

PARAMETER ESTIMATION OF DISTRIBUTION TRANSFORMER USING HARMONY SEARCH ALGORITHM

A Dissertation submitted in fulfillment of the requirements for the Degree
of

MASTER OF ENGINEERING
in
POWER SYSTEMS

Submitted by

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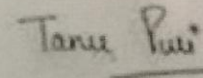
2015

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CERTIFICATE

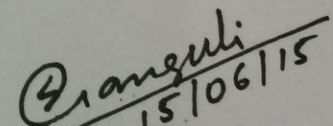
I hereby certify that the work which is being presented in the dissertation entitled "Parameter estimation of Distribution transformer using Harmony Search Algorithm" in partial fulfillment of the requirement for the award of the degree of Master in Engineering in Power Systems submitted in the Electrical & Instrumentation Engineering Department of Thapar University, Patiala, is an authentic record of my own work carried out under supervision of Mr. Souvik Ganguli, Assistant Professor, EIED.

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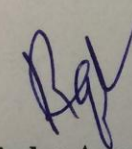


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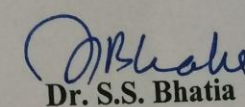
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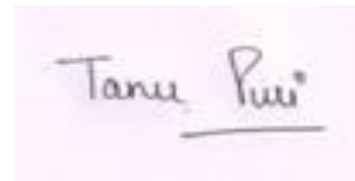
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I am also thankful to my batch mates who devoted their valuable time for the successful completion of dissertation. I extend my gratitude to the researchers and scholars whose hours of toil have produced the papers that I have utilized in my project.

A handwritten signature in black ink on a light pink background. The signature reads "Tanu Puri" with a horizontal line underneath the name.

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LIST OF ABBREVIATIONS

Harmony Search –HS

Least Error Square Algorithm – LESA

Recursive Least Square Algorithm - RLSA

Bacterial Foraging Algorithm -BFA

Genetic Algorithm -GA

Artificial Neural Network Method -ANN

Simulated Annealing Method - SA

Particle Swarm Optimization - PSO

Firefly Algorithm -FA

Harmony memory size - HMS

Harmony memory considering rate - HMCR

Pitch adjusting rate - PAR

Harmony memory - HM

Bat Algorithm - BA

Cuckoo Search - CS

SYNOPSIS

In this work, the harmony search algorithm is applied to optimize the different unconstrained non linear benchmark functions viz. Sphere & Rosenbrock to highlight the efficacy of the algorithm and also observe the effect of user defined parameters of harmony search algorithm in the function optimization problems. The study of harmony search algorithm and its modified/improved version in the field of electrical engineering has also been surveyed. To estimate the parameters of distribution transformer, two objective functions have been taken: (1) minimize the voltage regulation (2) minimize the voltage regulation and maximize the efficiency simultaneously. Then the estimated results are compared with measured values and other different techniques existing in literature.

CHAPTER 1

INTRODUCTION

1.1 Background of work

Transformer is one of the most common equipment in power systems. Single phase transformers find major usage in the field of power electronics [26]. In the field of Power system, transformers perform the task of voltage, current transformation and electrical isolation. Due to massive iron cores and copper windings, transformers are one of the heaviest and most expensive electrical equipment in the distribution system [46]. Transformers are very common and can be found across everywhere. It has various applications such as supplying electricity to the escalator in the department store, the oven in the local bakery, the office computer, the hotel lift, the farm machinery and the petrochemical plant. Transformers are the most important units in every production process. Without transformers, the core activities of nearly every business and factory would come to a standstill with serious financial consequences [22]. Basically, a transformer consists of core, coil, tank, insulation and other accessories. The iron core is made up of laminations to reduce eddy current losses and the material is silicon alloy to reduce hysteresis losses and to improve magnetization characteristics. Reducing the thickness of laminations reduces the eddy current losses in the core. There are two classes of coils - concentric (cylindrical) windings and interleaved (pancake) windings. For concentric windings, the high-voltage coil is typically wound over the low-voltage coil to obtain good coupling between windings. For interleaved windings, the high-voltage and the low-voltage windings are stacked in alternating pancake-shaped coils. In actual design, many modifications are used by the various manufactures. Paper, pressboard, mineral oil, and epoxy resin are used for insulation [6]. Pole mounted Single phase transformer supplies single phase residential load. This type pole mounted transformer consists of three secondary terminals, one of which is ground and other two are phase terminals. Two phase wires provide 240 volts across them, and the voltage across a random phase wire and the ground wire is 120 volts. So there is an option to supply consumer either of 120 or 240 volts supply according to his requirement. Actually in this system, the secondary winding of the distribution transformer is centre tapped. The centre wire is grounded and marked as neutral. The two end conductors of the winding are called hot wire.

Distribution system is of various types such as single phase transformer, three phase transformer, pad mounted transformer, pole mounted transformer, and underground transformer. Distribution transformers are small in size and consist of insulating oil. These transformers are available in different sizes and efficiencies. The purpose and budget of the end users are the basis of selection of a particular transformer. Distribution transformers are not supposed to run with constant load throughout 24 hours. At day peak time its loading is high, on contrary at night time its loading may be negligible. So conventional efficiency as a selection criterion is not practical and economical [57]. The secondary voltage is the voltage delivered to the end consumer. Due to the voltage drop limitations, it is usually not possible to deliver secondary voltage over great distances. Ultimately, most distribution systems involve many 'clusters' of loads fed by distribution transformers, and eventually it means that the thermal rating of distribution transformers does not have to be high enough to support the loads served by them [58].

Estimation of its equivalent circuit parameters is particularly useful in performance computations, load flow studies, monitoring of rise in winding temperature and health of transformer, design of relays in protection circuit of transformer etc.[45] The conventional method for parameter estimation of transformer is difficult due to its physical construction and measurements of parameters are not always reliable. The parameters can be calculated using open and short circuit test which are based on least error square approach [42]. The bacterial foraging technique for optimal design of transformer was developed in [14].

There are two tests are performed on a transformer to determine equivalent circuit of transformer [56].

1.1.1 Open Circuit Test

The connection diagram of open circuit test on transformer is as per the figure. A voltmeter, wattmeter, and an ammeter are connected in LV side of the transformer. With the help of variac of auto transformer, the voltage at rated frequency is applied to that LV side. The HV side of the transformer is kept open. Now applied voltage gets slowly increased with the help of variac until the voltmeter gives reading equal to the rated voltage of the LV side. After reaching at rated LV side voltage, all three instruments reading (Voltmeter, Ammeter and Wattmeter readings) are recorded.

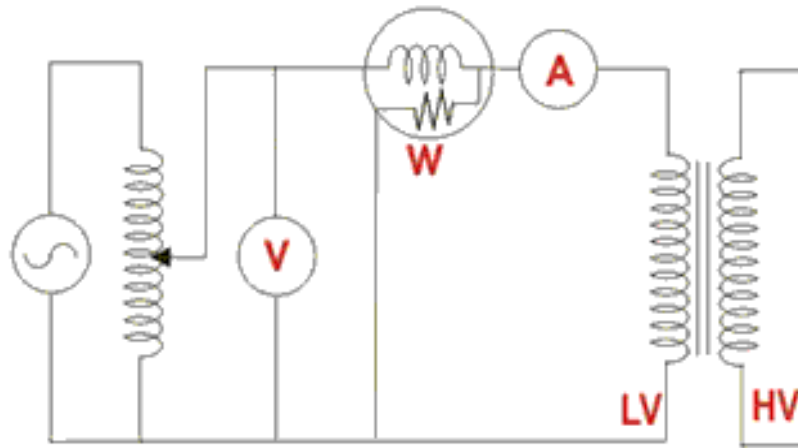


Fig.1.1 Open Circuit test of transformer

Since, voltmeter reading V_1 can be considered equal to secondary induced voltage of the transformer, the input power during test is indicated by watt-meter reading. As the transformer is open circuited, there is no output, hence the input power here consists of core losses in transformer and copper loss in transformer during no load condition. But as said earlier, the no load current in the transformer is quite small compared to full load current, so copper loss due to the small no load current can be neglected. Hence, the wattmeter reading can be taken as equal to core losses in transformer. Let us consider wattmeter reading is P_o .

$$P_o = \frac{V_1^2}{R_m} \quad \text{..... (1.1)}$$

Where R_m is shunt branch resistance of transformer.

If, Z_m is shunt branch impedance of transformer.

$$\text{Then, } Z_m = \frac{V_1}{I_e} \quad \text{..... (1.2)}$$

Therefore, if shunt branch reactance of transformer is X_m ,

$$\text{Then, } \left(\frac{1}{X_m}\right)^2 = \left(\frac{1}{Z_m}\right)^2 - \left(\frac{1}{R_m}\right)^2 \quad \text{..... (1.3)}$$

These values are referred to the LV side of transformer as because the test is conducted on LV side of transformer. These values could easily be referred to HV side by multiplying these values with square of transformation ratio. Therefore it is seen that the open circuit test on transformer is used to determine core losses in transformer and parameters of shunt branch of the equivalent circuit of transformer.

1.1.2 Short Circuit test

The connection diagram for short circuit test on transformer is shown in the figure. An Ammeter, wattmeter and a voltmeter are connected in HV side of the transformer as in figure. The voltage at rated frequency is applied to that HV side with the help of a variac of variable ratio auto transformer.

The LV side of the transformer is short circuited. Now with the help of variac applied voltage is increased slowly leading to ammeter giving reading equal to the rated current of the HV side. After rated current of HV side is achieved, all three instruments reading (Voltmeter, Ammeter and Watt-meter readings) are recorded. The ammeter reading represents the primary equivalent of I_L (full load current). The core losses in transformer can be taken as negligible here, as the voltage corresponding full load current for short circuit test on transformer is quite small as compared to the rated primary voltage of the transformer.

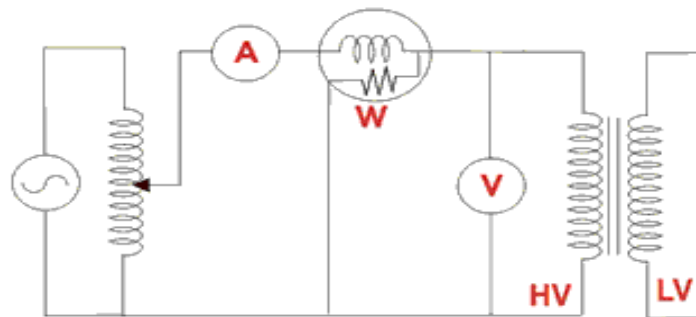


Fig. 1.2 Short Circuit test of transformer

Let's say, voltmeter reading is V_{sc} . The input power during test is indicated by watt-meter reading. As the transformer is short circuited, there is no output; hence the input power here consists of copper losses in transformer. Since, the applied voltage V_{sc} is short circuit voltage in the transformer and hence it is quite small compared to rated voltage, so core loss due to the small applied voltage can be neglected. Hence the wattmeter reading can be taken as equal to copper losses in transformer. Let us consider wattmeter reading is P_{sc} .

$$P_{sc} = R_e I_L^2$$

Where R_e is equivalent resistance of transformer.

If, Z_e is equivalent impedance of transformer.

$$\text{Then, } Z_e = \frac{V_{sc}}{I_L} \quad \dots\dots\dots(1.4)$$

Therefore, if equivalent reactance of transformer is X_e

$$\text{Then, } X_e^2 = Z_e^2 - R_e^2 \quad \dots\dots\dots (1.5)$$

These values are referred to the HV side of transformer as because the test is conducted on HV side of transformer. These values could easily be referred to LV side by dividing these values with square of transformation ratio.

