# Loss Minimization and Allocation of Unbalanced Radial Distribution Network

***A Thesis***

*Submitted in the fulfilment of the requirement*
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**DOCTOR OF PHILOSOPHY**
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*Submitted by*

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# *CERTIFICATE*

I hereby certify that the work which is being presented in thesis entitled "***Loss Minimization and Allocation of Unbalanced Radial Distribution Network***" to the Department of Electrical and Instrumentation Engineering, Thapar Institute of Engineering & Technology (Deemed to be university), Patiala in the fulfilment of the requirements for the award of degree of "Doctor of Philosophy" is an authentic record of my own research work carried out under the guidance of Dr. Smarajit Ghosh and refers other research work which are duly listed in the reference section. The matter presented in this thesis has not been submitted in part or full for the award of any degree in any other University or Institute.

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This is to certify that the above statement made by the candidate is correct and true to the best of my knowledge.

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**(Manvir Kaur)**

*To My Adoring Daughter*

***Ikagar***

# ABSTRACT

In this thesis it has been tried to discover the possibilities of loss minimization in unbalanced radial electrical power distribution networks. It has been found that the losses can be minimized by two main methods, which are network reconfiguration and optimal placement of DG and capacitor. To apply these remedial steps on the distribution networks an efficient load-flow solution method for three-phase unbalanced radial distribution network has been proposed so that the actual condition related to node voltage and its angle, branch current, real power loss, reactive power loss, branch losses etc. of the network can be computed. Simple equations are used to relate the sending-end voltage, receiving-end voltage and voltage drops in each branch of the distribution system. An algorithm is developed to find out the respective parameters. The angle of the receiving-end voltage is also computed along with the magnitude of the voltage. It is an iterative method. The flat voltage (1p.u.) start from substation to every end-node is considered. The voltage magnitude and angle are updated after each successive iteration and the voltage drops are then computed by using the new obtained values of voltage magnitude and angle. The proposed method has been implemented on 19-node and 25-node unbalanced distribution networks. The comparison of speed requirement by the proposed method with the other recent method has been verified to show its efficiency.

In power distribution network losses occurring in the network are one of the important components, and effort should be done to reduce their value. There exist different approaches for loss minimization and most important one is, reduction of distribution network losses by network reconfiguration. In the present work 19-node and 25-node unbalanced distribution networks have been considered for loss reduction. Fuzzy –firefly algorithm is applied to find out the optimal configuration of the system with minimum losses, giving the status of opened and closed switches. This approach is applied on both the test systems and the results are recorded and compared with the other techniques found in literature work. The voltage profile of distribution network has been improved by reducing the reactive component of power by optimal capacitor placement and for the reduction of active power loss, DG has also been allocated in the reconfigured network. The sizes of DG and capacitor are computed by utilizing Bacteria foraging optimization algorithm (BFOA). Results are also compared for real power loss, reactive power loss and minimum voltage for before and after integration of DG and capacitor. The results obtained are effective and DG and capacitor placement for loss minimization along with reconfiguration comes out to be a decent choice.

Nowadays, the classic model of functioning of regulated electricity market is being replaced by the newly formed deregulated energy market, where generation, transmission and distribution comes out as single independent entities. The main burden in this market comes in the form to maintain low-cost electricity, efficient capacity expansion planning, and better service. So here reconfiguration of 25-node unbalanced distribution network is also done in deregulated environment taking minimization of operating cost and reliability optimization as main components of objective function. The optimal reconfigured network of 25-node unbalanced radial distribution network in deregulated environment is found by the firefly algorithm. DG and capacitor are placed in reconfigured network for further loss reduction and results are compared and found to be effective.

After reducing the distribution network losses, the important part is to allocate the losses to different system entities, so that we can find the contribution of each and every important component towards network losses. Loss allocation basically refers to the expenditures linked with losses to distinct customers of the distribution network. In the present work the loss allocation of unbalanced radial distribution network has been carried out by using fuzzy-firefly algorithm. Also, a loss allocation method by integrating of DG and Capacitor in the reconfigured network is formulated. The loss allocation in unbalanced distribution networks in both the regulated and deregulated environments are presented for 25-node unbalanced distribution networks for before and after network reconfiguration and also after integration of DG and capacitor in the reconfigured network. Also, loss allocation is performed for IEEE 13-node test feeder and the results obtained by the proposed method and method available in literature are compared and the proposed method gives the loss allocation in more uniform way as compared to existing technique.

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# LIST OF SYMBOLS

$n$ : Total number of nodes
$k$ : Node Number: 1, 2, 3… N
$Jj$ : Branch number: 1, 2, 3… N-1

$V_k$ : Sending-end voltage

$V_{k+1}$ : Receiving-end node's voltage

$\delta_k$ : Sending-end node's voltage angle
$\delta_{k+}1$ : Angle of Receiving-end node's voltage
$I_{jj}$ : Branch current

$Z_{jj}$ : Branch impedance
$R_{jj}$ : Branch resistance

$X_{jj}$ : Branch reactance
$Y^c{}_m$ : Admittance of the charging capacitance

$I^c{}_m$ : Current of charging capacitor

$P_m$ : Real power load connected to node (m)

$Q_m$ : Reactive power load respectively connected to the node (m)
$S_D$ : Complex power demand
$P_D$ : Real power demand
$Q_D$ : Reactive power demand
$P_{LOSS}$ : Real power losses in the network

$K$ : Voltage ratio

$Br$ : Branch number
$N$ : Bus number
$\phi$ : Phase

$R$ : Resistance

# CHAPTER -1: INTRODUCTION

## 1.1 Introduction

Electrical utility provides three visual areas, namely generation, transmission along with distribution. The power plants typically produce 50 Hz, alternating-current (AC) electricity at 11 kV voltage in Indian scenario. The 3-phase generated voltage is actually stepping up to the higher voltage for transmission of power. The power plant must be able to transmit AC power over very long distances at voltages level of 230 kV to 345 kV and 500 kV to 765 kV respectively. Electric utilities foremost difficulties in India are to increase the reliability, improvement in the quality of power, better use of distribution network and reduction in the cost of electricity.

Nowadays, the electric power industry is going through major changes because of system restructuring. The older power system network was unified in nature, but in the present age of the deregulated power system network, there exists flow of energy from central to several distribution networks. Also, this structure leads to Distributed generations (DGs) integration in power system network. These major changes in the network have introduced the competition in the electricity market to deliver the power to the consumers at increased efficiency and at low cost. In a power system network, 80 percent of the total expenditure is towards the generation and distribution network (40 percent each), the remaining 20 percent accounts for transmission cost. This results in the need to allocate the cost of transmission and distribution among the users of the utilities. Amongst all cost components, losses of distribution power are the significant one to be assigned, as $I^2R$ losses are high because of low voltage and high current in the distribution network.

In distribution network there exists two types of losses, namely non-technical losses and technical losses. A non-technical loss is defined as, any consumed energy, which is not billed. In other words, these losses arise due to the power theft, unbilled accounts and estimated customer accounts and errors are due to the approximation of consumption by un-metered supplies and metering errors. Technical losses are regarded as the electrical system losses, which involve the substation, transformer and line related losses. These include resistive losses of the primary feeders, the distribution transformer losses, resistive losses in secondary network, resistive losses in service connection wires and losses due to nature of consumer loads. Therefore, reduction in technical losses is the major concern for any electrical utility. Also, distribution networks are practically unbalanced resulting in capacity limit violation due to loss of energy.

In any distribution networks, there exists sub-categories namely: Distribution Substation, Primary Distribution and Secondary distribution. Distribution substation passes on the power received from transmission or sub-transmission lines to the distribution feeders. In distribution substation, transformers are placed to step down the voltage at an acceptable level for primary distribution purpose.

Distribution feeders are vitally organised in a radial way for synchronisation and subsiding outages and reducing costs. In this radial structure, end consumer faces fluctuation in voltage when distribution load changes, secondly the reliability of the radial distribution network is not said to be very good as a fault in main feeder results in power blackout to all the consumers being served by the system. Reliability of this type of network can be improved by network reconfiguration and placement of automatic circuit breakers.

## 1.2 Loss minimization in distribution network

The active power loss of any distribution network occurs only for its high value of resistances across the branches. This loss is also called the resistive loss or line loss. The phase shifting transformers along with optimal load-flow can minimize this loss. If distributed generations are placed properly, this type loss of the system can also be reduced. Reactive power loss of the system can be slashed by proper installing shunt capacitors. Now days restructuring of the distribution system network along with distributed generations (DGs) and capacitors placement is the main approach for loss minimization and allocation.

### 1.2.1 Network reconfiguration for loss minimization of the unbalanced radial distribution network

In the present era of technology and communication, distribution automation has become the prior interest of utilities participating in power system network. Here the distribution network reconfiguration is the main zone where automation can be applied. Reconfiguration of the distribution network is the opening and closing of switches in the system to change the topology of the network. System reconfiguration of a network depends on the loading conditions of the network and may be necessary to abolish surpluses on particular components of the system e.g., section lines and transformers. Here the reconfiguration is termed as load balancing. In distribution network, system reconfiguration gives numerous advantages being tested by various researchers like reduction in active power losses, system restoring, increasing reliability and load balancing. Therefore, reconfiguration of the network has proved to be economically beneficial as compared to other techniques.

### 1.2.2 Role of distribution generation (DG) and capacitor integration for loss minimization

In the present time, accumulation of distribution generations in the network has become a tedious practice. The working of the distribution network is influenced due to the assimilation of DGs for reducing active power losses. The optimal allocation and sizing of a DG unit are one of the important factors for loss reduction in any distribution system. The DG size is optimized for an appropriate bus, so that the losses of a distribution network are reduced. However, the loss is increased if the DG size is increased beyond the optimal DG size at that particular location and vice-versa. Hence the minimization of losses directly depends on the location of DG.

Placement of capacitors reduces the current and MVA in lines by supplying the reactive power to the circuit. Thus, installing shunt capacitors in distribution networks reduces energy losses and peak demand losses. This also improves the voltage profile, power factor and reliability of the system. Installing of shunt capacitor involves determining the optimal location as well as the size of the capacitor to be placed so as to reduce maximum losses. Network reconfiguration can be done with capacitor allocation to have more benefits.

Accordingly, from the ongoing research, reconfiguration of the network is characterised as basic implementation for network reconfiguration for loss minimization and loss allocation is having a fascinating concern with the network reconfiguration, integration of DG and capacitor in the distribution network, which becomes indispensable for the performance of service contention.

## 1.3 Scope of the research

After the literature survey, the following areas of research are noticeable as the scope of further research:

I. In load-flow studies, the most of the works were with balanced distribution networks. Practically the distribution networks are unbalanced; hence the above said work should be focused for unbalanced distribution networks with faster convergence.

II. Reconfiguration of the distribution network was performed on balanced and regulated distribution network, where maximum work is done without counting the participation of DGs and capacitor for loss minimization in reconfigured network. In present work the scope is taken in the form of reconfiguration of unbalanced distribution network without and with integration of DG and capacitor.

III. In loss allocation of distribution network majority of works have been done either on balanced distribution network in regulated environment or balanced distribution network with deregulated environment. Hence, loss allocation of unbalanced distribution network in regulated and deregulated environments has been taken as the scope of the research work. The loss allocation of reconfigured network of unbalanced network before and after integration of DG and capacitor have been put in the scope of the research work.

## 1.4 Objectives of the research

The research work accomplishments start from driving a new load-flow solution method and following towards network reconfiguration, DG and capacitor placement for regulated and deregulated radial distribution network and getting results for loss minimization and allocation. The research work is divided into following objectives:

- To develop an efficient load-flow method for unbalanced radial distribution network to compute current at each node, branch current, the voltage at each node, voltage angle, branch voltage drops, branch real power losses and reactive power losses.
- To develop a reconfiguration method for loss minimization of the three-phase unbalanced radial distribution network in the regulated environment and also to integrate DG and capacitor in the reconfigured network.
- To develop a reconfiguration method for loss minimization of the three-phase unbalanced radial distribution network in the deregulated environment and also to integrate DG and Capacitor in the reconfigured network.
- To allocate loss of the base network, reconfigured network before and after integration of DG and capacitor in the regulated and deregulated environment.

## 1.5 Organization of the thesis

**Chapter-1** has presented the introduction of basic nature and problems of the distribution network, network reconfiguration and loss minimization, objectives of research, the scope of research and organization of thesis.

**Chapter-2** presents the literature survey on load-flow, distribution network reconfiguration and loss allocation in the radial distribution network.

**Chapter-3** presents a new and efficient load-flow method for the three-phase unbalanced radial distribution network. The proposed load-flow method results are compared with other existing methods. The evaluation of computer memory and CPU time for each of the standing method and suggested technique is shown.

**Chapter-4** presents reconfiguration in the regulated environment before and after incorporation of DG and capacitor in the reconfigured network.

**Chapter-5** presents reconfiguration in the deregulated environment before and after incorporation of DG and capacitor in the reconfigured network.

**Chapter-6** presents loss allocation in the regulated and deregulated environments, carried out for the above cases.

**Chapter-7** presents conclusion and future scope of research.

**References** show the list of previous papers, books, reports etc. those are discussed in literature survey and other chapters of this thesis on various topics related to the research work.

**Appendix-A** presents the line data and load data of 19-node unbalanced distribution network.

**Appendix-B** presents the line data and load data of the 25-node unbalanced distribution network.

**Appendix-C** presents the line data, load data for the 13-node unbalanced distribution network.

**List of Publications**

**Biography of the author**

**Biography of supervisor**

# CHAPTER -2: LITERATURE SURVEY

## 2.1 Literature survey of electric power distribution networks

Literature survey on the following areas has been presented in the subsequent articles:

i. A load-flow solution of electric power distribution networks.
ii. Reconfiguration of electric power distribution networks in the regulated and deregulated environments.
iii. Loss allocation of electric power distribution networks in the regulated and deregulated environments.

## 2.2 Survey on the load-flow solution of electric power distribution networks

In planning and expansion of distribution networks, load–flow solution plays a paramount part. An accurate and efficient load –flow method is required for distribution networks to compute power loss, voltage, reliability testing, reducing losses etc. for the planning of networks. There exist various traditionally known load-flow methods such as Newton–Raphson, Fast-decoupled, Quasi-static and many more, which were modified and proved by researchers according to the changing network needs. Some major research works related to the load-flow studies are discussed below.

Stubings and Berg (1991) proposed a method, for the analysis of distribution network with an unbalanced load. They applied their suggested method on 15-node and 57-node systems and technique was independent of manipulation in admittance matrices. They computed the voltages and currents until the variance in successive iterations comes out to be small. They utilized a theoretical analysis to verify the convergence.

Chen ***et al***. (1991a) proposed a solution method, which utilized optimally systematic triangular factorization implicit $Z_{bus}$ method. They introduced a new simulated system named as "Generalized Distribution Analysis Systems (GDAS)" for balanced and unbalanced system analysis utilizing the phase frame representation for all network

/elements, which incorporated a number of categories not found in that time existing simulation systems.

Zimmerman and Chiang (1995) considered a comprehensive model, which included almost all the distribution system constituents' along with different load types. They used fast decoupled method accompanied by the traditional formulation of backward/forward sweep, Newton and Gauss methods. Their proposed method was tested on two different three-phase unbalanced distribution networks. Their suggested formulation of the problem had reduced the number of equations to be solved for system analysis.

Cheng and Shirmohammadi (1995) suggested a power-flow analysis method, which was an extension of compensation-based method. They applied their compensation-based idea efficaciously to eradicate the voltage magnitude divergences at PV nodes. They made that method proficient in the supervision of dispersed generation in distribution structures. The proposed method came out to be proficient and vigorous, from their test results.

Zhang and Cheng (1997) formed a modified Newton method and changed the formation of the Jacobian matrix from traditional ways to direct backward/forward sweep method. Their suggested scheme could be stretched to the solution of structures with loops, dispersed generators and unbalanced three-phase system. They performed an investigation on numerous large distribution networks ranged from 490 to 1651 in nodes, 0.15 to 5.48 in R/X ratio and 0.0004 Ω to 3.07 Ω and had shown that the recommended method was effective and strong.

Thukaram ***et al.*** (1999) had proposed a load-flow technique for three-phase radial distribution network utilizing forward and backward propagation method. They tested the suggested technique on several distribution systems of several voltage levels and with high R/X ratio. The CPU time taken for the proposed method was very small in comparison to other available methods.

Miu and Chiang (2000) suggested a three-phase radial power-flow solution with complete system modelling. They had shown the systems with detailed forming for the presence and individuality of the three-phase radial load-flow solution through realistic voltage level and the monotonic performance of the voltage level with respect to realistic load changes. In their suggested technique, they had given an outline in which those roles could be applied well to mend the operation and planning of distribution networks.

Teng and Chang (2002) presented a load-flow solution for unbalanced radial distribution networks. They used the Jacobian matrix formation algorithm to form the matrix in spite of old time-consuming approaches. Their suggested technique could easily incorporate the distribution equipment model. They compared the results obtained by the proposed method with that of other existing best methods and found the proposed technique suitable for enormous distribution setups.

Ciric ***et al.*** (2003) presented a load–flow method for three-phase, four-wire radial distribution network using a backward-forward method including neutral grounding. They presented their test result on unbalanced distribution network. The suggested load-flow technique facilitates to examine the effects of neutrals and system grounding on the working of the practical distribution network.

Ramos ***et al.*** (2004) had also presented a power-flow solution for unbalanced distribution networks considering mutual coupling through branch voltages. Their suggested method was based on forward/backward sweep. They tested their method on four different unbalanced distribution networks to present the efficiency and accuracy of the suggested technique.

Ranjan ***et al.*** (2004) presented an algorithm for power-flow studies of unbalanced radial distribution networks. They formed their algorithm by using basic concepts of network analysis and mutual coupling between the phases for making the network model. The key benefit of the planned technique is that all the records are kept in the vector form. Their method gave the results efficiently and fast, so that it could be used for various power-flow study applications viz. reconfiguration of network and SCADA.

Wang and Chen (2004) proposed a load-flow method for unbalanced radial distribution networks utilizing backward/forward sweep method along with distribution transformer nodal admittance matrix. Their suggested algorithm could be used for solving the phase shift produced by different connections of the transformer winding. They tested the convergence and execution time of the method on three different unbalanced distribution networks.

Khodr ***et al.*** (2006) had proposed a load-flow method for balanced and unbalanced radial distribution networks. Their suggested technique was based on S-E power-flow algorithm. The consecutive iterations in this method comprised of even more intent the load and network losses at each node, beginning from far end node and moving on the way to the substation. They tested their method on 12-node, 23-node, 28-node, 69-node and 201-node systems and matched with the works offered in the literature. The suggested method came out to be vigorous, operative and fast.

Abdel-Akher ***et al.*** (2008) presented a load-flow method for unbalanced distribution networks. They divided the whole process of load-flow solution into three steps. Firstly, for each unbalanced lateral they computed equivalent current injection. Secondly, they solved the main three-phase network and then solved for in-phase components. The main benefit of the suggested method was that a complex distribution network was disintegrated to various sub-parts. They tested their method on two different unbalanced distributions networks. The resulting outcome proved that the suggested technique was efficient.

Penido ***et al.*** (2008) had formulated a new power-flow method for balanced and unbalanced radial distribution networks. They used the Newton-Raphson scheme for solving the current-injection equations. They compared their test results with the results available in the literature for the validation of the method and suggested method proved to be robust and effective. According to the authors that method would be a special help for solving distribution system with the neutral conductor, isolator or grounding.

Chen and Yang (2009) formulated a method for unbalanced distribution networks based on branch frame of reference. They basically utilized graph theory and current injection technique. The vibrant speculative basis and the simple topology of the radial distribution network made the formulated technique effective and consistent. They used four three-phase IEEE test feeders for comparison. The test results showed that the proposed method had robust convergence characteristics and high performance, especially for large-scale radial distribution systems.

Kalesar and Seifi (2010) had presented a load-flow method utilizing fuzzy methodology for integrating load model. They applied their suggested method on 19-node and 34-node test systems. The system trial outcomes illustrated that the suggested technique was appropriate for enormous distribution networks and efficient. That proposed technique could be used for analysis of balanced and unbalanced distribution network analysis.

Chen and Yang (2010) had proposed a method to fix the three-phase power-flow of unbalanced distribution networks. They used a mesh frame of reference instead of using a conventional node frame of reference, basic graph theory and current injection techniques. They applied a simple straight-forward iterative method in impedance form and compared their method with Gauss implicit Z-Bus and forward/backward sweep methods in terms of speed and number of power-flows to establish its superiority.

Al-Hajri and Hawary (2010) had developed a load-flow solution for unbalanced radial distribution networks. The foundation of the formulated method was assembling one block matrix, which was used in backward/forward iterative steps of load-flow. They tested their proposed technique on various test systems and it came out to be a robust one. Their suggested method was adaptable in accepting the deviations coming in a standing radial distribution network as the deviations could be entirely integrated within this matrix.

Elsaiah ***et al***. (2011) developed a power-flow method for balanced and unbalanced distribution networks utilizing the line Primitive Impedance Matrix and the Branch-Current Matrix. The suggested technique had been verified on 33-node balanced distribution network and 8-node unbalanced distribution network. The outcomes of the recommended method were originated to be similar to the other methods available in the literature. The method had recognized to be utilizing less memory and needed less computational time.

Hong-wei ***et al.*** (2011) developed a load-flow solution for handling distribution networks transformers with several mutual winding links in unbalanced distribution network of multi-voltage stages. In the suggested technique, they derived a sensitivity constant incident matrix between node voltages and injection currents. This matrix was used as a foundation stone in the proposed algorithm for load-flow studies. The validity and efficiency of the suggested technique and the transformer models had been tested by the IEEE 4 and IEEE 34 test feeder.

Janecek and Georgiev (2012) developed a method by incorporating all the generated formulas into older backward/forward algorithm and tested their suggested method on IEEE 32-bus system. That method gave an exact solution for multivariate distribution networks. Their proposed method had given a better estimation of power losses.

Melhorn and Dimitrovski (2015) formulated a load-flow method for balanced and unbalanced distribution networks exhausting the admittance matrix. It stood for discrete probability density functions as input participant. They tested their suggested technique on IEEE 123-node and IEEE 13-node feeders. They proved the validation of results by comparing their suggested technique outcomes to that of other methods existing in the literature. The formulated technique could be used for diverse representations and arrangements of the load.

Samal and Ganguly (2015) presented a power-flow procedure for unbalanced radial distribution networks based on an amended forward-backward sweep. The recommended set of rules transforms branch current computation methodology in a backward sweep through three different matrices. In the mathematical modelling, they had considered the coupling between three phases. They tested their suggested method on a 25-node unbalanced radial distribution network. The outcomes of testing proved that the formulated method converges in lesser iterations in comparison to the unedited method.

## 2.3 Survey on reconfiguration of electric power distribution networks

Reconfiguration of distribution network can be carried out by closing and opening of switches in a distribution network feeder. Distribution feeder supplies different types of load. For this varying load configuration, network reconfiguration is required for eminence services, consistency and efficiency of the distribution network. In literature, worthy research works had been exercised out, which are discussed below.

Sood ***et al.*** (2002) suggested an urgent need to keep a track of activities taking place in the emerging field of deregulated environment in distribution network. They gave a bibliographical survey and general backgrounds of research and development in the field of power system wheeling under deregulated environment in their research work.

Das (2006) had presented a fuzzy multi-objective process to resolve the network reconfiguration of balanced radial distribution network. Objectives were considered for reducing the real power loss, reducing the deviations of nodes voltage, minimization of the branch current limit violation, and feeder load balancing. The suggested technique also reduced the total of tie-switch procedures. The simulation results had proved the likelihood of the suggested method and the outcomes attained proved to be fairly decent.

Siti ***et al.*** (2007) had proposed a technique to complement network reconfiguration with the methods of load balancing along a feeder. They suggested the mutual problem and used the neural network in combination through a heuristic method, which allowed consumers to be switched amongst different phases to keep the load balanced. They presented a practical example utilizing the real data and it was found that the suggested method had taken lesser execution time and heuristic method found to be faster than the sole neural network.

Kargar ***et al.*** (2008) proposed a multi-objective function for the reconfiguration of distribution networks in the deregulated environment. They defined the multi-objective function for minimizing total energy supply costs and energy losses. The configured structure was found by using Binary Genetic Algorithm (BGA). They tested their suggested method on practical distribution networks and results found to be effective.

Raju and Bijwe (2008) had formed a two-stage algorithm for reconfiguration of balanced and unbalanced distribution networks. Initially it started with all switches closed. The recommended technique merely used the branch current information from a normal load-flow. In the second phase, branch exchange choices are discovered for additional loss minimization. Results for four balanced systems (16-node, 33-node, 69-node and 94-node) and one unbalanced system (25-node) had been obtained, which competed the consistent outcomes stated in the literature.

Subrahmanyam and Radhakrishna (2009) proposed an algorithm of network reconfiguration for both types of radial distribution networks, i.e., balanced and unbalanced. Their method was based on the least number of equations, which produced an efficient configuration after network reconfiguration in terms of power losses. The switches to be closed were chosen on the basis of bus voltage and minimum net loss of the system. Their method minimized the number of switching.

Vulasala ***et al.*** (2009) used the genetic algorithm (GA) for feeder reconfiguration to slash the losses of the system and to enhance the voltage profile. They had searched randomized information between strings after a performance of crossover and mutation. The results were tested in two unbalanced distribution networks, i.e., 19-node and 25-node reducing the switching options compared to other existing methods.

Chandramohan ***et al.*** (2010) suggested a technique for minimizing the operating cost of balanced radial distribution networks in the deregulated environment. They reconfigured the network using "non-dominated sorting genetic algorithm (NSGA)". They minimized the operating cost and maximized the operating reliability so that the operating constraints were satisfied. They used the related formulas available in the literature. They tested their method on balanced 33-node and 69-node radial distribution networks.

Kumar and Gao (2010) presented a mixed integer non-linear programming (MINLP) method to find optimum location and number of distributed generators in electricity market. At first, they found appropriate zone based on real power nodal price and real power loss sensitivity index as an economic and operational criterion.

Rugthaicharoencheep and Sirisumrannukul (2010) presented a reconfiguration method for loss minimization of unbalanced distribution network. They utilized Tabu search for development of this method. They tested the suggested technique on a 69-node system with various loading conditions, for the validation of the suggested method. The result outcomes showed that the proposed technique had given minimum power loss with effectively identifying the on-off position of switches in the network.

Ouyang ***et al.*** (2011) suggested heuristic approach to identify best site and size of DG to guide the connection of DG. They compared DG connection cost with the decrement of the network capacity cost resulting from the DG capacity and found the appropriateness of DG connecting to distribution network.

Rao ***et al.*** (2011) had put forward an algorithm for network reconfiguration using a harmony search algorithm (HSA) to get an efficient network configuration so that the losses were reduced and the voltage profiles had been improved. That algorithm bypassed the gradient search and used only random search to eliminate the derivative information. The results obtained were very encouraging for balanced networks.

Saffar ***et al.*** (2011) had presented a technique for optimal reconfiguration exhausting a multi-objective function with fuzzy variables. That process considered objectives of load balancing and loss minimization in the feeders. They utilized ant colony optimization to get the reconfigured network. The suggested technique had been applied on two 33-node and 69-node distribution networks. Simulation outcomes approved the efficiency of the anticipated technique in assessment with other methods stated in literature. In addition to the minimization of power losses, the load balancing on the branches were also enhanced.

Swarnkar ***et al.*** (2011) had presented an efficient method using Adapted Ant Colony Optimization (AACO) to obtain a new topological structure of radial distribution systems after network reconfiguration, which reduced the real power losses of the system. They adapted the conventional ant colony algorithm through graph theory to obtain radial network always during the evolutionary process to dodge the tiring check of the mesh network. They reduced the burden of computation. The effectiveness of the adapted ant colony optimization method was described on balanced and unbalanced distribution networks.

Jabr ***et al.*** (2012) formulated a network reconfiguration technique for minimization of losses. They suggested two methods mixed-integer conic programming (MICP) and mixed-integer linear programming (MILP). The key feature of the first method was that, it optimized the precise value of the network losses. The second method was based on a constricted polyhedral demonstration of the conic restraints. Their test results had shown that both methods were equally effective for reconfiguration. However, MICP was found to be faster and suitable for online applications and MILP provided better results for larger systems.

Navarro ***et al.*** (2012) presented a loss minimization for unbalanced radial distribution network with the grouping of load balancing and reconfiguration of networks utilizing canonical and spanning tree based genetic algorithm respectively. For validation of their method, they tested it on a 14-node and 123-node systems to prove their combinational method to be effective.

Amanulla ***et al.*** *(*2012) had formed a reconfiguration technique in view of increasing the reliability and reducing the power losses. The minimal set of components appearing between the feeder and any particular load point were found utilizing an algorithm to find minimal cut sets. Binary particle swarm optimization (BPSO)-based search algorithm was used to find the status of the switches. They tested the suggested technique on a 33-node and a 123-node radial distribution networks and it came as an effective method to be utilized in practical networks.

Lantharthong and Rugthaicharoencheep (2012) had suggested a competent algorithm for network reconfiguration to balance feeder loads and eliminate overload conditions. They utilized Tabu search technique for the optimization. They had presented the simulation outcomes for a radial 69-node system with DGs and capacitors employment. The outcomes achieved by that method had shown that the technique had recognized the utmost effective network reconfiguration for load balancing improvement. They also found that optimal configuration for load balancing also minimized losses and the voltage profile was improved. Simulation outcomes confirmed the suggested method as an useful tool for operation and planning of distribution networks.

Kavousi-Fard and RezaAkbari-Zadeh (2013) had proposed a multi-objective improved shuffled frog leaping algorithm (ISFLA) to explore the distribution feeder reconfiguration for the reliability improvement. A fuzzy clustering method was used to control the size of the repository in the pre-set bounds. In direction to perceive the possibility and dominance of the suggested technique, they used 32-node distribution test system. The simulation outcomes had shown that the proposed algorithm was suitable for large scale integer programming for optimization problems.

Murthy and Kumar (2013) proposed a method to place DG in balanced distribution networks using voltage sensitivity index. They explored the DG allocation in distribution network from the viewpoint of importance of power injections from renewable DG units located close to the load centers, as it provided an opportunity for system voltage support, reduction in energy losses, and reliability improvement.

Sedighizadeh ***et al.*** (2013) presented a hybrid algorithm after solving multi-objective network reconfigurations for balanced and unbalanced distribution networks. Their optimization algorithm was a combination of big bang-big crunch. They had fuzzified each objective before applying a hybrid combination and compared their methods with other existing methods. They applied the load balancing index membership function proposed by Saffar ***et al***. (2011) and suggested real power loss membership functions and maximum bus voltage membership function. The suggested algorithm avoided local optimum by using a mutation operator after position updating.

Zidan and Saadany (2013) formulated distribution network reconfiguration method making an allowance for switching process expenses in the path to reduce yearly energy losses by shaping the optimal outline for every term of the year. The formation and solution of the problem were done using the Genetic algorithm. They tested their suggested method on 119-node balanced and 25-node unbalanced test system and it proved a reduction in the periodic and yearly energy losses.

Imran ***et al.*** (2014) with an objective of reducing the power loss and improvement of voltage stability proposed a method for best network reconfiguration and integration of distributed generations (DGs) in distribution network. Fireworks Algorithm (FWA), which had been conceptualized using the fireworks explosion process of searching for a best location of sparks, was utilized by them in their suggested method. They kept in view six different settings during DG placement and reconfiguration of network to judge the presentation of the suggested technique. The simulated outcomes carried out on 33-node and 69-node test systems proved effectiveness of the suggested technique.

Mirhoseini ***et al.*** (2014) suggested a reconfiguration method established on a novel improved adaptive imperialist competitive algorithm (IAICA) improving the voltage profile and reducing real power losses. They utilized two other algorithms – Genetic Algorithm and Ant Colony Optimization (ACO**)** for reconfiguration of 33-node and 69-node test systems. They applied the same algorithm for network reconfiguration with

DG integration. They confirmed the competence of the suggested method by comparing the attained results with each other.

Taher and Karimi (2014) proposed an efficient technique for reconfiguration of balanced and unbalanced distribution networks and placed DG after network reconfiguration to get better loss reduction. They had taken the three-phase balancing of currents and voltages as a target in optimization process and found that DGs along with reconfiguration led to low power dissipation. The optimal solution of the multi-objective function had been searched by the Genetic Algorithm (GA).

Peng ***et al.*** (2015) had proposed a computationally efficient heuristic algorithm to obtain a network configuration, which gave better results. The proposed algorithm scaled linearly, which was based on the optimal load-flow method and did not require either tuning of the parameter or any variety of initialization of another type of meshes. The suggested algorithm solved the feeder reconfiguration problem optimally for opening a single redundant line only.

Sedighizadeh (2015) had given a hybrid approach in a fuzzy environment based on hybrid Shuffled Frog Leaping Algorithm (SFLA) and had applied both network reconfiguration and capacitor placement in balanced and unbalanced distribution networks to get better loss reduction compared to the method proposed by Sedighizadeh ***et al.***(2013) using the same membership functions. High accuracy and fast convergence were the major advantages of this approach.

## 2.4 Survey on loss allocation of electric power distribution networks

In the present era extending energy market and increasing competition among electricity suppliers, the allocation of distribution network losses has to turn out to be a stimulating assignment. With the allocation of losses among various entities of the network, the corresponding loss share and energy supply cost can be computed. This is an important part of today’s power system network to show the network stability, efficiency and cost value. There exists some significant works carried out by the researchers in this field, which are presented below.

