Design Optimization of a Single-phase small transformer using Genetic Algorithm

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Abstract— Application of appropriate optimization technique for a particular optimization problem in order to find minimum cost is the real challenge towards whole research community. Every day new algorithm develops and implemented in different optimization problems with some restrictions. Engineering design problems involves nonlinear functions and it is optimized under certain constraints. In few cases conventional optimization process is not capable enough to give optimal solution because there is a chance to trap into local minima. Comparatively the stochastic optimization methods are established as an effective tool because they give better flexibility in their performance either alone or in a mixed form. So new algorithm is getting more priority day by day and standing as a major field for research due to increased flexibility and accuracy. The present work deals with the optimal design to find the parameters for minimal cost of materials of 5kVA, 230:115-volt, single phase transformer using Genetic Algorithm (GA). The objective is to find optimized design parameters for low-cost single-phase transformer by applying a suitable optimization scheme and finally results is compared with method of exhaustive search and particle swarm optimization to show GA gives much more acceptable and improved solution. The total cost of copper and iron has been taken as the objective function.

Keywords— Optimal design, Genetic algorithm, Exhaustive Search, Particle Swarm Optimization

NOMENCLATURE

$V_1, V_2 S$	Primary/ Secondary voltage, kVA rating
K	Emf constant
I_1, I_2	Current in primary and secondary respectively
B_m, δ	Flux density in Tesla and Current density in Ampere/mm^2
K_s, K_w	Stacking and space factor of window respectively
H_w, W_w, R_w	Window height, window width in meter, ratio of height and width
E_t, T_1, T_2	Volt per turn; primary and secondary number of turns.
a_1, a_2	Primary and secondary cross sections in mm^2 respectively.
CI, CC, CM	Cost of iron, cost of copper, total cost in Rs

I. Introduction

It is the set of systematic process for obtaining the best result under certain circumstances. In some of the design problems, engineers has to take certain decision either minimize or maximize the few industrial issues. The objective function of the optimization problem begins with selection of design variables, which varies during the process [1]. A problem may have more than one feasible solution but optimal design indicates the best value maintaining the restriction imposed on it [2], [3]. These Problems are in general non-linear, multi-variable and constrained optimization problems.

In the first attempt, computers are used to design the transformer [4], [5]. The idea of optimization is suitably addressed within the programming part to get the desire output. There are various tools for optimization is available to reach global minima like classical and non-classical or stochastic. The classical techniques are applied in the 2nd half of 20th century [6, 7] and it has been quite successful to design transformers and other machines in engineering field [8].

The non-classical optimization techniques such artificial intelligence, soft computing now becomes very popular in engineering design problems. The present work is based on design optimization of a single-phase dry type by applying genetic algorithm [11]. The optimization techniques leading to optimization has been discussed by N.S. Kambo [12].

II. Design

Transformers are generally used in most of the electronic circuits and industries to get the variable the voltages. It may be single or three phases and used as power or distribution transformers. Copper or aluminium is used as conductor materials and various grades of silicon steel stampings are used for core materials. It may be classified as dry or oil-immersed, depending on the cooling systems.

In power transformers, copper is used as conductor material and cold rolled grain-oriented steel (CRGOS) is used as core material. It is large in size and they are designed for higher values of leakage reactance to have less current in short circuit condition and better rating of the circuit breaker (CB). Distribution transformers are design in such a way that it should have best possible economy due to competitive power market. Sometimes aluminium is used as conductor and inferior quality core is used to reduce the cost of production.

The design principles for transformers have been discussed by several authors [13], [14]. The most authentic treatise in this area is the J&P handbook [15]. A.K. Shawney has much simplified the design procedure and has hinted on computer-aided design [16] in the last part of his book. M. Ramamoorty [4], M.A. Tsili et al [6] etc. have made detailed discussion on computer-aided design and optimization. M. Polouiadoff et al in a paper has discussed about behavior of parameters due to design optimization of transformers.

