University of Rwanda

College of Science and Technology

OPTIMAL RENEWABLE ENERGY INTEGRATION FOR AN EFFICIENT OPERATION OF A MV DISTRIBUTION NETWORK. CASE STUDY OF GOMA DRC

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Master of Science (Renewable Energy Engineering)

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DECLARATION

I declare that this dissertation is the result of my own work and has not been submitted for any other degree at University of Rwanda or any other institution.

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Date: …..08/11/2021

This MSC dissertation has been submitted to the School of Science, Department of Science and Technology, The University of Rwanda with my approval as supervisor

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DR. FRANCIS MULOLANI

Date : …08/11/2021

DEDICATION

I dedicate this work to my father Bizimungu Mukanisa Charles who never stop encourage me in all the steps of my study, my mothers Batasema Clotilde and Karume Francoise for continually inspiring me with perseverance and hard work, my brothers and sisters for always being there for me. Let Good bless all of you, precious family!

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I first of all present my gratitude to my Lord for the life, grace and kindness he continues to bestow on me.

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ABSTRACT

Integrating VRES to the existing grid still challenging in Democratic Republic of Congo (DRC), where there are a lot of isolated electrical network and some of them like the Goma national distribution network operate with a high level of losses on certain feeders due to frequent extensions. Variable Renewable Source (VRESs) are growing faster in the region and are gradually produced in urban areas and more studies have to be carried out in the sense of reconciling the existing grid to Distributed Generation (DG). Even though a lot of DG optimization algorithms for placement and size in a distribution network have already been proposed with the objective of decreasing system power losses and improving voltage profile, they still suffer from several drawbacks and most of them have been tested only on IEEE test system. Thus, by creating new or improving the existing ones this important issue can be addressed more efficiently and effectively. Some works proposed hybrid methods to solve the accuracy issue of Heuristic methods but they were still applied on predefined test systems. This research work aimed at solving the power losses minimization problem by proposing a two-step Fuzzy Logic (FL) and Particle Swarm Optimization (PSO) methodology so as to allocate and size DGs while testing it on the Goma city MV distribution network. Power loss reduction index were utilized for FL-based DG location process and Backward/Forward sweep load flow model for PSO-based DG sizing process. This results in reducing the searching space and thus, raised up convergence rate while reducing the computation time of the algorithm. The result obtained were compared with those obtained in a previous study in which capacitor were optimally sized and allocate using analytical method. An analysis of the integration level was also done. The results showed that DG placement is more efficient than capacitor placement for the case studied. Indeed, the proposed method presented the highest power loss reduction. The percentage active and reactive power loss reduction was 51.4% each for Route-Sake and 61.2% each for Sotraki feeder. The voltage profile which was out of standards before DG placement was largely improved with 0.959 p.u as lowest buss voltage for Route-Sake and 0.94 p.u for Sotraki feeder. When studying DG penetration effect on system power losses and voltage profile, we found that more DG inclusion beyond the optimal number, although it was leading to more voltage improvement, it resulted in a sudden increase in power system losses.

Key words: Distribution generation, Renewable energy integration, Power loss reduction, Fuzzy logic, Particle Swarm optimization, Voltage profile, Distribution network, System power losses.

LIST OF SYMBOLS AND ACRONYMS

ABCA	Artificial Bee Colony Algorithm
BCBV	Branch-current to bus-voltage matrix
BIBC	Bus-injection to branch-current matrix
COP	Conference of the Parties
DC	Direct Current
DG	Distributed Generation
DISCO	Distribution Company
DNO	Distribution Network Operator
DRC	Democratic Republic of Congo
FL	Fuzzy Logic
GA	Genetic Algorithms
HS	Harmony Search
LP	Linear Programming (LP)
MINLP	Mixed Integer Nonlinear Programming
MV	Middle voltage
NLP	Non-Linear Programming
PQ	Power Quality
PSO	Particle Swarm Optimization
RE	Renewable Energy
REI	Renewable Energy Integration
SA	Simulated Annealing
SNEL	National electricity company
THD	Total Harmonic Distortion
TS	Tabu Search
VRE	Variable Renewable Energy
VRES	Variable Renewable Energy Source

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CHAPTER 1. INTRODUCTION

1.1 BACKGROUND

Renewable Energy has grown faster in electricity generation since the kick off of this century. The fact is, they are environmentally friendly. Indeed, the global warming has led to look for alternative energy sources other than fossil fuels in order to address greenhouse effect. Energy producers have been thus oriented to Renewable sources for the first time by the International Community in the Paris COP21 which took place in 2015 [1]. Since then, Wind and Solar Energy being the most Renewable Energy used worldwide, have seen their utilization in power generation increased considerably. The motivation behind this growth lies in their cost effectiveness, availability and the recent innovation in power electronic. Even though the initial cost of investment for Solar and Wind is higher, their running cost remains cheaper compared to diesel and conventional thermal power plant making them more profitable for long run. Being free resources, they are also counted among renewable resources which are widely spread over the earth. Regarding power electronic (which plays a major role in Wind and Solar energy deployment and implementation), it has evolved from the traditional vacuum tube to a multiple range of components which are more efficient such as IGBTs, MOSFETs, BJTs … Wherefore, several technologies have been born so as to facilitate electricity production from renewable energy resulting in more wind and solar power plant integration at different level of the Grid.

It can be observed that the mutation in power production leads inevitably to a restructuring of the grid. If we have noticed the early advancements that happen in the electrical industry, all power systems have been isolated. The first public power station in the world was initiated by Thomas Edison in the years 70s in London and later in 1882 at Manhattan that was an electricity generation unit powered by steam. DC generators was then used, but conversion of voltage to the desired levels was challenging [2]. Microgrids share a lot of similarities with these early systems as they too are generated locally with dedicated loads. Hence, we state that the early isolation strategies are now revisited in the form of large grids which have the distinct capability of integrating both distributed generation and microgrids interconnection when necessary. Indeed, older grids were isolated networks with one power plant owned by one company (generally the government) – the electricity market were thus a centralized one – but with the advent of solar and wind power plants, interconnection became essential due to the intermittency of these renewable sources and the liberalization policy seemed to be the good way to deal with this new design. There are several drawbacks that come with extreme centralization such as limitations on the use of non-renewable fuels, expansion of existing networks, reducing congestion on existing lines and threats from malicious entities. Decentralization in the other hand allows both large and low scale Renewable Energy Integration

(REI) and requires two ways flowing of power and communication between power suppliers and consumers so as to improve Distributed Generation (DG). The latter is still a big challenge in developing countries.

When Variable Renewable Energy Sources (VRESs) had been integrated to the grid for the first time, some issues such as change of short circuit level, reverse power flow, blinding of protection arose; but they were not that severe. REI through deployment of DGs, has become more attractive since renewable sources are free, environmentally friendly and some like solar can be directly produced in urban area (allowing then an interconnection to the distribution network without constructing new lines). But with more REI, several challenges that might lead to a blackout could occur in the power system if precautions regarding planning have not been taken into account. Intermittency issue of VRES comes with technical and economic problems which limit their integration level. Even though DGs from VRES have the benefits of being integrated with low risk and change in existing infrastructure, a random deployment and unplanned sizing of units can increase power losses and voltage fluctuations in the distribution network. These new challenges urged the need for mathematical tools that could help in planning and decision-making process, especially when it comes to the selection of RE plants' sizes and locations. Indeed, in a liberalized electricity market, opportunities for connected generation at distribution level increases, especially when the size and location of DGs from VRES are optimized given their big impact in reducing the technical challenges associated with REI such as energy losses.

1.2 STATEMENT OF THE PROBLEM

Developing countries are gradually following in the footsteps of developed countries in terms of energy policies. Several countries have decentralized the energy sector so as to increase electrification rate. But it is obvious that the biggest part of losses within the grid is located at distribution level and to deal with them requires creativity and a significant budget. In a liberalized market; network issues such as losses, harmonics, power system stability; are still a barrier for a good implementation of decentralization due to the strong competition that this causes. So, DGs from VRES are indicated for the energy market policy we are discussing on because not only they could reduce technical challenges but they are also clean and cost effective for long term run compare to fuel and some conventional power plants.

Developing countries and DRC in particular are facing the problem raised previously, although the electricity market has been liberalized since 2017, REI and interconnection still challenging. The existing infrastructure managed for long time by a monopoly company is strongly isolated and for the case of Goma city; a part from the national one, there are three other microgrids. The national distribution system is not reliable due to insufficient energy produced and has a high-power loss rate on some feeders leading to abnormal voltage drops. This notorious presence of microgrids revels that, investors are likely to invest in new production units (especially in solar power plants) and if tools that can allow their integration into the existing power system and which reconcile power injection with loss reduction are not developed, isolated microgrids will not stop increasing in the city.

From the above the following questions can be raised:

i) How can distributed generation from solar be implemented within the existing grid so as to limit the construction of new and expensive isolated network while improving its reliability?
ii) Which optimization technique can be used when integrating renewable sources for more power losses reduction and more distributed generation expansion?

1.3 AIM AND OBJECTIVES

This research aims to evaluate the optimal renewable energy integration at distribution level so as to decrease power system losses.

The major objectives are:

i) To select feeders with high level of power system losses and voltage drop out of standards.
ii) To optimally allocate and size DGs from Solar on selected feeders
iii) To evaluate the performance of that optimal VRES integration comparing to Capacitor placement.

1.4 SCOPE OF THE STUDY

This thesis is oriented to DG integration at distribution level of the grid. We are more focalized on the MV network and small-scale REI. Solar energy is the only intermittent renewable source in use all around the region of our study. The low-voltage side of the distribution network is not a part of this study.

CHAPTER 2. REVIEW OF OPTIMIZATION TECHNIQUES AND OBJECTIVE FUNCTION FORMULATION

Since REI has become a hot topic, many authors have made it the subject of their research. As soon as Variable Renewable Energy Sources (VRESs) like Solar Energy started to be integrated to the grid; new problems such as generation forecasting, uncontrollable generated power, energy curtailment, etc.; have appeared. Energy demand growth, environmental issues in generation based on fossil fuel, The need to reduce fossil energy utilization and the degradation of technical performance are the reasons behind the integration of small renewable distributed generation units and turning the existing power systems into a restructured one. Optimizing the technical benefits offered by DG placement is a well-known challenge for Distribution Network Operators (DNOs) for both fossil and renewable energy resource–based DGs, but renewable DG systems have several power quality (PQ) challenges associated additionally. Furthermore, this integration comes up with PED thus affecting the stability and the reliability of the grid. All these issues have been treated by different studies of which this chapter makes a review.

2.1 REVIEW OF RENEWABLE ENERGY INTEGRATION (REI) PROBLEMS

We can categorize studies that have been carried out by different researches in the following: quality, flow, stability and balance. Regarding the quality, J. Wong et all in [3] concluded that Variable Renewable Energy (VRE) generator raise up the customer’s voltage and this may lead to electrical surge when power is on lower grid levels at a time when the consumption is lower. One of solutions to adress the previous problem was proposed by J.G. Kassakian et R. Schmalensee [4]. They figured out a technique including both distributed and centralized demand response. When the first involves controlled growth or decline of energy demand of electrical components (mostly in residential houses or industrial areas), the second requires measuring technologies and estimation of the electrical condition of the grid. In the same shoes, X. Liang [5] shows that integration of RE increases the fluctuation of the supplied voltage. This shorten the equipement life duration and may be destructive at the end user.

Concerning stability, In [6] -C. A. Agricola et all showed that Comparatively to synchronous machines, VREs generators induce a low short-circuit power, which generally causes voltage instablility making then difficult the detection of the fault occuring suddenly. This leads to a violation of stability standards and the redispatching or curtailment of VRE generation. Inssuficient reactive power provision is one of the issues that A.-C. Agricola [7] studied on in their article. As alternative solutions, they listed the use of transformers with phase-shifting, static var compensator and Series compasators.

