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Optimal Design of Transformer using Tournament Selection based Elitist Genetic Algorithms

H. D. Mehta[1,2*] and Rajesh Patel[3]

[1]School of Engineering, R.K. University, Rajkot - 360 020, Gujarat, India; hdm732000@yahoo.com
[2]Electrical Engineering Department, L.D. Engineering College, Ahmedabad - 380 015, Gujarat, India
[3]HJD Institute of Technical Education and Research, Kera, Kachchh - 370 430, Gujarat, India;
r_mpatel77@hotmail.com

Abstract

Transformers are vital components of power systems and its design requires reliable and rigorous solution methods. Optimal design of transformer involves determination of design variables to optimize a particular objective, satisfying a set of constraints. This paper addresses the problem of optimal transformer design of a three phase core type distribution transformer using Elitist Genetic Algorithms. Two MATLAB programs have been developed to accomplish the task. The first program implements unconstrained minimization of the following four objective functions: total active part cost, total losses, percentage impedance and transformer tank volume using GA; while second program considers both GA and conventional method to minimize the active part cost while simultaneously satisfying BEE (Bureau of Energy Efficiency) standards and constraints. After performing exhaustive analysis and comparing the results with those obtained by conventional method it is concluded that the results obtained by Tournament Selection based Elitist Genetic Algorithm is near optimum. A design example on a 100 kVA, three phase core type distribution transformer using GA and conventional method is presented for illustration.

Keywords: Elitism, Genetic Algorithms, Optimal Transformer Design, Tournament Selection

1. Introduction

Transformer design is a complex task which requires the knowledge of magnetic circuits, electromagnetism, electric circuit analysis, loss calculations and heat transfer. There are more than 65 standards, 50 books and 400 published articles in the domain of transformers[1]. The main aim of the design engineer is to optimize a particular objective function depending upon the user requirement. In transformer design optimization studies, much of the effort has been devoted to minimize the transformer manufacturing cost[2–4] or active part cost[5,6]. Transformer design using multiple design method[7] iteratively assigns different values to transformer design variables, so as to generate large number of alternative designs. Finally the design which satisfies all the constraints with the optimum value of objective function is selected; however this technique may fail to find the global optimum[2]. Transformer design optimization using Geometric Programming was employed by Jabr[8] in which GP optimizer was used to design the transformer operating at 100 kHz and at 60 Hz. However as suggested in [9], it has two drawbacks (a) It requires large of number of coefficients in polynomial approximations and (b) Mathematical model is required to be developed for each specific transformer type in advance.

Transformer design consists of highly interrelated and heterogeneous design parameters[10,11]. A design is developed after certain trials and errors and by experienced judgment. Many design aids in the form of charts, curves, empirical constants and formulas have been created by experienced designers to minimize difficult calculations and to develop short cuts based on experience. However, the transformer design procedure basically depends on engineering's judgment[12,13.]

Whatever the chosen design optimization method is, the crux of the problem is to include how much detail in the problem description. Although, the main aim of design optimization is to find the lowest cost, the solution should

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**Author for correspondence*

be such that the actual design can be produced with little additional work. Further, one should also concentrate minimization of total losses, percentage impedance and transformer tank dimensions as they are very critical to overall efficiency, voltage regulation and available space respectively.

The studies carried out in [2–4] and [6–9] deal with optimization of shell type transformer, and very less attention has been devoted to optimal design of core type transformers. Design optimization using GA proposed in [5] does not give any idea regarding type of selection operator or type of crossover mechanism adopted for optimization process.

The main motive behind using GA for transformer design optimization problem is due to the fact that GA's have proved their mettle in solving various optimization problems such as unit commitment[14], reactive power planning studies[15], optimal DG placement in distribution network[16] etc.

This paper proposes GA based design methodology capable of minimizing (I) active part cost (II) total losses (III) percentage impedance and (IV) tank volume, using three different selection operators for core type transformers. A MATLAB program has been developed which allows the user to achieve any one of the objectives mentioned above.

Further, if the designer selects the option of minimizing the active part cost, another alternative is available to the user where a second MATLAB program using constrained GA has been developed which minimizes the active part cost, while simultaneously satisfying the BEE (Bureau of Energy Efficiency) standards and constraints.