Therefore it is seen that the short circuit test on transformer is used to determine copper loss in transformer at full load and parameters of approximate equivalent circuit of transformer.

Harmony Search (HS) is a search heuristic based on the improvisation process of jazz musicians. In jazz music the different musicians try to adjust their pitches, such that the overall harmonies are optimized due to aesthetic objectives. Starting with basic harmonies, they attempt to achieve better harmonies by implementing improvisation. This analogy can be used to derive search heuristics, which can be used to optimize a given objective function instead of harmonies. Here the musicians are identified with the decision variables and the harmonies correspond to solutions. Like jazz musicians create new harmonies by improvisation, the HS algorithm creates iteratively new solutions based on previous solutions and on random modifications [47]. Harmony Search is a successful example by transforming the qualitative improvisation process into some quantitative rules by idealization, and thus turning the harmony and beauty harmony of music into an optimization procedure through search for a perfect harmony, namely, the Harmony Search algorithm [49]. Thus, we have applied this algorithm to optimize the parameters of a distribution transformer.

1.2 Objective of work

The dissertation fulfils the following objectives:

- i. To explore parameter estimation techniques of distribution transformer.
- ii. To optimize few unconstrained non- linear test functions using Harmony Search Algorithm (HSA).
- iii. To observe the effect of user defined parameters of harmony search algorithm in function optimization problems.
- iv. To study the application of harmony search algorithm and its modified/improved version in electrical engineering applications.

v. To estimate the parameters of distribution transformers using single objective and multi-objective function. Minimizing the voltage regulation was considered in the first case while in the later case, simultaneous minimization of voltage regulation and maximization of efficiency were taken up.

1.3 Organization of dissertation

Chapter 2 elaborates the literature review of the techniques of distribution transformer using classical and intelligent algorithms.

Chapters 3 discuss the Harmony Search Algorithm and its implementation on various unconstrained, non-linear standard functions like Sphere function and Rosenbrock function. Further the effect of user defined parameters of harmony search algorithm has been observed. Electrical engineering applications of harmony search algorithm and its modified/improved versions have also been reported.

Chapter 4 presents the results of parameter estimation of distribution transformer using harmony search algorithm. Furthermore, overall conclusions and future perspectives of the dissertation are also highlighted.

CHAPTER 2

PARAMETER ESTIMATION OF DISTRIBUTION TRANSFORMER

2.1 Introduction

The system study has parameter estimation as one of the important problem to solve. The conventional method of using short-circuit test data of parameter determination provides an approximate equivalent circuit. This method needs minimum of two tests, Firstly short circuit test and other one is direct current resistance test. The both tests are conducted at supply conditions different from normal operation. [43]. It helps in circuit performance analysis, transient studies, identification of parasitic elements etc. An adequate modelling of the transformer equivalent circuit and various techniques has been applied for parameter estimation and are required in the electromagnetic transient studies [26].

A good accuracy in the estimation of equivalent circuit parameters is important as they directly influence the performance computations such as efficiency, voltage regulation, etc. The parameter estimation of transformer depends on its physical features and actual operating conditions. Hence, a powerful tool is needed to estimate the transformer equivalent parameters.

2.2 Literature review

Thilagar *et al.* [45] showed a method to find equivalent circuit parameters of transformer. This paper compared the results of conventional method with genetic algorithm and found superior results.

Soliman *et al.* [42] has a different approach to existing open and short tests for determining the parameters of transformer. It concluded that to identify the on-line parameters of the power transformer, least errors square algorithm can be used.

Cho *et al.* [6] developed the approach of parameters estimation to calculate the parameters of transformer. This method needed the nameplate data of transformer and physical dimensions of the core.

Feyzi *et al.* [11] proposed a recursive least square method to find the resistances and inductances of transformer. This method did not used any initial assumption. Forgetting factor was used to remove the previous data.

Bogarrra *et al.* [5] proposed a method to calculate the parameter of transformer using inrush and no load test. It is concluded that use of only no-load test data to determine the saturation curve can give wrong parameter estimation.

Xin-She Yang *et al.* [49] proposed a harmony search based on musical metaheuristic optimization algorithm. Harmony search is population based technique which depends on acceptance rate. It was concluded that this is easier algorithm to implement. (2009).

Arjona *et al.* [4] proposed a combined approach for estimating the parameters. The genetic algorithm first find the global solution and finite element method calculated the desired parameters. It is concluded that this approach gives best design results in short time. (2010)

Padma *et al.* [26] presented a technique for estimation of parameters of single phase transformer. This technique was compared with conventional method and it is concluded that proposed method gives less error and better efficiency. (2010)

Alia *et al.* [3] presented an overview of basic concept of Harmony search algorithm and it was concluded that this method gives better results than other meta-heuristic algorithms. (2011)

Subramanian *et al.* [43] proposed an optimal design method of single phase transformer with the used of bacterial foraging algorithm. This technique used the behaviour of E coli bacteria to reduce the transformer cost and increase its efficiency. (2011)

Qin *et al.* [31] presented a harmony search algorithm with differential mutation. It improved the original pitch adjustment. This technique can be used to solve numerical and real world optimization problem. (2011)

2.3 Parameter estimation methods

Parameter estimation is the process of using sample data to estimate the parameters of the selected distribution. Parameters can be estimated by different ways. Brief explanation of methods is as below:

2.3.1 Equivalent Circuit Method

To determine the steady state parameters of the transformer by conventional method is to perform the open and short-circuited tests. In the open-circuit a voltage equals to the rated primary voltage at rated frequency is applied to the primary windings with the secondary windings open. The current and active power at the primary windings is measured in open-circuit voltage, and the core parameters (R_c , X_m ,) are calculated by using the approximate no-load equivalent circuit. Whereas in the short-circuit test, a reduced voltage at rated frequency is applied to the primary windings to get the rated current in the primary windings, while the

secondary windings is short-circuited. The short-circuit current, voltage and active power values are measured and the windings parameters (R_{eq1} , X_{eq1}) referred to the primary side are computed by using the approximate short circuit equivalent circuit.[42]

2.3.2 Least Error Square Algorithm (LESA)

The digitized samples of the input current and voltage as well as the output current and voltage of the transformer windings are used in Least Error Square Algorithm. The proposed algorithm estimates the winding parameters in two steps; the algorithm identifying the winding parameters in the first step, while the algorithm identifying the core parameters in the second step.

The basic steps included in the method are:

- (1) Identifying the winding parameters.
- (2) Identifying the core parameters.
- (3) Simulated results.

The advantages of using LESA is that it can be implemented to:

- Identify the on-line parameters of the power transformer
- Identify the internal winding fault of the transformer, by measuring the variation in the winding parameters. [42]

2.3.3 Recursive Least Square Algorithm (RLSA)

RLSA method helps in estimating the dynamic equivalent circuit parameters of a transformer at its actual operating point. The proposed method needs only four terminal variables of the transformer which can be easily sampled in any actual transformer. No external excitation signals & no initial information are needed. As the actual sampled data is directly fed to the routine, no variable conversion like reference frame conversion is required. In this work, the simulation results from PSCAD are applied as the representative of sampled data from an actual transformer. The advantage of using RLSA is that it gives a quick and successful convergence in the estimation of required parameters [11].

2.3.4 Bacterial Foraging Algorithm (BFA)

Bacterial Foraging Algorithm are used to estimate the equivalent circuit parameters of the Three Winding Transformer (TWT). This method needs minimum of two tests: short circuit

test and direct current resistance test and are conducted at supply conditions different from normal operation. The group foraging behaviour of bacteria such as E.coli and M.xanthus forms the basis of BFOA. Specifically the chemotaxis behaviour of bacteria in which it will perceive chemical gradients in the environment (such as nutrients) and move toward or away from specific signals. Based on the gradients of chemicals in their environment, bacteria perceive the direction to food. Similarly, attracting and repelling chemicals are secreted by the bacteria into the environment and can perceive each other in a similar way. Bacteria can move around in their environment using locomotion mechanisms (such as flagella), or may move chaotically (tumbling and spinning), and other times move in a directed manner like swimming. Bacterial cells are treated like agents in an environment, using their perception of food and other cells as motivation to move, and stochastic tumbling and swimming like movement to re-locate. Cells may swarm a food source, and/or may aggressively repel or ignore each other depending on the cell-cell interactions. The information processing strategy of the algorithm allow cells to stochastically and collectively swarm toward optima. This is achieved through a series of three processes on a population of simulated cells:

- 1) 'Chemotaxis' where the cost of cells is derated due to proximity to other cells and cells move one at a time along the manipulated cost surface (the majority of the work of the algorithm),
- 2) 'Reproduction' the only cells which performed well over their lifetime may contribute to the next generation, and
- 3) 'Elimination-dispersal' in which cells are discarded and new random samples with a low probability are inserted [58].

The basic steps included in the algorithm are:

Step 1: Intialize parameters P, s, Nre, Ned, Ped, C (i)

Step 2: Elimination-dispersal loop: l =

Step 3: Reproduction loop: k = k +

Step 4: Chemotaxis loop: j = j + 1

Step 5: If $j < N_c$, go to step 4.

Step 6: Reproduction:

Step 7: If $k < N_{re}$ go to 3.

Step 8: Elimination-dispersal.

The BFA has the advantages of having less mathematical burden, accurate estimate, high quality solution, fast convergence and less computational time. Also, this method can be applied to any capacity of transformer [43].

