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FACULTY OF ENGINEERING
DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING

A PROJECT REPORT ENTITLED

OPTIMAL PLACEMENT AND SIZING OF CAPACITORS IN A 9 BUS RADIAL DISTRIBUTION NETWORK

BY
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SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE AWARD OF THE DEGREE OF BACHELOR OF SCIENCE IN ELECTRICAL AND ELECTRONIC ENGINEERING

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……………………………..
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AUGUST 2021

DECLARATION

I declare that this project work is my own work. It is being submitted for the degree of Bachelor of Science in Electrical and Electronic Engineering in the University of Mines and Technology (UMaT), Tarkwa. It has not been submitted for any degree or examination in any other University.

…………………………………………

(Signature of Candidate)

5th day of August, 2021.

ABSTRACT

The distribution system is the final stage in the delivery of electric power, it carries electricity from the transmission system to individual costumers. Capacitors provide reactive power compensation which reduces power losses, improve voltage profile and increase the capacity of the system. The Improved Harmony Search algorithm is applied to solve the capacitor sizing and placement problem. An effective and simple power flow method based on the backward /forward sweep power flow is also employed for power flow simulations. The effectiveness of the proposed solution is tested on a 9 bus distribution system. The results obtained after validating the Improved Harmony Search Algorithm on a 9 bus distribution system is compared with the particle swam optimization and the traditional harmony search algorithm.

DEDICATION

To my family

ACKNOWLEDGEMENT

I extend my sincerest gratitude to all staff of the Electrical and Electronic Engineering Department for their service during my years of study. I am deeply indebted to Mr Emmanuel Nyankomago for his unfailing support. I thank Dr Joseph Cudjoe Attachie for his great supervision and Mr Joseph Obeng for his inputs. Also, not forgetting Mr Emmanuel Mensah for his assistance.

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LIST OF ABBREVIATIONS

Abbreviation	**Meaning**
AC	Alternating Current
AI	Artificial Intelligence
APSO	Accelerated Particle Swarm Algorithm
BCBV	Branch Current and Bus Voltage
BIBC	Bus Injection and Branch Current
CSA	Cuckoo Search Algorithm
DC	Direct Current
DLF	Distribution Load Flow
FBS	Forward and Backward Sweep
GA	Genetic Algorithm
HM	Harmony Memory
HMCR	Harmony Memory Considering Rate
HMS	Harmony Memory Size
HSA	Harmony Search Algorithm
HSSA	Hyper Spherical Search Algorithm
HV	High Voltage
IEEE	Institute of Electrical and Electronics Engineers
IHSA	Improved Harmony Search Algorithm

LSF	Loss Sensitivity Factors
MATLAB	Matrix Laboratory
MOV	Metal Oxide Varistor
MV	Medium Voltage
NI	Number of Improvisations
OCPS	Optimal Capacitor Placement and Sizing
PAR	Pitch Adjustment Rate
PLI	Power Loss Index
PSO	Particle Swarm Algorithm
QN	Quasi Newton
SCA	Sine Cosine Algorithm
SLD	Single Line Diagram

LIST SYMBOLS

Annual capacitor cost constant	k_i^c
Best position found by a particle	$\vec{P}_i$
Bus indices	i
Bus injection current	I
Bus injection current at the k-th iteration	I^k
Distance travelled by particle i	$\vec{r}_i$
Generation number	gn
Global best position found by the swarm	$\vec{P}_g$
Inertia weight	ω
Number of designed variables	N
Pitch adjustment decision	x_i'
Position of particle	z_i
Possible capacitor placement location	K_p
Resistance of the branch i	R_i
Root mean square	rms
Total active power	P_{Σ}
Total reactive power	Q_{Σ}
Total voltage drop at the k-th iteration	∇V^{k+1}
Voltage at bus i	V_i
Voltage deviation	ΔV

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Quantity	Units of Measurement	Symbol
Active power	megawatt	MW
Electric current	ampere	A
Electric potential	kilovolts	kV
Electric resistance	ohm	Ω
Power	Watt	W
Reactive power	mega voltage ampere reactive	MVAr
Time	seconds	s
Voltage	Volt	V

CHAPTER 1

GENERAL INTRODUCTION

1.1 Problem Definition

The final stage in the transfer of electricity from the transmission system to the consumer is distribution. Electric distribution systems are becoming large and complex causing the reactive currents to produce losses and result in increased ratings for distribution components. Studies have indicated that as much as 13% of total power generated is wasted in the form of losses at the distribution level (Hirsch *et al*., 2018).

Most of these losses occur on the distribution system. It is widely recognized that placement of shunt capacitors on the distribution system can lead to a reduction in power losses. Increased competition in the industry has created a renewed interest in improving efficiency by reducing these losses (Tellez *et al*., 2015). One of the most efficient and effective ways of reducing these losses is by connecting capacitors in shunt to locally supply a considerable portion of the reactive power demanded by the consumers and thereby reducing the reactive component of branch currents. Recent problems reveal that when the load on each distributor increases, the voltage at the consumer end of each distributor decreases.

Shunt capacitor banks are being built on the distribution network to mitigate these power losses and maintain a voltage profile within acceptable norms. However, the size and location of capacitors should be determined to fulfil these goals while keeping overall economy in mind. This work seeks to present a relatively new heuristic technique using Improved Harmony Search Algorithm for finding the placement and size of capacitors in the radial distribution network.

1.2 Project Objectives

The objectives of this project are:

i. To implement an improved technique for optimal placement and sizing of capacitors in a radial distribution system;
ii. To minimize the total annual cost due to the radial distribution system power losses and improve the voltage profile; and

iii. To propose an algorithm for the identification of optimal sizes of capacitors to be placed in radial distribution systems.

1.3 Methods Used

The research methods used include:

i. Review of relevant literatures;
ii. Present a flowchart of research methodology indicating the steps to achieve the stated objectives;
iii. Describe the specific research methods (for example numerical, experimental, field observations, simulations, analytical, heuristics, etc.) that will be used to achieve the objectives;
iv. Analysis of Harmony Improvisation and modifications to the original HS algorithm using MATLAB/Simulink software; and
v. Generate and analyze graphs and tables.

1.4 Facilities Used

The facilities that were employed are:

i. Library, Internet and Computer facilities of UMaT;
ii. Laptop Computer with MATLAB/Simulink installed; and
iii. UMaT Electrical and Electronic Workstation.

1.5 Project Organization

This project work will be organized into five chapters as follows:

Chapter 1 gives the general introduction that looks at the problem definition, project objectives, research methods used, facilities used and the work organisation;

Chapter 2 elaborates of review of the relevant literature. It gives a general reviews of previous works and contribution on the topic ‘optimal placement and sizing of capacitors in a radial distribution network’ as well as their merits and demerits;

Chapter 3 focuses on the optimal placement of capacitors in radial distribution networks. It covers the overview of Harmony Search Algorithm, its application to optimization problem, Improved Harmony Search Algorithm and its implementation;

Chapter 4 presents results on the 9 bus system test in terms of capacitor sizes, capacitor locations, power loss and total cost using the improved harmony search algorithm are compared with particle swarm algorithm and the traditional harmony search algorithm; and

Chapter 5 gives the observations, conclusions, recommendations and future work.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter considers the concept of the distribution network and also reviews of previous works and contribution on the topic ‘optimal placement and sizing of capacitors in a radial distribution network’ as well as their merits and demerits are considered.

2.2 Distribution System

The distribution system is the electrical system that connects the transmission system's substation to the consumer end. Because it is the primary link between bulk electricity and consumers, distribution networks play a critical role in the power system (Bouchekara, 2020). To satisfy the current expanding home, industrial, and commercial load, effective radial distribution network planning is essential. Distribution networks have sparked widespread research interest among academics and industry professionals for nearly three decades.

2.3 Elements of the Distribution System

The distribution system is obtained in general from the electrical system, which is largely fed by the users' premises and the transmission system. Feeders, laterals (circuit-breakers), and service mains are the most common components.

2.3.1 Distribution feeders

A feeder is a conductor that runs from a substation (or localized producing station) to the area where power will be supplied. In most cases, no tapping is taken from the feeder, ensuring that the current in it remains constant. The current carrying capacity is the most important factor to consider when designing a feeder.

2.3.2 Distributor

A distributor is a conductor from which taps for supply to consumers are obtained. The distributors in Figure1.2 are AB, BC, CD, and DA. Because tapping is done at various points along the length of a distributor, the current through it is not continuous. The key consideration while designing a distributor is voltage drop along its length, because the statutory limit for voltage changes at the consumer's terminals is 10% of the rated value (Bouchekara, 2020).

2.3.3 Service Mains

A service main is generally a small cable which connects the distributor to the consumer's terminals.

2.4 Requirements of a Distribution System

The supply of electrical power must be maintained to meet the needs of a variety of users (Eismin, 2014). A good distribution system must meet the following requirements:

i. Availability of power demand: Power should be made available to the consumers in large amount as per their requirement. This is very important requirement of a distribution system.

ii. Reliability: As can be seen, modern industry is now completely reliant on electrical power to function. As a result, there is a pressing need for a dependable service. If there is a power outage, it should be for the shortest time possible at all costs. Improvement in reliability can be achieved to a large extent through
    a. Automated control system that is reliable.
    b. Increasing the number of reserve facilities.

iii. Proper voltage: A distribution system's most important criterion is that voltage differences at consumer terminals be as low as feasible. The main cause of voltage fluctuations is load variation on the distribution side, which must be decreased. As a result, a distribution system is only considered good if it keeps voltage changes at consumer terminals within acceptable ranges.

iv. Loading: The lines should not be overloaded.

v. Efficiency: The efficiency of the lines must be as high as possible, ideally around 90%.

2.5 Classification of Distribution System

A distribution system may be classified based on nature of current, type of construction and scheme of operation. Table 2.1 shows the classification of distribution system.

Table 2.1 Classification of the Distribution System

SN	Scheme of Operation	Type of Construction	Nature of Current
1.	Radial delivery network	Overhead system	AC distribution system
2.	Ring main system	Underground system	DC distribution system
3.	Interconnected system		

2.6 Common Distribution Systems Network Configurations.

An electrical network is an interconnection of electrical components or a model of such an interconnection, consisting of electrical elements.

2.6.1 Radial System

The radial type of distribution system, a simple form of which is shown in Fig. 2.1 (Anon., 2018a), is the most common. It is used extensively to serve the light- and – medium – density load areas where the primary and secondary circuits are usually carried overhead on poles. The radial system gets its name from the fact that the primary feeders radiate from the distribution substations and branch into sub-feeders and laterals which extend into all parts of the area served. It is also known as the spur network (Bouchekara, 2020).

Advantages of radial distribution system

Some of the advantages of the radial distribution system are:

i. Because the source is fed at one end, the arrangement is simple;
ii. Coordination of security and network monitoring is simple; and
iii. The cost of investment is modest (depending on the size of the network).

Disadvantages of radial distribution system

Some disadvantages of the radial distribution system are:

i. If the total connected load on the distributor varies, voltage fluctuation for consumers at the distributor's end; and
ii. If a problem occurs on the feeder or distributor to which they are attached, end users will be disconnected (no power supply).