The major highlights of this paper are:

- For the first time comparative analysis of various selection operators (i.e Roulette wheel selection, Stochastic remainder roulette wheel selection and Tournament selection) has been presented for transformer design optimization problem
- Elitism operator has been implemented, which ensures that optimal value of an objective function once found in any generation never worsens with successive generations
- Statistical analysis for optimization problem has been carried out and the results obtained are compared with those obtained from MDM method to ascertain the superiority of GA over conventional method for Transformer Design Optimization problem

2. Transformer Design Procedure

This section describes a brief outline of the design methodology of a three phase core type distribution transformer Some of the important assumptions made for the design are mentioned below: Transformer LV and HV coils are wound with aluminum conductors, as aluminum is found to be more economical than copper for transformers having rating of less than 190 kVA[17]. The core material is assumed to be of M4 grade, with a stacking factor of 0.97, and lamination thickness of 0.27 mm. Operating frequency is 50 Hz.

2.1 Calculation of Number of Turns for LV and HV

In a transformer, voltage per turn is calculated using the equation $Et = K\sqrt{S}$, where Et is volt per turn and the value of K is constant given by [18]

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

The number of turns in LV (N_{LV}) and HV (N_{HV}) are then calculated as follows

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

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

2.2 Core Area and Diameter

The gross core area is calculated using the equation

$$Ag = (Et \times 10^2) / (2.22 \times B_{max} \times Kf) \tag{2}$$

The value of Kf is assumed to be 0.97. The transformer diameter assuming 9-stepped core is obtained from [19]

$$d_c = \sqrt{\frac{Ag \times 4}{\pi \times 0.935}} \tag{3}$$

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

2.3 Calculation of Core Weight and Cost

Transformer core weight can be obtained from [19] using the equation

$$Wc = (4 \times Clc + 3 \times Hw) \times Ag \times Kf \times \rho_c \tag{4}$$

The core cost is then obtained by multiplying suitable cost co-efficient with the core weight

2.4 Conductor Weight and Cost

The total conductor weight in a transformer depends upon the mean diameter of LV and HV windings, total number of turns, cross sectional area and the density of winding material. It is given by

$$Wal = 3 \times \rho_{al} \times \pi \times (2 \times MD_{LV} \times N_{LV} \times A_{LV} + MD_{HV} \times N_{HV} \times A_{HV}) \times 10^{-6} \quad (5)$$

Once the winding weight is obtained, its cost can be calculated by multiplying it with suitable cost co-efficient. The factor of '2' appears in equation (5) as two strips of LV are used.

2.5 Load Losses of LV and HV Winding

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

$$LL_{LV} = 3 \times Is^2 \times \pi \times MD_{LV} \times N_{LV} \times \rho_R / A_{LV} \quad (6)$$

$$LL_{HV} = 3 \times Ip^2 \times \pi \times MD_{HV} \times N_{HV} \times \rho_R / A_{HV} \quad (7)$$

The total full load losses W_{fl} is then obtained by

$$W_{fl} = LL_{LV} + LL_{HV} \quad (8)$$

2.6 No Load Loss and No Load Current Calculation

The core loss curve for M4 grade material which gives specific no load loss W_{nlsp} at different values of flux density is converted into fourth order equation using MATLAB polyfit function as demonstrated below

$$W_{nlsp} = 1.5291B_{max}{}^4 - 5.9664B_{max}{}^3 + 8.6933B_{max}{}^2 - 4.9237B_{max} + 1.0388 \quad (9)$$

The total no load loss, is then obtained by

$$W_{nl} = W_{nlsp} \times Wc \quad (10)$$

Similarly, the curve of exciting volt-amperes versus flux density is converted into fourth order equation to obtain exciting volt amperes we

$$We = 8.8542B_{max}{}^4 - 36.3249B_{max}{}^3 + 54.6091B_{max}{}^2 - 34.8050B_{max} + 8.1222 \quad (11)$$