M. Cailliau et all [8] presented in their work a balance issue: poor firmness of VRE generators. Indeed the unpredictability of VRES grows up the uncertainty of the firm production capacity evaluation. That fact puts the reserve necessity very high and increases the unplanned disparity between production and demand (redispatch or curtailment issue). Following are the proposed solutions: Real-time curtailment of VRE generators, integration of SCADA techniques, use of both mecanical and electrical MPPT systems for PV Solar. The insufficient forecasting problem of VRE is raised in [9] by A. Von Meier. Storage and forecasting techiques like probabilistic forecasting, meteorological forecasting are cited in [10] as possible solution.

I. Pierre et all [11] oriented their research on the flow showing that VRESs affect the grid causing a loss of its distribution and transmission capacity. This can be fixed by applying different techniques; such as techniques of increasing the grid capacity, optimization of the reactive and active power flow, improvement of the reliability of the grid by optimal allocation of DGs from VRES; explained by F. Van Hulle in [12]. In the same paper they described how wind and solar energies make power flow becoming less predictable and more volatile. A. Sajadi et all [13] studied the fault current behaviou when VRE are integrated to the grid. They found that their generators, integrated at reduced voltages ranges, raise up the short circuit currents when a faut occurs. As proposed by V. Telukunta et all [14], current limiter devices and high impedance transformer can be used in oder to overcome that issue. Despite the diverse advantages resulting from the inclusion of DGs from VRES, studies pointed out that new challenges of increased power system losses created principally by inappropriate selection of size and allocation of DGs may occur at utilities. In what follows, a focus will then be oriented on DG placement and sitting.

1.2 REVIEW OF DGs OPTIMIZATION METHODS

2.2.1 Different algorithms used for DGs placement

To solve DGs placement models, differents optimization techniques have been presented in the litterature. These methods, as shown in Figure 2.1, can be generally classified as gradient and second order methods, heuristic methods, iterative methods and analytical-based techniques. Tabu Search (TS), Genetic Algorithms (GAs), Particle Swarm Optimization (PSO) and Artificial Bee Colony Algorithm (ABCA) are included in Heuristc methods. They have given admissible results over the years, in addition to mathematical programming such as Optimal Power Flow (OPF) and Linear Programming (LP), wich are also widely presented in the literature.

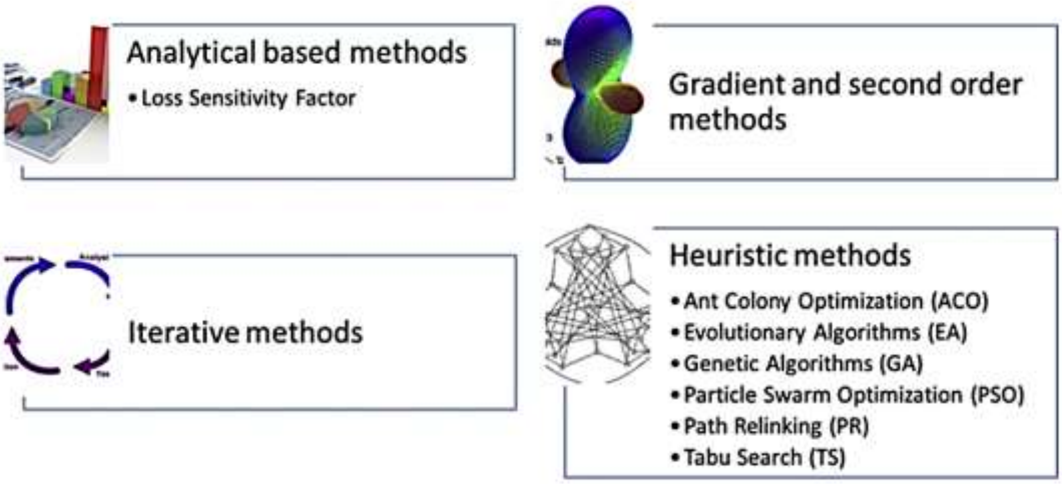

Figure 0.1 Classification of different methodologies to solve DGs placement and sizing problem.

a. Intelligent search methods

Artificial intelligence can be defined as the use of intellicence within machine and regroups heuristic techniques which consist on algorithms that fastern the process of piking up an appropriate solution or closest optimal one. The benefit of heuristic methods abide in their simplicity comparing to analytical methods. But that is at the desadvantage of accuracy and precision. To enhance the optimal solution searching, two or more heuristique approches can be joined together to form a so called meta-heuristic method. Figure 2.2 presents the historical evolution of these heuristic methods. Genetic algorithm (GA) was the first proposed method. Other methods that are based on natural evolution and animal social behaviors followed the GA. New methods such as harmony search (HS) were recently suggested which are based on different areas such as musical harmony.

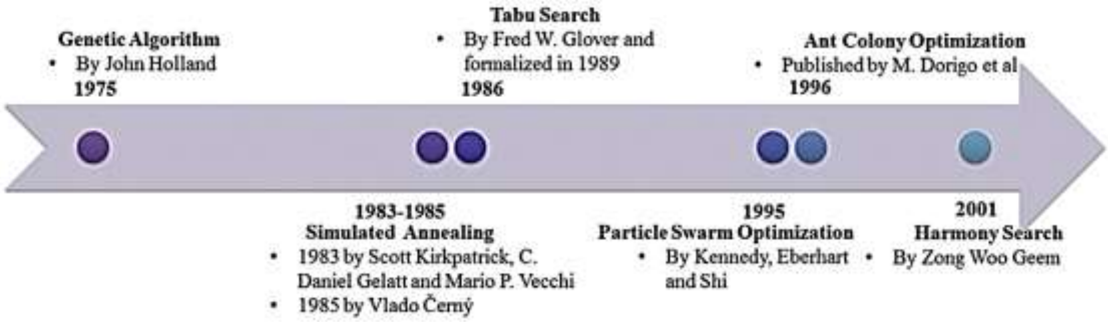

Figure 0.2 Historical developments of some heuristic optimization methods

In the literature, the highly applied optimization technique in solving the DGs sizing and siting, is considered to be GA [15]. In Reference [16] GA was used with the objective to save the expansion costs of the system and improve its reliability. These two objectives being conflicting pareto-optimum ones, the use of appropriate models allowed to choose the dominant solution at a single run. SA has been applied in [17] with the aim of optimizing DGs sizing and placing while decreasing calculation time comparing to GA and tabu search (TS). Additionally, when the optimization problem is based on defined reliability criteria, AS is highly indicated. For that reason, it has been used in [18] for power planning based on reliability criteria so as to result in optimal placement and sizing of DGs while meeting the requirements at consumer level with minimum system upgrade. In DGs locating and sizing problem, PSO has been frequently utilize in the literature. For example, in [19] PSO is applied by V. Pandi et all to choose the optimal size, type, and placement of DG units so as to achieve the optimal penetration of DG while considering protection constraints and harmonic limits. In addition, PSO was implemented in [20] to not only reduce losses, cost and Total Harmonic Distortion (THD), but also to enhance the voltage profile. Results indicated that PSO gave better solution quality and a lower number of iterations compared to GA method. In fact, PSO presents a shorter computational time in comparison with GA and can be adapted to real cases of power networks.

b. Analytical approaches

Analytical methods often produce a mathematical equation that can be solved for optimization. The model established, highly influence the accuracy of the method. The advantages of using these methods lies in their easiness in implementing while guarantying convergence and small time of computation. Nevertheless, when the problem gets bigger some assumptions for simplifying it are utilized and that may have an impact on the accuracy of the solution. By mean of analysis of continuous load flow computation and identification of the buses that are most susceptible to voltage drop, H. Hedayati et all in [21] applied analytical method for allocating and sizing DG. This approach proved to be successful in enhancing voltage profile and decreasing power system losses while increasing power transfer capacity.

c. Linear and Non-Linear Programming (LP & NLP)

This is kind of mathematical programming used to resolve a mathematical model where the decision variables are represented by linear relationships in order to maximize or minimize the objective function. Simplex is one of the methods used to solve LP problems, it is a method that it is based on polytope edges of the visualization solid to determine the optimal solution. LP is widely used in power system optimization problem as it gives the exact solution, such as finding the optimal size of DG units. M. Dicorato et all [22] implemented LP to enhance the effect of reactive power demand of DGs on the system voltages and to raise the number of connected DGs while respecting buss voltage limits. However, the mathematical model to solve is called Mixed Integer Nonlinear Programming (MINLP) when the variables are continuous and discrete and the objective function and constraints are non-linear (such as with power balance and cost equations). In the context of finding the optimal location and size of DGs in the power system, MINLP has been used in several papers, where the optimal locations of DGs were determined economically and operationally based on power loss sensitivity index as presented in [23] for example. The very large number of decision variables and the long computation time are the major drawbacks of MINLP.

d. *Fuzzy logic (FL)*

Fuzzy logic is greatly utilized in the sizing and siting problem of DGs. As an example, S. Kumar Injeti and Navuri P Kumar implemented FL in [24] to resolve the optimal location problem of DGs with the aim of minimizing active power losses and improve voltage profile.

2.2.2 Objective function and constraints

Different objective functions and constraints were used by authors in order to solves DGs placement and sizing optimization problem so far. The most common objective function is the power loss minimization. As for the constraint, voltage constraints are the most common ones.

In [17] L.T. Carmen Borges and M. Djalma Falcao allocated DGs by minimizing the total real power losses using GA and three principal constraints: Capacity limits, voltage constraints and Three-phase short circuit current. S. Tanasak S. and B. Pornrapeepat [17] minimized total system cost per year with network and stipulated reliability criteria as constraints. By using hybrid method combining GA and FL, Kyu-Ho Kim et all in [25] reduced power losses and costs of distribution systems. Technical constraints such as capacity limits, voltage, three-phase short circuit currents, number and size of DGs had been used to bound the problem. A rural system revenue maximization problem was formulated by M. Dicorato et all in [22] with a certain number of energy and non-energy related relevant constraint and the problem was solved by LP. A minimization multi objective problem of total system planning involving Cost of DG investment, DG operation & maintenance, Purchase of power is solved in [23] by Al Abri et all through Mixed-Integer linear programing.

2.3 MODELING AND PROBLEM FORMULATION

2.3.1 Distribution line model

A distribution line model (short line, i.e., less 80 km in length) contains a longitudinal impedance as shown in Figure 2.3 and the voltage-current equation for the start and the end of the line is given by equation 2.1. [26]

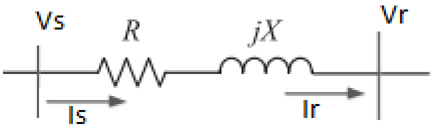

Figure 0.3 Distribution line model

$$\begin{bmatrix} \bar{V}_s \\ \bar{I}_s \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} \bar{V}_r \\ \bar{I}_r \end{bmatrix} \quad (2.1)$$

From equation (2.1), equations (2.2) and (2.3) are deducted:

$$\bar{V}_s = A\bar{V}_r + B\bar{I}_r \tag{2.2}$$

$$\bar{I}_s = C\bar{V}_r + D\bar{I}_r \tag{2.3}$$

Where :

- $\bar{V}_s$ is the voltage at the start of the line
- $\bar{V}_r$ is the voltage at the end of the line
- $\bar{I}_s$ the line current at the start
- $\bar{I}_r$ the line current at the end

A, B, C, D are line parameters (for a short line: A=1, B=Z which is the impedance matrix, C=0 and D=1).

