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Parametric Design Analysis, Cost Optimization and Lifetime Estimation of a Three Phase, 300KVA Recycled Electric Distribution Transformer

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Abstract:

The cost of transformer losses and manufacturing can be minimized if transformer cost optimization is carried out when designing and producing. Transformer design, cost optimization and lifetime estimation are complex tasks that need technical know-how to be carried out accurately. This paper presents parametric design analysis, cost optimization and lifetime estimation of a three phase, 300kVA recycled electric distribution transformer. The recycled transformer has efficiency of 97.14% with maximum load efficiency of 96.98% and 3.68% of total power losses. The research work will be relevant to transformer designers, network operators, power engineers, field workers, researchers, Lecturers and students, as it exposes the transformer design analysis and calculations, cost optimization, lifetime estimation of transformers and their parametric models.

Keywords **— Cost optimization, design analysis and calculations, flowchart, lifetime estimation, parametric model.**

1.0 Introduction

Transformers are the heart of electrical transmission and distribution systems and their design is a herculean task in which engineers strive to achieve the compatibility with the standards and imposed specifications, while keeping manufacturing costs low [1]. "Transformers are important assets in electrical power grids, in terms of both reliability and costs" [2]. Presently, society has become more and more dependent on the availability of power, putting pressure on the reliability, availability and cost efficiency of power supply [3 & 4]. Transformers being the hub of transmission and distribution network; as they ensure proper functioning of transmission and distribution networks for transportation of appropriate voltages.

It is worth saying here that despite the power reform the Nigerian government embark upon for several past decades, the Nigerian power system is still being characterized with inadequate and inefficient power supply, voltage drops, undervoltages and high power losses, especially in the distribution network today [5]. Distribution transformers are one of the main components of the electric power distribution network. They fulfill important tasks in the distribution network and they are responsible for consumers being supplied with the appropriate or correct voltage to power their household and industrial appliances and equipment respectively. "Transformers are veritable tools in electrical power system and their functions are significant especially in stepping up and stepping down (transformation) of voltages/currents for appropriate usage" [6].

"The advent of transformer has given leverage to long transmission and distribution of electricity from the point of production to the point of consumption" [6]. "Electricity is a particularly attractive form of energy that can be easily produced, transmitted and transformed into other forms of energy" [7]. "The transformation of voltage and current in electricity supply is carried out by an apparatus called the transformer" [6]. "Transformers are very useful in many electrical circuits. Consequently, the transformer is a device which plays vital and essential roles in many facets of electrical engineering" [8] and "The principle of transformer operation is based on the basic principle of electromagnetic induction which was discovered by Michael Faraday in 1813" [9]. "Transformers are basically passive devices for transforming voltage and current. One of the windings, generally termed as "secondary winding," transforms energy through the principle of mutual induction and delivers power to the load. The voltage levels at the primary and secondary windings are usually different and any increase or decrease of the secondary voltage is accompanied by corresponding decrease or increase in current. Transformers are among the most efficient machines; 95% efficiency being common in lower capacity range, while an efficiency of the order of 99% is achievable in high capacity range" [10].

The importance of distribution transformers in the distribution networks today cannot be overemphasized. They are the major focus of the power engineers or utility operators and their designs, reliability, cost and longevity called for serious attention from the utility engineers or operators. Consequently, this research work illustrates the parametric design analysis, cost optimization and lifetime estimation of a three phase, 300kVA recycled electric distribution transformer.

1.2 Materials and Methods

A 300kVA, 33/0.415kV, three phase distribution transformer which step down the 33kV voltage to 415volts to power a point load at the National Institute of Construction Technology (NICT), Uromi, Edo State, Nigeria was used as a model. The distribution transformer was redesigned and recycled using indigenous knowledge and materials. The K - factor method was used in this design to minimize and mitigate harmonic losses and also, the parametric modeling of the harmonic level of the distribution transformer was considered.

