Global Journal of
Technology & Optimization

Yadollahi and Lesani, Global J Technol Optim 2017, 8:1
DOI: 10.4172/2229-8711.1000206

Research Article Open Access

Global Transformer Design Optimization (GTDO) using Harmony Search and FEM Technique

Milad Yadollahi* **and Hamid Lesani**

Department of Electrical and Computer Engineering, University of Tehran, Tehran, Iran

Abstract

Transformers are the heart of electrical transmission and distribution systems. Global transformer design optimization (GTDO) is a complex multi-objective optimization problem. Aim of transformer design is to obtain the dimensions of all parts of the transformer in order to supply these data to the manufacturer. The transformer should be designed in a manner such that it is economically viable, has low weight, small size, good performance and at the same time it should satisfy all the constraints imposed by international standards. Many optimization methods proposed in literature for GTDO are prone to find local minimum instead of the global one. So, some design variables and constraints are neglected to reduce the SS size and alleviate the problem. To prevail over the aforementioned problems, this work aims to propose a Harmony Search (HS) combined with FEM technique and also some modifications to conventional GTDO procedure. To verify the effectiveness of the proposed method in achieving the global minimum, it is used to design a 190 MVA and 15.75/400 KV power transformer and also a 400 KVA as experimental case of this method.

Keywords: Global transformer design optimization; Harmony search; Finite element method; Short circuit impedance

Introduction

A transformer is a static electric device consisting of two or more windings, with or without a magnetic core, for introducing mutual coupling between electric circuits. The transformer is an electrical machine that allows the transmission and distribution of electrical energy simply and inexpensively.

Transformers play a key role in the interconnection of power systems at different voltage levels. Without the transformer, it would simply not be possible to use electric power in many of the ways it is used today. Consequently, transformers occupy important positions in the electric power system, being the vital links between power generating stations and points of electric power utilization. There are more than 400 published articles, 50 books and 65 standards in the domain of transformers [1], which have contributed vastly in the design improvement and performance of transformers. Also, Power transformer optimal design is one of the most important and interesting issues which has attracted attention in the last few decades [1,2]. To design power transformers in an economic way the cost optimization of the transformer design by reducing the mass of active part has become of vital importance. In traditional transformer design techniques, designers had to rely on their experience and judgment to design the required transformer. Early research in transformer design attempted to reduce much of this judgment in favor of mathematical relationships [1]. Several design procedures for low-frequency transformers have been developed in past research. Mathematical models were also derived for computer-aided design techniques in an attempt to eliminate time consuming calculations associated with reiterative design procedures [2-4]. These previously developed design techniques were focused on maximizing the (VA) capacity of transformers or loss minimizations. Some techniques like unconstrained optimization, genetic algorithms and neural networks etc. also aimed to minimize the mass and consequently the cost of active part of the transformer but it does not ensures the global minimization of the cost function [3-14]. The power transformer design is a multi-disciplinary and multi-objective optimization problem considering electromagnetic, thermal and cost requirements of the design [3-6]. To sum up, the importance of GTDO is because of three main reasons: 1) having numerous design variables [7], 2) having large number of constraint including manufacturing constraint as both linear and non-linear equations, 3) direct correlation between most of the variables and outputs.

Most of the optimization methods presented in literature focused on the optimal design problem for distribution transformers [8-11]. Mixed Integer Nonlinear Programming (MINLP) is compared to Harmony Search (HS), Differential Evolution (DE) and Genetic Algorithm (GA) for the transformer design optimization problem in [8]. In an innovative method has been proposed for GTDO [9]. This method employs continuous design variables, for which a movement step should be introduced by an operator, making it possible to change value of each variable and move over the SS. For high values of step, the local search ability of the algorithm is reduced, while for small steps, the algorithm suffers from a weak global search capability. So, it cannot be a certain way to reach the optimal response. Bacterial Foraging algorithm is used by [10] for optimum design of single phase transformer. It considers only four independent variables and two constraints to meet the requirement of the design.

To address the aforementioned problems, this paper proposes a HS algorithm combined with FEM (HS-FEM), in which the basic idea is to explore the entire feasible domain in a systematic way for a global minimum.