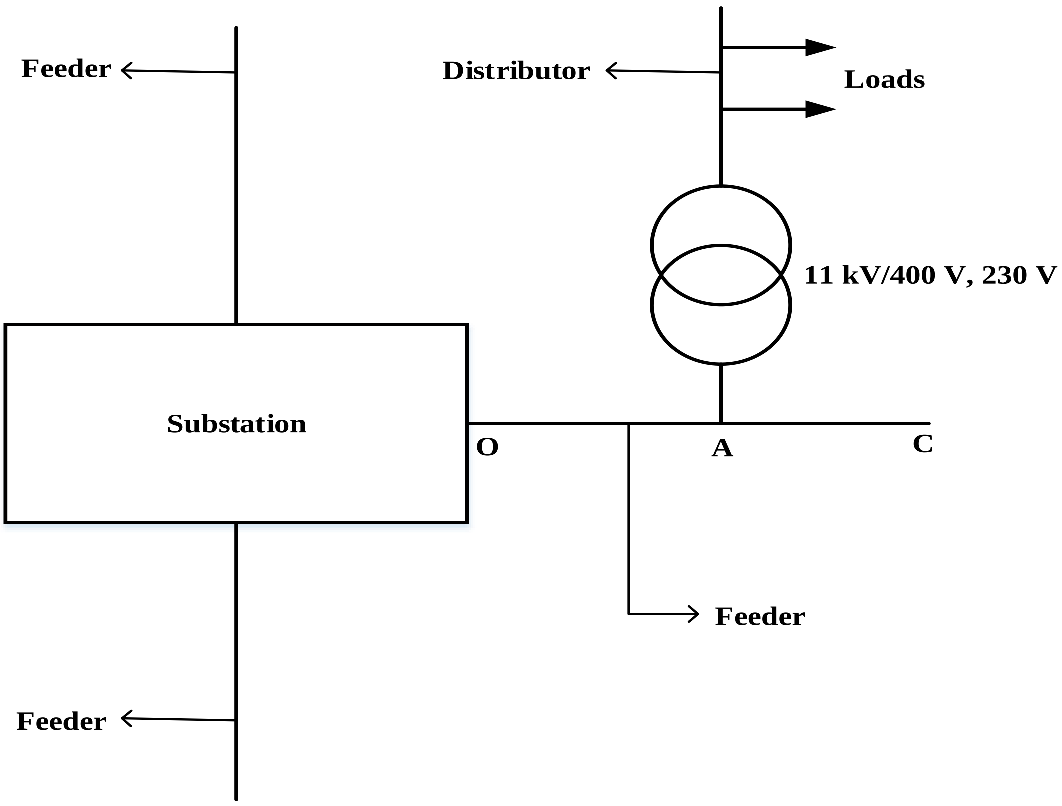

Fig. 2.1 Radial Distribution System

2.6.2 Parallel Distribution System

The disadvantage of a radial system can be minimized by introducing parallel feeders. The initial cost of this system is much more as the number of feeders is doubled. Such system may be used where reliability of the supply is vital or for load sharing where the load is higher. Capacitors, like other electrical elements, can be connected to other elements either in series or in parallel. Sometimes it is useful to connect several capacitors in parallel in order to make a functional block such as the one in the figure. In such cases, it is important to know the equivalent capacitance of the parallel connection block. When capacitors are connected in parallel, the total capacitance is the sum of the individual capacitors' capacitances. If two or more capacitors are connected in parallel, the overall effect is that of a single equivalent capacitor having the sum total of the plate areas of individualcapacitors. By connecting several capacitors in parallel, the resultant capacitance of the circuit increases and will be able to store more energy as the equivalent capacitance is the sum of individual capacitances of all capacitors involved.

2.6.3 Ring Main Distribution System

A similar level of system reliability to that of the parallel feeders can be achieved by using ring distribution system. Here, each distribution transformer is fed with two feeders but in different paths. The feeders in this system form a loop which starts from the substation bus-bars, runs through the load area feeding distribution transformers and returns to the substation bus-bars. Fig. 2.2 (Anon., 2018b) shows the diagram of a ring main distribution system.

Advantages of ring main distribution system

Some advantages of the ring main distribution system are:

i. Both ends of the circuit are powered; and
ii. In comparison to a radial network, a larger number of end users can be connected to the system.

Disadvantages of ring main distribution system

Some disadvantages of the ring main distribution system are:

i. Investment costs are higher as a result of the complicated protection coordination; and
ii. The fault localization switching operation is more complicated.

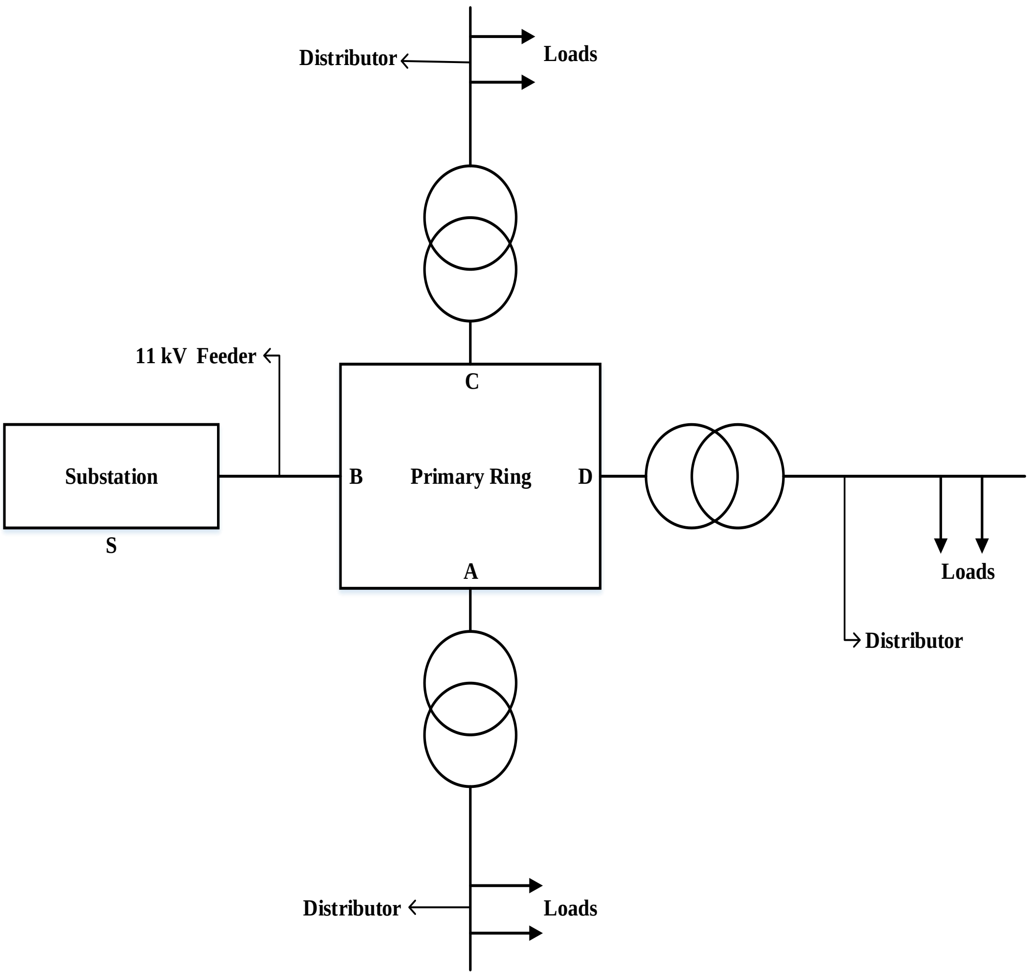

Fig. 2.2 Ring Main Distribution Network

2.6.4 Meshed Distribution System

When a ring main feeder is energized by two or more substations or generating stations, it is called as meshed distribution system. This system ensures reliability in an event of transmission failure. Also, any area fed from one generating stations during peak load hours can be fed from the other generating station or substation for meeting power requirements from increased load. Fig. 2.3 (Anon., 2018c) shows a diagram of a meshed distribution system.

Advantages of meshed distribution system

Some advantages of the ring main distribution system are:

i. It increases reliability the reliability of supply; and
ii. Increased efficiency.

Disadvantages of meshed distribution system

One disadvantages of the ring main distribution system is:

i. Complex protection coordination due to power flow from different sources.

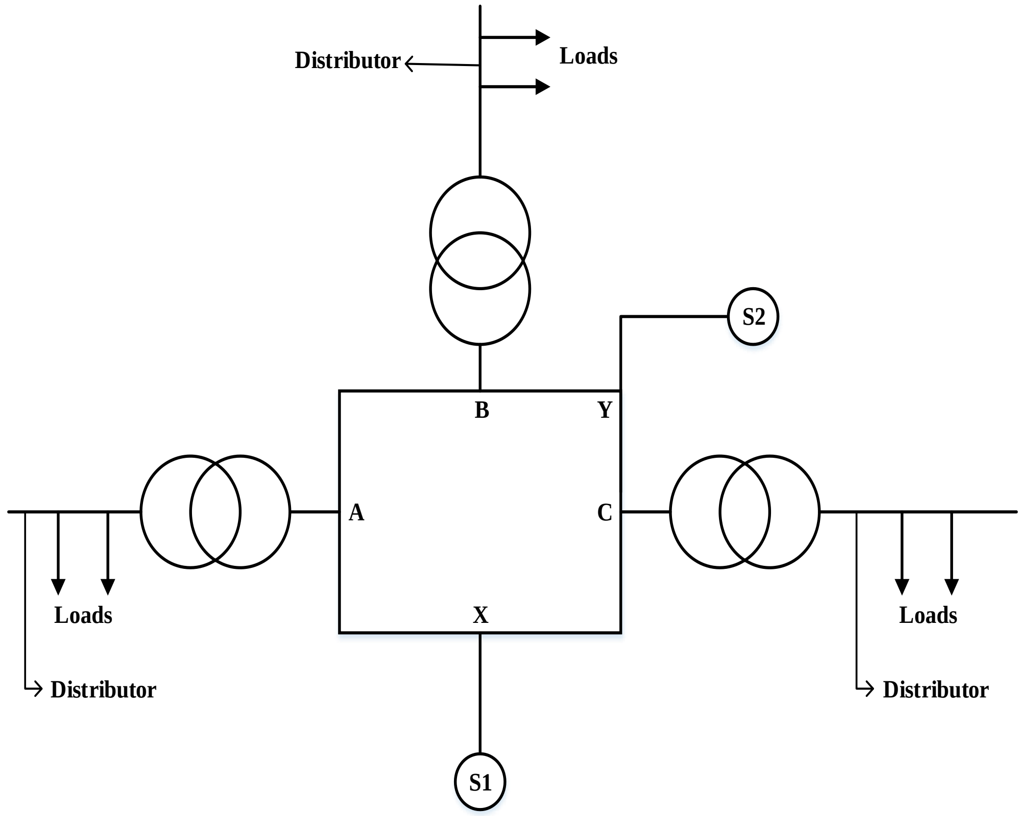

Fig. 2.3 Meshed Distribution System

2.7 Planning of Radial Distribution Systems

Distribution system planning, in general, entails the development and enhancement of an existing system. During the development stage, the main focus is on lowering the system's design cost. The general design of the system, including high voltage (HV) and medium voltage (MV) substation placement, MV feeders routing, load points, and transformer capacity, must be defined at this stage with the goal of minimizing costs (Samal, 2016). Simultaneously, technical constraints such as the maximum permitted voltage drops at load nodes and the maximum load carrying capacity of lines at peak load must be considered. Meanwhile, the key consideration for existing systems is to reduce operating costs and increase system reliability.

2.8 Optimal Conductor Size Selection

The proper sizing of conductors for the network is a crucial part of developing cost-effective and dependable distribution systems. High power losses result from poor conductor choices, which translates to high operational costs (Montoya *et al.*, 2020). As a result, the primary goal of this research is to reduce investment costs and energy losses while remaining within operational limits. Several factors must be considered when determining conductor ideal sizing, including the conductor's economic life, discount rate, cable and installation costs, and circuit type (overhead or underground).

2.9 Overview of the Capacitor

The capacitor is a passive component and it stores the electrical energy into an electrical field. The effect of the capacitor is known as the capacitance. The capacitor is made up of two close conductors and separated by the dielectric material. If the plates are connected to the power then the plates accumulates the electric charge. One plate accumulates the positive charge and another plate accumulates the negative charge. Capacitors are used commonly as an electronic component in the modern circuits and devices. The capacitance of capacitor is also the ratio of electric charge (Q) to the voltage (V).