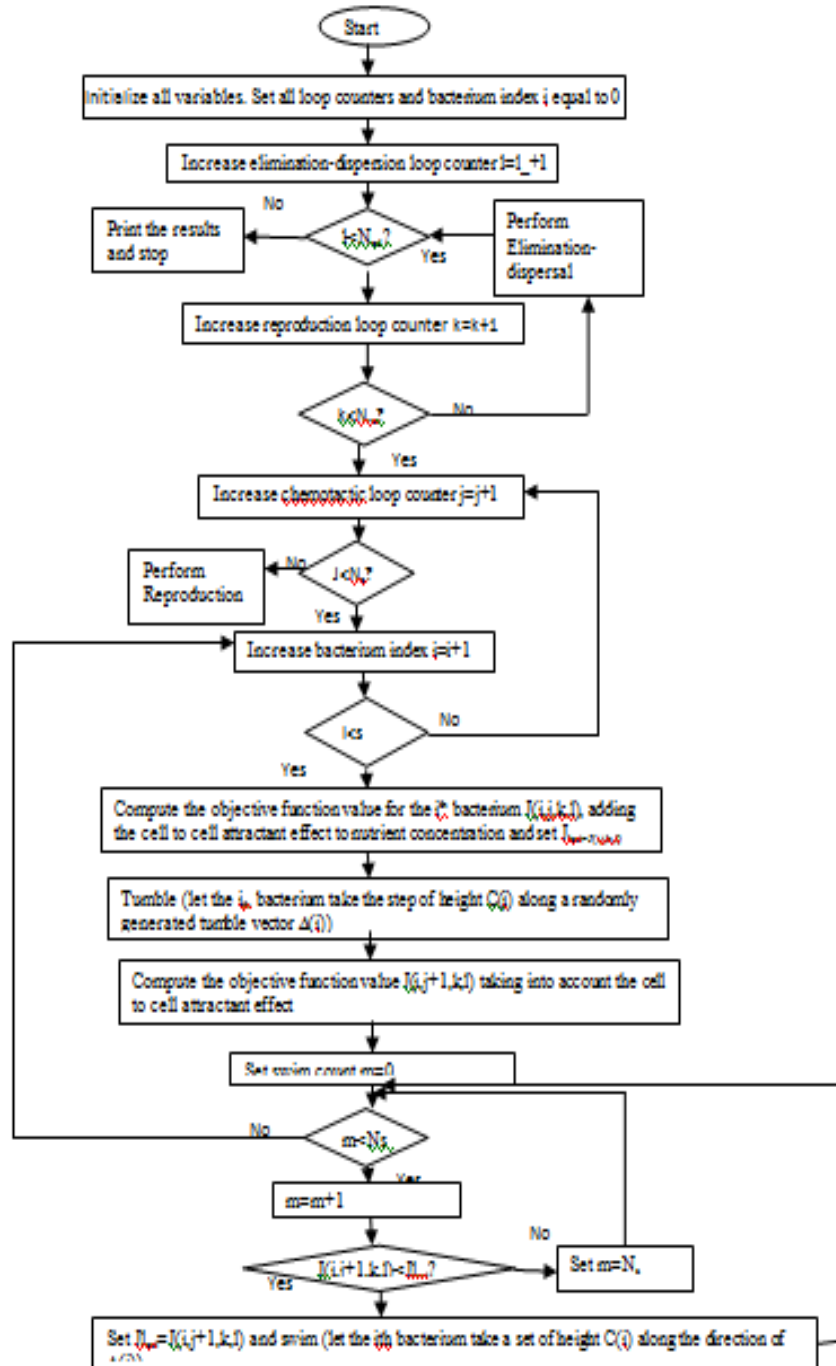


Fig 2.1: Flow Chart of Bacterial Foraging Algorithm

2.3.5 Genetic Algorithm (GA)

Genetic algorithm—a robust and global optimization technique—is applied in the parameter estimation problem. It is an Adaptive Strategy and an Evolutionary Algorithm which belongs to the broader study of Evolutionary Computation. The Genetic Algorithm is a sibling of other Evolutionary Algorithms like Genetic Programming, Evolution Strategies, Evolutionary Programming and Learning Classifier Systems. It is a parent of a large number of variant techniques and sub-fields too numerous to list. Population genetics (including heredity and gene frequencies), and evolution at the population level, as well as the Mendelian understanding of the structure (such as chromosomes, genes, alleles) and mechanisms (such as recombination and mutation) inspires The Genetic Algorithm. This is the so-called new or modern synthesis of evolutionary biology. In the form of offspring, individuals of a population contribute their genetic material (called the genotype) proportional to their suitability of their expressed genome (called their phenotype) to their environment. The next generation is created by mating the recombination of two individual's genomes in the population with the introduction of random copying errors (called mutation). This iterative procedure may outcome in an improved adaptive-fit between the phenotypes of individuals in a population and the environment. To maximize the payoff of candidate solutions in the population against a cost function from the problem domain is the objective of the Genetic Algorithm. The approach for the Genetic Algorithm is to repeatedly employ surrogates for the recombination and mutation genetic mechanisms on the population of candidate solutions. Where the cost function (also known as objective or fitness function) applied to a decoded representation of a candidate governs the probabilistic contributions a given candidate solution can make to the subsequent generation of candidate solutions [58].

The basic steps included in the algorithm are:

- 1) The first population of individuals is chosen
- 2) The fitness of each individual in above population is evaluated
- 3) The best-fit individuals for reproduction are selected
- 4) New individuals through crossover and mutation operations to give birth to offspring are breed
- 5) The individual fitness of each of the new individuals is estimated
- 6) The least-fit population is replaced with the new individuals

GA based in situ parameter estimation of TWT has superior results than conventional optimization methods because in GA method, the search starts parallel at several points in the solution space and it exploits the historical information of better individuals to survive and reproduce to provide still better solutions. It helps the search to come out of local optimum solutions and converge to global optimum solutions in presence of non-linear parameters and the parameters with large magnitude difference.

The GA can obtain global optimum solution rather than just providing local minima. GA is mainly used in image processing, system identification, and fuzzy logic controller design [45].

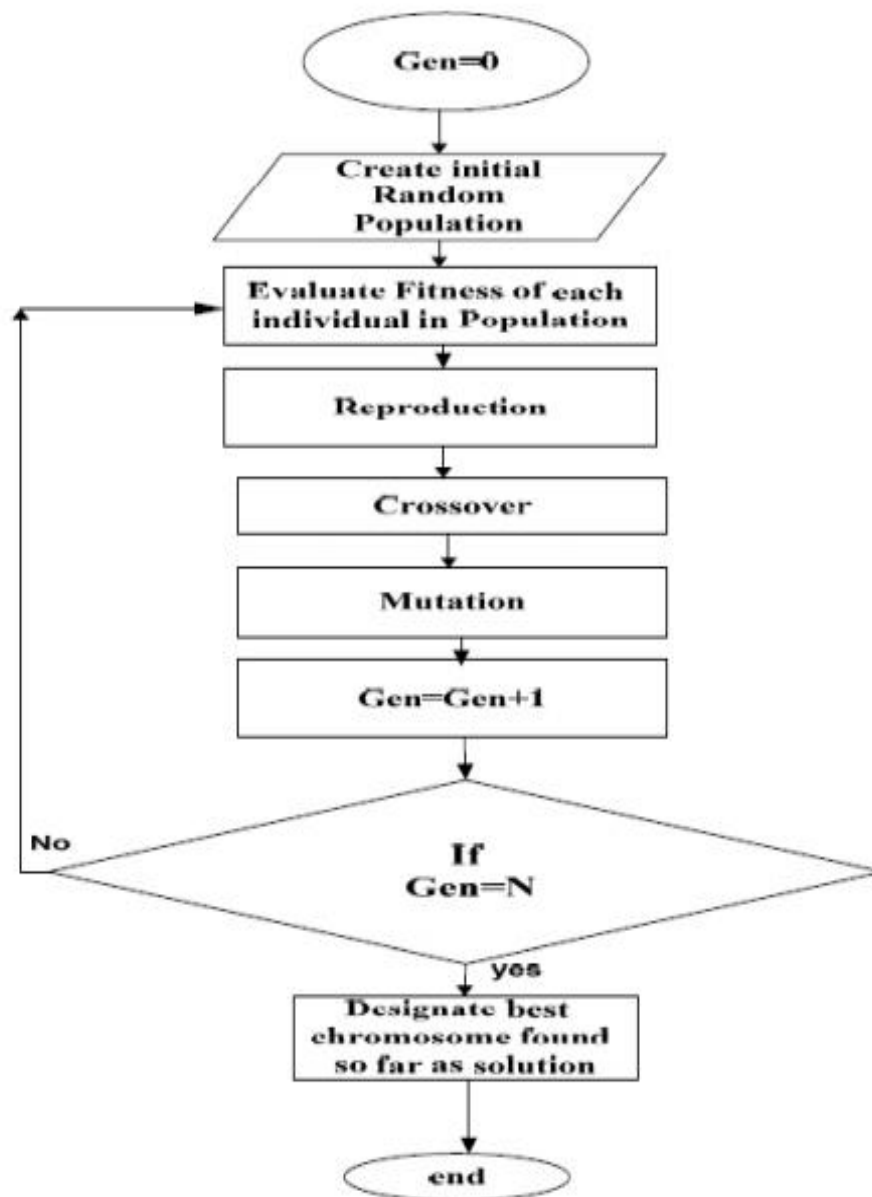


Fig 2.2: Flow Chart of Genetic Algorithm

2.3.7 Artificial Neural Network Method (ANN)

Artificial neural networks (ANN) have been used in this paper to estimate the winding transient parameters. After parameter estimation of transformer winding it is possible to compare the results with the design parameters. A deviation between these two sets of parameters indicates a design problem which is detected before applying a destructive impulse voltage on transformer winding. The capability of ANN technique to give an attractive solution to different transformers problems is due to map complex and highly non-linear input/output patterns [18]. The use of this method is in transformer manufacturing industry.

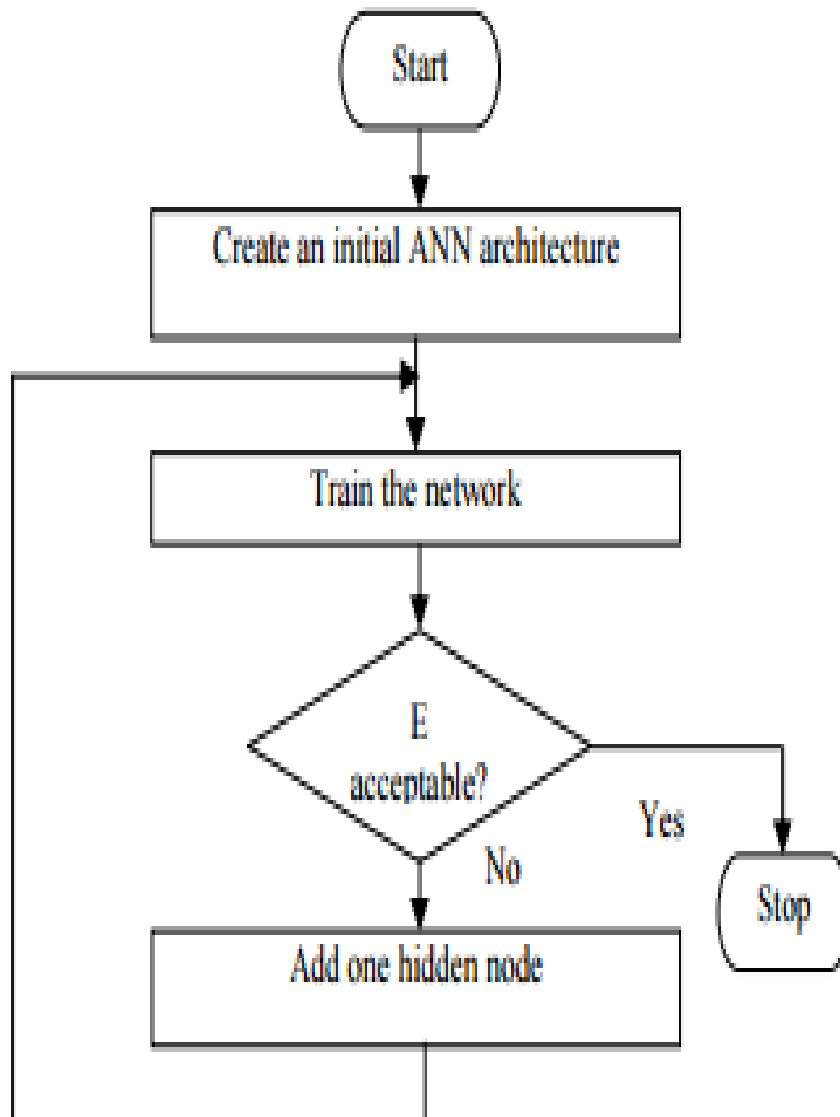


Fig. 2.3 Flow Chart of Artificial Neural Network

2.3.8 Simulated Annealing Method (SA)

Simulated Annealing is a global optimization algorithm which belongs to the field of Stochastic Optimization and Metaheuristics. Simulated Annealing is a revision of the Metropolis-Hastings Monte Carlo algorithm. It is used in function optimization. It provides a basis for a large variety of extensions and specializations of the general method like the Genetic Algorithm and is not limited to Parallel Simulated Annealing, Fast Simulated Annealing, and Adaptive Simulated Annealing. Process of annealing in metallurgy forms the basis of Simulated Annealing. A material is heated and slowly cooled under controlled conditions to increase the size of the crystals in the material and reduce their defects. It improves the strength and durability of the material. The heat raises the energy of the atoms which allows them to move simply, and the slow cooling schedule permits a new low-energy configuration to notice and exploit. Each unit of a solution in the search space represents a different internal energy of the system. Heating the system causes the relaxation of the acceptance criteria of the samples taken from the search space. The acceptance criteria of samples is narrowed to focus on improving movements upon cooling the system. After the system has cooled, the configuration will represent a sample at or close to a global optimum. The main objective of the technique is to locate the minimum cost configuration in the search space. The algorithm's plan of action is to re-sample the problem space probabilistically where the acceptance of new samples into the currently held sample is managed by a probabilistic function. It becomes more discerning of the cost of samples it accepts over the execution time of the algorithm. Metropolis-Hastings algorithm for simulating samples from a thermodynamic system forms the basis of this probabilistic choice. [58]

The steps of the algorithm are:

Step 1: Transformer data read, independent variables, constraints and set initial temperature.