2.3.2 Backward/Forward sweep power flow model

The previous equations can be extended to a radial distribution network with n nodes. For that purpose, the single source radial distribution network represented by Figure 2.4 is considered.

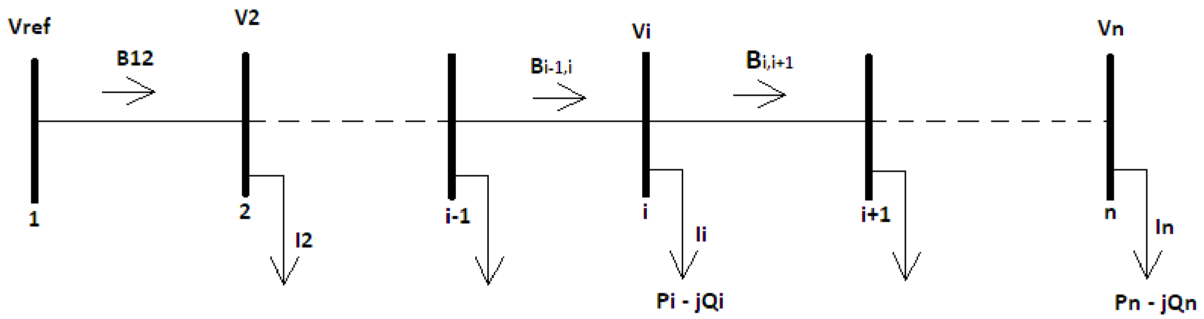

Figure 0.4. Radial distribution network

For the last branch the equation (2.3) can be rewritten as follows:

$$\bar{B}_{n-1,n} = \bar{I}_n \tag{2.4}$$

Where :

- n is the number of busses
- $\bar{B}_{n-1,n}$ is the last line current
- $\bar{I}_n$ is the last node current injection

A node current injection depends on the power injected at the considered node. The power injected at node *i* is given by:

$$\bar{S}_i = P_i - jQ_i = \bar{V}_i . \bar{I}_i^* \tag{2.5}$$

Where:

- P_i and Q_i are respectively real and reactive power injected at node *i*

- $\bar{V}_i$ and $\bar{I}_i^*$ are respectively the node voltage and the complex conjugate of the current injected at buss i.

From equation (2.5), node current at node *i* is calculated as follows:

$$\bar{I}_i = \frac{P_i - jQ_i}{\bar{V}_i^*} \tag{2.6}$$

Equation (2.2) can be rewritten for the first branch as follows:

$$\bar{V}_2 = \bar{V}_1 - \bar{Z}_{12}\bar{B}_{12} \tag{2.7}$$

Where :

- $\bar{V}_1$ and $\bar{V}_2$ are respectively the first and the second node voltage
- $\bar{Z}_{12}$ and $\bar{B}_{12}$ are respectively the impedance and the line current in the branch linking node 1 to node 2

Backward/Forward sweep power flow model has two steps each one using one of Kirchhoff law: the backward and the forward sweep. During the Backward sweep, line currents are calculated starting with the node furthest from the reference node while in the Forward sweep, the downstream node voltage is calculated beginning by the reference node [27]. As a matter of fact, by gradually evolving toward the first node, all lines current can be expressed with respect to the current injected and therefore D matrix can be the readjust to this proposed model as follows.

$$\bar{B}_{ij} = \bar{I}_j + \sum_{i=1}^{n} \bar{I}_i \tag{2.8}$$

Where *i* and *j* are consecutive nodes linked by a distribution line.

By grouping all line currents in a matrix, the equation (2.8) can take the following form:

$$\begin{bmatrix} \bar{B}_{12} \\ \bar{B}_{23} \\ \bar{B}_{34} \\ \vdots \\ \bar{B}_{n-1,n} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & \dots & 1 \\ 0 & 1 & 1 & \dots & 1 \\ 0 & 0 & 1 & \dots & 1 \\ \vdots & \vdots & \vdots & & \vdots \\ 0 & 0 & 0 & \dots & 1 \end{bmatrix} \begin{bmatrix} \bar{I}_2 \\ \bar{I}_3 \\ \bar{I}_4 \\ \vdots \\ \bar{I}_n \end{bmatrix} \Rightarrow [B] = [BIBC][I] \tag{2.9}$$

BIBC (bus-injection to branch-current matrix) is an upper triangular matrix which relates node currents to branch currents (depends therefore on the network configuration) and filled only by zeros and ones.

However, node voltages are determined beginning by the first node up to the last using the general form of equation (2.7):

$$\bar{V}_j = \bar{V}_i - \bar{B}_{ij}.\bar{Z}_{ij} \tag{2.10}$$

Where:

- $\bar{V}_j$ and $\bar{V}_i$ are respectively the voltages at downstream node *j* and upstream node *i* which are directly linked
- $\bar{Z}_{ij}$ is the line impedance between node *i* and *j*

In matrix form and for all busses, the equation (2.10) can be rewritten as follows:

$$\begin{bmatrix} \bar{V}_1 \\ \bar{V}_1 \\ \bar{V}_1 \\ \vdots \\ \bar{V}_1 \end{bmatrix} - \begin{bmatrix} \bar{V}_2 \\ \bar{V}_3 \\ \bar{V}_4 \\ \vdots \\ \bar{V}_n \end{bmatrix} = \begin{bmatrix} \bar{Z}_{12} & 0 & 0 & \dots & 0 \\ \bar{Z}_{12} & \bar{Z}_{23} & 0 & \dots & 0 \\ \bar{Z}_{12} & \bar{Z}_{23} & \bar{Z}_{34} & \dots & 0 \\ \vdots & \vdots & \vdots & & \vdots \\ \bar{Z}_{12} & \bar{Z}_{23} & \bar{Z}_{34} & \dots & \bar{Z}_{n-1,n} \end{bmatrix} \begin{bmatrix} \bar{B}_{12} \\ \bar{B}_{23} \\ \bar{B}_{34} \\ \vdots \\ \bar{B}_{n-1,n} \end{bmatrix} \Rightarrow [\Delta V] = [BCBV][B] \qquad (2.11)$$

BCBV (branch-current to branch-voltage matrix) is an under triangular matrix which relates branch current to voltage drop in a branch (depends therefore on the network configuration) and filled by branch impedances.

As long as the result obtained does not meet the tolerance in the computation error, the two sweeps are repeated. The stopping criteria is given by:

$$\Delta V_i^k = \left|V_i^k\right| - \left|V_i^{k-1}\right| < Error \qquad (2.12)$$

Where *k* is the iteration number.

After determining all line currents, power system losses are determined as follows:

$$\begin{cases} P_{loss} = \sum_{\substack{i=1 \\ j\neq i}}^{n} R_{ij}\, B_{ij}^2 \\ Q_{loss} = \sum_{\substack{i=1 \\ j\neq i}}^{n} X_{ij} B_{ij}^2 \end{cases} \qquad (2.13)$$

Where R_{ij} and X_{ij} are respectively the resistance and the reactance of the line between node *i* and node *j*.

Figure 2.5 gives a step-by-step algorithm developed for this research in order to implement Backward/Forward sweep for power system losses determination.

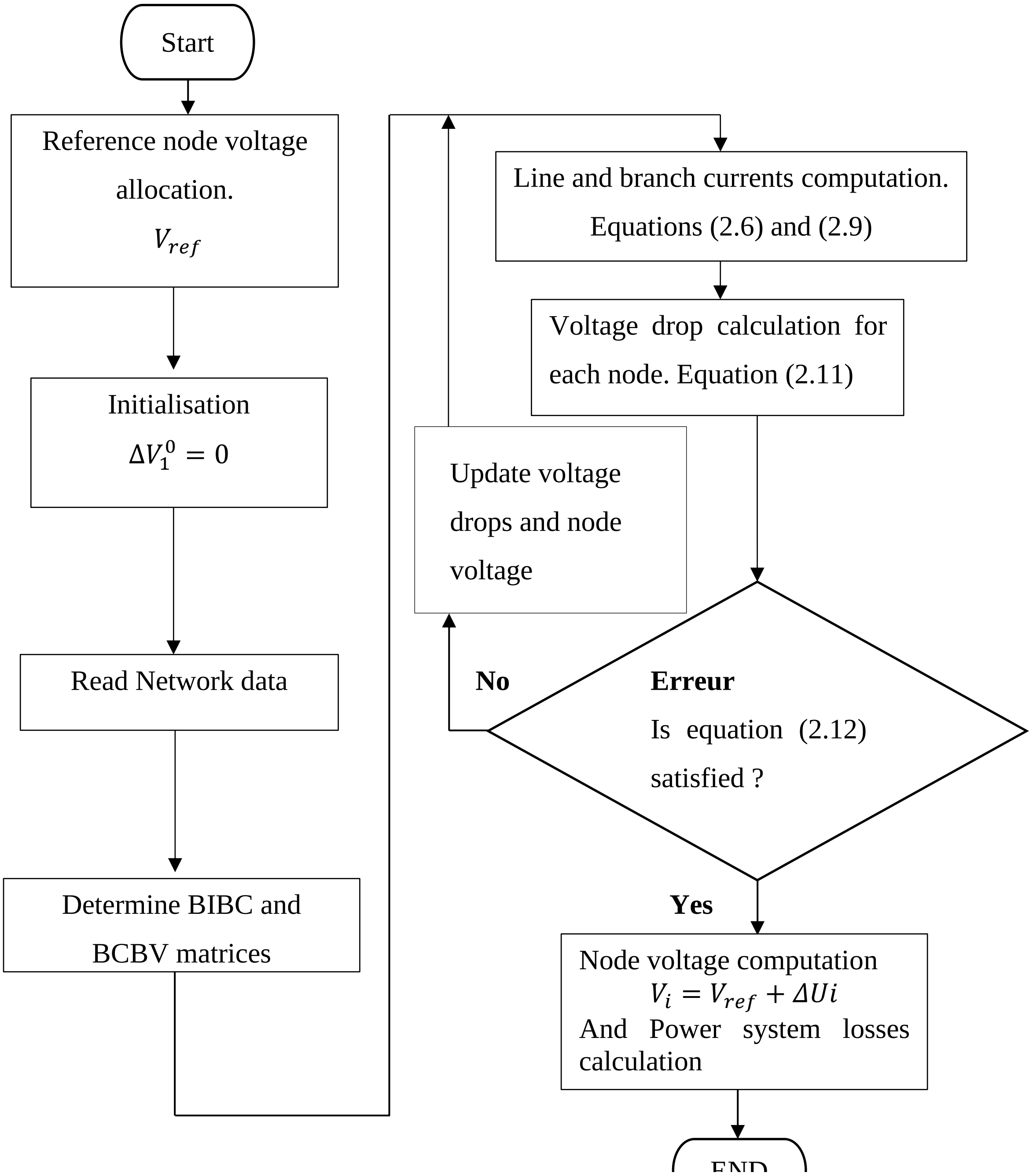

Figure 0.5 Backward/Forward sweep algorithm

2.3.3 Real power loss reduction index for DG placement

A single source radial distribution network is characterized by a one-way flow of current and in such a network, DGs are intuitively allocate at high consumption nodes [28]. In fact, the lower is the power consumption at a given node, the less rate its power loss reduction is going to be. Thus, power loss reduction plays an important role when it comes to DG location and it the principal parameter to be used for finding the real power loss reduction index per node. We have to notice that the last has been used in this research as one of the inputs parameters of the Fuzzy Inference System (FIS) for DG allocation. Real power loss reduction at node *i* is given by:

$$PLR_i = PL_{base} - PL_i \qquad (2.14)$$

Where:

- PL_{base} is the active power loss of the existing power system
- PL_i is the active power loss after compensating active load at buss i.