Dry type transformers are more expensive, as oil is not used as coolant but they are less hazardous and safer due to absence of oil, small rating transformers are preferred for the specific applications. The design principle of transformers and the corresponding design data is given in the standard books and hand-books. Some modifications have been incorporated in the Dry type transformers to avoid insulation failure and the temperature rise below certain limits. The step by step calculation for the design remains unaltered. The goal is to reach the global optima by computationally efficient algorithm. Stampings can be produce in factory itself for mass production but for job-production, standard stampings will be economical.

A discrete optimization technique for such dry type transformers made of standard stampings has been reported by R. Basak et al [17].

III. Objective Function

The optimizing has been developed with the design variables. The performance of which is controlled by the constraints and the cost depends on several design variables. Two key variables have been chosen out of the selected number of variables which significantly controls the value of the objective function. Design constraints have been imposed upon it to get the desire level of output. A 5 kVA, 230:115V, 50 Hz transformer is taken for a case study which is designed and optimized under certain restrictions.

IV. VARIABLES

The function is formed with two Design variables as follows:

- k is taken from the equation $E_t = k\sqrt{Q}$
- Window height to width ratio is considered from $R = H_W / W_W$

Some of the standard values for other design and decision variables is considered for the optimal design.

- Cold Rolled Steel is used for core material (CRS)
- Copper is used for conductor materials.
- B_m = 1.3 Weber/m^2
- δ = 2.3 Ampere/mm^2
- Number of steps = 3
- K_w = 0.41
- (for CRS core): K_s = 0.9

V. LIMITS OF CONSTRAINTS

Constraints are imposed considering the performance of the transformer in the practical field. The following are the constraint has been taken to design the standard transformers [16, 19].

- Full load Efficiency > 96%
- Full load Voltage regulation <5%
- No load current < 2%;
- Temperature rise < 50^o C

VI. OPTIMIZATION

The function for optimization is framed which is very hard to express in a given form below.
Appendix A contains the detailed calculation procedure of the function.

The total cost of material (Rs.) = $CM = 1131(\sqrt{R_W K} + \sqrt{K / R_W}) + 3371K^{1.5} + 2520/\sqrt{K} + 803/(K^{1.5}\sqrt{R_W})$

The above function is the objective function which is optimized by Genetic algorithm (GA) quiet successfully to find out the global minima. More than ten trial has been made to find the ultimate results and the values of the fifty number of iterations is projected in table 1 near the convergence. Particle swarm optimization and method of Exhaustive search is also used to compare and validate the results. GA and PSO gives almost same results but GA converge with a smaller number of iterations quiet smoothly. The results from method of exhaustive search is not as good as the other two methods.

VII. GENETIC ALGORITHM

Developed by John Holland and established by Holland and Dejong, genetic algorithm has been popularized by Goldberg. Several researchers have contributed on various aspects and applications of genetic algorithms. It has found application in almost every branch of engineering and research. It simulates natural genetics, consisting of reproduction, crossover and mutation. Initially single population is produced having encoded chromosomes, where each chromosome is represented by a probable solution. Encoded chromosomes undergo natural selection for recombination through the crossover operator. So, improved off-springs generate in successive generations. Probabilistic bit mutation incorporates new property to the child chromosomes in search of diversity and better-quality solutions. Natural process of evolution of the population continues until a definite number is reached, which gives a final generation of extremely fit chromosomes representing optimal solutions to the problem. The biggest advantage of this population base search is that a number of feasible solutions can be achieved throughout the population. A multiple optimal solution can be obtained from a complex objective function with the help of these unique features.

The flow chart for GA showing in figure 1 and step by step calculation is done on the basis of the chart.