Step 2: Formulate of the objective function (i.e., initial mass of core and copper) and calculate the initial mass of core and copper of transformer.

Step 3: Set $i=1$ compute $X_i = X_i + \Delta X$ and calculate the value of objective function ($F_{i_{new}}$)
Also calculate $\Delta F = F_{i_{new}} - F_1$.

Step 4: Take or discard each point using Metropolis's criterion.

- Step 5:** Check if the number cycles is greater than maximum number of cycles go to next step or go to step 3.
- Step 6:** Change step size, reset number of cycle.
- Step 7:** Check if the number of step adjustment is greater than maximum number of cycles go to below step or go to step 3.
- Step 8:** Reduce temperature, reset number of change to 0. Fix current point as optimum.
- Step 9:** Stop, if temperature is low otherwise go to step 3.

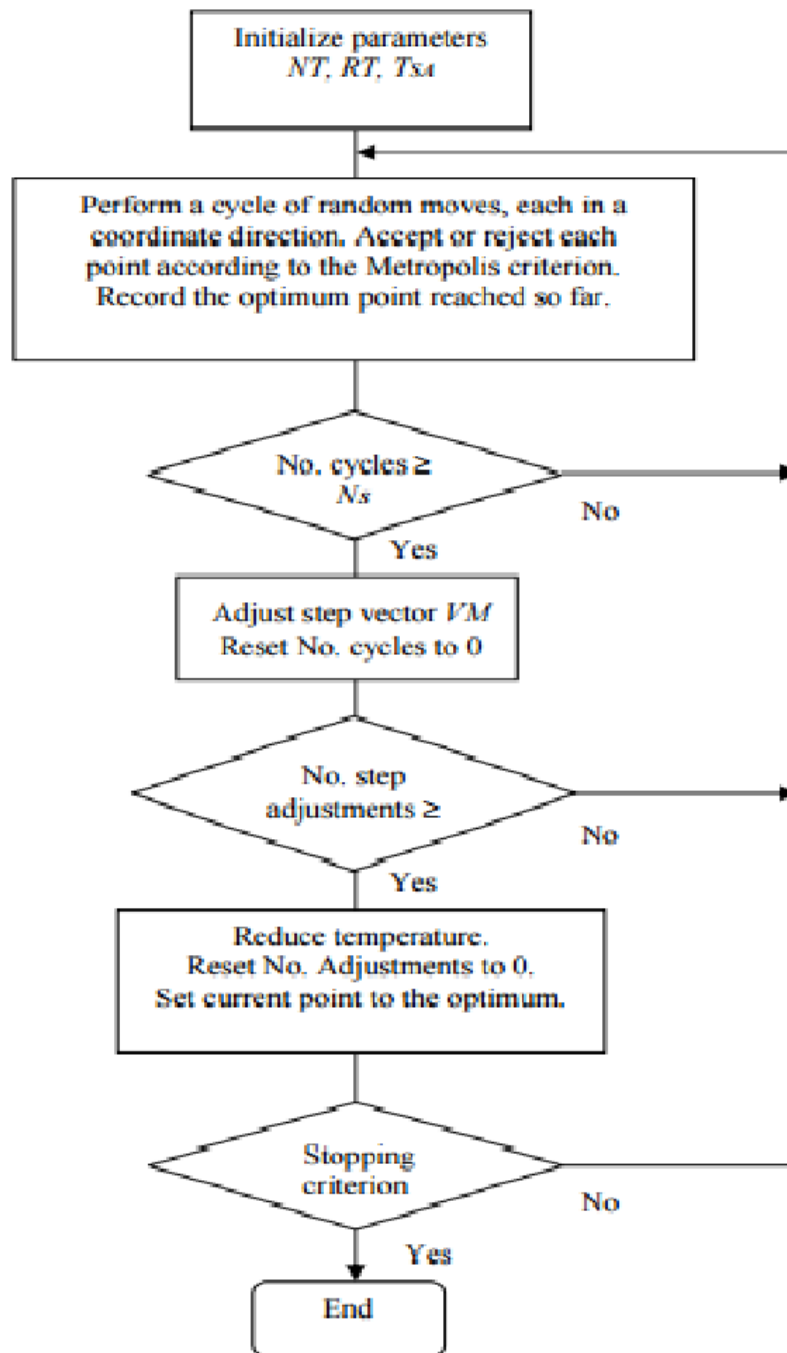


Fig. 2.3 Flow Chart of Simulated Annealing

2.4 Conclusion

In this chapter, we have carried out the literature review of the parameter estimation techniques pertaining to distribution transformer. These techniques are broadly classified as classical and intelligent algorithm based methods. This chapter also briefly discusses these techniques employed for parameter estimation of distribution transformer. In the next chapter, Harmony Search Algorithm (HSA) is discussed in detail. The chapter further discusses the effect of user defined parameters of Harmony Search Algorithm for unconstrained optimization functions such as: sphere, and rosenbrock. Electrical engineering applications of harmony search algorithm are also reported in the next chapter.

CHAPTER 3

HARMONY SEARCH ALGORITHM

3.1 Introduction

Optimization techniques in engineering can be found in several analysis problems arising in engineering model development. Given a set of test data, this parameter estimation problem inherently transforms to an optimization problem to define the parameters of some semi-theoretical model, because the model parameters must be chosen so that the model fits the data as closely as possible. A wide-ranging formulation of nonlinear constrained optimization problem can be given by:

$$\text{Minimize } F(\mathbf{x}) \text{ for } \mathbf{x} = (x_1, x_2, \dots, x_N) \quad \text{.....(3.1)}$$

$$\text{subject to } g_j(\mathbf{x}) \geq 0 \text{ for } j=1, 2, \dots, J \text{ and } h_k(\mathbf{x}) = 0 \text{ for } k=1, 2, \dots, K$$

where, \mathbf{x} variables (a set of design parameters)

$F(\mathbf{x})$: objective functions to be minimized

$g_j(\mathbf{x})$: inequality constraints

$h_k(\mathbf{x})$: equality constraints

The parameters may be determined by minimizing the sum of quadratic errors of the approximate values with respect to the exact values.

$$F(x) = \sum_{i=1}^N [y_i - f(x, \theta_i)]^2 \quad \text{..... (3.2)}$$

Where, y_i : test data at the test condition θ_i

$F(\mathbf{x}, \theta_i)$: predicted value at the test condition θ_i

The difference $y_i - f(\mathbf{x}, \theta_i)$ between the test data y_i and the predicted value $f(\mathbf{x}, \theta_i)$ measured the closeness of prediction to the test data and is called the residual. At all the test points, the sum of the squares of the residuals gives an indication of goodness of the fit. This data-fitting problem is the optimization problem in which $F(\mathbf{x})$ is minimized by appropriate choice of \mathbf{x} . The tasks in the unconstrained optimization approach of the Equation (3.2) are false solutions like “local optima” that only satisfy the requirements on the derivatives of the functions without constraints. Therefore, a constrained optimization approach may be suitable for parameter estimation of transformer model. Lagrange multipliers are the necessary conditions of optimality for equality-constrained problems. Kuhn-Tucker conditions are the necessary conditions of optimization problems with equality and inequality constraints:

$$\nabla F(x) - \sum_{j=1}^J u_j \nabla g_j(x) - \sum_{k=1}^K v_k \nabla h_k(x) = 0 \quad \text{..... (3.3)}$$

$g_j(\mathbf{x}) \geq 0$ for $j=1,2,\dots,J$ and $h_k(\mathbf{x})=0$ for $k=1,2,\dots,K$

$u_j g_j(\mathbf{x})=0$ and $u_j \geq 0$ for $j=1,2,\dots,J$

Where, $\nabla F(\mathbf{x})$: N-component column vector of first derivatives of $F(\mathbf{x})$

$\nabla g_j(\mathbf{x})$: J-component column vector of first derivatives of $g_j(\mathbf{x})$

$\nabla h_k(\mathbf{x})$: K-component column vector of first derivatives of $h_k(\mathbf{x})$

u_j : Lagrange multiplier corresponding to constraint $g_j(\mathbf{x})$

v_k : Lagrange multiplier corresponding to constraint $h_k(\mathbf{x})$

The solutions of Kuhn-Tucker conditions inspire many nonlinear programming algorithms, which directly compute the Lagrange multiplier [6].

Engineering optimization has many strategies. In unconstrained optimization, methods are chiefly categorized in terms of the derivative information. Search methods which do not need gradients or other derivative information and use only function evaluations are most suitable for the problems that are nonlinear or have a number of discontinuities. Simplex search method is one of the typical numerical search method.

Gradient procedures are generally efficient when the function to be minimized is continuous in its first derivative. Gradient procedures use information about the slope of the function $\nabla F(\mathbf{x})$ to decide a direction of search where the minimum is thought to lie. Procedures that use gradient information, there are the quasi-Newton methods or the Conjugate Gradient procedures. Quasi-Newton methods only require differences of gradients of the Lagrangian function. The gradient information is either provided through analytically calculated gradients, or resultant of a numerical differentiation method.

Higher order methods, such as Newton's methods, are only appropriate when the second order information is easily determined since calculation of the second order information, using numerical differentiation, is computationally costly. There are approaches for exploiting linear approximations to nonlinear problems like feasible direction procedures, successive linear approximation methods, quadratic approximation methods or constrained variable metric procedures. There are a number of different optimization approaches. An efficient and precise solution to a given optimization problem is not only dependent on the

size of the problem in terms of the number of constraints and design variables. It also depends on characteristics of the objective function and constraints.[6]

Optimization algorithms are generally categorised as deterministic and stochastic algorithms. Deterministic algorithms i.e. hill-climbing process will produce the same set of solutions if the iterations start with the right values of input whereas, stochastic algorithms do not recurrence the same set of solutions even they are called with the same initial starting point due to randomness component attached with it, though the final outcomes obtained by stochastic algorithms will usually converge to the same optimal solutions within a given correctness. Stochastic algorithms regularly have a deterministic component and a random component attached with it so that it is probable to find global optimum solution in less time. The stochastic component may take several forms such as simple randomization by random sampling the search space or by random walks [52].