2.9.1 Types of capacitors

Capacitors can be employed in a number of different manners in a variety of electronic circuits. Even though their method of functioning remains precisely similar. They can be employed to supply a range of different circuit operations such as coupling capacitor, decoupling capacitor, smoothing capacitor and many more. There are many other types of capacitors too that can be employed.

Electrolytic capacitor

Electrolyte capacitors are typically utilized when large capacitor values are required. A thin metal film layer is employed for one electrode, while a semi-liquid electrolyte solution in jelly or paste is used for the second electrode (cathode). The dielectric plate is a thin layer of oxide that is electrochemically produced in manufacturing with a film thickness of less than ten microns. Because this insulating layer is so thin, it is possible to build capacitors with a big capacitance value for a tiny physical size and a short distance between the two plates (Both, 2015). The majority of electrolytic capacitors are polarized, which means that DC voltage is provided to the capacitor terminal and the polarity must be right. Electrolytic capacitors are commonly used in DC power supply circuits because of their huge capacitance and small ripple voltage reduction. Coupling and decoupling are two applications for electrolytic capacitors. Electrolytic capacitors have a low voltage rating due to their polarization, which is a drawback. AI electrolytic capacitor (Anon., 2020) is shown in fig. 2.4.

Fig. 2.4 AI Electrolytic Capacitor

Mica capacitor

The mica capacitors are the low loss capacitors, used at high frequencies. This capacitor is very stable chemically, electrically, and mechanically because of its specific crystalline structure binding and it is a typically layered structure. The most common used are Muscovite and phlogopite mica (Zakuan, 2020). The Muscovite mica is better in the electrical properties and the other Mica has a high-temperature resistance. High voltage mica capacitor is shown in fig. 2.5 (Anon., 2021).

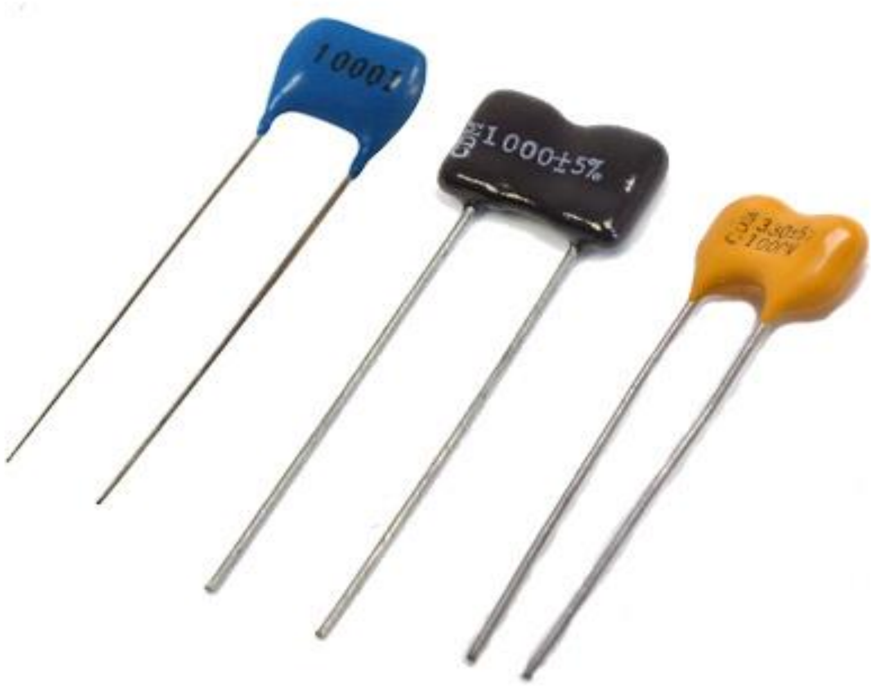

Fig. 2.5 High Voltage Mica Capacitor

Paper capacitor

The silver mica capacitors use the dielectric, which is made up of a set of natural minerals. Clamped capacitors and silver mica capacitors are the two types of mica capacitors. Because of their poor performance, clamped mica capacitors are deemed outdated. The silver mica capacitors are made by sandwiching mica sheets with metal coatings on both sides and encasing them in epoxy to protect them from the elements. The paper capacitor is made out of two tin foil sheets that are separated by paper, or oiled paper with a thin wax coating. The thin foils and papers sandwich is then curled into a cylindrical shape and placed inside a plastic capsule. The external load is connected to the two thin foils of the paper capacitors. The paper capacitor has a capacitance range of 0.001 to 2.000 micro farad. The voltage range is very high which is up to 2000V. Fig. 2.6 (Anon., 2019a) shows an axial lead type of paper capacitor.

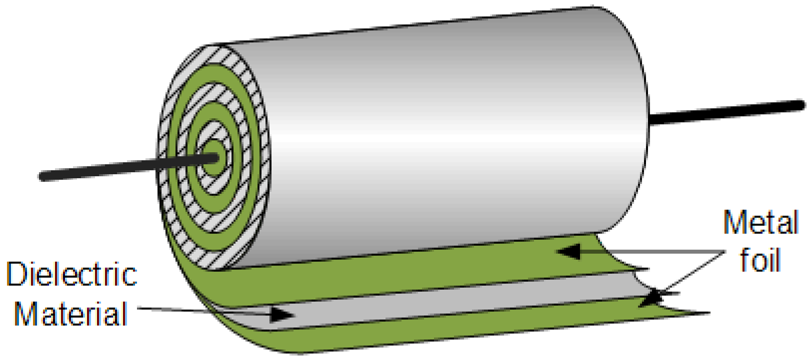

Fig. 2.6 Paper Capacitor

Non-polarized capacitors

Plastic foil non-polarized capacitors and electrolytic non-polarized capacitors are the two forms of non-polarized capacitors. The plastic foil capacitor is non-polarized by nature, and electrolytic capacitors are often two capacitors in series, back to back, resulting in a non-polarized capacitor with half capacitance. The AC applications in series or parallel with the signal or power source are required for the non-polarized capacitor. Speaker crossover filters and a power factor correction network are two examples. In these two applications, a large AC voltage signal is applied across the capacitor. Fig. 2.7 (Anon., 2017a) shows the axial non-polarized capacitor.

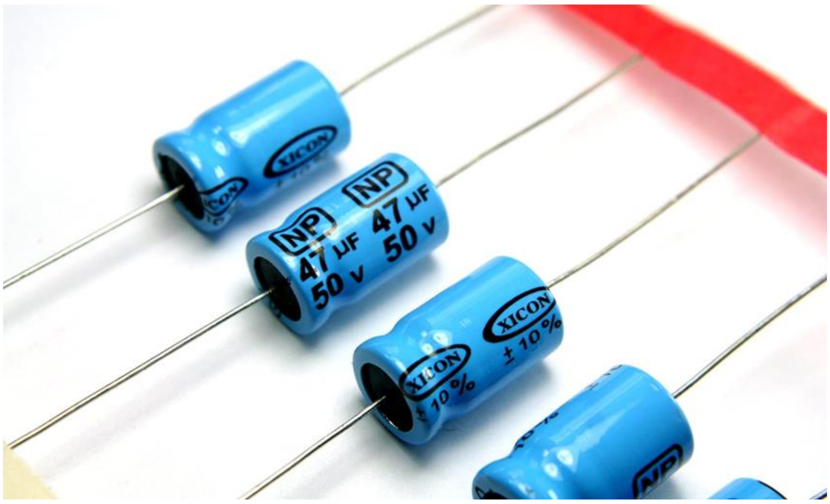

Fig. 2.7 Non-Polarized Capacitor

2.9.2 Capacitor Bank

A capacitor bank is a critical piece of electrical power system equipment. The load is the amount of power required to run all of the electrical appliances, as useful power is active power. The active power is measured in kilowatts (kW) or megawatts (MW). Electrical transformers, induction motors, synchronous motors, electric furnaces, and fluorescent lights are all examples of inductive loads that are connected to the electrical power system (Riyas, 2020). Inductance is also contributed to the system by the inductance of separate lines. The system current lags behind the system voltage due to these inductances. The power factor of the system diminishes as the lag angle between voltage and current grows. When the power factor falls, the system draws more current from the source to meet the same active power requirement. Line losses increase as current increases. Voltage regulation is hampered by a low electrical power factor. To avoid these issues, the system's electrical power factor must be enhanced. Capacitive reactance can be utilized to cancel the system's inductive reactance since a capacitor causes current to lead voltage. The capacitor reactance can be used to cancel the inductive reactance of the system. Fig. 2.8 (anon., 2019b) shows high voltage capacitor bank mounted on a platform.

Fig. 2.8 High Voltage Capacitor Bank

2.9.3 Types of Capacitor Banks

Our modern world of electronics requires a lot of energy. To meet this demand, energy must be stored electrically for easy access. Capacitors are ideal for storing large electrical energy charges as well as conditioning the flow of energy as needed.

Shunt capacitor

Shunt capacitor banks are used to increase the electrical supply's quality and the power system's efficiency. According to studies, a system with a flat voltage profile can greatly reduce line losses. Shunt capacitor banks are relatively low-cost and simple to install anyplace on the network. Shunt capacitors have a variety of functions that vary depending on the application. However, it is useful in stabilizing power to avoid a lag between the voltage and current within a power system. A lag between the voltage and current causes a decrease in the electrical power factor , which leads to an increase in the demand for more power from the source. In the long run, the cycle leads to power surges and loss of lines, also known as inductive reactance. Fig. 2.9 (anon., 2016) shows a shunt capacitor bank.

Fig. 2.9 Shunt Capacitor Bank

Series capacitor bank

Series capacitor banks are made up mostly of capacitors and related protective systems, and their purpose is to maximize power flow via an existing system by lowering line impedance. The series capacitance of capacitors in a transmission system effectively compensates for inherent line inductance, lowering total impedance. As a result, the circuit may transfer more energy while producing less heat. These series banks are usually found at one of the substations in either location. They are sometimes placed in the middle of a line to reduce the worst-case potential fault current, which allows the metal oxide varistor (MOV) bank to be constructed smaller. These days, with difficulty in obtaining right-of-ways for new power lines coupled with rising building costs, use of a series capacitor bank is increasingly a favored option. Fig. 2.10 (anon., 2017b) shows series capacitor bank and its components.

