ISSN (Online) 2321 – 2004
ISSN (Print) 2321 – 5526

INTERNATIONAL JOURNAL OF INNOVATIVE RESEARCH IN ELECTRICAL, ELECTRONICS, INSTRUMENTATION AND CONTROL ENGINEERING
Vol. 2, Issue 2, February 2014

Minimization of Active Part Cost of a 100 kVA Distribution Transformer Using Exhaustive Search Method

H.D. Mehta[1], **Rajesh Patel**[2]

School of Engg., R.K. University, Rajkot, India, Asso. Prof., Electrical Engg.,L.D. Engg. College, Ahmedabad, India [1]

Professor, Electrical Engg. Department, HJD Institute of Technical Education and Research, Kera, Kachchh,India [2]

Abstract: This paper addresses the optimum transformer design problem to minimize the active part cost of three phase core type distribution transformer. The transformer design process involves substantial heuristic exercise to select the design, best suited to a set of specifications. The design problem considers minimization of total cost of core and conducting material, while constraints are imposed on no load losses, total losses and percentage impedance as they are very critical to all day efficiency, overall efficiency and voltage regulation of a transformer. A MATLAB program has been developed which calculates all dimensions and performance parameters of 4080 transformer designs, out of which, the design having the minimum cost, satisfying the manufacturing specifications, BEE standards and constraints is selected. The transformer dimensions and performance parameters are compared with the transformers made by Jyoti Transelect Company, Bhuj, (India) and necessary changes are suggested in transformer dimensions to obtain optimal design

Keywords: Design Optimization, Active part cost minimization, Distribution transformer, MATLAB

NOMENCLATURE

List of Symbols

Q	kVA rating of transformer
Φ_m	Maximum flux in core (webers)
AT	Number of ampere turns
N_{LV}	Number of turns in LV or secondary winding
N_{HV}	Number of turns in HV or primary winding
V_{LV}	Voltage of LV winding
V_{HV}	Voltage of HV winding
Et	Volt per turn
Ag	gross core area (sq.cm)
Bm	Maximum flux density in core (Wb/m^2)
Kg	Stacking factor
d_c	Core diameter (cm)
Cw	Core weight (kg)
Clc	Core limb centre (cm)
Hw	Window height (cm)
Wds	Width of largest stamping (cm)
δ_{CL}	Density of core material (gm/cm^3)
Alw	Weight of aluminium winding (kg)
δ_{AL}	Density of aluminium (gm/cm^3)
MDLV	Mean diameter of LV winding (mm)
MDHV	Mean diameter of HV winding (mm)
A_{LV}	Cross sectional area of LV (sq.mm)
A_{HV}	Cross sectional area of HV (sq.mm)
LL_{HV}	Load losses in HV (watts)
LL_{LV}	Load losses in LV (watts)
NLL_{sp}	Specific no load losses (watts/kg)
NLL	No load loss (watts)
We	Exciting power (VA/kg)
Im	Magnetizing component of no load current (A)
Iw	Core loss component of no load current (A)
I_0	No load current (A)
Asl	Average stack length of LV and HV coil (mm)
R_{BHV}	Radial build of HV winding (cm)
R_{BLV}	Radial build of LV winding (cm)

I. INTRODUCTION

A transformer has been defined by ANSI/IEEE [1] as a static electric device consisting of two or more windings, with or without a magnetic core, for introducing mutual coupling between electric circuits. The transformer is an electrical machine that allows the transmission and distribution of electrical energy simply and inexpensively, as its efficiency is from 95% to 99%, i.e., the transformer operates more efficiently than most of all other electrical devices. Traditionally, the aim of transformer design optimization is to optimize an objective function (generally cost) subject to constraints imposed by international standards and specifications. There are more than 400 published articles, 50 transformer books and 65 standards in the domain of transformers [2]. The first computerized transformer design was performed in 1955 [3]. Thereafter, transformer designs using computer software were carried out by many researchers [4-6]. An optimizing routine called Monica was