The magnetizing component, core loss component and no load current are then obtained as shown below

$$I\mu = We \times Wc / \left(\sqrt{3} \times V_{LV}\right)$$

$$Iw = Wi / \left(\sqrt{3} \times V_{LV}\right)$$

$$I_0 = (I\mu^2 + Iw^2)^{½}$$

2.7 Percentage Reactance, Resistance and Impedance Calculation

Percentage reactance, resistance and impedance are calculated using the following relations

$$\%X = \frac{7.91 \times f \times Is \times N_{LV}{}^2 \times \pi \times DM \times}{V_{LV} \times AsI \times 106}(a + \frac{R_{BHV} + R_{BLV}}{3}) \quad (12)$$

$$\% R = (LL_{LV} + LL_{HV}) \times 100/S \quad (13)$$

$$\%Z = \sqrt{\%X^2 + \%R^2} \quad (14)$$

2.8 Efficiency and Voltage Regulation

The efficiency η at full load for power factor of cosΦ is given by

$$\eta = (S \times \cos\Phi)/(S \times \cos\Phi + W_{nl} + W_{fl}) \quad (15)$$

The percentage voltage regulation Vr at different values of power factors is given by

$$Vr = \% R \times \cos\varphi + \% X \times \sin\varphi \quad (16)$$

3. Transformer Design Optimization using Conventional Method

This section describes the method for optimal design of a three phase core type distribution transformer using Multiple Design Methodology (MDM). This method is basically a heuristic technique that assigns many alternative values to the design variables so as to generate large number of alternative designs[13]. Finally the design which satisfies all the problem constraints with minimum manufacturing cost of active materials (cost of aluminium and CRGO) is selected.

This method optimizes the design of transformer with the following technical characteristics

- Three-phase oil immersed distribution transformers
- Magnetic circuit of core type transformers
- Rectangular wire consisting of two strips for LV conductors and round cross sectional conductors for HV conductors.

The computer program takes into account many variations in design variables. These variations permit the investigation of a candidate solution. For each one of the candidate solutions, it is checked whether all constraints are satisfied, and if they are satisfied, the cost of active materials is estimated and the solution is considered as acceptable. Finally, among the acceptable solutions, the transformer with the minimum manufacturing cost is selected, which is the optimum transformer. In this design it has been assumed that cost of aluminium is Rs. 177 per kg and the cost of CRGO (M4 grade, 0.27 mm thickness of lamination) is Rs. 210 per kg.

There are four design variables that are taken into account

- Value of constant ‘K’
- Value of maximum flux density ‘Bmax’
- Value of current density in HV winding
- Value of current density in LV winding

Giving different values to ‘K’, ‘Bmax’, ‘Current density in LV and HV’, the total candidate solutions (loops of the computer program) are calculated from the following sequence

Loops = Different values of K*No. of values of Bmax*No. of values of current density

For step size of 0.01, the program takes into account 16 different values of ‘K’, 51 different values of flux density ‘Bmax’ and 5 different values of current density ‘δ’ in LV and HV. Hence, total number of designs that are calculated by the program are 16×51×5×5 = 20400. The flowchart for active part cost minimization is shown in Figure 1, while results for cost minimization obtained from this method are depicted in Table 4.