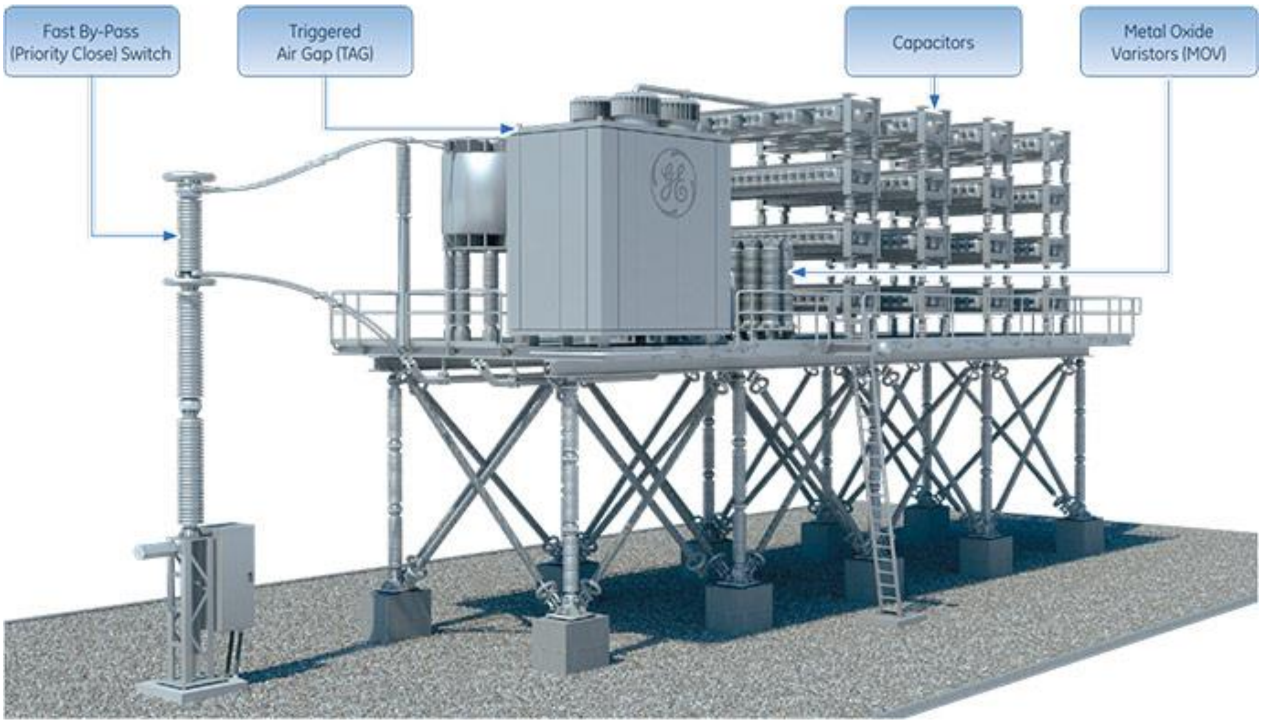

Fig. 2.10 Series Capacitor Bank

2.10 Optimal Siting and Sizing of Capacitors

Capacitors are energy storage devices that are utilized in power systems for a variety of purposes. Capacitors are commonly used in distribution systems to compensate for reactive power loss. High reactive power losses in the distribution network cause a variety of problems, including high system loss, high voltage drop, and poor power factor (Prakash *et al.*, 2016). Choosing the capacitor's placement, size, type, and control scheme is one of the obstacles in integrating the capacitor into the distribution system. The capacitor's incorrect sizing and position resulted in lower system benefits, voltage profile disruptions, greater power loss, and an unfavorable power factor (Diab *et al.*, 2017). The capacitor sizing and position problem considers objective functions such as total system losses minimization, bus voltage violation minimization, and load balancing in feeders. Because the distribution network includes both linear and non-linear loads, capacitor placement and size must be done carefully. As a result, power quality limits are implemented to ensure that problems like harmonics do not arise. Current study has highlighted the significance of switching transient overvoltage of capacitor banks, which is a key power quality issue that could jeopardize the distribution network's reliability (Javadi *et al*., 2017). As a result, the capacitor's proper sizing and location will ensure lower system loss, better system advantages, improved voltage profile, and higher power quality.

2.11 Related Works on Optimal Placement and Sizing of Capacitors

Lohia *et al*. (2016), proposed a Genetic Algorithm for the optimal placement and sizing of capacitors in a radial distribution network with an objective function of power loss reduction and voltage profile improvement. In this work, the Genetic algorithm was implemented for optimal placement and sizing of capacitors by first generating initial strings as initial population of capacitors placed at random feeders. Crossover and mutation parameters were used to generate new capacitor values. Objective function values of each solution were then estimated and the better solution was joined a new population. Individuals in the initial population with better fitness values were used to replenish the sunken population. A new genetic cycle was started after the iteration until the maximum iteration. This algorithm proved to be fast and easy to understand with respect to its computation. However, the algorithm has a high computational time and very slow convergence rate making it inefficient and hence needs to be improved.

Baysal (2016), proposed one of the latest nature inspired meta-heuristics algorithms known as Cuckoo Search Algorithm (CSA) to solve optimal capacitor placement and sizing (OCPS) problem in radial power systems. In this work, the main purpose was maximizing annual net saving by reducing the power losses with the acceptable voltage ranges. The discrete nature of the capacitors were considered. Forward and backward sweep (FBS) algorithm was applied for computing power losses and bus voltages. Load flow was then performed to calculate total power loss and bus voltages. Algorithm parameters and search space dimensions were randomly generated. The obtained results when compared to other works showed that, by installing shunt capacitors at the proper locations, the total power losses of the system are reduced efficiently and annual net savings are increased and at the same time the bus voltages are improved substantially. The drawback of this approach was that, the algorithm easily falls into local optimal solution and hence making it inefficient for maximizing the annual net savings by reducing power losses.

Singh *et al*. (2014), proposed Ant Colony Optimization Algorithm for optimal capacitor placement and sizing problem in radial power systems. This method was inspired by observation of the behavior of ant colonies. This theorem applies on the state transition rule to favour transition towards nodes connected by shorter edges. Then it applies local updating rule. Finally it applies a global updating rule to make search more directed and enhance the capability of finding the optimal solution in capacitor placement problem. It was observed that optimal capacitor placement process not only reduce the power loss, but also improve the voltage profile and maximizing the net savings. However, the proposed algorithm has low accuracy and convergence rate making it inefficient

Ceylan *et al.* (2017), also proposed the Moth Flame Algorithm for optimal capacitor placement and sizing of capacitors in radial distribution systems. The optimization model finds placement and sizes of capacitors considering variations on load profiles with 15-minute resolution. Optimization model was tested on a modified 33-node distribution feeder. Two simulation cases were considered. The first one assumes a constant tap position of the regulators, the second one adjusts the tap positions optimally to some constant daily values. The simulated results proved that, the proposed algorithm has better performance in convergence speed and search accuracy hence making it a better solution to the optimization problem. Although the proposed algorithm presented one of the most flexible methods of solving the optimal capacitor placement and sizing problem, it also suffered from high computational time when large variables were involved.

Vuletic *et al.* (2014), proposed the Clustering based optimization which was based on a simple search that places the capacitors at locations that yield maximum reduction of loss in the objective function. The effectiveness of the algorithm was demonstrated on a 22 bus, 34 bus, 69 bus and 85 bus distribution system. The clustering based optimization results were better than the results from other optimization methods. The proposed method gave repetitive and unique results in significantly shorter time. Clustering based optimization involves a number of iterations. The first iteration begins with placement of capacitors at candidate buses. Load flow was performed and the reactive powers were calculated as well as objective function values. The calculated vectors were then stored in temporary vectors. The objective function values of solutions were compared, solutions with lower values were updated in the next iteration. Reactive powers were added to appropriate locations with better solutions. The proposed algorithm has very low computational time hence making it use very efficient. However, this approach is very sensitive to initial parameters and hence leading to so many errors.

Diab *et al*. (2016), also proposed a Novel Hybrid Algorithm for optimal placement and sizing of capacitors in a radial distribution system. In this work, loss sensitivity analysis was employed to select the most appropriate candidate buses for capacitor placement. The proposed alternative hybrid method combines the particle swarm optimization (PSO) in evolution phase and the Quasi-Newton (QN) technique in the learning phase (after the stopping criterion of PSO be satisfied) to solve the optimal capacitor placement and size. The proposed algorithm was implemented by the input of system data such as the number of buses, active and reactive power loads and line impedance. Voltage at each bus was calculated as well as the power loss and line flows. Algorithm parameters were initialized according to the particle position. Backward/forward sweep flow was performed for each particle to obtain voltage at each bus and active power losses. From the test results, the proposed algorithm proved to be very effective in minimizing net losses and costs. The drawback of this approach was that, the Novel Hybrid Algorithm required a large number of iterations to produce accurate results which rendered the proposed method complex and slow.

Basyarach *et al.* (2017), proposed Accelerated Particle Swarm algorithm as a method for placement and sizing of capacitors in a radial distribution system. The proposed method uses loss sensitivity factors (LSF) to identify the buses requiring compensation and then an accelerated particle swarm optimization (APSO) algorithm is used to determine the sizes of the capacitors to be installed. The proposed method was tested on 84 distribution systems. Absolutely, it was compared with PSO algorithm to find out the performance of convergence. By using proposed method, it could reach 99.79 second computational times. It showed that proposed method has good performance of convergence than PSO algorithm. The Accelerated Particle Algorithm is very fast as compared to other algorithms however, it easily falls into local optima making it inefficient approach.

Abdelaziz *et al*. (2016), also proposed a new and powerful algorithm called the Flower Pollination Algorithm for optimal allocations and sizing of capacitors in various distribution systems. First, candidate buses for installing capacitors were suggested using loss sensitivity factors and the voltage stability index. Then the proposed flower pollination algorithm is employed to deduce the locations of capacitors and their sizing from the selected buses. The objective function was designed to reduce the total cost and, consequently, to increase the net savings per year. The proposed algorithm was tested on 10-, 69-, and 118-bus radial distribution systems. The obtained results via the proposed algorithm were compared with other algorithms to highlight the benefits of the proposed algorithm. Moreover, the results were introduced to verify the effectiveness of the suggested algorithm to minimize the losses and total cost and to enhance the voltage profile and net savings for various distribution systems and different loading conditions. The obtained results showed that power loss and total cost were greatly minimized by the proposed method compared with other optimization techniques, it also suffered from local optima problems.

Biswal *et a l*. (2018), proposed the Sine Cosine Algorithm (SCA) for obtaining optimal location and size of capacitors for addressing problems like voltage instability and line losses in radial distribution systems. By using power loss index (PLI) method, the buses that were more sensitive to the capacitor placement were identified and, thereafter, the location and size were optimized by using proposed SCA. The main objective of the system was considered as the minimization of the total cost. The Sine Cosine algorithm being a population based algorithm uses sine cosine function in its mathematical model to allow the solution to converge to optimum solution. The algorithm was implemented by first reading input data and running base case load flow. Optimization parameters were initialized and total population was determined. Search agents were estimated to find the best solution. Algorithm control parameters together with position of search agents were updated. New solutions were found until the maximum number of iterations is reached. The Sine Cosine Algorithm although converges early but easily falls into local optima solution.

Aboelyousr *et al*. (2018), proposed the Hyper-spherical Search Algorithm (HSSA) to increase the annual net saving. In this work, HSSA was employed to obtain the optimal sizing and allocations of the candidate buses to contribute effectively in decreasing the total costs and system losses in different distributed systems. Power loss index (PLI) was utilized to find the candidate buses with the highest possibility for capacitor banks installation. Then, the developed HSSA was employed with inequality constraints to determine the most elected buses for installing and sizing of shunt capacitor banks. HSSA was tested on IEEE-15 bus, IEEE-69 bus, and IEEE-119 bus systems. Applying the developed algorithm to minimize an objective function with constraints shows its ability in dealing with different radial systems. Simulated results proved that, the proposed algorithm converges faster but involves complex computations.

2.12 Summary on Related Works

The distribution system, radial distribution system planning, ideal conductor size selection, basic overview of the capacitor, and optimal capacitor siting and sizing were all covered in this chapter. Some mitigation approaches for power loss reduction and voltage profile improvement on radial distribution networks that have been established so far as well as some related studies in this field of research were also reviewed.

Several Artificial Intelligence algorithms have been developed to determine the best location and sizing of capacitors in radial distribution systems. Each of the issues mentioned took a different strategy to get a certain result that was less than ideal. This research filled a void in the field of capacitor placement and sizing. Researchers have used these methods to identify and size a capacitor in a radial distribution network to improve voltage profile and reduce power loss, but this study addresses the application of the improved harmony search algorithm (IHSA). In the improvisation step, the suggested method improves the results by employing variable Pitch Adjustment Rate and bandwidth values, which helps to get a certain desired outcome.

CHAPTER 3

METHODS USED

3.1 Introduction

In this chapter, an improved harmony search algorithm (IHSA) is applied to solve the optimal capacitor placement and sizing problem. The performance of the proposed improved harmony search algorithm is validated on the 9-bus distribution system. The obtained capacitor placement results using the IHS algorithm are compared with the particle swarm optimization and harmony search algorithm. The study will rely on the IEEE network in the lack of data from the distribution system (due to unfulfilled commitments from the utility company). Fig. 3.1 shows a single line diagram (SLD) of IEEE 9-bus system. Table 3.1 contains the data for the single line diagram.