Considering all busses, the range of the real power loss reduction is to change depending on the network configuration. Therefore, if the network has a lot of feeders which are feed by the same buss barre and we have to study them separately, it is common to normalize the real power loss reduction into a [0,1] range by calculating the real Power Loss Reduction Index per node (PLRI):

$$PLRI_i = \frac{PLR_i - PLR^{max}}{PLR^{max} - PLR^{min}} \qquad (2.15)$$

Where:

- PLR^{max} is the highest power loss reduction of the feeder
- PLR^{min} is the lowest power loss reduction of the feeder

2.3.4 Objective function formulation for DG sizing

Intermittency and uncertainty are the principal issues associated with VRES, mostly with discontinuous availability of solar and wind resources. To accommodate the integration of large share of VRES, it is important to have appropriate planning tools able to optimize the integration of VRES. In principle, searching for the optimal capacity of DG is usually modelled as a nonlinear mathematical optimization problem. Various constraints and objective functions are first set. For an efficient operation of a distribution network, this optimal integration has to meet a certain standard so as to benefit all advantages which come with DG when avoiding its drawbacks such as reverse power flow, overvoltage, increased power losses. In the proposed formulation, whether the objective function or the constraints have been set in relation to these challenges. Total real power system losses minimization problem is formulated based on Backward/Forward Sweep power flow model; while inequality constraints are node voltages, branch currents and DG output power limits

The objective function is given by:

$$Minimize\ \ P_{loss} = \sum_{\substack{i=1 \\ j\neq i}}^{n} R_{ij}\, B_{ij}^2 \qquad (2.16)$$

Subject to:

- Current constrains

$$\left|B_{ij}\right| \leq \left|B_{ij}^{max}\right| \qquad (2.17)$$

Where B_{ij}^{max} is the branch current limit for the line *i-j*.

Figure 0.6. Backward/Forward sweep algorithm

- Voltage limits constraint

$$V^{min} \leq V_i \leq V^{max} \tag{2.18}$$

where V^{min} and V^{max} are minimum and maximum values of voltage at bus i; normally the bus voltage lies between 0.9 $\leq V_i \leq$ 1 pu.

- DG real power output constraint

$$P_{DG}^{min} \leq P_{DG} \leq P_{DG}^{max} \tag{2.19}$$

where P_{DG}^{min} and P_{DG}^{max} are minimum and maximum active power output of DG

2.4 CHAPTER CONCLUSION

This chapter made a brief review of REI problems and their possible solutions. When it comes to the flow issues, dealing with power losses is an important factor that could limit integration of VRES. A review of optimization techniques shows that an optimal placement and sizing of DGs from VRES can reduce power losses at distribution level. The chapter end with the formulation of the objective function focused on power losses minimization.

CHAPTER 3. PROPOSED ALGORITHM AND OPTIMAZATION TECHNIQUE

New trend in optimization methods is to combine two different techniques in order to gain all advantages that each one can offer and at the same time to reduce the lack of accuracy and precision of heuristic methods. The so-called Hybrid technique is a new combined method introduced by researchers in order to refine solutions. However, the proposed method is a two steps methodology combining Fuzzy Logic (FL) and Particle Swam optimization (PSO). FL is in charge of giving the optimal DG siting while PSO select the optimal size among multiple ones that have been generated randomly. The advantages of relieving PSO from determination of locations of DGs are improved convergence and less computation time.

3.1 PROPOSED METHOD

3.1.1 Fuzzy logic

FL is a robust system where no precise inputs are required (able to accommodate several types of inputs including vague, distorted or imprecise data). It is flexible and rules can be modified. For DG siting problem, the common sense may lead to this approximate reasoning: when it comes to study losses and voltage levels of a distribution system, an experienced planning engineer can choose locations for DG installations, which are probably highly suitable. For example, it is intuitive that a section in a distribution system with high losses and low voltage is highly ideal for allocation of DG. Whereas a low loss section with good voltage is not ideal for DG placement.

Three parameters are then required for this idea to be implemented using Fuzzy Expert System (FES) which are PLRI, Voltage Index (VI) and DG Suitability Index (DSI). The two first parameters are input ones while the last is an output parameter. VI is actually the per unit nodal voltage and it has to vary from 0.9 to 1 p.u. Each parameter has five membership functions which are low (L), low medium (LM), medium (M), high medium (HM) and high (H). Those are linguistics terms in which both VI and PLRI are converted during the fuzzification process. Membership function are all triangular for both input parameter VI and output parameter DSI but PLRI has two trapezoidal and three triangular memberships as Figure 3.1, 3.2 and 3.3 show.

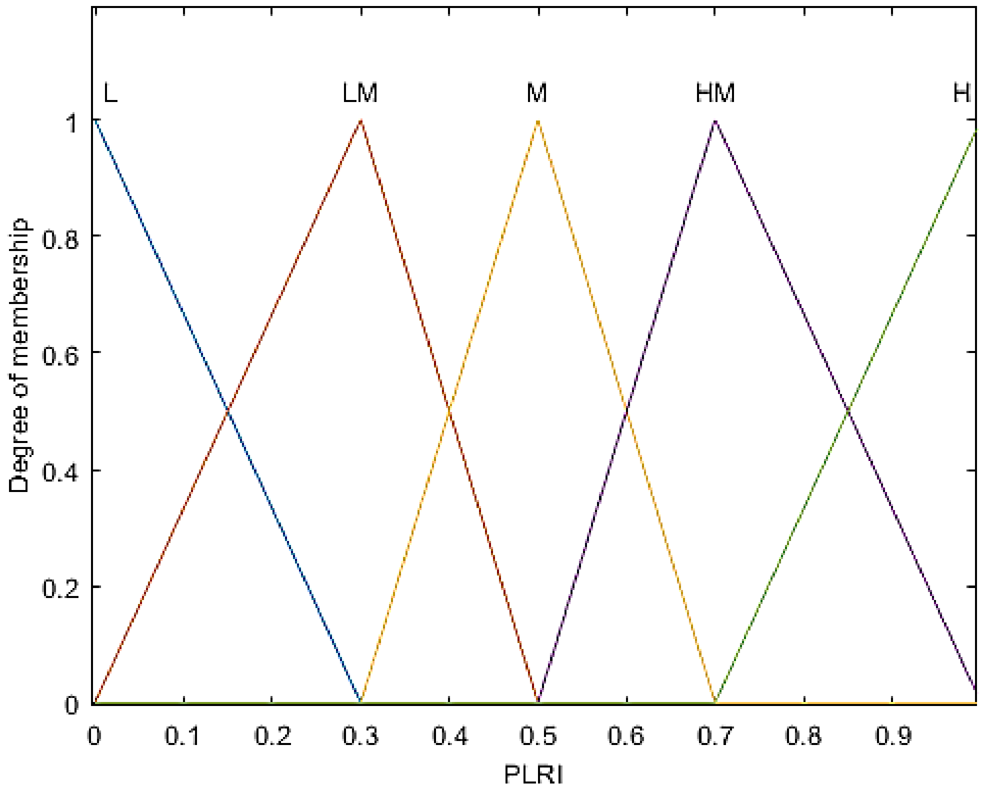

Figure 0.1 Membership function for PLRI

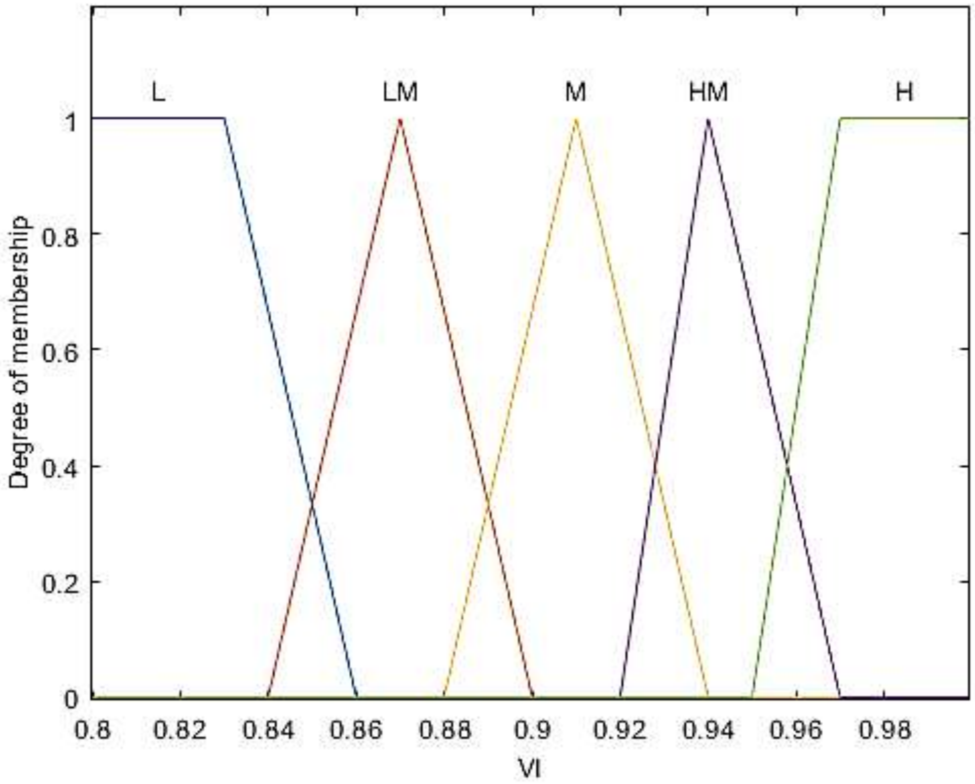

Figure 0.2 Membership functions for VI

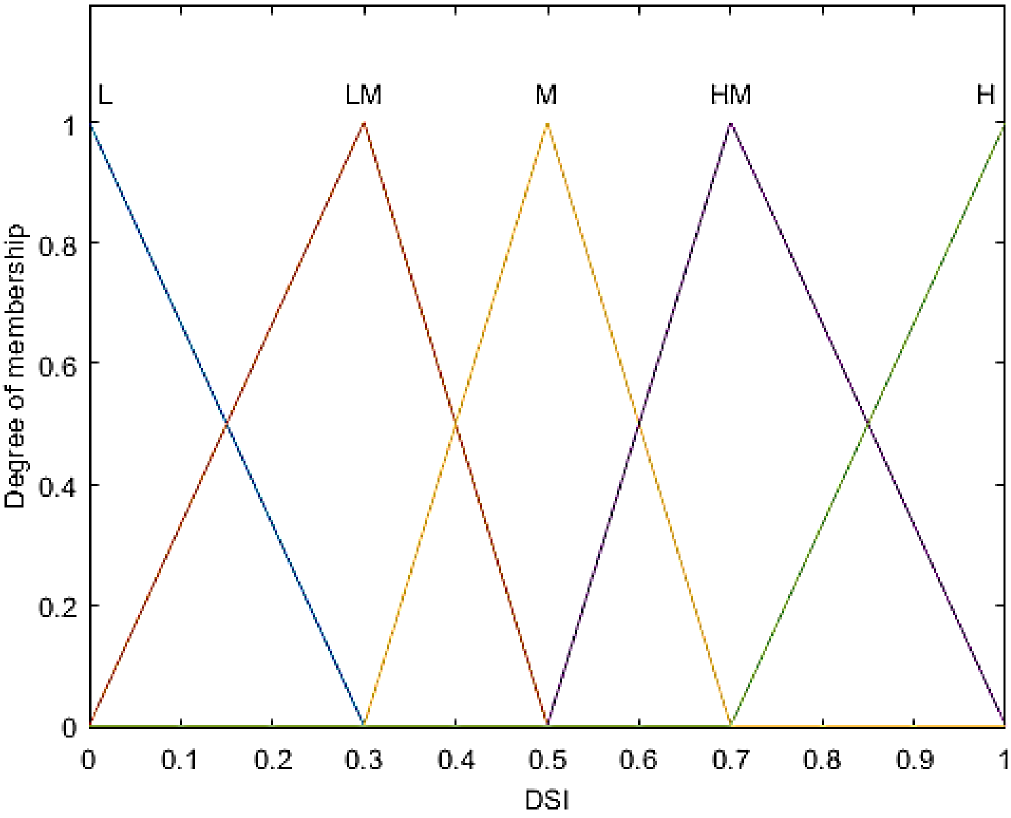

Figure 0.3 Membership function for DSI

As DGs have to be placed in the radial distribution system such that PLRI should be maximum and the voltage index minimum, several heuristics rules are set carefully so as to take into account that philosophy. Table 3.1 represents a set of fuzzy rules that has been used during the fuzzy inference process. The output of the Fuzzy Inference System (FIS) is the DG suitability Index (DSI), whose scalar value is obtained after the defuzzification process. Busses that have a large DSI are selected as candidate busses for DG sizing. On the other hands, they are inputs parameters of the PSO-based DG sizing algorithm. The node with the highest DSI has to receive at first its optimal DG size.

