38	106.39	101.62
34.17	38.83	116.89	106.39	126.51
28.72	38.86	98.53	106.40	117.97
19.17	38.91	65.74	106.39	113.55
29.17	38.86	99.88	106.40	119.80
41.27	38.78	141.07	106.40	111.67
45.83	38.75	156.56	106.39	112.4
47.10	38.75	160.87	106.39	126.33
57.10	38.69	194.75	106.40	138.45
92.50	38.48	313.71	106.39	178.17
97.10	38.45	329.05	106.40	183.33
79.53	38.55	270.26	106.39	158.94
36.67	38.81	125.46	106.39	103.11
32.93	38.83	112.69	106.39	114.55
32.93	38.83	112.69	106.39	114.55
30.43	38.85	104.38	106.39	101.62
45.83	38.75	156.56	106.40	112.4
57.10	38.69	194.75	106.40	138.45

Table 5 compares the practical load current and simulated load current obtained during the simulation with the relative error computed. The relative error indicates a strong correlation between the simulated result and the practical result from PHCN. However, it is obvious that the simulated load current produced smaller loses which can be attributed to higher efficiency by this approach, thus validating the goal of this study.

Table 5: Shows the Comparison of Simulated Load Current and Practical Load Current of T3 TELK Transformer at Different Load Condition

% Loading	Impedence (Ω)	Practical Current (A)	Simulated Current (A)	Relative Error	Simulated Power (W)	Practical Power (W)	Absolute Error
19.17	568.075	92	88.34	3.66	4808187	4433232.08	-8.457818
28.72	378.52	138	132.29	5.71	7208535	6624343.8	-8.818852
29.17	373.52	140	134.16	5.84	7320992	6722951.22	-8.89551
30.43	357.87	156	140.14	15.86	8709124	7028287.52	-23.91531
30.43	357.87	156	140.14	15.86	8709124	7028287.52	-23.91531
32.93	330.7	158	151.28	6.72	8255595	7568280.62	-9.08151
32.93	330.7	158	151.28	6.72	8255595	7568280.62	-9.08151
34.17	318.7	164	157.04	6.96	8571755	7859639.68	-9.060409
36.67	296.97	176	168.42	7.57	9198943	8423642.07	-9.203865
41.27	263.87	198	189.46	8.54	10344759	9471637.82	-9.218275
45.83	237.62	220	210.22	10.22	11500808	10501009.6	-9.520974
45.83	237.62	220	210.22	10.22	11500808	10501009.6	-9.520974
47.10	231.21	226	215.96	10.04	11809282	10783338.8	-9.514151
47.93	227.21	230	220.48	10.48	12019409	11045003.1	-8.822142
48.77	223.29	234	223.68	10.32	12226467	11171811.1	-9.440333
50.83	214.24	244	232.8	11.2	12754993	11610916.8	-9.85345
56.27	193.53	270	257.62	12.38	14108337	12844211.5	-9.841986
57.10	190.72	274	261.62	12.38	14318495	13053835.1	-9.688032
57.10	190.72	274	261.62	12.38	14318495	13053835.1	-9.688032
58.77	185.52	282	268.88	13.12	14753292	13412438.2	-9.997096
71.67	151.95	344	327.72	16.28	17981155	16319490.5	-10.18209
79.53	136.93	380	363.12	16.88	19772692	18055060.5	-9.513297
92.50	117.73	444	421.57	22.43	23208821	20923124.5	-10.92426
97.10	112.15	466	442.21	23.79	24354045	21930897.1	-11.04902

Efficiencies were computed and tabulated in Table 6 for different phases and different loading conditions.

Table 6: Efficiency Comparison along the Phases Obtained from each Limbs of T3 TELK Transformer at Different Load Conditions.