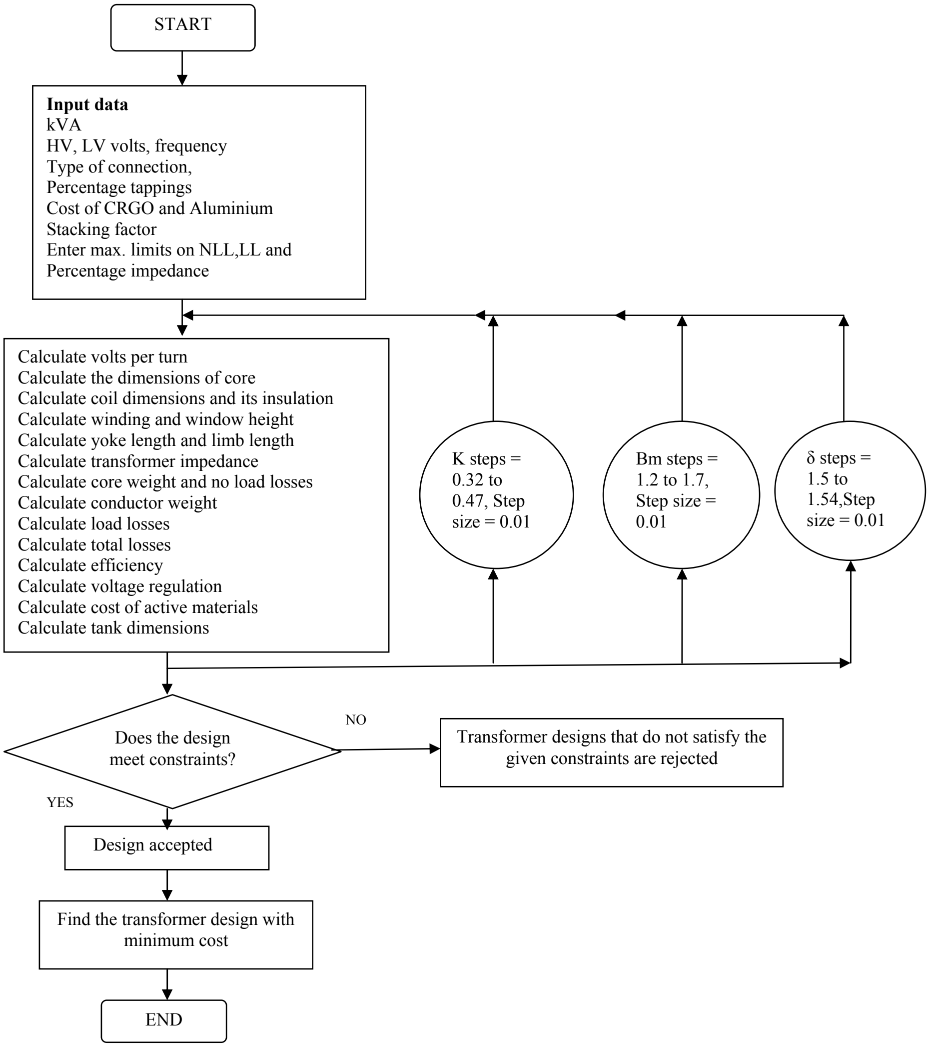

Figure 1. Flowchart for Multiple Design Methodology.

4. Genetic Algorithms

Genetic Algorithms are based on random search method that can be used to optimize complex problems. Some fundamental ideas of genetics are borrowed and used artificially to construct search algorithms that are robust and require minimal problem information. The main advantages of GA are

- GA's do not need a good initial estimation for the sake of problem solution. In other words, if the initial estimates are weak, they can be corrected by an evolutionary process of fitness.
- GA's explore several areas of the search space simultaneously because of its population based approach, which reduces the probability of being trapped in local optimum
- GA's do not require any prior knowledge or properties of the function to be optimized such as convexity, smoothness, modality or existence of derivatives[20]

The following three sub-sections describe basic operators of Genetic Algorithms

4.1 Reproduction

Reproduction is the first operator applied on population. The reproduction operator is also called the selection operator because it selects good strings of the population. The reproduction operator is used to pick above-average strings from the current population and insert their multiple copies in the mating pool based on probabilistic procedure. Performance of three different selection operators for unconstrained optimization have been compared as shown in Table 1 and the best performing selection operator is then utilized for Transformer Design Optimization (TDO) as per BEE standards and constraints. Elitism has been employed in all the three selection operators. A copy of elite individual is not only stored but it also takes part in crossover and mutation. If a better individual is found, it replaces the current elite individual; otherwise the same elite individual is carried over to the next generation.

4.2 Crossover

After reproduction, the crossover operator is implemented. The purpose of crossover is to create new strings by exchanging information among strings of the mating pool. Many crossover operators have been used in the literature of GAs. In most crossover operators, two individual strings (designs) are picked (or selected) at random from the mating pool generated by the reproduction operator and some portions of the strings are exchanged between the strings. A single point crossover preserves the structure of parent strings to the maximum extent in child string. However, the preservation reduces with the increase of cross sites and is minimum in case of uniform crossover[21]. In this paper, crossover is done at four different points along the chromosome length, which combines the advantage of multipoint crossover and at the same time helps in preserving some portion of parent strings.