Table 0.1 Fuzzy decision matrix

AND		VI				
		L	**LM**	**M**	**HM**	**H**
PLRI	**L**	LM	LM	L	L	L
	LM	M	LM	LM	L	L
	M	HM	M	LM	L	L
	HM	HM	HM	M	LM	L
	H	H	HM	M	LM	LM

3.3.2 Particle Swam Optimization

PSO has higher probability and efficiency in finding the global optima, has few parameters to adjust, is able to run parallel computation and can be efficient for solving problems presenting difficulty to find accurate mathematical models. It can also converge fast thus has short computational time.

PSO algorithm starts with a population of particles with random positions in the search space. Each particle is a solution of the problem and has a fitness value. The fitness is evaluated and is to be optimized. A velocity is defined which directs each particle's position and gets updated in each iteration. Particles gradually move toward the optima due to their best position they have ever experienced and the best solution which group has experienced [29]. The velocity of a particle is updated with respect to three factors: the past velocity of the particle, the best position particle has experienced so far and the best position the entire swarm has experienced so far as shown in figures 3.3 and 3.4.

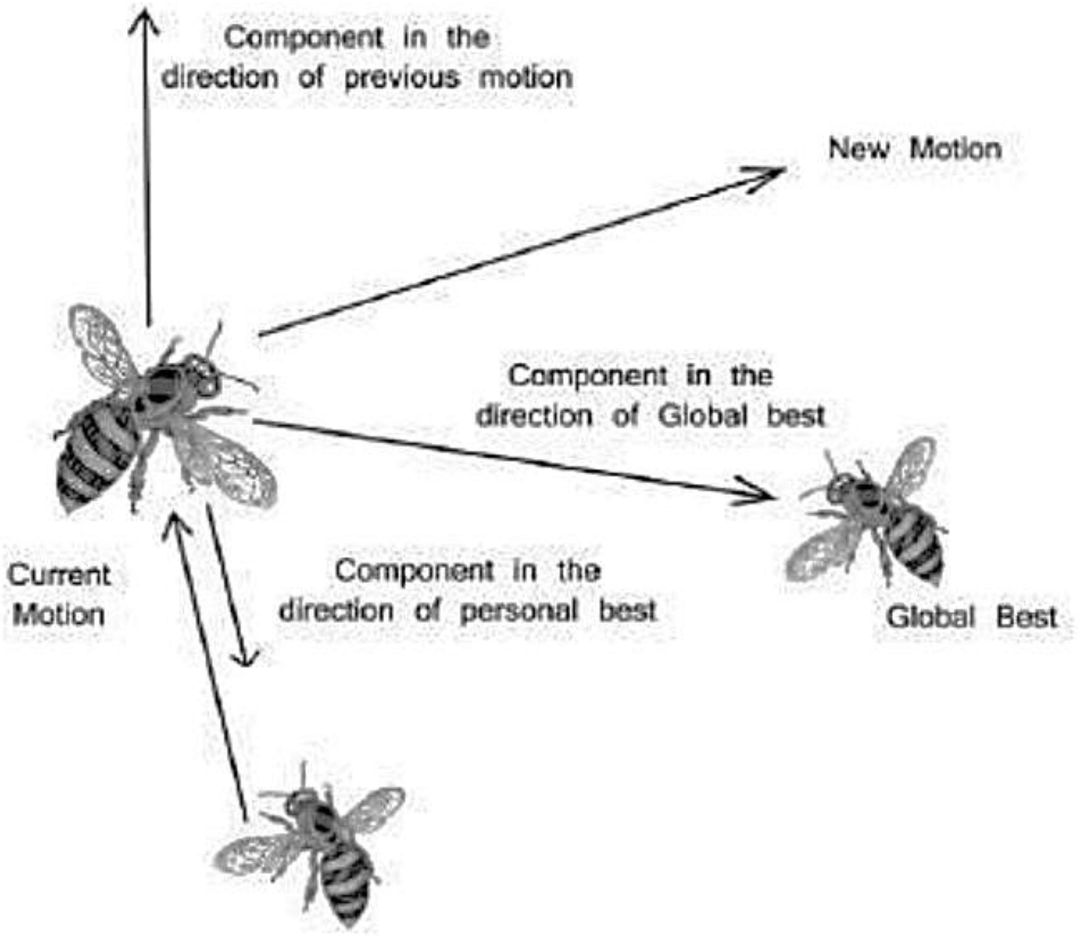

Figure 0.4 Concept of a searching point by PSO

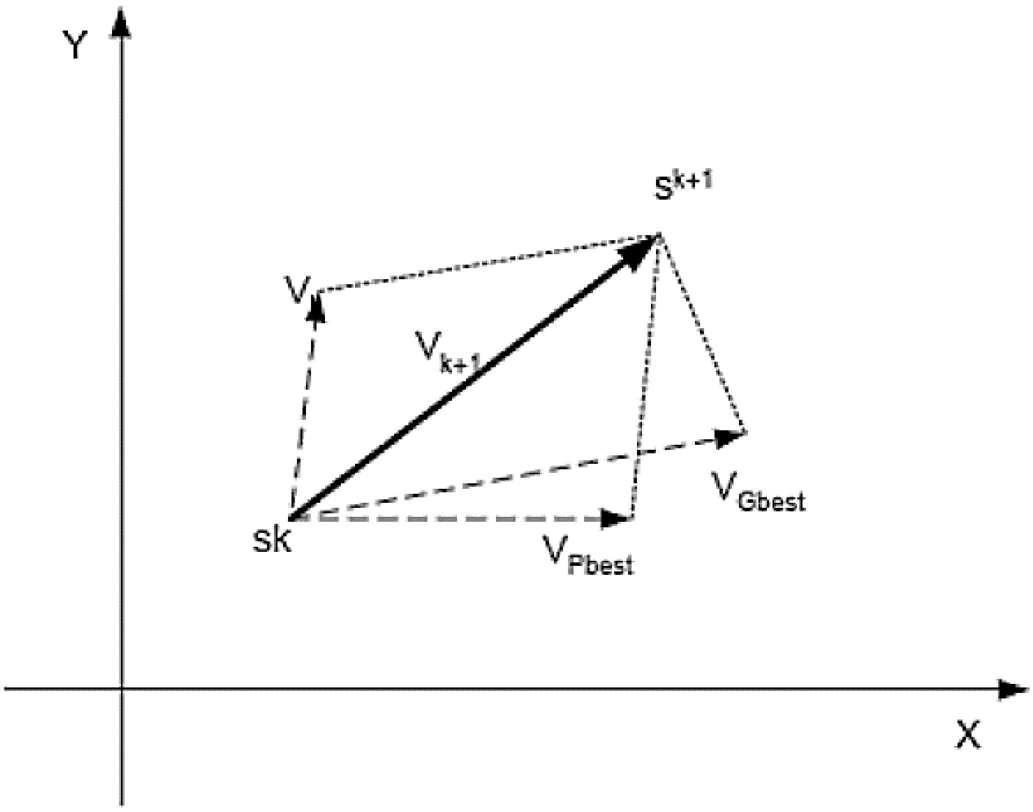

Figure 0.5 Velocity updating in PSO

The modification process can mathematically be expressed as follows:

$$V_{id}^{k+1} = wV_{id}^{k} + c_1 r \left(P_{best_{id}} - S_{id}^{k}\right) + c_2 r \left(G_{best_{id}} - S_{id}^{k}\right) \qquad (3.1)$$

$$S_{id}^{k+1} = S_{id}^{k} + V_{id}^{k+1} \qquad (3.2)$$

Where:

- V_{id}^{k+1} is modified velocity of agent *i*
- w is weight function for velocity of agent
- V_{id}^{k} is current velocity
- c_1 and c_2 are weight coefficients for each term respectively
- r is a random number
- $P_{best_{id}}$ is the particles best position
- S_{id}^{k} is current searching point
- S_{id}^{k+1} is the modified searching point
- $G_{best_{id}}$ is the groups best position
- *n* is number of particles in a group
- *m* is number of members in a particle

The weight function is updated for each iteration using the following equation:

$$w_k = w_{max} - \frac{(w_{max} - w_{min})}{k_{max}} k \tag{3.3}$$

Where:

- w_{max} and w_{min} are respectively minimum and the maximum weight
- k_{max} and k are maximum and current iteration.

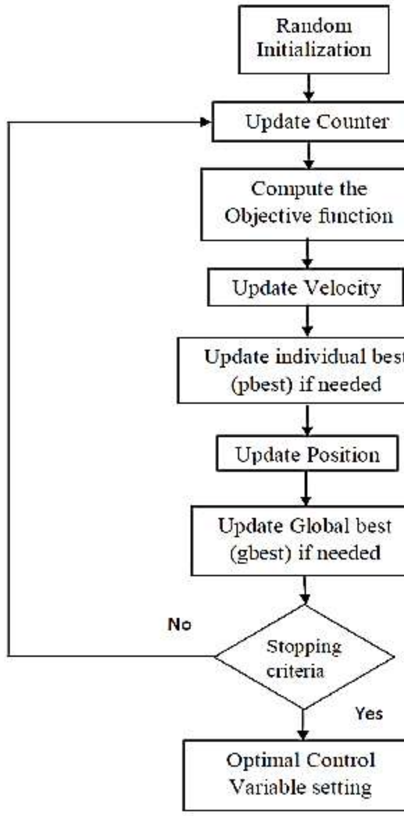

Figure 0.6 Flowchart of PSO algorithm

When implementing PSO, the intrinsic parameters were chosen as described below:

a) Random numbers

The uniform random values were in the range [0, 1].

b) Weighting Coefficients

The weighting coefficient were chosen as follows: $c_1 = c_2 = 2$.

c) Inertia Weight

Both w_{min} and w_{max} were taken as 0.4 and 0.9 respectively.

3.2 SOFTWARE TO BE USED (MATLAB SIMULINK)

Simulink of MATLAB 2019a is the proposed software to be used for simulation purpose. Indeed, the software is a powerful environment for project design and REI simulations. Although being made principally for numerical computing, some toolbox like MuPAD symbolic engine give an access to symbolic computation when the Simulink package is a model-based design toolbox for dynamic and embedded systems. The main advantage of using MATLAB is that, many libraries developed in different languages (Java script, Perl, .Net, ActiveX) can be integrated by calling them directly from MATLAB, thus allowing a communication with another software. Table 3.2 list some strengths and weaknesses of MATLAB.