ISSN (Online) 2321 – 2004
ISSN (Print) 2321 – 5526

INTERNATIONAL JOURNAL OF INNOVATIVE RESEARCH IN ELECTRICAL, ELECTRONICS, INSTRUMENTATION AND CONTROL ENGINEERING
Vol. 2, Issue 2, February 2014

developed by Andersen [7] in which random numbers were used to generate feasible design, from which lowest cost design was chosen. The transformer design problem by Hurley [8] and Poloujadoff [9] describes the transformer price variation with primary turns which is approximately a hyperbolic function. Transformer design using geometric programming was employed by Jabr [10] in which GP optimizer was used to design the transformer operating at 100 kHz and at 60 Hz, while object oriented programming was used in [11] for distribution transformer design. The herculean task of achieving the optimum balance between transformer performance and cost is complicated, and it would be unrealistic to expect that the optimum cost design would satisfy all the mechanical, thermal and electrical constraints. The constraints on excitation current, no-load losses, total losses, impedance and efficiency were considered by Olivares [12] in which the optimal design of 25 kVA single phase shell type transformer using multiple design methodology was presented for illustration. Generally, designers consider transformer manufacturing cost as the objective function [13], in which special attention is paid to cost of active materials (i.e. cost of core and conducting material) which play a crucial role for manufacturer and industrial companies.

In this paper an attempt has been made to minimize the cost of active materials of a 100 kVA, 11/0.433 kV distribution transformer using MATLAB .m file programming, while ensuring the fulfilment of constraints, for a three phase transformer manufactured with M4 grade core material having aluminium conductors, as aluminium is found to be more economical than copper in transformers having a rating of less than 190 kVA [14]. This technique can be extended to other distribution transformers ranging from 25 kVA to 200 kVA with little modification. This software would be immensely helpful to small distribution transformer manufacturing companies as they could save substantial design man-hours and minimize transformer material cost with minimum intervention of the designer.

II. DESIGN PROCEDURE OF TRANSFORMER

This section describes a brief outline of the transformer design methodology for a three phase core type transformer having a rating of 100 kVA, 11/0.433 kV, Dyn-11, with aluminium winding material. In the software, core material is assumed to be of M4 grade with stacking factor of 0.97, having a cost of Rs. 210 per kg while the winding material is of aluminium having a cost of Rs. 177 per kg. However, the software permits the user to enter different values of cost/kg for core and winding material, if required.

A. Calculation of Number of Turns

The voltage per turn in a transformer is calculated using the equation = $K\sqrt{Q}$, where the value of K is obtained from [15] and is given by

$$K = (4.44 f \Phi_m / AT \times 10^3)^{1/2}. \qquad (1)$$

The number of secondary and primary turns is calculated as follows,

$N_{LV} = V_{LV}/(\sqrt{3} \times Et)$

$N_{HV} = \sqrt{3} \times V_{HV} \times N_{LV}/ V_{LV}$

where LV is considered as secondary and HV as primary

B. Estimation of Core Window Height

After calculating rated HV current, cross sectional area, diameter of HV, the number coils per phase and the number of turns per coil are calculated. The numbers of layers are then selected and number turns per layer are found out which helps in estimating core window height.

C. Core Area and diameter

The gross core area (in sq.cm) of a transformer is calculated using the equation

$$Ag = \frac{Et \times 10^2}{2.22 \times Bm \times Kg} \qquad (2)$$

The transformer core diameter, assuming 9-stepped core is obtained from [15]

$$d_c = \sqrt{\frac{Ag \times 4}{\pi \times 0.935}} \qquad (3)$$

The core diameter obtained from eqn. (3) is then rounded off to the nearest value

D. Core Weight and Cost

Transformer core weight can be obtained from [16] using the relation

$$Cw = (4 \times Clc + 3 \times Hw + 2 \times Wds \times 0.86) \times Ag \times Kg \times \delta_{CL} \qquad (4)$$

The core cost can be obtained by multiplying suitable cost co-efficient with the core weight

E. Winding Weight and Cost

Transformer winding weight depends mean diameter of LV and HV windings, its cross sectional area, number of turns and density of winding material. It is given by

$$Alw = 3 \times \delta_{AL} \times \pi \times (2 \times MDLV \times N_{LV} \times A_{LV} + MDHV \times N_{HV} \times A_{HV}) \times 10^{-6} \qquad (5)$$