Oliveira ***et al.*** (2005) had presented a simulator based on the graphic for distribution networks with network reconfiguration and earmark of losses applications. They used current summation backward-forward technique considering DG to form a power-flow algorithm for solving reconfiguration problem. They implemented and did a comparison of four loss allocation methods, which were "$Z_{bus}$, Direct Loss Coefficient, Substitution and Marginal Loss Coefficient" on a 32-node distribution network. From the comparison of these methods, it was found that the $Z_{bus}$ method had a better performance and was simple to implement, while "Substitution and Marginal Loss Coefficient methods" required an adjustment factor.

Carpaneto ***et al.*** (2006) had formulated network-based loss allocation method, created on the basis of the disintegration of the branch currents for radial distribution network with the integration of DG. They verified the proposed technique on a 32-node test system and also compared with the existing methods and the proposed branch current decomposition loss allocation (BCDLA) method proved to be effective and influential.

Savier and Das (2007) proposed a loss allocation technique for the deregulated environment before and after reconfiguration. The method was formed in a quadratic way and stood on the determination of two different parts of current in each branch. The suggested algorithm was based on multi-objective optimization in a fuzzy environment. For this, three objectives were examined and were modelled in a fuzzy framework. The 69-node balanced test system results revealed that there was a reduction in real power losses with reconfiguration and loss allocation to most of the consumers were reduced, but it was also observed that loss allocation to some consumers might increase, resulting in more payment after reconfiguration. From these observations, they found that the allocation of real power loss to each consumer was affected by the objectives that were considered for network reconfiguration.

Carpaneto ***et al.*** (2008) had deliberated about characteristics regarding the use of loss allocation methods to distribution network with DGs. They had shown the necessity to acclimate the loss allocation methods initially established for transmission network to make them appropriate for loss allocation in distribution network with DGs. They had identified a set of circuit-based methodologies, which were proved to be capable of considering the existence of DGs. Among circuit-based approaches the Branch current decomposition loss allocation method appeared to be utmost capable technique as that method did not require to compute neither the admittance matrix nor the impedance matrix constants.

Atanasovski and Taleski (2011) had proposed a “Power Summation Method” to allocate loss in radial distribution networks with DG. The suggested approach was branch oriented, which was formed from the backward sweep power summation method without any kind of approximations and assumptions. They treated active and reactive loads as positive, and DGs were representing negative loads. They decomposed the branch losses to node related components, which made their suggested method simple and efficient for distribution networks. The suggested method is applied to a balanced 32-node radial distribution network and results were correlated with the “Branch Current Decomposition Loss Allocation (BCDLA)” method and “Marginal Loss Coefficients (MLC)” method.

Savier and Das (2012) had given a method to allocate real power loss in radial distribution network in a deregulated environment. They compared their suggested “Exact Method” with two algorithms that were available in the literature; first was depended on each consumer load demand called “Pro rata algorithm” and second was “Quadratic loss allocation” scheme, those identified the two different components of current in each branch. Loss allocation to each consumer was carried out and the suggested method was tested on a balanced 30-node radial distribution network.

Ghofrani-Jahromi ***et al.*** (2014) had presented a loss allocation technique for radial distribution networks depending on the outcomes of power-flow and considering the active and reactive power-flow through the lines. They considered three steps. The power loss designated to all of the nodes starting from the nodes having generation greater than their load computed in the earlier step. At the same time, the power loss that was designated to the loads associated with each node was achieved. In the next step, the loss allocation started from the sink nodes, i.e., nodes having a load greater than their generation. In the last step, the execution of normalization was done. Their suggested method was tested on 17-node and 69-node radial distribution networks.

Heidari-Kapourchali (2014) addressed distribution network reconfiguration influence on every consumer’s part of the loss. The branch current decomposition method was applied to determine the distributed losses to every bus. The group search optimizer was used to find the prominent results. The formulated technique was tested on a 33-node distribution network and investigated the effect of reconfiguration on loss allocation. It has been found that allocated loss to each load could be organized so that the part of every network member was monitored.

Jagtap and Khatod (2015) had offered a method for loss allocation to DGs and consumers those who were associated with radial distribution networks in the emancipated market. The prime motives of that paper were focused on the nonlinear alliance between the flow of power and losses, revisions of system losses due to the variation of voltage, and benefaction of DG to system's loss. The technique presented by Oliviera ***et al.*** (2005) had been used in loss allocation. The application of the method was once again limited to 28-node and 33-node balanced radial distribution networks.

Jagtap and Khatod (2016) had also proposed a technique for the loss allocation in balanced radial distribution networks using diverse models of DGs and loads in a deregulated environment. Without assuming and approximating anything, they derived a straight relation between active and reactive power-flow and its losses. "Power summation algorithm" (PSA) was used to derive approximate expressions/relations for power-flow of network and any cross term was avoided. A network dependent branch-oriented technique was used to allocate the losses among the members of the network. Allocation of losses to any DG/load at different nodes was carried out using backward sweep network diminution algorithm. Loss allocation in two different radial distribution networks (9-node and 33-node) had been performed in the presence of different types of DGs and load models.

Sharma and Abhyankar (2017) presented an efficient method of loss allocation with Shapley value and network laws. They had provided a solution with a cooperative game theory approach. They used Shapley value for balanced radial and weekly meshed distribution system to solve the analytical solution provided by the proposed method. They used the network data and power-flow solutions without any assumptions in their proposed method. They had given the results with different setups of network topologies.

# CHAPTER-3: LOAD-FLOW FOR UNBALANCED RADIAL DISTRIBUTION NETWORKS

## 3.1 Introduction

In the power system planning and operational studies load-flow analysis plays a key role. Definite applications, mainly in distribution automation and optimization of a power system, necessitate repetitive load-flow solution and in these applications, it is very significant to solve the load-flow problem as proficiently as possible. Nowadays, as distribution networks becoming more complex and these networks need for effective and consistent system operation. Therefore, the utmost significant system exploration tool, power- flow studies, should have the ability to handle different system arrangements with adequate precision and execution time. In various cases, it is perceived that the radial distribution networks are unbalanced because of single-phase (1-Φ), two-phase (2-Φ) and three-phase (3-Φ) loads. Thus, power-flow solution of any unbalanced radial distribution network, requires distinctive treatment. Moreover, the methods for power-flow analysis of unbalanced distribution networks cannot be formulated by merely lengthening the single-phase balanced techniques to three phase systems. A three-phase load-flow method has to report problems like modelling of various forms of component connections, defining initial point for three-phase load-flow results, as there are phase changes and transformation ratios for every phase and at diverse buses.

## 3.2 Load-flow study of unbalanced radial distribution networks

The load-flow analysis is the elementary computation utilized to analyze a certain power system functioning at steady-state beneath the itemized conditions of power input, load demand, and network arrangement. The load-flow solution of any radial distribution network gives information on the voltage magnitudes and angles at each bus, the real and reactive power supplied at the substation, the real and reactive power-flows in each line section, and the losses occurring in the system.

The outcomes of a power-flow exploration can be used for functioning purposes to compute different operational states of an existing network. These can also be utilized in the forecasting phases to estimate conceivable future schemes. In network reconfiguration, the load-flow analysis is cast-off to evaluate the overall real power loss for a given system arrangement in a directive to validate it alongside other arrangements. Applications like the integration of DG or capacitor need repetitive power-flow solution. The outcomes of the power-flow are also used in the estimation of the electrical load, and functioning limitations.

The development of digital computers and their wide use in the power system made to develop many algorithms in 1950's. The most popular algorithms such as Gauss-Seidel, Newton-Raphson and their decoupled versions have been designed for transmission systems. These methods are unsuitable for distribution systems due to its own inherit characteristics like radial in structure, an unbalanced distributed load, a large number of nodes and branches and wide range of resistance and reactance values. The basic building block of the distribution system is shown in Figure 3.1.

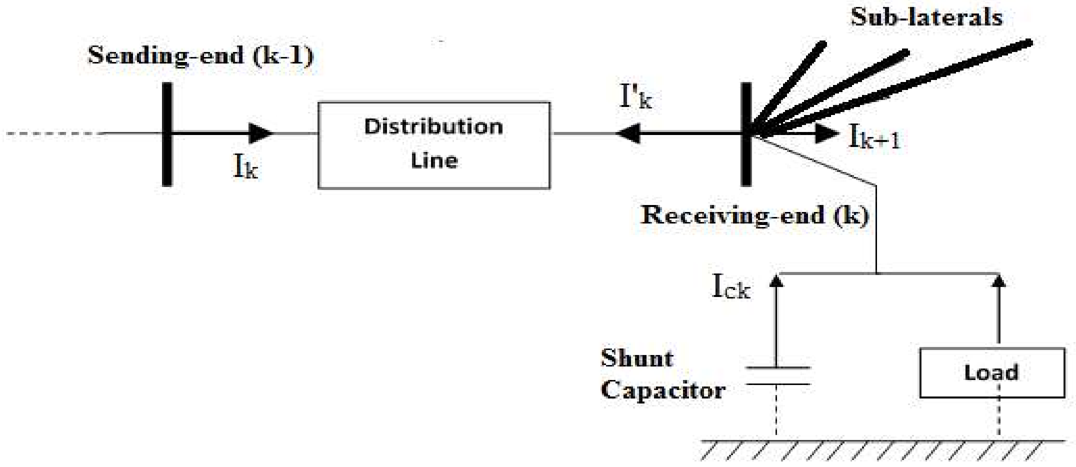


**Figure 3.1:** Basic block diagram of distribution system

The high R/X ratio of distribution system causes the system to be ill-conditioned for conventional power-flow methods, especially the fast-decoupled newton method, which diverges in most cases. Therefore, due to the characteristics of radial distribution networks, conventional methods for the study of the radial distribution networks should be modified.

## 3.3 Load-flow analysis of unbalanced radial distribution networks

In this work, a novel method on load-flow analysis of the unbalanced radial distribution networks is developed, which includes assessments of an algebraic expression of the magnitude of the voltage and no trigonometric functions as opposite to the normal load-flow analysis. The detailed literature survey has already been discussed in **Section 2.2** (**Chapter 2**). In all the discussed work on load-flow, majority of the research was based on the balanced distribution network. Here the load-flow technique for practically existing networks, which are unbalanced, is presented. Computationally the proposed load-flow is more efficient and it needs less computer memory storage because all the data can be stored in the vector form. The electrical equivalent of a radial distribution system is shown in Figure 3.2.

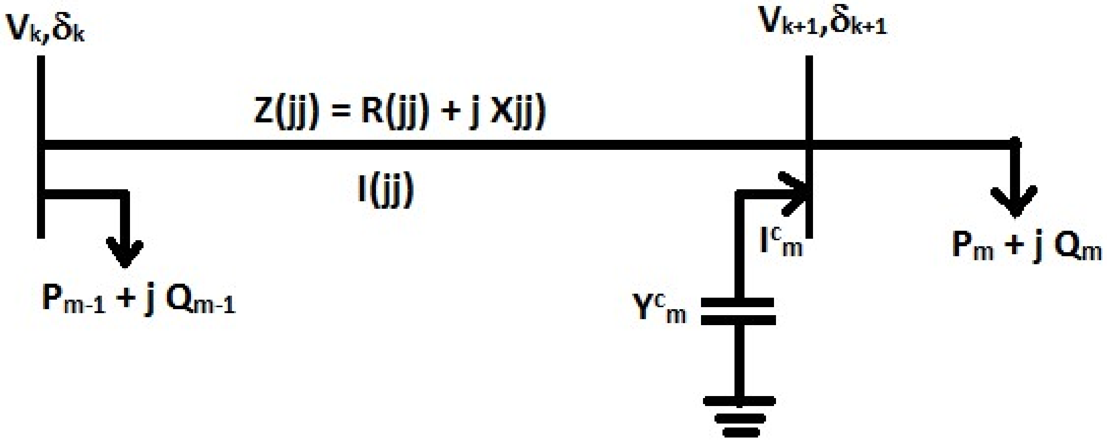


**Figure 3.2:** Electrical equivalent of the distribution network

The voltages, real power and reactive power-flow at the buses of the unbalanced distribution network are computed by using subsequent recursive equations. The $n^{th}$ line is represented by a series impedance and the impedance of the phases is given below.

$$Z_{An} = R_{An} + jX_{An} \tag{3.1}$$

$$Z_{Bn} = R_{Bn} + jX_{Bn} \tag{3.2}$$

$$Z_{Cn} = R_{Cn} + jX_{Cn} \tag{3.3}$$

where $R_{An}$, $R_{Bn}$, $R_{Cn}$ are the resistances of phase A, B, and C at the nth line, $X_{An}$, $X_{Bn}$, $X_{Cn}$ are the reactances of phase A, B, and C at the nth line. The real power demand is $P_D$ and reactive power demand is $Q_D$, which is related to complex power demand ($S_D$). The complex power for phases A, B and C are represented by the Equation (3.4), Equation (3.5) and Equation (3.6) respectively.

$$\left(S_D\right)_{A(k)} = \left(P_D\right)_{A(k)} + j\left(Q_D\right)_{A(k)} \tag{3.4}$$

$$\left(S_D\right)_{B(k)} = \left(P_D\right)_{B(k)} + j\left(Q_D\right)_{B(k)} \tag{3.5}$$

$$\left(S_D\right)_{C(k)} = \left(P_D\right)_{C(k)} + j\left(Q_D\right)_{C(k)} \tag{3.6}$$

The branch current flowing from the bus k to the bus k+1 (branch-jj) and the phases A, B and C are given by the Equation (3.7), Equation (3.8) and Equation (3.9) respectively.

.

$$I_{A(jj)} = \frac{\left|V_{A(k)}\right| \angle \delta_{A(k)} - \left|V_{A(k+1)}\right| \angle \delta_{A(k+1)}}{Z_{A(jj)}} \tag{3.7}$$

$$I_{B(jj)} = \frac{\left|V_{B(k)}\right| \angle \delta_{B(k)} - \left|V_{B(k+1)}\right| \angle \delta_{B(k+1)}}{Z_{B(jj)}} \tag{3.8}$$

$$I_{C(jj)} = \frac{\left|V_{C(k)}\right| \angle \delta_{C(k)} - \left|V_{C(k+1)}\right| \angle \delta_{C(k+1)}}{Z_{C(jj)}} \tag{3.9}$$

Where $\left|V_{A(k)}\right| \angle \delta_{A(k)}, \left|V_{B(k)}\right| \angle \delta_{B(k)}, \left|V_{C(k)}\right| \angle \delta_{C(k)}$ are the voltage magnitude and phase angle of the phase A, phase B and phase C at the kth node, $\left|V_{A(k+1)}\right| \angle \delta_{A(k+1)}, \left|V_{B(k+1)}\right| \angle \delta_{B(k+1)}, \left|V_{C(k+1)}\right| \angle \delta_{C(k+1)}$ are the voltage magnitude and phase angle of the phase A, phase B and phase C at (k + 1)th node. Here current through the branch jj is entering at its receiving-end node k + 1, which is the sum of the load current of node (k + 1) and the current flowing through the other branches emanating from this node.

The branch currents of the phase A, phase B and phase C can also be represented by Equation (3.10), Equation (3.11) and Equation (3.12) respectively.

$$I_{A(jj)} = \frac{P_{A(k+1)} - jQ_{A(k+1)}}{V^*_{A(k+1)}} \tag{3.10}$$

$$I_{B(jj)} = \frac{P_{B(k+1)} - jQ_{B(k+1)}}{V^*_{B(k+1)}} \tag{3.11}$$

$$I_{C(jj)} = \frac{P_{C(k+1)} - jQ_{C(k+1)}}{V^*_{C(k+1)}} \tag{3.12}$$

In Equation (3.10), Equation (3.11) and Equation (3.12) the power $P_{m\,(k+1)}$ and $Q_{m(k+1)}$ are the total real and reactive power load at the (k+1)th node respectively and are expressed by

$$P_{m(k+1)} = \sum_{j=k+1}^{n_{bus}} \left(P_D\right)_{m(j)} + \sum_{jj=jj+1}^{n_{branch}} \left(P_{Loss}\right)_{m(jj)} \tag{3.13}$$

$$Q_{m(k+1)} = \sum_{j=k+1}^{n_{bus}} \left(Q_D\right)_{m(j)} + \sum_{jj=jj+1}^{n_{branch}} \left(Q_{Loss}\right)_{m(jj)} \tag{3.14}$$

In Equation (3.13) and Equation (3.14), the phases A, B and C have been denoted as 'm' for simplification, jj = 1, 2, … , $n_{branch}$ where $n_{branch} = n_{bus} - 1$. Branch jj is the branch between the nodes k and k+1.

For end - node

$$\left(P_m\right)_{n_{bus}} = \left(P_{D_m}\right)_{n_{bus}} \tag{3.15}$$

From Equation (3.7) and Equation (3.10), the following relation can be expressed.

$$\frac{\left|V_{m(k)}\right|\angle\delta_{m(k)} - \left|V_{m(k+1)}\right|\angle\delta_{m(k+1)}}{Z_{m(jj)}} = \frac{P_{m(k+1)} - jQ_{m(k+1)}}{V^*_{m(k+1)}} \tag{3.16}$$

i.e., $$\frac{\left|V_{m(k)}\right|\angle\delta_{m(k)} - \left|V_{m(k+1)}\right|\angle\delta_{m(k+1)}}{Z_{m(jj)}} = \frac{P_{m(k+1)} - jQ_{m(k+1)}}{\left|V_{m(k+1)}\right|\angle-\delta_{m(k+1)}}$$

i.e., $$\left|V_{m(k)}\right|\left|V_{m(k+1)}\right|\angle\left(\delta_{m(k)} - \delta_{m(k+1)}\right) - \left|V_{m(k+1)}\right|^2 = \left(P_{m(k+1)} - jQ_{m(k+1)}\right)(Z_{m(jj)}) \tag{3.17}$$

i.e., $$\begin{aligned}&\left|V_{m(k)}\right|\left|V_{m(k+1)}\right|\cos\left(\delta_{m(k)} - \delta_{m(k+1)}\right) - \left|V_{m(k+1)}\right|^2 + j\left|V_{m(k)}\right|\left|V_{m(k+1)}\right|\sin\left(\delta_{m(k)} - \delta_{m(k+1)}\right) \\ &= \left(P_{m(k+1)}R_{m(jj)} + Q_{m(k+1)}X_{m(jj)}\right) + j\left(P_{m(k+1)}X_{m(jj)} - Q_{m(k+1)}R_{m(jj)}\right)\end{aligned} \tag{3.18}$$

Separating real and imaginary parts of Equation (3.18), Equation (3.19) and Equation (3.20) are obtained.

$$\left|V_{m(k)}\right|\left|V_{m(k+1)}\right|\cos\left(\delta_{m(k)}-\delta_{m(k+1)}\right)-\left|V_{m(k+1)}\right|^{2}=P_{m(k+1)}R_{m(jj)}+Q_{m(k+1)}X_{m(jj)} \tag{3.19}$$

$$\left|V_{m(k)}\right|\left|V_{m(k+1)}\right|\sin\left(\delta_{m(k)}-\delta_{m(k+1)}\right)=P_{m(k+1)}X_{m(jj)}-Q_{m(k+1)}R_{m(jj)} \tag{3.20}$$

Squaring Equation (3.19) and Equation (3.20) and adding, we have

$$\left|V_{m(k)}\right|^{2}\left|V_{m(k+1)}\right|^{2}=\left[\left|V_{m(k+1)}\right|^{2}+\left(P_{m(k+1)}R_{m(jj)}+Q_{m(k+1)}X_{m(jj)}\right)\right]^{2}+\left[P_{m(k+1)}X_{m(jj)}-Q_{m(k+1)}R_{m(jj)}\right]^{2} \tag{3.21}$$

On expanding and rearranging Equation (3.21),

$$\left|V_{m(k+1)}\right|^{4}+2.0\times\left[\left(P_{m(k+1)}R_{m(jj)}+Q_{m(k+1)}X_{m(jj)}\right)-\frac{\left|V_{m(k)}\right|^{2}}{2}\right]\times\left|V_{m(k+1)}\right|^{2}+\left(R_{m(jj)}^{2}+X_{m(jj)}^{2}\right)\left(P_{m(k+1)}^{2}+Q_{m(k+1)}^{2}\right)=0 \tag{3.22}$$

The solution of Equation (3.22) is given by

$$\left|V_{m(k+1)}\right|=\sqrt{\sqrt{\left[\left(P_{m(k+1)}R_{m(jj)}+Q_{m(k+1)}X_{m(jj)}-\frac{\left|V_{m(k)}\right|^{2}}{2}\right)^{2}-\left(R_{m(jj)}^{2}+X_{m(jj)}^{2}\right)\left(P_{m(k+1)}^{2}+Q_{m(k+1)}^{2}\right)\right]}-\left(P_{m(k+1)}R_{m(jj)}+Q_{m(k+1)}X_{m(jj)}-\frac{\left|V_{m(k)}\right|^{2}}{2}\right)} \tag{3.23}$$

The voltage of each node of the phases A, B, and C can be computed by Equation (3.23). From Equation (3.19) and Equation (3.20), we have

$$\delta_{m(k)}-\delta_{m(k+1)}=\tan^{-1}\left[\frac{P_{m(k+1)}X_{m(jj)}-Q_{m(k+1)}R_{m(jj)}}{\left|V_{m(k+1)}\right|^{2}+P_{m(k+1)}R_{m(jj)}+Q_{m(k+1)}X_{m(jj)}}\right]$$

$$\delta_{m(k+1)}=\delta_{m(k)}-\tan^{-1}\left[\frac{P_{m(k+1)}X_{m(jj)}-Q_{m(k+1)}R_{m(jj)}}{\left|V_{m(k+1)}\right|^{2}+P_{m(k+1)}R_{m(jj)}+Q_{m(k+1)}X_{m(jj)}}\right] \tag{3.24}$$

The voltage angle of each node can be computed from Equation (3.24).

Similarly, the real and reactive power losses at branch jj in the three phases are given by Equation (3.25) and Equation (3.26) respectively.

$$\left(P_{Loss}\right)_{m(jj)}=R_{m(jj)}\times\left[\frac{P_{m(k+1)}^{2}+Q_{m(k+1)}^{2}}{\left|V_{m(k+1)}\right|^{2}}\right] \tag{3.25}$$

$$\left(Q_{Loss}\right)_{m(jj)} = X_{m(jj)} \times \left[ \frac{P^2_{m(k+1)} + Q^2_{m(k+1)}}{\left|V_{m(k+1)}\right|^2} \right] \tag{3.26}$$

Here, the substation or the root node voltage value is taken as 1 p.u. and the remaining node voltages and their angles are computed by using Equation (3.23) and Equation (3.24) respectively, where m denotes the phases A, B and C.

In this load-flow analysis of distribution network, further, the impact of distribution transformer has been included. Studies found that while concluding the total losses of an unbalanced distribution network, transformer model should be included as this is having a high impact on large-scale unbalanced distribution system problems such as load-flow and system losses. Chen ***et al.*** (1991b) in their work had shown the transformer modelling, core loss calculations and admittance matrix formation of transformer models to be utilized in various studies and their suggested transformer model is shown in Figure 3.3.

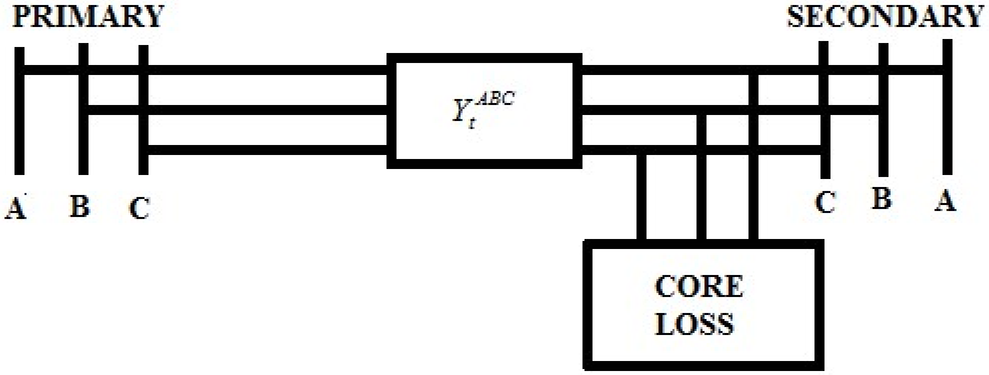


**Figure 3.3:** Transformer model

The core losses of the transformers can be expressed by Equation (3.27) and Equation (3.28) respectively.

$$P_{p.u.} = \frac{S_n}{S_b}\left(A|V|^2 + Be^{C|V|^2}\right) \tag{3.27}$$

$$Q_{p.u.} = \frac{S_n}{S_b}\left(D|V|^2 + Ee^{F|V|^2}\right) \tag{3.28}$$

In Equation (3.27) and Equation (3.28), V is the bus voltage in per unit, $S_n$ is nominal transformer capacity in kVA, $S_b$ is base power in kVA. The constant values are

“$A=0.00267$, $B=0.734\times10^{-9}$, $C=13.5$, $D=0.00167$, $E=0.268\times10^{-13}$, $F=22.7$” Here A, B, C, D, E and F are constants, which are machine dependent.

The following steps are used to solve the power-flow of unbalanced distribution networks by the suggested method.

Step-1 : Start

Step-2 : Read line data and load data, the maximum number of iterations, base kV and base MVA and the value of $\varepsilon$

Step-3 : Make $V(k) = 1 + j0$ for all nodes in each phase

Step-4 : Make initial loss $P_{LOSS} = 0$ and $Q_{LOSS} = 0$

Step-5 : Step Iteration Count (ITC) = 1

Step-6 : Compute load current of each node for each phase

Step-7 : Compute the flow of current through each branch

Step-8 : Compute voltage of each node using Equation (3.23) and voltage angle of each node using Equation (3.24)

Step-9 : Compute $|\Delta V(k)| = \big|\, |V(k)|_{OLD} - |V(k)|_{NEW} \,\big|$

Step-10 : Compute $|\Delta V(k)|_{MAX}$

Step-11 : If $|\Delta V(k)|_{MAX} < \varepsilon$, GOTO Step-14

Step-12 : Increase ITC by 1

Step-13 : If ($IT \leq ITMAX$) GOTO Step-6. Otherwise, Print Solution Has Not Converged and GOTO Step-15

Step-14 : Compute real and reactive power losses of each branch of the system using Equation (3.25) and Equation (3.26) respectively. Display bus voltage, ITC, $P_{LOSS}$ and $Q_{LOSS}$.

Step-15 : Stop

## 3.4 Simulation results and discussions

The proposed method for load-flow is implemented on MATLAB 2013 working platform (Windows 8, Intel Core i3-3210, 3.19 GHz). The parameters used for simulation are shown in Table 3.1.

**Table 3.1:** The parameters used for Simulation

| Parameters | Specifications |
|---|---|
| Substation voltage | $1\angle 0$ p.u. |
| Maximum branch voltage | 1.05 |
| Minimum branch voltage | 0.95 |
| Maximum branch current | 1.0 |

### 3.4.1 Load-flow results of 19-node unbalanced distribution network

The network data is available in Vulasala ***et al.*** *(*2009). Figure 3.4 shows the 19-node unbalanced radial distribution network having **11 kV** and **1 MVA** as base values. The detailed data of this system has been presented in **Appendix-A**. The magnitude of voltage in p.u. of each node and voltage angle (deg.) shown in Table 3.2. The real power loss, reactive power loss, minimum voltage of each phase with status of open switches is shown in Table 3.3.

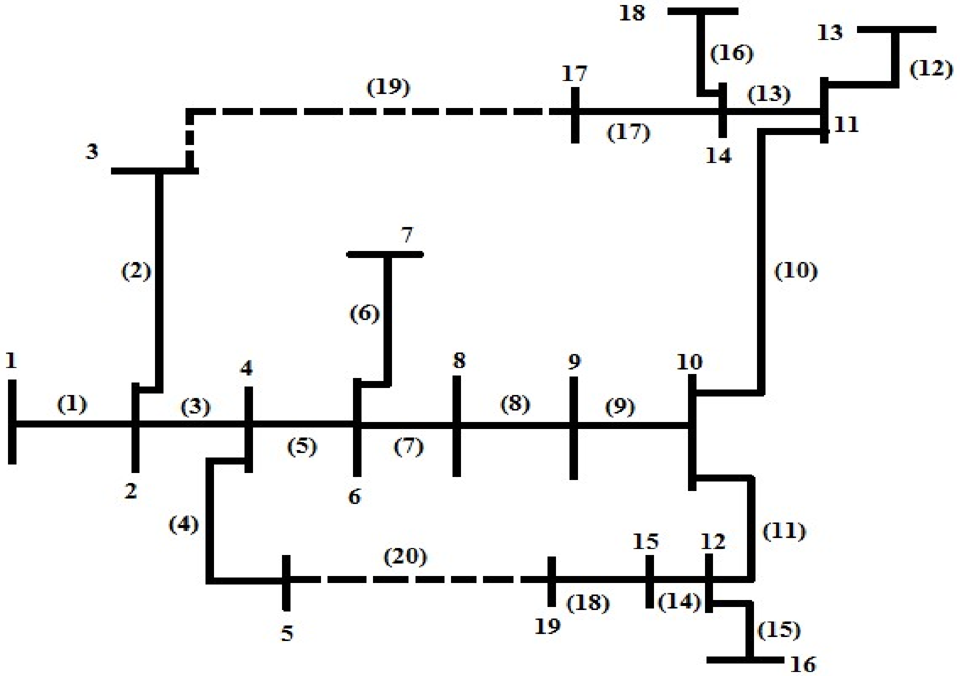


**Figure 3.4:** 19-node unbalanced distribution network

**Table 3.2:** Magnitude of voltage in p.u. of each node and voltage angle (deg.) of 19-node unbalanced distribution network

| Node Number | Voltage (p.u.) | | | Voltage angle (deg.) | | |
|---|---|---|---|---|---|---|
| | Phase A | Phase B | Phase C | Phase A | Phase B | Phase C |
| 1 | 1.0000 | 1.0000 | 1.0000 | 0.00 | -120.00 | 120.00 |
| 2 | 0.9875 | 0.9891 | 0.9880 | 0.01 | -119.98 | 120.05 |
| 3 | 0.9854 | 0.9887 | 0.9863 | 0.00 | -119.98 | 120.06 |
| 4 | 0.9824 | 0.9839 | 0.9830 | 0.03 | -119.97 | 120.06 |
| 5 | 0.9820 | 0.9837 | 0.9828 | 0.03 | -119.97 | 120.07 |
| 6 | 0.9793 | 0.9808 | 0.9801 | 0.04 | -119.96 | 120.07 |
| 7 | 0.9786 | 0.9803 | 0.9796 | 0.04 | -119.96 | 120.08 |
| 8 | 0.9728 | 0.9738 | 0.9735 | 0.06 | -119.94 | 120.08 |
| 9 | 0.9659 | 0.9660 | 0.9657 | 0.08 | -119.91 | 120.09 |
| 10 | 0.9563 | 0.9555 | 0.9550 | 0.09 | -119.86 | 120.09 |
| 11 | 0.9550 | 0.9543 | 0.9533 | 0.10 | -119.86 | 120.10 |
| 12 | 0.9548 | 0.9538 | 0.9536 | 0.11 | -119.87 | 120.10 |
| 13 | 0.9544 | 0.9534 | 0.9521 | 0.10 | -119.85 | 120.11 |
| 14 | 0.9545 | 0.9539 | 0.9528 | 0.10 | -119.86 | 120.11 |
| 15 | 0.9527 | 0.9512 | 0.9513 | 0.11 | -119.83 | 120.12 |
| 16 | 0.9534 | 0.9515 | 0.9522 | 0.13 | -119.86 | 120.10 |
| 17 | 0.9537 | 0.9534 | 0.9523 | 0.10 | -119.90 | 120.11 |
| 18 | 0.9538 | 0.9532 | 0.9521 | 0.10 | -119.82 | 120.10 |
| 19 | 0.9514 | 0.9494 | 0.9501 | 0.13 | -119.86 | 120.10 |

**Table 3.3:** Load-flow results of 19-node unbalanced distribution network

| Parameters | Phase A | Phase B | Phase C |
|---|---|---|---|
| **Real Power Loss (kW)** | 4.85 | 4.56 | 4.78 |
| **Reactive Power Loss (kVAr)** | 1.99 | 1.90 | 1.97 |
| **Magnitude of Minimum Voltage (p.u.)** | 0.9514 (19) | 0.9494 (19) | 0.9501 (19) |
| **Switches Opened** | 19, 20 | | |

### 3.4.2 Load-flow results for 25-node unbalanced distribution network

A **4.16 kV** and **30 MVA**, 25-node unbalanced distribution network is taken as a common test case. It has 3 tie switches and its total load is 3.239 + j2.393 MVA. Network data are available in Vulasala ***et al.***(2009). The detailed data of this system has been presented in **Appendix-B**. The 25-node unbalanced test system is shown in Figure 3.5. The magnitude of voltage in p.u. of each node and voltage angle (deg.) for each phase is shown in Table 3.4. The real power loss, reactive power loss and minimum voltage of each phase with status of open switches is shown in Table 3.5.