The paper is organized as follows: Section Mathematical Formulation describes the mathematical formulation of the GTDO and

---

***Corresponding author:** Milad Yadollahi, Department of Electrical and Computer Engineering, University of Tehran, Tehran, Iran, Tel: +989113200647; E-mail: m.yadollahi@ut.ac.ir

Received February 11, 2017; **Accepted** March 04, 2017; **Published** March 10, 2017

Citation: Yadollahi M, Lesani H (2017) Global Transformer Design Optimization (GTDO) using Harmony Search and FEM Technique. Global J Technol Optim 8: 205. doi: 10.4172/2229-8711.1000206

Citation: Yadollahi M, Lesani H (2017) Global Transformer Design Optimization (GTDO) using Harmony Search and FEM Technique. Global J Technol Optim 8: 205. doi: 10.4172/2229-8711.1000206

the software developed to implement it. Section Power Transformer Optimal Design (GTDO) Methodology presents the proposed transformer design optimization method, while an application of the proposed methodology to an actual transformer design case is rendered by section Result of Proposed Algorithm. Finally, Section Conclusion concludes the paper.

Mathematical Formulation

The optimization algorithm proposed in this paper focused on transformer's active parts including coil and windings. Optimization of the insulation between the windings and obtaining intervals kopeks and more secure insulation structure wouldn't fall within the scope of this work, and can be thought of as a new issue.

Input data

The proposed method is implemented as software which has a graphic user interface (GUI) by which the following input data are entered by the user for a specific design case before running the algorithm:

1. The line voltage of each terminal.
2. The connection type of each winding in each voltage level.
3. The nominal power.
4. The nominal frequency.
5. The environment temperature and installation height.
6. The voltage regulating switch type and the voltage regulation percentage % VR, and also the number of positive and negative steps.
7. The guaranteed full-load and no-load losses.
8. The guaranteed short circuit impedance and its allowed tolerance.
9. The core sheet type.
10. The winding type in each of voltage levels.
11. The conductor type in each winding.
12. The prices of copper, core sheets, and oil to be used in objective function for costs.

Objective function

The aim of the GTDO is to design the transformer so as to minimize the transformer manufacturing cost, i.e. the sum of materials costs, subject to constrains imposed by international standards, transformer characteristics and manufacturing, technical and consumer constrains. In this paper a heuristic method combined with HS and FEM (HS-FEM) used to optimize the transformer design is based on the minimization of the cost of the transformer materials, according to the following equation:

$$\sum_{j=1}^{4} c_j f_j(x)$$

Transformer material Cost = min

Where cj and fj are unit cost (€/kg) and the weight (kg) of jth main materials, respectively, including:

The primary and secondary winding copper, The magnetic materials, The transformer oil, The tank sheet steel of transformer.

Design variables

In our proposed method for GTDO, the number of design variables is a function of the winding numbers NW. Here, considering a transformer with regulating winding (NW=4), the transformer constructing chromosome (TCC) X, which includes 20 genes of the discrete design variables, is divided into sub- chromosomes including VPT sub-chromosome x1, low voltage sub-chromosome x2 and high voltage sub-chromosome x3, and voltage regulation sub-chromosome x4:

$X^T = [[x_1],[x_2],[x_3],[x_4]]$ in which:

x1: The Volt Per Turn (VPT) sub-chromosome

The genes forming this sub-chromosome are the Number of turn in Low voltage winding (NLV), Number of turn in High voltage winding (NHV), and Number of turn in Regulating voltage winding (NReg).

x2: The low voltage winding sub-chromosome

The genes forming this sub-chromosome are [H, B, NPA, NPR, NT].

x3: High voltage winding sub-chromosome

The genes forming this sub-chromosome are [H, B, NPA, NPR, NT].

x4: Voltage regulating winding sub-chromosome

The genes forming this sub-chromosome are [H, B, NPA, NPR, NT].

All above variables are discrete variables.

These variables describes as below:

1. NL Number of Layers.
2. H (mm) Height of wires.
3. B (mm) Width of wires.
4. NPR Number of radial parallel wires.
5. NPA Number of axial parallel wires.
6. NP Number of parallel wires in subdivided wires.

