GENETIC ALGORITHM FOR DESIGN OPTIMIZATION OF A FURNACE TRANSFORMER

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Abstract--This paper presents design optimization of a class of special purpose transformers used in direct-arc melting furnace, adopting Genetic Algorithm (GA). The operation and performance characteristics of a medium size 150 tons per hour furnace transformer are considered for realizing the mathematical model for design. All the optimal solutions involve determining the design parameters satisfying performance constraints for minimum active material cost or weight or volume or a multi-objective combining the three objectives. The results of a 3-phase, core type 64.5 MVA, 33kV / 384 – 712 volts, star-delta connected furnace transformer show the potential for implementation of GA as an efficient search technique for design optimization of transformers.

Key Words: Furnace Transformers; Genetic Algorithm; Optimal Design; Multi-objective Optimization.

1. Introduction

In a direct-arc furnace, heat is generated by a powerful electric arc struck between carbon or graphite electrodes and the metal charge. In addition to the normal constructional methods, a transformer for an arc furnace must be designed to supply a very large current by its secondary winding at a very low voltage dictated by the arc resistance. The arc voltage must be large enough to supply the desired power and permit operation at higher than normal current with maximum voltage [1,2]. Regulation of a furnace voltage over a wide range is usually achieved by tap settings normally extend from maximum secondary voltage down to 50-25 percent. Arc power, secondary circuit impedance and arc resistance are important factors for the development of the rating of a furnace transformer. The secondary circuit consists of secondary bus, flexible cables, copper bus tubes and the electrodes. For a specified effective arc voltage and arc current, a wide range of circuit impedances can be applied that result in the same average arc resistance [3]. The optimal design procedure of a transformer employed for furnace loads does not figure in the published literature. Classical optimization technique such as the sequential unconstrained minimization technique by Powell [4] together with Zangwill's exterior penalty function method [5] has been applied for conventional and special purpose transformers [6]. Arc furnace transformer constructional aspects, electrical characteristics and various types of connections are discussed in [7 – 11]. Evolutionary programming by GA based design schemes for power transformers has been shown to be effective to find solutions close to global optimum [12]. In this paper, the optimum design of a furnace transformer is to obtain a design for minimum active material cost or weight or volume or a multi-objective function involving the three by GA.

2. Configuration and Rating of Transformer

A 3-phase star-delta connected, core-type transformer is considered to supply a 22 feet shell diameter, 150 tons per hour direct-arc melting furnace. A single line connection diagram of the power system, transformer and arc furnace is illustrated in Fig. 1.

A typical average arc resistance curve when a transformer operating on highest voltage tap is shown in Fig. 2 [3].

The rating of a transformer [3] is derived from Figs. 1 and 2 as follows:

For a secondary circuit current, I_c	= 60 kA, assume
(i) Average arc resistance/phase, R_A	= 4.8 milliohms and
(ii) Secondary circuit impedance/phase, Z_s	= 0.5 + j 2.7 milliohms
Total circuit impedance/phase, Z_c	= 5.3 + j 2.7 milliohms
Secondary circuit voltage, V_c	$= \sqrt{3}\, I_c\, Z_c$
	= 620 V
Transformer kVA rating	$= \sqrt{3}\, V_c\, I_c$
	= 64500 kVA

A primary high voltage of 33 kV is assumed and a total number of nine tap settings with a variation of ±30 % on hv winding develop a secondary voltage range of 384 V to 712 V. The highest tap feeds the stipulated power to the furnace and at lowest tap, a stable arc is maintained for holding the melt. Forced oil cooling is considered and the configuration of the transformer under discussion is in line with similar furnace transformers [7 – 11] used in medium size furnaces.

4. Optimization Procedure with GA

GA operates on a population of points in the search space and offers a convenient way of handling constraints and single or multi objective functions. In GA approach, each design variable is represented as a binary string (chromosome) of fixed length and the search operations are typically selection, crossover, and mutation. An index of merit is assigned to each chromosome and is evaluated by using a fitness function.

A new generation is selected having largest probability of the fittest individual. A next generation is developed from pairs of chromosomes as parents with reproduction operators, mutation and crossover. GA provides solutions by generating a set of chromosomes referred to as a generation. If the search has to continue, the GA creates a new generation from the old one until a decision is made on the convergence.
A number of evolutions of the objective function is necessary to arrive at a final optimal solution.