Once the winding is known its cost is obtained by multiplying it with its cost co-efficient. The factor of ‘2’ appears in eqn.(5) as two strips of LV winding are used

F. Load losses of LV and HV winding

The load losses of LV and HV winding are calculated using the following equations

$$LL_{LV} = 3 \times Is^2 \times \pi \times MDLV \times N_{LV} \times \rho_{AL}/ A_{LV} \qquad (6)$$

$$LL_{HV} = 3 \times Ip^2 \times \pi \times MDHV \times N_{HV} \times \rho_{AL}/ A_{HV} \qquad (7)$$

G. No load loss and no load current calculation

The core loss curve for M4 grade material which gives specific iron loss (watts/kg) at different values of flux density is converted into fourth order equation using MATLAB polyfit function as shown below

ISSN (Online) 2321 – 2004
ISSN (Print) 2321 – 5526

INTERNATIONAL JOURNAL OF INNOVATIVE RESEARCH IN ELECTRICAL, ELECTRONICS, INSTRUMENTATION AND CONTROL ENGINEERING
Vol. 2, Issue 2, February 2014

$$NLLsp = 1.5291Bm^4 - 5.9664Bm^3 + 8.6933Bm^2 \ldots \ldots - 4.9237Bm + 1.0388 \quad (8)$$

The total no load loss is then obtained by

$$NLL = NLLsp \times Cw \quad (9)$$

Similarly, the curve of Exciting Power (VA/kg) versus flux density is converted into fourth order equation to obtain no load current as demonstrated below

$$We = 8.8542Bm^4 - 36.3249Bm^3 + 54.6091Bm^2 \ldots \ldots - 34.8050Bm + 8.1222 \quad (10)$$

The magnetizing component and core loss component of current are then obtained from equations (11) and (12)

$$Im = We \times Cw/(\sqrt{3} \times V_{LV}) \quad (11)$$

$$Iw = NLL/(\sqrt{3} \times V_{LV}) \quad (12)$$

$$I_0 = \sqrt{Im^2 + Iw^2} \quad (13)$$

H. Percentage impedance calculation

Before calculating percentage impedance, percentage reactance and resistance are determined from [15] as follows

$$\% X = \frac{7.91 \times f \times Is \times N_{LV}{}^2 \times \pi \times Dm \times}{V_{LV} \times Asl \times 10^6} \left(a + \frac{R_{BHV} + R_{BLV}}{3}\right) \quad (14)$$

$$\% R = (LL_{LV} + LL_{HV}) \times 100/Q \quad (15)$$

$$\% Z = \sqrt{\%X^2 + \%R^2} \quad (16)$$

I. Efficiency and voltage regulation

The efficiency is computed for full-load at unity power factor

$$\eta = \frac{Q}{LL + NLL + Q} \times 100 \quad (17)$$

The voltage regulation at different values of power factor angles φ is determined using the equation

$$\%Vreg = \% R \times \cos\varphi + \% X \times \sin\varphi \quad (18)$$

III. PERFORMANCE CONSTRAINTS

Performance constraints are used to investigate the feasibility of transformer design. The following constraints pertaining to IS 2026 and IS 1180 (part 1) are considered in the design optimization method.

A. Total losses at full load and half load

According to bureau of energy efficiency [17] the total losses pertaining to 100 kVA transformer at full load and half load for 1- star and 2-star ratings of transformer are stated in Table –I

TABLE-I
LOSSES PERMITTED AT HALF LOAD AND FULL LOAD

Type	Max total permissible losses at full load	Max total permissible losses at half load
1-star	2020 watts	700 watts
2-star	1910 watts	610 watts

B. Percentage impedance

The percentage impedance at 75^0 C should be 4.5% for 100 kVA, 11/0.433 kV distribution transformer (IS tolerance of ±10% applicable)

C. Excitation current

The excitation current should not exceed as per guidelines given below:
At rated voltage: 2% of full load current in LT winding
At 112.5% rated voltage: 4% of full load current

D. Current density in LV and HV conductors

The current density for LV and HV winding should not exceed 1.6 A/sq. mm for Aluminium conductors.