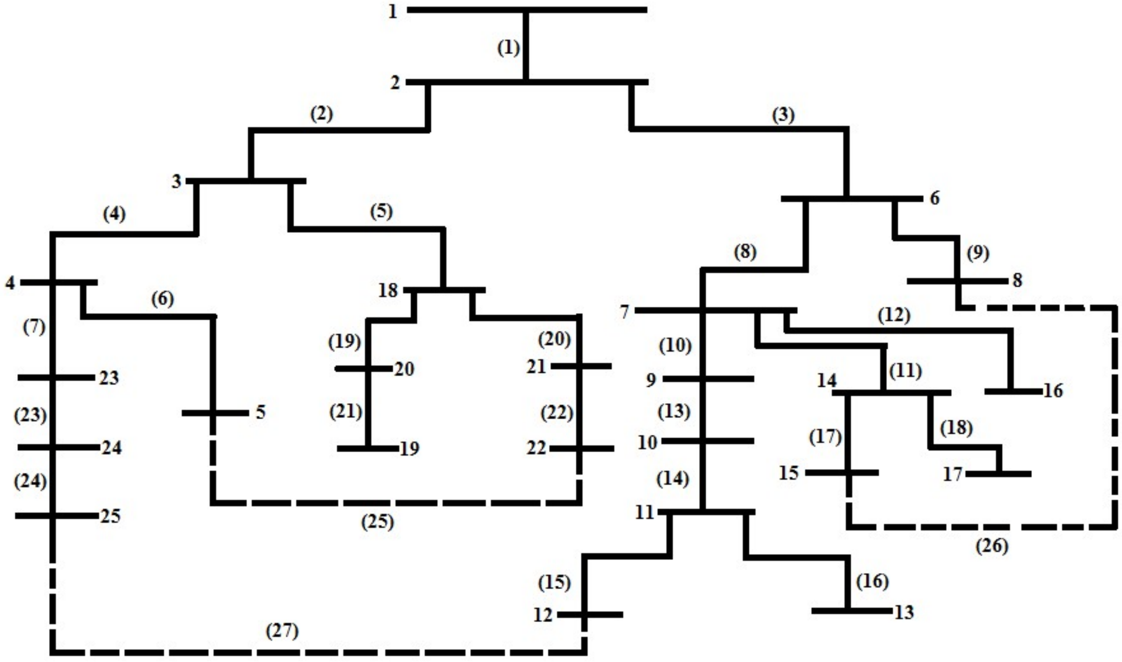


**Figure 3.5:** 25-node unbalanced distribution network

**Table 3.4:** Magnitude of voltage in p.u. of each node and voltage angle in deg. of 25-node unbalanced distribution network

| Node Number | Voltage (p.u.) | | | Voltage angle (deg.) | | |
|---|---|---|---|---|---|---|
| | Phase A | Phase B | Phase C | Phase A | Phase B | Phase C |
| 1 | 1.0000 | 1.0000 | 1.0000 | 0.00 | -120.00 | 120.00 |
| 2 | 0.9702 | 0.9711 | 0.9755 | -0.57 | -120.41 | 119.31 |
| 3 | 0.9632 | 0.9644 | 0.9698 | -0.70 | -120.52 | 119.15 |
| 4 | 0.9598 | 0.9613 | 0.9674 | -0.77 | -120.57 | 119.08 |
| 5 | 0.9587 | 0.9603 | 0.9664 | -0.76 | -120.57 | 119.08 |
| 6 | 0.9550 | 0.9559 | 0.9615 | -0.56 | -120.36 | 119.29 |
| 7 | 0.9419 | 0.9428 | 0.9492 | -0.55 | -120.30 | 119.27 |
| 8 | 0.9529 | 0.9538 | 0.9596 | -0.56 | -120.35 | 119.29 |
| 9 | 0.9359 | 0.9367 | 0.9438 | -0.55 | -120.28 | 119.26 |
| 10 | 0.9315 | 0.9319 | 0.9395 | -0.55 | -120.26 | 119.25 |
| 11 | 0.9294 | 0.9296 | 0.9376 | -0.55 | -120.26 | 119.25 |
| 12 | 0.9285 | 0.9287 | 0.9369 | -0.55 | -120.25 | 119.26 |
| 13 | 0.9287 | 0.9287 | 0.9373 | -0.55 | -120.26 | 119.25 |
| 14 | 0.9359 | 0.9370 | 0.9434 | -0.55 | -120.27 | 119.26 |
| 15 | 0.9338 | 0.9349 | 0.9414 | -0.55 | -120.27 | 119.25 |
| 16 | 0.9408 | 0.9418 | 0.9483 | -0.55 | -120.30 | 119.27 |
| 17 | 0.9347 | 0.9360 | 0.9420 | -0.55 | -120.27 | 119.26 |
| 18 | 0.9573 | 0.9586 | 0.9643 | -0.70 | -120.50 | 119.15 |
| 19 | 0.9524 | 0.9544 | 0.9600 | -0.69 | -120.49 | 119.16 |
| 20 | 0.9548 | 0.9563 | 0.9620 | -0.70 | -120.49 | 119.15 |
| 21 | 0.9537 | 0.9549 | 0.9605 | -0.69 | -120.49 | 119.16 |
| 22 | 0.9518 | 0.9525 | 0.9585 | -0.69 | -120.48 | 119.17 |
| 23 | 0.9565 | 0.9584 | 0.9648 | -0.76 | -120.57 | 119.08 |
| 24 | 0.9544 | 0.9565 | 0.9631 | -0.76 | -120.57 | 119.07 |
| 25 | 0.952 | 0.9547 | 0.9612 | -0.76 | -120.57 | 119.08 |

**Table 3.5:** Load-flow results of unbalanced 25-node unbalanced distribution network

| Parameters | Phase A | Phase B | Phase C |
|---|---|---|---|
| **Real Power Loss (kW)** | 52.92 | 54.44 | 43.97 |
| **Reactive Power Loss (kVAr)** | 60.43 | 52.32 | 55.87 |
| **Magnitude of Minimum Voltage (p.u.)** | 0.9285 (12) | 0.9287 (12) | 0.9369 (12) |
| **Switches Opened** | 25, 26, 27 | | |

### 3.4.3 Performance comparison

The available method presented by Chen and Yang (2010) is simulated again on the present platform and implemented on unbalanced distribution networks. The proposed load-flow method is also implemented for the above two unbalanced distribution networks. The comparison of the proposed method and the existing method proposed by Chen and Yang (2010) in terms of the relative CPU time and iteration number is shown in Table 3.6 for the unbalanced distribution networks.

**Table 3.6:** Comparison of relative CPU Time and Iteration Number of the proposed method with method (Chen and Yang (2010))

| **Unbalanced Distribution Networks** | **Relative CPU Time** | | **Iteration Number** | |
|---|---|---|---|---|
| | **Proposed Method** | **Method (**Chen and Yang (2010)) | **Proposed Method** | **Method (**Chen and Yang (2010)) |
| 19-node Network | 1 | 1.13 | 5 | 6 |
| 25-node Network | 1 | 1.18 | 6 | 7 |

## 3.5 Conclusion

An efficient load-flow method has been proposed in this chapter. The proposed load-flow analysis for unbalanced radial distribution networks takes less CPU time for all cases and takes the least number of iterations in some cases compared to the existing method given by Chen and Yang (2010). CPU time spent in computing and identifying the set of possible solutions depends on the time necessary for the objective functions evaluation, time for verification of defined constraints by power-flow computing and active losses.

# CHAPTER -4: RECONFIGURATION OF UNBALANCED RADIAL DISTRIBUTION NETWORKS IN REGULATED ENVIRONMENTS ALONG WITH DG AND CAPACITOR INTEGRATION

## 4.1 Introduction

Electric power systems are widespread, normally interconnected and impressively more complex. Practically, in distribution networks the loadings at the nodes are unbalanced, which causes losses of the system resulting in capacity limit violation. Hence power quality becomes crumbled and electricity cost is also increased (Raju and Bijwe (2008)). There are a few operational plans in power distribution systems and one of these is the system reconfiguration. Reconfiguration of any network not only reduces the active power loss but also releases the system from overloads as there are change in operating conditions (Siti ***et al.*** (2007)).

The tie-line switches of a power distribution system are closed and sectionalizing switches are opened during the process of network reconfiguration to obtain a network topology so that the goals are achieved (Das (2006)). The circuit topology gets changed due to operation of switches to get a new network configuration, reducing losses of the system and working costs (Imran ***et al.*** (2014)). Network reconfiguration is a noteworthy distribution system administrator control, which is utilized for different purposes (Capitanescu ***et al.*** (2015)). Contingent upon the present loading conditions, reconfiguration may get to be vital so as to take out overloads on a particular system segments, for example, transformers and this is known as load balancing. The system load balancing index is utilized to focus the loading status of the system and greatest system loading limit (Lantharthong and Rugthaicharoencheep (2012)). The network reconfiguration issue in studies has been detailed as a single target optimization issue with uniformity and imbalance constraints (Ahmadi and Martí (2015)).

In conventional power systems, network reconfiguration adds to the accompanying advantages, which a few researchers had tested using smart routines, like decreasing system power losses (Amanulla ***et al.*** (2012)), effective restoring system (Gholami ***et al.*** (2015)), enhancing system reliability (Kavousi-Fard and Akbari-Zadeh (2013)), and balancing load (Mirhosein ***et al.*** (2014)). The primary contrast between these networks is the presence of numerous vitality merchants with different conditions for offering energy in a focused cost (Kargar ***et al.*** (2008)). These days, distribution networks that are being affected by expanding the addition of distributed generations (DGs), which are constantly utilized as a part of the transmission network. There could be found considerable reduction in real power losses with DGs integration in the network, which results in saving of energy and fuel cost. Also, there will be overall improvement in terms of technical and economic benefits in the energy market operation (Kumar and Gao (2010)). Hereafter, DG got to be one of the applicable parameters in the assessment of network reconfiguration. Incorporation of DG in any distribution network influences the operation of this distribution network in different courses, which needs a research-based exploration.

In this chapter, the focused work on optimal network reconfiguration of unbalanced distribution network in regulated environment along with integration of DG and capacitor is presented, so that the power losses are reduced and the voltage profiles are improved. Role of network reconfiguration and integration of DG and capacitor has been discussed in **Section 1.2 (Chapter 1**) and literature survey is detailed in **Section 2.3 (Chapter 2).** In this work fuzzy firefly algorithm is applied for optimal network reconfiguration and is a different technique than those existing in literature. Also, the DG and capacitor have been integrated in the reconfigured network to reduce the system losses.

The formulation of the problem proposed herein considers the accompanying viewpoints in regulated environments:

- System losses before network reconfiguration.
- Network reconfiguration using the fuzzy-firefly algorithm.
- Losses computed after reconfiguration.
- Integration of DG and capacitor in reconfigured network for further loss reduction.

## 4.2 Proposed method for network reconfiguration of unbalanced distribution networks

Most of the network reconfiguration issues for reduction of power loss and improvement of voltage profile concentrate on balanced distribution networks. In this research work, a new methodology is proposed for network reconfiguration of unbalanced distribution networks by using fuzzy-firefly (FF) algorithm for reduction of losses of the system and improving the voltage profiles under acceptable limits. Initially, the load-flow analysis is done on unbalanced radial distribution networks. The metaheuristic algorithm called firefly algorithm, which has been motivated by the flashing manner of fireflies with fuzzy dependent objective function in terms of real power loss, bus voltage and load equalizing index to get a suitable solution for the optimal network reconfiguration. This proposed methodology for network reconfiguration of unbalanced distribution networks using Fuzzy Firefly algorithm produces better results in terms of power loss reduction as well as maintaining a voltage profile. The steps of the suggested method are shown in Figure 4.1.

**Figure 4.1:** Steps of the proposed method

From Figure 4.1, an unbalanced distribution network is considered in which the magnitude of voltage, currents and power losses at all the nodes are computed by using load-flow analysis. In the next step a fuzzy-firefly (FF) algorithm is designed for optimal network reconfiguration in which the objective function is computed based on fuzzy membership functions. Finally, an optimized unbalanced distribution network with reduced power losses as well as improved voltage profile will be obtained from this work. In the next section, detailed explanation of the proposed load-flow analysis of unbalanced distribution network is presented.

## 4.3 Fuzzy – firefly (FF) algorithm

In this proposed method, a Fuzzy-firefly algorithm is designed for optimal network reconfiguration. Objective functions have dissimilar dimensions. For easier contrast, a fuzzy multi-objective approach is used. In the fuzzy sphere, a membership function is extracted for each target, which signifies the degree of fuzzy satisfaction of the objective. The membership value for each target is a real number between 0 and 1 and in this segment it is squared up by using the trapezoidal fuzzy membership function. In this research work, minimization of power losses, minimizing the bus voltage deviation and load balancing in the feeders are deliberated as the objectives and fuzzified as described below.

### 4.3.1 Real power loss membership function ($\lambda P_i$)

Mathematically, the real power losses in the network can be expressed by Equation (4.1)

$$P_{Loss} = \sum_{jj=1}^{N_{branch}} \left| I_{(jj)} \right|^2 R_m(jj) = \sum_{jj=1}^{N_{branch}} \left[ \frac{P_{m(k+1)}{}^2 + Q_{m(k+1)}{}^2}{\left| V_{m(k+1)} \right|^2} \right] R_m(jj) \tag{4.1}$$

In Equation (4.1), jj is the branch between nodes k and k + 1, where k is the sending-end node and k + 1 is the receiving-end node. $I_{(jj)}$ is the current through the branch-jj**.** $R_m$ (jj) is the resistance of the branch (jj) for phase m. $P_{m\,(k+1)}$ and $Q_{m(k+1)}$ have already been defined in **Chapter 3** [vide Equation (3.13) and (3.14) respectively]. The magnitude of voltage at each bus should remain within its allowable intervals. On the other hand, the current in each branch should satisfy the branch current limitations as presented by Equation (4.2) and Equation (4.3) respectively.

$$V_{\min} \le \left| V_{m(k+1)} \right| \le V_{\max} \tag{4.2}$$

$$\left| I_{(jj)} \right| \le I_{(jj),\max} \tag{4.3}$$

Where $V_{m(k+1)}$ is the voltage at bus (k+1) of phase 'm' and $N_{branch}$ is the total number of branches in the system. $V_{min}$ and $V_{max}$ are the acceptable minimum and maximum voltages such that $V_{min} = 0.95$ and $V_{max} = 1.05$. $I_{(jj),max}$ is the maximum value of current through the branch-jj ,which is $I_{(jj),max} = 1$. The power loss minimization index is expressed by Equation (4.4).

$$XP_{L_i} = \frac{P_{L_i}}{P_{L_0}} \tag{4.4}$$

In Equation (4.4), $P_{L_0}$ and $P_{L_i}$ are the respective real power losses before reconfiguration of the network and after reconfiguration in i th system. The degree of fuzzy satisfaction of power loss objective function can be computed by using the membership function as described in fuzzy domain. The membership function in the fuzzy domain helps to compute the degree of fuzzy satisfaction of power loss objective function and expressed by Equation (4.5) **(**Saffar ***et al.*** (2011)).

$$\lambda P_{L_i} = \begin{cases} 1 & XP_{L_i} < XP_{L_{\min}} \\ \dfrac{XP_{L_{\max}} - XP_{L_i}}{XP_{L_{\max}} - XP_{L_{\min}}} & XP_{L_{\min}} < XP_{L_i} < XP_{L_{\max}} \\ 0 & XP_{L_i} > XP_{L_{\max}} \end{cases} \tag{4.5}$$

In Equation (4.5), $XP_{L_{\min}}$ and $XP_{L_{\max}}$ represent the respective lower and upper limits of $XP_{L_i}$ index. The best and the worst system configuration for real power losses are deliberated to compute these two limits. $P_{L_i}$ will have a minimum value of the power loss for the best system configuration where as if the power loss is equal to that of at the initial configuration, the worst system configuration will be anticipated.

### 4.3.2 Maximum bus voltage membership function:

The index of bus voltage $XV_i$ is described by Equation (4.6), which is for the purpose of minimizing the bus voltage deviation.

$$XV_i = \max\left(\left|1 - V_{\min}\right| \text{ and } \left|1 - V_{\max}\right|\right) \tag{4.6}$$

In Equation (4.6) $V_{\min}$ and $V_{\max}$ are the respective minimum and maximum value of bus voltage. The membership function of maximum bus voltage deviation index (Sedighizadeh ***et al.*** (2013), Sedighizadeh ***et al.*** (2015)) is expressed by Equation (4.7).

$$\lambda V_i = \begin{cases} 1 & XV_i \le XV_{\min} \\ \dfrac{XV_{\max} - XV_i}{XV_{\max} - XV_{\min}} & XV_{\min} < XV_i < XV_{\max} \\ 0 & XV_i \ge XV_{\max} \end{cases} \tag{4.7}$$

In Equation (4.7) the respective lower limit and upper limit of $XV_i$ index are $XV_{\min}$ and $XV_{\max}$. To compute the $XV_{\min}$ and $XV_{\max}$, the best and worst system configurations are required for respective minimum and maximum bus voltage deviation.

### 4.3.3 Load balancing index (LBI) membership function:

An appropriate parameter is required to be defined at first, which will indicate what portion of the branches is loaded. This is needed for the purpose of load balancing **(**Saffar ***et al.*** (2011)). This portion is termed as the line usage index for the jjth branch. If $I_{(jj)}$ is the current through the branch-jj and $I_{(jj),\max}$ is its maximum current carrying capacity, the line usage index for jj<sup>th</sup> branch is defined by Equation (4.8).

$$\text{Line Usage Index} = \frac{I_{jj}}{I_{(jj)\max}} \tag{4.8}$$

The load balancing index for all the branches of the system is to be computed, which is defined by Equation (4.9).

$$Y = \left[ \frac{I_1}{I_{(1)\max}} \frac{I_2}{I_{(2)\max}} \frac{I_3}{I_{(3)\max}} \cdots\cdots \frac{I_N}{I_{(N_{br})\max}} \right] \tag{4.9}$$

$$LBI = Var(Y) \tag{4.10}$$

In Equation (4.10) $Var$ denotes the variance operation. If the LBI has the minimum value, i.e., smaller one, successful achievement of load balancing is done. In the next phase, the index of $XB_i$ for load balancing is expressed by Equation (4.11).

$$XB_i = \frac{LBI_i}{LBI_0} \tag{4.11}$$

In Equation (4.11), $LBI_0$ represents the load balancing of the base network, i.e., before network reconfiguration, which is computed in the initial power-flow. $LBI_i$ in Equation (4.11) is the i<sup>th</sup> radial system's load balancing after network reconfiguration. Membership function for feeder load balancing index is defined by Equation (4.12).

$$\lambda I_i = \begin{cases} 1 & XB_i \le XB_{\min} \\ \dfrac{XB_{\max} - XB_i}{XB_{\max} - XB_{\min}} & XB_{\min} < XB_i < XB_{\max} \\ 0 & XB_i \ge XB_{\max} \end{cases} \tag{4.12}$$

In Equation (4.12), the respective lower and upper limits of $XB_i$ are $XB_{\min}$ and $XB_{\max}$. The best and the worst system configuration is considered for feeder load balancing so that $XB_{\min}$ and $XB_{\max}$ are computed.

### 4.3.4 Formation of objective function

The objective function is designed for the two purposes. The objective function is designed to obtain the finest as well as the most matched network configuration so that the operational limits such as voltage and current constraints are satisfied and load islanding will also be presented (Sedighizadeh ***et al.*** (2013), Sedighizadeh ***et al.*** (2015)). The objective function is given by Equation (4.13).

$$\lambda F_i = \left(\lambda P_{L_i} \times \lambda V_i \times \lambda I_i\right)^{1/3} \tag{4.13}$$

The best well matched configuration will be acquired when the fitness function in Equation (4.13) will be maximized during the optimization process. $\lambda F_i$ will be allocated a value zero when any membership function of each objective attains the value of zero. The correct information regarding the achievement of ideal state, i.e., a value of 1 is provided by this objective function. The objective function given in Equation (4.13) is utilized as a fitness function. The algorithm used for optimization purpose is explained in the next section.

### 4.3.5 Optimal reconfiguration by firefly algorithm

The firefly algorithm is a nature enlivened algorithm for optimization (Yang (2010)) and it is by all accounts more proficient than different algorithms like particle swarm optimization (PSO). As in nature, the firefly is pulled into a flashing light created from alternate ones. This is to be mated by the same species or lethally luring by alternate species. One firefly tends to move toward the brightest flashing light and the brightness is shifted by the separation. Three idealized rules are used in the firefly algorithm. The main is that all fireflies are unisex accordingly they are pulled into the next depending just on the brightness. The attractiveness of a firefly can be figured as one takes over, which is expressed by Equation (4.14).

$$\beta(r) = \beta_0 e^{-\gamma r^2} \tag{4.14}$$

The next one is that the brightness varies by distance, which can be computed by using Equation (4.15).

$$r_{mn} = \|x_m - x_n\| \tag{4.15}$$

Between two fireflies, the smaller brightness moves to the brighter one. The movement of firefly '*m'* attracted to firefly '*n'* is computed by Equation (4.16).

$$x_m^{'} = x_m + \beta_0 e^{-\gamma r_{mn}^2}\left(x_n - x_m\right) + \alpha\left(rand - 0.5\right) \tag{4.16}$$

Where, $\beta$ is intensity or attractiveness of the firefly's flashing light,

$\beta_0$ is attractiveness at zero distance,

$r_{mn}$ is the distance between two fireflies *m* and *n* (*m* and *n* are firefly numbers),

*x is* location of the firefly,

$x^{'}$ is new location of the firefly,

$\gamma$ is light absorption coefficient of a given medium,

$\alpha$ is randomization parameter, $\alpha \in [0,1]$ and

$rand$ is uniformly distributed random number *n* [0, 1].

The third is that the brightness is exaggerated by the objective function. Consequently, in this proposed method fuzzy based fitness function is formed, which is given by Equation (4.13). In this method, the firefly algorithm is implemented to reconfigure any unbalanced distribution network. A required solution is a set of the switching status. Though, in a certain system, the number of feeders is fixed and so does the number of open switches. Consequently, a solution set to deliberate here contains only switch numbers to be open, which is encoded as the location of fireflies.

The fuzzy firefly algorithm is used to decide the optimal network reconfiguration issue. The process of searching an optimal network reconfiguration of the distribution network utilizing firefly algorithm starts with parameter readings and network data. The firefly population number is the solution set number. Each and every set comprises of different open switches and denotes to a resultant network configuration. The open switches in each and every set are initially produced randomly, which are the initial location of fireflies. The firefly brightness at each location is computed by inverse of the fuzzy based objective function. The most promising one is reserved as local optimum for initial placement.

Regard it as global optimum, if that is the best solution ever found. Each and every firefly is combined randomly and then it is actuated to the other new location due to the attractiveness among each other. After the relocation, the algorithm initializes the next iteration. The firefly brightness at the new location is computed to obtain the new local optimum, which needs to relate with the global optimum of the current iteration. The brighter one is reserved as a new global solution. This procedure is carried on until the maximum iteration is reached. The procedure of incorporating the algorithm to solve network reconfiguration is shown beneath.

***Initialization:*** *The algorithm starts with encoding parameters like set of branches (switches), where each switch has two possible states either '0' for tie switch (Opened Switch) or '1' for sectionalizing switch (closed switch), set of buses, base configuration and firefly parameters.*

***Process:*** *Run the load flow analysis for each reconfigured pattern and compute the fuzzy based objective function.*

***Termination:*** *The process continues until maximum number of iterations reached or until no improvement of objective function detected after specified number of iterations.*

***Print:*** *Display the result.*

The objective function is a combination of real power loss, maximum bus voltage deviation, and load balancing index, which is given in Equation (4.13). In firefly algorithm, the opposite of the target function is deliberated as brightness, which signifies that the lower losses are the most promising. The solution candidate with the corresponding brightest at the final iteration is considered to be a global solution. In this proposed method, the fireflies move with, $\beta = 1$, $\gamma = 0.75$ and $\alpha = 0.25$. These sets of parameter values gave better results. The number of firefly population is 100 and the maximum number of iterations is selected as 150. The flow chart of the suggested method for optimal network reconfiguration is shown in Figure 4.2.

In this process of reconfiguration to find out the system parameters load-flow solution suggested in **Chapter 3** is utilized and gave us promising results.

## 4.4 Cost of energy loss

The monetary value of energy losses (Murty and Kumar (2015)) (CL): The annual price of energy loss is made by

$$CL = (\text{Net active power loss}) \times (E_c \times T)\ \$ \tag{4.17}$$

Where $E_c$=Energy Rate = 0.06 \$/kW h and T = time duration = 8760 h.

## 4.5 DG and capacitor placement in unbalanced distribution network

The optimum location of DG and capacitor in unbalanced distribution network is decided by Equation (4.18) (Hong (2014)), which presents the mathematical expression of "Loss Sensitivity Factor" (LSF) of three phase unbalanced distribution network. LSF is arranged in descending order and the highest value is considered for placement of DG and capacitor.

$$\begin{aligned} LSF = \frac{dP_{Loss}}{d\left|I-\phi\right|} &= 2K_{br-n}\left|I_{br-a}\right|R_{br-\phi.a}\cos(\theta_{I-br-a}-\theta_{I-n-\phi}) \\ &+2K_{br-n}\left|I_{br-b}\right|R_{br-\phi.b}\cos(\theta_{I-br-b}-\theta_{I-n-\phi}) \\ &+2K_{br-n}\left|I_{br-c}\right|R_{br-\phi.c}\cos(\theta_{I-br-c}-\theta_{I-n-\phi}) \end{aligned} \tag{4.18}$$

In Equation (4.18), K, I, br, n, ϕ and R are the voltage ratio, current, branch number, bus number, phase and resistance.

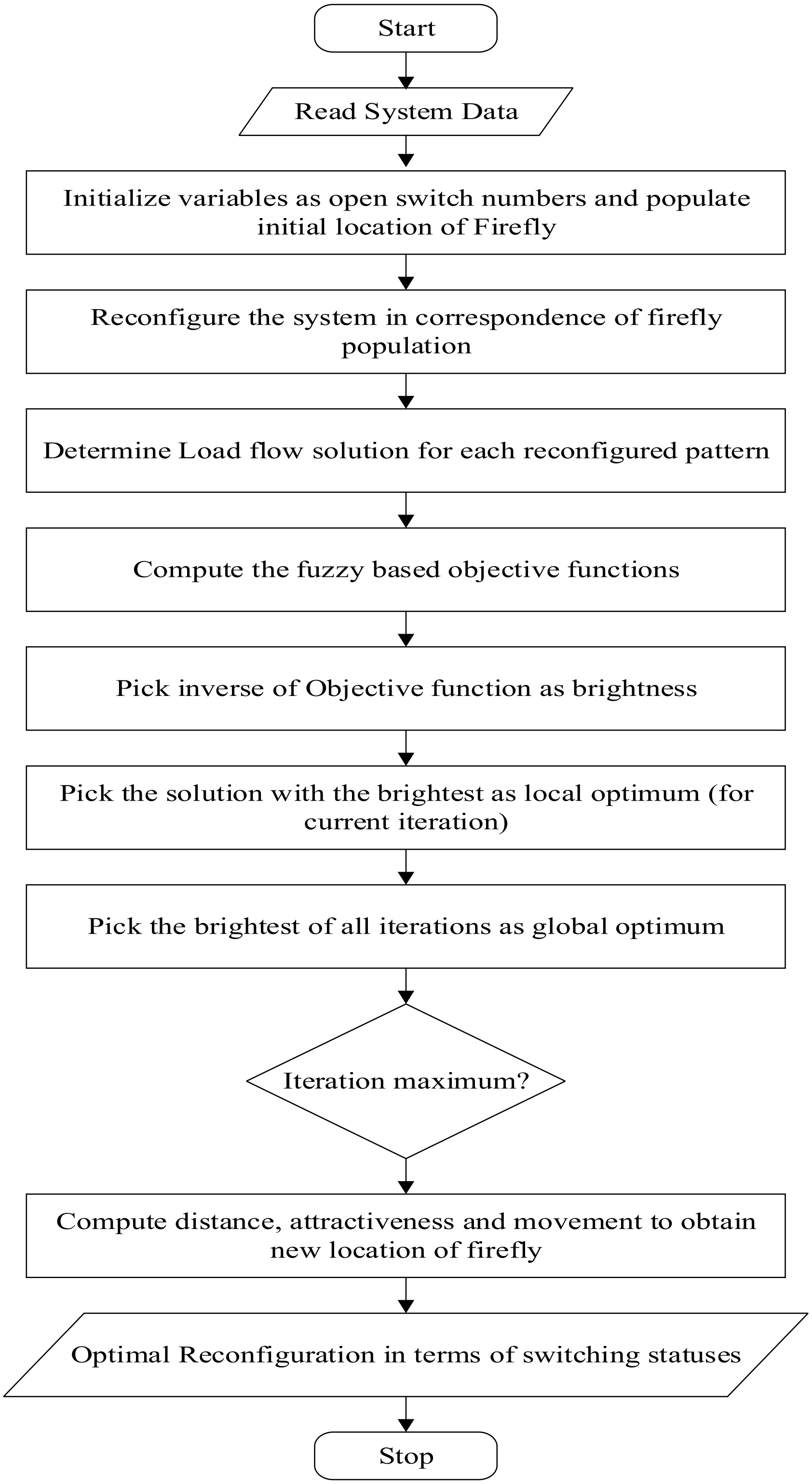


**Figure 4.2:** Flowchart of unbalanced distribution network reconfiguration using fuzzy-firefly algorithm

The DG (Type-I i.e., it delivers only active power) is placed at first to the most sensitive node and its size is determined by Bacteria foraging optimization algorithm (BFOA). The details of BFOA are available in Das ***et al.*** (2009). The objective function in this case is given in Equation (4.19).

$$\text{Objective function (OF)} = \text{Minimize (Real power loss)} \qquad (4.19)$$

Next LSF is found once again. The capacitor is placed to the most sensitive node and its size is determined by Bacteria foraging optimization algorithm (BFOA). Here DG is placed at first because the available LSF is related to resistance of the network. The proposed LSF-BFOA method for placement of DG and capacitor is to be compared with LSF-GA method. The details of Genetic algorithm (GA) are available in Yadav and Prajapati (2012).

## 4.6 Simulation results and discussions

The proposed method, i.e., load-flow and network reconfiguration are implemented in MATLAB 2013a working platform (Windows 8, Intel Core i3-3210, 3.19 GHz). The parameters used for simulation are shown in Table 4.1.

**Table 4.1:** The parameters used for simulation

| **Parameters** | **Specifications** |
|---|---|
| Substation voltage | $1\angle 0$ p.u. |
| Maximum branch voltage | 1.05 |
| Minimum branch voltage | 0.95 |
| Maximum branch current | 1.0 |
| Alpha | 0.25 |
| Beta | 1.0 |
| Gamma | 0.75 |
| Firefly population | 100 |
| Maximum number of iterations | 150 |

The effectiveness of the proposed Fuzzy-Firefly algorithm for network reconfiguration of unbalanced distribution networks is tested rigorously on 19-node and 25-node unbalanced distribution networks as discussed below.

### 4.6.1 19-node unbalanced distribution network

Figure 4.3 shows the initial configuration of 19-node unbalanced radial distribution network having **11 kV** and **1 MVA** as base values. The network data is available in Vulasala ***et al.***(2009). The magnitude of voltage in p.u. of each node and voltage angle (deg.) before network reconfiguration for each phase is shown in Table 4.2.