1.3 Design Specifications and Analysis

The machine design procedure for core and shell types of power and distribution transformers have been reported by [10 & 11]. The design difference lies on the specifications of the machine to be designed, planned [6] and the concept involved in the processes. The following are the specifications of the three phase - step down distribution transformer that the design strives to achieve [5].

Power rating, $S = 300\text{kVA}$
Input voltage, $V_1 = 33\text{kV}$
Output voltage, $V_2 = 415\text{V}$
Frequency, $F = 50\text{Hz}$
Maximum flux density, $B_m = 1.35\text{wbm}^{-2}$
Number of phase = 3
Type of connection = Δ - Y (Delta - Star)
Type of transformer = Distribution
Current density, $\delta = 2.5\text{A/mm}^2 = 2.5\text{x}10^6\ \text{Amp/m}^2$
Constant K = 0.45
Ambient temperature = 45°C

Window space factor $k_w = \dfrac{10}{30 + kV}$ = 0.16

Type of construction : Core type
Type of Cooling: Oil Natural Air Natural (ONAN)
Tappings = ± 21/2%, ± 5% on the high voltage side

1.3.1 Design Analysis and Calculations

Core - Design

The voltage per turn, $E_t = K\sqrt{S}$ (1)

$E_t = 7.79\text{V}$

Calculating the core area, A_i

$$A_i = \frac{E_t}{4.44 F B_m} \tag{2}$$

$A_i = 259.8\text{cm}^2$

Calculating the magnetic flux, ϕ_m

$$\phi_m = A_i B_m \tag{3}$$

ϕ_m = 35.09 mWb

Calculating the diameter of circumscribing circle around core, d

Since the transformer is a core type and assuming a three stepped core.

$$A_i = 0.6d^2 \tag{4}$$

$$\Rightarrow d = \sqrt{\frac{A_i}{0.6}} \tag{5}$$

d = 20.81cm

Calculating the width of laminations

a = 0.9d = 18.73cm (6)
b = 0.7d = 14.57cm (7)
c = 0.42d = 8.74cm (8)

Calculating the Gross core section, A_{gi}

Gross core section, $A_{gi} = \dfrac{A_i}{k_s}$ (9)

Assuming stacking factor $k_s = 0.9$

$A_{gi} = 288.78\text{cm}^2$

Window - Design

Calculating the net window area, A_w

The expression for the output power of a three phase transformer:

$$KVA_{3\text{-ph}} = S = 3.33 f\, B_m A_i A_w\, K_w\, \delta \text{x} 10^{-3} \tag{10}$$

$$A_w = \frac{Sx10^{-3}}{3.33fB_m A_i \delta K_w} \quad (11)$$

$A_w = 1283.8cm^2$

Calculating window dimensions, (h_w, w_w)

Assuming $\frac{h_w}{w_w} = 2.5$ (12)

$h_w = 2.5w_w$ (13)

Calculating the window width, w_w

$A_w = h_w \times w_w$ (14)

$$\Rightarrow w_w = \sqrt{\frac{A_w}{2.5}} \quad (15)$$

$w_w = 22.66cm$

Calculating the window height, h_w

$$h_w = \frac{A_w}{w_w} \quad (16)$$

$h_w = 56.65cm$

Yoke - Design

Assuming the section to be 1.2 x limb section

Calculating the net iron area of the yoke, A_y

$A_y = 1.2A_i$ (17)

$A_y = 1540.56cm^2$

Calculating the gross area of the yoke, A_{yg}

Gross area of yoke, $A_{yg} = \frac{A_y}{k_s}$ (18)

$A_{yg} = 1711.7cm^2$

Calculating the magnetic flux density in the yoke, B_y

$$B_y = \frac{B_m}{1.2} \quad (19)$$

$B_y = 1.125Wb/m^2$

Calculating the depth of yoke, D_y

Assuming the yoke section is rectangular

Depth of yoke, $D_y = a$ (20)

$D_y = 18.73cm$

Calculating the height of the yoke, h_y

Height of yoke, $h_y = \frac{A_{yg}}{D_y}$ (21)