Table 1. Performance of various selection operators for TDO problem

Sr. No	Selection Operator	Objective Function	Best value	Worst value	Mean	Standard Deviation
1	RWS	Active part cost (INR)	45662	47554	46516	499.82
		Total losses(Watts)	1622.39	1703.94	1657.67	20.50
		Percentage Impedance	3.192	3.330	3.259	0.037
		Tank Volume (cm^3)	228358	244905	231970	3978
2	SRWS	Active part cost (INR)	45545	46841	45977	327.18
		Total losses (Watts)	1616.23	1662.35	1638.26	16.50
		Percentage Impedance	3.191	3.270	3.211	0.027
		Tank Volume (cm^3)	227354	230958	226139	917.45
3	TS	Active part cost (INR)	45165	45207	45174	12.08
		Total losses (Watts)	1612.37	1639.85	1614.34	6.040
		Percentage Impedance	3.176	3.181	3.178	0.002
		Tank Volume (cm^3)	226098	227210	226289	403.96

4.3 Mutation

The mutation operator is applied to the new strings with a specific small mutation probability, p_m. The need for mutation is to maintain diversity in the population. The mutation operator changes the binary digit (allele's value) 1 to 0 and vice versa. In this paper, single point mutation has been used in which a mutation site is selected at random along the string length and the binary digit at that site is then changed from 1 to 0 or 0 to 1 with a probability of p_m.

5. Implementation of GA Technique for Transformer Design

This section describes the methods for optimal design of 100 kVA, 11/0.433 kV, distribution transformer using Genetic Algorithms. The main advantage of GA is that different objective functions can be optimized with little modification in the program. Two MATLAB programs have been developed to avoid complexity and to maintain clarity.

Method-I

The first MATLAB program implements unconstrained GA technique to minimize any one of the four objectives namely (1) Active part cost (2) Total losses (3) Percentage impedance (4) Transformer tank volume. The user can select any one of the above mentioned objective as per requirement.

Method-II

The second MATLAB program considers the constraints pertaining to IS 2026 and IS 1180 (part 1) and implements constrained GA technique to minimize active part cost of a transformer. This transformer design satisfies 1-star and 2-star rating of distribution transformer as per BEE (Bureau of Energy Efficiency) standards and specifications[22].

The design inputs for design of 100 kVA, 11/0.433 kV, Dyn-11 distribution transformer are shown in Table 2. The control parameters for GA are: Population size = 40, Max. Generations = 100, Crossover probability = 0.8, Mutation probability = 0.02, No. of dimensions = 4, Chromosome length = 80, Elite count = 1. It should be noted that input parameters mentioned in Table-1 are used as inputs to minimize active part cost as per BEE standards and constraints. For unconstrained transformer design optimization, no limits are imposed on total losses, no-load losses, and percentage impedance.

After trial and error, it was found that population size of 40 and a number of 100 generations, with crossover probability of 0.8 and mutation probability of 0.02 provide good results for TDO.

Table 2. Input parameters for 1-star and 2-star rated transformers

Sr.No	Parameter	1-star	2-star	Units
1	Rated power	100	100	kVA
2	Max. Total Losses permitted	2020	1910	W
3	Max. Losses permitted at half load	700	610	W
4	Max. NLL permitted	220	200	W
5	Percentage impedance permitted	4.7	4.7	%
6	Rated low voltage	433	433	V
7	Rated high voltage	11000	11000	V
8	Temperature rise	50	50	^{0}C

6. Results and Discussion

This section has been divided into two parts. The first part demonstrates the results for minimizing different objective functions using unconstrained GA optimization technique. The choice is left to the user to decide any one objective as per requirement. The second part minimizes the active part cost, subject to constraints specified in [22] for 1-star and 2-star rated transformers. Although [22] does specify general guidelines about the limiting values of total losses at full load and half load for different star rating of transformers, information regarding bifurcation of no-load and load losses is not available. Therefore, their limiting values mentioned in Table 2 are selected as per customer's requirement.

6.1 Minimization of Various Objectives using Unconstrained Genetic Algorithms

Table 1 shows the performance of various selection operators for unconstrained TDO problem. By trial and error, it was found that 20 trial runs were sufficient for assessing the performance analysis of selection operators. As evident from Table 1, Tournament Selection is the most reliable selection operator in terms of best value, mean and standard deviation. Figure 2 to Figure 5 indicates the optimum value of each objective function, obtained in each generation using TS operator. Presence of elitism ensures that the optimum value of objective function, once obtained in particular generation is not lost in successive generations.

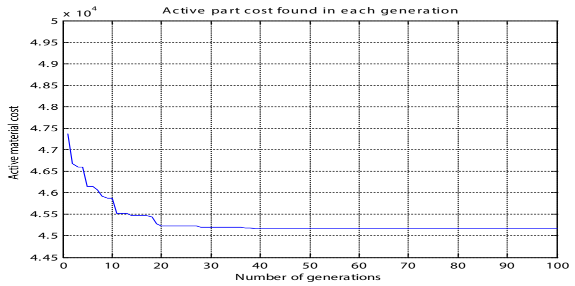

Figure 2. Variation of Active Part Cost (INR) with generations using TS operator.