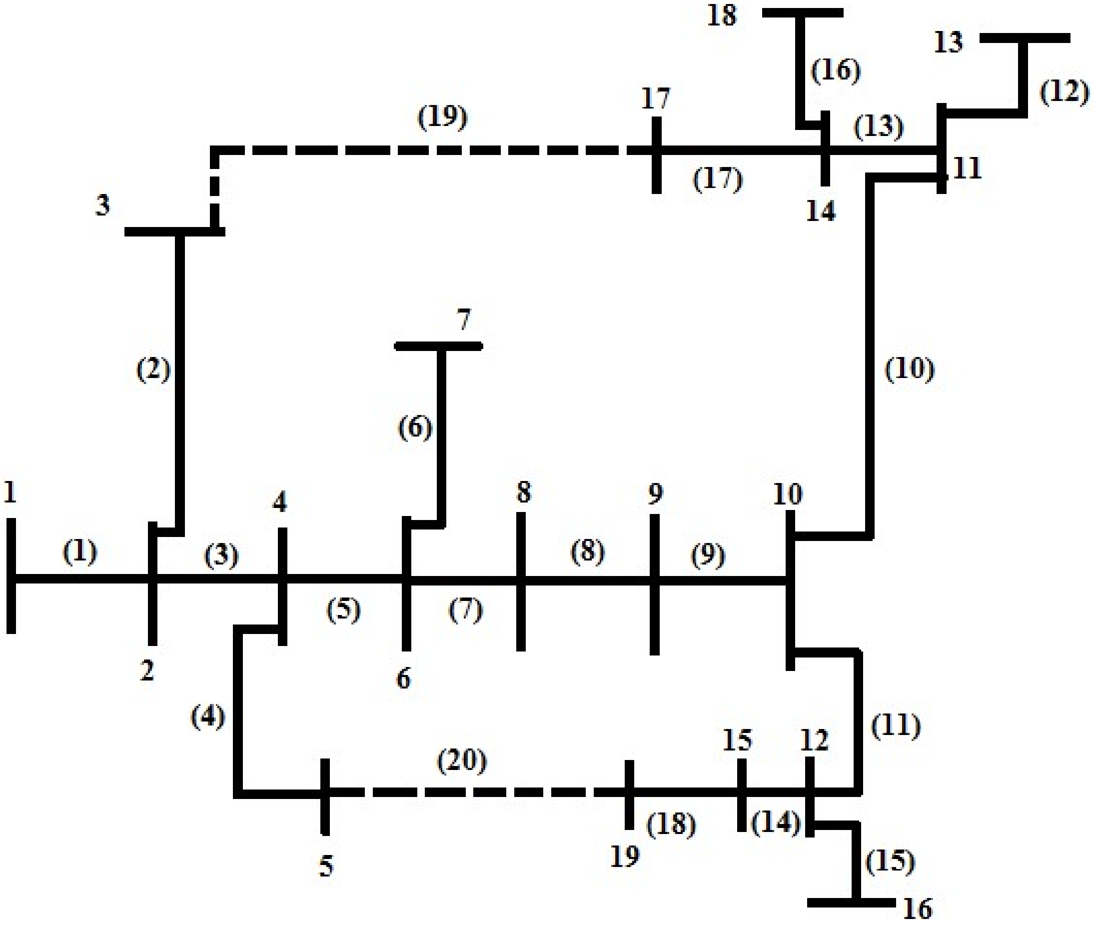


**Figure 4.3**: 19-node unbalanced distribution network

**Table 4.2:** Magnitude of voltage in p.u. of each node and voltage angle (deg.) before network reconfiguration for 19-node unbalanced distribution network

| Node Number | Voltage (p.u.) | | | Voltage angle (deg.) | | |
|---|---|---|---|---|---|---|
| | **Phase A** | **Phase B** | **Phase C** | **Phase A** | **Phase B** | **Phase C** |
| 1 | 1.0000 | 1.0000 | 1.0000 | 0.00 | -120.00 | 120.00 |
| 2 | 0.9875 | 0.9891 | 0.988 | 0.01 | -119.98 | 120.05 |
| 3 | 0.9854 | 0.9887 | 0.9863 | 0.00 | -119.98 | 120.06 |
| 4 | 0.9824 | 0.9839 | 0.9830 | 0.03 | -119.97 | 120.06 |
| 5 | 0.9820 | 0.9837 | 0.9828 | 0.03 | -119.97 | 120.07 |
| 6 | 0.9793 | 0.9808 | 0.9801 | 0.04 | -119.96 | 120.07 |
| 7 | 0.9786 | 0.9803 | 0.9796 | 0.04 | -119.96 | 120.08 |
| 8 | 0.9728 | 0.9738 | 0.9735 | 0.06 | -119.94 | 120.08 |
| 9 | 0.9659 | 0.9660 | 0.9657 | 0.08 | -119.91 | 120.09 |
| 10 | 0.9563 | 0.9555 | 0.9550 | 0.09 | -119.86 | 120.09 |
| 11 | 0.9550 | 0.9543 | 0.9533 | 0.10 | -119.86 | 120.10 |
| 12 | 0.9548 | 0.9538 | 0.9536 | 0.11 | -119.87 | 120.10 |
| 13 | 0.9544 | 0.9534 | 0.9521 | 0.10 | -119.85 | 120.11 |
| 14 | 0.9545 | 0.9539 | 0.9528 | 0.10 | -119.86 | 120.11 |
| 15 | 0.9527 | 0.9512 | 0.9513 | 0.11 | -119.83 | 120.12 |
| 16 | 0.9534 | 0.9515 | 0.9522 | 0.13 | -119.86 | 120.10 |
| 17 | 0.9537 | 0.9534 | 0.9523 | 0.10 | -119.90 | 120.11 |
| 18 | 0.9538 | 0.9532 | 0.9521 | 0.10 | -119.82 | 120.10 |
| 19 | 0.9514 | 0.9494 | 0.9501 | 0.13 | -119.86 | 120.10 |

In the initial configuration of the network, the tie-line switches **19 and 20** are opened. After closing these two tie line switches, the proposed method for network reconfiguration is implemented and Figure 4.4 is obtained after opening the switches **2 and 4**. The magnitude of voltage in p.u. of each node and voltage angle (deg.) after network reconfiguration for each phase is shown in Table 4.3. The real and reactive power losses of each branch at three phases before and after network reconfiguration are shown in Figure 4.5 and Figure 4.6 respectively. The respective voltage profile of 19-node unbalanced distribution network before and after network reconfiguration at three phases is shown in Figure 4.7. The results obtained for 19-node unbalanced distribution network before and after network reconfiguration using the suggested method is shown in Table 4.4. Table 4.4 shows that there is improvement of minimum voltage for each phase and the real power loss and reactive power loss of each phase are considerably reduced. The energy cost is also reduced drastically after network reconfiguration.

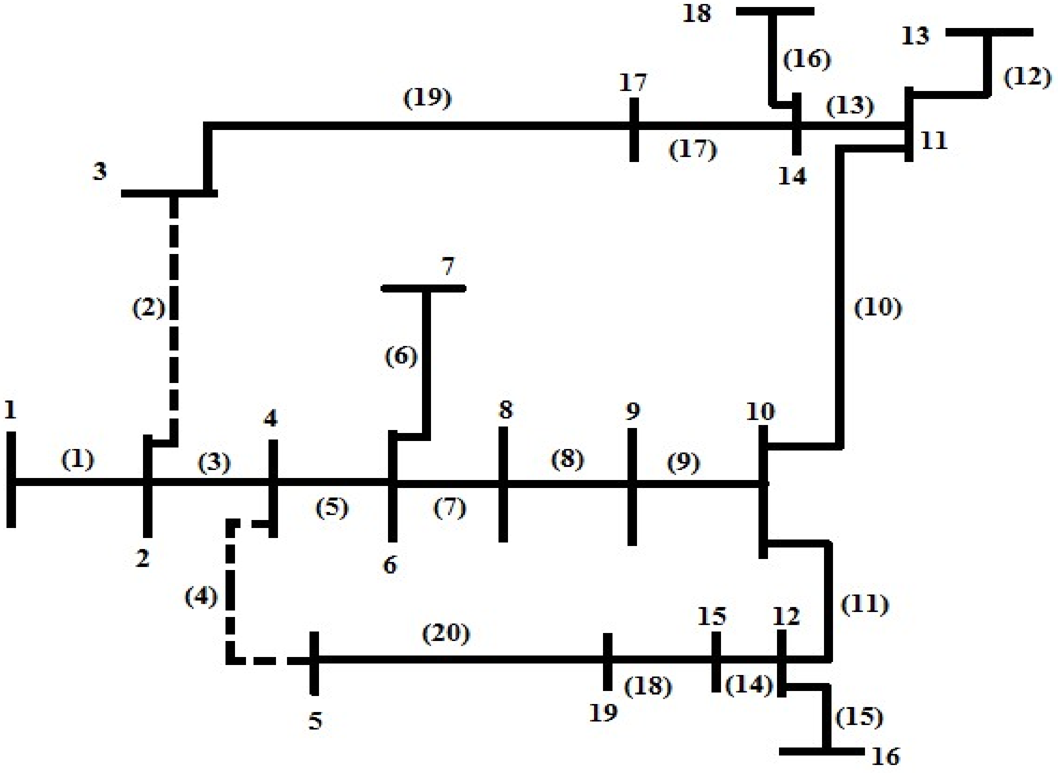
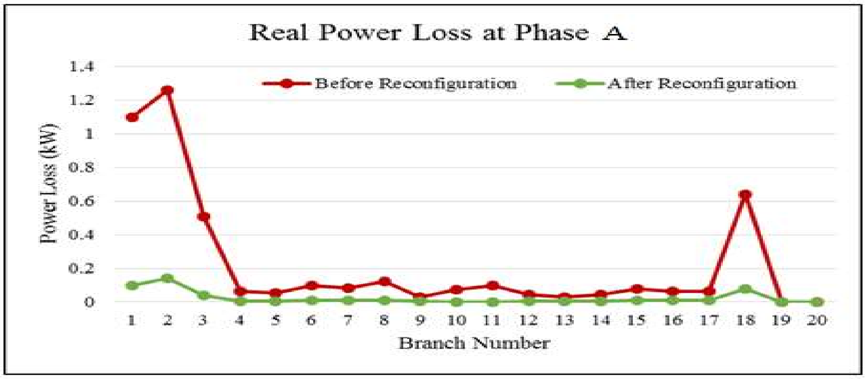


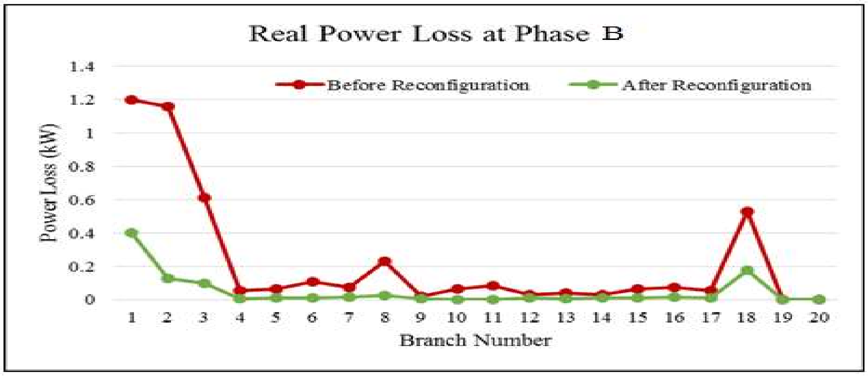
**Figure 4.4:** Reconfigured 19-node unbalanced distribution network in regulated environment

**Table 4.3:** Magnitude of voltage in p.u. of each node and voltage angle (deg.) after network reconfiguration for 19-node unbalanced distribution network

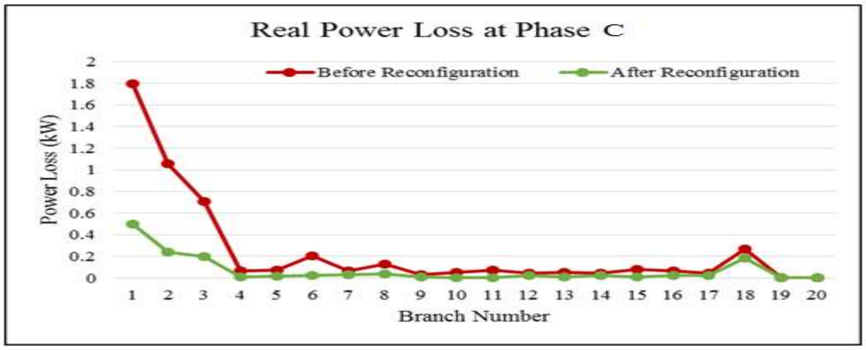
| Node Number | Voltage (p.u.) | | | Voltage angle (deg.) | | |
|---|---|---|---|---|---|---|
| | Phase A | Phase B | Phase C | Phase A | Phase B | Phase C |
| 1 | 1.0000 | 1.0000 | 1.0000 | 0.00 | -120.00 | 120.00 |
| 2 | 0.9917 | 0.9922 | 0.9982 | 0.02 | -119.97 | 120.06 |
| 3 | 0.9831 | 0.9847 | 0.9893 | 0.00 | -119.93 | 120.10 |
| 4 | 0.9904 | 0.9902 | 0.9958 | 0.05 | -119.96 | 120.06 |
| 5 | 0.9836 | 0.9848 | 0.9893 | 0.04 | -119.96 | 120.06 |
| 6 | 0.9887 | 0.9890 | 0.9941 | 0.04 | -119.97 | 120.07 |
| 7 | 0.9838 | 0.9887 | 0.9936 | 0.07 | -119.97 | 120.07 |
| 8 | 0.9867 | 0.9871 | 0.9937 | 0.05 | -119.97 | 120.07 |
| 9 | 0.9856 | 0.9864 | 0.9924 | 0.10 | -119.96 | 120.06 |
| 10 | 0.9851 | 0.9861 | 0.9915 | 0.09 | -119.96 | 120.06 |
| 11 | 0.9845 | 0.9859 | 0.9912 | 0.13 | -119.86 | 120.13 |
| 12 | 0.9848 | 0.9860 | 0.9914 | 0.10 | -119.94 | 120.07 |
| 13 | 0.9841 | 0.9855 | 0.9902 | 0.14 | -119.85 | 120.13 |
| 14 | 0.9840 | 0.9850 | 0.9909 | 0.12 | -119.86 | 120.13 |
| 15 | 0.9844 | 0.9858 | 0.9896 | 0.10 | -119.94 | 120.07 |
| 16 | 0.9844 | 0.9857 | 0.9907 | 0.15 | -119.93 | 120.06 |
| 17 | 0.9835 | 0.9848 | 0.9899 | 0.10 | -119.89 | 120.12 |
| 18 | 0.9825 | 0.9844 | 0.9891 | 0.12 | -119.86 | 120.13 |
| 19 | 0.9840 | 0.9851 | 0.9895 | 0.10 | -119.95 | 120.07 |



(a) Real power loss at phase A

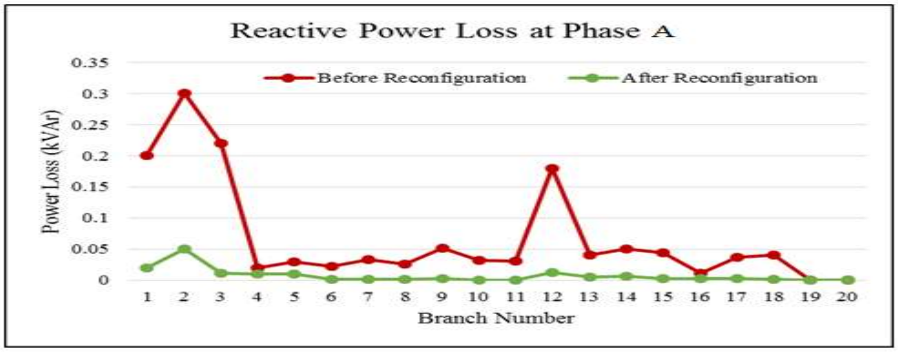


(b) Real power loss at phase B

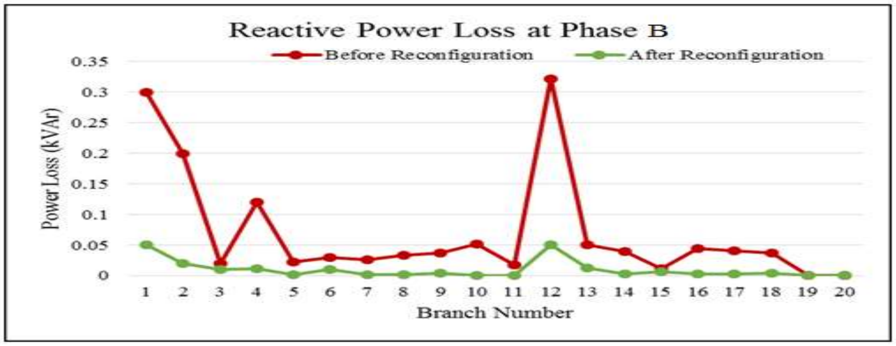


(c) Real power loss at phase C

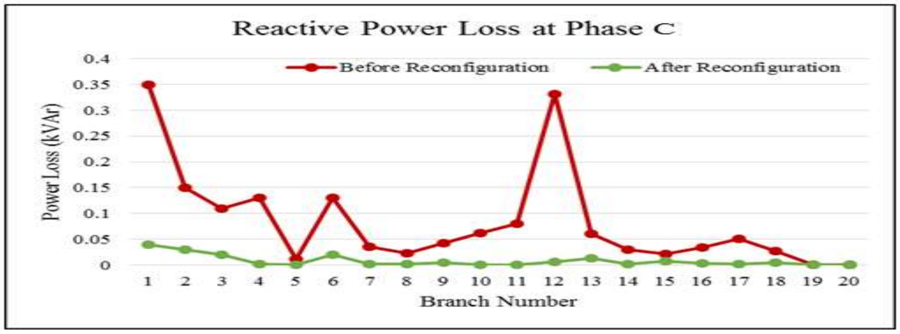
**Figure 4.5:** Real power losses at three phases of 19-node unbalanced distribution network



(a) Reactive power loss at phase A

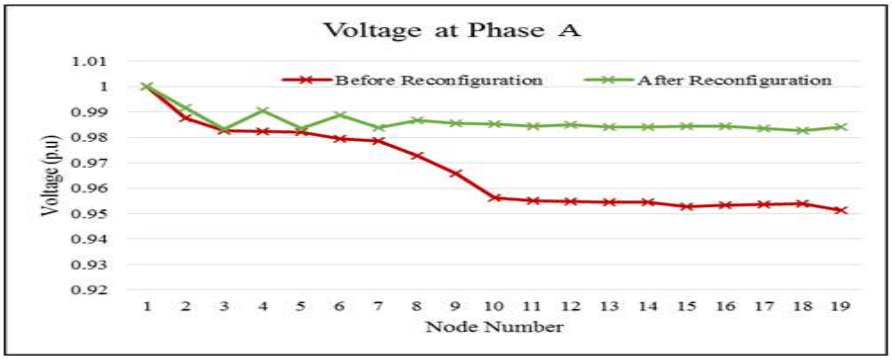


(b) Reactive power loss at phase B

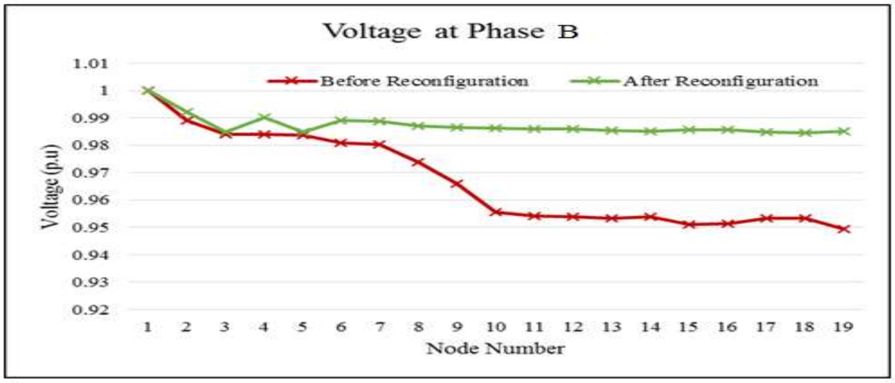


(c) Reactive power loss at phase C

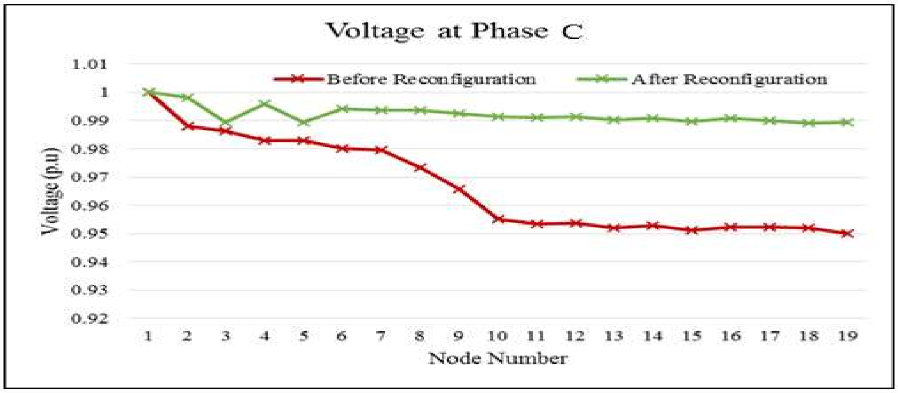
**Figure 4.6:** Reactive power losses at three phases of unbalanced 19-node unbalanced distribution network



(a)Voltage Profile at phase A



**(b)** Voltage Profile at phase B



**(c)** Voltage Profile at phase C

**Figure 4.7** Voltage Profiles at three phases of 19-node unbalanced distribution network

**Table 4.4:** Results of 19-node unbalanced distribution network before and after network reconfiguration

| **Parameters** | **Before Reconfiguration** | | | **After Reconfiguration** | | |
|---|---|---|---|---|---|---|
| | **Phase A** | **Phase B** | **Phase C** | **Phase A** | **Phase B** | **Phase C** |
| **Real Power Loss (kW)** | 4.85 | 4.56 | 4.78 | 0.41 | 1.02 | 1.3 |
| **Reactive Power Loss (kVAr)** | 1.99 | 1.9 | 1.97 | 0.155 | 0.169 | 0.14 |
| **Magnitude of Minimum Voltage (p.u.)** | 0.9514<br>(19) | 0.9494<br>(19) | 0.9501<br>(19) | 0.9825<br>(18) | 0.9844<br>(18) | 0.9891<br>(18) |
| **Switches Opened** | 19, 20 | | | 2, 4 | | |
| **% Real Power Loss Reduction** | - | - | - | 91.55 | 77.63 | 72.80 |
| **% Reactive Power Loss Reduction** | - | - | - | 92.21 | 91.11 | 92.89 |
| **Load Balancing Index (LBI)** | 0.0329944 | | | 0.1035784 | | |
| **Energy Cost ($/kWh)** | 7458.264 | | | 1434.89 | | |

### 4.6.2 25-node unbalanced distribution network

Among a few unbalanced studies that have been performed in reconfiguration problem, a **4.16 kV, 30 MVA**, 25-node unbalanced distribution network is considered. It has 3 tie switches and its total demand is 3.239 + j2.393 MVA. The initial configuration is shown in Figure 4.8. The fuzzy based objective function, which is the combination of real power loss, bus voltage deviation and load balancing, is considered as fitness function for firefly algorithm. In the initial configuration of this network, the tie-line switches 25, 26 and 27 are opened. After closing these tie line switches, the suggested method for network reconfiguration is used and Figure 4.9 is obtained after opening the switches 6, 15, and 17. The magnitude of voltage in p.u. of each node and voltage angle (deg.) before network reconfiguration for each phase is shown in Table 4.5. The magnitude of voltage in p.u. of each node and voltage angle (deg.) after network reconfiguration for each phase is shown in Table 4.6.

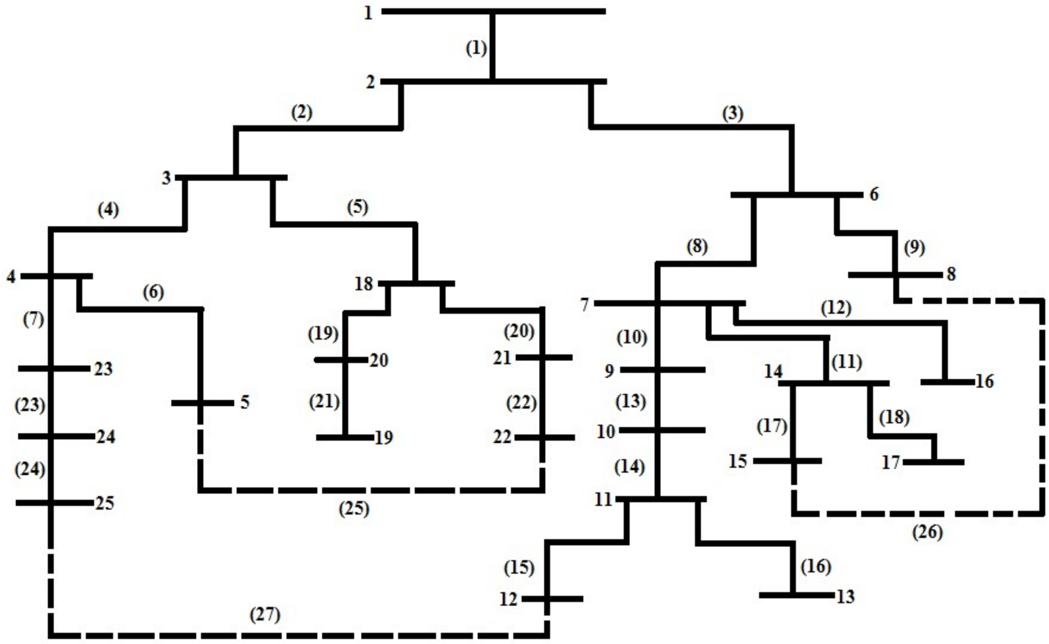


**Figure 4.8**: 25-node unbalanced distribution network

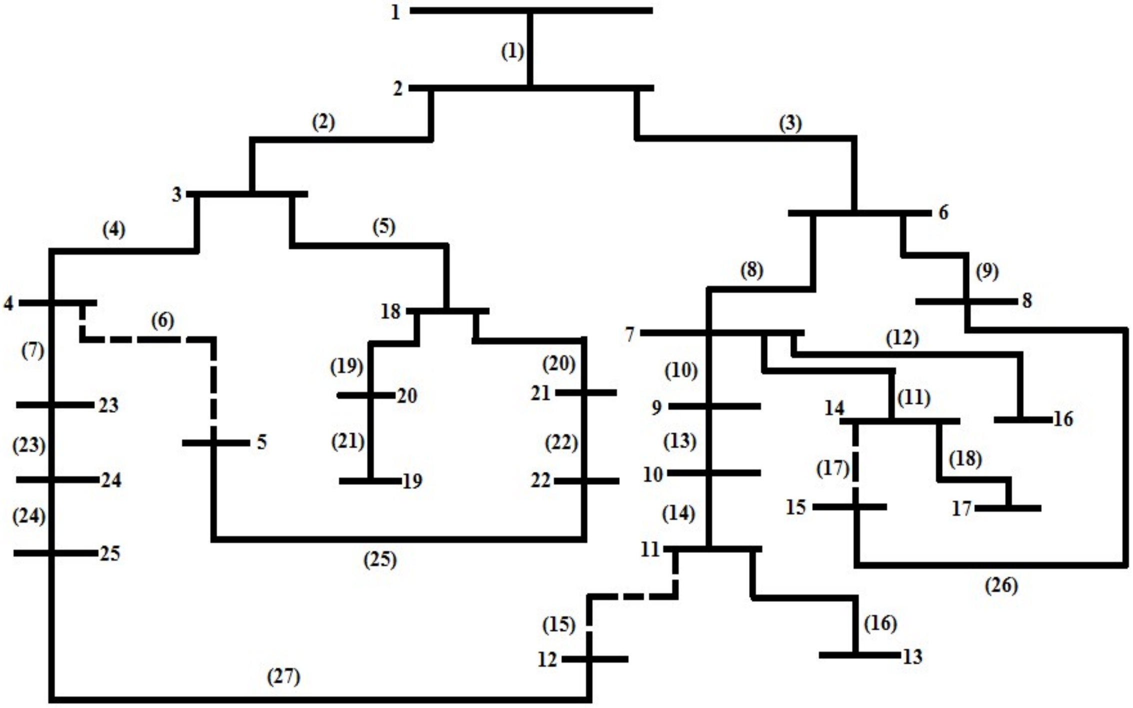


**Figure 4.9:** Reconfigured unbalanced 25-node unbalanced distribution network in regulated environment

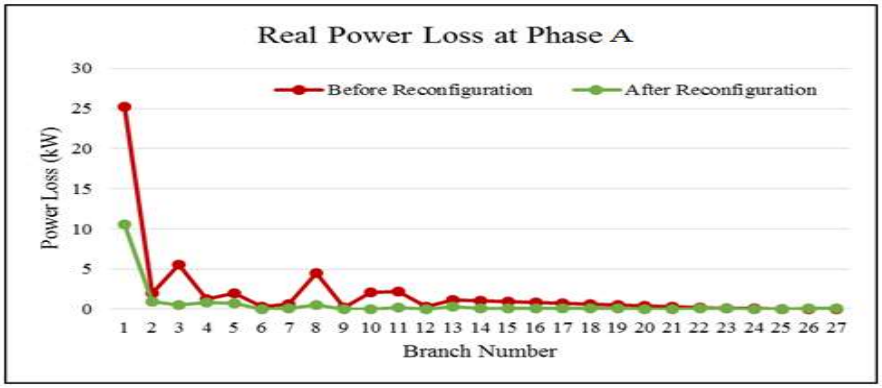
**Table 4.5:** Magnitude of voltage in p.u. of each node and voltage angle (deg.) before reconfiguration for 25-node unbalanced distribution network

| Node Number | Voltage (p.u.) | | | Voltage angle (deg.) | | |
|---|---|---|---|---|---|---|
| | Phase A | Phase B | Phase C | Phase A | Phase B | Phase C |
| 1 | 1.0000 | 1.0000 | 1.0000 | 0.00 | -120.00 | 120.00 |
| 2 | 0.9702 | 0.9711 | 0.9755 | -0.57 | -120.41 | 119.31 |
| 3 | 0.9632 | 0.9644 | 0.9698 | -0.70 | -120.52 | 119.15 |
| 4 | 0.9598 | 0.9613 | 0.9674 | -0.77 | -120.57 | 119.08 |
| 5 | 0.9587 | 0.9603 | 0.9664 | -0.76 | -120.57 | 119.08 |
| 6 | 0.9550 | 0.9559 | 0.9615 | -0.56 | -120.36 | 119.29 |
| 7 | 0.9419 | 0.9428 | 0.9492 | -0.55 | -120.30 | 119.27 |
| 8 | 0.9529 | 0.9538 | 0.9596 | -0.56 | -120.35 | 119.29 |
| 9 | 0.9359 | 0.9367 | 0.9438 | -0.55 | -120.28 | 119.26 |
| 10 | 0.9315 | 0.9319 | 0.9395 | -0.55 | -120.26 | 119.25 |
| 11 | 0.9294 | 0.9296 | 0.9376 | -0.55 | -120.26 | 119.25 |
| 12 | 0.9285 | 0.9287 | 0.9369 | -0.55 | -120.25 | 119.26 |
| 13 | 0.9287 | 0.9287 | 0.9373 | -0.55 | -120.26 | 119.25 |
| 14 | 0.9359 | 0.9370 | 0.9434 | -0.55 | -120.27 | 119.26 |
| 15 | 0.9338 | 0.9349 | 0.9414 | -0.55 | -120.27 | 119.25 |
| 16 | 0.9408 | 0.9418 | 0.9483 | -0.55 | -120.30 | 119.27 |
| 17 | 0.9347 | 0.9360 | 0.9420 | -0.55 | -120.27 | 119.26 |
| 18 | 0.9573 | 0.9586 | 0.9643 | -0.70 | -120.50 | 119.15 |
| 19 | 0.9524 | 0.9544 | 0.9600 | -0.69 | -120.49 | 119.16 |
| 20 | 0.9548 | 0.9563 | 0.9620 | -0.70 | -120.49 | 119.15 |
| 21 | 0.9537 | 0.9549 | 0.9605 | -0.69 | -120.49 | 119.16 |
| 22 | 0.9518 | 0.9525 | 0.9585 | -0.69 | -120.48 | 119.17 |
| 23 | 0.9565 | 0.9584 | 0.9648 | -0.76 | -120.57 | 119.08 |
| 24 | 0.9544 | 0.9565 | 0.9631 | -0.76 | -120.57 | 119.07 |
| 25 | 0.952 | 0.9547 | 0.9612 | -0.76 | -120.57 | 119.08 |

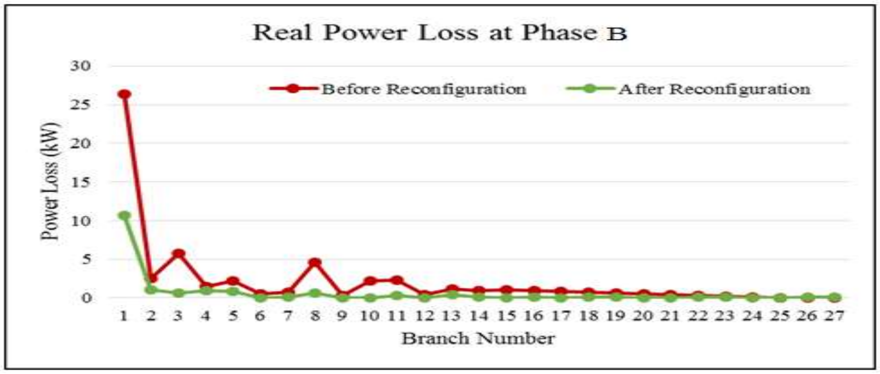
**Table 4.6:** Magnitude of voltage in p.u. of each node and voltage angle (deg.) of 25-node reconfigured unbalanced distribution network

| Node Number | Voltage (p.u.) | | | Voltage angle (deg.) | | |
|---|---|---|---|---|---|---|
| | Phase A | Phase B | Phase C | Phase A | Phase B | Phase C |
| 1 | 1.0000 | 1.0000 | 1.0000 | 0.00 | -120.00 | 120.00 |
| 2 | 0.9805 | 0.9825 | 0.9880 | -0.56 | -120.41 | 119.32 |
| 3 | 0.9798 | 0.9813 | 0.9825 | -0.71 | -120.53 | 119.14 |
| 4 | 0.9786 | 0.9801 | 0.9805 | -0.80 | -120.61 | 119.04 |
| 5 | 0.9601 | 0.9759 | 0.9730 | -0.80 | -120.60 | 119.03 |
| 6 | 0.9797 | 0.9815 | 0.9871 | -0.56 | -120.36 | 119.29 |
| 7 | 0.9775 | 0.9788 | 0.9838 | -0.56 | -120.32 | 119.28 |
| 8 | 0.9790 | 0.9801 | 0.9850 | -0.55 | -120.32 | 119.28 |
| 9 | 0.9755 | 0.9763 | 0.9788 | -0.56 | -120.3 | 119.27 |
| 10 | 0.9699 | 0.9760 | 0.9755 | -0.56 | -120.29 | 119.26 |
| 11 | 0.9619 | 0.9759 | 0.9738 | -0.56 | -120.29 | 119.26 |
| 12 | 0.9587 | 0.9758 | 0.9730 | -0.79 | -120.59 | 119.05 |
| 13 | 0.9581 | 0.9756 | 0.9728 | -0.56 | -120.29 | 119.26 |
| 14 | 0.9734 | 0.9758 | 0.9835 | -0.56 | -120.31 | 119.27 |
| 15 | 0.9718 | 0.9755 | 0.9761 | -0.54 | -120.32 | 119.28 |
| 16 | 0.9686 | 0.9757 | 0.9742 | -0.56 | -120.32 | 119.27 |
| 17 | 0.9685 | 0.9756 | 0.9830 | -0.55 | -120.30 | 119.27 |
| 18 | 0.9676 | 0.9763 | 0.9738 | -0.71 | -120.51 | 119.14 |
| 19 | 0.9623 | 0.9752 | 0.9736 | -0.70 | -120.50 | 119.14 |
| 20 | 0.9631 | 0.9761 | 0.9737 | -0.71 | -120.50 | 119.13 |
| 21 | 0.9634 | 0.9762 | 0.9735 | -0.71 | -120.51 | 119.14 |
| 22 | 0.9628 | 0.9760 | 0.9733 | -0.80 | -120.59 | 119.03 |
| 23 | 0.9697 | 0.9799 | 0.9797 | -0.80 | -120.60 | 119.03 |
| 24 | 0.9696 | 0.9762 | 0.9736 | -0.80 | -120.60 | 119.03 |
| 25 | 0.9687 | 0.9760 | 0.9731 | -0.79 | -120.60 | 119.04 |

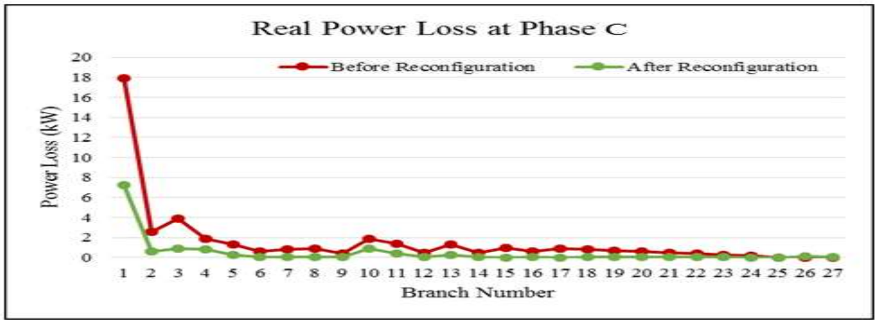
The real and reactive power losses of each branch at three phases before and after reconfiguration of 25-node unbalanced distribution network is shown in Figure 4.10 and Figure 4.11 respectively. The respective voltage profile of 25-node unbalanced distribution network before and after network reconfiguration at three phases is shown in Figure 4.12.



