Optimization of Transformer Design using Bacterial Foraging Algorithm

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ABSTRACT

Transformers are widely used in electric power system to perform the primary functions, such as voltage transformation and isolation. So the transformer design is emphasize. In this paper, a transformer design optimization method is proposed aiming at designing the transformer to optimize the efficiency and cost. The design optimization of transformer is formulated as unconstrained non linear multivariable programming technique. Five independent variables and three constraints are taken to meet the requirement of the design. A heuristic search technique Bacterial Foraging Algorithm (BFA) is used to solve the optimization problem. The effectiveness of the proposed approach has been tested with two sample transformers and the simulation results are compared against with the conventional method, Simulated Annealing (SA) technique and Particle Swarm Optimization (PSO) method. The simulation results reveal that the proposed method determines the optimal variables of transformer long with the performance parameters efficiently and accurately.

Keyword

Transformer design optimization, cost, efficiency, bacterial foraging algorithm.

Nomenclature

C (i)	-	Step size
I	-	Bacterium number
j	-	Counter for chemotactic step
J (i, j, k, *l*)	-	Cost at the location of i^{th} bacterium
J_{cc}	-	Swarm attractant cost
J^{i}_{health}	-	Health of bacterium *i*
k	-	Counter for reproduction step
l	-	Counter for elimination-dispersal step
m	-	Counter for swimming locomotion
N_c	-	Maximum number of chemotactic steps
N_{ed}	-	Number of elimination-dispersal events
N_{re}	-	Maximum number of reproduction steps
N_s	-	Maximum number of swims
P	-	Dimension of the optimization problem
P_{ed}	-	Probability of occurrence of elimination - dispersal events
s	-	Population of the E. coli bacteria
θ^i (j, k, *l*)	-	Location of the i^{th} bacterium at j^{th} chemotactic step, k^{th} reproduction step, and *l* the elimination-dispersal step
$\omega_{attract}$	-	Width of attractant
$\omega_{repellant}$	-	Width of repellent
$h_{repellent}$	-	Height of repellent
$d_{attract}$	-	Depth of attract

1. INTRODUCTION

In this new and challenging environment, there is an urgent need for the transformer manufacturing industry to improve transformer efficiency and to reduce costs, since high quality, low cost products have become the key to survival. To achieve accurate design with less time an economical manner using digital computers was discussed [1]. A unified method has been developed for the design of electrical machines including power transformers [2]. The circulating and rotational fluxes make large contribution to the total power loss in the transformer and it requires the optimal design of joint [3]. The joint design based on the knowledge about the localized flux distribution, both in the corners and in the limbs.

The transformer design with the cost analysis has been reported in the literature. The authors developed a step by step procedure for the transformer design involved the material cost and labour cost [4]. The cost analysis involves with the material costs in detail and a labour analysis that sets forth a detailed list of labour operations necessary to construct the transformer being analyzed. Material costs are listed in the form of a parts list. Labour costs are summarized by listing all the required operations in units of time several optimization techniques have been reported in the literature. Simulated Annealing (SA) technique [5] has been applied to solve the transformer design problems. The minimization of material cost is taken as an objective. Evolutionary algorithm based optimum design of induction motor was discussed [6]. A combined genetic algorithm-neural network approach applied to distribution transformers for iron loss reduction was presented [7]. Optimum transformer design based on the given specification, using available materials economically to achieve lower cost, reduced size and better operating performance was discussed [8]. Application of radial based function to optimum design of single phase induction motor was presented [9]. The performance of two optimal design methods, Hooke Jeeves and, respectively, genetic algorithms, are compared in terms of performance and computation time effort in an exercise design of induction machine was reported [10]. A new evolutionary computation technique, called Bacterial foraging algorithm has been developed based on modeling of bacteria *E.coli* behaviour present in human intestines and it has been proven that is efficient [11-16] for various optimization problems. In this article, BFA has been applied to obtain optimum design of transformer. The effectiveness of the proposed BFA approach has been tested with the two sample transformers.