IV. INPUT PARAMETERS AND FLOWCHART FOR OPTIMAL TRANSFORMER DESIGN

In this section the input parameters required for optimum design of transformer has been discussed. The design satisfies the technical specifications and requirements of 1-star and 2-star rating. The software requires eight input parameters: 1) Transformer rating in kVA 2) Rated high voltage (V_{HV}) 3) Rated low voltage (V_{LV}) 4) Max. no load losses permitted (NLL) 5) Max. load losses permitted (LL) 6) Total losses permitted at half load (HLL) 7) Short circuit impedance (%Z) 8) Temperature rise θ. The software assumes that HV winding is connected in delta and LV winding in star as majority of the 100 kVA, 11/0.433 kV distribution transformers have star as the secondary winding and delta as primary. The software takes into account multiple values of K, Bm and δ_{HV} in steps of 0.01 as shown Table-II

TABLE-II
RANGE OF DESIGN PARAMETERS

Variable	Range	No. of values
K	0.32-0.47	16
Bm	1.20-1.70	51
δ_{HV}	1.5-1.54	05

As depicted in Table-II, 16 values are selected for 'K', 51 values for Bm and 5 values for δ_{HV}, which means that in total, 16*51*05 = 4080 candidate transformer designs are considered by the software.

The constraints on no-load losses, load losses, percentage impedance and total losses at half load for 1-star and 2-star rating transformer, as well as other parameters entered in the software are mentioned in Table-III

TABLE-II
INPUT PARAMETER VALUES FOR 1-STAR AND 2-STAR RATED TRANSFORMERS

Parameter	1-star	2-star	Units
Rated power	100	100	kVA
Max. total losses permitted	2000	1900	W
Max. losses at half load	690	605	W
Max. NLL permitted	200	200	W
Percentage impedance	4.7	4.7	%
Rated low voltage	433	433	V
Rated high voltage	11000	11000	V
Temperature rise	50	50	^{0}C

ISSN (Online) 2321 – 2004
ISSN (Print) 2321 – 5526

INTERNATIONAL JOURNAL OF INNOVATIVE RESEARCH IN ELECTRICAL, ELECTRONICS, INSTRUMENTATION AND CONTROL ENGINEERING
Vol. 2, Issue 2, February 2014