S/No	%Loading	Efficiency1	Efficiency2	Efficiency3
1	19.17	17.74	21.17	28.47
2	28.72	25.27	30.51	42.17
3	29.17	26.42	30.45	43.66
4	30.43	30.57	37.51	38.19
5	30.43	30.57	37.51	38.19
6	32.93	36.12	44.38	64.57
7	32.93	36.12	44.38	64.57
8	34.17	29.32	32.72	46.50
9	36.67	28.18	35.90	47.48
10	41.27	39.50	46.04	70.60
11	45.83	39.50	39.12	70.60
12	45.83	39.50	39.12	70.60
13	47.10	41.39	50.74	70.20
14	47.93	31.00	42.29	58.96
15	48.77	38.64	42.61	63.10
16	50.83	41.00	46.46	64.78
17	56.27	46.00	52.00	72.77
18	57.10	39.20	45.83	63.32
19	57.10	39.20	45.83	63.32
20	58.77	49.46	57.07	77.09
21	71.67	53.21	59.75	78.40
22	79.53	61.00	64.86	81.40
23	92.50	46.00	51.15	71.31
24	97.10	58.61	64.18	80.84

Figure 5, shows the efficiency comparison along the phases of power transformer for different loading conditions on daily basis. Transformer efficiency increases with percentage loading, reaching maximum at 75%-80% of rated load. Core losses dominate low loads, while copper losses increase efficiency. Beyond optimal load, copper losses outweigh output benefits, reducing efficiency.

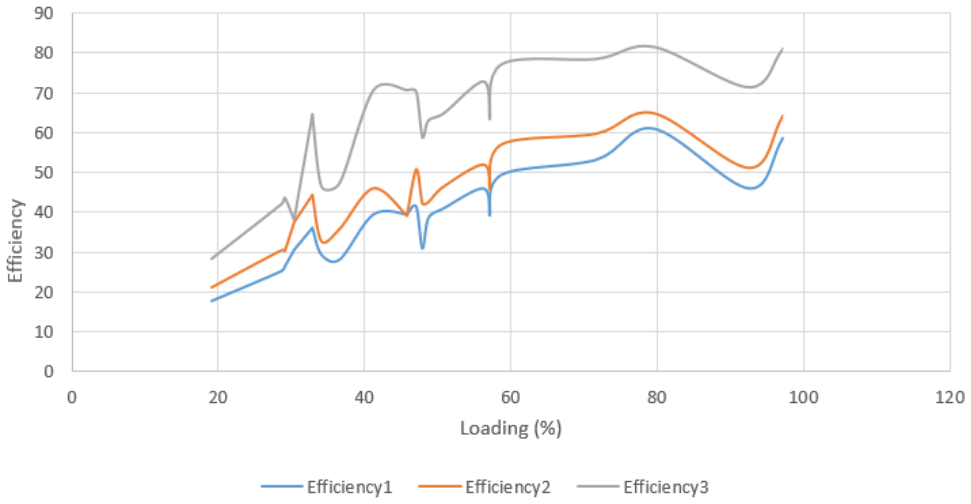


Figure 5: Loading against Efficiency

Figure 6 shows the magnetic flux distribution. The study reveals that when the red phase was excited alone, it created a doubled flux density in the red phase limb, while when the red and blue phases were excited, the flux density in the blue limb was the sum of the yellow and red phases. The nano plot showed a maximum of 1.9684T for 132 kV.

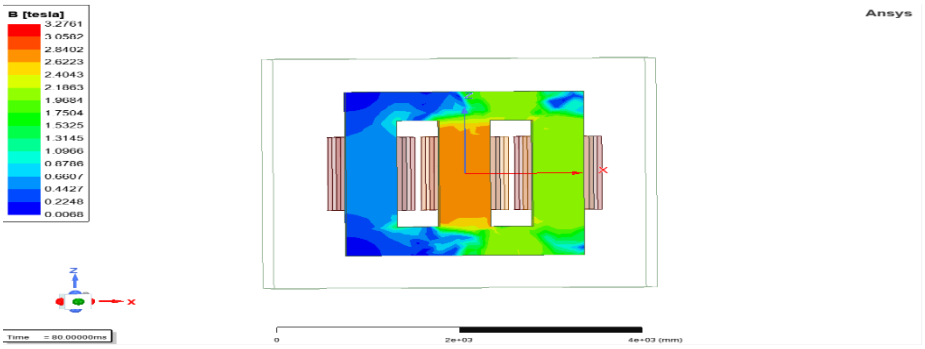


Figure 6: Magnetic Flux Distribution

Figure 7 shows the variation of core loss versus time from the nano plot the maximum core loss is about 17.37 kW