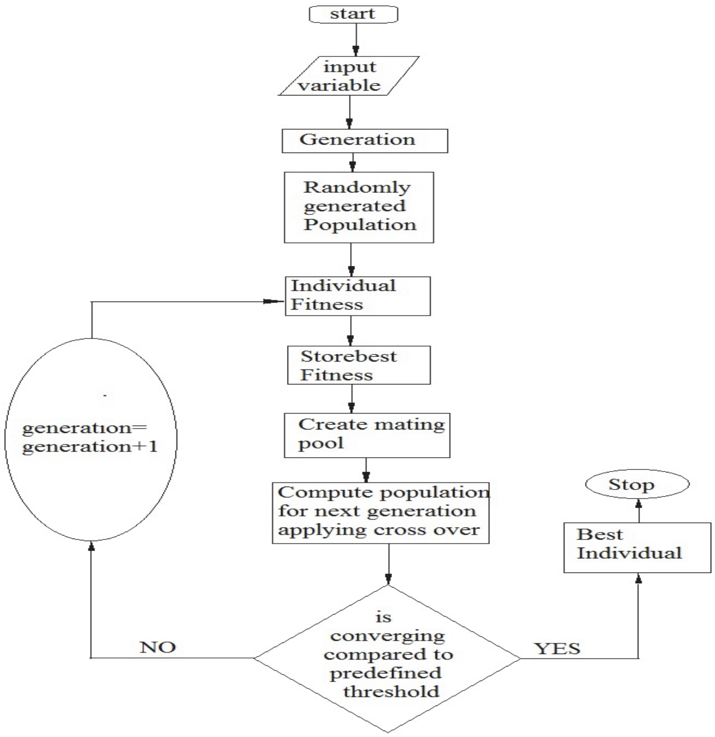

Fig 1 Flow Chart for GA

VIII. EXHAUSTIVE SEARCH

Exhaustive search is a general problem-solving process. This method is the simplest of all the methods because the optimal value of the function is calculated by a number of equally spaced points. The search process continues throughout the search space bounded by lower and upper bound until minimum value is reached. The Algorithm is simple as follows:

Step 1: Input specifications: power, voltage etc.

Step 2:Choose material for conductor and core, set: $\min \leftarrow$ a big number

Step 3: Input specified data: flux density (B_m), current density (δ), Number of steps (N_{st}) etc.

Step 4: for $i = 1$ to 100 (DO); $k \leftarrow 0.5 + i/1000$ ‘lower and upper bound: 0.5 to 0.6

Step 5: for $j = 1$ to 100 (DO) ; $R \leftarrow 3.0 + j/100$ ‘lower and upper bound: 3.0 to 4.0

Step 6: For $C(i,j) \leftarrow 1131(\sqrt{Rk} + \sqrt{k/R}) + 3371k^{1.5} + 2520/\sqrt{k} + 803/(k^{1.5}\sqrt{R})$

Step 7: if $C(i,j) > \min$ go to step 12

Step 8: $k_{\min} \leftarrow k(i)$; $R_{\min} \leftarrow R(j)$; $C_{\min} \leftarrow C(i,j)$

Step 9: end

Step 10: end

Step 11: Put $K \leftarrow K_{\min}$; $R_w \leftarrow R_{w\min}$

Step 12: Go to sub routine and calculate dimension and variables.

Step 13: Stop

Step 14: end

IX. PARTICLE SWARM OPTIMIZATION

Particle swarm optimization is one of the most recent tools for optimization. It is under the domain of 'Artificial *Intelligence'* and designated to such a task which is able to execute by computer systems and also require human intelligence. The task is not so easy and it is possible through artificial intelligence only. The other types of human intelligence may include decision making, language translation, visual perception etc. These techniques can be executed through computers by artificial intelligence.

Swarm Intelligence is considered as a branch of Artificial Intelligence where it is recognized how the concept of different biological phenomena can be executed through computer system to optimize the scheduling algorithms. In the swarm intelligence, we concentrate on the behavior of the organisms with the nature. In this method, the entire particles fly throughout the search space. The swarm direction is characterized by the particles neighboring and from their history of experience.

Let Y and R be the co-ordinate of the particle and the velocity in the search domain.