2. TRANSFORMER DESIGN OPTIMIZATION–PROBLEM FORMULATION

The optimization of transformer design problem is formulated as non linear programming problem, expressing the objective function and constraint function in term of the specified independent variable. The problem can be stated is mathematical terms as follows.

Find:

$$X = [X_1, X_2, X_3 ... X_n] \qquad (1)$$

Such that $F = f(X)$ is minimum subject to

$$X_{imin} < X_i < X_{imax}\text{ , i=1, 2….n} \qquad (2)$$

And $g_i(X) < 0$, i=1, 2, .m (3)

Where X_1, X_2,……X_n are the set of independent design variables with their lower and upper bounds as X_{imin} and X_{imax}. F=f(X) is the objective function to be optimized and $g_i(X)$ are the constraints imposed on the design.

2.1 Design variables

In the design optimization of a transformer, if large number of variables is selected, the problem will become complicated. The following quantities are chosen as transformer design variables for optimization.

1. Maximum flux density (x_1) Wb/m^2
2. Current density in HV winding (x_2) A/mm^2
3. Current density in LV winding (x_3) A/mm^2
4. Mean height of winding (x_4) m
5. EMF per turn (x_5) volts

2.2 Constraints

g_j(X) is the set of m explicit constraints imposed on a design to make it feasible and practically acceptable, the constraints that have been used in this study are

1. No load current
2. Temperature rise
3. Regulation

The objective function optimization problem is to optimize the efficiency and cost. Total cost is sum of iron and copper cost. In the computation of F(X) and g_j (X) as well as in calculating the performance of the machine, the standard mathematical formulation is used. [17].

3. BACTERIAL FORAGING OPTIMIZATION

The selection behaviour of bacteria tends to eliminate poor foraging strategies and improve successful foraging strategies. After many generations a foraging animal takes actions to maximize the energy obtained per unit time spent foraging. This activity of foraging led the researchers to use it as optimization process. The E coli bacterium has a control system that enables it to search for food and try to avoid noxious substances. The bacteria distributed motion can model as the following four stages:

3.1 Swarming and Tumbling via flagella (N_s)

The flagellum is a left-handed helix configured so that as the base of the flagellum (i.e. where it is connected to the cell) rotate counter clockwise, from the free end of the flagellum looking towards the cell, it produces a force against the bacterium pushing the cell. This mode of motion is called swimming. A bacterium swims either for maximum number of steps Ns or less depending on the nutrition concentration and environment condition. During clockwise rotation each flagellum pulls on the cell shown in Figure 1. So that the net effect is that each flagellum operates relatively independently of the others and so the bacterium "tumbles".

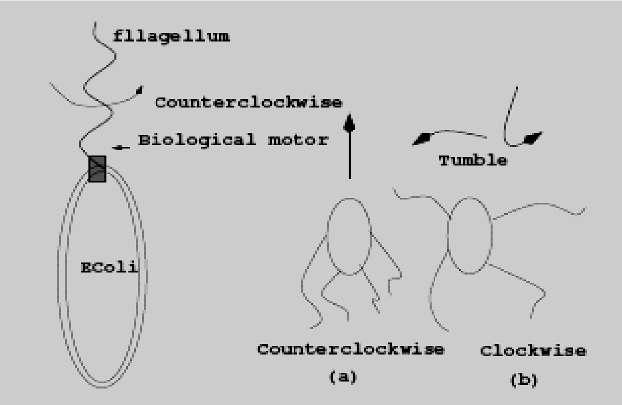

Figure 1. Swarming and Tumbling behaviour

3.2 Chemotaxis (N_c)

A chemotaxis step is a set of consequence swim steps following by a tumble. A maximum of swim steps with a chemotactic step is predefined by Ns. The actual number of swim steps is determined by the environment. If the environment shows good nutrients concentration in the direction of the swim, the bacteria swim more steps. When the swim steps is stopped a tumble action takes place.