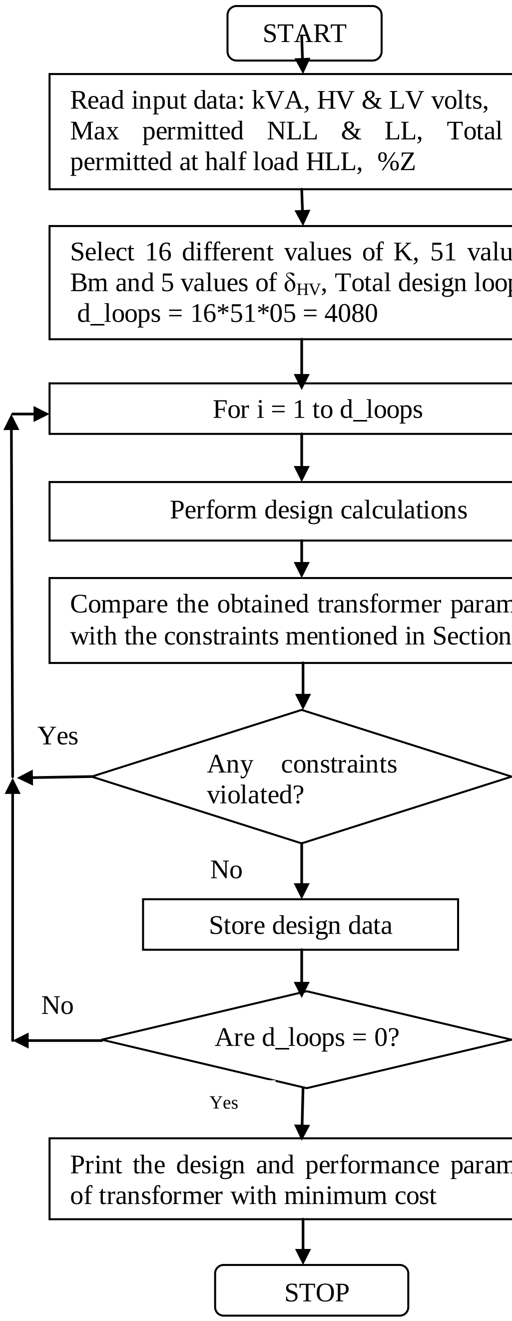

Fig.1Flowchart for optimum transformer design

The designs which violate the constraints are rejected and the costs of all acceptable solutions including the design and performance parameters of transformer with minimum cost are printed on the command window. The flowchart for active part cost minimization is shown in Fig.1

V. RESULTS AND DISCUSSION

Tables IV and V show the results of software for 1-star and 2-star rating of 100 kVA, 11/0.433 kV, distribution transformer.

TABLE-IV
ACCEPTABLE SOLUTIONS AS PER 1-STAR RATING

Sr. No	Active part cost (INR)	NLL (watts)	LL (watts)	%Z	Efficiency (Full load,upf)
1	55522.77	197.58	1723.54	4.69	98.115088
2	55204.91	199.81	1719.86	4.68	98.116486
3	62516.18	174.40	1735.97	4.69	98.125443
4	62026.12	175.37	1731.66	4.68	98.128659
5	61620.11	176.65	1727.40	4.67	98.131529
.					
771	72780.00	198.16	1553.81	4.08	98.278198
772	72255.19	199.42	1549.59	4.07	98.281061
773	76088.56	197.06	1555.65	4.13	98.277486
774	75518.90	198.26	1551.24	4.12	98.280581
775	74851.69	199.15	1546.88	4.11	98.283930

Total transformer designs = 4080
Designs rejected due to violation of constraints = 3305
Designs accepted = 775
Design selected from all short listed solutions = 2

TABLE-V
ACCEPTABLE SOLUTIONS AS PER 2-STAR RATING

Sr. No	Active part cost (INR)	NLL (watts)	LL (watts)	%Z	Efficiency (Full load,upf)
1	62877.10	179.25	1698.50	4.57	98.156866
2	62463.29	180.56	1694.30	4.56	98.159651
3	61977.24	181.62	1690.14	4.55	98.162626
4	61576.09	183.02	1686.04	4.53	98.165238
5	61103.57	184.17	1681.98	4.52	98.168041
.		.			
60	61442.29	196.14	1632.65	4.39	98.204050
61	61101.00	197.87	1621.76	4.37	98.212891
62	60720.88	199.66	1617.98	4.36	98.214807
63	70732.41	177.35	1665.24	4.52	98.190754
64	70687.44	177.35	1672.43	4.52	98.183820
.		.			
426	72780.00	198.16	1553.81	4.08	98.278198
427	72255.19	199.42	1549.59	4.07	98.281061
428	76088.56	197.06	1555.65	4.13	98.277486
429	75518.90	198.26	1551.24	4.12	98.280581
430	74851.69	199.15	1546.88	4.11	98.283930

Table-V enlists the cheapest active part cost, design dimensions, technical and performance characteristics of 100 kVA, 11/0.433 kV transformers

TABLE-V
MAIN DESIGN DIMENSIONS AND IMPORTANT TECHNICAL PARAMETERS OF 1-STAR AND 2-STAR RATED TRANSFORMERS

Parameter	1-star rating	2-star rating	Units
Cheapest cost	55204	60720	INR
Flux density	1.48	1.40	Wb/m^2

Axial length of HV coil	424	384	mm
Gross core area	106.682	126.046	cm^2
Distance between adjacent core centres	270	281	mm
Window height	494	454	mm
Core weight	202.817	232.522	kg
Conductor weight	71.261	67.181	kg
Tank length	847	880	mm
Tank breadth	337	348	mm
Tank height	913	893	mm
No load losses	199.81	199.66	watts
Total losses	1919.66	1817.64	watts
Total losses at half load	629.77	604.15	watts
Percentage impedance	4.681	4.363	%
Efficiency (full load,upf)	98.116	98.214	%
No. of elliptical tubes (Each of 590 mm length)	60	56	--------

If the designer wants slight modification in the transformer design dimensions obtained from software, alternative values of permitted no load and load losses should be entered in the software, as long as the constraints mentioned in Table-I are not violated.