Most of the stochastic algorithms are meta-heuristic. Such as Genetic Algorithms (GA), Particle Swarm Optimization (PSO), Firefly Algorithm (FA), Harmony Search (HS) etc. Most of the meta-heuristic algorithms are nature-inspired. Two major parts of any meta-heuristic algorithms are: intensification (selection of the best solutions) and randomization or diversification. The best solution selection will converge to the optimality but randomization avoids the solutions to be trapped at local optima and increase the diversity of the solutions to find the global optima too. The decent combination of these two components will reflect the capacity of the algorithms.

Harmony Search Algorithm (HSA) [53] developed by Zong woos Geem in the year 2001 is a music-based meta-heuristic optimization algorithm. The algorithm is inspired by the music harmony for obtaining optimal harmony in every new improvisation. The best harmony is found in three ways by musician, first is to pick up the best harmony from memory, and second is to adjust the pitch or lastly do the randomization to get optimal solution of the problem.

3.2 Meta-heuristic Harmony Search Algorithm

Harmony Search was motivated by the improvisation of Jazz musicians. Mainly, the process in which the musicians (who may have never played together before) rapidly refine their individual improvisation through variation resulting in an aesthetic harmony.

Each musician match to an attribute in a candidate solution from a problem domain, and each instrument's pitch and range match to the bounds and constraints on the decision variable. At a given time the harmony between the musicians is a complete candidate solution while the audience aesthetic appreciation of the harmony represent the problem specific cost function. Over time the musicians seek harmony through small variations and improvisations, which causes an improvement against the cost function. The objective of the technique is to use good candidate solutions already discovered to influence the creation of new candidate solutions toward locating the problems optima. This is done by stochastically creating candidate solutions in a step-wise manner, where each unit is either drawn randomly from a memory of high-quality solutions, attuned from the memory of high-quality solutions, or allotted randomly within the bounds of the problem. The memory of candidate solutions is initially random, and a new candidate solutions is admitted by desirous acceptance criteria only if they have an improved objective value, replacing an existing member [58].

3.2.1 Mathematical Model of Harmony Search Algorithm

The main steps in the procedure of Harmony Search Algorithm (HSA) are as follows.

Step 1: Set the problem and algorithm parameters

Step 2: Set the harmony memory

Step 3: Improvise a new harmony

Step 4: Update the harmony memory

Step 5: Check the termination criterion

A. Initialize the problem and algorithm parameters

The HS parameters are specified in the step. These are harmony memory size (HMS), or number of solution vectors in the harmony memory; harmony memory considering rate (HMCR); pitch adjusting rate (PAR); and number of improvisations (NI) or stopping criterion. All solution vectors (sets of decision variables) are kept in the harmony memory (HM), a memory location. The parameters HMCR and PAR improve the solution vector and are defined in step 3[3].

B. Initialize the Harmony Memory

The HM matrix is filled with many randomly generalized solution vectors.

$$\begin{bmatrix} x_1^1 & x_2^1 & \dots & x_{N-1}^1 & x_N^1 \\ x_1^2 & x_2^2 & \dots & x_{N-1}^2 & x_N^2 \\ \vdots & \vdots & \dots & \vdots & \vdots \\ x_1^{HMS-1} & x_2^{HMS-1} & \dots & x_{N-1}^{HMS-1} & x_N^{HMS-1} \\ x_1^{HMS} & x_2^{HMS} & \dots & x_{N-1}^{HMS} & x_N^{HMS} \end{bmatrix}$$

C. Generating a new harmony:

When a new control variable is created for the new solution vector as per the first rule variable (x_1') is chosen from the column of the control variable and from a random row in the range of $x_1' - x_1^{HMS}$ from the memory matrix. The other control variables are created in the same manner. In the first stage the HMCR parameter is between 0 and 1. For the memory consideration rule a random number is created. If this number is smaller than the HMCR parameter the control variable is chosen from the memory matrix. Otherwise it is created random in the defined range and the generation step for this control variable is stopped [3].

$$x_1' = \begin{cases} x_1' \mathcal{E} \{ x_i^1 & x_i^2 & \dots & x_i^{HMS} \} \\ x_1' \mathcal{E} X_i \end{cases} \quad \text{..... (3.4)}$$

Pitch Adjusting decision x_1' : Yes with probability PAR

No with probability 1- PAR

The second rule is applied if the control variable is chosen from memory matrix. In this step a random number is created and if this number is smaller than the PAR parameter as told in the first stage, the control variable is pitch adjusted. The pitch adjust is done as below [14]:

The value of 1-PAR sets the rate of doing nothing. If the pitch adjustment decision for x_1' is Yes, x_1' is replaced as:

$$x_1^i = x_1^i \pm rand \times bw \quad \dots \dots (3.5)$$

Where bw is an arbitrary bandwidth and rand is a random number between 0 and 1. HM consideration, pitch adjustment or random selection is applied to each variable of the New Harmony vector in the third step.

D. Updating HM

From the viewpoint of the objective function value, if the new harmony vector $x' = (x_1', x_2', \dots, x_n')$ is better than the worst harmony in the HM, then the new harmony is written in the HM and the existing worst harmony is deleted from the HM.

If the stopping criterion (based on the maximum number of improvisations) is satisfied, then computation is stopped. Otherwise, steps 3 and 4 are repeated [3].

3.2.2 Flow chart of Harmony Search Algorithm:

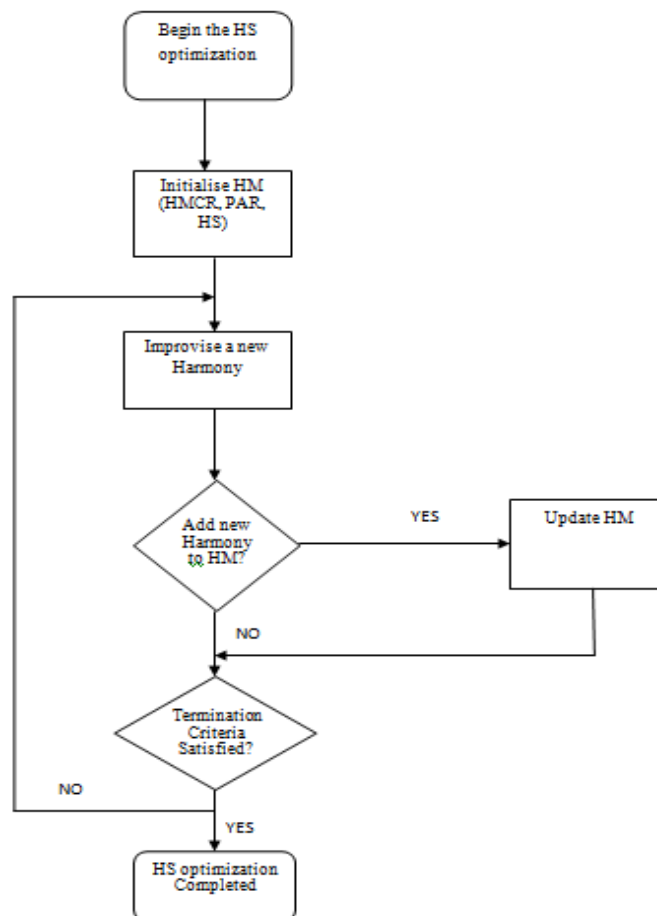


Fig 3.1 Flow Chart of Harmony Search Algorithm

In the next section, electrical engineering applications of harmony search and its modified/improved versions are reviewed.

The salient applications of HSA and their modified /improved versions are tabulated below.

3.3 Literature survey

Majidi et al. [21] applied harmony search algorithm to reduce low order harmonics in multilevel inverters.

Kazemi et al. [25] applied it for the optimal location of FACTS devices to increase the power system security and reduce the cost of total investment.

Pandi et al. [27] showed an improved harmony search algorithm for economic dispatch problem.

Ghosh et al. [13] established a modified harmony search algorithm by setting the bandwidth value in the harmony memory to design IIR filter.

Panigrahi et al. [28] discussed a harmony search base to define the problem of optimal power flow with the help of fuel cost characteristics of generator.

Sinsupan et al. [40] compared harmony search approach with intelligent algorithms to solve the optimal power flow solutions.

Paqaleh et al. [1] concluded that harmony search technique solved power scheduling problem better than the other intelligent techniques.

Ratniyomchai et al. [35] showed the parent harmony search algorithm to solve out the problem of economic load dispatch.

Khazali et al. [16] showed an increased harmony search method for the optimal voltage control and concluded that this gave less transmission loss and better voltage stability.

Yadav et al. [48] suggested a harmony search method to get the best design of brushless DC motor for increasing the efficiency.

Sirjani et al. [41] showed an improved harmony search approach to find the best location of SVC devices and minimized the total power loss.

Shafaati et al. [38] discussed a harmony search based approach to identify the infinite impulse response models. The selected approach converges faster than other techniques.

Boroujeni et al. [23] suggested a harmony search based approach for optimal tuning of power system stabilizers

Lalitha et al. [17] presented a harmony search method for the allotment of real power transmission losses.

Orfanos et al. [12] suggested an increased harmony search algorithm to reduce the investment cost of new transmission line for better power system operation.

Kandezy et al. [15] applied harmony search algorithm to remove the voltage harmonics in the output of multilevel inverters. Convolution operator was used to minimize the needed time.

Sinsuphan et al. [39] developed an improved algorithm for the best performance of power flow in the power system.

Luong et al. [20] showed a hybrid approach based on differential evolution and harmony search to solve the economic dispatch.

Yang et al. [50] suggested a self adaptive harmony search algorithm for the planning of power distribution.

Prabhu et al. [30] established a harmony search approach for the optimum location of wind turbine to obtain maximum generation.

Nekoeei et al. [24] established an improved harmony search algorithm for the best location of distributed generators in the radial distribution system.

Lenin et al. [19] suggested a harmony search based method for the optimal power dispatch for the safe operation of power system.

Saha et al. [37] developed a harmony search algorithm to design the infinite impulse response (IIR) filter. The approach performed the randomized search to find the optimal solution.

Ren et al. [36] showed a harmony search algorithm based approach for the optimal estimation of fault location in the power system.

Rani et al. [33] applied a Harmony Search Algorithm (HSA) for reconfiguration of a radial distribution feeder network.

Effatnejad et al. [9] harmony search algorithm to reduce the operational cost of micro grid when it was isolated and increase its revenue when it was connected.

Sun et al. [44] presented an improved harmony search algorithm to solve the problem of distribution network planning.