Table 0.2 Strengths and weaknesses of MATLAB

Strengths		**Weaknesses**
Flexibility	Visualization of results is easy and any change in the model does not require a change in scale when plotting results (fast adaptive scale)	Compatibility: it requires a big resource in the computer
Adaptability	MATLAB can easily work with libraries developed in another language	
Accessibility	Easily accessible to engineers and students	Lack of weather data for RE sources.
User-friendly	Reduce the programming work by implementing graphic models.	Lack of Economic and environmental analysis tools for RE projects
Offers many alternatives	Integration of many optimization methods	

3.3 FLOWCHART OF THE PROPOSED ALGORITHM

The proposed algorithm has two different steps: a FL-based DG siting followed by a PSO-based DG sizing. The algorithm developed for this research is described by the flowchart of Figure 3.7.

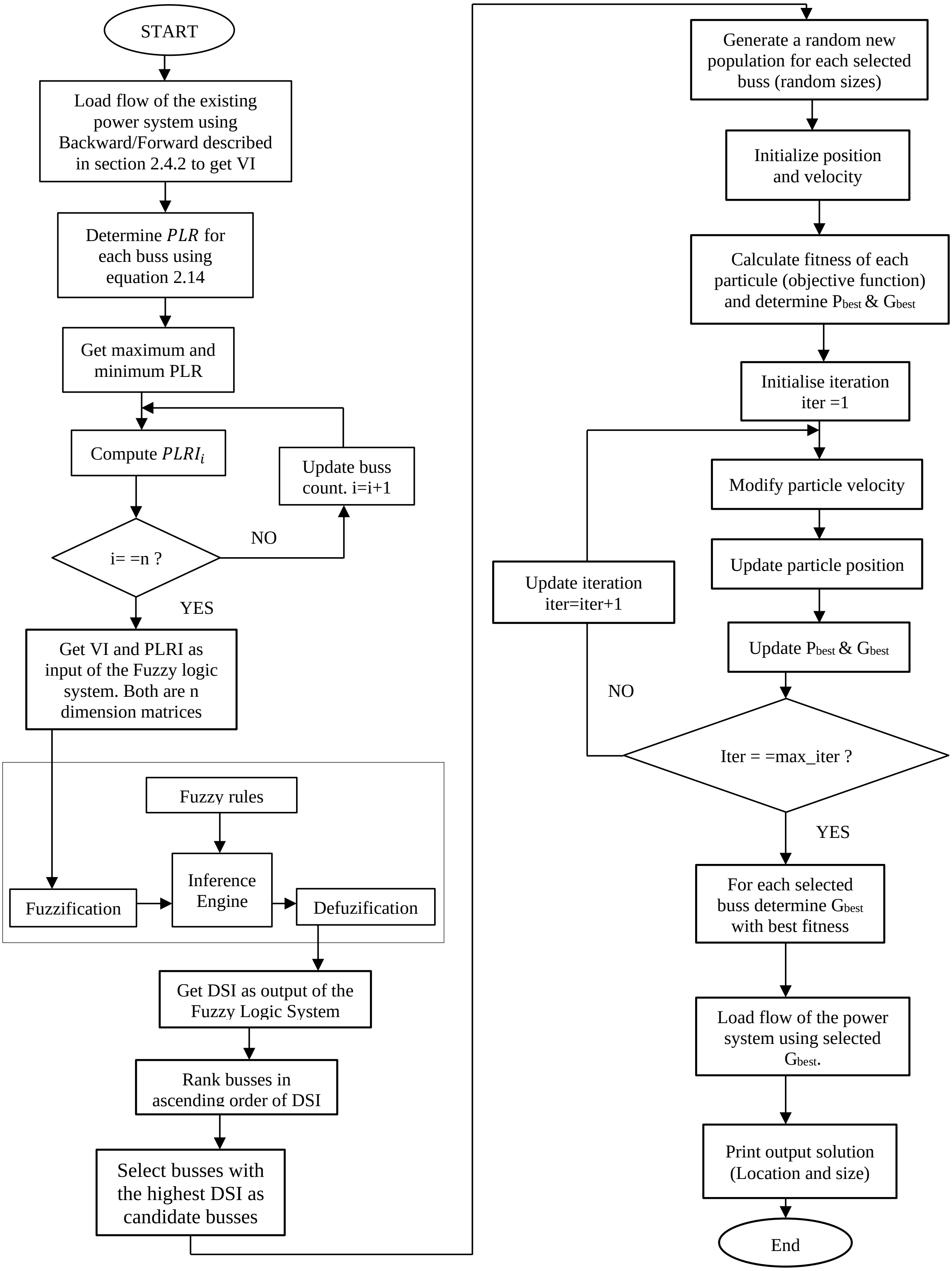

Figure 0.7 Flowchart of the proposed algorithm

3.4 CASE STUDY

The proposed method is used to find location and size of DGs from solar power plant in the Goma power distribution system. It is an old network owned by the national electricity company SNEL, undergoing frequent extensions leading to a noticeable increase in power system losses on certain feeders. The MV distribution system studied here has 5 feeders described in the table 3.3 and its single-line diagram is given by Figure 3.8

Table 0.3 Feeder characteristics of the Goma distribution network

Feeders	Conductor section (mm^2)	Material	Nominal power (MVA)	Nominal voltage (kV)
North	50	Alu-steel	3.94	15
South			12	
Center			7.73	
Sotraki			6.89	6.6
Route Sake	70		15.6	15

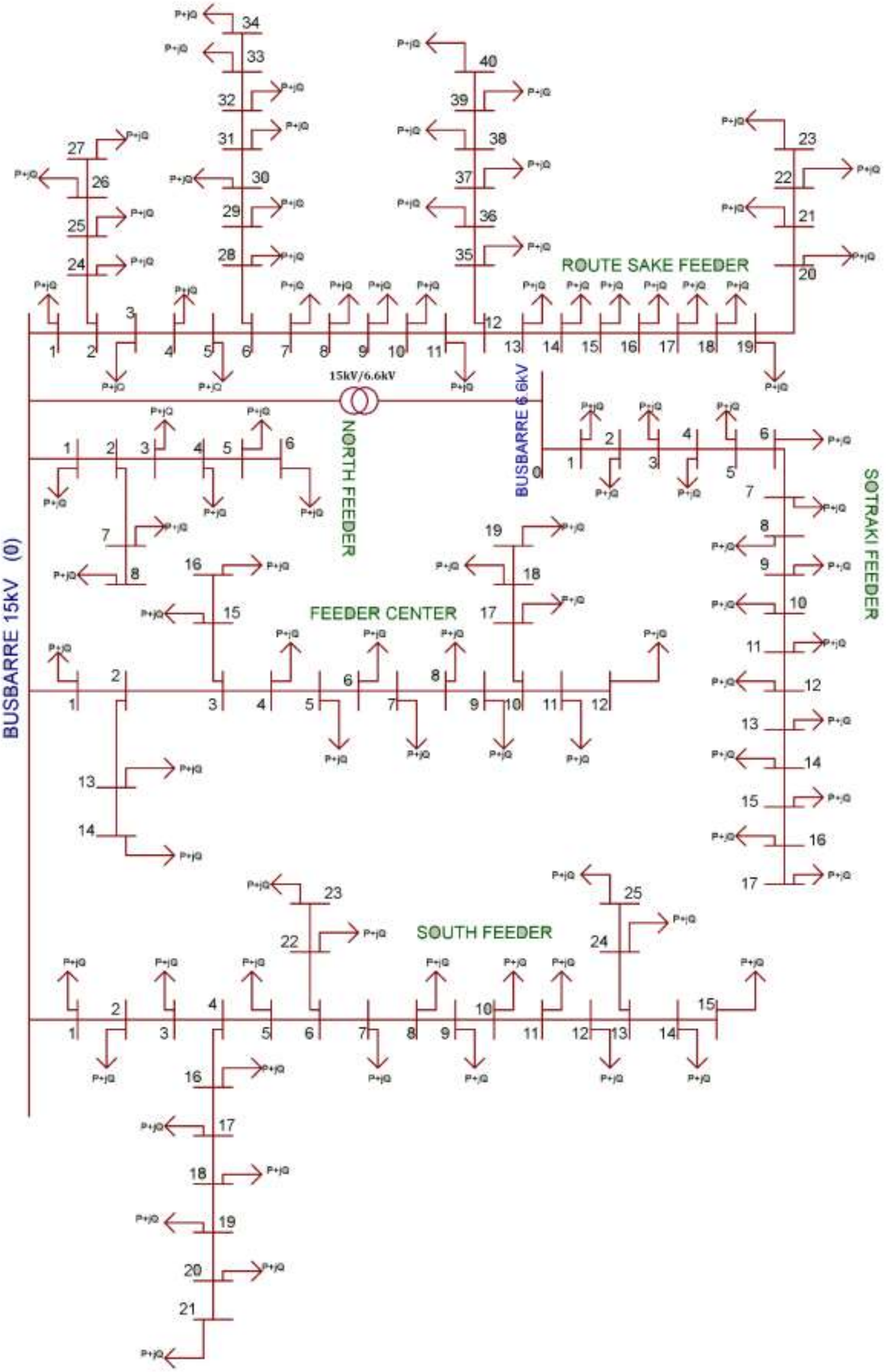

Figure 0.7 Case study single-phase diagram

3.5 CHAPTER CONCLUSION

In this chapter, a quick review of strengths and weaknesses of methods used in different works has been presented. The proposed method also presented in this chapter combines strengths of PSO and FL, it is a two-steps technique that fasten the convergence and improve the accuracy. The chapter ends with a brief presentation of the power system on which the proposed method will be applied.

CHAPTER 4. RESULT AND DISCUSSIONS

4.1 INTRODUCTION

This chapter present the result obtained using FL for placement and PSO for sizing of DGs. The step-by-step algorithm sketched in the previous chapter was implemented and programmed in Matlab 2019a, whose codes are given in Appendix 3. The results are divided in tow sections; the first gives the result of DGs placement and sizing while the second is focused on DG integration effect on the power system losses and voltage profile. Comparison have also been done so as to show the ability of DG optimal sizing and allocation in reducing real and reactive network losses and improving voltage profile in relation to optimal capacitor sizing and placement using analytical method. Table 4.1 gives DSI of all busses and as it can be clearly seen, only Route-sake and Sotraki feeders have some busses which are suitable for DG placement. This is because their lowest buss voltages are out of standards, consequence of a high loss rate. They are the only ones considered in what will follow for optimal placement of DGs.