In binary tournament selection two individuals are selected at random from the population, and the better one is duplicated in the next generation. This process is repeated until the individuals reach a specified population size. A crossover operator exchanges information contained in two parent individuals to produce two offspring and then replace the parents. The number of times the crossover operator is applied to the population is determined by the probability of crossover and the population size. The mutation operator randomly selects an individual from the population and then chooses two elements in this individual to exchange positions [13].
In this paper design variables and constraints are selected as in Table 1, considering the effect on core dimensions, losses, short-circuit reactance, weight, volume and finally on the cost of the transformer.

A mathematical model in terms of design variables for objective and constraint functions is developed for the specification in Table 2.

4. Objective functions

The goal of optimization is to obtain minimum cost or minimum weight or minimum volume or a combined multi-objective function of a specified furnace transformer.

Cost function consists of active material cost of stampings, windings and capitalized cost of losses [6].

$$F_c(X) = c_i G_i + c_c G_c + c_1 P_c + c_2 P_i \tag{1}$$

where c_i , c_c = cost of iron, cost of copper Rs./kg

c_1 , c_2 = loss capitalization factors, Rs./kg

G_i , G_c = weight of iron, weight of copper, kg

Similarly the volume and weight functions are defined as

$$F_w(X) = G_i + G_c \tag{2}$$

$$F_v(X) = V_i + V_c \tag{3}$$

where V_i , V_c = volume of iron, volume of copper, m^3

5. Design Analysis

A main program together with function programs for the design of windings, calculation of losses, temperature rise, mechanical forces in windings, and the GA optimization routine is developed in C++. For a three-legged core type construction, a high voltage continuous disc winding near the core and a low voltage helical winding for large secondary circuit current is suitable. The low voltage winding consists of a number of multi-strand conductor coils connected in parallel and arranged one above the other. Transformer losses consists of no-load or core loss and load losses. Load losses consist of I^2R loss, eddy current loss and stray loss.

5.1. Core loss

Assuming a sixth degree polynomial for B-H curve, the core losses are computed from (4)

Core loss,

$$P_i = FF(B_c)\,G_l + 1.075\,FF(B_y)\,G_y \tag{4}$$

where

B_c, B_y = Flux density in the core and yoke, Tesla

G_l , G_y = Weight of the limbs and yoke, kg

$FF()$ = Polynomial to represent core loss in watts/kg,

5.2. Eddy current loss

As the eddy current losses are proportional to the square of the frequency, to the fourth power of the dimension of that side of the conductor perpendicular to the direction of flux and to the square of the number of conductors in the same direction [14], the hv and lv conductor eddy current losses are computed from (5)

$$P_e = k_1\, b^4\, n_R^{\,2}\, f^2\, a^2\, n_A^{\,2}\, (3\,I^2\, R)/x_4 \tag{5}$$

a, b = Dimensions of strap conductor, mm

n_A , n_R = Number of axial and radial straps

f = Frequency, Hz

x_4 = Height of the windings, m

I = Current per phase, A

R = Resistance per phase, Ohms

k_1 = Constant

5.3. Stray losses

Stray losses in the core, clamps, tank and other parts increase the oil and windings temperature rise and are computed [14] from (6)

$$P_s = \frac{k_2 X_{sc}^{\ 2} x_1^{\ 2} A_i^{\ 2} x_4^{\ 3} f}{M_t [x_4 + 2(K_z - 0.5 D_{12})]^2} \tag{6}$$

X_{sc} = % Short-circuit reactance

x_1 = Flux density in the core, T

A_i = Net core cross section, m^2

M_t = Perimeter of the tank, m

K_z = Distance between the limb centers, m

D_{12} = Mean diameter between the windings, m

k_2 = Constant

6. Non-linear optimization Problem

The constrained optimum design problem of a furnace transformer is formulated as follows (7).

Find $X = (x_1, x_2 .... x_n)$, design variables

Minimizing $F(X)$

s.t. $g_j(X)\{\leq=\}0, \ j = 1,2,....m$ (7)

where $F(X)$, the nonlinear objective function

$g_j(X)$, the nonlinear constraint functions

As GA is basically a Sequential Unconstrained Minimization Technique (SUMT), the constraints on design problem can be disposed of by Zangwill's exterior penalty function method [5].

Accordingly an augmented objective function, $F_a(X,r_k)$ with a penalty parameter, r_k is formulated as in (8).

$$F_a(X, r_k) = F(X) + r_k \sum_{j=1}^{m} \left[g_j(X)\right]^q, \quad r_k \geq 0 \tag{8}$$

where $g_j(X)$ is defined as $\max\left[g_j(X,0)\right]$

and $\quad q = 2, 3, ...$

The augmented objective function for cost, weight, volume or a combined multi-objective function is formulated from (1), (2), (3), and (8).