The position of the i number of particles at k^{th} **iteration is describing by the equation (1):**

$$Y_{i,k}^{k} = \left[Y_{i,1,} Y_{i,2,} \ldots\ldots. Y_{i,N} \right] \tag{1}$$

The velocity and its position are defined accordingly by the equations (3) and (2) respectively.

$$R_{i,k}^{k} = \left[R_{i,1,} R_{i,2,} \ldots\ldots. R_{i,N} \right] \tag{2}$$

$$R_{i,n}^{k+1} = W \times R_{i,n}^{k} + C_1 \times rand_1 \times \left(PB_{i,n} - Y_{i,n}^{k} \right) + C_2 \times rand_2 \times \left(GB_n - Y_{i.n}^{k} \right) \tag{3}$$

$$i = 1, 2 \ldots\ldots\ldots M$$

$$n = 1, 2 \ldots\ldots.. N$$

$$\begin{aligned} Y_{i,n}^{k+1} &= Y_{i,n}^{k} + R_{i,n}^{k+1} if \left(Y_{\min} \right)_{i,n} \leq Y_i^{k+1} \leq \left(Y_{\max} \right)_{i,n} \\ &= \left(Y_{\min} \right)_{i,n} if Y_{i,n}^{k+1} < \left(Y_{\min} \right)_{i,n} \\ &= \left(Y_{\max} \right)_{i,n} if Y_{i,n}^{k+1} > \left(Y_{\max} \right)_{i,n} \end{aligned} \tag{4}$$

Where M and N are the number of particles in swarm, number of dimensions respectively.
K is the number of iterations
$Y_{i,n}^{k+1}$ is current position i of k th iteration
$R_{i,n}^{k}$ is velocity of I th position at k th iteration
W is the weighting factor
C_j is accelerating coefficient
$(Rand)_j$ is the randomly generated number between 0 and 1
$(PB)_i$ is the personal best of i th particle
GB indicates the best result globally.

The speed of the convergence of every particle will depend on accelerating factors C_1 and C_2 on the other side if the factors are high the problem converge quickly. Weighting factor maintains the equilibrium between local and global search. The optimization process will move slowly with their particle position if accelerating factors are low. The weighting factor is represented by the following equation (5):

$$Q = Q_{\max} - \left(Q_{\max} - Q_{\min}\right) \times {G_c}/{G_{\max}} \tag{5}$$

$Q_{\max}$ and $Q_{\min}$ are the initial and final weighting factors respectively. G_c is the current generation and G_{max} is the maximum number of generations**.**
There are two types of Swarm Intelligence:

- Ant Colony Optimization (ACO), where the algorithm is derived on the basis of the activity of the ants.
- Particle Swarm Optimization (PSO), where the behavior of group of birds is considered

This group of birds is known as a '*swarm* '.

PSO is used to search the value of a set of design variables with the optimum value of the objective function maintaining the restrictions imposed on it.

Steps involve for particle swarm optimization

Step: 1. Initialize parameters

Step: 2. Generate population along with their position and corresponding velocities.

Step: 3. Calculate the value of the objective function and performances

Step: 4. Find the fitness function

Step: 5. Updating personal best value by comparing fitness of each particle with the individual best, if it is better then taking present value as the personal best.

Step:6 Updating Global: fitness of each particle is compared with global best, if the present value is better than global best takes present value as global best.

Step: 7 Updating Velocities: Calculate the velocities using equation [3]

Step: 8 calculate the new positions by using equation [4].

Step: 9 go back to step 3 and continue until it reaches the maximum number of iterations.

Step: 10 Results is the optimized values of the function and variables.

X. CASE STUDY AND RESULTS

A 5 kVA, 230: 115 V transformers is taken for Case-study and it is optimized by using Genetic algorithm, Particle swarm optimization and Exhaustive Search. The results obtained by running the program are given in the table-1, table-2 and table-3. The convergence graph of the above three method is shown in figure-2. Fifty number of iterations is shown near the convergence area along with the variations of the objective function helps to draw the conclusion.