Constraints

All the guaranteed constrains, international standards, and manufacturing limitations have been considered in the design process. These constraints include:

1. Turn ratio error constrain.
2. Limitation of current density in each winding.
3. The winding temperature gradient.
4. Limitation of winding height that may be applied by manufacturer constraints.
5. Full-load losses.
6. No-load losses.
7. No-load current.
8. Sound level constraint.
9. Upper and lower bounds of short circuit impedance.
10. The axial and radial forces of windings.
11. Constraints regarding the transformer ability to dissipate its heat to environment regarding its dimensions.

Power Transformer Optimal Design (GTDO) Methodology

Harmony search

The Harmony Search (HS) is a new meta-heuristic population search algorithm. HS was derived from the natural phenomena of musicians' behavior when they collectively play their musical instruments (population members) to come up with a pleasing harmony (global optimal solution). This state is determined by an aesthetic standard (fitness function). The HS is simple in concept, less in parameters, and easy in implementation. It has been successfully applied to various benchmarking, and real-world problems like traveling salesman problem [8]. The main steps of HS are as follows:

Step 1) Initialize the algorithm parameters.

Step 2) Initialize the harmony memory.

Step 3) Improvise a new harmony.

Step 4) Update the harmony memory.

Step 5) Check the termination criterion.

These steps are described in the next subsections [8].

Figure 1 shows the flowchart of the proposed algorithm for the solution of the GTDO process. The flowchart describes the steps for the calculation of the transformer.

Implementing proposed algorithm

The proposed algorithm includes 9 steps describing as follows.

Step 1: Constructing the first sub-chromosome x1 (The VPT sub-chromosome).

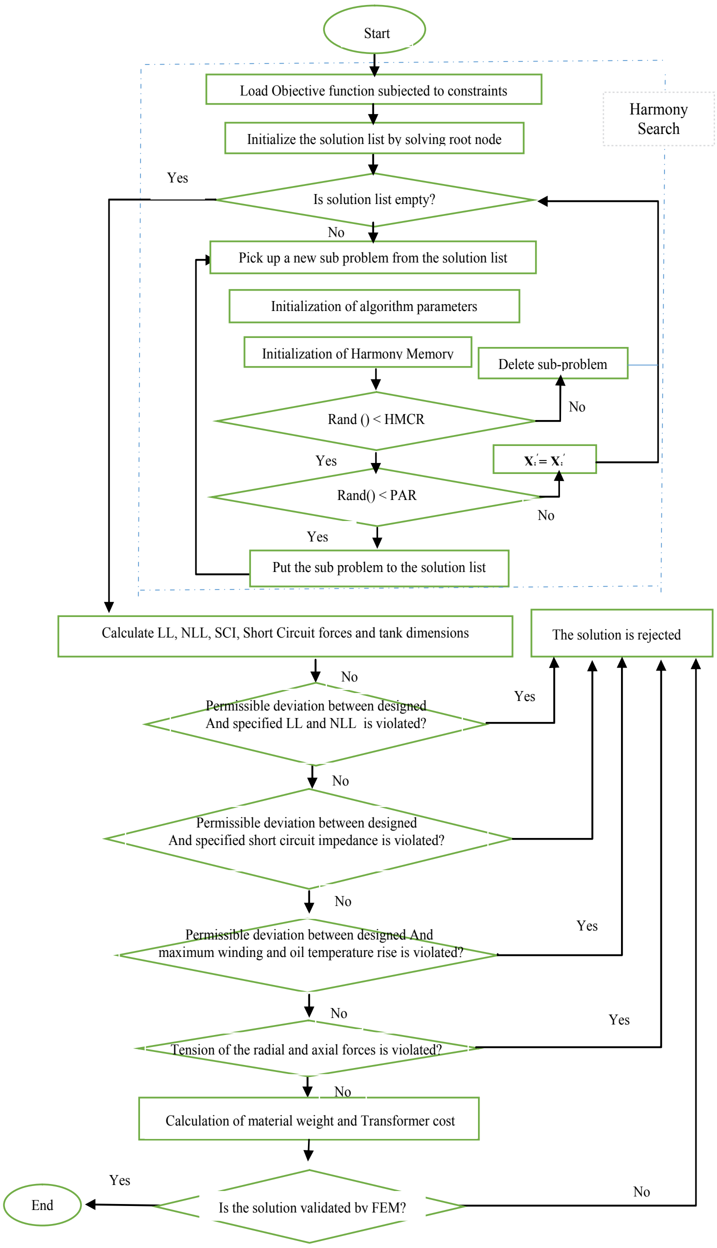

Figure 1: Flowchart of the HS algorithm combined with FEM for the GTDO.