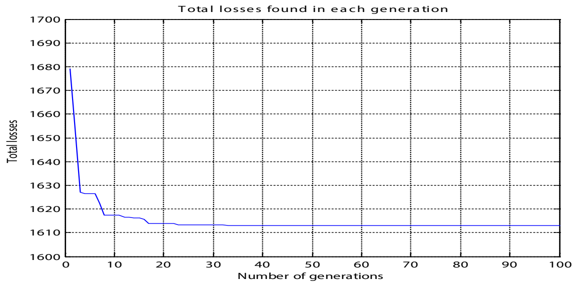

Figure 3. Variation of Total losses (watts) with generations using TS operator.

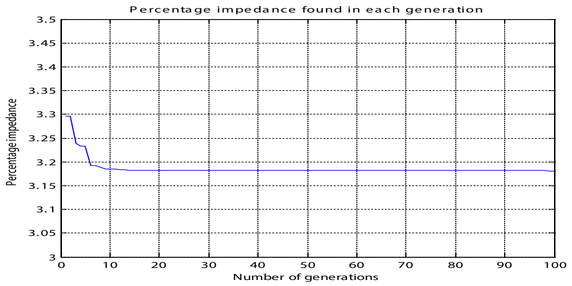

Figure 4. Variation of Percentage Impedance with generations using TS operator.

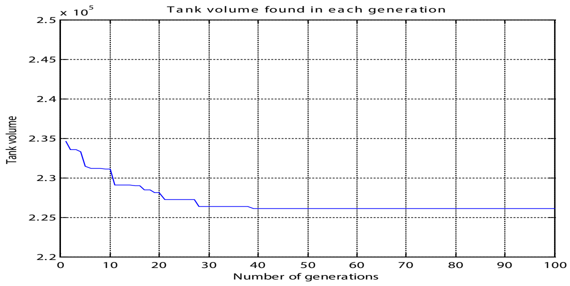

Figure 5. Variation of Tank Volume (cm^3) with generations using TS operator.

6.2 Active Part Cost Minimization using MDM and Constrained Genetic Algorithms

Since cost minimization is the prime requirement in any optimization process, this section deals with minimization of active part cost of a transformer, while simultaneously satisfying BEE standards and constraints for 1-star and 2-star rated transformers. Table 2 demonstrates the inputs to the program while Table 4 exemplifies important design dimensions and performance parameters of 100 kVA, 11/0.433 kV Dyn-11 transformer obtained by MDM and TS based GA method. The value of penalty factors must be chosen judiciously and it requires extensive experimentation[21]. A very high value of penalty factor quickly helps in steering GA towards convergence, however sometimes it may converge to a local optimum because of high selection pressure. On the contrary, a low value of penalty factor helps more effectively in exploring the search space; however it may sometimes lead to infeasible solution because of low selection pressure[21].

In this paper, initially all penalty factors are set to zero. If an infeasible solution is generated, penalty is imposed as shown in Table 3. After performing number of trials, the value of penalty factors tuned for different objective functions are depicted in Table 3. From Table 4 it is evident that GA is able to obtain solution which is 2.71% and 1.34% cheaper for 1-star and 2-star rated transformers respectively as compared to Multiple Design Methodology.

Table 3. Penalty factors and objective function for constrained TDO

Sr. No	Penalty factor	1-star rated transformer	2-star rated transformer
1	P_NLL (for W_{nl} > NLL_max)	1000*(W_{nl} - NLL_max)	1000*(W_{nl} - NLL_max)
2	P_TLL (for W_{tl} > TLL_max)	100*(W_{tl} – TLL_max)	100*(W_{tl} – TLL_max)
3	P_HLL(for W_{thl} > HLL_max)	100*(W_{thl} – HLL_max)	1000*(W_{thl} – HLL_max)
4	P_IM (for %Z > PIM_max)	40000*(%Z – PIM_max)	25000*(%Z – PIM_max)
Objective function F(x) = Total Active Part Cost + P_NLL + P_TLL + P_HLL + P_IM			