Table 3.1 Modifications of Harmony Search Algorithm

S.No	Algorithm	Modification/Improved/ Hybrid	Applications	Ref. No.
1.	Harmony Search	Harmony Search Algorithm	Harmonic Optimization in multilevel inverters	[21]
2.	Harmony search	Harmony Search Algorithm	Optimal placement of FACTS devices	[25]
3.	Harmony search	Bandwidth is adjusted by population variance	Economic Power Dispatch	[27]
4.	Harmony search	Harmony Search Algorithm	Infinite impulse response filter	[13]
5.	Harmony search	Harmony Search Algorithm	Economic Power Dispatch	[28]
6.	Harmony search	Population variance rises exponentially	Optimal power flow	[40]
7.	Harmony search	Harmony Search Algorithm	Power generation scheduling	[1]
8.	Harmony Search	Bandwidth is changed by population variance	Economic Load Dispatch	[35]
9.	Harmony Search	Pitch Adjusting rate and Bandwidth can be adjusted	Optimal placement and sizing of SVC devices	[41]
10.	Harmony Search	Harmony Search Algorithm	Identification of Infinite impulse response system	[38]
11.	Harmony Search	Harmony Search Algorithm	Controlled tuning of Power system stabilizer	[23]
12.	Harmony search	Harmony Search Algorithm	Allocation of real power transmission losses	[17]
13.	Harmony Search	Bandwidth can be adjusted	Static Transmission Expansion Planning	[12]
14.	Harmony Search	Harmony Search Algorithm	Improvement in the output of multilevel inverter	[15]
15.	Harmony Search	Pitch Adjustment rate can be adjusted	Optimal power Flow	[39]
16.	Harmony Search	Hybrid Differential Evolution + Harmony Search	Non convex economic Dispatch	[20]

17.	Harmony search	Increased the search efficiency in radial structure problem	Distribution system planning	[50]
18	Harmony Search	Pitch Adjusting rate and Bandwidth can be adjusted	Optimal placement of wind turbine	[30]
19.	Harmony search	Pitch Adjusting rate and Bandwidth can be adjusted	Optimal placement of Distributed Generators	[24]
20.	Harmony search	Harmony Search Algorithm	Reactive Power Dispatch	[19]
21.	Harmony search	Harmony Search Algorithm	Identification of infinite impulse response system	[37]
22.	Harmony search	Harmony Search Algorithm	Fault location in power system	[36]
23.	Harmony search	Pitch Adjusting rate can be adjusted	Optimal network reconfiguration	[33]
24.	Harmony search	Harmony Search Algorithm	Unit commitment	[9]
25.	Harmony search	Pitch Adjusting rate and Bandwidth can be adjusted	Power Distribution Network Planning	[44]

3.4 Nonlinear benchmark function and its implementations using Harmony Search

3.4.1. Sphere Function

Sphere function also called as De Jong’s function since it is the first function of De Jong. It is one of the simplest benchmark functions. This function is continuous, unimodal and convex. It has below general definition as per [55].

$$f(x) = \sum_{i=1}^n x_i^2 \quad \text{..... (3.6)}$$

Test area is usually limited to hypercube $-5.12 \leq x_i \leq 5.12$, $i = 1.. n$. Global minimum $f(x) = 0$ is available for $x_i = 0$, $i = 1.. n$. The 2D and the 3D view for sphere function are shown in Fig. 3.2 and Fig. 3.3 respectively.

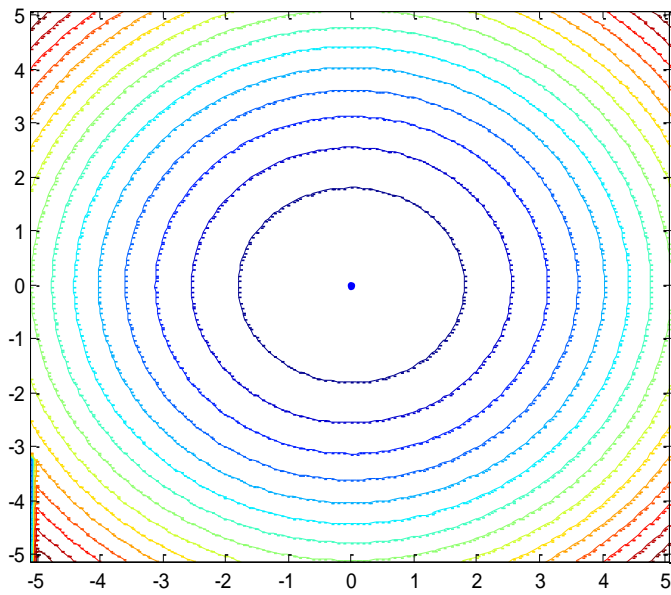


Fig. 3.2 2D view of Sphere Function

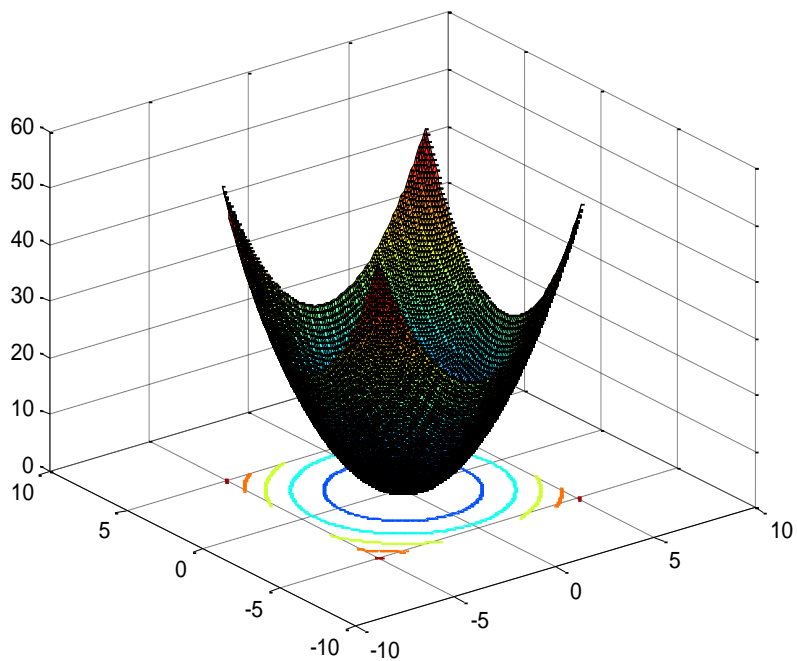


Fig. 3.3 3D view of Sphere Function

3.4.2. Rosenbrock Function

The Rosenbrock function, also referred to as the Valley or Banana function is a popular test problem for gradient-based optimization algorithm [55]. The function is described by the formula:

$$f(x) = \sum_{i=1}^{n-1} [100(x_{i+1} - x_i^2)^2 + (1 - x_i)^2] \quad \dots (3.7)$$

Test area is usually limited to hypercube $-5 \leq x_i \leq 5$, $i = 1 \dots n$. Its global minimum equal $f(x) = 0$ is available for x_i , $i = 1 \dots n$. The 2D and the 3D view for rosenbrock function are shown in Fig. 3.4 and 3.5 respectively.

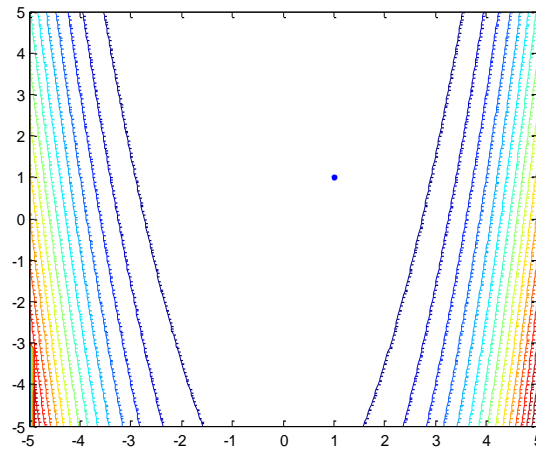


Fig.3.4 2D view of Rosenbrock Function

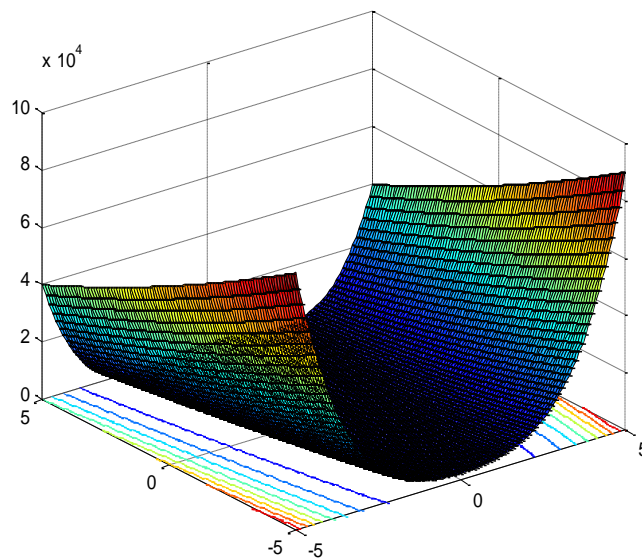


Fig. 3.5 3D view of Rosenbrock Function

3.5 Results

Table I shows the best estimates of sphere and rosenbrock functions using harmony search algorithm. Table II to VII reported the effect of Harmony Search parameters mainly harmony memory accepting rate, harmony memory size and pitch adjusting rate on the non-linear benchmark functions.

Table 3.2 Results of Harmony Search Algorithm

Function	Dimension (N)	HMS	PAR	HMCR	Search Domain	x1	x2	fmin	count	CPU time (seconds)
Rosenbrock	2	20	0.7	0.95	[-5 5]	0.9975	0.9950	6.6876×10^{-6}	3224	1.559414
Sphere	2	20	0.7	0.95	[-5.12 5.12]	0.0029	0.0001	8.4162×10^{-6}	560	1.846967

Table 3.3 Results of Rosenbrock function by varying Pitch adjusting rate (PAR)

Function	Dimension (N)	HMS	PAR	HMCR	Search Domain	x1	x2	fmin	count	CPU Time (seconds)
Rosenbrock	2	20	0.5	0.95	[-5 5]	1.0007	1.0011	9.3984×10^{-6}	24480	6.504243
			0.55			1.0011	1.0021	1.8761×10^{-6}	17135	4.814750
			0.6			0.9513	1.0170	1.2564	25000	6.532225
			0.65			0.9979	0.9959	5.6707×10^{-6}	12698	3.817439

Table 3.4 Results of Rosenbrock function by varying Harmony memory Accepting rate (HMCR)

Function	Dimension (N)	HMS	PAR	HMCR	Search Domain	x1	x2	fmin	count	CPU Time (seconds)
----------	---------------	-----	-----	------	---------------	----	----	------	-------	--------------------

Rosenbrock	2	20	0.7	[-5 5]	0.7	1.0014	1.0025	6.8230×10^{-6}	18898	5.177858
					0.75	1.0011	1.0023	2.0686×10^{-6}	21406	5.768367
					0.8	0.9989	0.9979	2.2546×10^{-6}	22378	6.004149
					0.85	1.0009	1.0017	1.9592×10^{-6}	5530	2.141367
					0.9	0.9971	0.9941	0.9941×10^{-6}	21064	5.683221

Table 3.5 Results of Rosenbrock function by varying Harmony Memory Size (HMS)

Function	Dimension (N)	HMS	PAR	HMC R	Search Domain	x1	x2	fmin	count	CPU Time (seconds)
Rosenbrock	2	10	0.7	0.95	[-5 5]	0.9986	0.9969	8.7541×10^{-6}	9197	2.970938
		30				0.9989	0.9975	6.4426×10^{-6}	21211	5.632414
		40				1.0008	1.0017	7.7780×10^{-7}	8674	2.786523
		50				0.9988	0.9975	1.5890×10^{-6}	20793	5.577444
		60				1.0023	1.0047	6.4308×10^{-6}	16240	4.515762

Table 3.6 Results of Sphere function by varying Harmony Memory Considering rate (HMCR)

Function	Dimension (N)	HMS	PAR	HMCR	Search Domain	x1	x2	fmin	count	CPU Time (seconds)
Sphere	2	20	0.7	0.7	[-5.12 5.12]	0.0018	-0.0008	3.9856×10^{-6}	371	0.865585
				0.75		0.9484	0.1737	9.2960×10^{-7}	1049	1.069324
				0.8		-0.0003	-0.0015	2.4409×10^{-6}	302	0.859589
				0.85		0.0014	-0.0019	5.4515×10^{-6}	497	0.884250
				0.9		0.0021	0.0012	5.9454×10^{-6}	257	0.835925

Table 3.7 Results of Sphere function by varying Pitch Adjusting Rate (PAR)

Function	Dimension (N)	HMS	PAR	HMCR	Search Domain	x1	x2	fmin	count	CPU Time (seconds)
Sphere	2	20	0.5	0.95	[-5.12 5.12]	0.0013	0.0023	7.1269×10^{-6}	395	0.963389
			0.55			-0.0022	-0.0023	9.7974×10^{-6}	406	0.888991
			0.6			0.0002	-0.0011	1.3386×10^{-6}	312	0.886139
			0.65			0.6366	0.3009	4.9575×10^{-6}	288	0.900525

Table 3.8 Results of Sphere function by varying Harmony memory Size (HMS)

Function	Dimension (N)	HMS	PAR	HMC R	Search Domain	x1	x2	fmin	count	CPU Time (seconds)
Sphere	2	10	0.7	0.95	[-5.12 5.12]	- 0.0022	-0.0003	4.8402 x 10 ⁻⁶	284	0.871129
		30				- 0.0009	0.0019	4.4837 x 10 ⁻⁶	334	0.908296
		40				- 0.7569	0.5456	8.7058x1 0 ⁻⁷	920	1.021674
		50				- 0.0010	0.0011	2.2599x 10 ⁻⁶	561	1.020708
		60				0.0026	0.0002	6.8373x 10 ⁻⁶	1219	1.090346

3.6 Conclusion

We have studied the effects of harmony search parameters on nonlinear standard functions such as: sphere, and rosenbrock. It can be concluded that by varying harmony search parameters, the rosenbrock function takes more time to give the accurate results. The suggested process can further be used in some constrained optimization problems.