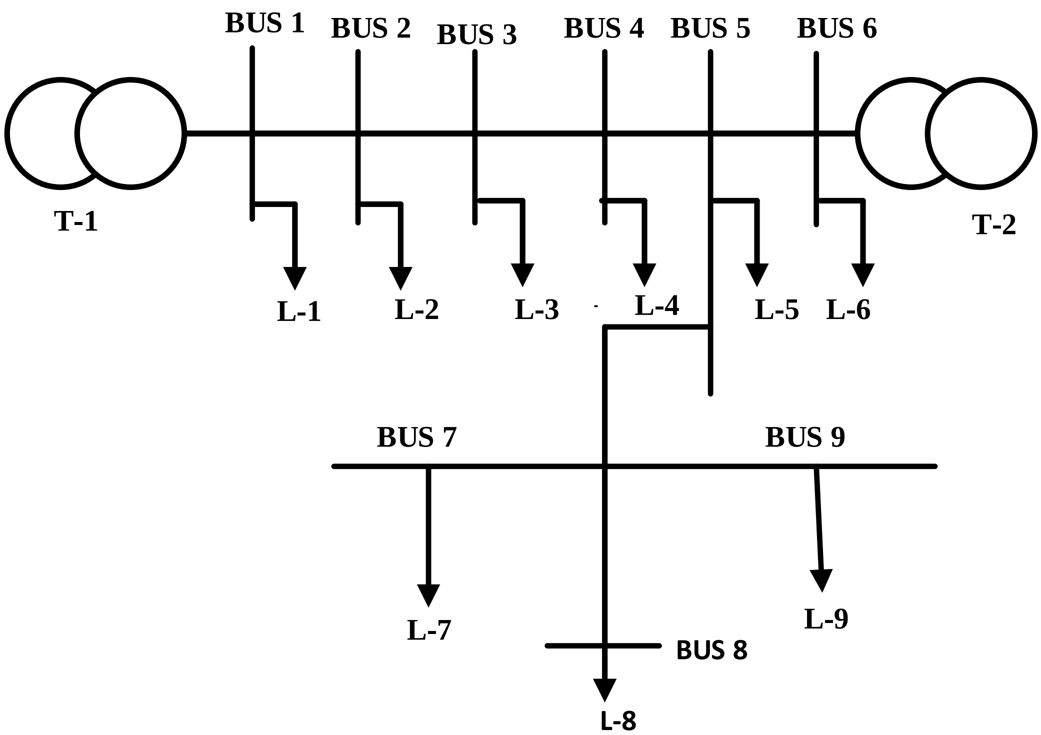

Fig. 11 IEEE 9-Bus System

The greatest capacitor size will not exceed the total reactive load of 4186 kvar, according to the decision. The capacitor values are believed to be continuous in this case. The voltage restrictions on the rms voltage are assumed to be Vmin = 0.9 p.u. and Vmax = 1.1 p.u. in this study, with the equivalent annual cost of power loss (KP) set at 168 $/year (kW-year).

Table 3.1 Load and Feeder data of the 9 Bus Test System

Bus No.	Load		Line		
	P (kW)	Q (kvar)	From	To	Length (mile)
1	1840	460	0	1	0.63
2	980	340	1	2	0.88
3	1790	446	2	3	1.70
4	1598	1840	3	4	0.84
5	1610	600	4	5	2.30
6	780	110	5	6	1.05
7	1150	60	6	7	1.50
8	980	130	7	8	3.50
9	1640	200	8	9	3.90

(Source: Sirjani *et al.*, 2011)

3.2 Design Concept and Criteria

3.2.1 Design Criteria

The design of the proposed system should satisfy the following criteria:

i. The controller should respond faster and take less time to reach the steady state;
ii. The design should be relatively easy to implement;
iii. It should be simulated using user friendly software;
iv. The design should not easily fall into local optimal; and

v. The design should improve the performance of the harmony search algorithm and eliminate the drawbacks of fixed values of pitch adjustment rate (PAR) and bandwidth (bw).

3.2.2 Design of Particle Swarm Optimisation Algorithm

Kennedy and Eberhart proposed particle swarm optimiser (PSO) as a heuristic approach of global optimization in 1995. It is based on the flocking and swarming behavior of birds in the wild. While birds travel from one location to another in quest of food, there is always one bird that can smell the food very well and hence has better food resource knowledge (Bai, 2010). This approach simply requires fundamental mathematical operators and is low-cost in terms of memory and processing time (Premkumar and Manikandan, 2016). PSO is made up of a group of people who refine their understanding of the provided search space, and these people are known as particles because of their position and velocity. Each particle contains a memory function that allows it to adapt its movement to the best position it has ever visited, as well as the best global position the entire swarm has ever achieved. The global best represents the position of the best fitness value visited by the entire swarm, while the local best represents the position of the best fitness value visited by each particle. The inertia-weighted canonical PSO has grown in popularity. Within the canonical PSO, particle i has position z_i and velocity v_i which is modified by Equation (3.1) (Neupane *et al.,* 2019).

$$\vec{V_i} = \omega \vec{v_i} + C_1 \vec{r_{1i}} (\vec{p_i} - \vec{z_i}) + C_2 \vec{r_{21}} (\vec{p_g} - \vec{z_i}) \qquad 3.1$$

where, $\vec{V_i}$ = velocity of each particle

ω = inertia weight

z_i = position of each particle

C_1 and C_2 are positive constant parameters called acceleration co-efficients

$\vec{p}_i$ = best position found so far by a particle

$\vec{p}_g$ = global best position found by the swarm

$\vec{r_{1i}}$ and $\vec{r_{2i}}$ are the distances travelled by particle i with respect to C_1 and C_2

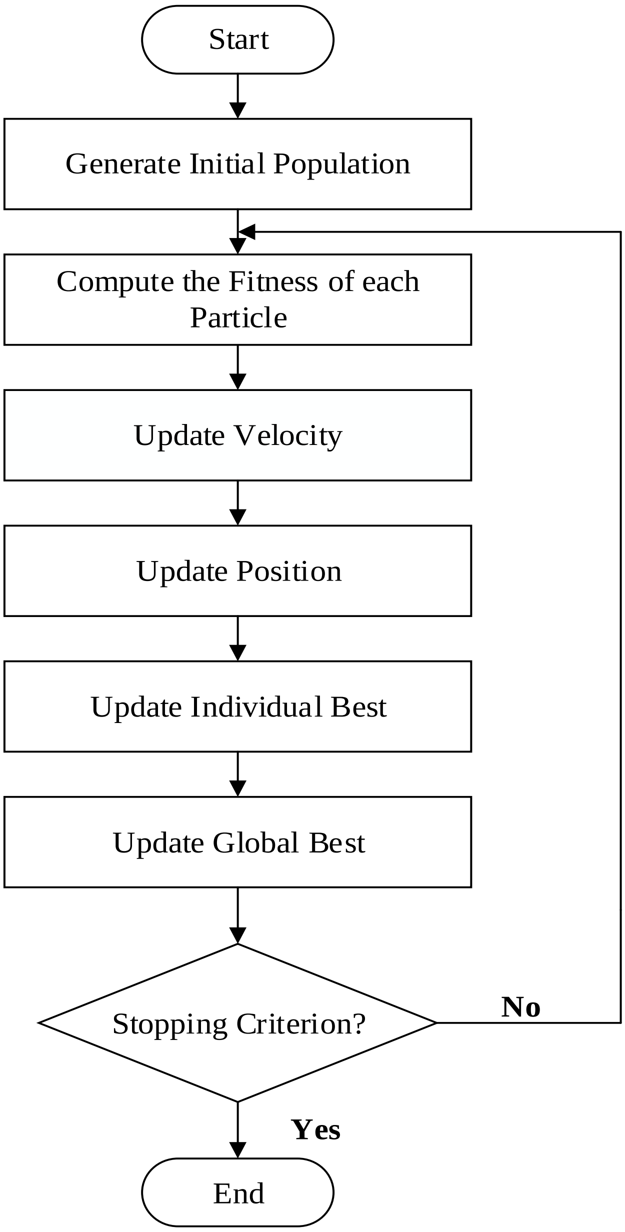

Fig. 12 Flowchart of Particle Swarm Algorithm

The flowchart of the PSO algorithm is further explained in the following steps:

Step 1: Begin to set up the MATLAB software.

Step 2: All particles in the population have their location vectors and related velocity initialized at random.

Step 3: Using the fitness function, assess each particle's fitness.

Step 4: After assessing each particle's fitness, compare the particle's fitness evaluation t the particle's best solution.

Step 5: If the current solution's fitness is better than the previous best solution, the current solution will be changed and become the best local solution.

Step 6: Compare the individual particle's fitness to that of the global population's finest.

Step 7: When the fitness of the current solution exceeds that of the previous global best, it will be updated, and the current solution will be designated as the new global best.

Step 8: Each particle's velocities and locations are updated.

Step 9: If the swarm does not meet the termination criteria, go back to step 3 and adjust the particle position and velocity; otherwise, stop iterating.

Step 10: End.

3.2.3 Design of Harmony Search Algorithm for the Optimisation Problem

The harmony search algorithm is a meta-heuristic optimization method inspired by musicians' improvisation of instrument pitch to find better harmony. It is based on numerous aspects of jazz music's improvisation process. Different artists in jazz music aim to modify their pitches so that overall harmonies are optimized for aesthetic reasons. They begin with some harmonies and improvise their way to stronger harmonies. Instead of harmonics, this analogy can be used to create search heuristics that may be utilized to optimize a given objective function (Kim, 2016). The decision variables relate to the musicians, and the harmonies correlate to the solutions. The Harmony Search algorithm iteratively develops new solutions based on previous solutions and random alterations, similar to how jazz players develop new harmonies through improvisation. It has various advantages, including the fact that the decision variables do not require starting value sets and that it can handle both discrete and continuous variables. In music improvisation, each artist creates a harmony vector by playing within the range of potential pitches. If all of the pitches produce good harmony, the musician remembers them and increases good or better harmony for the following performance. In the discipline of engineering optimization, each decision variable value is first selected within the possible range and a solution vector is then constructed (Gao *et al*., 2015). If all of the choice variable values result in a good solution, each variable that has been encountered is saved in memory, increasing the likelihood of good or better solutions in the future. Figure 3.2 (Devabalaji and Ravi, 2014) shows a harmony search by musicians. This algorithm has the advantages of being able to consider both discontinuous and continuous functions because it does not require differential gradients; it does not require initial value setting for the variables; it is free of divergence; and it can escape local optima. The modified harmony search algorithm is introduced in order to improve the traditional HS method's performance and accuracy (Rani *et al*., 2013).

Application of harmony search algorithm to the optimization problem

Step 1: Initialization of the Optimization Problem

Consider an optimization problem which is described as,

Minimize $F(x)$ subject to the constraints $x_i \in X_{i,}\ i = 1, 2, 3, \ldots N$.

where, $F(x)$: Objective function

x: Set of each design variable (x_i)

X_i: Set of the possible range of values for each design variable ($Lx_i < X_i < Ux_i$)

N: Number of design variables

The harmony memory size (HMS) or the number of solution vectors in the harmony memory; harmony memory considering rate (HMCR); pitch adjusting rate (PAR); number of decision variables (N); number of improvisations (NI); and the stopping criterion are all parameters of the HS algorithm.