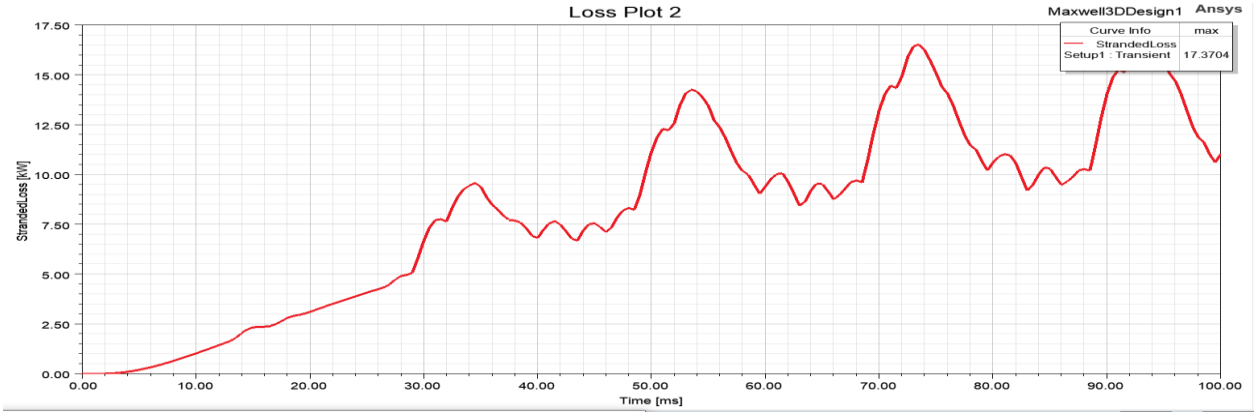


Figure 7: Plot of Core Loss of the Transformer against Time

The efficiency of the transformer was observed by investigating these different conditions in other to analyzed the optimized design for different load conditions and lagging power factor values. The results are presented below for power factor equal to 1, 0.9, 0.85 and 0.8, respectively. As it can be seen in Table 7, the most efficient transformer is obtained at 75%-80% load conditions.

Table 7: Efficiency Comparison at Different Lagging Power Factor of T3 TELK Transformer at Different Load Condition.

Power Factor	100% (Efficiency)	75% (Efficiency)	50% (Efficiency)	25% (Efficiency)
1	82.92	88.08	61.99	30.78
0.9	88.6	89.1	53.96	27.35
0.85	80.54	91.76	47.34	26.32
0.8	70.15	79.04	58.97	26.01

Table 8 shows variation of temperature against percentage loading upon which the temperature increases with increase in percentage loading.

Table 8: Percentage Loading and Temperature Distribution of T3 TELK Transformer at Different Load Condition.

Loading (%)	**Temp (°C)**
56.27	93.93
50.83	92.69
47.93	91.25
48.77	91.99
58.77	94.99

Loading (%)	Temp (℃)
71.67	95.01
30.43	82.49
34.17	88.99
28.72	76.49
19.17	70.48
29.17	79.99
41.27	88.49
45.83	89.50
47.10	90.42
57.10	93.33
92.50	95.78
97.10	96.42
79.53	95.50
36.67	87.33
32.93	84.42
32.93	84.42
30.43	82.49
45.83	89.50
57.10	93.33

Table 9 shows the life cycle cost computation carried out using present value method for future cash flow and the result obtained was tabulated.

Table 9: Initial Cost Offers and Technical Parameters Received from the Manufacturer.

	Value
A: Initial Cost Offers	
1.Transformer Price	N72,000,000
2. Transport Price	N3,600,000
3. Installation and Commissioning Price	N4,320,000
4. Spares and Consumables (5 Yrs) Price	N5,760,000
Quoted Total Price	**N80,496,000**
B: Other Offered Terms	
1. Space Required $(meter \times meter)$	$10m \times 10m$
2. Installation and Commissioning (Days)	100
C: Technical Parameter	
1. Applicable Standard IEC	IEC 60076 all parts