This sub-chromosome includes the high voltage, low voltage, and voltage regulation turns. Regarding the input information of the program, in this step, we form a list of VPTs that their turn ratio error in all taps are less than permissible value.

Step 2: Constructing the second sub-chromosome x2 (The low voltage winding sub-chromosome).

Considering the lower and upper limits of each variable, we save all sub-chromosomes which meet the following constraints:

1. The lower and upper bounds of the current density.

2. Maximum value of the skin effect and eddy current stemed from the leakage fluxes components in the core window space which can create a hot spot in the winding.

3. The winding temperature gradient.

Step 3: Constructing the third sub-chromosome x3 (The high voltage winding sub-chromosome).

We should go over through all the steps of step 2 for the high voltage winding as well. This stage output is the dimensions of allowable high voltage windings sorted according to their dimensions.

Step 4: Constructing the fourth sub-chromosome x4 (The: Voltage regulating sub-chromosome).

We should go over through all the steps of step 2 for the high voltage winding as well. This stage output is the dimensions of allowable high voltage windings sorted according to their dimensions.

Step 5: Harmony Search.

Initialization of algorithm parameters: The algorithm parameters are: the harmony memory size (HMS), or the number of solution vectors in the harmony memory; harmony memory considering rate (HMCR); pitch adjusting rate (PAR); and the number of improvisations (NI), or stopping criterion. The harmony memory is a memory location where all the solution vectors (sets of decision variables) are stored. Here HMCR and PAR are parameters that are used to improve the solution vector, which are defined in Step C.

Initialization of harmony memory: In this step, the HM matrix with as many randomly generated solution vectors. Static penalty functions are used to calculate the penalty cost for an infeasible solution.

Improvisation of a new harmony: A new harmony vector $\overrightarrow{x^{i}} = (x_1', x_2', \ldots, x_N')$ is generated, based on three criteria: 1) memory consideration, 2) pitch adjustment, and 3) random.

Update of harmony vector: If the new harmony vector $\overrightarrow{x^{i}} = (x_1', x_2', \ldots, x_N')$ has better fitness function than the worst harmony in the HM, the new harmony is included in the HM and the existing worst harmony is excluded from the HM.

Check of the termination criterion: The HS is terminated when the termination criterion (e.g., maximum number of improvisations) has been met. Otherwise, steps C and D are repeated.

In our case, various values of parameters for the HAS were tested and the following ones were chosen for the transformer design optimization process:

HMS=6, HMCR=0.9, 0.4 < PAR< 0.9

Step 6: The best rendered solution is validated by FEM technique. Magnetic FEM is used to calculate transformer parameters such as SCI, short circuit forces, and eddy current loss in the winding, Load Loss (LL) and No Load Loss (NLL). If validation of the best solution fails, the solution is rejected, and then the next best solutions sorted by a specific fitness function should be validated until a valid solution is found. This enhances the accuracy of the proposed method and eliminates the possibility of infeasible optimum designs.

Figure 1 shows the whole flowchart of the proposed optimization method for the GTDO.

Result of Proposed Algorithm

In this section, to verify the effectiveness of proposed approach for solving the optimization problem, it is used to optimally design tow transformers which its parameters are presented in Table 1. We further investigate the results of an optimum design of transformer in order to show the efficacy of the algorithm.

The chosen objective function is cost of transformer material. To demonstrate the superiority of the proposed method, the results obtained from this algorithm are compared with to those of MINLP methods, GA method, and DE method [8].