$h_y = 91.39cm$

Design of Overall Core Dimensions

Calculating the distance between adjacent core centre, D

$D = w_w + d$ (22)

$D = 43.47cm$

Calculating overall core width, W

Overall core width, $W = 2D + a$ (23)

$W = 105.67cm$

Calculating overall core height, H

$H = hw + 2hy$ (24)

$H = 239.43cm$

Calculating the depth of frame, D_y

$D_y = a$ (25)

$D_y = 18.73cm$

Design of Low Voltage (L.V) Winding

Low voltage (line voltage (V_{Line})) = 415V

connection type = star (Y)

Low voltage winding phase voltage

$$= \frac{V_{Line}}{\sqrt{3}} \quad (26)$$

= 240V

Calculating the secondary turns, N_2

Number of turns per phase $N_2 = \frac{V_{ph}}{E_t}$ (27)

N_2 = 31 turns

Calculating the secondary current, I_2

Current per phase, $I_2 = I_{ph} = \frac{S}{\sqrt{3}V_{Line}}$ (28)

$I_2 = I_{ph}$ = 417.4Amps

Calculating the secondary conductor size, a_2

Current density δ = 2.5A/mm^2

$$a_2 = \frac{I_2}{\delta} \tag{29}$$

a_2 = 166.94mm^2

Since the area is greater than 50mm^2, a single conductor will not be used because of flexibility during coiling and for more current handling. Hence, choosing a rectangular copper conductor with section of 1.7mm thickness x 25mm width; four (4) numbers of the conductor strips forming the conductor of the low voltage side with area of a_2 = 42.20 x 4 = 169 mm^2 will be used.

Designing of High Voltage (H.V) Winding

The high voltage (H.V) side line voltage, $V_2 = V_L$ = 33kV

$$\frac{V_1}{V_2} = \frac{N_1}{N_2} = \frac{I_2}{I_1} \tag{30}$$

$$\frac{V_1}{V_2} = \frac{N_1}{N_2} \tag{31}$$

$$N_1 = \frac{V_1}{V_2} \times N_2 \tag{32}$$

N_1 = 4263 turns

Calculating tapping turns on the high voltage side at ±5% and ±21/2% which is to be provided on H.V side.

Normal turns N_1 = 4263 turns

At +5% tappings = 4476 turns

At +21/2% tappings = 4370 turns

At -5% tappings = 4050 turns

At -21/2% tappings = 4156 turns

Calculating the primary current, I_1

Current per phase, $I_1 = I_{ph} = \frac{S}{3V_{phase}}$ (33)

I_1 = 3.03 Amps

Calculating the primary conductor size, a_1

Current density δ = 2.5A/mm^2

$$a_1 = \frac{I_1}{\delta} \tag{33}$$

a_1 = 1.212mm^2

Calculating the diameter of the conductor

$$a = \frac{\Pi d^2}{4} \tag{34}$$

$$d = \sqrt{\frac{4a}{\Pi}} \tag{35}$$

Where d is the diameter of the conductor

Calculating the diameter of the secondary conductor, d_2

d_2 = 1.242mm

Calculating the diameter of the primary conductor, d_1

d_1= 7.330mm

Choosing a round conductor for the high voltage side of a nearest size from standard table.

Calculating the total copper area in a window, A_t

$A_t = 2(a_1N_1 + a_2N_2)$ (36)

A_t = 213.278cm^2

Calculating the window space factor, K_w

$$k_w = \frac{A_t}{A_w} \qquad (37)$$

$k_w = 0.166 \approx 0.17$

Which is very close to 0.16 chosen

Calculating the mean length per turn (L_{mt}) for both primary and secondary coils

$L_{mt} = \pi[d + W_w/2]$ (38)

$L_{mt} = 1.0097$m

Calculating the length of primary turns, L_1

Length of primary coils, $L_1 = L_{mt} \times N_1$ (39)