Table 0.1 Node voltages and DSI of all feeders

Bus number	North feeder		South feeder		Center feeder		Sotraki feeder		Route-Sake feeder	
	Voltage (p.u)	DSI	Voltage (p.u)	DSI	Voltage (p.u)	DSI	Voltage (p.u)	DSI	Voltage (p.u)	DSI
0	1.000	0	1.000	0	1.000	0	1.000	0	1.000	0
1	0.999	0.0821	0.998	0.0907	0.985	0.0995	0.991	0.1041	0.991	0.1011
2	0.998	0.0834	0.994	0.0939	0.973	0.1102	0.989	0.0974	0.977	0.0967
3	0.991	0.9145	0.987	0.1167	0.970	0.1114	0.986	0.0988	0.973	0.1029
4	0.985	0.9101	0.986	0.1397	0.964	0.1042	0.984	0.0967	0.970	0.1072
5	0.982	0.0923	0.982	0.1399	0.956	0.1046	0.977	0.1116	0.960	0.1129
6	0.981	0.1023	0.976	0.1003	0.955	0.2124	0.974	0.1016	0.951	0.1073
7	0.998	0.0901	0.975	0.2768	0.954	0.1022	0.970	0.1111	0.948	0.1029
8	0.998	0.0915	0.973	0.2002	0.952	0.1028	0.968	0.1123	0.942	0.2665
9			0.971	0.2925	0.951	0.2667	0.960	0.1140	0.934	0.2528
10			0.969	0.1762	0.951	0.0986	0.941	0.1120	0.926	0.3520
11			0.968	0.1641	0.950	0.1761	0.918	0.5000	0.920	0.4596
12			0.968	0.1884	0.950	0.1884	0.889	0.6471	0.912	0.0974
13			0.967	0.1455	0.972	0.1995	0.888	0.3717	0.906	0.2662
14			0.966	0.2071	0.972	0.2046	0.883	0.2728	0.900	0.2515
15			0.966	0.1992	0.970	0.0993	0.880	0.2811	0.895	0.3099
16			0.985	0.1519	0.970	0.1014	0.871	0.2623	0.889	0.2461
17			0.985	0.0917	0.950	0.1037	0.867	0.3032	0.885	0.3529
18			0.985	0.0959	0.950	0.0986			0.881	0.3565
19			0.985	0.1167	0.950	0.1148			0.877	0.3645
20			0.985	0.1339					0.875	0.3699
21			0.985	0.1406					0.873	0.3752
22			0.976	0.1053					0.871	0.6883
23			0.976	0.2768					0.871	0.3796
24			0.967	0.2002					0.976	0.1038
25			0.966	0.2071					0.976	0.1042
26									0.975	0.1047
27									0.975	0.1080
28									0.950	0.1059
29									0.949	0.2639
30									0.949	0.1084
31									0.948	0.1041

32									0.948	0.2637
33									0.948	0.1056
34									0.948	0.1034
35									0.908	0.2665
36									0.905	0.2660
37									0.902	0.2650
38									0.899	0.5060
39									0.899	0.1780
40									0.898	0.2739
P Loss (kW)	22.15		179.8		219.6		267.3		558,8	
Q Losse (kVAr)	25.97		210.9		257.5		318.0		888,2	

4.2 RESULTS FOR ROUTE-SAKE FEEDER

The diagram of this feeder is given in Appendix 1 and bus data are as shown in ref [30]. From Table 4.1 busses with DSI more than 0.45 were selected as candidate for optimal DG sizing. The three selected optimal locations and their respective optimal DG sizes were as follows in order of effectiveness:

1. Bus number 22 with a DG size of 2.84 MW
2. Bus number 38 with a DG size of 2.68 MW
3. Bus number 11 with a DG size of 3 MW

4.2.1 Results for real and reactive power losses using different comparisons

Table 4.2 gives optimal DG size for this feeder while comparing this result to what had been found in previous study.

Table 0.2 DG optimal placement and sizing for Route-Sake feeder

Methodology	**Optimal Capacitor placement (Analytical method) ref** [30]												**Optimal DG placement (FL&PSO)**		
Location (Buss N°)	**8**	**10**	**11**	**20**	**21**	**22**	**24**	**27**	**29**	**32**	**34**	**38**	**11**	**22**	**38**
Size (MVar/ MW)	0.9	0.75	0.9	0.075	0.121	0.25	0.3	0.6	0.75	0.9	0.075	0.4	3	2.84	2.68
Active power loss for base case (kW)	558.8														
Reactive power loss for base case (kVar)	888.2														
Active power loss reduction (kW)	153.85												271.23		
Reactive power loss reduction (kVar)	251.23												431.0678		
% Active loss reduction	17.3												51.4		
% Reactive loss reduction	28.3												51.4		

DG placement has a high-power loss reduction potential compare to capacitor due to the fact that they produce active power that can be directly consumed at buss level if we consider a PQ buss. Indeed, reactive power being often just used to create the electro-magnetic field in rotating machines; active component of the complex power carried through the distribution network is therefore more important because it is supposed to produce the work needed at consumer's level (it is higher than the reactive power needed). Producing it optimally at consumption point may decrease the power flowing through distribution networks.

The effect of sizing and locating DG, on both real and reactive power losses is shown by Figure 4.1. Optimal capacitor placement required 12 sites against 3 for DG allocation and the percentage active power loss reduction was 51.4% for this study compared to 17.3% for capacitor placement and sizing. Furthermore, we found that DGs reactive power loss reduction is higher than what had been found in the previous study (51.4% against 28.3%).

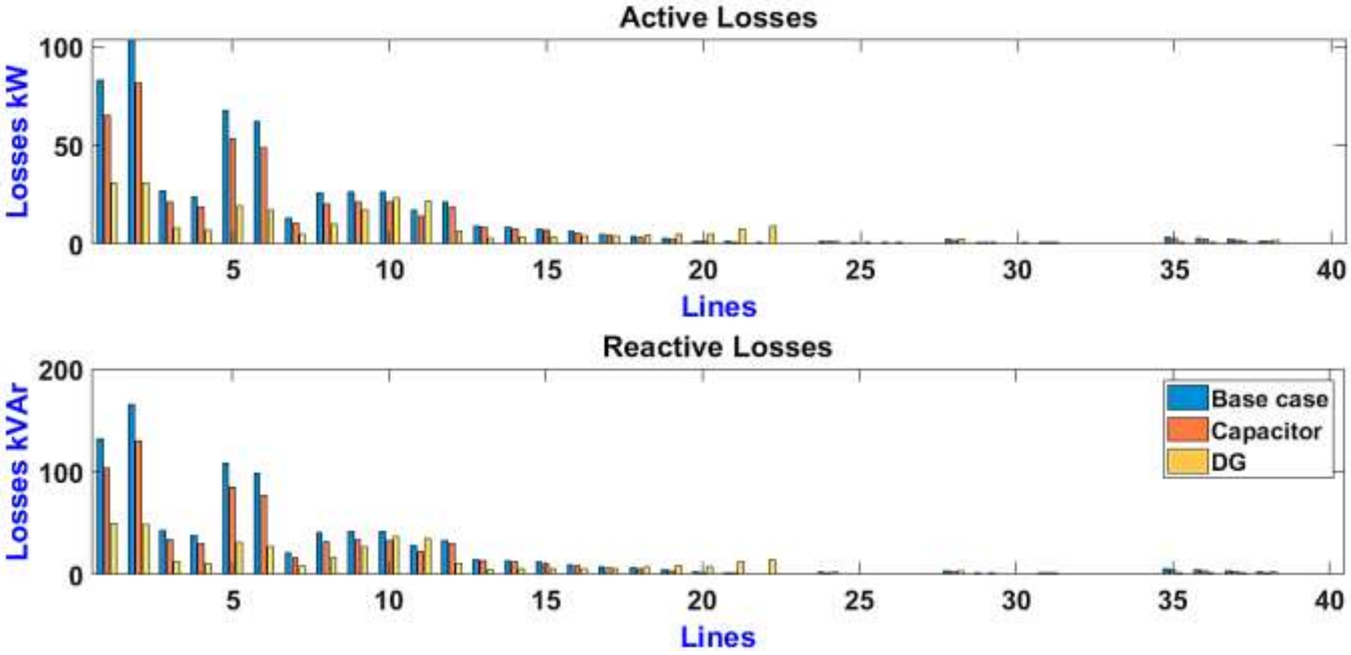

Figure 0.1 Line losses for Route-Sake feeder

4.2.2 Voltage profile comparisons

Producing active power needed by industries, buildings, residential houses at buss level (PQ busses) leads immediately to a reduction in line current magnitude whose impact is voltage profile improvement as shown in figure 4.2. Therefore, voltage drop decreases, enhancing at the same time system power quality.

From Table 4.3 below we can clearly see that the lowest voltage drop with DG is 0.9599 p.u (4 % of the voltage reference) which is a great improvement compare to the base case (without DG). This represents a voltage improvement of 10.2%.

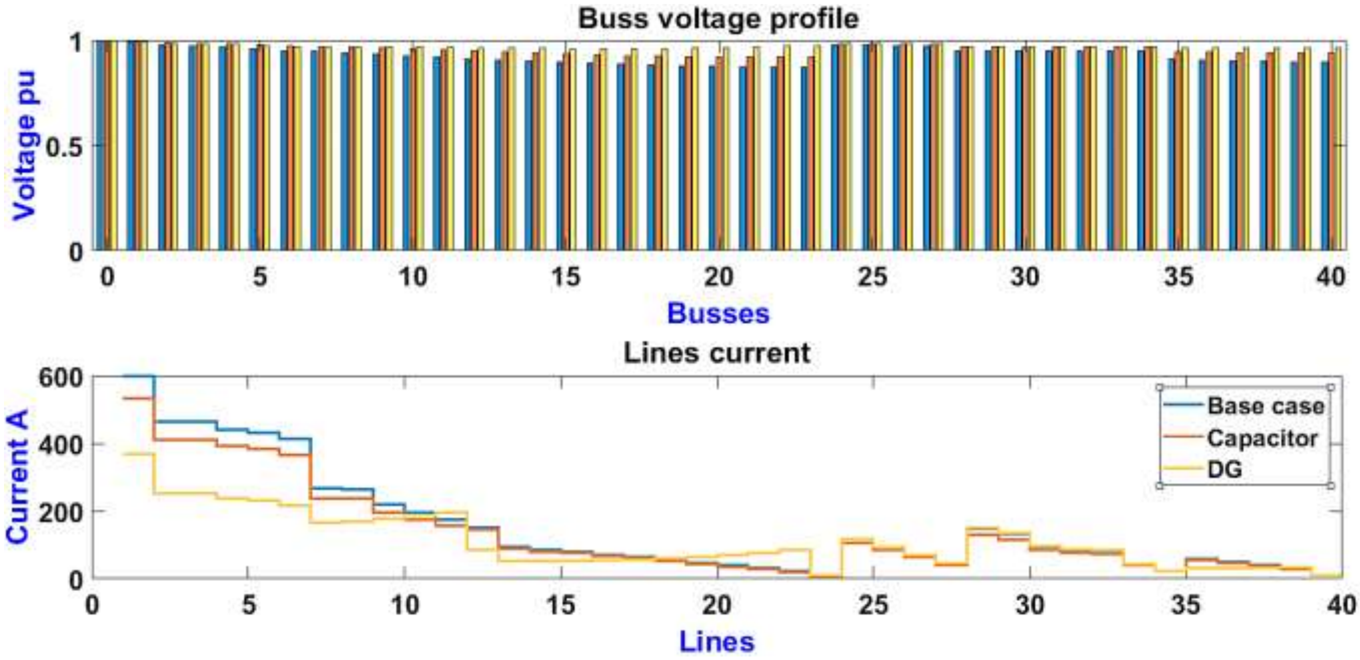

Figure 0.2 Voltage and Current profile for Route-Sake feeder

Table 0.3 Percentage improvement on the lowest buss voltage for Route-Sake feeder

Methodology	Lowest buss voltage (p.u)	% Voltage improvement
Load flow (base case)	0.8711	-
Analytical method (Capacitors) [30]	0.9189	5.49
FL & PSO (DG)	0.9599	10.2

4.3 RESULTS FOR SOTRAKI FEEDER

The diagram of this feeder is given in Appendix 2 and bus data are as shown in ref [30]**.** From Table 4.1 busses with DSI more than 0.45 were selected as candidate for optimal DG sizing. The two selected optimal locations and their respective optimal DG sizes were as follows in order of effectiveness:

1. Bus number 12 with a DG size of 2 MW
2. Bus number 11 with a DG size of 1.8744 MW

4.3.1 Results for real and reactive power losses using different comparisons

Table 4.4 gives optimal DG size for this feeder while comparing this result to what had been found in previous study.