7. Results and Observations

GA optimization program, together with the design analysis program is applied to the specified 64.5 MVA furnace transformer design. Optimal design parameters and performance data minimizing the cost or weight or volume or the combined multi-objective function are derived for a set of GA parameters and a penalty factor. After checking with several runs of optimization program for different combination of parameters, the following GA parameters and penalty factor of Table 3 are finally adopted for obtaining optimal designs.

In order to study the results of optimal solutions, the number of generations in GA has been changed. Figs. 3 to 5 shows the corresponding graphs for each minimized objective function for a variation in number of generations, satisfying the constraints. It is observed from the graphs that the single objective functions converged to a minimum value for a penalty factor of 5 and number of generations above 400, together with the specified values of other GA parameters.

With the same GA parameters and a penalty factor of 10, 2 and 0.01 respectively for cost, weight and volume functions, the number of generations is changed and minimum objective functions are obtained as shown in Table 4. As observed from Table 4, the optimal solutions are not affected with an increase in penalty factors. The study is further carried out to derive optimal solutions of multi-objective function, combining the three single augmented objective functions with proper weighting and penalty factors. It is observed that while minimizing the multi-objective function satisfying the constraints, the cost function is very close to the minimum cost that is derived in minimizing the single objective cost function. Tables 5 and 6 show a comparison of design variables, constraints and minimum cost for both cases.

The weight and volume functions derived while minimizing the multi-objective function have deviated more from those obtained in minimization of single objective functions as in Table 7, for an increase in number of generations.

For a set of GA parameters and a penalty factor, optimal design variables, objective function and the constraints of the specified 64.5 MVA furnace transformer are presented in Tables 5 and 6. The transformer design and performance data for minimum cost at optimal solution of Table 5 is presented in Table 8.

8. Conclusions

This paper presents a GA-based optimization technique for design of furnace power transformer. A non-linear mathematical model with a single or multi-objective function together with important constraints is developed. The design analysis and optimization program determines the optimal design data of a medium size furnace transformer. An example of the design of a 64.5 MVA furnace transformer is presented. All the optimization results are satisfactory and show that GA based approach for the complete design of furnace power transformer of any specification is adoptable.

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10. References

[1] J.A. Ciotti, C.G. Robinson, 400 Ton Arc Furnace, Journal of Metals, AIME (1973) 17.

[2] C.R. Hatch, Arc Furnace Transformers – Modern Design Developments, Electrical Review, 166 (1960) 52-56.

[3] E.J. Borrebach, Maximum Power Operation of Arc Furnaces, Iron and Steel Engineer, (1969) 74-83

[4] M.J.D. Powell, An Efficient Method for Finding the Minimum of a Function of Several Variables Without Calculating Derivatives, Computer Journal, 7 (1964) 155-162.

[5] W.I. Zangwill, Nonlinear Programming Via Penalty Functions, Management Science, 13 (1967) 344-358.

[6] K.S. Rama Rao, Optimal Design of Electromagnetic Devices, Ph. D. Thesis, IIT Kanpur, (1978).

[7] Transformers with Off-Load Tap Changing for Direct Arc Melting Furnaces, AEI Publication, 1563-1, GEC Ltd., UK

[8] Transformers with On-Load Tap Changing for Direct Arc Melting Furnaces, AEI Publication, 1563-1a, GEC Ltd., UK.

[9] P. Bonis, F. Coppadora, Transformers for Arc Furnace, Brown Boveri Review, 60

(1973) 456-457.

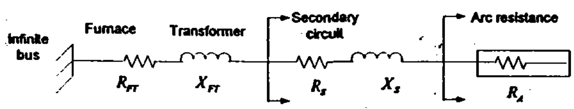
[10] B. Grundmark, Large Furnace Transformers, ASEA Journal, 6 (1972) 151-156.

[11] W.H. Gorga, Design Considerations for the Installation of Modern High Power Electric Arc Furnaces, Iron and Steel Engineer, 49 (1972) 35-41

[12] Li Hui, Han Li, He Bei, Yang Shunchang, Application Research Based on Improved Genetic Algorithm for Optimum Design of Power Transformers, ICEMS 2001, Proc. of V International Conf.,1 (2001) 242-245.

[13] D. Dumitrescu, B. Lazzerini, L.C. Jain, A. Dumitrescu, Evolutionary Computation, CRC Press LLC, Florida, 2000.

[14] S.B.Vasutinsky, Principles, Operation and Design of Power Transformers, P.S.G. College of Technology, India, 1962.