TABLE I. CONVERGENCE FOR GA

No. of Iteration	Objective function	No. of Iteration	Objective function
1.	9136.17	26.	8101.91
2.	9136.08	27.	8101.42
3.	9135.01	28.	8101.32
4.	9135.27	29.	8101.19
5.	9134.67	30.	8101.09
6.	9133.96	31.	8080.18
7.	9132.18	32.	8073.88
8.	9132.18	33.	8068.94
9.	9132.18	34.	8008.25
10.	9132.15	35.	7990.04
11.	9132.08	36.	7901.12
12.	9131.10	37.	7842.88
13.	9131.10	38.	7842.34
14.	9115.03	39.	7838.22
15.	9103.83	40.	7838.02
16.	8700.23	41.	7837.35
17.	8661.53	42.	7837.28
18.	8634.51	43.	7836.88
19.	8222.06	44.	7836.01
20.	8122.73	45.	7836.01
21.	8122.23	46.	7836.01
22.	8121.10	47.	7836.01
23.	8120.12	48.	7836.01
24.	8102.20	49.	7836.01
25.	8101.92	50	7836.01

TABLE II. ITERATIONS NEAR THE CONVERGENCE FOR PSO

No. of Iteration	**Objective function**	**No. of Iteration**	**Objective function**
1.	9336.27	26.	8121.92
2.	9336.28	27.	8121.92
3.	9336.31	28.	8121.92
4.	9336.37	29.	8121.89
5.	9190.96	30.	8121.89
6.	9190.96	31.	8121.88

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7.	9190.98	32.	8121.88
8.	9130.56	33.	8008.94
9.	9132.55	34.	8008.25
10.	9132.55	35.	7990.04
11.	9132.55	36.	7901.92
12.	9131.23	37.	7840.88
13.	9131.10	38.	7840.34
14.	9125.83	39.	7839.22
15.	9125.83	40.	7839.12
16.	8125.23	41.	7838.78
17.	8122.53	42.	7837.18
18.	8122.53	43.	7836.98
19.	8122.36	44.	**7836.21**
20.	8122.53	45.	7836.21
21.	8122.53	46.	7836.21
22.	8121.12	47.	7836.21
23.	8121.12	48.	7836.21
24.	8122.20	49.	7836.21
25.	8121.92	50	7836.21

TABLE III. ITERATIONS NEAR THE CONVERGENCE OF EXHAUSTIVE SEARCH

No. of Iteration	Objective function	No. of Iteration	Objective function
1.	8036.38	26.	7996.67
2.	8035.18	27.	7970.12
3.	8035.11	28.	7950.88
4.	8034.52	29.	7942.12
5.	8034.15	30.	7931.54
6.	8032.98	31.	7922.88
7.	8031.33	32.	7910.32
8.	8030.61	33.	7890.66
9.	8029.53	34.	7881.08
10.	8028.30	35.	7863.55
11.	8022.11	36.	7854.09
12.	8020.13	37.	7843.88
13.	8016.23	38.	7842.43

14.	8013.55	49.	7841.53
15.	8011.34	40.	7840.76
16.	8010.42	41.	7840.33
17.	3008.72	42.	7840.14
18.	8005.89	43.	7840.11
19.	8005.33	44.	**7840.07**
20.	8004.67	45.	7840.07
21.	8002.55	46.	7840.07
22.	8001.22	47.	7840.07
23.	8001.10	48.	7840.07
24.	7999.66	49.	7840.07
25.	7997.01	50.	7840.07