3.3 Reproduction (N_{re})

After Nc chemotactic steps, a reproduction step is taken. Let Nre be the number of reproduction steps to be taken. It is assumed that half of the population members have sufficient nutrients so that they will reproduce with no mutations. For reproduction, the population is sorted in order of ascending accumulated cost accumulated cost represents that it did not get as many nutrients during its lifetime of foraging and hence, is not as "healthy" and thus unlikely to reproduce).Least healthy group of bacteria dies out and the other healthiest splits into two.

3.4 Elimination and Dispersal (N_{ed})

Elimination event may occur for example when local significant increases in heat kill a population of bacteria that are currently in a region with a high concentration of nutrients. A sudden flow of water can dispose bacteria from one place to another. The effect of elimination and dispersal event is possibly destroying chemotactic progress, but they also have the effect of assisting in Chemotaxis, since dispersal may place bacteria near good food sources.

The detailed computational flow chart of BFA is presented in Figure 2.

4. BACTERIAL FORAGING ALGORITHM BASED OPTIMUM DESIGN OF TRANSFORMER

The proposed method is employed to search the optimal values of transformer independent variables. The procedure of optimum transformer design as follows:

First input the bacterial foraging parameters, transformer data's, initialize the values for independent variables with specify lower and upper limits and also give the constraints with limits. Next generate the positions of the variables randomly and evaluate the objective value of each bacterium. After evaluating the objective function, modify the position of the variables for all the bacteria using the tumbling/swimming process and perform reproduction and elimination operation. The output is obtained when the maximum steps is reached. Finally, compute the operating performances of the transformer such as efficiency and cost. In proposed method, the process of "chemotaxis" enables bacteria to obtain a satisfactory ability of local search. It is worth notice that the individuals in bacterial foraging algorithm could converge rapidly without information sharing between each other, which is different from other methods. Bacterial foraging algorithm based optimum design of transformer is performed in accordance with the following steps

Step-1 Initialize parameters P, s, N_{re}, N_{ed}, P_{ed}, C (i) (i=1, 2,……s), and X_i. Also initialize all the counter values to zero.

Step-2 Elimination-dispersal loop: $l=l+1$

Step-3 Reproduction loop: $k=k+1$

Step-4 Chemotaxis loop: $j=j+1$

(a) For i=1, 2,…, s, calculate cost function value and efficiency- for each bacterium i as follows.

1. N_{is} signal samples are passed through the model.
2. The output is then compared with the corresponding desired signal to calculate the error.
3. The same of the squared error averaged over N_{is} is finally stored in J (i, j, k, l). The cost function is calculated for number of input samples.
4. End of for loop.

(a) For i=1,2,…s take the tumbling/swimming decision Tumble : Generate a random vector Δ(i) with each element $\Delta_m(i)$ m=1, 2,… p, a random number.

Move: Let

$$\theta^{i}(j+1,k,l)=\theta^{i}(j,k,l)+C(i)\frac{\Delta(i)}{\sqrt{\Delta^{T}(i)\Delta(i)}} \tag{4}$$

Fixed step size in the direction of tumble for bacterium i is considered.

Compute J(i, j+1, k, l) and then

Let

$$Jsw(i,j+1,k,l)=J(i,j+1,k,l) + J_{CC}(\theta^{i}(j+1,k,l),P(j+1,k,l)) \tag{5}$$

Swim:

(i) Let m=0; (counter for swim length)

(ii) While m<N_s (have not climbed down too long)

- Let m=m+1
- If Jsw(i, j+1, k, l) < J_{last} (if doing better), let J_{last}= Jsw(i, j+1, k, l) and Let

$$\theta^{i}(j+1,k,l)=\theta^{i}(j,k,l)+C(i)\frac{\Delta(i)}{\sqrt{\Delta^{T}(i)\Delta(i)}}$$

  And use this θ^i (j +1, k,l) to compute the new J (i, j+1, k, l)
- Else, let m=N_s. This is the end of the while statement.

(b) Go to next bacterium (i+1) if $i \neq$ s (i.e. go to b) to process the next bacterium.

Step-5 If $j < N_c$, go to step 4. In this case, continue Chemotaxis since the life of the bacteria is not over.