(a) Real power loss at phase A

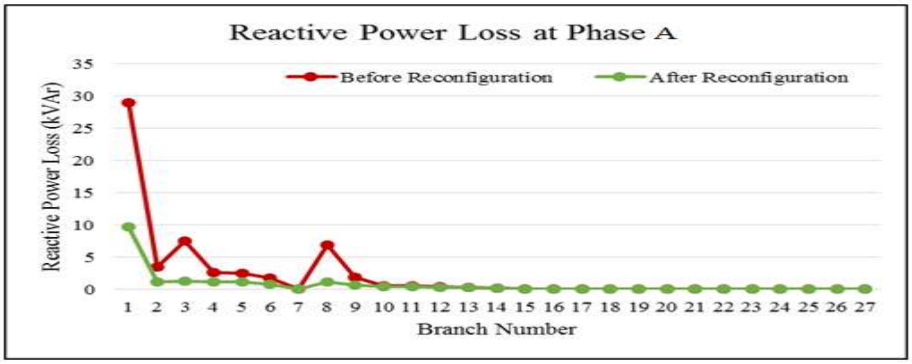


(b) Real power loss at phase B

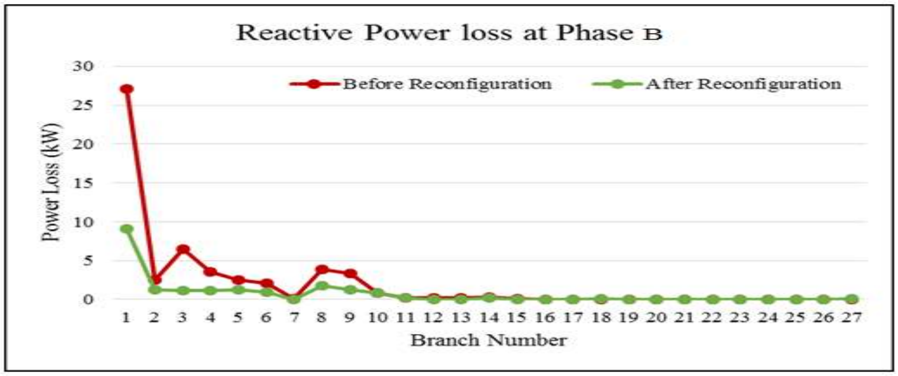


(c) Real power loss at phase C

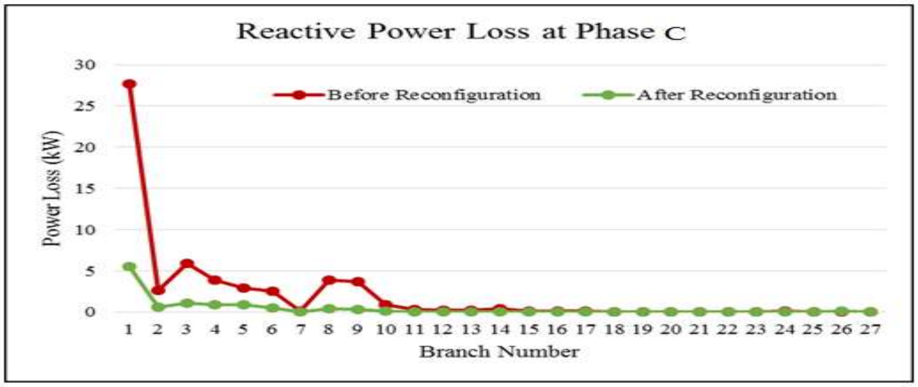
**Figure 4.10:** Real power losses at three phases of unbalanced 25-node unbalanced distribution network before and after network reconfiguration in regulated environment



(a) Reactive power loss at phase A

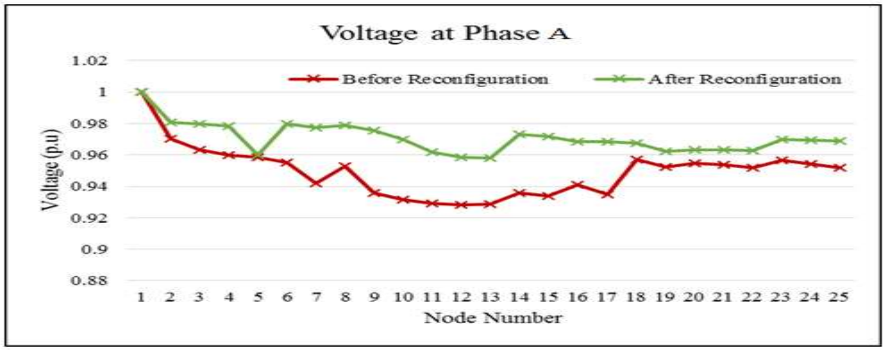


(b) Reactive power loss at phase B

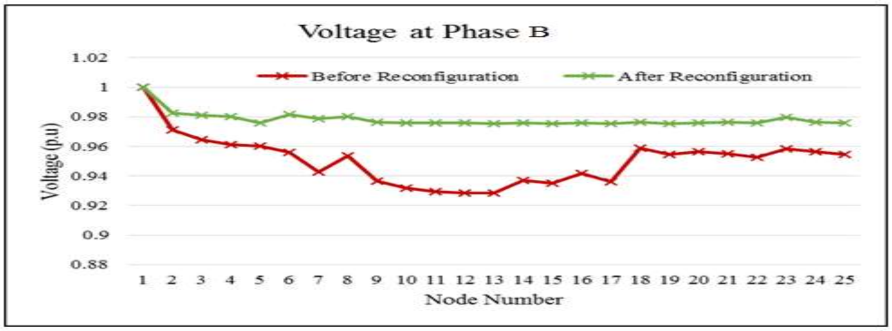


(c) Reactive power loss at phase C

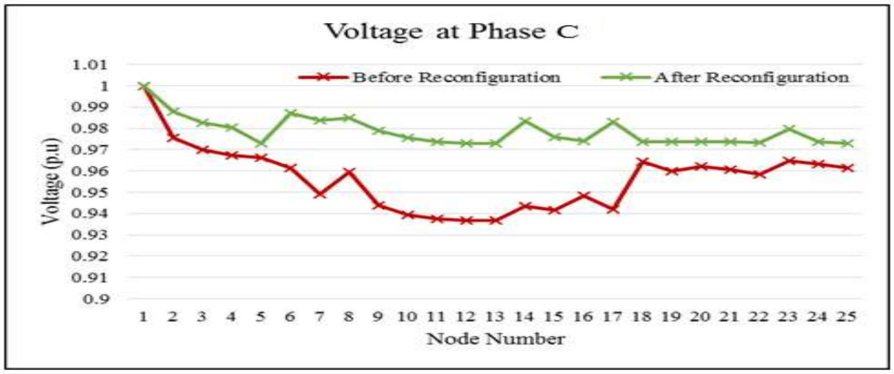
**Figure 4.11:** Reactive power losses at three phases of unbalanced 25-node unbalanced distribution network before and after network reconfiguration in regulated environment



(a) Voltage profile at phase A



(b) Voltage profile at phase B



(c) Voltage profile at phase C

**Figure 4.12:** Voltage profiles at three phases of unbalanced 25-node unbalanced distribution network before and after network reconfiguration in regulated environment

The results obtained for of 25-node unbalanced distribution network before and after network reconfiguration using the proposed method are shown in Table 4.7.

**Table 4.7:** Results of 25-node unbalanced distribution network before and after network reconfiguration

| **Parameters** | **Before Reconfiguration** | | | **After Reconfiguration** | | |
|---|---|---|---|---|---|---|
| | **Phase A** | **Phase B** | **Phase C** | **Phase A** | **Phase B** | **Phase C** |
| **Real Power Loss (kW)** | 52.92 | 54.44 | 43.97 | 14.95 | 15.03 | 9.75 |
| **Reactive Power Loss (kVAr)** | 60.43 | 52.32 | 55.87 | 17.30 | 15.39 | 9.54 |
| **Magnitude of Minimum Voltage (p.u.)** | 0.9285 (12) | 0.9287 (12) | 0.9369 (12) | 0.9581 (13) | 0.9756 (13) | 0.9728 (13) |
| **Switches Opened** | 25, 26, 27 | | | 6, 15, 17 | | |
| **% Real Power Loss Reduction** | - | - | - | 71.75 | 72.39 | 77.85 |
| **% Reactive Power Loss Reduction** | - | - | - | 71.37 | 70.58 | 82.92 |
| **Load Balancing Index (LBI)** | 0.1009658 | | | 0.0454214 | | |
| **Energy Cost ($/kWh)** | 79539.048 | | | 20882.088 | | |

Table 4.7 shows that there is improvement of minimum voltage for each phase and the real power loss and reactive power loss for each phase are considerably reduced. The energy cost is also reduced drastically after network reconfiguration.

### 4.6.3 Performance comparison

In the proposed method, firefly algorithm has been used. In order to prove or justify its superiority, the results (real power and reactive power losses, minimum voltage of each phase along with its node number, CPU time, number of power-flows and energy cost) obtained by the proposed method have been compared with that of obtained by other optimization algorithms like “Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Artificial Bee Colony (ABC) and GA-PSO algorithm” using the same objective function and proposed load-flow method. The outcomes have been presented in Table 4.8 for 25-node and 19-node unbalanced distribution networks (**UDN**s).

**Table 4.8:** Performance comparison of suggested technique of network reconfiguration with other algorithms

| Methods | UDNs | Open Switches | Real Power Loss (kW) | Reactive Power Loss (kVAr) | Magnitude of Minimum Voltage (p.u.) | CPU Time (sec.) | No. of Power-Flows | Energy Loss ($/kWh) | Value of fitness function |
|---|---|---|---|---|---|---|---|---|---|
| **Fuzzy-Firefly Algorithm** | **25-node** | **6, 15, 17** | **39.73** | **42.23** | **0.9581 (13), 0.9756 (13), 0.9728 (13)** | **0.52** | **21** | **20882.088** | **0.925** |
| | **19-node** | **2, 4** | **2.73** | **0.464** | **0.9825 (18), 0.9844 (18), 0.9891 (18)** | **0.35** | **16** | **1434.89** | **0.942** |
| **Genetic Algorithm** | 25-node | 17, 22, 24 | 91.36 | 105.41 | 0.9408 (25), 0.9487 (25), 0.9523 (25) | 2.110 | 98 | 48018.816 | 2.917 |
| | 19-node | 9, 14 | 12.05 | 4.95 | 0.9624 (16), 0.9503 (16), 0.9509 (16) | 1.586 | 84 | 6333.48 | 2.723 |
| **ABC Algorithm** | 25-node | 15, 17, 22 | 71.14 | 81.98 | 0.9468 (12), 0.9568 (12), 0.9591 (12) | 2.01 | 44 | 37391.184 | 2.674 |
| | 19-node | 17, 18 | 9.59 | 3.39 | 0.9685 (18), 0.9588 (18), 0.9606 (18) | 1.29 | 35 | 5040.504 | 2.701 |
| **PSO Algorithm** | 25-node | 15, 17, 20 | 62.14 | 63.21 | 0.9489 (13), 0.9618 (13), 0.9641 (13) | 1.421 | 31 | 32660.784 | 2.225 |
| | 19-node | 2, 14 | 5.89 | 2.22 | 0.9729 (18), 0.9624 (18), 0.9689 (18) | 1.12 | 26 | 3095.784 | 2.187 |
| **GA-PSO Algorithm** | 25-node | 6, 17, 24 | 45.32 | 49.147 | 0.9521 (25), 0.9699 (25), 0.9697 (25) | 0.99 | 27 | 23820.192 | 1.688 |
| | 19-node | 10, 11 | 4.0 | 1.11 | 0.9790 (16), 0.9715 (16), 0.9803 (16) | 0.59 | 18 | 2102.4 | 1.680 |

Table 4.8 shows that the firefly algorithm has better performance than other algorithms like Genetic Algorithm, ABC algorithm, PSO algorithm and GA-PSO algorithm.

The suggested method has also been compared with the methods of (Vulasala ***et al.***(2009), Subrahmanyam and Radhakrishna (2009)**,** Sedighizadeh ***et al.*** (2013)**,** Taher and Karimi (2014), Sedighizadeh (2015)) as presented in Table 4.9.

**Table 4.9:** Performance Comparison of suggested technique of network reconfiguration with Existing Methods (Vulasala ***et al.***(2009), Subrahmanyam and Radhakrishna (2009)**,** Sedighizadeh ***et al.*** (2013)**,** Taher and Karimi (2014) and Sedighizadeh (2015))

| **Methods** | **Bus System** | **Open Switches** | **Real Power Loss (kW)** | **Reactive Power Loss (kVAr)** | **Magnitude of Minimum Voltage (p.u.)** | **Energy Cost ($/kWh)** |
|---|---|---|---|---|---|---|
| **Proposed Method** | **25-node System** | **6, 15, 17** | **39.78** | **42.27** | **0.9581 (13)**<br>**0.9756 (13)**<br>**0.9728 (13)** | **20908.368** |
| | **19-node System** | **2, 4** | **2.73** | **0.464** | **0.9825 (18)**<br>**0.9844 (18)**<br>**0.9891 (18)** | **1434.888** |
| Vulasala ***et al.*** (2009) | 25-node System | 15,17,22 | 133.5 | 157.61 | 0.9389<br>0.9401<br>0.9460 | 70167.5 |
| | 19-node System | 10,11 | 8.22 | 3.53 | 0.9703<br>0.9694<br>0.9690 | 4320.43 |
| Subrahmanyam and Radhakrishna (2009) | 25-node System | 22, 17, 15 | 136.13 | - | 0.9389,<br>0.9401,<br>0.9459 | 71549.928 |
| | 19-node System | 10, 11 | 8.42 | - | 0.97043,<br>0.96954,<br>0.96724 | 4425.552 |
| Sedighizadeh ***et al.*** (2013) | 25-node system | 15, 17, 22 | 133.49 | - | 0.93889,<br>0.94015,<br>0.94596 | 70162.344 |
| Taher and Karimi (2014) | 25-node System | 11, 14, 21 | 120.2829 | - | - | 63220.69 |
| Sedighizadeh (2015) | 25-node system | 25, 17, 15 | 94.179 | - | - | 49500.482 |

The effectiveness of the proposed method is compared with the existing method (Vulasala ***et al.*** (2009)) in terms of real and reactive power losses, minimum voltage magnitudes at three phases and energy cost. The suggested method is compared with the existing methods (Subrahmanyam and Radhakrishna (2009)], Sedighizadeh ***et al.*** (2013)) in terms of real power loss, minimum voltage magnitudes at three phases and energy cost. The suggested method is set side by side with the methods (Taher and Karimi (2014), Sedighizadeh (2015)) in terms of the real power loss and energy cost. The real and reactive power losses obtained by the proposed method are lower compared to that of obtained by the method proposed by Vulasala ***et al.*** (2009) for 25-node and 19-node unbalanced distribution networks. The real power loss obtained by the proposed method is lower compared to that of obtained by the method proposed by Subrahmanyam and Radhakrishna (2009) for the above two networks and the magnitude of minimum voltages at three phases obtained by the proposed method compared to that of obtained by the methods of Vulasala ***et al***. (2009), Subrahmanyam and Radhakrishna (2009) for these two networks has been improved. The energy cost obtained by the proposed method is lower compared to that of obtained by the methods of Vulasala ***et al.*** (2009), Subrahmanyam and Radhakrishna (2009) for the above two networks.

The loss reduction obtained by the proposed method is higher compared to that of obtained by the method proposed by Sedighizadeh ***et al.*** (2013) for 25-node unbalanced distribution network. The magnitude of minimum voltage of each phase obtained by the proposed method compared to that of obtained by the method given by Sedighizadeh ***et al.*** (2013) for this network has also been improved. The energy cost obtained by the proposed method is lower compared to that of obtained by the method Sedighizadeh ***et al.*** (2013) for this network. The proposed method also gives better results in terms of loss reduction and reduction of energy cost compared to that of obtained by the methods proposed by Taher and Karimi (2014) and Sedighizadeh (2015) for 25-node unbalanced distribution network.

From Table 4.8 and Table 4.9, it is evident that the proposed method produces an efficient network configuration after network reconfiguration of an unbalanced distribution network, which has lower real and reactive power losses, improved voltage profiles and lower energy cost.

### 4.6.4 Integration of DG and capacitor in 25-node unbalanced distribution network in regulated environment

The detailed results for the base case and after network reconfiguration of 25-node unbalanced distribution network are discussed in section 4.5.2. In the same distribution network, the DG and capacitor have been integrated and the results are compared before and after integration. The location DG and capacitor are obtained by the LSF (Loss sensitivity factor). Their sizes are determined by Genetic Algorithm (GA), Particle Swarm Optimization (PSO) algorithm, Artificial Bee Colony (ABC) Algorithm and Bacterial Foraging Optimization algorithm (BFOA ). The outcomes in terms of DG size (kW), capacitor size (kVAr), Real power loss (kW) and Reactive power loss (kVAr) have been depicted in Figure 4.13, Figure 4.14, Figure 4.15 and Figure 4.16 respectively. The BFOA gives the better results. The DG and capacitor are integrated into the 25-node unbalanced reconfigured network shown in Figure 4.9 using the LSF and BOFA to reduce the losses. The comparison of results before and after the integration of DG and capacitor in the reconfigured network are presented in Table 4.10. The results of voltage levels before and after integration of DG and capacitor in the 25-node unbalanced reconfigured distribution network are presented in Table 4.11.

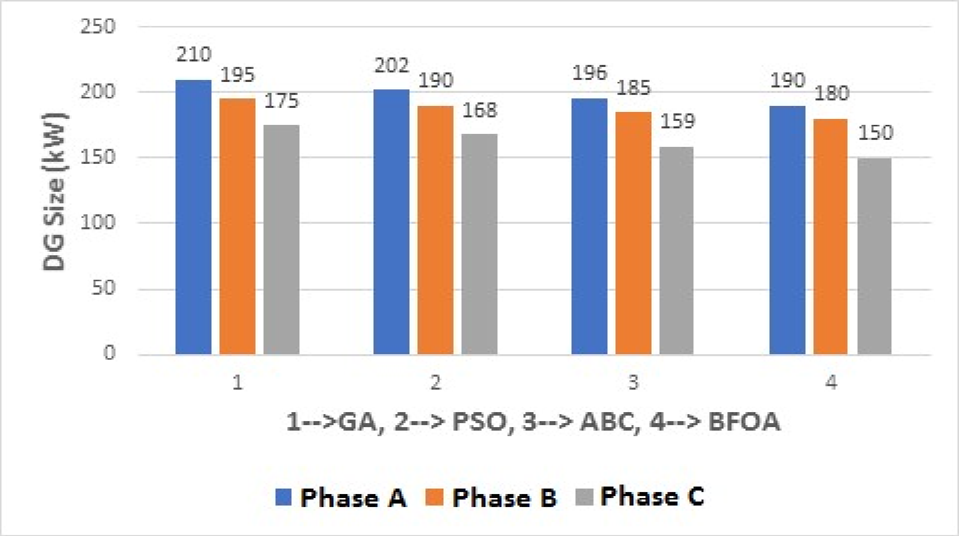


**Figure 4.13:** DG sizes (kW) by GA, PSO, ABC and BFOA at Phase A, Phase B and Phase C

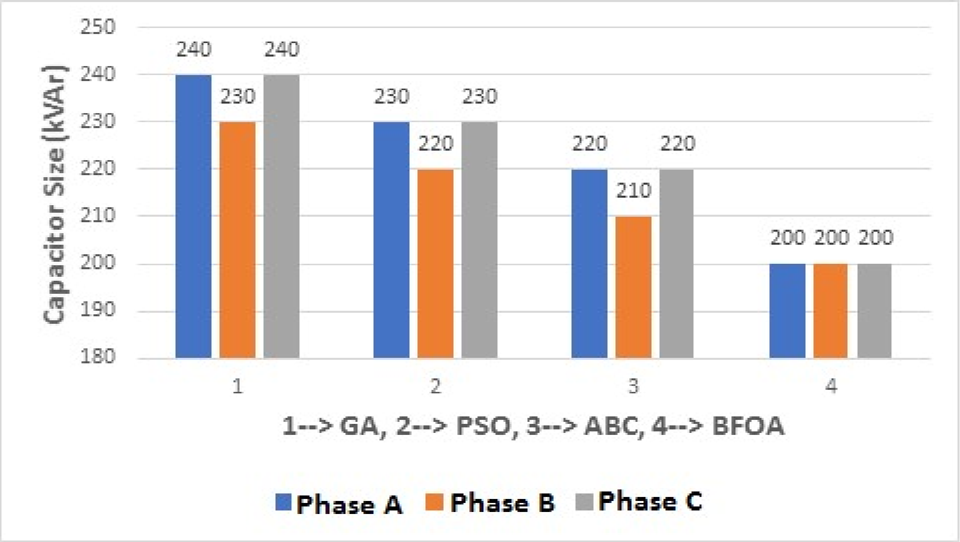


**Figure 4.14:** Capacitor sizes (kVAr) by GA, PSO, ABC and BFOA at Phase A, Phase B and Phase C

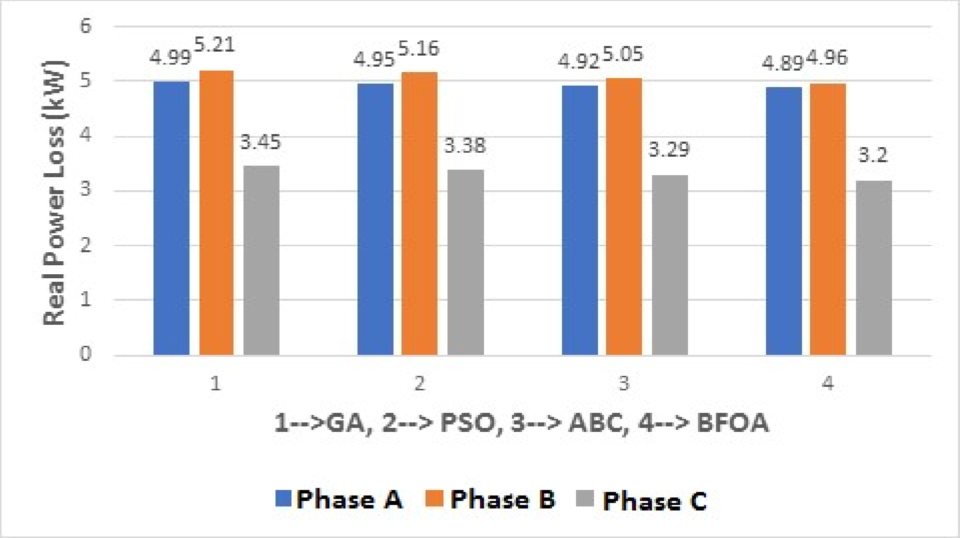


**Figure 4.15:** Real power losses at Phase A, Phase B and Phase C

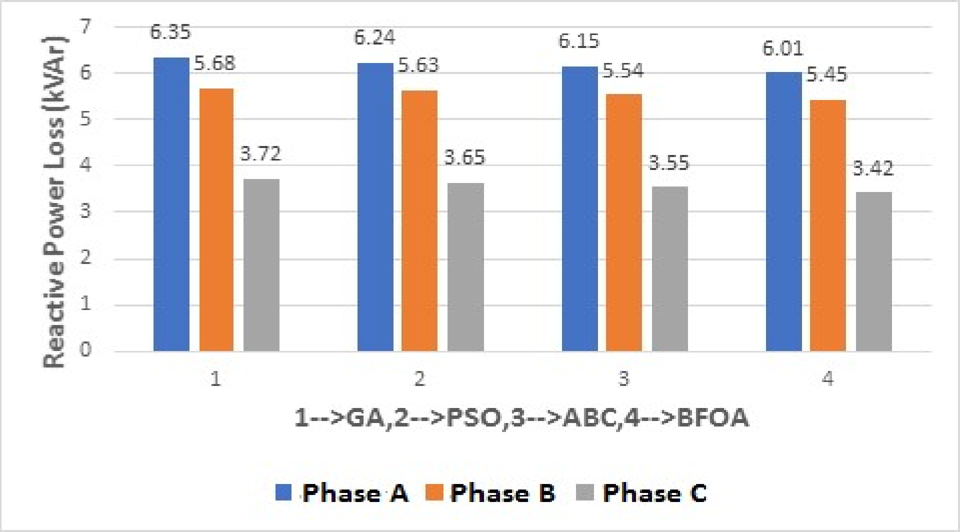


**Figure 4.16:** Reactive power losses at Phase A, Phase B and Phase C

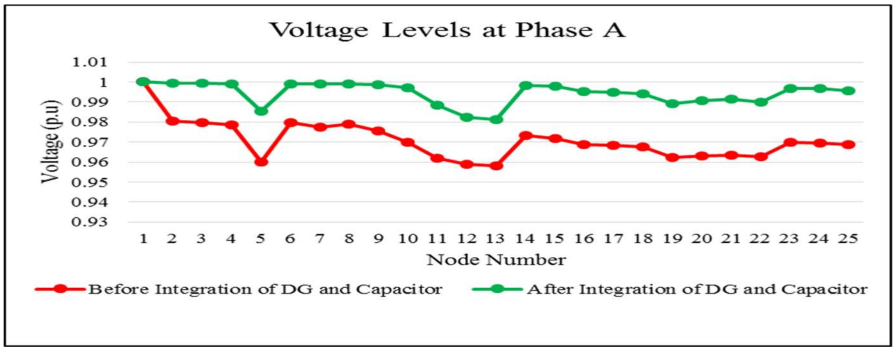
**Table 4.10:** Comparison results before and after Integration of DG and capacitor in 25-node unbalanced reconfigured distribution network

| Parameters | Before Integration | | | After Integration | | |
|---|---|---|---|---|---|---|
| | Phase | | | Phase | | |
| | A | B | C | A | B | C |
| Real Power Loss (kW) | 14.95 | 15.03 | 9.75 | 4.89 | 4.96 | 3.20 |
| Reactive Power Loss (kVAr) | 17.30 | 15.39 | 9.54 | 6.01 | 5.45 | 3.42 |
| Minimum Voltage (p.u.) | 0.9581 (13) | 0.9756 (13) | 0.9728 (13) | 0.9813 (13) | 0.9901 (13) | 0.9891 (13) |
| Switches Opened | 6, 15, 17 | | | - | | |
| DG Location | - | - | - | 7 | 7 | 7 |
| DG Size (kW) | - | - | - | 190 | 180 | 150 |
| Capacitor Location | - | - | - | 15 | 15 | 15 |
| Capacitor Size (kVAr) | - | - | - | 200 | 200 | 200 |
| Energy Cost ($/kWh) | 20882.088 | | | 11063.88 | | |

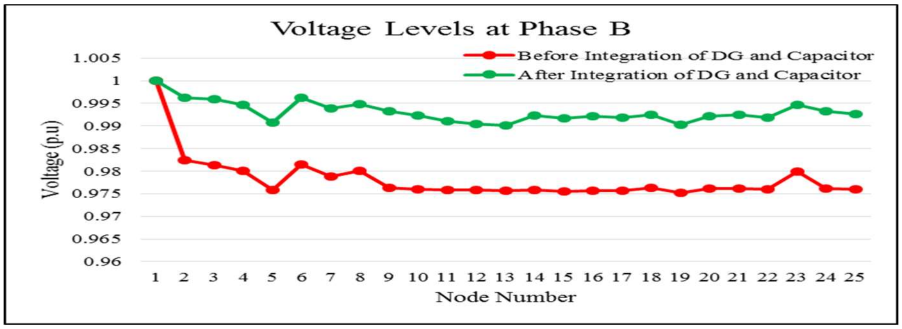
**Table 4.11:** Voltage levels before and after integration of DG and capacitor in 25-node unbalanced reconfigured distribution network

| Node No. | Voltage Levels (p.u.) | | | | | |
|---|---|---|---|---|---|---|
| | Before Integration | | | After Integration | | |
| | Phase A | Phase B | Phase C | Phase A | Phase B | Phase C |
| 1 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 |
| 2 | 0.9805 | 0.9825 | 0.9880 | 0.9994 | 0.9963 | 0.9946 |
| 3 | 0.9798 | 0.9813 | 0.9825 | 0.9993 | 0.9959 | 0.9931 |
| 4 | 0.9786 | 0.9801 | 0.9805 | 0.9989 | 0.9947 | 0.9919 |
| 5 | 0.9601 | 0.9759 | 0.9730 | 0.9853 | 0.9908 | 0.9898 |
| 6 | 0.9797 | 0.9815 | 0.9871 | 0.9992 | 0.9962 | 0.9945 |
| 7 | 0.9775 | 0.9788 | 0.9838 | 0.9989 | 0.9939 | 0.9930 |
| 8 | 0.9790 | 0.9801 | 0.9850 | 0.9990 | 0.9948 | 0.9943 |
| 9 | 0.9755 | 0.9763 | 0.9788 | 0.9988 | 0.9933 | 0.9915 |
| 10 | 0.9699 | 0.9760 | 0.9755 | 0.9972 | 0.9923 | 0.9914 |
| 11 | 0.9619 | 0.9759 | 0.9738 | 0.9883 | 0.9910 | 0.9912 |
| 12 | 0.9587 | 0.9758 | 0.9730 | 0.9825 | 0.9905 | 0.9896 |
| 13 | 0.9581 | 0.9756 | 0.9728 | 0.9813 | 0.9901 | 0.9891 |
| 14 | 0.9734 | 0.9758 | 0.9835 | 0.9984 | 0.9923 | 0.9929 |
| 15 | 0.9718 | 0.9755 | 0.9761 | 0.9980 | 0.9917 | 0.9913 |
| 16 | 0.9686 | 0.9757 | 0.9742 | 0.9953 | 0.9921 | 0.9899 |
| 17 | 0.9685 | 0.9756 | 0.9830 | 0.9949 | 0.9918 | 0.9909 |
| 18 | 0.9676 | 0.9763 | 0.9738 | 0.9940 | 0.9925 | 0.9917 |
| 19 | 0.9623 | 0.9752 | 0.9736 | 0.9891 | 0.9903 | 0.9910 |
| 20 | 0.9631 | 0.9761 | 0.9737 | 0.9907 | 0.9921 | 0.9915 |
| 21 | 0.9634 | 0.9762 | 0.9735 | 0.9915 | 0.9924 | 0.9914 |
| 22 | 0.9628 | 0.9760 | 0.9733 | 0.9901 | 0.9919 | 0.9907 |
| 23 | 0.9697 | 0.9799 | 0.9797 | 0.9969 | 0.9947 | 0.9918 |
| 24 | 0.9696 | 0.9762 | 0.9736 | 0.9966 | 0.9932 | 0.9908 |
| 25 | 0.9687 | 0.9760 | 0.9731 | 0.9956 | 0.9927 | 0.9898 |

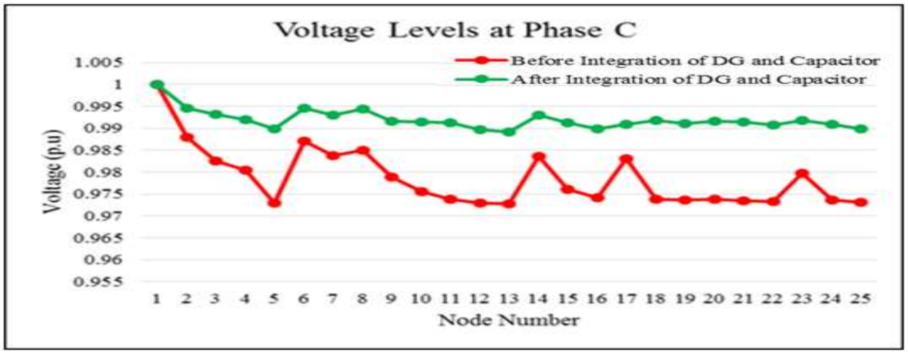
Figure 4.17 shows the representation of voltage levels of the Phases A, B and C respectively before and after integration of DG and capacitor in the reconfigured network.