VI. CONCLUSION

This paper considers systematic analysis of all design possibilities by rejecting all candidate solutions (designs) which violate the constraints entered by the user. The software then displays all the acceptable solutions and gives the design dimensions and performance parameters of the optimum transformer. The method presented is beneficial for distribution transformer manufacturers, as it results in substantial saving of design man hours

ACKNOWLEDGMENT

The authors are thankful to thank Mr. Vasant C. Vyas (Proprietor, Jyoti Transelect, Co. Bhuj, India) and Mr. P.H. Trivedi (Design Engineer, Jyoti Transelect, Co. Bhuj, India) for their valuable inputs and feedbacks.

REFERENCES

[1] Standard Terminology for Power and Distribution Transformers, IEEE Std. C. 57.12.80-2002
[2] E. I. Amoiralis, M. A. Tsili, A.G. Kladas, "Transformer Design and Optimization: A Literature Survey", *IEEE Transactions on Power Delivery*, vol. 24, no. 4, pp 1999-2024, Oct 2009
[3] S.B. Williams, P.A. Abetti, E.F. Magnesson, "How digital computers aid transformer designer", *Gen Electr Rev* 58: pp 24-25, 1955
[4] S.W. Oldfield IV, "The digital computer applied to the design of large power system", *Proc IEE* Part A 105:pp 112-125, 1958
[5] S.B. Williams, P.A. Abetti, H.J. Mason "Complete design of power transformers with large size digital computer, *AIEEE Trans* Part III 77, pp 1282-1291, 1959
[6] H.H. Wu, R. Adams " Transformer design using time-sharing computer, *IEEE Trans Magn* 6:67, 1970
[7] O.W. Andersen, "Optimized design of electric power equipment", *IEEE Compu Appl Power* V4: pp 11-15, 1991
[8] W.G. Hurley, W.H. Wolfle, J.G. Breslin, "Optimized transformer design: Inclusive of high frequency effects", *IEEE Trans. Power Electron*., vol. 13, no 4, pp 651-659, July 1998
[9] M. Poloujadoff, R.D. Flindlay, "A procedure for illustrating the effect variations of parameters on optimal transformers design", *IEEE Trans. Power Sys*., vol. PWRS-1, no.4, pp 202-205, Nov 1986
[10] Rabih A. Jabr, "Application of Geometric Programming to Transformer Design", *IEEE Transactions on Magnetics*, vol. 41, no. 11, pp 4261-4269, Nov 2005
[11] C. Hernandez, M. Arjona, Shi-Hai Dong, "Object Oriented Knowledge-Based System for Distribution Transformer Design", *IEEE Transactions on Magnetics*, vol. 44, no. 10, pp 2332-2337, Oct 2008
[12] J.C. Olivares, P.S. Georgilakis, R.E. Perez, E.C. Littlewood, "Optimal design of single phase shell type distribution transformers based on multiple design method validated by measurements", Springer Electr. Engg 93: pp 237-246, 2011
[13] E.I. Amoiralis, P.S. Georgilakis, "Mehthodology for Optimum Design of Power Transformer Using Minimum Number of Input Parameters" ICEM 2006, Paper No. 470, pp 1-6
[14] J.C. Olivares, F. de Leon, P.S. Georgilakis, R. Escarela-Perez, "Selection of copper against aluminium windings for distribution transformers" *IET Electr. Power Appl*.,2010, Vol. 4, Iss. 6, pp. 474-485
[15] A. K. Sawhney, *A course in Electrical Machine Design*, 6th ed. Dhanpat Rai Publication & Co, 2006
[16] Indrajit Dasgupta, *Design of Transformers* McGraw Hill Education (India) Private Limited, 2013
[17]http://beeindia/about_bee/documents/gaette_notifications/notifications/SL/ DT/185%28E%29.PDF