Step-6 Reproduction:

(a) For the given k and l, and for each i=1, 2,..s,

Let J^i_{health}=min $Jsw(,i, j, k, l)$ be the health of the bacterium i (a measure of how many nutrients it got over its life time and how successful it was at avoiding noxious substance). Sort bacteria in order of ascending cost J_{health} (higher cost means lower health).

(b) The S_r=s/2 bacteria with highest J_{health} values die and other S_r bacteria with the best value split (and the copies that are made are placed at the same location as their parent)

Step-7 If $k < N_{re}$ go to 3. In this case, the number of specified reproduction steps has not been reached, so the next generation of the chemotactic loop is started.

Step-8 Elimination-dispersal: For i=1, 2, s, with probability P_{ed}, eliminates and disperses each bacterium (this keeps the number of bacteria in the POPULATION constant). To do this, if a bacterium is eliminated, simply disperse another one to a random location on the optimization domain. If $l < N_{ed}$, then go to step 2; otherwise, print the results and stop.

5. RESULTS AND DISCUSSION

To verify the effectiveness of the proposed BFA for optimizing the transformer design problem has been tested on two sample transformers. The specifications of sample transformers are presented in Table 1.

Table 1. Sample transformers specifications

Specifications	Sample transformer 1	Sample transformer 2
Rated Power(KVA)	100	4000
Internal (LV) Coil Voltage (V)	433	6600
External (HV) Coil Voltage (V)	11000	11000
Connection of Internal (LV) Coil	Y	Δ
Connection of External (HV) Coil	Δ	Δ
Frequency (Hz)	50	50

The optimization procedure starts with the design variables, in the design optimization problem five independent variables are chosen, such as flux density, current density in LV and HV winding, mean height of winding and Emf per turn changed during the iteration.

Table 2. Comparison SA, PSO and BFA results with conventional design for sample transformer1 (cost as objective function)

Variables	Conventional method	SA based results	PSO based results	BFA based Results
Maximum flux density (Wb/m^2)	1.35	1.349	1.33	1.3
Current density in high voltage winding (A/mm^2)	2.5	2.43	2.38	2.43
Current density in low voltage winding (A/mm^2)	2.5	2.58	2.18	2.39
Mean height of winding (m)	0.23	0.214	0.21	0.21
EMF per turn (V)	4.5	4.54	4.44	4.42
No load current(A)	0.16	0.11	0.12	0.14
Temperature rise (^{0}C)	58.1	54.3	56	55.85
Regulation (%)	0.047	0.043	0.049	0.046
Efficiency (%)	97.7	97.83	97.85	97.86
Cost (Rs)	**1,15765**	**1,09398**	**1,12773**	**1,08550**

Table 3. Comparison SA, PSO and BFA results with conventional design for sample transformer1 (Efficiency as objective function)

Variables	Conventional method	SA-based results	PSO-based results	BFA- based results
Maximum flux density (wb/m^2)	1.35	1.3	1.23	1.28
Current density in high voltage winding (A/mm^2)	2.5	2.55	2.15	2.45
Current density in low voltage winding (A/mm^2)	2.5	2.12	2.09	2.19
Mean height of winding (m)	0.23	0.23	0.23	0.22
EMF per turn (V)	4.5	4.1	4.58	4.53
No load current(A)	0.16	0.14	0.13	0.12
Temperature rise (^{0}C)	58.1	57.4	55.15	55.2
Regulation (%)	0.047	0.046	0.045	0.048
Efficiency (%)	**97.7**	**97.85**	**97.87**	**97.88**
Cost (Rs)	1,15765	1,12580	1,24410	1,12320

Table 4. Comparison SA, PSO and BFA results with conventional design for sample transformer 2(cost as objective function)