In the next chapter, the results are presented and discussed. The electrical parameters are measured from open and short circuit test and are used to obtain unknown parameters such as Voltage regulation and Multi objective function by using Harmony Search Algorithm.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Introduction

In this chapter, the electrical parameter of distribution transformer has been determined from the experimental set up. Then we optimize these parameters using Harmony Search Algorithm and obtain the results for single and multi objective functions and also compare the performance with other intelligent techniques existing in literature.

4.2 Methodology

The formulation of estimation problem attempts to solve the unconstrained optimization problem. It is done by implementing Harmony search Algorithm (HSA). In the first case, voltage regulation is minimized to obtain the parameters of distribution transformer. In the second case we have minimized the voltage regulation and maximized the efficiency simultaneously assigning equal weights to each one of them. The values of parameters viz. resistance & reactance referred to primary side (r_{e1} , x_{e1}) & resistance & reactance referred to secondary side (r_{e2} , x_{e2}) are measured from experimental set up. Then, we optimize these parameters using harmony search algorithm and compare the outcome with that obtained from the experiment as well as using some intelligent algorithms namely Bacterial Foraging (BF) and Genetic Algorithm (GA).

4.3 Problem Formulation

The problem includes the computation of Open and Short circuit tests and then calculates the equivalent circuit parameters to find the voltage and efficiency of distribution transformer.

The O.C and S.C test data are listed as following for a single phase, 5 kVA, 200V/400V, and 50Hz transformer [59].

O.C test from LV side :	200V	1.25A	150W
S.C test from HV side :	20VV	12.5A	175W

4.3.1 Analytical Solution

Let's assume LV side parameters with suffix 1 and HV side parameters with suffix 2.

4.3.1.1. Computation with O.C test data

Let us represent the test data in the approximate equivalent circuit (Figure 4.1) of the transformer as following.

As HV side is open circuited, there will be no current in the branch $r_{e1} + jx_{e1}$. So entire power of 150W is nearly degenerated in R_{c11} . The no load current $I_{01} = 1.25$ A is distributed into: magnetizing component I_{m1} and core loss component I_{c11} as showed in the phasor diagram figure 4.1.

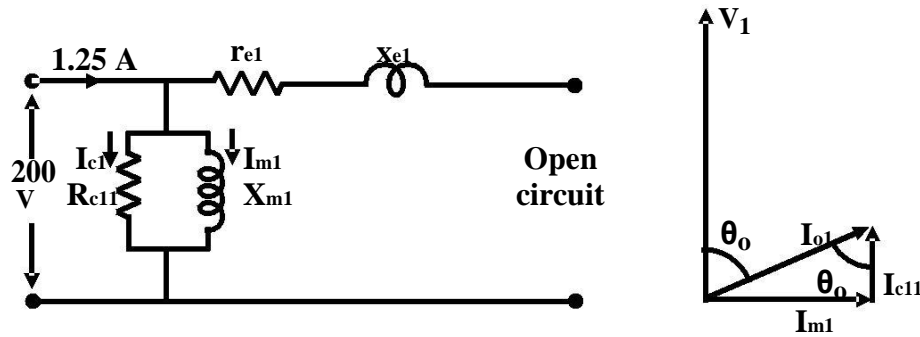


Figure 4.1 O.C equivalent circuit and phasor diagram

$$\begin{aligned} \text{No load (or O.C) power factor } \cos \theta_o &= \frac{150}{200 \times 1.25} \quad \dots\dots\dots(4.1) \\ &= 0.6 \\ \therefore \theta_o &= \cos^{-1} 0.6 \\ &= 53.13^\circ \\ \text{Hence, } \sin \theta_o &= 0.8 \end{aligned}$$

After identifying the value of $\cos \theta_o$ and $\sin \theta_o$ and stating to the no load phasor diagram, I_{m1} and I_{c11} can be analysed as follows.

$$\text{Magnetizing component } I_{m1} = I_{01} \sin \theta_o \quad \dots\dots\dots(4.2)$$

$$= 1.25 \times 0.8$$

$$\therefore I_{m1} = 1\text{A}$$

$$\text{core loss component, } I_{c11} = I_{01} \cos \theta_o \quad \dots\dots\dots(4.3)$$

$$= 1.25 \times 0.6$$

$$\therefore I_{c11} = 0.75\text{A}$$

Thus the parallel branch parameters X_{m1} and R_{c11} can be calculated.

$$\text{Magnetizing reactance } X_{m1} = \frac{V_1}{I_{m1}} \quad \dots\dots\dots(4.4)$$

$$= \frac{200}{1}$$

$$=$$

$$1$$

$$\therefore X_{m1} = 200\Omega$$

$$= \frac{V_1}{I_{c11}}$$

$$\dots\dots\dots(4.5)$$

$$\text{Resistance representing core loss } R_{c11} =$$

$$= \frac{200}{0.75}$$

$$=$$

$$266.67$$

$$\therefore R_{c11} = 266.67\Omega$$

It may be observed that from the O.C test data we can obtain the parallel branch impedances mainly the magnetizing reactance and the resistance representing the core loss referred to the side where dimensions have been taken.

4.3.1.2 Computation with S.C test data

As the test has been done from the HV side with LV side shorted, we draw the equivalent circuit mentioned to the HV side as in figure 4.2. Parameters are denoted by using suffix 2. Important point to note here is the absence of the parallel branch. Because of the voltage applied during S.C test is quite low causing a low flux level. Hence magnetizing and core loss component of currents will be very less compared to the rated current flowing through $r_{e2} + jx_{e2}$. In this case, power drawn from the supply gets nearly degenerated in winding resistances i.e r_{e2}

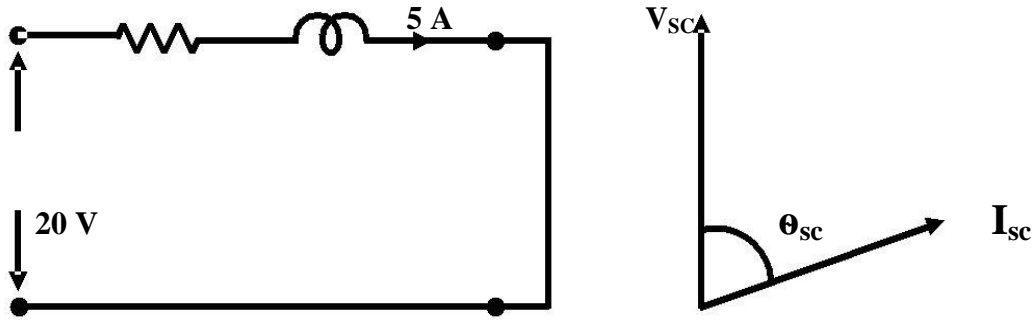


Figure 4.2: S.C equivalent circuit and phasor diagram.

Calculation of series parameters is rather easy and as below.

$$\text{Power drawn } W_{sc} = I_{sc}^2 r_{e2} \quad \dots\dots\dots (4.6)$$

$$\text{Or } r_{e2} = \frac{W_{sc}}{I_{sc}^2}$$

$$= \frac{175}{12.5^2}$$

$$\therefore r_{e2} = 1.12 \Omega$$

$$\text{Now S.C Impedance } Z_{sc} = \frac{V_{sc}}{I_{sc}} \quad \dots\dots\dots (4.7)$$

$$= \frac{20}{12.5}$$

$$= 1.6 \Omega$$

$$x_{e2} = \sqrt{Z_{sc}^2 - r_{e2}^2} \quad \dots\dots\dots (4.8)$$

$$= \sqrt{1.6^2 - 1.12^2}$$

$$= 1.14 \Omega$$

4.3.1.3 Equivalent circuit referred LV side

The parallel branch parameters $R_{e11} = 266.67\Omega$ and $X_{m1} = 200\Omega$ are calculated w.r.t LV side. So, no more transformations are needed. However, series parameters r_{e2} and x_{e2} are calculated from the above test data. Hence, we need to calculate r_{e1} and x_{e1} so as to rightly show the equivalent circuit referred to primary side.

$$\text{Turns ratio, } a = 200/400 = 0.5 \quad \text{.....(4.9)}$$

$$\text{but we know, } r_{e1} = a^2 r_{e2} \quad \text{.....(4.10)}$$

$$\text{and } x_{e1} = a^2 x_{e2} \quad \text{.....(4.11)}$$

$$\text{Thus } r_{e1} = 0.5^2 \times 1.12 = 0.28\Omega$$

$$\text{and } x_{e1} = 0.5^2 \times 1.14 = 0.285\Omega$$

So the equivalent circuit referred to LV side are shown with all the parameter values in figure 4.3.

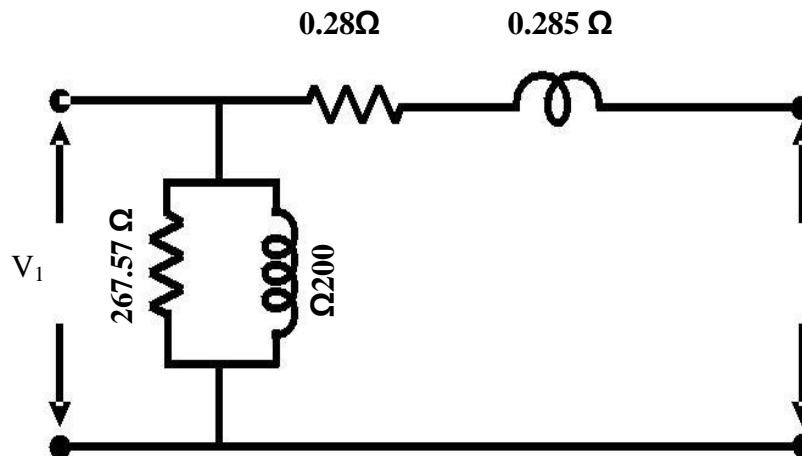


Figure 4.3: Equivalent circuit referred to LV side.