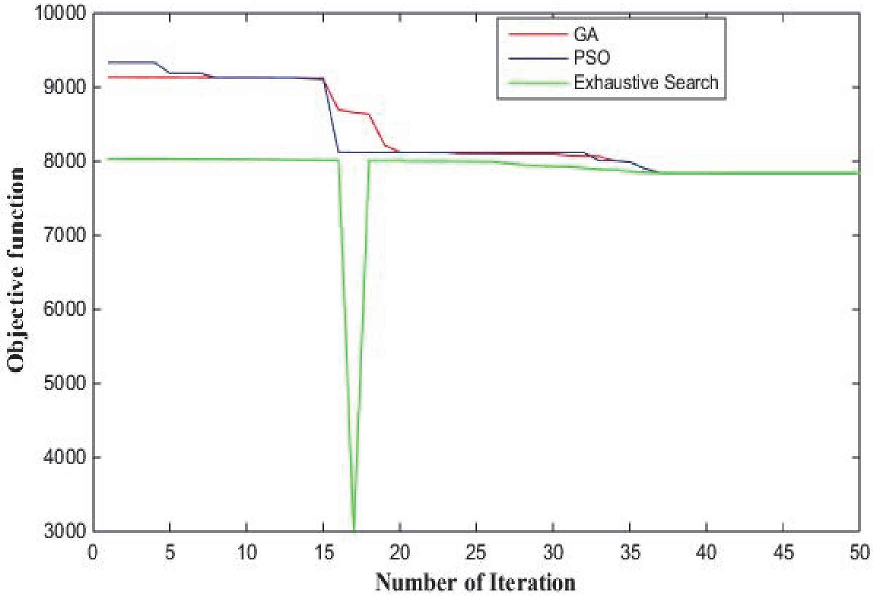

Fig 2 Graph of Convergence

XI. CONCLUSION

Cost of the material has been optimized by Genetic Algorithm, PSO and Exhaustive Search for single-phase dry transformer. Emf constant K and the window height: width ratio R_w is taken as the design variables and these variables are directly related to the cost of production. CRGOS and copper is taken as core and conductor material respectively. In order to design perfectly from performance point of view the current density and the flux-density has been limits to meet the desire specification. The optimizing function (cost of iron and copper) has been derived with the design variables to obtain a single function of cost. The minimum cost of Rs. 7836.01 has been found out using Genetic Algorithm and Rs. 7836.21 for PSO, which is almost same but

GA take less number of steps to converge. The value has been compared with method of Exhaustive search also to validate result and found to be quiet closer to global minima, which is found to be Rs. 7840.07. The dimension of the transformer is calculated with the help of design variables obtained against the global minima. The optimized results are calculated without violating the design constraints. An attempt is also been taken to establish that the non-classical or probabilistic optimization schemes are capable of giving optimal solution with smaller number of iterations in comparison with the classical methods

ANNEXURE A

Derivation of the optimizing function

Considering a specific transformer,

Volt/turn= $k\sqrt{Q} = k\sqrt{5}$

Maximum flux can be expressed as follows $\phi_m = k\sqrt{Q}/(4.44f)$

Net area of the core $a_i = \phi_m / B_m$

Gross area of the core

$a_{gi} = a_i / K_s$

Where a_i and K_s is the net area of iron and stacking factor.

Diameter of the circumscribing circle for a three stepped core $(d) = \sqrt{a_{gi}/0.6} = \sqrt{0.007k/0.6} = 0.107\sqrt{k}$

Area of the window in m^2 can be expressed as $a_w = Q/[2.22 f \phi_m K_w \delta .10^3] = 4.69\times10^{-3}/k$

Window width is formulated by the variables in meter $(W_w) = \sqrt{a_w/R} = \sqrt{0.004/(kR)} = 0.068/\sqrt{kR}$

Similarly window height is derived with the variables in meter $(H_w) = W_w R = 0.06\sqrt{R/k}$

The distance between the core centers is expressed as $d_c = d + W_w = 0.1\sqrt{k} + 0.06/\sqrt{kR}$