Result of Proposed Algorithm (HS-FEM)

After running the program the proposed algorithm finds and sorts all feasible solutions rapidly. shows acceptable solutions sorted by manufacturing cost.

The total number of acceptable solutions are equal to 194652. The most important and critical step in designing a power transformer is to select the proper VPT. This parameter is directly proportional to the core cross section. Hence, the core diameter is increased for an increase in the VPT for a fixed flux density. On the other hand, the VPT is inversely proportional to the number of winding turns, meaning that the number of turns is increased for a decrease in VPT. Furthermore, this parameter is inversely proportional to the square of transformer SCI percent. According to the aforementioned results, the appropriate selection of the VPT is very important both economically and technically.

The best result is validated by FEM using JMAG-Designer for

Parameters	Experimental case	Power transformer
Capacity	190 MVA	400 KVA
Phase	Three phase	Three phase
Primary voltage	15.75 KV	0.4 KV
Secondary voltage	420 KV	20 KV
Type	Core	Core
Frequency	50	50
Vector group	YNd	Dyn11
Installation level	1000 m	1000 m
Ambient temperature	48°C	45°C
Tap changer	On-load (± 1 0%, ± 10 step)	Off-load (± 5%, ± 2 step)
Simple wire unit cost (€/kg)	8	8
Fe unit cost (€/kg)	2.1	2.1
Oil unit cost (€/kg)	2	2
Tank material unit cost(€/kg)	1	1

Table 1: Desired parameters of power transformer.

Citation: Yadollahi M, Lesani H (2017) Global Transformer Design Optimization (GTDO) using Harmony Search and FEM Technique. Global J Technol Optim 8: 205. doi: 10.4172/2229-8711.1000206

magnetic design and COMSOL software for electrical design.

Figures 2a and 2b show short circuit force vectors and magnetic flux density for the best output result. Output results of FEM are shown in Table 2.

Figures 2c and 2d show contour diagram of electric potential (v) and stream line of electric field (v/m) in the core window are shown in Table 2.

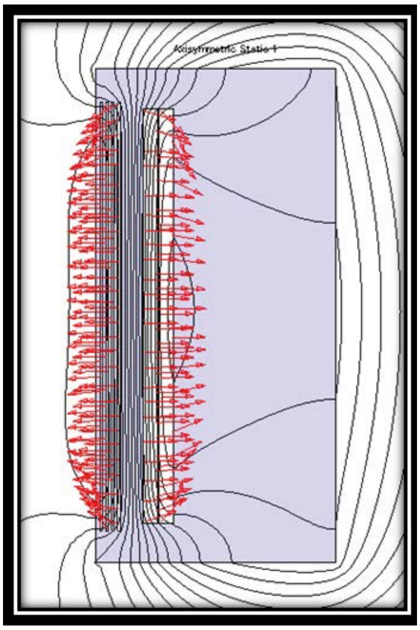

Figure 2a: Short circuit force vectors, and magnetic flux lines in the JMAG-Designer Software.

The best result validated by FEM can now be used to compare the proposed HS-FEM with other methods.

The proposed algorithm in comparison with other methods

In this section, the proposed method is compared to DE [11], GA method [8], and MINLP method [8]. For the GA, it was found that a population size of 120 chromosomes and a number of 80 generations provide very good result for optimization. The results comparison of the optimization algorithms for sample transformer is given in Tables 3 and 4.

The results presented in Table 3 are also shown by graphical diagram in Figure 3, where it can be deduced that the cost function in our proposed HS-FEM is reduced by 2.5%, 3.7%, and 7.6% in comparison to GA [8], DE [11], and MINLP [8], respectively.

Producing a 200 MVA power transformer needs a lot of time. On the other hand, we can't afford the production cost of such a transformer. So, a 400 kVA distribution transformer test results are presented to assess the effectiveness of the proposed algorithm. Figure 4 shows test object of 400 KVA transformer. Tables 4 and 5 shows test and output result of 400 KVA transformers.

Conclusion

In this paper, an innovative algorithm has been introduced in detail. Experimental testing as well as other presented computational results clearly demonstrates the qualitative and quantitative accuracy of the methodology.