4.3.1.4 Equivalent circuit referred HV side

It was noted that series parameters referred to HV side are already known to be $r_{e2} = 1.12\Omega$ and $x_{e2} = 1.14\Omega$. Though, the parallel branch parameters are transformed as follows.

$$\text{Turns ratio, } a = 0.5 \quad \dots\dots\dots (4.12)$$

$$\text{but we know, } R_{cl2} = R_{cl1}/a^2 \quad \dots\dots\dots(4.13)$$

$$\text{and } X_{m2} = X_{m1}/a^2 \quad \dots\dots\dots (4.14)$$

$$\text{Thus, } R_{cl2} = 266.67/0.5^2 = 1066.68\Omega$$

$$\text{and } X_{m2} = 200/0.5^2 = 800\Omega$$

We can now draw the equivalent circuit of the same transformer referred to the HV side as shown in figure 4.4.

Regulation and efficiency of the transformer can be predicted under various loading conditions after getting the equivalent circuit. Solution of the next problem showed in what way equivalent circuit can be used to assume the performance.

2. For the same transformer (single phase, 5 kVA, 200V/400V, 50 Hz) of problem 1, of known equivalent circuit, calculate the following:

- i. the efficiency of the transformer at 75% loading with load power factor = 0.7
- ii. At what load or kVA the transformer is to be operated for highest efficiency? Also analyse the value of maximum efficiency.
- iii. The regulation of the transformer at full load 0.8 power factor lag.
- iv. What should be the applied voltage to the LV side when the transformer delivers rated current at 0.7
- v. Power factor lagging, at a terminal voltage of 400 V?

The solution of the above mentioned problems are as followed:

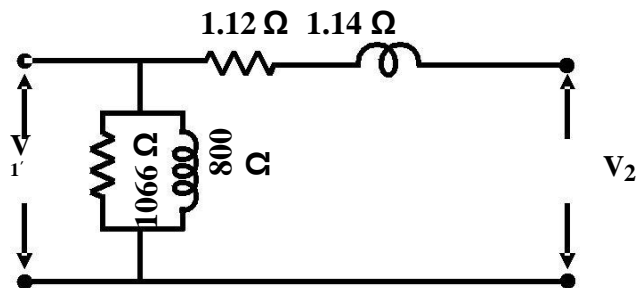


Figure 4.4 Equivalent circuit referred to HV side.

Solution

i. From the test data of the earlier problem, we have:

$$\text{Full load kVA rating, } S = 5\text{kVA}$$

$$\text{Core loss at rated voltage \& frequency, } P_{\text{core}} = 150\text{W}$$

$$\text{Full load copper loss, } P_{\text{cu}} = 175\text{W}$$

We know, efficiency,

$$\eta = \frac{xS \cos \theta}{xS \cos \theta + P_{\text{core}} + x^2 P_{\text{cu}}}$$

$$75\% \text{ loading means, } x = 0.75 \quad \text{.....(4.15)}$$

$$\text{load power factor, } \cos \theta = 0.7$$

$$\begin{aligned} \therefore \eta &= \frac{0.75 \times 5000 \times 0.7}{0.75 \times 5000 \times 0.7 + 150 + 0.75^2 \times 175} \\ &= 2625 / 2873.44 \end{aligned}$$

$$\therefore \% \text{ efficiency, } \eta = 91.35\%$$

ii. We know it has maximum efficiency when $x^2 P_{\text{cu}} = P_{\text{core}}$, where P_{cu} is the full load copper loss and P_{core} is the iron loss. Now $P_{\text{cu}} = 175 \text{ W}$ and $P_{\text{core}} = 120 \text{ W}$.

$$\text{Per unit value of loading for } \eta_{\text{max}} \text{ is } x = \sqrt{P_{\text{core}} / P_{\text{cu}}} \quad \text{..... (4.16)}$$

$$= \sqrt{120 / 175}$$

$$\therefore x = 0.83$$

$$\text{Thus the load for } \eta_{\text{max}} = x S \quad \text{..... (4.17)}$$

$$= 0.83 \times 5\text{kVA}$$

$$\therefore \text{the required load for } \eta_{\text{max}} = 4.15\text{kVA}$$

iii. To calculate the regulation of the transformer at load current I_2 and load power factor $\cos \theta$, we use the below formula in terms of HV side parameters.

$$\text{Per unit regulation, } R = \frac{I_2 r_{e2} \cos \theta + I_2 x_{e2} \sin \theta}{V} \quad \text{.....(4.18)}$$

$$\text{Putting the values, } R = \frac{12.5 \times 1.12 \times 0.7 + 12.5 \times 1.14 \times 0.71}{400}$$

∴ % regulation, R = 4.9%

4.4 Experimental setup

The rating of the distribution transformer for the estimation technique is in Table 4.4

Table 4.1 Specification of Transformer used for the experiment

Type	Distribution Transformer
Rated KVA	5 KVA
Supply Voltage	200 V
Output Voltage	400 V



Fig 4.5 Experimental set up

4.5 Harmony Search Algorithm for Parameter Estimation Technique defining single objective function.

Step 1. Define the number of parameters to be evaluated for a Transformer.

Step 2. Set the parameters of Harmony Search algorithm (HSA) viz. HM (Harmony memory), HMCR (Harmony memory considering rate), PAR (Pitch adjusting rate), Maximum iteration, Stopping criteria.

Step 3. Define the objective function (x).

Step 4. Choose the value of user defined parameter and also the range for the given objective function parameters.

Step 5. Create the initial Harmony memory (= 1: number of model parameters) of the model randomly within the range.

Step 6. Define functional value of initial Harmony memory.

Step 7. Set iteration count, iteration =1

Step 8. Starting of Harmony Search, if generated random value > HMCR, after that choose the value of parameter randomly as below,

$$x_{new} = L(x_{old}) + rand \varepsilon(0,1) * bandwidth$$

Or, choose value from the Harmony memory and adjust the pitch as below:

$$x_{new} = x_{old} + bandwidth(rand - 0.5)$$

Step 9. Update the value of objective function and replace the worst solution with new solution.

Step 10. Check stopping criteria and iteration > maximum iteration, if it is satisfied GO TO step 12.

Step 11. Advance the iteration count, iteration = iteration+1 and GOTO step 8.

Step 12. Find the optimal value of the function.

Step 13. Stop.

The user defined parameters of the Harmony Search Algorithm corresponding to minimization of voltage regulation problem is tabulated below:

Table 4.2 Parameter values for Harmony Search Algorithm are given below:

S.No	Parameters	Values
1.	Harmony Memory Size	20
2.	HM Accepting rate	0.95
3.	Pitch Adjusting rate	0.7

4.5.1 Objective Function: Voltage regulation:

The objective is to minimize the voltage regulation.

$$F = I_2 \times r_2 \times \cos \phi + I_2 \times x_2 \times \sin \phi \quad \text{..... (4.19)}$$

4.5.2 Results

The comparison of the results of the system using Harmony search algorithm with classical and intelligent methods for distribution transformer is given below in Table 4.3

Table 4.3 Results of Voltage regulation function

S.No.	Parameters	Measured	Estimated		
			GA	BFA	HS
1.	r_{e1}	0.28	0.2733	0.2810	0.1067
2.	r_{e2}	1.12	0.5376	0.5468	0.4268
3.	x_{e1}	0.285	0.4381	0.4223	0.0435
4.	x_{e2}	1.14	0.4981	0.5122	0.1743
5.	Voltage regulation (%)	4.9	7.10	7.02	4.9444

4.5.3 Conclusion

We have done the comparison of classical technique and intelligent techniques like BFA, GA and HSA and the result shows that after using the algorithm, parameter estimated values of distribution transformer are far better than the other techniques.

4.6 Harmony Search Algorithm for Parameter Estimation Technique defining multi objective function.

Step 1. Describe the number of parameters to be estimated for a Transformer.

Step 2. Set the parameters of Harmony Search algorithm (HSA) viz. HM (Harmony memory), HMCR (Harmony memory considering rate), PAR (Pitch adjusting rate), Maximum iteration, Stopping criteria.

Step 3. Describe the objective function (x).

Step 4. Initialize the value of user defined parameter and also the range for the given objective function parameters.

Step 5. Create the initial Harmony memory (= 1: number of model parameters) of the model randomly within the range.

Step 6. Define functional value of initial Harmony memory.

Step 7. Set iteration count, iteration =1

Step 8. Starting of Harmony Search, if generated random value > HMCR, Then select the value of parameter randomly as given,

$$x_{new} = L(x_{old}) + rand \varepsilon(0,1) \times bandwidth$$

or choose value from the Harmony memory and adjust the pitch as follows:

$$x_{new} = x_{old} + bandwidth(rand - 0.5)$$

Step 9. Update the value of objective function and replace the worst solution with new better solution.

Step 10. Check stopping criteria and iteration > maximum iteration, if it is satisfied GOTO step 12.

Step 11. Advance the iteration count, iteration = iteration+1 and GOTO step 8.

Step 12. Find the optimal value of the function.

Step 13. Stop.

The user defined parameters of the Harmony Search Algorithm corresponding to minimization of voltage regulation problem is tabulated below:

Table 4.4 Parameter values for Harmony Search Algorithm are given below:

S.No	Parameters	Values
1.	Harmony Memory Size	20
2.	HM Accepting rate	0.95
3.	Pitch Adjusting rate	0.7

4.6.1 Multi objective function (Efficiency+ Voltage regulation): The objective is to minimize the voltage regulation and maximize the efficiency simultaneously.

$$F = 0.5 \times x_1 - 0.5 + 0.5 \times x_2 \quad \text{..... (4.20)}$$

x_1 represents efficiency

x_2 represents voltage regulation

4.6.2 Results

The comparison of the results of the system using Harmony search algorithm with classical method for distribution transformer is given below in Table 4.3

Table 4.5 Results of Multi objective Function

S.No	Parameters	Measured	Estimated
1.	Voltage regulation (%)	4.9	6.0379
2.	Efficiency (%)	91	89.1299

4.6.3 Conclusion

We have done the comparison of classical technique with HSA and the result shows that after using the algorithm, parameter estimated values of distribution transformer are little better than the classical method.

4.7 CONCLUSION AND FUTURE SCOPE

4.7.1 Conclusion

The harmony search algorithm is used to optimize the different unconstrained non linear benchmark functions viz. Sphere & Rosenbrock to highlight the efficacy of the algorithm and also observe the effect of user defined parameters of harmony search algorithm in the function optimization problems. The study of harmony search algorithm and its modified version in the field of electrical engineering has also been surveyed. To estimate the parameters of distribution transformer, two objective functions have been taken: (1) minimize the voltage regulation (2) minimize the voltage regulation and maximize the efficiency simultaneously. Then the estimated results are matched with measured outcomes and other different methods and concluded that Harmony Search Algorithm (HSA) performs better as compared to the existing techniques.

4.7.2 Future Scope of Work

Future considerations are depicted as follows:

Modified or improved approach (like variants of Harmony search algorithm) can also be applied for the transformer parameter estimation purpose. Hybridization with different algorithms like GA, BFA etc can also be used for parameter estimation of transformer to improve its performance. Newly developed nature inspired algorithms like Firefly Algorithms (FA), Bat Algorithm (BA) and Cuckoo Search (CS) can be further applied to validate the results. We have applied this algorithm to solve unconstrained single and multi objective optimized problems adding constraints may further improve the results. Fine tuning of the parameters can further be applied to obtain the better results.

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