(a) Voltage level at Phase A



(b) Voltage level at Phase B



(c) Voltage level at Phase C

**Figure 4.17:** Voltage levels of 25-node unbalanced reconfigured network before and after integration of DG and capacitor in regulated environment

## 4.7 Conclusion

A Fuzzy Firefly optimization algorithm has been implemented for multi-objective reconfiguration of three-phase unbalanced radial distribution networks. The minimization of total power losses and bus voltage deviation as well as balancing the load in the feeders, are the main objectives of this method. To acquire the optimal solution for the multi-objective fitness function, initially each objective is transferred into the fuzzy domain at first utilizing the membership function and then the resultant overall fuzzified function is considered as a fitness function, which is maximized during the optimization process. The Fuzzy-Firefly algorithm for network reconfiguration has been successfully tested on 25-node and 19-node unbalanced distribution networks. Simulation results show that the fuzzy based firefly algorithm has produced better outcomes in terms of reduction of real and reactive power losses, improvement of the magnitude of minimum voltage for each phase and reduction of energy cost in these two unbalanced distribution networks compared to that of obtained by the other optimization existing algorithms like GA, ABC, PSO and GA-PSO using the same objective function and proposed load-flow method. This Fuzzy-Firefly algorithm takes less CPU time and least number of power-flows compared to that of obtained by the other optimization algorithms like GA, ABC, PSO and GA-PSO algorithms. The proposed method also gives better results in terms of loss reduction, improvement of the magnitude of minimum voltage of each phase and reduction of energy cost compared to that of obtained by the methods Vulasala ***et al.*** (2009) and Subrahmanyam and Radhakrishna (2009) for 25-node and 19-node unbalanced distribution networks and that obtained by the method of Sedighizadeh ***et al.*** (2013) for 25-node unbalanced distribution network respectively. The suggested method also yields better performance in terms of loss reduction and reduction of energy cost compared to that of obtained by the methods Taher and Karimi (2014) and Sedighizadeh (2015). In this work the DG and capacitor are placed optimally in reconfigured network in the regulated environment using LSF and BFOA. The results in terms of voltage level and other parameters are compared for before and after integration of DG and capacitor. The results obtained are effective and DG and capacitor placement for loss minimization along with reconfiguration comes out to be a decent choice.

# CHAPTER-5: RECONFIGURATION OF UNBALANCED RADIAL DISTRIBUTION NETWORK IN DEREGULATED ENVIRONMENT ALONG WITH DG AND CAPACITOR INTEGRATION

## 5.1 Introduction

The dynamic conduct of current power systems has been encountering noteworthy changes for the most part because of the transformation of electric power industry (Pisica ***et al***. (2013)). In the present era, electric power commercial enterprises are on the move from extensive and coordinated utilities to private and sectorial businesses. This new structure is called deregulated power system. Deregulated energy market takes generation, transmission, and distribution as self-regulating endeavors. Main benefits from the deregulation comprise low-cost electricity, efficient capacity expansion planning, more choice, and better service (Sood ***et al***. (2002)). One of the fundamental target elements of deregulated power systems is diminishing energy supply costs. In this rebuilt environment of power system, there are numerous energy merchants with different conditions, offering their energy with distinctive costs. These distinctions cause the configuration of the distribution system consequences for the estimation of the energy supply cost (Arias-Albornoz and Sanhueza-Hardy (2004)).

Traditional unified power system networks are taking energy from HV levels and sending it to low voltage (LV) level distribution network (DN), but in the era of the deregulated environment, there will be a need of lively distribution network management; from central to many distribution networks. In this kind of network, there will be more DG’s in the system along with latest advanced ideas (Bayod-Rujula (2009)). Along these lines, overhead distribution frameworks are fundamentally arranged in a radial way to make simple inherent components of the system assurance, for example, coordination and lessening of short out streams, decreasing hardware costs (Khalid ***et al.*** (2012)). Low adaptability and dependability for the functioning of radial distribution networks (RDNs) cause those frameworks to be developed through the sectionalizing switches (**SS**) (Jabr ***et al.*** (2012)). By varying the condition of the SS i.e., opening or closing, the network is being reconfigured, and the function of the network is also enhanced (Wu ***et al.*** (2010)). Modification in the topology of any distribution network reduces system's loss, enhances the system's voltage profile (VP) and restores the power supply. Along these lines, SS are utilized for fault segregation in addition to the reconfiguration.

These days, distribution networks that are being affected by expanding the addition of distributed generations (DGs), which are constantly utilized as a part of the transmission network (Viral and Khatod (2012)). Hereafter, DG got to be one of the applicable parameters in the assessment of network reconfiguration (Zidan and El-Saadany (2013)). Incorporation of DG in any distribution network influences the operation of this distribution network in different courses (Penido ***et al.*** (2008)).

In this chapter, the dedicated work on optimal network reconfiguration of unbalanced distribution network along with integration of DG and capacitor in deregulated environment to reduce the losses of the system is presented. Role of network reconfiguration and integration of DG and capacitor has been discussed in **Section 1.2 (Chapter 1**) and literature survey is detailed in **Section 2.3 (Chapter 2).** In this work fuzzy firefly algorithm is applied for optimal network reconfiguration that had already been explained in **Chapter 4.**

## 5.2 Reconfiguration of unbalanced distribution network in deregulated environment

Any unbalanced distribution network consists of two types of switch known as normally open switch (tie-line switch) and normally closed switch (sectionalizing switch). By closing the tie-line switches and opening sectionalizing switches, the arrangement of the distribution network can be modified. The loss minimization may not be optimal with the opening and closing of improper switches. Hence the selection of switches is the most vital to get the optimal network, which gives a maximum loss reduction and superior voltage profile (VP). Any predetermined reason identifies the function of a specific configuration.

For example, a configuration with maximum loss reduction and superior voltage profile is always expected. The aim is to reconfigure any network to reduce loss, expand reliability indices, use of a maximum number of switches and cut down the working cost of the system. The intelligent algorithm can be used to compute the objective function having multiple variables. The consequence of any objective can be determined by the weighting elements. It is not required to install any additional instruments to take care of network issues those solely can be done by reconfiguring the network. Any network having 'n' number of open or closed switches will have '2n' number of arrangements. Hence it is not feasible to think about all states of reconfiguring the network. During reconfiguring the network, the following limitations are considered:

- All network buses must be limited.
- Summation of net load and net losses must tally with the generation and should be neither equal nor exceed the capacity of the network.
- The final structure of the network must be radial.
- Bus voltages should be within the limits.

The reconfiguration problem becomes a complex optimization problem due to its huge solution space and a number of constraints. The cost of the network in the deregulated environment should be paid the highest attention in comparison to any general network in the regulated environment and hence objective function in a deregulated environment becomes entirely different. This paper considers multi-objective optimization for reconfiguring the network. In this proposed methodology, for the case of reconfiguration in a regulated environment, reducing the power loss, reducing the bus voltage deviation and load equalizing done by the feeders are considered as the objectives and fuzzified as mentioned in **Chapter 4 (Section 4.3).** The objective function for network reconfiguration in a regulated environment as described in **Chapter 4** is presented below.

$$\lambda F_m = \left( \lambda P_{L_m} \times \lambda V_m \times \lambda I_m \right)^{1/3} \tag{5.1}$$

The fitness function is deliberated in Equation (5.1) is maximized during the optimization procedure to acquire the best well-matched configuration. This operator has numerous benefits. For instance, if any membership function of each objective reaches the value of zero, $\lambda F_m$ is allocated to a value of zero. Additionally, this function delivers correct information as about how making this algorithm achieving an ideal state, namely a value of 1. This objective function is utilized as the fitness function. As the network cost is more significant in the case of deregulated environment compared to the traditional network, the deregulated environment has a different objective function. In the deregulated environment, the main objective is to improve the benefits for the company. Here two objectives are considered for the deregulated environment such as operational cost minimization and reliability maximization.

In this work, the fireflies move with the values of $\beta = 1$, $\gamma = 0.75$ and $\alpha = 0.25$ are considered where $\beta$, $\gamma$ and $\alpha$ are intensity or attractiveness of the firefly's flashing light, light absorption coefficient of a given medium and randomization parameter, $\alpha \in [0,1]$. The number of firefly population is taken as 100 and the maximum number of iterations is selected as 150.

### 5.2.1. Minimization of operational cost

There are two parts of the net operating cost. The cost due to real power loss is considered as operation cost at first that can be reduced by reducing the losses in the distribution network. The cost due to real power loss is equal to $A_1 \times P_S$ where $A_1$ is the coefficient for the price of real power and its unit is \$/kW and a net loss of system's active power ($P_S$) in kW. The second component is the reactive power cost, procured with the distribution network. The cost component can be decreased if the system's reactive power loss is decreased. The second component is represented by $A_2 \times Q_S$ where $A_2$ represents the coefficient of price in \$/kVAr and $Q_S$ represents the reactive power consumed by the distribution network from the transmission system connected to it. The Operating Cost (C) is represented by Equation (5.2).

$$\text{Operating Cost (C)} = A_1P_S + A_2Q_S \tag{5.2}$$

The operational cost minimization index is given by

$$XC_m = \frac{C_m}{C_0} \tag{5.3}$$

where $C_0$ indicates the initial operating cost before reconfiguration and $C_m$ indicates the operating cost after reconfiguration in the m th system. The fuzzy satisfaction degree of the operating cost objective function is computed by exploiting the membership function as represented by the fuzzy domain, which is expressed by Equation (5.4)

$$\lambda C_m = \begin{cases} 1 & XC_m < XC_{\min} \\ \dfrac{XC_{\max} - XC_m}{XC_{\max} - XC_{\min}} & XC_{\min} < XC_m < XC_{\max} \\ 0 & XC_m > XC_{\max} \end{cases} \tag{5.4}$$

Where, $XC_{\min}$ and $XC_{\max}$ are the lower and upper limits of $XC_m$ index, correspondingly. To compute the $XC_{\min}$ and $XC_{\max}$, consider both the best and worst system configuration of the operating cost. $C_m$ for system's best configuration is the least value of the operating cost and for the system's worst configuration is anticipated to be equal to the operating cost of the initial configuration.

## 5.2.2. Reliability optimization

The crucial principle for the optimal operation of any distribution network is the operational reliability. For the optimization process, the operational reliability is considered. The reliability is calibrated by computing failure cost. The interruption of the customer's activity is occurring by the service disruption to every customer. The total service interruption duration function is represented as Customer Interruption Cost (CIC) that boosts with time. Here Customer Interruption Cost is the measured cost averaged through time. Let the m th bus is being supplied power by the link, which is the nth element of the system. Let $\lambda_n$ failures/year be the average failure rate of the nth element of the system and $r_n$ minutes/year taken as "average failure duration" acknowledging records for considerable years. If $L_m$ is the load of the m th bus, the "Cost of Service Interruption" for the consumer at the same bus is expressed by Equation (5.5).

$$IC_m^n = L_m \times \lambda_n \times r_n \times CIC(r_m) \tag{5.5}$$

In Equation (5.5), $r_m$ is the entire service break period at the $m^{th}$ bus seeing all the other breaks, which will be described later. The load is considered as the set of elements that are supplied to the mth bus. The indices generate a set k (m). Using Equation (5.6) "total interruption cost" for a service break at the same bus can be computed.

$$IC_m = \sum_{n \in k(m)} IC_m^n = \sum_{n \in k(m)} L_m \times \lambda_n \times r_n \times CIC(r_m) \tag{5.6}$$

Rearranging Equation (5.6),

$$IC_m = L_m \left[ \sum_{n \in k(m)} \lambda_n \times r_n \right] \times CIC(r_m) = L_m \left[ \sum_{n \in k(m)} \lambda_n \right] \frac{\sum_{n \in k(m)} \lambda_n \times r_n}{\sum_{n \in k(m)} \lambda_n} \times CIC(r_m) \tag{5.7}$$

Defining $\lambda_m = \left[ \sum_{n \in k(m)} \lambda_n \right]$ and $r_m = \frac{\sum_{n \in k(m)} \lambda_n \times r_n}{\sum_{n \in k(m)} \lambda_n}$

$\lambda_m$ represents "average interruption rate" and $r_m$ represents "average interruption duration" those are foreseen by a consumer at the m th bus contemplating the failures of all components those committed to "service interruption" on the same bus. $IC_m$ in Equation (5.7) is known as "value-based reliability index", which assessed by probabilistic study, probable financial loss in a year through the service break at the same bus. For a specific configuration "Total Interruption Cost (TIC)" can be expressed by Equation (5.8).

$$TIC = \sum_{m=2}^{N} IC_m \tag{5.8}$$

Where N is the total number of buses.

The total interruption cost index can be computed by Equation (5.9).

$$XT_m = \frac{TIC_m}{TIC_0} \tag{5.9}$$

Where $TIC_0$ indicates the initial total interruption cost before reconfiguration and $TIC_m$ indicates the total interruption cost after reconfiguration in the mth system. The fuzzy satisfaction degree for the total interruption costs is computed by exploiting the membership function as represented by the fuzzy domain, which is represented by Equation (5.10).

$$\lambda T_m = \begin{cases} 1 & XT_m < XT_{\min} \\ \dfrac{XT_{\max} - XT_m}{XT_{\max} - XT_{\min}} & XT_{\min} < XT_m < XT_{\max} \\ 0 & XT_m > XT_{\max} \end{cases} \tag{5.10}$$

Where, $XT_{\min}$ and $XT_{\max}$ are the lower and upper limits of $XT_m$ index, correspondingly. To compute the $XT_{\min}$ and $XT_{\max}$, consider both the best and worst system configuration of the operating cost. $T_m$ is the minimum value of the entire interruption cost for the best system configuration and for the worst system configuration it is anticipated to be equal to the total interruption cost of the initial configuration. Finally, for reconfiguration in a deregulated environment, there are two objectives, namely, optimize “operational cost minimization and operational reliability maximization” obtained by curtailing TIC of customer after merging two objectives as given in Equation (5.11).

$$\lambda F_{Dm} = \left(\lambda C_m \times \lambda T_m\right)^{1/3} \tag{5.11}$$

Equation (5.11) is regarded as the “fitness function” to be maximized through the process of optimization so that the best well-matched configuration in the deregulated environment is obtained. The optimal network reconfiguration at deregulated environment is obtained by the established “Fuzzy-Firefly algorithm” for the regulated environment as presented in **Chapter 4**.

## 5.3. Simulation results and discussion

In this work reconfigured network for 25-node unbalanced distribution network in deregulated environment is achieved. Equipment failure data in deregulated environment is given in Table 5.1 (Chandramohan ***et al.*** (2010)) and “the customer interruption cost” in \$ per minute per kW are given in Table 5.2 (Chandramohan ***et al.*** (2010)) and $K_1$ = 5\$/kW and $K_2$ =2 \$/kVAr (Chandramohan ***et al.*** (2010)), respectively and the customers considered are of commercial type load.

**Table 5.1:** Equipment failure data in deregulated environment

| **Equipment** | **Failure rate (failure/year)** | **Failure duration (min/failure)** |
|---|---|---|
| Cable | $3.0\times10^{-5}$/m | 150 |
| Elbow | $6.0\times10^{-4}$ | 110 |
| Fuse | $3.7\times10^{-3}$ | 50 |
| Fault Interrupter | $5.0\times10^{-3}$ | 100 |
| Overhead line | $6.0\times10^{-5}$/m | 100 |
| Splice | $6.0\times10^{-4}$ | 200 |
| Switch | $4.0\times10^{-3}$ | 60 |
| Transformer | $2.0\times10^{-3}$ | 160 |

**Table 5.2**: Customer interruption rates in C$/min/kW

| **Duration** | **Commercial load** |
|---|---|
| 1 | 0.492 |
| 20 | 0.259 |
| 60 | 0.253 |
| 240 | 0.241 |
| 480 | 0.284 |

### 5.3.1 Reconfiguration of 25-node unbalanced distribution network in deregulated environment

The 25-node unbalanced distribution network is reconfigured in the deregulated environment using fuzzy firefly algorithm as discussed in **Section 4.3 (Chapter 4)** and the final configuration is shown in Figure 5.1. The simulation results of this network before and after network reconfiguration is shown in Table 5.3. The voltage levels in the deregulated environment before and after network reconfiguration are shown in Table 5.4. Figure 5.2 shows the representation of voltage levels of base and reconfigured networks for the Phases A, B and C respectively. It is found that the voltage level has been improved after network reconfiguration.

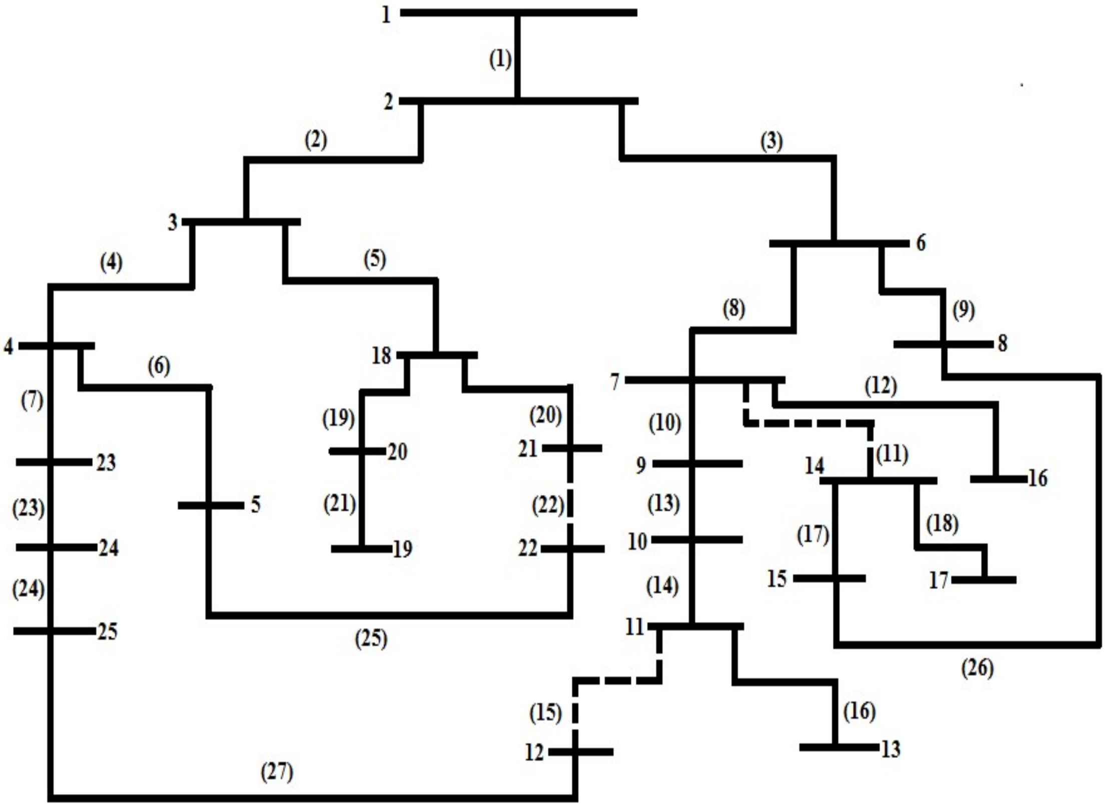


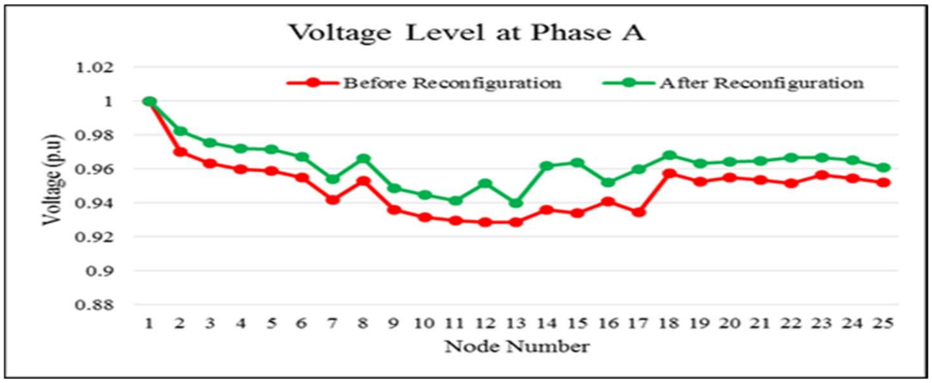
**Figure 5.1:** 25-node reconfigured unbalanced distribution network in deregulated environment

**Table 5.3:** Results for 25-node unbalanced distribution network before and after network reconfiguration in deregulated environment

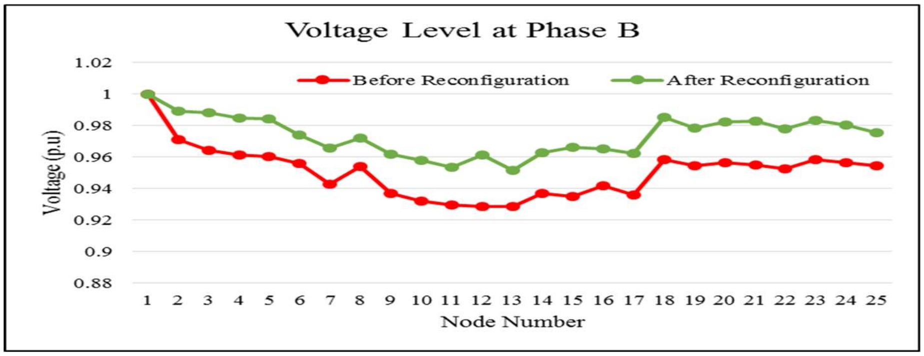
| Parameters | Before Reconfiguration | | | After Reconfiguration | | |
|---|---|---|---|---|---|---|
| | Phase | | | Phase | | |
| | **A** | **B** | **C** | **A** | **B** | **C** |
| Real Power Loss (kW) | 52.92 | 54.44 | 43.97 | 29.34 | 32.025 | 25.87 |
| Reactive Power Loss (kVAr) | 60.43 | 52.32 | 55.87 | 50.21 | 42.78 | 45.29 |
| Operating Cost (C$) | 8355.080 | | | 4816.331 | | |
| Total Interruption Cost (C$) | 102.90 | | | 46.29 | | |
| Switches Opened | 25, 26, 27 | | | 11, 15, 22 | | |
| Energy Cost ($/kWh) | 79539.048 | | | 45850.716 | | |

**Table 5.4:** Voltage levels of 25-node unbalanced distribution network obtained before and after network reconfiguration in deregulated environment

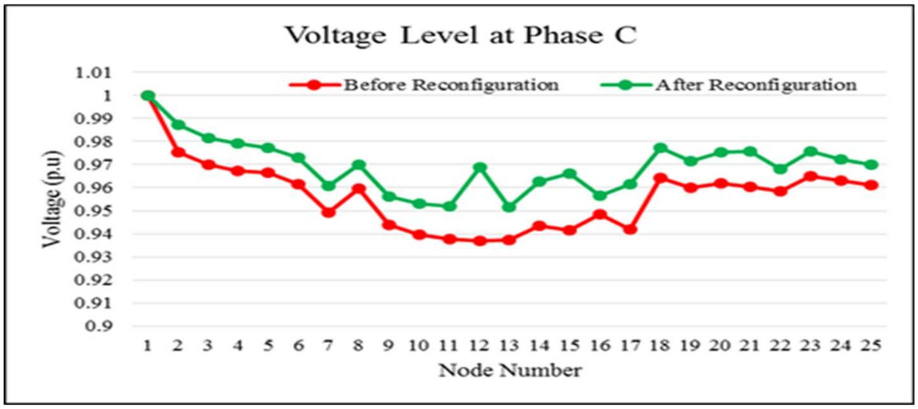
| Node No. | Voltage Levels (p.u.) | | | | | |
|---|---|---|---|---|---|---|
| | Base Network | | | Reconfigured Network | | |
| | Phase A | Phase B | Phase C | Phase A | Phase B | Phase C |
| 1 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 |
| 2 | 0.9702 | 0.9711 | 0.9755 | 0.9824 | 0.9893 | 0.9871 |
| 3 | 0.9632 | 0.9644 | 0.9698 | 0.9754 | 0.9880 | 0.9814 |
| 4 | 0.9598 | 0.9613 | 0.9674 | 0.9720 | 0.9849 | 0.9790 |
| 5 | 0.9587 | 0.9603 | 0.9664 | 0.9717 | 0.9844 | 0.9771 |
| 6 | 0.9550 | 0.9559 | 0.9615 | 0.9672 | 0.9741 | 0.9731 |
| 7 | 0.9419 | 0.9428 | 0.9492 | 0.9541 | 0.9659 | 0.9607 |
| 8 | 0.9529 | 0.9538 | 0.9596 | 0.9661 | 0.9722 | 0.9701 |
| 9 | 0.9359 | 0.9367 | 0.9438 | 0.9487 | 0.9618 | 0.9563 |
| 10 | 0.9315 | 0.9319 | 0.9395 | 0.9447 | 0.9580 | 0.9530 |
| 11 | 0.9294 | 0.9296 | 0.9376 | 0.9415 | 0.9534 | 0.9520 |
| 12 | 0.9285 | 0.9287 | 0.9369 | 0.9515 | 0.9612 | 0.9688 |
| 13 | 0.9287 | 0.9287 | 0.9373 | 0.9399 | 0.9516 | 0.9514 |
| 14 | 0.9359 | 0.9370 | 0.9434 | 0.9621 | 0.9629 | 0.9628 |
| 15 | 0.9338 | 0.9349 | 0.9414 | 0.9640 | 0.9661 | 0.9661 |
| 16 | 0.9408 | 0.9418 | 0.9483 | 0.9500 | 0.9655 | 0.9565 |
| 17 | 0.9347 | 0.9360 | 0.9420 | 0.9598 | 0.9624 | 0.9614 |
| 18 | 0.9573 | 0.9586 | 0.9643 | 0.9681 | 0.9851 | 0.9771 |
| 19 | 0.9524 | 0.9544 | 0.9600 | 0.9633 | 0.9784 | 0.9714 |
| 20 | 0.9548 | 0.9563 | 0.9620 | 0.9645 | 0.9824 | 0.9754 |
| 21 | 0.9537 | 0.9549 | 0.9605 | 0.9647 | 0.9830 | 0.9759 |
| 22 | 0.9518 | 0.9525 | 0.9585 | 0.9668 | 0.9778 | 0.9681 |
| 23 | 0.9565 | 0.9584 | 0.9648 | 0.9667 | 0.9831 | 0.9759 |
| 24 | 0.9544 | 0.9565 | 0.9631 | 0.9655 | 0.9803 | 0.9724 |
| 25 | 0.9520 | 0.9547 | 0.9612 | 0.9611 | 0.9753 | 0.9698 |



(a) Voltage level at Phase A



(b) Voltage level at Phase B



(c)Voltage level at Phase C

**Figure 5.2:** Voltage levels at three phases of 25-node unbalanced distribution network before and after network reconfiguration in deregulated environment

### 5.3.2 Integration of DG and Capacitor in 25-node unbalanced reconfigured distribution network in deregulated environment

The DG and capacitor are being integrated into the reconfigured network in a deregulated environment to reduce the losses further. The results before and after the integration of DG and capacitor in the reconfigured network are shown in Table 5.5. The voltage levels, before and after integration of DG and capacitor are shown in Table 5.6.

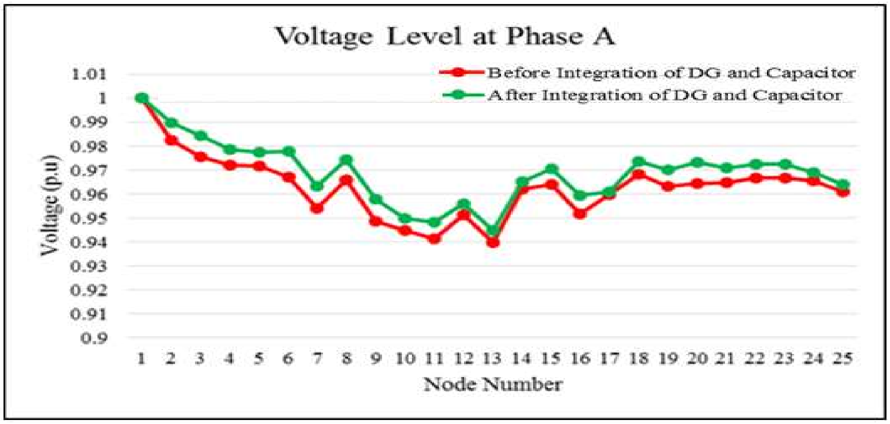
Figure 5.3 shows the representation of voltage levels of the Phases A, B and C respectively before and after integration of DG and capacitor in the reconfigured network.

**Table 5.5:** Results obtained after integration of DG and capacitor in 25-node reconfigured unbalanced distribution network in deregulated environment

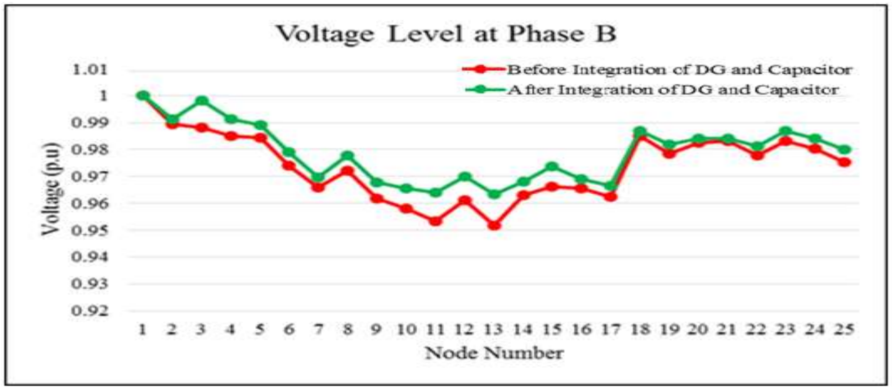
| Parameters | Before integration | | | After integration | | |
|---|---|---|---|---|---|---|
| | Phase | | | Phase | | |
| | A | B | C | A | B | C |
| Real Power Loss (kW) | 29.34 | 32.025 | 25.87 | 19.6 | 20.99 | 16.42 |
| Reactive Power Loss (kVAr) | 50.21 | 42.78 | 45.29 | 30.24 | 23.41 | 24.87 |
| Minimum Voltage (p.u.) | 0.9399 | 0.9516 | 0.9514 | 0.9449 (13) | 0.9632 (13) | 0.9612 (13) |
| Switches Opened | 11, 15, 22 | | | - | | |
| DG Location | - | - | - | 12 | 12 | 12 |
| DG Size (kW) | - | - | - | 185 | 185 | 185 |
| Capacitor Location | - | - | - | 8 | 8 | 8 |
| Capacitor Size (kVAr) | - | - | - | 190 | 190 | 190 |
| Energy Cost ($/kWh) | 45850.716 | | | 29964.456 | | |

**Table 5.6:** Voltage levels before and after Integration of DG and capacitor in 25-node reconfigured unbalanced distribution network in deregulated environment

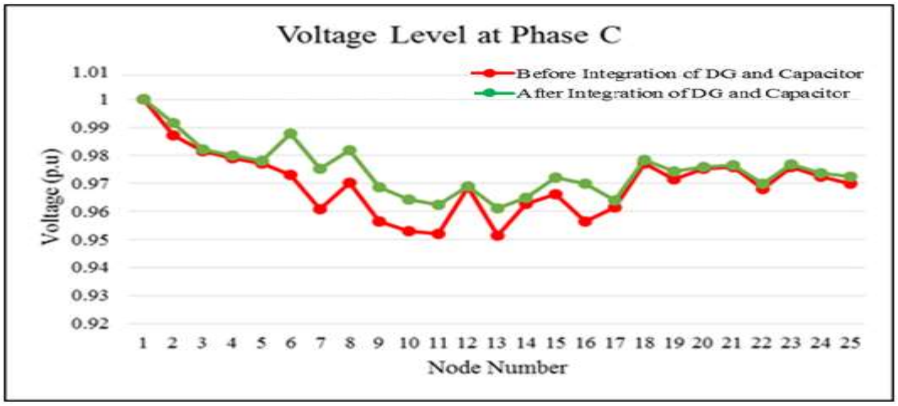
| Node No. | Voltage Levels (p.u.) | | | | | |
|---|---|---|---|---|---|---|
| | Before Integration | | | After Integration | | |
| | Phase A | Phase B | Phase C | Phase A | Phase B | Phase C |
| 1 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 |
| 2 | 0.9824 | 0.9893 | 0.9871 | 0.9899 | 0.9912 | 0.9915 |
| 3 | 0.9754 | 0.9880 | 0.9814 | 0.9843 | 0.9982 | 0.9822 |
| 4 | 0.9720 | 0.9849 | 0.9790 | 0.9785 | 0.9912 | 0.9799 |
| 5 | 0.9717 | 0.9844 | 0.9771 | 0.9773 | 0.9891 | 0.9782 |
| 6 | 0.9672 | 0.9741 | 0.9731 | 0.9777 | 0.9789 | 0.9877 |
| 7 | 0.9541 | 0.9659 | 0.9607 | 0.9631 | 0.9697 | 0.9753 |
| 8 | 0.9661 | 0.9722 | 0.9701 | 0.9745 | 0.9779 | 0.9817 |
| 9 | 0.9487 | 0.9618 | 0.9563 | 0.9577 | 0.9676 | 0.9687 |
| 10 | 0.9447 | 0.9580 | 0.9530 | 0.9497 | 0.9656 | 0.9644 |
| 11 | 0.9415 | 0.9534 | 0.9520 | 0.9481 | 0.9641 | 0.9624 |
| 12 | 0.9515 | 0.9612 | 0.9688 | 0.9559 | 0.9698 | 0.9690 |
| 13 | 0.9399 | 0.9516 | 0.9514 | 0.9449 | 0.9632 | 0.9612 |
| 14 | 0.9621 | 0.9629 | 0.9628 | 0.9653 | 0.9680 | 0.9648 |
| 15 | 0.9640 | 0.9661 | 0.9661 | 0.9705 | 0.9738 | 0.9721 |
| 16 | 0.9519 | 0.9655 | 0.9565 | 0.9595 | 0.9689 | 0.9699 |
| 17 | 0.9598 | 0.9624 | 0.9614 | 0.9611 | 0.9665 | 0.9640 |
| 18 | 0.9681 | 0.9851 | 0.9771 | 0.9737 | 0.9870 | 0.9785 |
| 19 | 0.9633 | 0.9784 | 0.9714 | 0.9701 | 0.9819 | 0.9742 |
| 20 | 0.9645 | 0.9824 | 0.9754 | 0.9731 | 0.9839 | 0.9759 |
| 21 | 0.9647 | 0.9830 | 0.9759 | 0.9711 | 0.9841 | 0.9764 |
| 22 | 0.9668 | 0.9778 | 0.9681 | 0.9724 | 0.9811 | 0.9699 |
| 23 | 0.9667 | 0.9831 | 0.9759 | 0.9725 | 0.9869 | 0.9769 |
| 24 | 0.9655 | 0.9803 | 0.9724 | 0.9689 | 0.9842 | 0.9738 |
| 25 | 0.9611 | 0.9753 | 0.9698 | 0.9642 | 0.9799 | 0.9724 |



(a) Voltage level at Phase A



(b) Voltage level at Phase B



(c)Voltage level at Phase C

**Figure 5.3:** Voltage levels before and after integration of DG and capacitor in 25-node unbalanced reconfigured network in deregulated environment

## 5.4 Conclusion

In this chapter we have presented minimizing the distribution network losses in three-phase unbalanced radial distribution network in deregulated environment. It is found that network reconfiguration reduces the losses of the network and optimal placement of DG and capacitor in reconfigured network further reduces the losses occurring in the system. The reconfiguration is performed using fuzzy firefly algorithm as utilized in Chapter 4 for regulated environment and DG and Capacitor placement is achieved using LSF and BFOA. The suggested method is implemented on MATLAB platform and tested on a 25-node unbalanced distribution network. The results achieved by the suggested method are effective and promising.