All of variables have been selected discrete and all the guaranteed constrains, international standards, and manufacturing limitations have been considered in the design process. According to proposed methodology, programming techniques, and modifications to design process, the search space is limited and the program execution speed is increased, enabling it to effectively search the large solution space. The

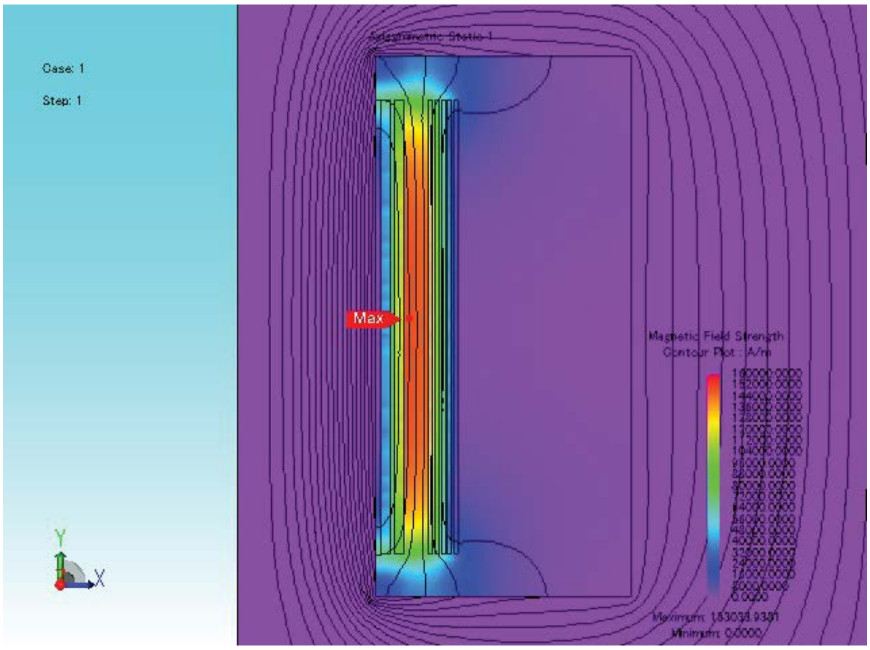

Figure 2b: Magnetic flux density in the JMAG-Designer Software

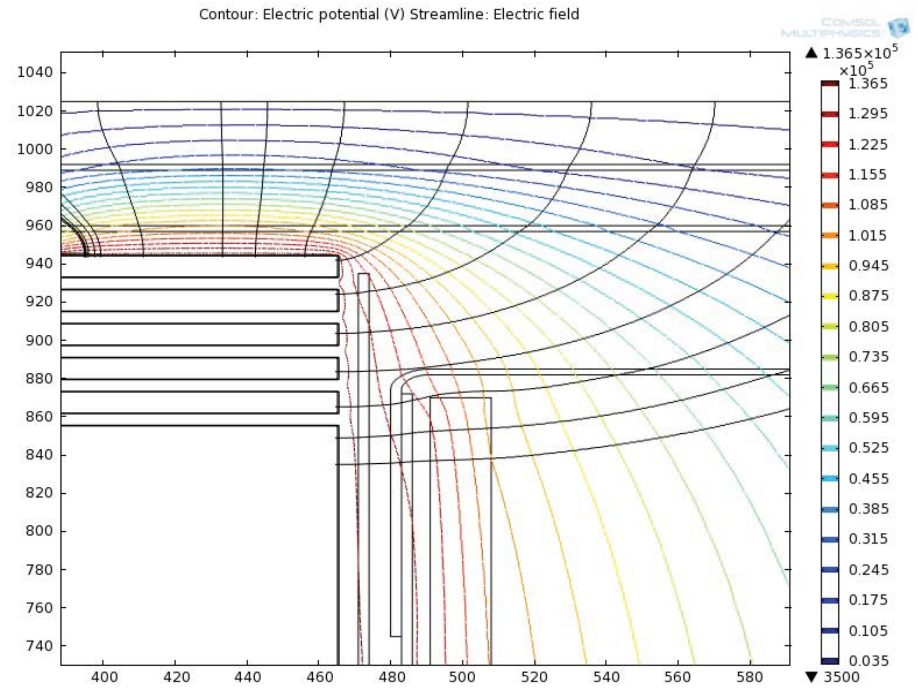

Figure 2c: Contour diagram of electric potential (v) and stream line of electric field in the COMSOL.