$L_1 = 4204.35\text{m} \approx 4204\text{m}$

Calculating the length of secondary turns, L_2

Length of secondary coils, $L_2 = L_{mt} \times N_2$ (40)

$L_2 = 31.30\text{m} \approx 31\text{m}$

Calculating the resistance of the primary winding, R_1

$$R_1 = \frac{\rho L_1}{a_1} \qquad (41)$$

$R_1 = 74.57\Omega$

Calculating the resistance of the secondary winding, R_2

$$R_2 = \frac{\rho L_2}{a_2} \qquad (42)$$

$R_2 = 0.00391\ \Omega$

Calculating total resistance referred to primary side at 75^0C, R_t

$$R_t = R_1 + \left(\frac{N_1}{N_2}\right)^2 \times R_2 \qquad (43)$$

$R_t = 148.5\Omega$

Calculating the per unit (P.U) resistance at the primary side, ε_T

$$\varepsilon_T = \frac{I_1 R_t}{V_1} \qquad (44)$$

$\varepsilon_T = 0.0136$

Calculating the weight of both primary and secondary coils or windings, W_c

Calculating the weight of primary (H.V) windings, W_{c1}

$W_{c1} = Da_1L_{mt}N_1$ (45)

$W_{c1} = 48.70$kg

Calculating the weight of the secondary (L.V) windings, W_{c2}

$W_{c2} = Da_2L_{mt}N_2$ (46)

$W_{c2} = 47.03$kg

Calculating the total weight of copper in transformer, W_{CT}

$W_{CT} = 3(W_{c1} + W_{c2})$ (47)

$W_{CT} = 287.19$kg

Calculating the weight of iron core in transformer, W_{ic}

Weight of iron core W_{ic} = (iron volume) x (iron density) (48)

Volume of iron core = total length of mean flux path (L_m) x iron area (49)

Total length of mean flux path, $L_m = 2[w_w + d] + 2[h_w + a]$ (50)

$L_m = 237.7$cm

Volume of iron core = L_mA_i (51)

$= 61778.23\text{cm}^3$

Weight of iron core, $W_{ic} = L_mA_iD$ (52)

$W_{ic} = 486.19$kg

Calculating the weight of iron core and yoke assembly

Weight of three limbs in a core = $3h_wA_iD_L$ (53)

= 335.69kg

Weight of two yokes = $2WA_yD_L$ (54)

= 2474.42kg

Calculating the total weight of iron core, W_{icT}

Total weight of iron core $W_{icT} = 3h_wA_iD_L + 2WA_yD_L$ (55)

$W_{icT} = 2810.11$kg

Calculating the core losses in the limbs and yokes

Core loss in limbs = 2 x weight of limbs (56)

= 671.38W

Core loss in yokes = 1.4 x weight of yokes (57)

= 3.46kW

Calculating total core loss (Iron loss) P_i,

Total core loss (Iron loss) P_i = Core loss in yokes + Core loss in limbs (58)

$P_i = 4135.57\text{W} \approx 4.135\text{kW}$

Calculating the total copper losses at 75°C, P_c

Total copper loss P_c at 75°C $= 3[I_1^2R_1 + I_2^2R_2] = 3I_1^2R_T$ (59)

$P_c = 4090.09$W

Calculating stray load loss, P_s

P_s = total copper loss (P_c) x 71/2% (60)

$P_s = 0.075P_c$ (61)

$P_s = 306.757W$

Calculating copper loss under load at 75°C, P_{cL}

$P_{cL} = P_c + P_s$ (62)

$P_{cL} = 4396.85W$

Calculating total power losses in transformer, P_T

Total power loss in transformer, P_T = Copper loss under load at 75°C (P_{cL}) + Iron losses (P_i) (63)

$P_T = P_{cL} + P_i$ (64)

$P_T = 8833.42W \approx 8.833kW$

Calculating the load for maximum efficiency, X

For maximum efficiency to occur:

$X^2P_{CL} = P_i$ (65)

$$\Rightarrow X = \sqrt{\frac{P_i}{P_{CL}}} \quad (66)$$

X = 0.9698

Meaning that the maximum efficiency occurs at 0.9698 times full load

Calculating the efficiency of the distribution transformer

Efficiency at full load and unity power factor (P.F), η_T

$$\eta_T = \frac{Output - Power}{Input - power} X100 \quad (67)$$

$\eta_T = 97.14\%$

Cooling-Design

Transformer tank dimensions

Height of transformer tank (h) = 133cm

Length of transformer tank (L) = 127cm

Width of transformer tank (w) = 104cm

Calculating the surface area of the transformer tank, S_t

S_t = 2 x height x length + 2 x height x width (68)

$S_t = 2hL + 2hw$ (69)

$S_t = 6.145m^2$

Calculating the temperature rise in tank of transformer, Tr

Total specific loss dissipation due to convention and radiation is 12.5W/m²/°C temperature rise

Temperature rise in tank °C

$$(Tr) = \frac{Total - Power - Loss - at - full - load}{12.5xS_t} \quad (70)$$

$$Tr = \frac{P_T}{12.5S_t} \quad (71)$$

Tr = 115°C

1.4 Parametric Modeling of Harmonics Effects Mitigation on Electric Distribution Transformer

The failure rate of transformers caused by harmonics effect is very high in India; around 25% per annum, which is not favourably comparable to international norms of 1 - 2% [12]. Harmonics affect transformers primarily in two major ways: voltage harmonics and current harmonics. "The voltage harmonics produces additional losses in the transformer core as the higher frequency harmonic voltages set up hysteresis loops, which superimpose on the fundamental loop. The second and a more serious effect of harmonics is due to harmonic frequency currents in the transformer windings" [13]. The harmonic currents increase the net RMS current flowing in the transformer windings which result in additional I^2R losses [13]. Winding eddy currents are circulating currents induced in the conductors by the leakage magnetic flux [13]. "And this winding eddy current increases the losses in the system by causing temperature rise in the windings. In order to handle these losses and the temperature effect, the k - factor method is employed for transformers that supply nonlinear load." The k - factor transformer is designed to accommodates the temperature rise caused by current harmonic in the transformer windings. In addition to the fundamental frequency losses. "K - factor is a constant that specifies the ability of the transformer to handle harmonic heating as a multiple of the normal eddy current losses which are developed by a sinusoidal current in the transformer windings." A good engineering practice calls for the derating of transformer that serves nonlinear loads to an equivalent 80% of nameplate kVA [12]. The parametric modeling of the k - factor is given as:

$$k = \sum I_h^2 h^2 \left(h = 1, 2, 3, \dots n\right) \qquad (72)$$

1.5 Modeling of Harmonics Level in Electric Distribution Transformer

The harmonic level of the electric transformers can be determined by the ratio between the effective value of the fundamental as shown in the parametric model:

$$Y_{Level} = \frac{V_h}{V_1} x\, 100\% \qquad (73)$$

Where Y_{level} is the harmonic level of the transformer, V_1 is the fundamental voltage and V_h is the harmonic voltage considered.

1.6 Transformer Cost Optimization Modeling

Transformers, being one of the major and the most expensive component of the transmission and distribution network, it is imperative to carry out the cost optimization during design and manufacturing processes. "The transformer design is a complex task that involves many variations of design variables so as to manage lowering transformer materials cost, minimizing labour cost and also, satisfying transformer specifications with respect to electric strength, mechanical endurance, dynamic and thermal resistance of windings in the event of short - circuit" [14]. Transformer cost optimization is done to meet objectives of optimizing efficiency and reducing transformer total cost (TTC) such as labour cost, windings cost, manufacturing cost, total owing cost etc, without violating optimal performance of the transformer. "The main objective of transformer cost optimization (TCO) is to design the transformer so as to minimize the transformer manufacturing cost; that is, the sum of materials cost plus labour cost, all subject to constraints imposed by international standards and transformer user specification" [15]. Hence, transformer cost optimization is crucial in minimizing the total cost of transformer production.