R_{FT} Resistance of furnace transformer
R_S Resistance of secondary circuit
X_{FT} Reactance of furnace transformer
X_S Reactance of secondary circuit
R_A Arc resistance

Fig. 1 Furnace Transformer Power System

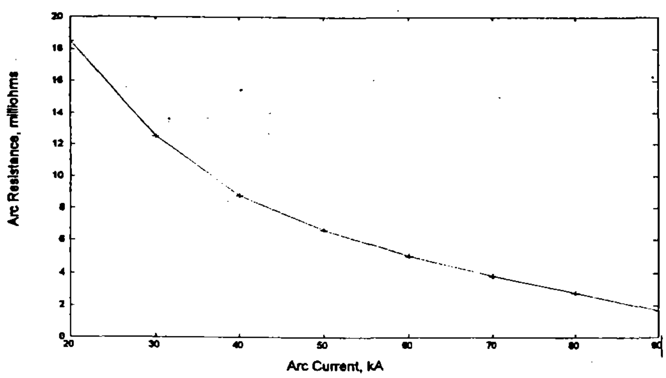


Fig. 2. Arc resistance for highest tap

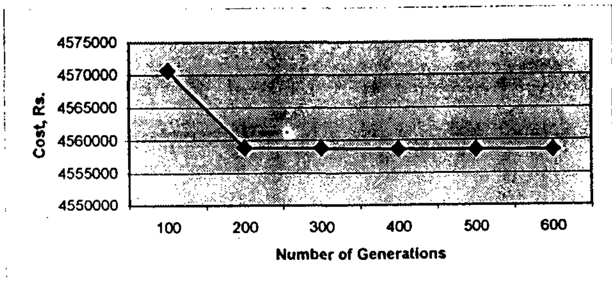


Fig. 3 Cost Function

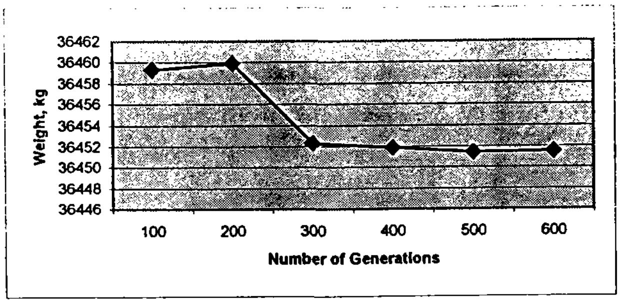


Fig.4 Weight Function

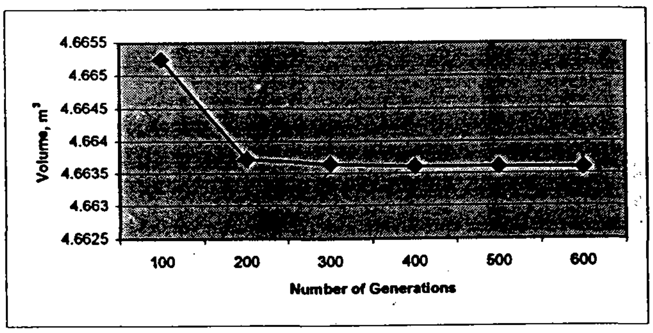


Fig.5 Volume Function

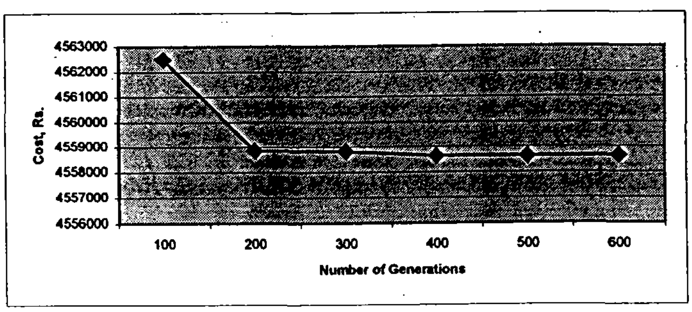


Fig. 6 Cost Function in Multi-objective Function

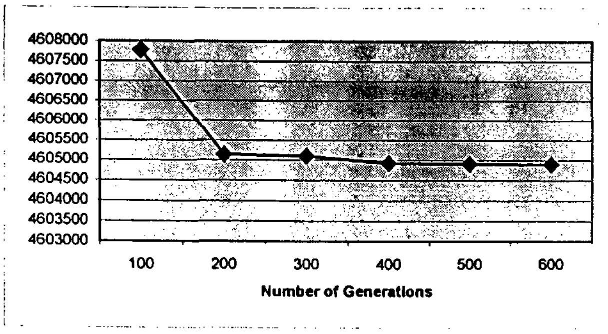


Fig. 7 Combined Objective Function

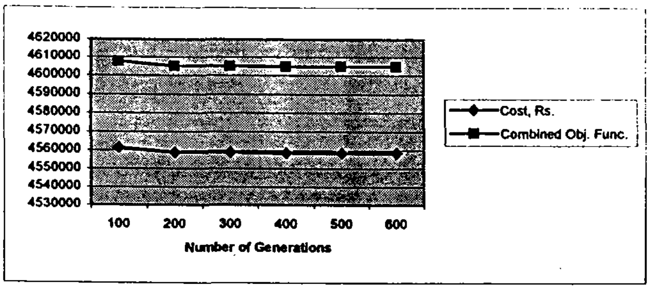


Fig. 8 Cost and Combined Objective Functions

Table 1 Design variables and constraints

Specified design variables	Constraints
x_1 Flux Density in the Core, T	Temperature rise of windings above ambient, °C
x_2 Current density in hv winding, A/mm^2	Temperature rise of oil above ambient, °C
x_3 Current density in lv winding, A/mm^2	% Short circuit reactance
x_4 Height of the windings, m	% No-load current
x_5 Voltage per turn, V	% Efficiency
x_6 Distance between core centers, m	Clearance between different phase windings, m

Table 2 Specification of Furnace Transformer

3-phase core type 64.5 MVA, 33 kV / 384 – 712 V, star- delta connected furnace transformer with forced oil cooling.

Table 3 GA Parameters and penalty factor

Number of generations	= 100
Population size	= 50
Probability of mutation	= 0.044
Probability of cross-over	= 0.866
Penalty factor for constraints	= 5
Exponent q of constraint function	= 2

Table 4 Optimal values for different penalty factors

Generations	100	200	300	400	500	600
Cost, Rs.	4559346	4559135	4558815	4558573	4558557	4558404