Table 4. Main design dimensions and important technical parameters of 1-star and 2-star rated transformers by MDM and TS

Parameter	Design of 1-star rated transformer by MDM	Design of 1-star rated transformer by TS	Design of 2-star rated transformer by MDM	Design of 2-star rated transformer by TS	Units
Active part cost	50051	48693	57921	57144	INR
No load losses	219.22	219.86	196.83	199.93	W
Load losses	1795.85	1799.12	1651.04	1639.97	W
Total losses	2015.07	2018.98	1847.87	1839.90	W
Total half load losses	668.18	669.64	609.59	609.92	W
Volt per turn	3.400	3.268	3.600	3.649	------
HV turns	3419	3511	3188	3142	------
LV turns	74	76	69	68	------
Gross core area	100.56	95.41	116.90	117.20	cm^2
Core limb centre	259	255	276	276	mm
Total yoke length	1036	1020	1104	1104	mm
Total limb length	1470	1518	1410	1374	mm
Core weight	187.01	179.69	218.09	215.51	kg
Conductor weight	60.89	61.90	68.48	67.15	kg
Percentage impedance	4.344	4.367	4.437	4.436	%
Tank length	81.4	80.2	86.5	86.5	cm
Tank breadth	32.6	32.2	34.3	34.3	cm
Tank height	90.2	91.3	90.0	88.8	cm
Tank volume	239358	235776	267025	263465	cm^3
Efficiency (full load, upf)	98.02	98.02	98.18	98.19	%

7. Conclusion

In this paper, design optimization of transformer using Genetic Algorithms and conventional method has been demonstrated. Although, no constraints were imposed in first method (i.e. minimization of cost, total losses, percentage impedance and tank dimensions), the program can be modified to accommodate any constraints, desired by the user. The proposed method is very effective as GA's are more likely find the global optimum because of their population based approach. A saving of 2.71% and 1.34% obtained by TS based GA method as compared to conventional method may not sound great, but considering the fact that the numbers of distribution transformers in any region far exceed the number of power transformers in the same region, the cost benefits obtained from GA based transformer design can be appreciated. Small transformer manufacturing companies and even inexperienced engineers can successfully use this software.

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9. References

1. Amoiralis EI, Tsili MA, Kladas AG. Transformer design and optimization: A Literature Survey. IEEE Transactions on Power Delivery. 2009; 24(4):1999–24.
2. Georgilakis PS, Olivares JC, Esparza-Gonzalez MS. An Evolutionary computation solution to transformer design optimization problem. 7th International Conference on Electrical and Electronics Engineering Research; Aguascalientes, Mexico. 2010. p. 226–31.
3. Amoiralis EI, Georgilakis PS, Tsili MA, Kladas AG. Global transformer optimization method using evolutionary design and numerical field computation. IEEE Transactions on Magnetics. 2009; 45(3):1720–3.
4. Georgilakis PS, Tsili MA, Souflaris AT. A heuristic solution to transformer manufacturing cost optimization problem. Journals of Materials Processing Technology. 2007; 81(1-3):260–6.
5. Khatri A, Malik H, Rahi OP. Optimal Design of Power Transformer using Genetic Algorithm. Proceedings of International Conference on Communication Systems and Network Technologies; 2012. p. 830–3.
6. Amoiralis EI, Tsili MA, Georgilakis PS, Kladas AG. A parallel mixed integer programming-finite element technique for global design optimization of power transformer. IEEE transactions on Magnetics. 2008; 44(6):1022–5.
7. Olivares JC, Georgilakis PS, Escarela-Perez R, Campero-Littlewood E. Optimal design of single-phase shell type distribution transformers based on a multiple design method validated by measurements. Electr Engg. 2011; 93:237–46.
8. Jabr RA. Application of Geometric Programming to Transformer Design. IEEE Transactions on Magnetics. 2005; 41(11):4261–9.
9. Georgilakis PS. Recursive genetic algorithm-finite element method technique for the solution of transformer cost minimization problem. IET Electr Power Appl. 2009; 3(6):514–9.
10. Grady WM, Chan R, Sarnotyj MJ, Ferraro RJ, Bierschenk JL. A PC-based computer program for teaching the design and analysis of dry type transformers. IEEE Transactions on Power Systems. 1992; 7(2):709–17.
11. Geromel LH, Souza CR. The application of intelligent systems in power transformer design. Proceedings of

IEEE Canadian Conference Electrical and Computer Engineering; Winnipeg, Canada. 2002. p. 285–90.