Step 2: Initialization of the Harmony Memory

The harmony memory (HM) matrix, shown in (), is filled with as many randomly generated solution vectors as HMS and sorted by the values of the objective function, $f(x)$

$$HM = \begin{bmatrix} x_1^1 & x_2^1 & \ldots & x_{N-1}^1 & x_N^1 \\ x_1^2 & x_2^2 & \ldots & x_{N-1}^2 & x_N^2 \\ . & . & . & . & . \\ . & . & . & . & . \\ . & . & . & . & . \\ x_1^{HMS-1} & x_2^{HMS-1} & \ldots & x_{N-1}^{HMS-1} & x_N^{HMS-1} \\ x_1^{HMS} & x_2^{HMS} & \ldots & x_{N-1}^{HMS} & x_N^{HMS} \end{bmatrix} \cdots \begin{matrix} f(x^{(1)}) \\ f(x^{(2)}) \\ . \\ . \\ . \\ f(x^{(HMS-1)}) \\ f(x^{(HMS)}) \end{matrix} \qquad 3.2$$

Step 3: Improvisation a New Harmony from the HM set

A New Harmony vector, $x' = (x^{1'}, x^{2'} \dots x^{n'})$, generated based on three rules, namely, random selection, memory consideration and pitch adjustment.

Random Selection: When HS determines the value, x_i' for the new harmony,$x' = (x^{1'}, x^{2'} \dots x^{n'})$, it randomly picks any value from the total value range with a probability of (1-HMCR). Random selection is also used for previous memory initialization.

Memory Consideration: When HS determines the value x_i', it randomly picks any value x_{ij}' from the HM with a probability of HMCR since $j = \{1,2, \dots, HMS\}$.

Step 4: Updating HM

If the New Harmony vector, $x' = (x^{1'}, x^{2'} \dots x^{n'})$, is better than the worst harmony in the HM, from the viewpoint of the objective function value, the New Harmony is entered in the HM and the existing worst harmony is omitted from the HM.

Step 5: Checking stopping criterion.

If the stopping criterion which is based on the maximum number of improvisations is satisfied, computation is terminated. Otherwise, step 3 and 4 are repeated.

3.2.4 Design of Proposed Improved Harmony Search Algorithm

The standard HS algorithm uses set Pitch Adjustment Rate and bandwidth parameters, which can only be altered during the initialization step (Step 1) and cannot be changed during subsequent generations. The main disadvantage of this strategy is that finding an ideal solution requires a lot of iteration. After that, an improved Harmony Search (IHS) algorithm is created. Various benchmarking and conventional engineering optimization issues have been successfully solved using the IHS methodology (Wang *et al*., 2018). The IHS algorithm can provide better solutions than the classic HS algorithm and other heuristic or deterministic approaches, according to numerical results, and it is also a powerful search algorithm for tackling many engineering optimization issues. The way the

Pitch Adjustment Rate and bandwidth values are adjusted is the fundamental distinction between the IHS and regular HS algorithms. The IHS algorithm uses variable Pitch Adjustment Rate and bandwidth values in the improvisation step to increase the performance of the Harmony Search algorithm and eliminate the downsides of fixed values of Pitch Adjustment Rate and bandwidth (Step 3). The Pitch Adjustment Rate value changes dynamically with generation number.

Pitch adjustment rate

To decide whether the new harmony vector $x' = (x^{1'}, x^{2'} \dots x^{n'})$, should be pitch-adjusted, each component is analysed. Following the aforesaid memory consideration process, the value x_i' can be further changed into surrounding values by adding a specified amount to the value, with the likelihood of PAR. The PAR parameter, which represents the rate of pitch adjustment, is used in this operation:

$$x_i' \leftarrow \begin{Bmatrix} Yes & with\ probablity\ PAR \\ No & with\ probability\ \ (1 - PAR) \end{Bmatrix} \qquad 3.3$$

The value of $(1 - PAR)$ sets the rate of doing nothing. If the pitch adjustment decision for x_i' is yes, x_i' is replaced as follows:

$$x_i' \leftarrow x_i' \pm bw$$

3.4

where, bw is the arbitrary distance bandwidth for a continuous design variable. In this approach, pitch adjustment or random selection is applied to each variable of the new harmony vector.

$$PAR(gn) = PAR_{min} + \frac{(PAR_{max} - PAR_{min})}{NI} \times gn \qquad 3.5$$

The value of $(1 - PAR)$ sets the rate of doing nothing. If the pitch adjustment decision for x_i' is yes, x_i' is replaced as follows:

where, PAR = Pitch adjusting rate for each generation

PAR_{min} = Minimum pitch adjusting rate

PAR_{max}= Maximum pitch adjusting rate

NI= Number of solution vector generations

gn = Generation number

The Bandwidth values also change dynamically with generation number

$$bw(gn) = bw_{max} \exp(c.gn) \tag{3.6}$$

$$c = \frac{Ln\left(\frac{bw_{max}}{bw_{min}}\right)}{NI} \tag{3.7}$$

where, $bw(gn)$ = Bandwidth for each generation

bw_{min}= Minimum bandwidth

bw_{max} = Maximum bandwidth

3.3 Optimal Capacitor Placement and Sizing Problem Formulation

The objective function in solving the capacitor placement problem is to discover the location and size of shunt capacitors in a radial distribution system in order to maximize the savings owing to reduced power loss. To solve the optimal capacitor placement problem, we consider,

$$f = Minimize\ \{Yearly\ Power\ Loss\ Cost + Yearly\ Capacitor\ Cost\} \tag{3.8}$$

$$Yearly\ Power\ Loss\ Cost = K_p P_{loss} \tag{3.9}$$

$$Yearly\ Capacitor\ Cost = \sum_{i=1}^{n} k_i^c Q_i^c \tag{3.10}$$

Where f is the objective function, P_{loss} denotes total power loss, n is the number of possible capacitor placement locations, and K_p is the equivalent annual cost per unit of power loss in dollars (kWyear). The annual capacitor installation cost is constant k_i^c, and the indices of the buses chosen for compensation are $i = 1,2, \dots n.$ The ideal capacitor location at the buses is determined by an optimization technique, with the optimal capacitor set resulting in the least amount of power loss (Sirjani, 2011).

The greatest capacitor size will not exceed the total reactive load of 4186 kvar, according to the decision. The capacitor values are believed to be continuous in this case. The voltage restrictions on the rms voltage are assumed to be V_{min} = 0.9 p.u. and V_{max} =1.1 p.u. in this research work, with the equivalent annual cost of power loss K_p set at 168 $/year (kW-year).

3.4 Load Flow

Because the method does not need the construction of the Jacobian matrix, a simpler power flow approach known as the backward/forward sweep power flow is utilized for radial distribution networks. The relationship between Bus Current Injections and Branch Currents $(BIBC)$ is represented by the matrix $[BIBC]$, and the relationship between Branch Currents and Bus Voltages is represented by the matrix $[BCBV]$ in this power flow approach (Devabalaji *et al.*, 2014). The above mentioned matrices $[BIBC]$ and $[BCBV]$ are then multiplied to obtain the relationship between the voltage deviation, $[\Delta V]$ and the bus current injections $[I]$, which is given by $[DLF]$.

$$[B] = [BIBC]\,[I] \tag{3.11}$$

$$[\Delta V] = [BCBV]\,[BIBC]\,[I] = [DLF]\,[I] \tag{3.12}$$

Where $[I]$ is bus current injection vector and $[B]$ is branch current vector. $[\Delta V]$ is voltage drop vector and $[DLF]$ is voltage drop to bus current injection matrix.

The backward/forward sweep power flow method at the k iteration considers equations:

$$I_i^k = \left(\frac{P_i + jQ_i}{V_i^k}\right) \tag{3.13}$$

$$\nabla V^{k+1} = [DLF][I^k] \tag{3.14}$$

Total power loss is then given by the equation;

$$P_{loss} = \sum_{i=1}^{n} \frac{R_i(P_{\Sigma,i}^2 + Q_{\Sigma,i}^2)}{V_i^2} \tag{3.15}$$

Where R_i is resistance of the branch i; P_{Σ} is total active power at bus i ; $Q_{\Sigma,}$ i is total reactive power at bus i and V_i is voltage at bus i.

The backward/forward sweep power flow is used to compute the power loss in this research. Fig. 3.3 is the flowchart for improved harmony search algorithm. The Updated Harmony Search algorithm is a version of the standard harmony search algorithm that has been improved to improve performance and efficiency. The Harmony search method is used to start the optimization process before it is upgraded. Using the improved harmony search algorithm, the following procedures are utilized to determine the best capacitor placement and sizing in a radial distribution system (Devabalaji *et al*., 2014).

i. Input system parameters such as line and load data.

ii. Build the BIBC and BCBV matrices and compute the DLF matrix.

iii. Randomly add the capacitors for reactive power compensation at the buses. Calculate the total power loss and total cost, respectively. The harmony vectors are assigned to each capacitor set. Randomly initialize the HM arrays as in Equations (3.2). The HM has the same number of columns as the number of buses in the test system. The test system's ideal parameter s, Lx_i and Ux_i, are assumed to have minimum and maximum kvar values of 0 kvar and 4050 kvar, respectively, in this scenario. As a result, the harmony memory size (HMS) is set to ten.

iv. Improvise a new harmony using the three rules of random selection, memory consideration and pitch adjustment.

v. Run the backward/forward sweep power flow to calculate the bus current injections and bus voltages.

vi. Calculate power loss and total cost.

vii. Check if the capacitor set (New Harmony) gives less total cost than the worst harmony in the HM. If yes, the worst harmony is replaced with the New Harmony in the HM. Otherwise, generate new Pitch Adjustment Rate and new bandwidth.

viii. Determine the optimal capacitor set (best harmony) which gives maximum power loss reduction and maximum cost saving.