1.6.1 Mathematical Formulation of the Transformer Cost Optimization Problem

The purpose of transformer cost optimization is to determine the main materials cost, labour cost, total owing cost and remaining materials cost not included in the main materials cost with a view to reducing the costs without violating the transformer constraints. One common method, for formulation of objective function of the transformer cost optimization (TCO) is the minimization of the total cost of the transformer from the designing point to purchasing point. This method is to model the formula from the total cost. The scalarized form of the optimization problem is obtained by using the minimal cost method [16]. Where k is the cost coefficient levels. This approach yields meaningful result to the decision maker when solved often for different values of k [16].

Minimize C_T =

$$Minimize \sum [K_{RM} + K_L + K_{TO} + \sum_{g=1}^{n} uK_g . W_g\,] \qquad (74)$$

Subject to the following constraints [15 & 17]:

$$V_{ph} = 4.44.f.N_{ph}.B_m.D.2.E_u \quad (75)$$

$$\frac{V_1}{V_2} = \frac{N_1}{N_2} \quad (76)$$

$$NLL \triangleleft NLL_{\max} \quad (77)$$

$$LL \triangleleft LL_{\max} \quad (78)$$

$$TTL \triangleleft TTL_{\max} \quad (79)$$

$$Z_{k\min} \triangleleft Z_k \triangleleft Z_{k\max} \quad (80)$$

$$B_m \triangleleft B_{sat} \quad (81)$$

$$TTL \triangleleft TH_{CCR} \quad (82)$$

$$\Delta T_r \triangleleft \Delta T_{r\max} \quad (83)$$

$$Induced_{L.V} \triangleleft Induced_{LV\max} \quad (84)$$

$$Induced_{HV} \triangleleft Induced_{HV\max} \quad (85)$$

$$\operatorname{Im} pulse_{L.V} \triangleleft \operatorname{Im} pulse_{LV\max} \quad (86)$$

$$\operatorname{Im} pulse_{HV} \triangleleft \operatorname{Im} pulse_{HV\max} \quad (87)$$