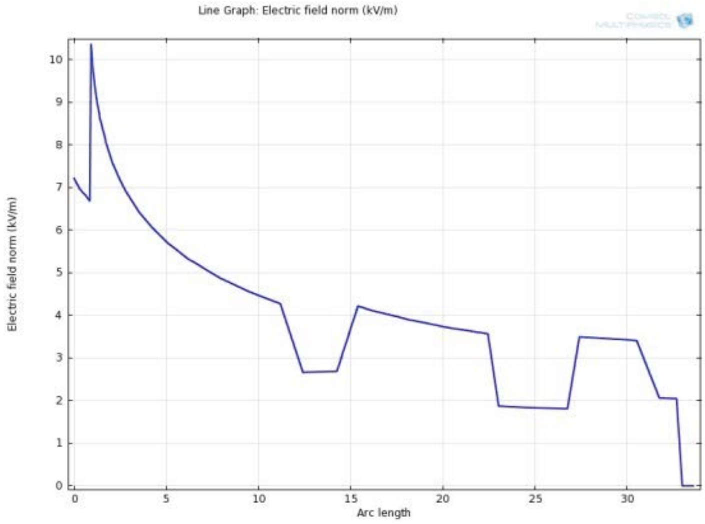

Figure 2d: Distribution of the electric field along stream line in the COMSOL Software.

Sl. No	VPT	LL (kw)	NLL (kw)	SCI (%)	Magnetic steel (kg)	Copper (kg)	Manufacturing cost ($)
1	266.9	499.3	99.8	13.75	85843	18816	527541
2	266.9	499.8	100.9	13.28	86773	18472	527895
3	271.5	497.3	101.8	13.21	87567	18487	527951
4	266.9	495.8	100.4	13.45	86319	18648	528016
194652	276.3	363.7	102.4	13.2	101212	30251	678059

Table 2: Acceptable solutions sorted by manufacturing cost.

Parameter	**Best solution of 190 MVA**			
	MINLP	**DE**	**GA**	**Proposed algorithm**
N_{LV}	57	59	64	59
D_S	1023	1015	968	1015
NL_{LV}	2	2	2	2
H_{LV}	7.4	5.7	5.5	6.9
B_{LV}	1.6	1.5	1.8	1.5
PAC_{LV}	3	4	4	3
PRC_{LV}	1	1	1	1
NT_{LV}	51	39	35	41
H_{HV}	8.8	8.3	9.8	9.5
B_{HV}	2.6	2.5	2.5	2.2
NL_{HV}	8	10	10	12
PAC_{HV}	1	1	1	1
PRC_{HV}		2	2	2
NT_{HV}		1	1	1
H_{Reg}	4.6	4.5	4	3.6
B_{Reg}	2	2.1	2.3	2
NT_{Reg}	9	9	11	11

Table 3: Comparison of the optimization algorithms for 190 MVA transformer.

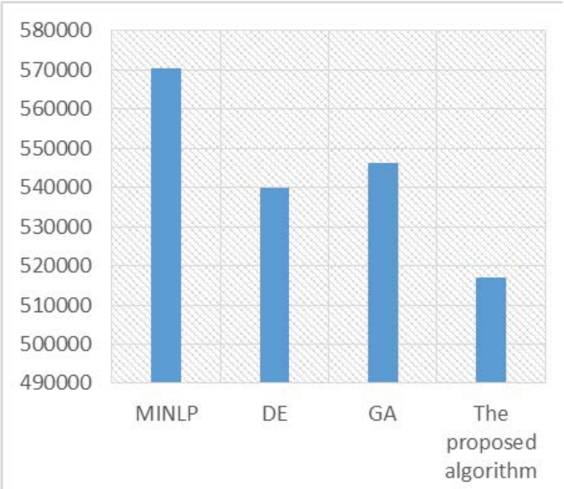

Figure 3: The graphical diagram comparing our proposed HS-FEM method with DE, GA, and MINLP.