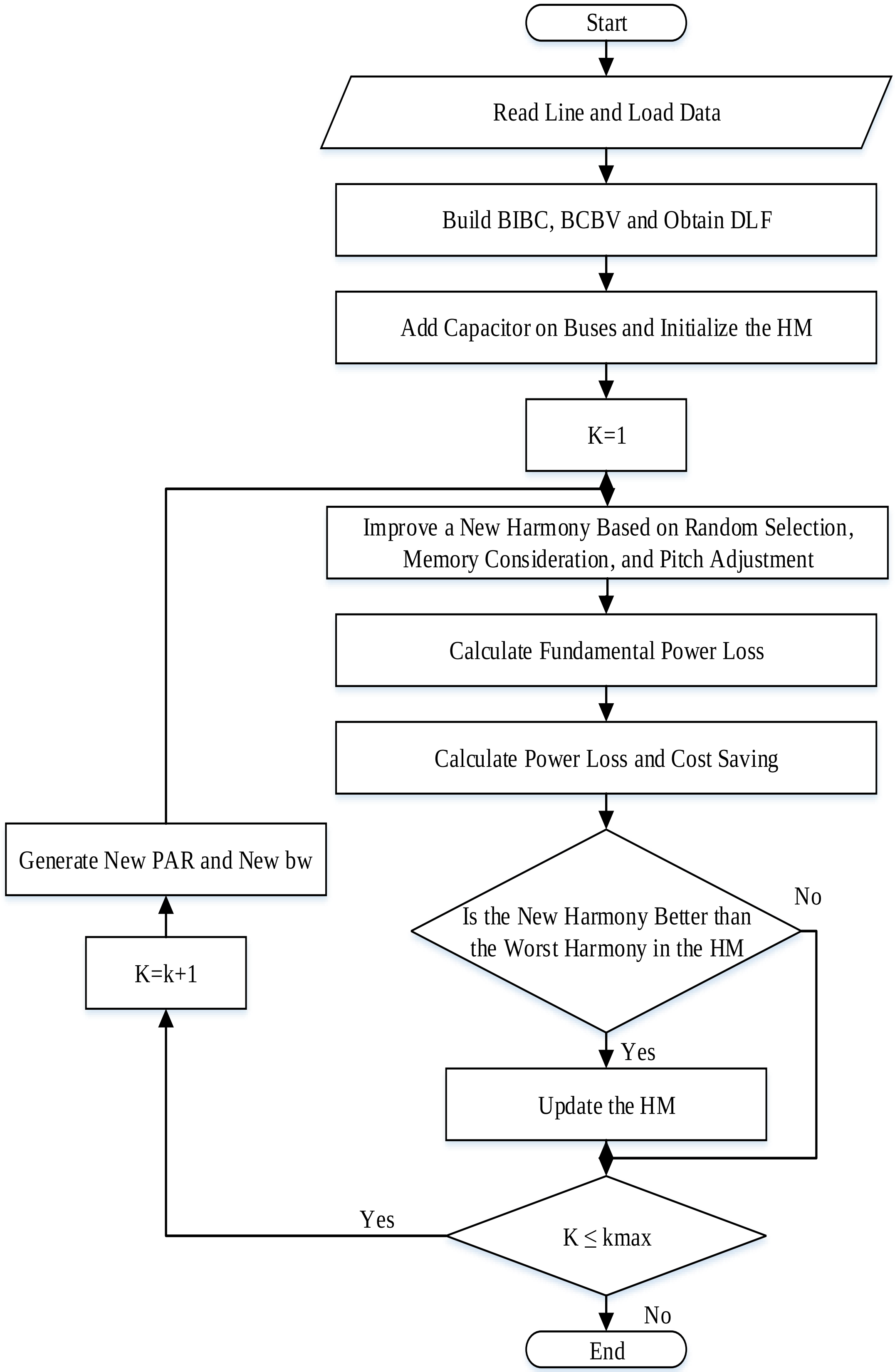

Fig. 13 Flowchart of Improved Harmony Search Algorithm

3.5 Summary of Chapter

This chapter presented the most efficient methods used in finding the optimal placement and sizing of capacitors in the radial distribution network. The flowchart and steps of the optimisers were clearly stated. The results from the proposed optimiser were clearly analysed with the help of MATLAB/Simulink software. Also, the proposed optimiser was validated on the IEEE 9-bus system. . The aim of this project work is to reduce yearly power loss and capacitor cost and also, to improve the voltage profile in the IEEE 9-bus system using the improved harmony search algorithm.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Introduction

This chapter presents the results obtained when the improved harmony search algorithm was validated on the IEEE 9-bus system.

4.2 Capacitor Placement Results

The results of the 9 bus system test utilizing the improved harmony method are compared to other optimizations utilizing particle swarm optimization and the traditional harmony search algorithm in terms of capacitor sizes, capacitor positions, power loss, and total cost. Table 4.1 shows the comparison of capacitor placement results of the 9 bus system after the last iteration.

Table 4.1 Comparison of the Capacitor Placement Results of the 9 Bus Test System

Bus No.	**Before Capacitor Placement**	**PSO**	**HSA**	**IHSA**
1(kvar)	---------	0.00	679.00	0.00
2(kvar)	---------	0.00	4042.00	449.00
3(kvar)	--------	0.00	680.00	3600.00
4(kvar)	--------	1174.00	2157.00	2091.00
5(kvar)	--------	1182.00	764.00	892.00
6(kvar)	--------	0.00	522.00	231.00
7(kvar)	--------	0.00	268.00	392.00
8(kvar)	--------	264.00	236.00	293.00
9(kvar)	--------	566.00	314.00	293.00
Power loss (kW)	783.80	696.21	649.10	643.28
Capacitor Cost ($/year)	--------	1309.10	2095.20	1685.90
Total Cost ($/year)	131,675	118, 582	111, 144	109,866

The obtained results after the last iteration shows that the improved harmony Search algorithm gives greater reduction in power loss and total costs compared to the PSO and the traditional HS algorithm.

4.3 Computational Time Results

Also for each iteration, the computational durations in the IHS method are substantially lowered compared to the traditional HS algorithm, as shown in table 4.2. This was due to the dynamic computation of PAR and bw in the IHS algorithm and the use of the backward/forward sweep power flow.

Table 4.2 Comparison of Computational Times

Optimization Method	PSO	HSA	IHSA
Calculation Duration (Sec.)	3.98	2.81	0.92

4.4 Voltage Profile Improvement Results

In fig. 4.1, it is shown that the voltage magnitudes of the 9 bus system are very close to 1 p.u. after placing the capacitors of various sizes at almost all the buses using the improved harmony search algorithm.

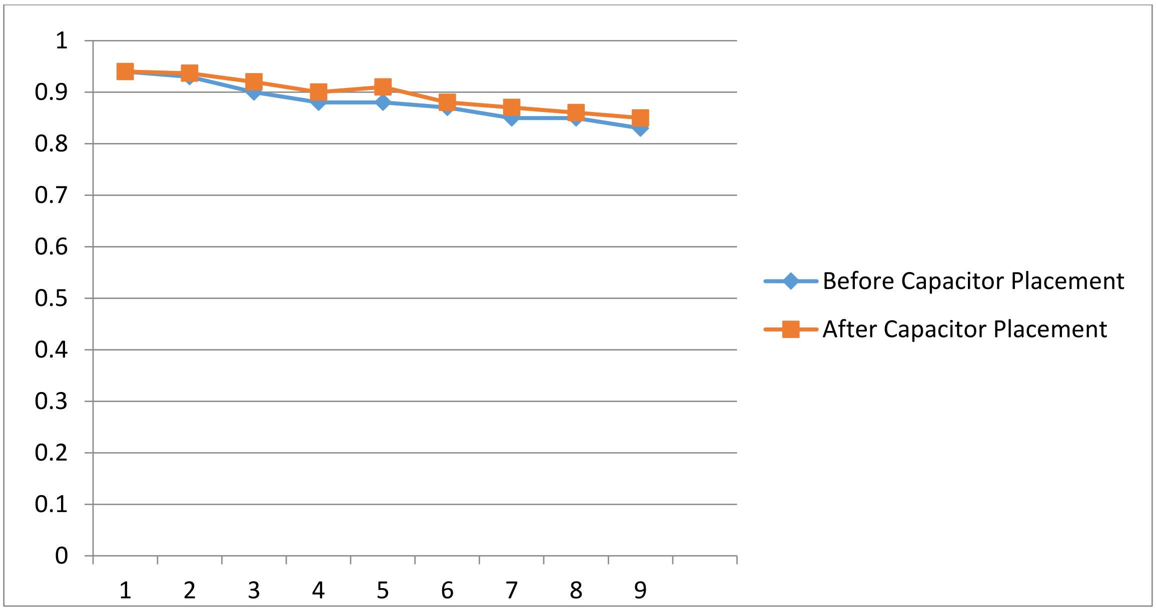

Fig. 4.1 Voltage Profile Improvement on the 9-Bus System

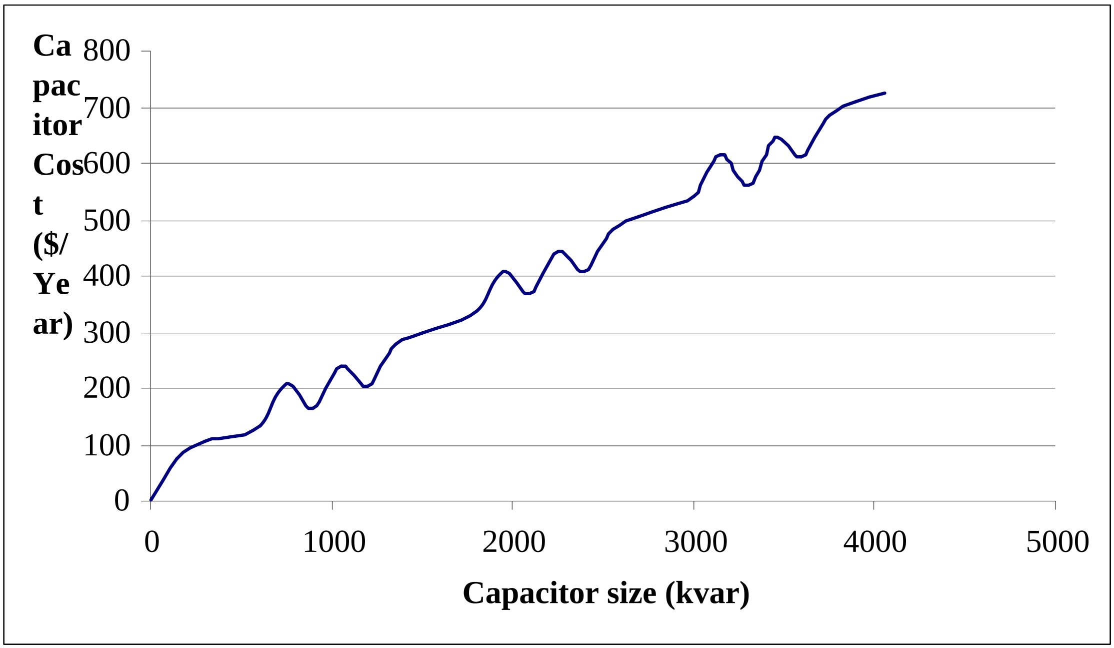

Fig. 4.2 Yearly Cost of Fixed Capacitors

4.5 Discussion of Simulation Results

Table 4.1, Table 4.2, Figure 4.1 and Figure 4.2 are the output responses for the simulation with the improved harmony algorithm for determining the bus location and Var rating of the capacitor. The load flow used was the backward/forward sweep power flow for calculating the reactive and active power losses. The backward/forward sweep power flow was very efficient because the power loss was reduced at the end of the year as seen in table 4.1. After the last improvisation, PSO algorithm gave power loss of 696.21 kW which is about 11.07% reduction in power loss and also gave annual capacitor cost of $ 118,582 which is also about 9.94% reduction in the annual capacitor cost. Also, after the simulation, HSA also optimised the power loss and capacitor cost to 649.10 kW and $ 111,144 respectively and this represent about 17.19% and 15.59% reduction in the annual power loss and capacitor cost respectively. When the IHSA was implemented, the power loss and capacitor cost were optimised to 643.28 kW and $ 109,866 which also represent about 17.93% and 16.56% reduction in the yearly power loss and capacitor cost respectively. Also, the computational time for the PSO, HSA, and IHSA algorithms were recorded to be 3.98 seconds, 2.81 seconds and 0.92 seconds respectively. Moreover, in figure 4.1, the voltage magnitude of the 9 bus system before the capacitor placement was estimated to be 0.89 p.u and after the capacitor placement, the IHSA together with the backward/forward sweep power flow improved the voltage profile to 0.95 p.u and gave a better voltage profile. Hence voltage of the system is within allowable tolerance.

After the validation of each algorithm on the 9 bus system, the improved harmony search algorithm together with the backward/ forward sweep power flow gave a better result as compared to the PSO and HSA algorithms.

4.6 Summary of Findings

Based on the results obtained, the following findings were obtained:

i. IHS algorithm gives greater reduction in power loss and total costs compared to the PSO and the traditional HS algorithm.
ii. The computational speed of the IHS algorithm is higher than the PSO and the traditional HS algorithm in solving the capacitor placement in distribution systems.
iii. The backward/forward sweep power flow also gave faster power flow solutions.

CHAPTER 5

CONCLUSIONS, RECOMMENDATIONS AND FUTURE WORKS

5.1 Conclusions

Based on the results obtained in chapter 4, the following conclusions can be drawn:

i. The application of the improved harmony search algorithm as a new meta-heuristic optimisation method for determining the optimal location and size of shunt capacitors in a distribution network was successfully achieved;
ii. Also, the obtained results when compared to the PSO and the traditional HS, gave greater reduction in power loss and total costs; and
iii. Finally, the proposed algorithm was successfully used to identify the optimal sizes of capacitors to be placed in the radial distribution system.

5.2 Recommendations

The following are recommended after completion of the work:

i. Optimisation techniques such as Genetic Algorithm, Shark Smell Optimisation Algorithm and Hybrid Bat Algorithm can be used easily to optimise and locate the size of the capacitor.
ii. Other load flow techniques with high complexity analysis such as the load flow algorithm can be considered.