Weight, kg	36463.91	36454.18	36452.78	36452.35	36452.31	36451.98
Volume, m^3	4.664399	4.663839	4.663791	4.663628	4.663631	4.663599

Table 5 Design Variables at minimum cost

S.No.	Variable	Single objective	Multi-objective
1.	x_1,Tesla	1.68	1.67999
2.	x_2, A/mm^2	3.63188	3.64005
3.	x_3, A/mm^2	2.50003	2.50055
4.	x_4, m	3.13618	3.13679
5.	x_5, volts	111.113	111.111
6.	x_6, m	1.19999	1.2

Table 6 Constraints and Minimum Cost

S.No.	Constraint	Single objective	Multi-objective
1.	Temperature rise of windings above ambient, °C	57.6317	57.8738
2.	Temperature rise of oil above ambient, °C	48.4405	49.3349
3.	% Short circuit reactance	8.98729	8.97334
4.	% No-load current	1.28311	2.28299
5.	% Efficiency	99.296	99.4407
6.	Clearance between different phase windings, m	0.07088	0.063061
Obj-Fun - Cost, Rs.		4558547	4558644

Table 7 Optimal Values with Multi-objective Function

Generations	100	200	300	400	500	600
Cost, Rs	4561484	4558872	4558824	4558649	4558650	4558644
Weight, kg	46141.8	46200.44	46158.21	46200.43	46195.74	46201.46
Volume, m^3	5.954209	5.961071	5.956321	5.961051	5.960462	5.961177
Multi-Obj. Func.	4607780	4605146	4605105	4604924	4604904	4604900

Table 8 Optimal Design Data

<u>HV Continuous Disc Winding</u>	
Turns per phase	198
Coils	60
Width, mm	22.9537
Area of c.s. of conductor, mm^2	37.5
Conductor dimensions, mm	11.6 x 3.28
<u>LV Helical Winding</u>	
Turns per phase	4
Coils	10
Parallel conductors	4
Width, mm	20.982
Area of c.s. of conductor, mm^2	346.3626
Conductor dimensions, mm	80.55 x 4.3
<u>Other Data</u>	
Core circle diameter, m	0.6999
Width of core, m	3.0298
Length of core, m	3.356
Dimensions of tank, m	1.682 x 4.082 x 5.027
Weight of copper, kg	7875.656
Weight of iron, kg	38322.12
Volume of copper, m^3	0.9193
Volume of iron, m^3	3.7422
Secondary Voltages	384, 407, 435, 464, 501, 540, 586, 646, 712