Parameter	**Best solution of 190 MVA**			
	MINLP	**DE**	**GA**	**Proposed algorithm**
Magnetic steel (kg)	90290	90101	82114	85343
Copper (kg)	22695	19054	21820	18726
Oil (kg)	75827	81591	74494	73655
Tank (kg)	12339	12853	12094	12448
LL (kw)	432.6	503	481.4	495.1
NLL (kw)	106.5	106.1	97	99.2
Material cost ($)	570425	546242	540046	527541

Table 4: Comparing output results.

Citation: Yadollahi M, Lesani H (2017) Global Transformer Design Optimization (GTDO) using Harmony Search and FEM Technique. Global J Technol Optim 8: 205. doi: 10.4172/2229-8711.1000206

H_{LV}	11.2	-
B_{LV}	5.6	-
H_{HV}	2	-
B_{HV}	2	-
Magnetic steel (kg)	606	-
Copper (kg)	304	-
SCI (%)	6.3	6.2
Top oil temperature rise (°C)	48	49
Average LV temperature rise (°C)	45	44
Average HV temperature rise (°C)	58	57
LL (kw)	4.1	4.06
NLL (kw)	0.7	0.69

Table 5: Comparison of experimental test result and output result of algorithm for 400 KVA.

Figure 4: Transformer test object.

output results are finally validated by FEM. An exhaustive comparative study is carried out and shows that the cost function in our proposed HS-FEM is reduced by 2.5%, 3.7%, and 7.6% in comparison to GA, DE, and MINLP, respectively.

References

1. Mehta HD, Patel RM (2014) A review on transformer design optimization and performance analysis using artificial Intelligence techniques. Int J Sci Res 3: 726-733.
2. Amoiralis I, Tsili A, Kladas AG (2009) Transformer design and optimization: A literature survey. Power Delivery. IEEE Transactions 24: 1999-2024.
3. Coelho LS, Mariani VC, Guerra FA, Luz MVF, Leite JV (2014) Multi objective optimization of transformer design using a chaotic evolutionary approach. IEEE Transactions on Magnetics 50.
4. Versele C, Deblecker O, Lobry J (2009) Multi objective optimal design of high frequency transformers using genetic algorithm. Proc. 13th European Conference on Power Electronics and Applications.
5. Kulkarni SV, Khaparde SA (2004) Transformer engineering design & practice. Marcel Dekker, Inc., New York.
6. Karsai K, Kerenyi D, Kiss L (1987) Large power transformers studies in electrical and electronic engineering. 25.
7. Gerome LH, Souza CR (2002) The applications of intelligent systems in power transformer design in Proc. of the IEEE Canadian Conf. Electrical Computer Eng 1: 285-290.
8. Amoiralis EI, Tsili MA, Kladas AG (2007). Global transformer design optimization using deterministic and non-deterministic algorithms. IEEE Transactions on Industry Applications.
9. Georgilakis PS, Tsili MA, Souflaris AT (2007) A heuristic solution to the transformer manufacturing cost optimization problem. J Materials Process Tech 181: 260-266.
10. Subramanian, Padma S (2011) Optimization of transformer design using bacterial foraging algorithm. Int J Comp Application 19.
11. Coelho LS, Mariani VC, Luz MCF, Leite JV (2013) Novel gamma differential evolution approach for multi objective transformer design optimization. IEEE Transaction on magnetic 49.
12. Amoiralis EI, Tsili MA, Georgilakis PS, Kladas AG, Souflaris AT (2008) A parallel mixed integer programming-finiteelement method technique for global design optimization of power transformers. IEEE Transactions on Magnetics 44: 1022-1025.
13. Georgilakis PS, Gioulekas AT, Souflaris AT (2007) A decision tree method for the selection of winding material in power transformers. J Mater Processing Tech 181: 281-5.
14. Amoiralis EI, Georgilakis PS, Kefalas TD, Tsili MA, Kladas AG (2007) Artificial intelligence combined with hybrid FEM-BE techniques for global transformer optimization. IEEE Transaction on magnetic 43: 1633-1636.