Length of the largest stamping

$l = 0.09\sqrt{k}$

Over all width $(W) = d_c + l = 0.06/\sqrt{kR} + 0.2\sqrt{k}$

Considering the flux density of core = flux density of yoke

The height of yoke can be derived in meter as follows $H_y = a_{gi}/l$

Over all height

$H = H_w + 2H_y$

Volume of iron can be calculated in m^3 as $(Vol)_i = 2(H_w + W)a_i = 2\{0.06(\sqrt{R/k} + \sqrt{kR}) + 0.2\sqrt{k}\}0.007k =$

$0.0009(\sqrt{Rk} + \sqrt{k/R}) + 0.002k^{3/2}$

Taking density of iron as 7650 Kg/m^3 and cost of high-grade CRS as Rs. 150/- per Kg.

Cost of iron (Rs.), $CI = 1131(\sqrt{Rk} + \sqrt{k/R}) + 3371k^{1.5}$

Mean length of turn, m $= l_{mt} = \pi(d + W_w/2) = \pi(0.107\sqrt{k} + 0.06/2/\sqrt{kR})$

$= 0.337\sqrt{k} + 0.107/\sqrt{kR}$

Total copper area in the window, mm^2

$= N_1 I_1 + N_2 I_2 = 2S \times 10^3 / E_t \delta$

$= 10000/2.23k \times 2.4$

$= 1834.40/k$

$\therefore$ Volume of copper $= 1863.4(0.337\sqrt{k} + 0.107/\sqrt{kR})/(k \times 10^6)$

$= 6.29 \times 10^{-4}/\sqrt{k} + 2.005 \times 10^{-4}/(k^{1.5}\sqrt{R})$

Considering density of copper = 8900 Kg/m^3
Cost of super enameled refined copper =Rs. 450/- per Kg,
Total cost of material in Rs. (CM) =

$$1131\left(\sqrt{Rk} + \sqrt{k/R}\right) + 3371k^{3/2} + 2520/\sqrt{k} + 803/\left(k^{3/2}\sqrt{R}\right)$$

ANNEXURE B

Design Details

The values of the design variables from genetic algorithm:
$k = 0.557$; $R = 3.57$
Dimension of the transformers and the corresponding performance variables:
Specifications: 5 KVA, 230: 115 Volt, 50 Hz., dry type.
The design has to be made subject to given design constraints.

Decision variables	
Core material:	CRGOS
stacking factor (K_s)	0.93
cost of iron per Kg	Rs. 150/-
Number. of core steps	3
Flux-density (B_m)	1.4 wb/m^2
Iron loss per Kg	1.331 Watt.
Conductor material:	copper
current density	2.4 A/mm^2 ;
Cost of copper per Kg	Rs. 450/-
Resistivity of copper	0.022 Ω/m/mm^2

Dimensions	
Volt per turn	1.288 V
diameter of the circumscribing circle	0.0816 m
Length of the largest stamping	0.074 m
window area	0.008 m^2
Width, and height of window	0.051 m and 0.16 m
distance between core centres	0.13268 m
width of core	0.20668 m
Width and height of yoke	0.074m and 0.06 m
height of core	0.28 m
primary and secondary turns	178 and 89
length of mean turn	0.33677 m

Primary and Secondary current	21.739A and 43.478 A

Cost Analysis	
Volume	0.00304 m^3,
weight of iron	23.324 Kg
Total cost of iron	Rs. 3499/-
Volume of copper	0.00108 m^3
weight of copper	9.665 Kg
Cost of copper	Rs. 4349/-
Total cost of material	Rs. 7848/-

Performance Analysis	
Iron loss	31.046 watt
Iron loss	0.62093%
Ccopper loss	137.61watt
Copper loss	2.7523%
Full load efficiency	0.9618
Magnetizing current from primary	0.3105 A
Magnetizing current	1.428%
Core loss current	0.6209 %
No. load current	1.5576%
Leakage reactance with respect to primary	0.4957 Ω
Leakage reactance	4.6854
Full load vvoltage regulation	4.808%
Full load ttemperature rise	42^o C

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