Variables	Conventional method	SA-based results	PSO-based results	BFA-based results
Maximum flux density (wb/m^2)	1.6	1.55	1.68	1.58
Current density in high voltage winding (A/mm^2)	2.5	2.4	2.36	2.46
Current density in low voltage winding (A/mm^2)	2.5	2.45	2.47	2.37
Mean height of winding (m)	0.639	0.61	0.67	0.62
EMF per turn (V)	37.4	29.5	30.54	32
No load current(A)	0.15	0.13	0.11	0.14
Temperature rise (^{0}C)	102	97.4	72.31	82.4
Regulation (%)	0.034	0.049	0.059	0.05
Efficiency (%)	99.52	99.59	99.75	99.58
Cost (Rs)	**11,16381**	**825352**	**548685**	**546523**

Table 5. Comparison SA, PSO and BFA results with conventional design for sample transformer 2 (Efficiency as objective function)

Variables	Conventional method	SA-based results	PSO-based results	BFA-based Results
Maximum flux density (wb/m^2)	1.6	1.58	1.65	1.62
Current density in high voltage winding (A/mm^2)	2.5	2.31	2.32	2.22
Current density in low voltage winding (A/mm^2)	2.5	2.39	2.38	2.34
Mean height of winding (m)	0.639	0.62	0.674	0.65
EMF per turn (V)	31.4	30.5	32.6	33.6
No load current(A)	0.15	0.14	0.12	0.11
Temperature rise (^{0}C)	102	97.6	69.8	89.4
Regulation (%)	0.034	0.047	0.042	0.044
Efficiency (%)	**99.52**	**99.68**	**99.81**	**99.74**
Cost (Rs)	11,16381	812500	593581	604471

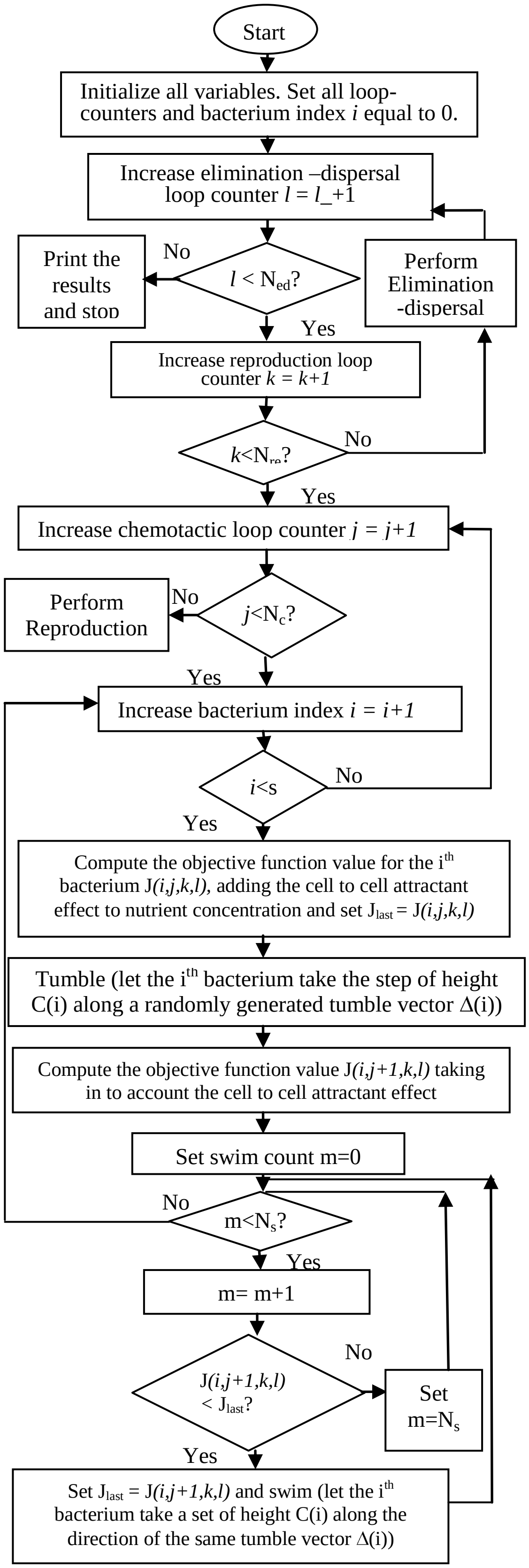

Figure 2. Flow Chart for Bacterial Foraging Algorithm

In the present work the chosen objectives are cost and efficiency of the transformer. The results obtained by proposed method are compared with the conventional method and SA, PSO techniques. The comparison of results for sample transformer 1is presented in Table 2 and Table 3 respectively. And also results for sample transformer 2 are given in Tables 4 and 5 respectively.