# CHAPTER-6: LOSS ALLOCATION OF UNBALANCED RADIAL DISTRIBUTION NETWORK IN REGULATED AND DEREGULATED ENVIRONMENT

## 6.1. Introduction

In regulated environment the customers have to pay the set price as established by the utility company. In this environment the power-flow from the generation to consumer meter is entirely controlled by the vertically integrated utility. Recently the power system has encountered real changes and has also been operating in a deregulated environment. The vertically coordinated systems are being rebuilt and unbundled into generation, transmission; and distribution entities. In this environment, customers will get reliable services, more choices and need to pay less amount for consumption of electricity in the competitive market. In addition to these, privatization and functional separation of existing power system entities are the stands behind the causes of deregulated power industry (Srivastava ***et al.*** (2011)). In this new environment, the traditional centralized system is lost and leads to the formation of new companies participating in the generation. This made the generating companies more dependent on decision-making tools for the analysis of all possible investment and selling options in the present competitive environment (Pereira and Saraiva (2010)).

In the present era, deregulation of power system anticipated to interrupt the energy market's traditional sheer unified organization into dispersed bodies with generators contending for trading through conjoint transmission lines to confine distribution channels. In this kind of structure, there will arise competition among generating companies to supply more than one service distributor. Therefore, the generating entity vending electrical energy at the lowest price would have maximum number of customers. In energy market, deeds of transmission and distribution are largely deliberated as an expected domination. The price of transmission and distribution actions necessities to be assigned to the consumers of these systems. Division can be prepared through system use pricelists, by an attention on the factual influence they have on these prices. Amongst others, distribution network power losses are one of the losses to be allocated. The foremost effort challenged in assigning losses is the nonlinearity between the losses and delivered power, which confounds the effect of every consumer on distribution network losses **(**Savier and Das (2012)**).**

Loss allocation refer to the expenditures linked with losses to distinct customers of the distribution network. Loss division does not disturb power-flows. It is about dispersal of returns and expenses between contractors and customers. Accordingly, loss allocation must not be confused with loss supply. Supply of losses is a mechanism by which the system losses are created when these are not accounted for throughout the unique supply and this amenity deviates the system variables. The network losses are recognized from the state of the system and these are alienated by means of some standards among the contributors. Various loss allocation schemes emerged in literature as discussed in **Chapter 2 (Section 2.4)** from the desire to establish fair criteria for loss allocation.

In this chapter we are presenting the loss allocation of unbalanced radial distribution network using fuzzy-firefly algorithm. Also, in the present-day distribution network an intriguing issue identified with DG is the loss allocation (LA) issue that turns out to be essential to the presentation of utility rivalry (Carpaneto ***et al.*** (2008)). Therefore, a loss allocation method by integrating DG and capacitor in the reconfigured network is formulated.

## 6.2. Loss allocation in unbalanced distribution networks

The three phase currents are recognized by $\overline{I}_A, \overline{I}_B$ and $\overline{I}_C$, however, $\overline{I}_n$ is the neutral current. For the purpose of notation, the vector $i = \left[\overline{I}_A \quad \overline{I}_B \quad \overline{I}_C\right]^T$ is the phase current vector, and the vector $v_k = \left[\overline{V}_{k,A} \quad \overline{V}_{k,B} \quad \overline{V}_{k,C}\right]$ includes the complex voltages in the phase terminals of the genetic node k. The total losses can be computed as the sum of losses due to each physical current path

$$\Delta P_{Total} = R_A I_A^2 + R_B I_B^2 + R_C I_C^2 + R_n I_n^2 \tag{6.1}$$

Or utilizing the $4\times4$ primitive impedance matrix Zprime .

$$\Delta P_{Total} = \text{Real}\left\{ \begin{bmatrix} \overline{I}_A & \overline{I}_B & \overline{I}_C & \overline{I}_n \end{bmatrix} Z_{prim} \begin{bmatrix} \overline{I}_A^* \\ \overline{I}_B^* \\ \overline{I}_C^* \\ \overline{I}_n^* \end{bmatrix} \right\} \tag{6.2}$$

Or utilizing the 3×3 primitive impedance matrix $Z_{ABC}$

$$\Delta P_{Total} = \text{Real}\left\{ i^T Z_{ABC} i^* \right\} \tag{6.3}$$

According to the impedances matrix symmetry, Equation (6.2) can be altered applying the real part operator only to the impedance in order to extract its resistive components. The overall branch losses can be computed through the real part of impedance matrix $Z_{ABC}$.

$$R_{ABC} = \text{Real}\left\{ Z_{ABC} \right\} \tag{6.4}$$

$$\Delta P_{Total} = i^T \, \text{Re}al\left\{ Z_{ABC} \right\} i^* = i^T R_{ABC} i^* \tag{6.5}$$

The formulation of Equation (6.2) leads to the loss partitioning. Here it is suggested to estimate the loss partitioning by utilizing Equation (6.5). By representing with ⊗ the component by-component vector product, the loss partition vector $\Delta p = \begin{bmatrix} \Delta P_A & \Delta P_B & \Delta P_C \end{bmatrix}$ denoted to three phases a, b and c in the equivalent $3 \times 3$ matrix representation of the branch is considered as below.

$$\Delta p = \text{Real}\left\{ i \otimes \left( R_{ABC} i^* \right) \right\} \tag{6.6}$$

The total loss $\Delta P_{Total}$ in Equation (6.5) corresponds to the sum of the components of the vector Δp. The real part operator is required in Equation (6.6) because of the effect of the off-diagonal components of the matrix $R_{ABC}$. It is no longer needed in Equation (6.5), as all the imaginary parts are mutually compensated in the sum.

## 6.3. Proposed methodology for loss allocation in unbalanced distribution network

The formations of unbalanced distribution networks might be changed with manual or programmed switching application in order to decrease power loss, expand network security, and improve power quality. Despite the fact that the principal mission of network reconfiguration is to decline the losses of the system in a deregulated environment, the reconfiguration deliberates the objectives identified with expanding the benefits of an organization, for example, operational cost minimization and reliability maximization. Likewise, in the deregulated environment, the losses are assigned to various purchasers in the network. In this work, the effect of network reconfiguration, the integration of DG and capacitor in the reconfigured network; and the impact of loss allocation in unbalanced distribution networks in both the regulated and deregulated environments are presented. The network reconfiguration problem is defined as a fuzzy based multi-objective problem. For optimization of the network, the Firefly optimization algorithm is utilized, which augments the fuzzy based objective function. The proposed formulation of problem considers the following accompanying standpoints:

- Loss Allocation of 13-node unbalanced distribution network and comparison of outcomes obtained by proposed method and that of by Carpaneto ***et al.*** (2008).
- Loss Allocation of base network (25-node unbalanced distribution network) and its reconfigured network in regulated environment.
- Loss Allocation of the network after placement of DG and capacitor in the reconfigured network.

The above steps are also carried for deregulated environment. Network reconfiguration in the deregulated environment using the established Fuzzy-Firefly algorithm is carried out in **Chapter 5.** Loss Allocation is also done for reconfigured network integrated with the DG and capacitor. The details of Firefly algorithm and different aspects related to DGs and capacitor placement are discussed in **Chapter 4.** The well-established optimization equations available in ((Billinton and Billinton (1989), Allan ***et al***. (1991), Chen ***et al.*** (1994)) used by Chandramohan ***et al.*** (2010) also have been used in unbalanced systems. The same optimization algorithm i.e., Firefly has been used to obtain the loss allocation.

## 6.4. Outcomes and discussion

In this section, the efficiency of the suggested algorithm is tested. In MATLAB working platform the proposed method of loss allocation is implemented on 13-node unbalanced distribution network at first to check its performance compared to other existing technique and then finally implemented on 25-node unbalanced distribution network. The system has the following configuration:

Windows 8, 4 GB RAM, Intel Core i3-3210 Processor, 3.19 GHz frequency, MATLAB 2013a

### 6.4.1 Loss allocation in 13-node unbalanced distribution network

The proposed method of loss allocation is implemented on IEEE 13-node unbalanced distribution network. The network configuration is shown in Figure 6.1 and other parameters are available in Carpaneto ***et al.*** (2008) and IEEE/PES Distribution System Analysis Subcommittee, Radial Test Feeders. The detailed data of this system has been presented in **Appendix-C.** Table 6.1 shows the outcomes obtained by the proposed method and that of by Carpaneto ***et al.*** (2008). The proposed method gives the loss allocation in more uniform way as compared to (Carpaneto ***et al.*** (2008)).

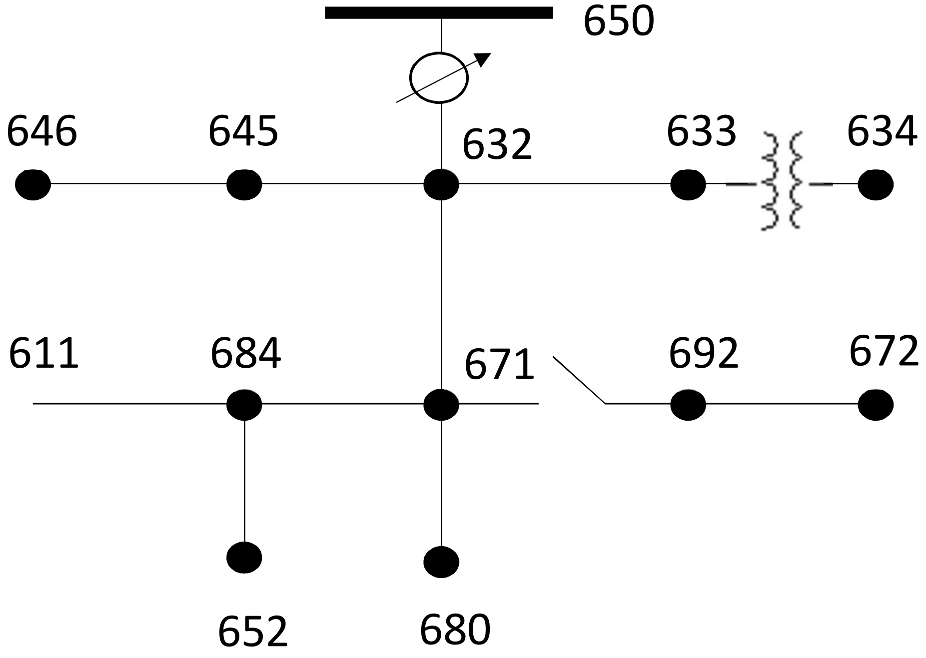


**Figure 6.1:** IEEE 13-node test feeder

**Table 6.1:** Loss Allocation obtained by proposed method and by the method (Carpaneto ***et al.*** (2008))

| Branch No. | Branch Losses (kW) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Method (Carpaneto *et al.* (2008)) | | | | Proposed Method | | | Total Losses (kW) |
| | Phase | | | Total Losses (kW) | Phase | | | |
| | A | B | C | | A | B | C | |
| 632 | 17.912 | 4.787 | 18.38 | 41.079 | 17.51 | 4.521 | 17.45 | 39.481 |
| 633 | 0.401 | 0.195 | 0.218 | 0.814 | 0.385 | 0.21 | 0.234 | 0.829 |
| 634 | 2.542 | 1.408 | 1.531 | 5.481 | 2.539 | 1.502 | 1.529 | 5.57 |
| 645 | -- | 2.389 | 0.36 | 2.749 | -- | 2.44 | 0.39 | 2.83 |
| 656 | -- | 0.27 | 0.269 | 0.539 | -- | 0.26 | 0.271 | 0.531 |
| 671 | 13.624 | -0.195 | 9.481 | 22.91 | 13.645 | -0.186 | 10.338 | 23.797 |
| 680 | 0.502 | 0.251 | 0.085 | 0.838 | 0.502 | 0.342 | 0.185 | 1.029 |
| 684 | 0.304 | -- | -- | 0.304 | 0.306 | -- | -- | 0.306 |
| 611 | 0 | -- | -- | -- | 0 | -- | -- | 0 |
| 652 | 0 | -- | 0 | -- | 0 | -- | 0 | 0 |
| 692 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 675 | 3.144 | 0.397 | 0.606 | 4.147 | 3.542 | 0.413 | 0.533 | 4.488 |
| Total Losses (kW) | 38.429 | 9.502 | 30.93 | 78.861 | 38.429 | 9.502 | 30.93 | 78.861 |

### 6.4.2. Loss allocation in 25-node unbalanced distribution network in regulated environment

A 25-node unbalanced distribution network is considered as a common test case having **4.16 kV** and **30 MVA** as base values. It consists of switches with 3 tie lines and the total load is 3.239 + j2.393 MVA. Initial configuration of the network and final configuration after network reconfiguration is shown in Figure 6.2 and Figure 6.3 respectively. The detailed results for the base case and after network reconfiguration in regulated environment and result for before and after DG and capacitor integration are available in **Chapter 4**. The Loss Allocation to each consumer for base network and reconfigured network of 25-node unbalanced distribution network in a regulated environment are given in Table 6.2.

The DG and capacitor are integrated to the reconfigured unbalanced distribution network and the outcomes have been presented in **Table 4.10 (Chapter 4)**. The results of Loss Allocation (24 branches) before and after integration of DG and capacitor in the reconfigured network are shown in Table 6.3. Figure 6.4 shows the loss allocation of the Phases A, B and C respectively before and after integration of DG and capacitor in the reconfigured network.

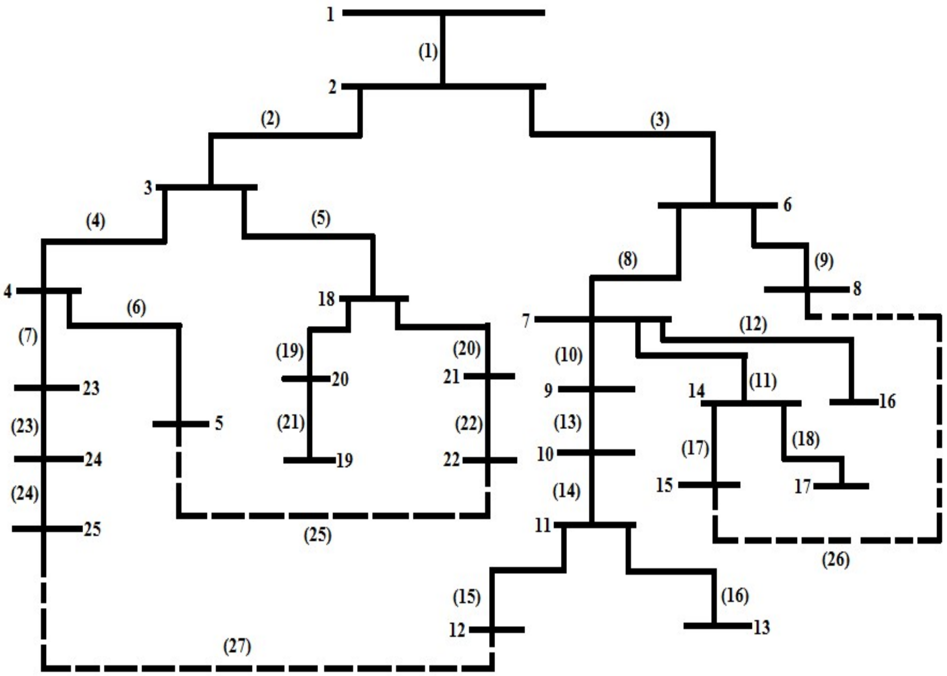


**Figure 6.2:** 25-node unbalanced distribution network

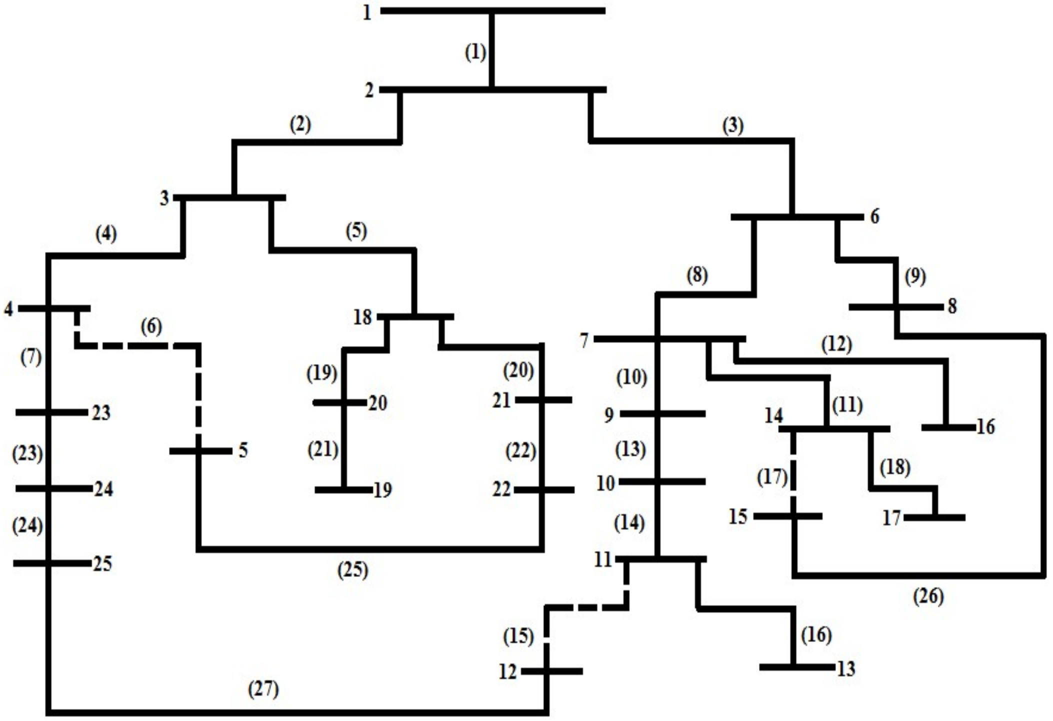


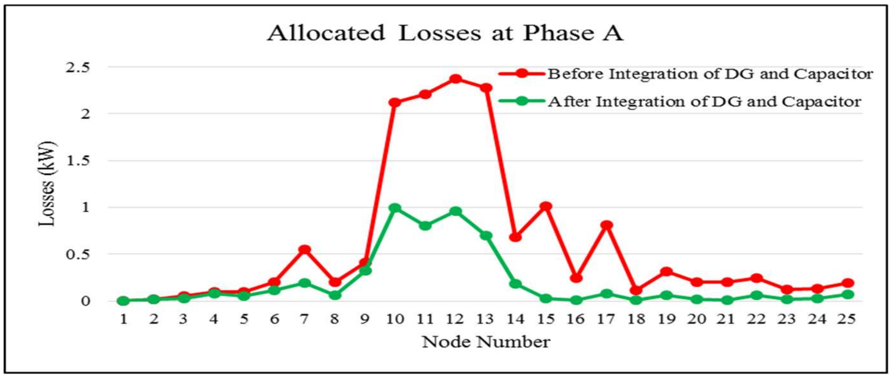
**Figure 6.3:** 25-node unbalanced reconfigured distribution network in regulated environment

**Table 6.2:** Loss Allocation to each consumer for base and reconfigured networks in regulated environment

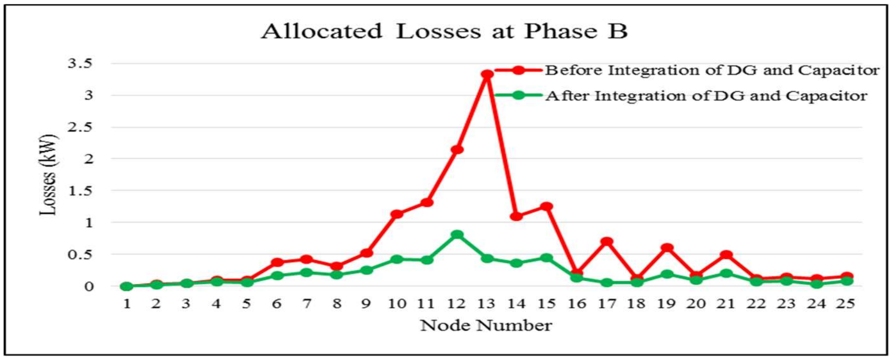
| **Branch No.** | **Loss allocated (kW)** | | | | | |
|---|---|---|---|---|---|---|
| | **Before Reconfiguration** | | | **After Reconfiguration** | | |
| | Phase A | Phase B | Phase C | Phase A | Phase B | Phase C |
| 1 | 0.02 | 0.03 | 0.009 | 0.02 | 0.03 | 0.006 |
| 2 | 0.05 | 0.04 | 0.039 | 0.05 | 0.04 | 0.021 |
| 3 | 0.10 | 0.10 | 0.06 | 0.10 | 0.09 | 0.04 |
| 4 | 0.12 | 0.12 | 0.07 | 0.10 | 0.10 | 0.07 |
| 5 | 0.21 | 0.40 | 0.26 | 0.20 | 0.38 | 0.11 |
| 6 | 0.87 | 1.51 | 1.60 | 0.55 | 0.43 | 0.38 |
| 7 | 0.21 | 0.60 | 0.92 | 0.20 | 0.31 | 0.21 |
| 8 | 2.48 | 2.87 | 1.78 | 0.41 | 0.52 | 1.08 |
| 9 | 6.8 | 4.47 | 4.12 | 2.12 | 1.13 | 1.1 |
| 10 | 7.68 | 5.38 | 5.80 | 2.21 | 1.32 | 1.01 |
| 11 | 9.76 | 12.30 | 9.52 | 2.37 | 2.14 | 1.27 |
| 12 | 7.88 | 7.44 | 6.962 | 2.28 | 3.33 | 2.10 |
| 13 | 2.41 | 2.79 | 2.81 | 0.68 | 1.10 | 0.52 |
| 14 | 5.01 | 5.10 | 3.12 | 1.01 | 1.26 | 0.62 |
| 15 | 2.02 | 3.01 | 1.52 | 0.24 | 0.20 | 0.43 |
| 16 | 4.82 | 4.14 | 3.01 | 0.81 | 0.71 | 0.27 |
| 17 | 0.14 | 0.20 | 0.08 | 0.11 | 0.12 | 0.02 |
| 18 | 0.38 | 0.82 | 0.30 | 0.31 | 0.61 | 0.11 |
| 19 | 0.30 | 0.38 | 0.19 | 0.20 | 0.17 | 0.12 |
| 20 | 0.31 | 0.51 | 0.29 | 0.20 | 0.50 | 0.08 |
| 21 | 0.61 | 1.02 | 1.10 | 0.24 | 0.12 | 0.04 |
| 22 | 0.14 | 0.26 | 0.08 | 0.12 | 0.14 | 0.07 |
| 23 | 0.18 | 0.34 | 0.09 | 0.13 | 0.12 | 0.03 |
| 24 | 0.42 | 0.61 | 0.24 | 0.19 | 0.16 | 0.05 |

**Table 6.3:** Loss Allocation before and after integration of DG and capacitor in reconfigured network in regulated environment

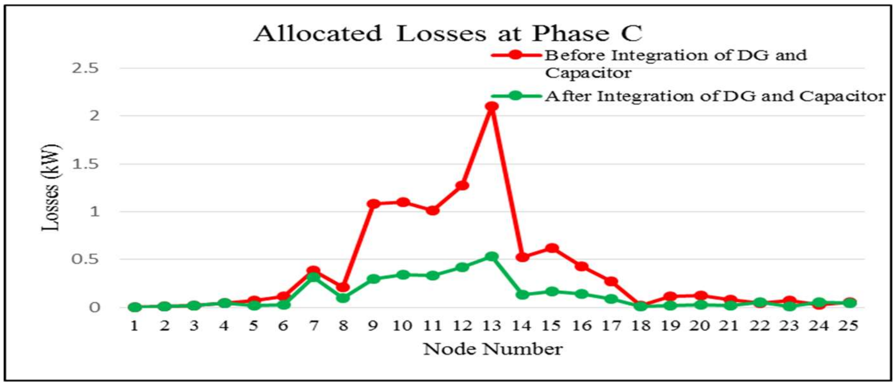
| Branch No. | Loss allocated (kW) | | | | | |
|---|---|---|---|---|---|---|
| | Before Integration | | | After Integration | | |
| | Phase A | Phase B | Phase C | Phase A | Phase B | Phase C |
| 1 | 0.02 | 0.03 | 0.006 | 0.02 | 0.02 | 0.005 |
| 2 | 0.05 | 0.04 | 0.021 | 0.03 | 0.04 | 0.015 |
| 3 | 0.10 | 0.09 | 0.04 | 0.08 | 0.07 | 0.04 |
| 4 | 0.10 | 0.10 | 0.07 | 0.05 | 0.06 | 0.02 |
| 5 | 0.20 | 0.38 | 0.11 | 0.11 | 0.17 | 0.03 |
| 6 | 0.55 | 0.43 | 0.38 | 0.19 | 0.22 | 0.31 |
| 7 | 0.20 | 0.31 | 0.21 | 0.06 | 0.18 | 0.10 |
| 8 | 0.41 | 0.52 | 1.08 | 0.32 | 0.25 | 0.30 |
| 9 | 2.12 | 1.13 | 1.10 | 0.99 | 0.42 | 0.34 |
| 10 | 2.21 | 1.32 | 1.01 | 0.80 | 0.41 | 0.33 |
| 11 | 2.37 | 2.14 | 1.27 | 0.96 | 0.81 | 0.42 |
| 12 | 2.28 | 3.33 | 2.10 | 0.70 | 0.44 | 0.53 |
| 13 | 0.68 | 1.10 | 0.52 | 0.18 | 0.36 | 0.13 |
| 14 | 1.01 | 1.26 | 0.62 | 0.03 | 0.45 | 0.17 |
| 15 | 0.24 | 0.20 | 0.43 | 0.01 | 0.13 | 0.14 |
| 16 | 0.81 | 0.71 | 0.27 | 0.08 | 0.06 | 0.09 |
| 17 | 0.11 | 0.12 | 0.02 | 0.01 | 0.06 | 0.01 |
| 18 | 0.31 | 0.61 | 0.11 | 0.06 | 0.19 | 0.02 |
| 19 | 0.20 | 0.17 | 0.12 | 0.018 | 0.09 | 0.03 |
| 20 | 0.20 | 0.50 | 0.08 | 0.012 | 0.20 | 0.02 |
| 21 | 0.24 | 0.12 | 0.04 | 0.06 | 0.07 | 0.05 |
| 22 | 0.12 | 0.14 | 0.07 | 0.02 | 0.08 | 0.01 |
| 23 | 0.13 | 0.12 | 0.03 | 0.03 | 0.03 | 0.05 |
| 24 | 0.19 | 0.16 | 0.05 | 0.07 | 0.08 | 0.04 |



(a) Loss allocation at Phase A



(b) Loss allocation at Phase B



(c) Loss allocation at Phase C

**Figure 6.4:** Loss allocations in three phases of 25-node unbalanced reconfigured network before and after integration of DG and capacitor in regulated environment

### 6.4.3 Loss allocation in 25-node Unbalanced Distribution Network in Deregulated Environment

In deregulated environment data of equipment failure is shown in **Table 5.1** (Chandramohan ***et al.*** (2010)) and "the customer interruption cost" in \$ per minute per kW are given in **Table 5.2** (Chandramohan ***et al.*** (2010)) and $K_1$ = 5\$/kW and $K_2$ =2 \$/kVAr (Chandramohan ***et al.*** (2010)), respectively and the customers considered are of commercial type load. The configuration of 25-node reconfigured network in deregulated environment after reconfiguration is shown in Figure 6.5**.** The results for the base case and after network reconfiguration in deregulated environment and results for before and after DG and capacitor integration are already presented in **Chapter 5.** This configuration has 25 nodes and 24 branches. The loss allocation in the deregulated environment before and after network reconfiguration are shown in Table 6.4. Figure 6.6 shows the loss allocated base and reconfigured networks for the Phases A, B and C respectively. Since the losses are reduced after network reconfiguration, the amount of allocated loss is also reduced. In the deregulated reconfigured network, for better results DG and capacitor are integrated and results are recorded. The loss allocation in the deregulated environment before and after integration of DG and capacitor is shown in Table 6.5 respectively. Figure 6.7 shows the loss allocation of the Phases A, B and C respectively before and after integration of DG and capacitor in Figure 6.5.