5.3 Future Works

For future research, the following are recommended:

i. An Improved Harmony Search Algorithm with Differential Mutation Operator for reducing power loss in distribution systems can be considered; and
ii. The adaptation of the Improved Harmony Search Algorithm to the asymmetric case of the Travelling Salesman Problem with the evaluation of the influence of the pitch adjustment place on the quality of results.

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APPENDIX

CODES FOR OPTIMISERS

```
%---------------------------------------------------------------------
% Particle Swarm Optimisation Algorithm
%---------------------------------------------------------------------
```

Main_codes

```
clc
close all
rng default
LB=[0 0 0 0 0 0 0]; %lower bounds of variables
UB=[0.0557 0.0653 0.076 0.3467 0.5433 0.078 0.453 ]; %upper bounds of variables
% pso parameters values
m=6; % number of variables
n=100; % population size
wmax=0.9; % inertia weight
wmin=0.4; % inertia weight
c1=2; % acceleration factor
c2=2; % acceleration factor
% pso main program-------------------------start
maxite=1000; % set maximum number of iteration
maxrun=10; % set maximum number of runs need
for run=1:maxrun
run
% pso initialization---------------------------start
for i=1:n
for j=1:m
x0(i,j)=round(LB(j)+rand()*(UB(j)-LB(j)));
end
end
x=x0; % initial population
v=0.1*x0; % initial velocity
for i=1:n
f0(i,1)=ofun(x0(i,:));
end
[fmin0,index0]=min(f0);
pbest=x0; % initial pbest
gbest=x0(index0,:); % initial gbest
% pso initialization-------------------------end
% pso algorithm----------------------------start
```

```
ite=1;
tolerance=1;
while ite<=maxite && tolerance>10^-12
w=wmax-(wmax-wmin)*ite/maxite; % update inertial weight
% pso velocity updates
for i=1:n
for j=1:m
v(i,j)=w*v(i,j)+c1*rand()*(pbest(i,j)-x(i,j))...
+c2*rand()*(gbest(1,j)-x(i,j));
end
end
% pso position update
for i=1:n
for j=1:m
x(i,j)=x(i,j)+v(i,j);
end
end
% handling boundary violations
for i=1:n
for j=1:m
if x(i,j)<LB(j)
x(i,j)=LB(j);
elseif x(i,j)>UB(j)
x(i,j)=UB(j);
end
end
end
% evaluating fitness
for i=1:n
f(i,1)=ofun(x(i,:));
end
% updating pbest and fitness
for i=1:n
if f(i,1)<f0(i,1)
pbest(i,:)=x(i,:);
f0(i,1)=f(i,1);
end
end
[fmin,index]=min(f0); % finding out the best particle
ffmin(ite,run)=fmin; % storing best fitness
ffite(run)=ite; % storing iteration count
% updating gbest and best fitness
if fmin<fmin0
gbest=pbest(index,:);
fmin0=fmin;
end
% calculating tolerance
if ite>100;
tolerance=abs(ffmin(ite-100,run)-fmin0);
end
```

```
% displaying iterative results
if ite==1
disp(sprintf('Iteration Best particle Objective fun'));
end
disp(sprintf('%8g %8g %8.4f',ite,index,fmin0));
ite=ite+1;
end
% pso algorithm-----------------------------------end
gbest;
fvalue=10*(gbest(1)-1)^2+20*(gbest(2)-2)^2+30*(gbest(3)-3)^2;
fff(run)=fvalue;
rgbest(run,:)=gbest;
disp(sprintf('-------------------------------------------'));
end
% pso main program------------------------------------------------------------end
disp(sprintf('\n'));
disp(sprintf('----------------------------------------------------------------'));
disp(sprintf('Final Results-----------------------------'));
[bestfun,bestrun]=min(fff)
best_variables=rgbest(bestrun,:)
disp(sprintf('**********************************************************'));

%----------------------------------------------------------------------
% Harmony Search Algorithm
%----------------------------------------------------------------------
% Base on:
% [1]:
clc;clear all;close all
%% Problem Prametters
Dim=2; % problem Dimention
Low=[-10 -10]; % Low Boundry of Problem
High=[10 10]; % High Boundry of Problem

Min=1; % Minimaization or maximaiz of Fun? if Min=1 it will be minimaze the function and if Min=0 it will be maximized the function.

%% Harmony Search Parametters

HMS=100;%Harmony Memory Size (Population Number)
bw=0.2;
HMCR=0.95;%[1], Harmony Memory Considering Rate
PAR=0.3;%[1], Pitch Adjustment Rate

MaxItr=10000;% Maximum number of Iteration

%% Initialization
HM=zeros(HMS,Dim);
HF=zeros(HMS,1);
for i=1:HMS
   HM(i,:)=Low+(High-Low).*rand(1,Dim);
```

```
    HF(i,1)=MyFun(HM(i,:));
end

if Min==1
    [WorstFit,WorstLoc]=max(HF);
else
    [WorstFit,WorstLoc]=min(HF);
end


%% Iteration Loop
for Itr=1:MaxItr
    HarmonyIndex=fix(rand(1,Dim)*HMS)+1;% Random Selection of Harmony
    Harmony=diag(HM(HarmonyIndex,1:Dim))';% Extraxt Value of harmony from
Memory(Can Be better???)
    CMMask=rand(1,Dim)<HMCR;
    NHMask=(1-CMMask);
    PAMask=(rand(1,Dim)<PAR).*(CMMask);
    CMMask=CMMask.*(1-PAMask);
    NewHarmony=CMMask.*Harmony+PAMask.*(Harmony+bw*(2*rand(1,Dim)-
1))+NHMask.*(Low+(High-Low).*rand(1,Dim));
    OutOfBoundry=(NewHarmony>High)+(NewHarmony<Low);
    NewHarmony(OutOfBoundry==1)=Harmony(OutOfBoundry==1);
    NHF=MyFun(NewHarmony);
    if (NHF<WorstFit)&&(Min==1)
        HM(WorstLoc,:)=NewHarmony;
        HF(WorstLoc)=NHF;
        [WorstFit,WorstLoc]=max(HF);
    elseif (NHF<WorstFit)&&(Min==0)
        HM(WorstLoc,:)=NewHarmony;
        HF(WorstLoc)=NHF;
        [WorstFit,WorstLoc]=min(HF);
    end
end

%% Present Best Answer
if Min==1
    [BestFit,BestLoc]=min(HF);
else
    [BestFit,BestLoc]=max(HF);
end
Best=HM(BestLoc,:);

display(Best)
display(BestFit)


%-----------------------------------------------------------------------
% Improved Harmony Search Algorithm
%-----------------------------------------------------------------------
```

```
TOTALRUNS = 20;
NVAR = 4;
bestHarmonyArray = zeros(TOTALRUNS,NVAR+1);
bestArray = zeros(TOTALRUNS,1);
[LOW,HIGH,NVAR,INDEX] = userPrompt();
for run = 1:TOTALRUNS

    % Reseed the Random Number Generator
    rng shuffle

    % Parameters begin
    % LOW=[1 1 5 0.3];
    % HIGH=[100 6 40 0.5];
    % INDEX=4;
    % NVAR=Number of Variables
    % LOW=Vector containing lower bounds of parameters
    % HIGH=Vector containing upper bounds of parameters
    HMS = 10;% Harmony Memory Size
    MAXITERS = 5000;% Maximum Iterations
    PAR_MIN = 0.35;%Min. Pitch Adjusting Rate
    PAR = 0.4;%Pitch Adjusting Rate
    PAR_MAX = 0.35;%Max. Pitch Adjusting Rate
    BW_MIN = 0.00001;%Min Bandwidth
    BW = 0.02;%BandWidth or FretWidth
    BW_MAX = 0.002;%Max Bandwidth
    generation = 1;% Iteration Number
    bestHarmony = zeros(1,NVAR);% Best harmony obtained after evaluation
    NCHV = zeros(1,NVAR);% New Candidate Harmony Vector
    bestFitHistory = zeros(MAXITERS,1);% History of best harmonies
    worstFitHistory = zeros(MAXITERS,1);% History of worst harmonies
    HMCR = 0.9;% Harmony Memory Consideration Rate
    HM = initiator(HMS,NVAR,LOW,HIGH,INDEX);% Harmony Memory
    % Parameters end


    % Algorithm starts
    while generation <= MAXITERS
        standardDeviation = calculateStandardDeviation(HM(1:HMS,NVAR+1));
        [lowHM,highHM] = getsetMinMax(HM,HMS,NVAR);
        for i = 1:NVAR
            if rand < HMCR

                % Memory Consideration begins here
                temp_val1 = HM(randi([1,HMS],1),i);
                NCHV(i) = temp_val1;
                % Memory Consideration ends here

                %Pitch Adjust starts here
                if rand < PAR
```

```
            temp_rand = rand;
            temp = NCHV(i);
            if temp_rand<0.5
                temp = temp+temp_rand*BW;
                if temp < HIGH(i)
                    NCHV(i) = temp;
                end
            else
                temp = temp-temp_rand * BW;
                if temp > LOW(i)
                    NCHV(i) = temp;
                end
            end
        end
        %Pitch adjust ends here

    else

        % Random Selection begins here
        if standardDeviation > 0.0001
            temp_rand1 = rand;
            temp_val2 = LOW(i) + temp_rand1 * (HIGH(i)-LOW(i));
            NCHV(i) = temp_val2;
        else
            temp_rand2 = rand;
            temp_val3 = lowHM(i) + temp_rand2 * (highHM(i)-lowHM(i));
            NCHV(i) = temp_val3;
        end
        % Random Selection ends here

    end
end
currentFit = fitness(NCHV,INDEX);

%Dynamic adjust of BW and PAR
PAR = PAR_MIN + (PAR_MAX - PAR_MIN)*generation/MAXITERS;
c = log(BW_MIN/BW_MAX)/MAXITERS;
BW = BW_MAX*exp(c*generation);
%Process ends here

worst = HM(1,NVAR+1);
worstIndex = 1;

% Search for Worst Harmony in HM starts here
for i = 1:HMS
    if HM(i,NVAR+1) > worst
        worst = HM(i,NVAR+1);
        worstIndex = i;
    end
end
```

```
    % Search ends here

    worstFitHistory(generation) = worst;% History of worst harmonies

    % Update of HM starts here
    if(currentFit < worst)
        for k = 1:NVAR
            HM(worstIndex,k) = NCHV(k);
        end
        HM(worstIndex,NVAR+1) = currentFit;
    end
    % Update ends here

    % Search for best harmony in HM starts here
    best = HM(1,NVAR+1);
    bestIndex = 1;
    for i = 1:HMS
        if HM(i,NVAR+1) < best
            best = HM(i,NVAR+1);
            bestIndex = i;
        end
    end
    % Search for best ends here

    bestFitHistory(generation) = best;%History of best harmonies

    % Searching the best Harmony in besthistory starts here
    if (generation > 1) && (best ~= bestFitHistory(generation-1))
        for k = 1:NVAR
            bestHarmony(k) = HM(bestIndex,k);
        end
    end
    % Search ends here

    generation = generation + 1;
end
% Algorithm ends



% Display Results
disp('Optimized parameter values = ')
disp(bestHarmony)
for indx = 1:NVAR
    bestHarmonyArray(run,indx) = bestHarmony(indx);
end
bestHarmonyArray(run,NVAR+1) = best;
disp('Optimized Function Value = ')
disp(best)
bestArray(run,1) = best;
```

```
end

% Buffering in a excel file
if INDEX == 1
    filename = 'Spherical.xlsx';
elseif INDEX == 2
    filename = 'Rosenbrock.xlsx';
elseif INDEX == 3
    filename = 'Beale.xlsx';
elseif INDEX == 4
    filename = 'newHS_Values_Negative.xlsx';
elseif INDEX == 5
    filename = 'newHS_Values_Positive.xlsx';
else
    filename = 'Spherical.xlsx';
end
xlswrite(filename,bestHarmonyArray);
% end
```