12. Heathcote MJ. The J & P Transformer Book. 12th ed. London, U.K: Newness; 1998.
13. Georgilakis PS. Spotlight on Modern Transformer Design. London, U.K: Springer; 2009.
14. Rouhi F, Effetnejad R. Unit Commitment in Power System by Combination of Dynamic Programming (DP), Genetic Algorithm (GA) and Particle Swarm Optimization (PSO). Indian Journal of Science and Technology. 2015; 8(2):134–41.
15. Ambika R, Rajeshwari R, Nivedita A. Comparative Analysis of Nature Inspired Algorithms Applied to Reactive Power Planning Studies. Indian Journal of Science and Technology. 2015; 8(5):445–53.
16. Ali A, Mohsen D, Majid D. Optimal placement and estimation of DG capacity in distribution networks using genetic algorithm based method. Indian Journal of Science and Technology. 2012; 5(3):2281–6.
17. Olivares JC, de Leon F, Georgilakis PS, Escarela-Perez R. Selection of copper against aluminium windings for distribution transformers. IET Electr Power Appl. 2010; 4(6):74–85.
18. Sawhney AK. A course in Electrical Machine Design. 6th ed. Dhanpat Rai Publication & Co; 2006.
19. Dasgupta I. Design of Transformers. McGraw Hill Education (India) Private Limited; 2013.
20. Padhy NP. Artificial Intelligence and Intelligent Systems. Oxford University Press; 2005.
21. Deb K. Multiobjective Optimization using Evolutionary Algorithms. John Wiley & Sons; 2001.
22. Notification of the Gazette of India. Part II, Sec 3 (ii), S.O. Published. 12/1/2009; 185(E):44–9.

Appendix

List of symbols

Et	Volt per turn
S	Rating of transformer (kVA)
f	Frequency (Hz)
AT	Ampere turns
V_{LV}	Rating of LV winding (Volts)
V_{HV}	Rating of HV winding (Volts)
N_{LV}	Number of turns in LV winding
N_{HV}	Number of turns in HV winding
Ag	Gross core area (cm^2)
B_{max}	Maximum flux density in core (Wb/m^2)
Kf	Stacking factor
d_c	Core diameter (cm)
Wc	Core weight (kg)
Clc	Core limb centre (cm)
Hw	Window height (cm)
ρ_c	Density of core material (gm/cm^3)
Wal	Weight of aluminium (kg)
ρ_{al}	Density of aluminium (gm/cm^3)
MD_{LV}	Mean diameter of LV winding (mm)
MD_{HV}	Mean diameter of HV winding (mm)
A_{LV}	Cross sectional area of LV winding (mm^2)
A_{HV}	Cross sectional area of HV winding (mm^2)
LL_{LV}	Load losses in LV winding (watts)
LL_{HV}	Load losses in HV winding (watts)
Is	Rated current of LV winding (Amp)
Ip	Rated current of HV winding (Amp)
ρ_R	Resistivity of aluminium (ohm-cm)

W_{fl}	Total losses in LV and HV winding (watts)
W_{nlsp}	Specific no-load losses (watts/kg)
W_{nl}	No load losses (watts)
W_{tl}	Total losses (watts)
W_{thl}	Total losses at half load (watts)
We	Exciting volt-amperes (VA/kg)
Iμ	Magnetizing component of current (Amp)
Iw	Core loss component of current (Amp)
Dm	Mean diameter of LV and HV coil (mm)
R_{BHV}	Radial build of HV winding (mm)
RBLV	Radial build of LV winding (mm)
Asl	Axial stack of LV and HV winding (mm)
a	Gap between LV and HV winding (mm)
% X	Percentage reactance
% R	Percentage resistance
% Z	Percentage impedance
η	Efficiency
RWS	Roulette Wheel Selection
SRWS	Stochastic Remainder Roulette Wheel Selection
TS	Tournament Selection
NLL_max	Maximum permitted no-load losses (watts)
TLL_max	Maximum permitted total losses at full load (watts)
HLL_max	Maximum losses per permitted at half load (watts)
PIM_max	Maximum allowed percentage impedance
MDM	Multiple Design Methodology