$$TL \triangleleft TL_{\max} \quad (88)$$

$$TW \triangleleft TW_{\max} \quad (89)$$

$$TH \triangleleft TH_{\max} \quad (90)$$

$$\eta \triangleright \eta_{\min} \quad (91)$$

$$\Delta V \triangleleft \Delta V_{\max} \quad (92)$$

$$I_{NL} \triangleleft I_{NL\max} \quad (93)$$

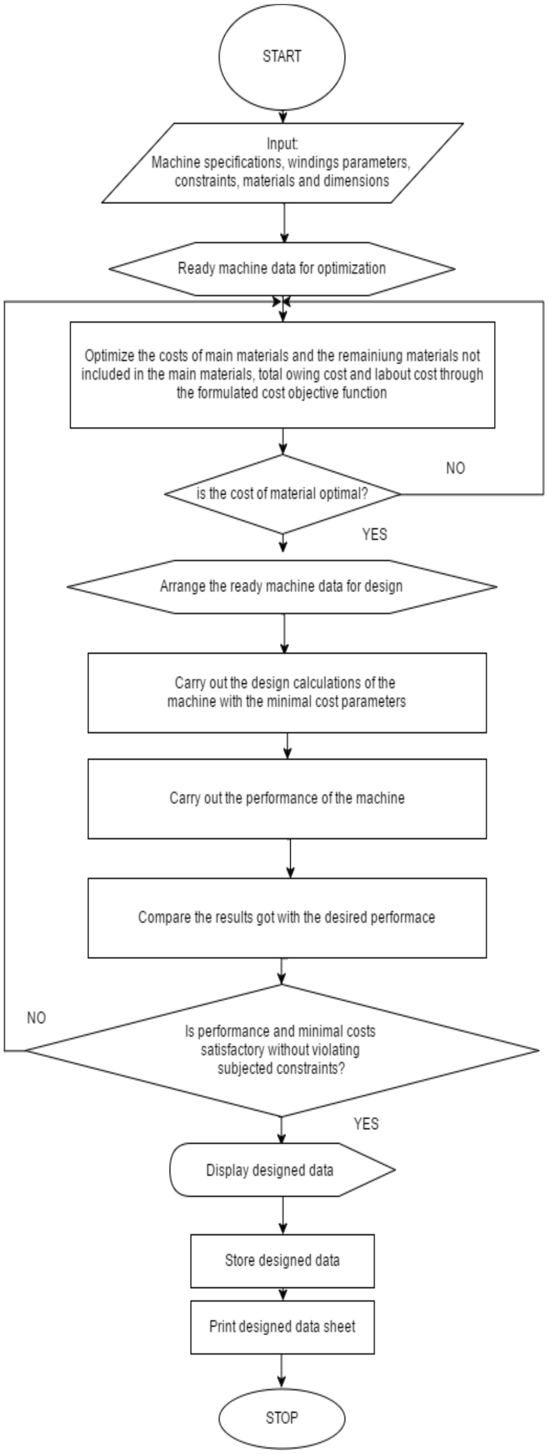

Figure 1: Flow chart Solution for Transformer Cost Optimization

1.7 Parametric Models of Lifespan and Lifetime Estimation of a Recycled Electric Distribution Transformer

"Most electric transformers are highly vulnerable to overheating, leading to insulation damage which causes the premature failure or unexpected shutdown of the transformer" [6]. The lifetime estimation of transformer is imperative as it seems it is the actual forecast of the lifespan of the transformer that it will actively be in service with respect to temperature changes, environmental factors etc.; of the operation of the device. "The life of a transformer is normally dependent upon the life of the insulations. When insulation fails, the transformer life has ended. The term "transformer life" gives an impression as if it was quite definite, but in-fact a transformer hardly ever dies" [10]. "In general, the expected lifespan of 30 years fits best case of a transformer used in transmission or distribution network" [18]. But the "Manufacturers often define the expected life of power transformers to be between 25 and 40 years. Although some transformers in service both in transmission and distribution network are now approaching this age and few are already 60 years old" [2] in service. Consequently, it is imperative to estimate the remaining lifetime of a transformer that is in active service or the lifespan of a recycled or new transformer in order to prevent unexpected or premature failure or shutdown of transformers [19].

Insulation failure may become the rife cause of transformers failure if the transformer temperature rise exceed the safe value due to overloading or excessive power loss causing ageing of insulation. According to IEC, ageing of insulation can be defined as the "irreversible deleterious change to the serviceability of insulation system," and this is caused by various factors: "Temperature (thermal stress), electrical stress, mechanical stress and environmental factors." "Models for thermal, electrical and mechanical stresses, singly applied, have been available as Arrhenius model for thermal stress" as [20]:

$$L_T = L_0 \exp^{(-BT)} \qquad (94)$$

$where:$

$$T = \frac{1}{\theta_0} - \frac{1}{\theta} \qquad (95)$$

$$\beta = \frac{E_a}{k} \qquad (96)$$

"And L_T is the lifetime , E_a is the activation energy of the degradation process, k is Boltzmann constant, Θ, Θ_0 are the absolute and reference temperature and L_o is the lifetime at temperature Θ_o "[20]. "The expected lifespan of a transformer with respect to degree of polymerization (DP) has been given by Emsley method. The ageing experiments approved the model as" [20]:

$$Expected - Life = \frac{\frac{1}{DP_{end}} - \frac{1}{DP_{start}}}{Ax8760} \, x \exp^{(\frac{13350}{T+273})} \qquad (97)$$

The transformer thermal lifetime model can also be taken from the ageing rate (k) as calculated as:

$$k = \frac{\frac{1}{DP_{assume}} - \frac{1}{DP_{new}}}{Years_{assume}} \qquad (98)$$

Then, the transformer thermal lifetime (t) can be calculated as:

$$t = \frac{\frac{1}{DP_{end}} - \frac{1}{DP_{new}}}{k} \qquad (99)$$

The thermal degradation model above in equation (99) was used to estimate the expected lifetime of the recycled electric distribution transformer. Consequently, the expected lifespan of the recycled electric distribution transformer was estimated to be 58 years at a reference temperature.