2. Location	Outdoor
3. No of phases	3
4. No of windings	2
5. Rated Frequency (Hz)	50
6. Rated Continuous Power (ONAN/ONAF)	30/40
7. Vector Group	YNd1
8. HV/LV (kV)	132/33
9. HSV HV (kV)	145.5
10. HSV LV (kV)	36.5
11. No-load losses (kW)	19.62
12. Load loss (kW)	97.03
13. Aux losses (kW)	2
14. Time (mins) transformer can be operated at full load after failure of cooling system w/o exceeding hot spot temperature rise 120°C	0
15. % impedance voltage	18 (±7.5%)
16. Design current density at nominal rating HV and LV (A/mm^2)	2.4
17. No load current on H.V. side	Approx 1%
18. Over flux withstand capability	
Continuous	110% of rated V
1 minute	125% of rated V/
10 secs	140% of rated V/
19. Max. flux density (T)	1.727
20. Max. flux density at 110% voltage (T)	1.90
21. Conductor HV and LV	Copper
22. Tap Changer Range, No of steps, Step Size	±10%, 17, 1.25%
23. Impedance at highest tap	19.4%± 10%
23. Impedance at highest tap	17%± 10%
25. Volume of Oil (Drum)	15 or 3150 litres
26. Discounting rate (%)	27.50
27. Energy cost per unit (Naira)	250
28. Year on year escalation	24. 23
29. Number of life time of transformer in year	22
30. Equity by the owner (%)	30
31. Cost of equity in percentage (%)	12
32. No of days of revenue loss in life cycle	5
33 Material cost (%)	60-70
34. Manufacturing cost (%)	15-20
35. Designing and development (%)	5-10
36. Transportation, and installation (%)	5-10
D. Life Cycle Cost Analysis	
1. No Load Losses (Annual, Naira)	N38, 671,200
2. No Load Losses (Life Cycle, Naira)	N534,223,148.5
3. Load Losses (Annual, Naira)	N114,747,678
4. Load Losses (Life Cycle, Naira)	N1,881,907,818
5. Installation and Commissioning (Life Cycle)	N739, 726.0274

6.Space Required (Naira)	N 750,000
7. Auxiliary Losses (Annual, Naira)	N3, 153, 600
8. Auxiliary Losses (Life Cycle, Naira)	N51,720,301.44
9. Recommended Spares (Life Cycle, Naira)	N3,269,595.645
10. Oil monitoring, top ups, replacement	N207,777,187.4
11.Transformer under cooling system failure	N36,986.3
12. Max Flux Density (Life Cycle, Naira)	N254,117.6471
13. Over flux withstand capability	N17,212,500
E. Life Cycle Cost Estimation	
1. Transformer Price (Quoted, Naira)	N72,000,000
2. Transport Price (Quoted, Naira)	N3,600,000
3.Installation and Commissioning Price	N4,320,000
4. No Load Losses (Life Cycle, Naira)	N534,223,148.5
5. Load Losses (Life Cycle, Naira)	N1,881,907,818
6. Installation and Commissioning Time	N739,726.0274
7.Space Required (Naira)	N750,000
8. Auxiliary Losses (Life Cycle, Naira)	N51,720,301.44
9. Recommended Spares (Life Cycle, Naira)	N3,269,595.645
10. Oil monitoring, top ups, replacement	N207,777,187.4
11.Transformer under cooling system failure	N36,986.30
12. Max Flux Density (Life Cycle, Naira)	N254,117.6471
13. Over flux withstand capability	N17,212,500
Life Cycle Cost (Naira)	**N2,777,811,381**

The table provides information of expected cost to be spent on the entire life cycle of the transformer.

CONCLUSION

The study successfully achieved several tangible outcomes that reinforce the effectiveness of the enhanced Finite Element Method in power transformer analysis and optimization. First, an optimal model of the transformer was developed, demonstrating high fidelity in simulating operational conditions. Efficiency evaluations yielded values of 28.47%, 70.60%, and 80.84% at corresponding loading conditions of 19.17%, 97.10%, and 45.83%, respectively, reflecting the model's adaptability across various operational states. The Life Cycle Cost (LCC) analysis estimated a total expenditure of ₦2,777,811,381, providing a crucial economic perspective for long-term asset planning. Furthermore, when compared with the practical performance of the TELK T3 transformer, the simulation exhibited consistent reductions in copper loss by 8.46%, 9.52%, 9.69%, and 11.05% under incremental loading conditions, underscoring the model's precision and practical relevance.

These outcomes collectively validate the enhanced modeling approach and demonstrate its utility in supporting efficient transformer design and economic evaluation.

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