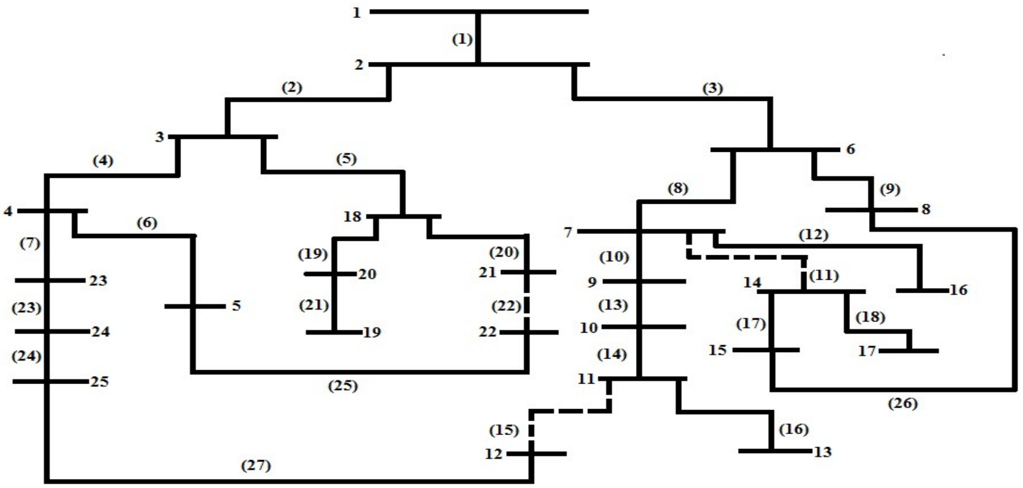
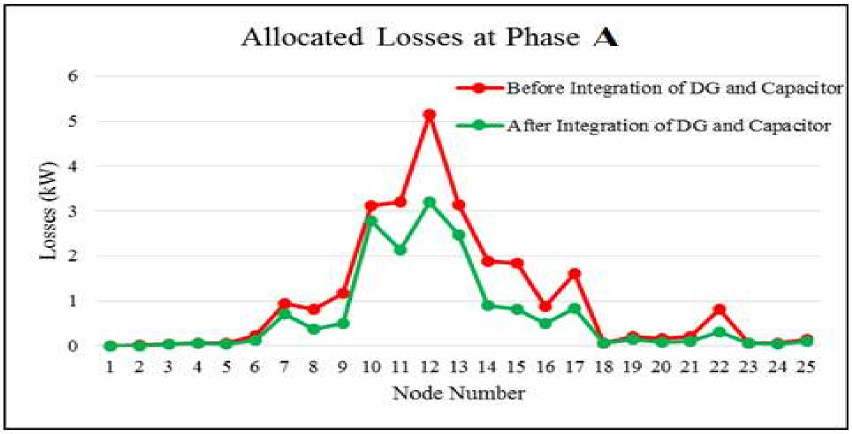


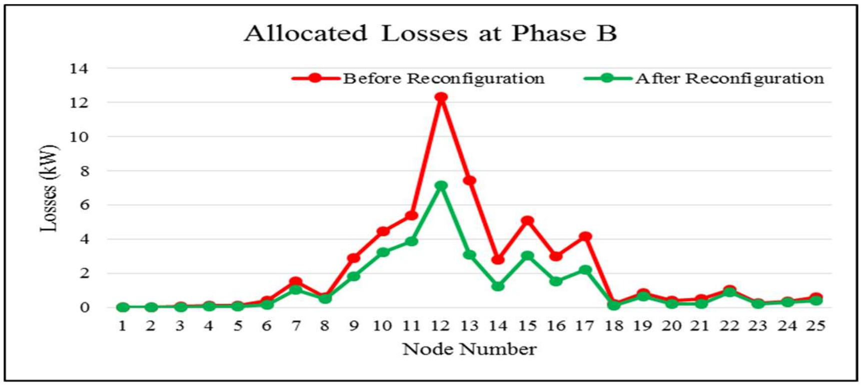
**Figure 6.5:** Reconfigured 25-node unbalanced distribution network in deregulated environment

**Table 6.4:** Loss allocations before and after network reconfiguration in deregulated environment

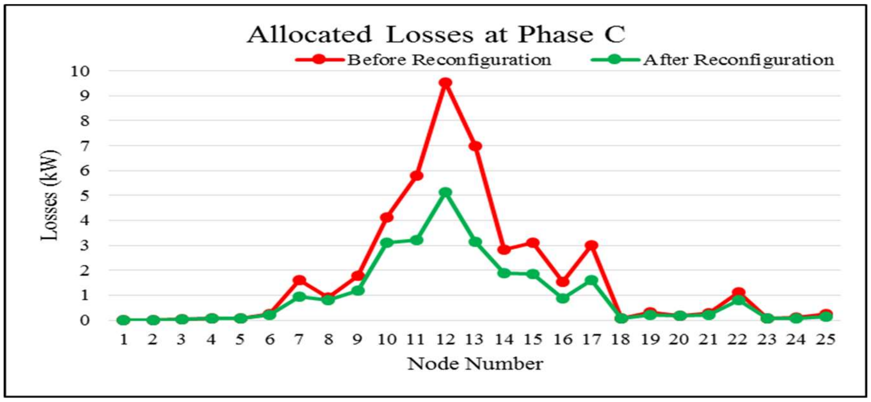
| Branch No. | Loss allocated (kW) | | | | | |
|---|---|---|---|---|---|---|
| | Base Network | | | Reconfigured Network | | |
| | Phase A | Phase B | Phase C | Phase A | Phase B | Phase C |
| 1 | 0.02 | 0.03 | 0.01 | 0.02 | 0.03 | 0.008 |
| 2 | 0.05 | 0.04 | 0.04 | 0.04 | 0.03 | 0.03 |
| 3 | 0.10 | 0.10 | 0.06 | 0.10 | 0.06 | 0.06 |
| 4 | 0.12 | 0.12 | 0.07 | 0.10 | 0.06 | 0.06 |
| 5 | 0.21 | 0.40 | 0.26 | 0.12 | 0.15 | 0.22 |
| 6 | 0.87 | 1.51 | 1.6 | 0.36 | 1.02 | 0.94 |
| 7 | 0.21 | 0.60 | 0.92 | 0.12 | 0.5 | 0.81 |
| 8 | 2.48 | 2.87 | 1.78 | 1.91 | 1.81 | 1.18 |
| 9 | 6.80 | 4.47 | 4.12 | 3.99 | 3.25 | 3.11 |
| 10 | 7.68 | 5.38 | 5.8 | 3.98 | 3.87 | 3.20 |
| 11 | 9.76 | 12.30 | 9.52 | 4.74 | 7.12 | 5.14 |
| 12 | 7.88 | 7.44 | 6.96 | 3.45 | 3.11 | 3.14 |
| 13 | 2.41 | 2.79 | 2.81 | 1.53 | 1.25 | 1.89 |
| 14 | 5.01 | 5.10 | 3.12 | 3.45 | 3.06 | 1.85 |
| 15 | 2.02 | 3.01 | 1.52 | 1.19 | 1.54 | 0.88 |
| 16 | 4.82 | 4.14 | 3.01 | 2.92 | 2.21 | 1.612 |
| 17 | 0.14 | 0.20 | 0.08 | 0.11 | 0.11 | 0.07 |
| 18 | 0.38 | 0.82 | 0.3 | 0.24 | 0.63 | 0.21 |
| 19 | 0.30 | 0.38 | 0.19 | 0.16 | 0.22 | 0.16 |
| 20 | 0.31 | 0.51 | 0.29 | 0.13 | 0.21 | 0.21 |
| 21 | 0.61 | 1.02 | 1.1 | 0.25 | 0.87 | 0.81 |
| 22 | 0.14 | 0.26 | 0.08 | 0.09 | 0.21 | 0.07 |
| 23 | 0.18 | 0.34 | 0.09 | 0.10 | 0.30 | 0.06 |
| 24 | 0.42 | 0.61 | 0.24 | 0.24 | 0.40 | 0.15 |



(a) Loss allocation at Phase A



(b) Loss allocation at Phase B

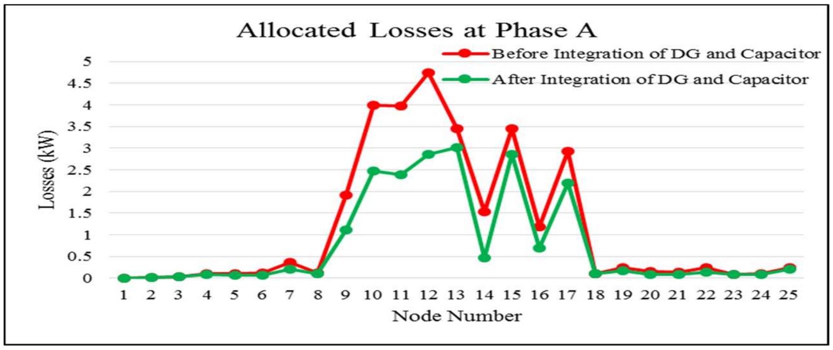


(c) Loss allocation at Phase C

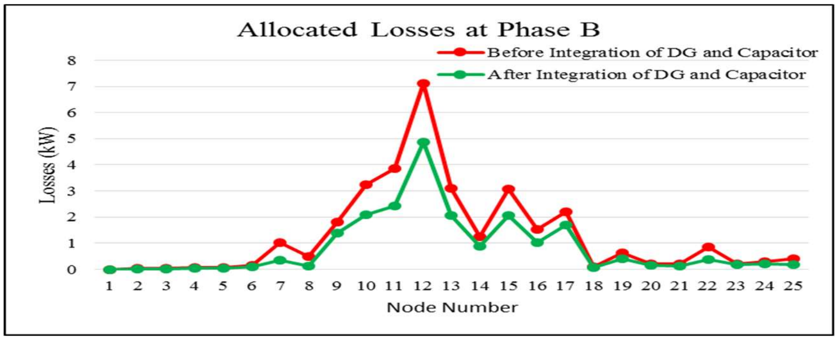
**Figure 6.6:** Loss allocations in three phases of unbalanced 25-node unbalanced distribution before and after network reconfiguration in deregulated environment

**Table 6.5:** Loss allocations before and after Integration of DG and capacitor in reconfigured network in deregulated environment

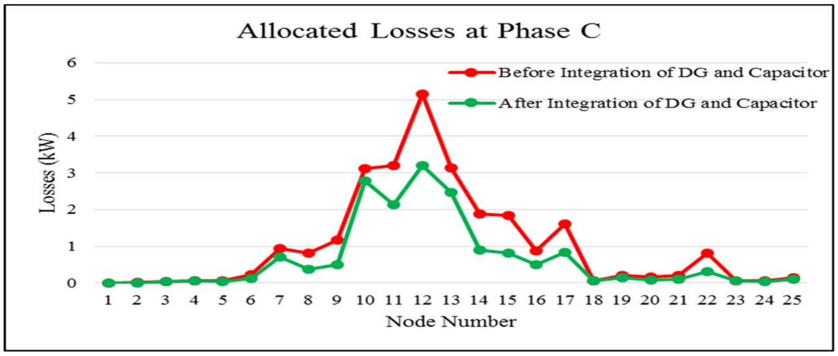
| Branch No. | Loss allocated (kW) | | | | | |
|---|---|---|---|---|---|---|
| | Before Integration | | | After Integration | | |
| | Phase A | Phase B | Phase C | Phase A | Phase B | Phase C |
| 1 | 0.02 | 0.03 | 0.008 | 0.02 | 0.02 | 0.003 |
| 2 | 0.04 | 0.03 | 0.03 | 0.03 | 0.02 | 0.03 |
| 3 | 0.10 | 0.06 | 0.06 | 0.08 | 0.05 | 0.05 |
| 4 | 0.10 | 0.06 | 0.06 | 0.075 | 0.04 | 0.04 |
| 5 | 0.12 | 0.15 | 0.22 | 0.072 | 0.11 | 0.12 |
| 6 | 0.36 | 1.02 | 0.94 | 0.21 | 0.36 | 0.71 |
| 7 | 0.12 | 0.50 | 0.81 | 0.10 | 0.12 | 0.38 |
| 8 | 1.91 | 1.81 | 1.18 | 1.12 | 1.38 | 0.51 |
| 9 | 3.99 | 3.25 | 3.11 | 2.48 | 2.09 | 2.79 |
| 10 | 3.98 | 3.87 | 3.20 | 2.39 | 2.44 | 2.14 |
| 11 | 4.74 | 7.12 | 5.14 | 2.85 | 4.87 | 3.20 |
| 12 | 3.45 | 3.11 | 3.14 | 3.01 | 2.06 | 2.47 |
| 13 | 1.53 | 1.25 | 1.89 | 0.47 | 0.89 | 0.9 |
| 14 | 3.45 | 3.06 | 1.85 | 2.85 | 2.07 | 0.81 |
| 15 | 1.19 | 1.54 | 0.88 | 0.7 | 1.02 | 0.49 |
| 16 | 2.92 | 2.215 | 1.612 | 2.193 | 1.69 | 0.84 |
| 17 | 0.11 | 0.11 | 0.07 | 0.1 | 0.08 | 0.06 |
| 18 | 0.24 | 0.63 | 0.21 | 0.17 | 0.41 | 0.15 |
| 19 | 0.16 | 0.22 | 0.16 | 0.09 | 0.16 | 0.09 |
| 20 | 0.13 | 0.21 | 0.21 | 0.08 | 0.14 | 0.11 |
| 21 | 0.25 | 0.87 | 0.81 | 0.14 | 0.39 | 0.32 |
| 22 | 0.09 | 0.21 | 0.07 | 0.08 | 0.18 | 0.05 |
| 23 | 0.10 | 0.30 | 0.06 | 0.08 | 0.21 | 0.04 |
| 24 | 0.24 | 0.40 | 0.15 | 0.21 | 0.19 | 0.11 |



(a)Loss Allocation at Phase A



(b) Loss Allocation at Phase B



(c) Loss Allocation at Phase C

**Figure 6.7:** Loss allocations in 25-node unbalanced distribution network before and after integration of DG and capacitor in deregulated environment

From these results, the losses are allocated before and after network reconfiguration in regulated and deregulated environments as well as we have analyzed loss allocation after the integration of DG and capacitor in the reconfigured network in both the environments. Nowadays, in most of the existing research the main focus was on balanced distribution networks but in the proposed method we have concentrated on unbalanced distribution network. In the already existing works, the focus is either on network reconfiguration or DG placement or capacitor placement. Here in our work, we are combining the advantage of network reconfiguration, DG and capacitor placement and we also have shown the impact of these in loss allocation in both regulated and deregulated environment.

## 6.5. Conclusion

This chapter presents loss allocation of three-phase unbalanced radial distribution network in regulated and deregulated environments before and after minimizing the loss. Reconfiguration can reduce the loss of the system. Optimal placement of DG and capacitor in reconfigured network further reduces the loss of the system. The loss allocations of base and reconfigured network in both the environments are carried out using Firefly algorithm. The loss allocation of this unbalanced distribution network is further carried out in both the environments. The suggested method is implemented on MATLAB platform and tested on a 25-node unbalanced distribution network. The simulation results obtained by the proposed method provide a clear representation of loss allocation in unbalanced distribution network before and after network reconfiguration. The loss allocation before and after integration of DG and capacitor in the reconfigured network in each environment has also been carried out and results obtained are effective.

# CHAPTER-7: OVERALL CONCLUSIONS AND FUTURE SCOPE OF WORK

The aim of this chapter is to give the overall conclusion of the thesis and to show the future scope of work. In this chapter the results and findings of each chapter are to be discussed.

## 7.1 Overall conclusions

A brief introduction of radial distribution networks, introduction to network reconfiguration, role of DG and capacitor, objectives of research, scope of research and organization of thesis are discussed in **Chapter 1**. The detailed literature survey of load-flow solution for distribution networks, distribution network reconfiguration and loss allocation of three-phase radial distribution networks is discussed in **Chapter 2**.

A new and efficient load-flow method is proposed in **Chapter 3**. The proposed load-flow analysis method is applied on 19-node and 25-node, three phase unbalanced radial distribution network .The suggested method takes less CPU time for all cases and takes the least number of iterations in some cases compared to the existing method given by Chen and Yang (2010).

In **Chapter 4** a fuzzy-firefly algorithm for network reconfiguration has been proposed. This suggested technique is successfully tested on 25-node and 19-node unbalanced radial distribution networks. Simulation outcomes has shown that the fuzzy based firefly algorithm has formed better results compared to that of obtained by the other optimization existing algorithms like GA, ABC, PSO and GA-PSO using the same objective function and proposed load-flow method in terms of reduction of real and reactive power losses, improvement of the magnitude of minimum voltage for each phase and reduction of energy cost in these two unbalanced distribution networks. The proposed algorithm takes less CPU time and least number of power-flows compared to that of obtained by the other optimization algorithms like GA, ABC, PSO and GA-PSO algorithms. The suggested method also gives better results in terms of loss reduction, improvement of the magnitude of minimum voltage of each phase and reduction of energy cost compared to that of obtained by the methods Vulasala ***et al.*** (2009) and Subrahmanyam and Radhakrishna (2009) for 25-node and 19-node unbalanced distribution networks and that obtained by the method of Sedighizadeh ***et al.*** (2013) for 25-node unbalanced distribution network respectively. This proposed technique also produces better results in terms of loss reduction and reduction of energy cost compared to that of obtained by the methods Taher and Karimi (2014) and Sedighizadeh (2015). In this work the DG and capacitor are placed optimally using LSF and BFOA in reconfigured network in the regulated environment. The results obtained are effective and DG and capacitor placement for loss minimization along with reconfiguration comes out to be a decent choice.

**Chapter 5** summarizes the minimization of the three-phase unbalanced distribution network losses in deregulated environment. Here the same fuzzy-firefly algorithm is used as suggested in **Chapter 4.** It is found from the results obtained that the losses of the network are reduced after network reconfiguration and optimal placement of DG and capacitor in reconfigured network further reduces the losses occurring in the system. The DG and capacitor placement is accomplished using LSF and BFOA. The suggested method is tested on a 25-node unbalanced radial distribution network. The results achieved by the suggested method are effective and encouraging.

In **Chapter 6** loss allocation of unbalanced distribution network in regulated and deregulated environments is presented. The loss allocations of base and reconfigured network in both the environments are carried out using Firefly algorithm. The suggested method is tested on a 25-node unbalanced radial distribution network. The suggested technique results for IEEE 13-node test feeder are also compared with the results obtained by Carpaneto ***et al.*** (2008) and the outcomes obtained by suggested method comes out to be uniform in comparison with technique proposed by Carpaneto ***et al.*** (2008) The results of simulation obtained by the suggested method deliver a clear representation of loss allocation in unbalanced distribution network before and after network reconfiguration. The loss allocation before and after integration of DG and capacitor in the reconfigured network in each environment has also been carried out and results obtained are effective.

## 7.2 Future Scope of the research work

After carrying out the widespread research work it realized that the present research work can be extended in following directions:

- In this work a load-flow solution algorithm is formed after solving for basic network equations for three-phase unbalanced radial distribution networks. This research work can be extended by including the effect of distribution transformer admittance matrix and transformer core losses together in load-flow study in Fuzzy environments.
- In present work for loss reduction single DG and capacitor are applied after network reconfiguration, reconfiguration of the distribution network could be extended by applying multi DG and capacitor for loss reduction.
- To find the reconfigured network different type of load modelling could be utilized in regulated and deregulated environment.

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# APPENDIX-A

**Table A1:** Line and load data of 19-node unbalanced radial distribution network

| Branch | Send-ing End | Recei-ving End | Conduc-tor Type | Length (km) | Phase A | Phase B | Phase C |
|---|---|---|---|---|---|---|---|
| 1 | 1 | 2 | 1 | 3.0 | 10.38 + j5.01 | 5.19 + j2.52 | 10.38 + j5.01 |
| 2 | 2 | 3 | 1 | 5.0 | 11.01 + j5.34 | 5.19 + j2.52 | 9.72 + j4.71 |
| 3 | 2 | 4 | 1 | 1.5 | 4.05 + j 1.95 | 5.67 + j2.76 | 6.48 + j3.15 |
| 4 | 4 | 5 | 1 | 1.5 | 6.48 + j3.15 | 5.19 + j2.52 | 4.53 + j2.19 |
| 5 | 4 | 6 | 1 | 1.0 | 4.20 + j2.04 | 3.09 + j1.50 | 2.91+ j1.41 |
| 6 | 6 | 7 | 1 | 2.0 | 9.72 + j4.71 | 8.10 + j3.93 | 8.10 + j3.93 |
| 7 | 6 | 8 | 1 | 2.5 | 7.44 + j3.60 | 5.34 + j2.58 | 3.39 + j1.65 |
| 8 | 8 | 9 | 1 | 3.0 | 12.3 + j5.97 | 14.9+ j7.23 | 13.29 + j6.42 |
| 9 | 9 | 10 | 1 | 5.0 | 3.39 + j1.65 | 4.20 + j2.04 | 2.58 + j1.26 |
| 10 | 10 | 11 | 1 | 1.5 | 7.44 + j3.60 | 7.44 + j3.60 | 11.01 + j5.34 |
| 11 | 10 | 12 | 1 | 1.5 | 9.72 + j4.71 | 8.10 + j3.93 | 8.10 + j3.93 |
| 12 | 11 | 13 | 1 | 5.0 | 4.38 + j2.13 | 5.34 + j2.58 | 6.48 + j3.15 |
| 13 | 11 | 14 | 1 | 1.0 | 3.09 + j1.50 | 3.09 + j1.50 | 4.05 + j1.95 |
| 14 | 12 | 15 | 1 | 5.0 | 4.38 + j2.13 | 4.86 + j2.34 | 6.96 + j3.36 |
| 15 | 12 | 16 | 1 | 6.0 | 7.77 + j3.78 | 10.38 + j5.01 | 7.77 + j3.78 |
| 16 | 14 | 17 | 1 | 3.5 | 6.48 + j3.15 | 4.86 + j2.34 | 4.86 + j2.34 |
| 17 | 14 | 18 | 1 | 4.0 | 5.34 + j2.58 | 5.34 + j2.58 | 5.52 + j2.67 |
| 18 | 15 | 19 | 1 | 4.0 | 8.76 + j4.23 | 10.05 + j4.86 | 7.14 + j3.45 |

**Table A2:** Impedance in Ohms/km

| Impedance in Ohms/km | | | | |
|---|---|---|---|---|
| Type | | A | B | C |
| 1 | A | 1.5609 + j0.67155 | 0.5203 + j0.22385 | 0.5203 +j0.22385 |
| | B | 0.5203 + j0.22385 | 1.5609 + j0.67155 | 0.5203 +j0.22385 |
| | C | 0.5203 + j0.22385 | 0.5203 + j0.22385 | 1.5609 +j0.67155 |

# APPENDIX-B

**Table B1:** Line and load data of 25-node unbalanced radial distribution network

| Branch | Send-ing End | Recei-ving End | Cond-uctor Type | Len-gth (ft) | Receiving end load in kVA | | |
|---|---|---|---|---|---|---|---|
| | | | | | Phase A | Phase B | Phase C |
| 1 | 1 | 2 | 1 | 1000 | 0 | 0 | 0 |
| 2 | 2 | 3 | 1 | 500 | 35 + j25 | 40 + j30 | 45 + j32 |
| 3 | 2 | 6 | 2 | 500 | 40 + j30 | 45 + j32 | 35 + j25 |
| 4 | 3 | 4 | 1 | 500 | 50 + j40 | 60 + j45 | 50 + j35 |
| 5 | 3 | 18 | 2 | 500 | 40 + j30 | 40 + j30 | 40 + j30 |
| 6 | 4 | 5 | 2 | 500 | 40 + j30 | 40 + j30 | 40 + j30 |
| 7 | 4 | 23 | 2 | 400 | 60 + j45 | 50 + j40 | 50 + j35 |
| 8 | 6 | 7 | 2 | 500 | 0 | 0 | 0 |
| 9 | 6 | 8 | 2 | 1000 | 40 + j30 | 40 + j30 | 40 + j30 |
| 10 | 7 | 9 | 2 | 500 | 60 + j45 | 50 + j40 | 50 + j35 |
| 11 | 7 | 14 | 2 | 500 | 50 + j35 | 50 + j40 | 60 + j45 |
| 12 | 7 | 16 | 2 | 500 | 40 + j30 | 40 + j30 | 40 + j30 |
| 13 | 9 | 10 | 2 | 500 | 35 + j25 | 40 + j30 | 45 + j32 |
| 14 | 10 | 11 | 2 | 300 | 45 + j32 | 35 + j25 | 40 + j30 |
| 15 | 11 | 12 | 3 | 200 | 50 + j35 | 60 + j45 | 50 + j40 |
| 16 | 11 | 13 | 3 | 200 | 35 + j25 | 45 + j32 | 40 + j30 |
| 17 | 14 | 15 | 2 | 300 | 133.3+ j100 | 133.3+j100 | 133.3 + j100 |
| 18 | 14 | 17 | 3 | 300 | 40 + j30 | 35 + j25 | 45 + j32 |
| 19 | 18 | 20 | 2 | 500 | 35 + j25 | 40 + j30 | 45 + j32 |
| 20 | 18 | 21 | 3 | 400 | 40 + j30 | 35 + j25 | 45 + j32 |
| 21 | 20 | 19 | 3 | 400 | 60 + j45 | 50 + j35 | 50 + j40 |
| 22 | 21 | 22 | 3 | 400 | 50 + j35 | 60 + j45 | 50 + j40 |
| 23 | 23 | 24 | 2 | 400 | 35 + j25 | 45 + j32 | 40 + j30 |
| 24 | 24 | 25 | 3 | 400 | 60 + j45 | 50 + j30 | 50 + j35 |

**Table B2:** Impedance in Ohms/mile

| | | Impedance in Ohms/mile | | |
|---|---|---|---|---|
| Type | | A | B | C |
| 1 | A | 0.3686 + j0.6852 | 0.0169 + j0.1515 | 0.0155 + j0.1098 |
| | B | 0.0169 + j0.1515 | 0.3757 + j0.6715 | 0.0188 + j0.2072 |
| | C | 0.0155 + j0.1098 | 0.0188 + j0.2072 | 0.3723 + j0.6782 |
| 2 | A | 0.9775 + j0.8717 | 0.0167 + j0.1697 | 0.0152 + j0.1264 |
| | B | 0.0167 + j0.1697 | 0.9844 + j0.8654 | 0.0186 + j0.2275 |
| | C | 0.0152 + j0.1264 | 0.0186 + j0.2275 | 0.9810 + j0.8648 |
| 3 | A | 1.9280 + j1.4194 | 0.0161 + j0.1183 | 0.0161 + j0.1183 |
| | B | 0.0161 + j0.1183 | 1.9308 + j1.4215 | 0.0161 + j0.1183 |
| | C | 0.0161 + j0.1183 | 0.0161 + j0.1183 | 1.9337 + j1.4236 |

# APPENDIX-C

## DATA RELATED TO IEEE 13-NODE TEST FEEDER

**Table C1:** Overhead line configuration data

| Configuration | Phasing | Phase | Neutral | Spacing |
|---|---|---|---|---|
| | | ACSR | ACSR | ID |
| 601 | B A C N | 556,500 26/7 | 4/0 6/1 | 500 |
| 602 | C A B N | 4/0 6/1 | 4/0 6/1 | 500 |
| 603 | C B N | 1/0 | 1/0 | 505 |
| 604 | A C N | 1/0 | 1/0 | 505 |
| 605 | C N | 1/0 | 1/0 | 510 |

**Table C2:** Underground line configuration data

| Configuration | Phasing | Cable | Neutral | Space ID |
|---|---|---|---|---|
| 606 | A B C N | 250,000 AA, CN | None | 515 |
| 607 | A N | 1/0 AA, TS | 1/0 Cu | 520 |

**Table C3:** Line segment data

| Node A | Node B | Length(ft.) | Configuration |
|---|---|---|---|
| 632 | 645 | 500 | 603 |
| 632 | 633 | 500 | 602 |
| 633 | 634 | 0 | XFM-1 |
| 645 | 646 | 300 | 603 |
| 650 | 632 | 2000 | 601 |
| 684 | 652 | 800 | 607 |
| 632 | 671 | 2000 | 601 |
| 671 | 684 | 300 | 604 |
| 671 | 680 | 1000 | 601 |
| 671 | 692 | 0 | Switch |
| 684 | 611 | 300 | 605 |
| 692 | 675 | 500 | 606 |

**Table C4:** Transformer data

| | kVA | kV-high | kV-low | R - % | X - % |
|---|---|---|---|---|---|
| Substation | 5,000 | 115 – D | 4.16 Gr. Y | 1 | 8 |
| XFM -1 | 500 | 4.16 – Gr.W | 0.48 – Gr.W | 1.1 | 2 |

**Table C5:** Capacitor data

| Node | Ph-A | Ph-B | Ph-C |
|---|---|---|---|
| | kVAr | kVAr | kVAr |
| 675 | 200 | 200 | 200 |
| 611 | | | 100 |
| Total | 200 | 200 | 300 |

**Table C6:** Regulator data

| | | | |
|---|---|---|---|
| Regulator ID | 1 | | |
| Line Segment | 650 – 632 | | |
| Location | 50 | | |
| Phases | A - B -C | | |
| Connection | 3-Ph,LG | | |
| Monitoring Phase | A-B-C | | |
| Bandwidth | 2.0 volts | | |
| PT Ratio | 20 | | |
| Primary CT Rating | 700 | | |
| Compensator Settings | Ph-A | Ph-B | Ph-C |
| R – Setting | 3 | 3 | 3 |
| X – Setting | 9 | 9 | 9 |
| Voltage Level | 122 | 122 | 122 |

**Table C7:** Spot load data

| Node | Load | Ph-1 | Ph-1 | Ph-2 | Ph-2 | Ph-3 | Ph-3 |
|---|---|---|---|---|---|---|---|
| | Model | kW | kVAr | kW | kVAr | kW | kVAr |
| 634 | Y-PQ | 160 | 110 | 120 | 90 | 120 | 90 |
| 645 | Y-PQ | 0 | 0 | 170 | 125 | 0 | 0 |
| 646 | D-Z | 0 | 0 | 230 | 132 | 0 | 0 |
| 652 | Y-Z | 128 | 86 | 0 | 0 | 0 | 0 |
| 671 | D-PQ | 385 | 220 | 385 | 220 | 385 | 220 |
| 675 | Y-PQ | 485 | 190 | 68 | 60 | 290 | 212 |
| 692 | D-I | 0 | 0 | 0 | 0 | 170 | 151 |
| 611 | Y-I | 0 | 0 | 0 | 0 | 170 | 80 |
| | TOTAL | 1158 | 606 | 973 | 627 | 1135 | 753 |

**Table C8:** Distributed load data

| Node A | Node B | Load | Ph-1 | Ph-1 | Ph-2 | Ph-2 | Ph-3 | Ph-3 |
|---|---|---|---|---|---|---|---|---|
| | | Model | kW | kVAr | kW | kVAr | kW | kVAr |
| 632 | 671 | Y-PQ | 17 | 10 | 66 | 38 | 117 | 68 |

# IEEE 13-node Test Feeder Impedances

## Configuration 601:

***Z (R +jX) in ohms per mile***

| | | | | | |
|---|---|---|---|---|---|
| 0.3465 | 1.0179 | 0.1560 | 0.5017 | 0.1580 | 0.4236 |
| | | 0.3375 | 1.0478 | 0.1535 | 0.3849 |
| | | | | 0.3414 | 1.0348 |

***B in micro Siemens per mile***

| | | |
|---|---|---|
| 6.2998 | -1.9958 | -1.2595 |
| | 5.9597 | -0.7417s |
| | | 5.6386 |

## Configuration 602:

**Z (R +jX) in ohms per mile**

| | | | | | |
|---|---|---|---|---|---|
| 0.7526 | 1.1814 | 0.1580 | 0.4236 | 0.1560 | 0.5017 |
| | | 0.7475 | 1.1983 | 0.1535 | 0.3849 |
| | | | | 0.7436 | 1.2112 |

**B in micro Siemens per mile**

| | | |
|---|---|---|
| 5.6990 | -1.0817 | -1.6905 |
| | 5.1795 | -0.6588 |
| | | 5.4246 |

## Configuration 603:

**Z (R +jX) in ohms per mile**

| | | | | | |
|---|---|---|---|---|---|
| 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| | | 1.3294 | 1.3471 | 0.2066 | 0.4591 |
| | | | | 1.3238 | 1.3569 |

**B in micro Siemens per mile**

| | | |
|---|---|---|
| 0.0000 | 0.0000 | 0.0000 |
| | 4.7097 | –0.8999 |
| | | 4.6658 |

## Configuration 604:

**Z (R +jX) in ohms per mile**

| | | | | | |
|---|---|---|---|---|---|
| 1.3238 | 1.3569 | 0.0000 | 0.0000 | 0.2066 | 0.4591 |
| | | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| | | | | 1.3294 | 1.3471 |

**B in micro Siemens per mile**

| | | |
|---|---|---|
| 4.6658 | 0.0000 | –0.8999 |
| | 0.0000 | 0.0000 |
| | | 4.7097 |

**Configuration 605:**

**Z (R +jX) in ohms per mile**

| | | | | | |
|---|---|---|---|---|---|
| 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| | | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| | | | | 1.3292 | 1.3475 |

**B in micro Siemens per mile**

| | | |
|---|---|---|
| 0.0000 | 0.0000 | 0.0000 |
| | 0.0000 | 0.0000 |
| | | 4.5193 |

**Configuration 606:**

**Z (R +jX) in ohms per mile**

| | | | | | |
|---|---|---|---|---|---|
| 0.7982 | 0.4463 | 0.3192 | 0.0328 | 0.2849 | -0.0143 |
| | | 0.7891 | 0.4041 | 0.3192 | 0.0328 |
| | | | | 0.7982 | 0.4463 |

**B in micro Siemens per mile**

| | | |
|---|---|---|
| 96.8897 | 0.0000 | 0.0000 |
| | 96.8897 | 0.0000 |
| | | 96.8897 |

**Configuration 607:**

**Z (R +jX) in ohms per mile**

| | | | | | |
|---|---|---|---|---|---|
| 1.3425 | 0.5124 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| | | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| | | | | 0.0000 | 0.0000 |

**B in micro Siemens per mile**

| | | |
|---|---|---|
| 88.9912 | 0.0000 | 0.0000 |
| | 0.0000 | 0.0000 |
| | | 0.0000 |

# *LIST OF PUBLICATIONS*

1. Manvir Kaur and Smarajit Ghosh, "Network Reconfiguration of Unbalanced Distribution Networks using Fuzzy-Firefly Algorithm", **Applied Soft Computing**, Vol. 49, pp. 868-886, 2016. **doi**: 10.1016/j.asoc.2016.09.019 (ASOC 3818) **(SCIE, Impact Factor: 3.541)**
2. Manvir Kaur and Smarajit Ghosh, "Effective Loss Minimization and Allocation of Unbalanced Distribution Network", **Energies**, Vol. 10, No. 12, 1931, pp. 1-17, 2017. **doi**: 10.3390/en10121931 **(SCIE, Impact Factor: 2.676)**

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**Manvir Kaur:** Born in Bathinda, Punjab, India on 16th October, 1983. She did B. Tech. (Elecrical Engineering) from Kukukshetra University Kurukshetra and M. Tech. (Instrumentation and control Engineering) from Sant Longowal Institute of Engineering and Technology (Deemed to be University), Longowal, Punjab, India, in 2005 and 2008 respectively. She is pursuing Ph.D. as part-time research scholar in Department of Electrical and Instrumentation Engineering of Thapar Institute of Engineering and Technology (Deemed to be University), Patiala, Punjab, India under the supervision of Prof. Smarajit Ghosh.

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