1.8 Conclusion

Design, cost optimization and lifetime estimation of transformers are complex tasks that include many variation of variables and technical know-how to be carried out accurately. "Transformers are the major and most important equipment in electrical power system. Their roles in changing voltage and current levels cannot be underestimated in electrical power grids" [6] for reliability and optimal operation of the network; hence this research. The recycled electric distribution transformer operates with efficiency of 97.14%, maximum load efficiency of 96.98% and 3.68% total power losses. The K - factor method was used in the design to mitigate harmonics losses; and the maximum temperature rise was 115^{o}C in the transformer tank which is within standard specification.

The research work gave general guidelines to transformer designers, researchers, power operators, power engineers, manufacturers, field workers and students who want to carry out full design work ; cost optimization of transformer and the estimation of their lifespan.

List of Symbols and Abbreviations:

V_1 = Input voltage
V_2 = Output voltage
AC = Alternating current
I_1 = Input current
I_2 = Output current
W = Overall width of core
H = Overall height of core
h_y = Height of yoke
D_y = Depth of yoke
D = Density
D_m = Mean diameter of turns
F = Frequency (Hertz)
K = Constant
δ = Current density (A/M^2)
K_w = Window space factor
B_m = Magnetic flux density (Telsa)
N_1 = Primary turns
N_2 = Secondary turns
A_w = Window area m^2
A_y = Area of yoke m^2
A_i = Net core section m^2
a_1 = Primary conductor section m^2
a_2 = Secondary conductor section m^2
d_1 = Primary conductor diameter, mm
d_2 = Secondary conductor diameter, mm
E_t = E.M.F. per turn
I_h = Harmonic current
η_T = Efficiency
Y_L = Harmonic level
K = K - factor
L_{mt} = Mean length of turn
ω = Angular frequency
P_c = Total copper loss
P_s = Stray losses
P_i = Total core loss
P_{cl} = Copper losses under load
P_T = Total power loss
S_t = Surface area Transformer tank
Lm = Total length of mean flux path
ε_T = Per unit resistance
R_t = total resistance referred
W_c = Weight of coils
W_{ic} = Weight of iron core
K_{RM} = Cost of transformer remaining material
K_{TO} = Total owing cost of transformer
K_L = Cost of Labour
uK = unit cost of main materials such as LV and HV windings, insulations, duct strips, etc.
V_{ph} = Voltage per phase
V_{max} = Maximum voltage
NLL = No -load losses
NLL_{max} = Maximum no-load losses
LL = Load losses
LL_{max} = Maximum load lossess
TTL = Transformer total losses
TTL_{max} = Maximum transformer total losses
Z_k = Impedance
Z_{min} = Minimum impedance
Z_{max} = Maximum impedance
Tr = Temperature rise
Tr_{max} = maximum temperature rise
HV = High voltage
HV_{max} = Maximum high voltage
LV = Low voltage
LV_{max} = Maximum low voltage
B_{sat} = Saturated magnetic flux density
TH_{CCR} = Total heat that can be carried away by conduction, convection and radiation
TL = Tank length
TL_{max} = Maximum tank length
TW = Tank width
TW_{max} = Maximum tank width
TH = Tank height
TH_{max} = Maximum tank height
I_{NL} = No-load current
I_{NLmax} = Maximum no-load current

$^{n}_{min}$ = Minimum efficiency
X = Maximum load efficiency
C_T = Total cost
TTC = Transformer total cost
TCO = Transformer cost optimization

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