From the results, it is observed that there is significant increase in efficiency. The increases in efficiency is noticed due to large reduction transformer losses resulting from the reduction in the flux density and current density, more over reduction in losses will lead to a lower temperature rise. Also winding height is reduced and the size of transformer is decreased.

The obtained results show that the cost of the transformer is considerably reduced. This will lead to interest of transformer manufactures in the money saving aspect.

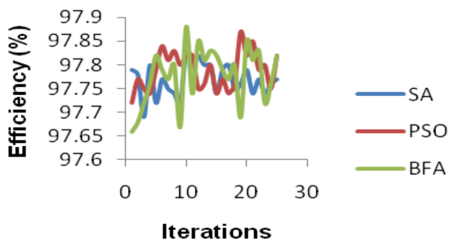

Figure 3: Variations of efficiency with iterations for sample transformer 1

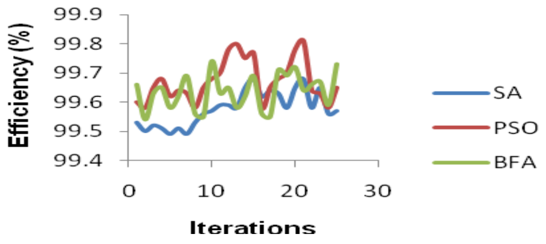

Figure 4: Variations of efficiency with iterations for sample transformer 2

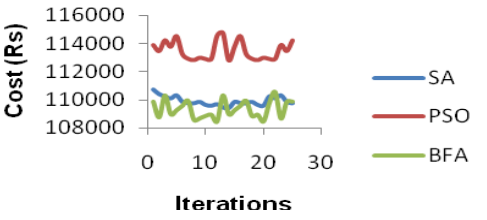

Figure 5 : Variations of cost with iterations for sample transformer 1

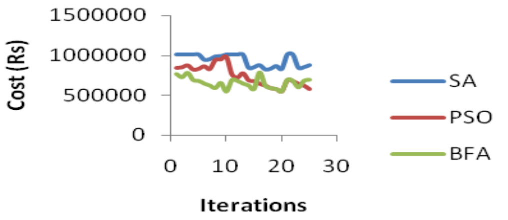

Figure 6 : Variations of cost with iterations for sample transformer 2

Table 6. Parameter selected for BFA

Parameter	Value
Number of bacterium (s)	20
Number of chemotatic steps (n_c)	10
Swimming length (n_s)	4
Number of reproduction steps (n_{re})	4
Number of elimination and dispersal events (n_{ed})	5
Depth of attractant ($d_{attract}$)	0.1
Width of attractant ($\omega_{attract}$)	0.2
Height of repellent ($h_{repellant}$)	0.1
Width of repellent ($\omega_{repellant}$)	10
Probability of elimination-dispersal events (p_{ed})	0.02

6. CONCLUSION

Transformer design is a complex task that includes many variations in design variables so as to manage lowering cost and improves performances with given transformer specifications. In this article presents the optimal design of transformer based on bacterial foraging algorithm. The proposed design approach to search for optimal values of design variables, so that to achieve minimum cost and improved performance. The feasibility of proposed technique has been tested on two sample transformers, and the results are compared to conventional method, SA and PSO based results. From that, it clearly shows the effectiveness of the proposed method via better solution and convergences. The bacterial foraging algorithm having the advantages such as less computation time, avoid heavy computation of design process, high quality solution. It is significant the proposed can be effectively used to optimize the electrical machine design problems.

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8. REFERENCES

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