Table 0.4 DG optimal placement and sizing for Sotraki feeder

Methodology	**Optimal Capacitor placement (Analytical method) ref** [30]				**Optimal DG placement (FL&PSO)**	
Location (Buss N°)	**8**	**11**	**21**	**29**	**11**	**38**
Size (MVar/ MW)	0.242	0.5	0.75	0.6	3	2.68
Active power loss for base case (kW)	267.34					
Reactive power loss for base case (kVar)	318.02					
Active power loss reduction (kW)	53.209				163.552	
Reactive power loss reduction (kVar)	63.289				194.756	
% Active loss reduction	19.9				61.2	
% Reactive loss reduction	19.9				61.2	

The effect of sizing and locating DG, on both real and reactive power losses is shown by Figure 4.4. Optimal capacitor placement required 4 sites against 2 for DG allocation and the percentage for both real and reactive power loss reduction was 61.2% each for this study compared to 19.9% each for capacitor placement and sizing.

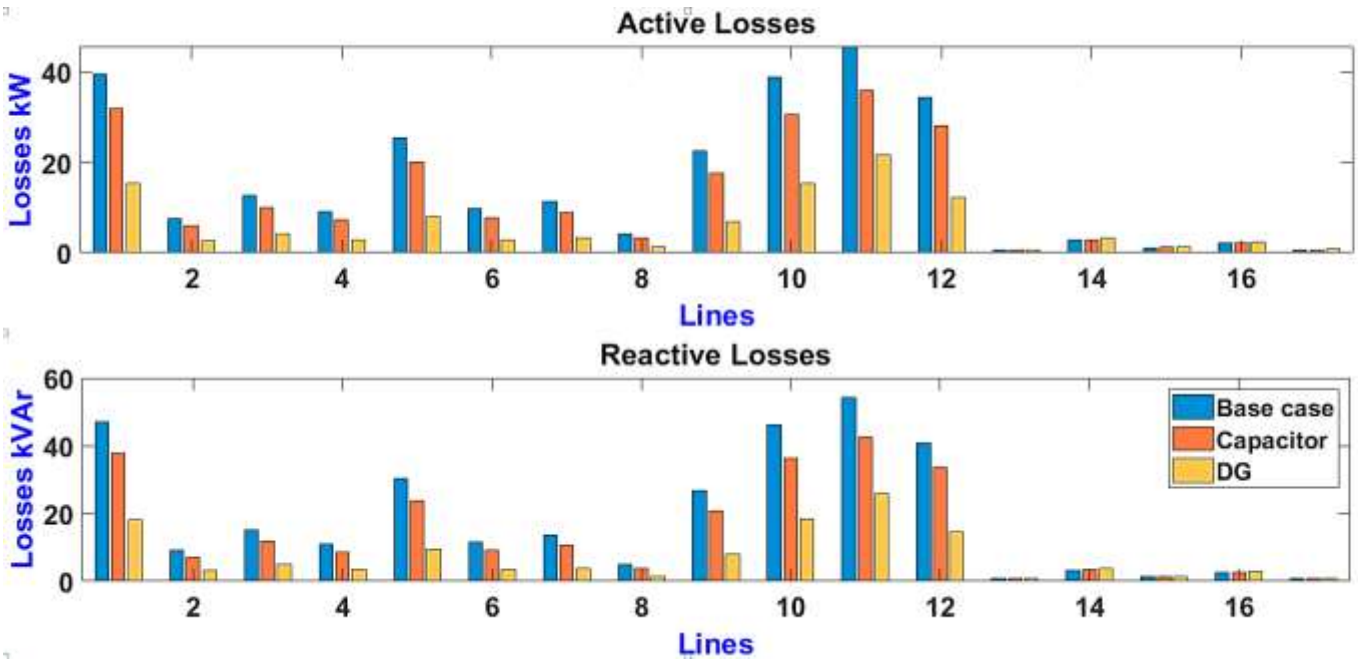

Figure 0.3 Line losses for Sotraki feeder

4.3.2 Voltage profile comparisons

Figure 4.4 gives voltage and line current profiles for different cases, allowing a comparison among them. The maximum line currents is 603 A for base case, 520 A for optimal capacitor placement and 375 A for DG. This reduction in line currents leads to an increase in buss voltage. DGs optimal placement and sizing is therefore more suitable than optimal capacitor location and sizing.

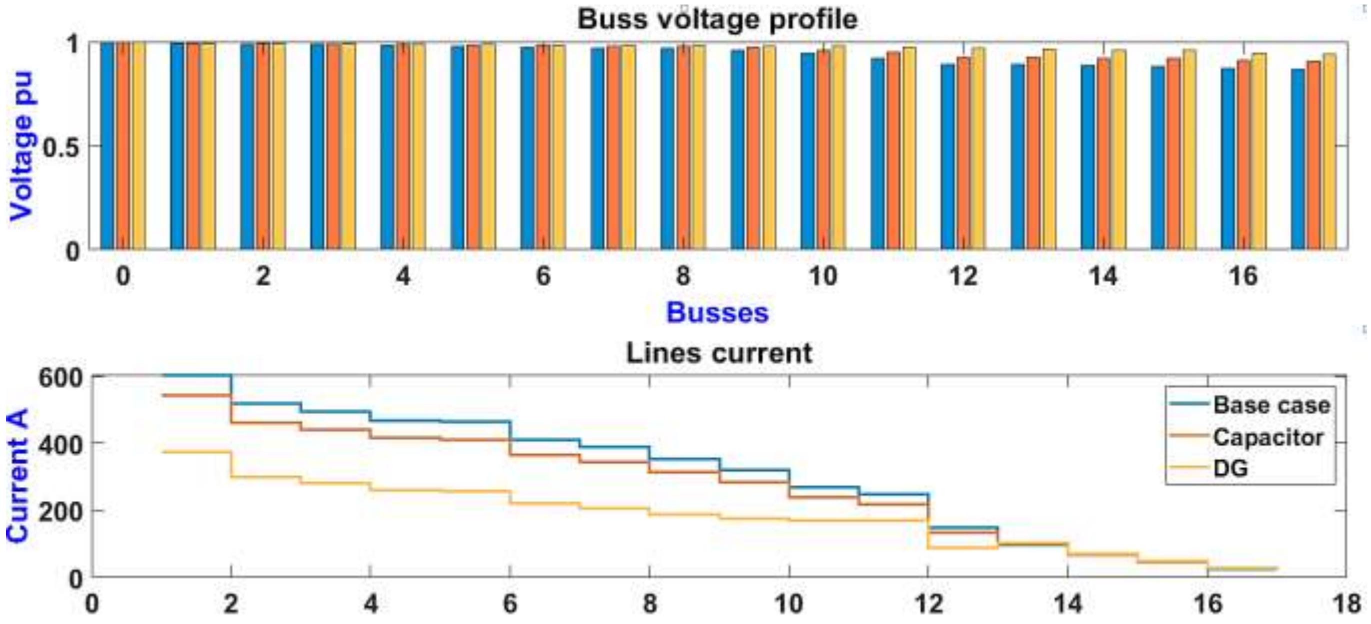

Figure 0.4 Voltage and Current profile for Sotraki feeder

From Table 4.5 below we can clearly see that the lowest voltage drop with DG is 0.9416 p.u (5,84% of the voltage reference) which is a great improvement compare to the base case (without DG). This represents a voltage improvement of 8.55%.

Table 0.5 Sotraki feeder's percentage improvement on the lowest buss voltage

Methodology	Lowest buss voltage (p.u)	% Voltage improvement
Load flow (base case)	0.8674	-
Analytical method (Capacitors) [30]	0.9047	4.3
FL & PSO (DG)	0.9416	8.55

4.4. EFFECTS OF DG PENETRATION ON POWER SYSTEM LOSSES AND BUSS VOLTAGE PROFILE

For this section a study is done so as to show the effects of DG penetration on power system losses and bus profile for both Route-Sake and Sotraki feeders. The number of DGs was assumed to increase from one up to four for both feeders. This was done sequentially ensuring that the candidate bus with the most optimal DSI was chosen first followed by the others in the same order. For location validation purpose, a comparison has been done with a reverse penetration scenario (beginning by the less suitable location). Thus, the most optimal DG location and size obtained in the previous section were considered as optimal DGs size during simulations. To reach the number of four DGs, the restriction on DSI has been reconsidered. Two scenarios have been used:

- Scenario 1: Allocating gradually DGs in ascending order of DSI
- Scenario 2: Allocating gradually DGs in descending order of DSI

4.4.1 Effects on power system losses

Table 4.6 shows the way power system losses evolve as the number of DGs is increased. By placing DGs in ascending order of DSI, we obtain a better power loss reduction than allocating them in descending order of DSI.

Table 0.6 Effect of DG penetration on system power losses

Scenarios	Route-Sake Feeder						Sotraki Feeder				
	Number of DGs	Buss N°	DSI	DG Size	Power losses		Buss N°	DSI	DG size	Power losses	
				MW	kW	kVar			MW	kW	kVar
Scenario 1	One	22	0.6883	2.84	375.051	589.327	12	0.6471	2	124.565	148.18
	Two	22	0.6883	2.84	287.6605	457.18	12	0.6471	2	103.791	123.468
		38	0.506	2.68			11	0.5	1.8744		
	Three	22	0.6883	2.84	271.230	431.0678	12	0.6471	2	155.065	184.461
		38	0.506	2.68			11	0.5	1.8744		
		11	0.4596	3			13	0.3717	0.9801		
	Four	22	0.6883	2.84	370.8084	596.0712	12	0.6471	2	203.134	241.643
		38	0.506	2.68			11	0.5	1.8744		
		11	0.4596	3			13	0.3717	0.9801		
		23	0.3796	1.1448			17	0.3032	0.518		
Scenario 2	One	23	0.3796	3	449.9180	715.0565	17	0.3032	0.518	212.392	252.656
	Two	23	0.3796	3	298.6668	474.6724	17	0.3032	0.518	141.858	168.75
		11	0.4596	2.68			13	0.3717	0.9801		
	Three	23	0.3796	3	289.6299	450.8448	17	0.3032	0.518	164.669	192.616
		11	0.4596	2.68			13	0.3717	0.9801		
		38	0.506	2.84			11	0.5	1.8744		
	Four	23	0.3796		375.0517	596.0712	17	0.3032	0.518	203.134	241.6431
		11	0.4596				13	0.3717	0.9801		
		38	0.506				11	0.5	1.8744		
		22	0.6883				12	0.6471	2		

For example when introducing the first DG considering Route-Sake feeder considering the first scenario real power losses decrease from the base case of 558.8 kW to 375.051 kW (representing 32.8 % of power loss reduction) and reactive from 888.2 kVar to 589.327 kVar (representing 33.6 % of power loss reduction); while the second scenario allows real power losses to decrease just up to 449.918 kW (just 19.4 % of power loss reduction) and reactive power losses to 715.0565 kVar (just 19,5% of power loss reduction).

The same observation can be made for Sotraki feeder where for the first scenario active and reactive power losses are respectively 124.565 kW and 148.18 kVar (53.4 % of power loss reduction from base case); while the second scenario presents active and reactive power losses of 212.392 kW and 252.656kVar (20,5% of power loss reduction from base case). As number of DG increases; power system losses decrease, pass through a minimum then start to raise again. For both scenarios, power systems losses are minimum when number of DGs are three for Route-Sake feeder and two for Sotraki feeder.

Thus, the optimal number of DGs is respectively three for Route-Sake feeder and two for Sotraki feeder. Those numbers of DGs give the highest percentage of power loss reduction which are 51,4 % (both real and reactive power loss reduction) on Route-Sake feeder and 61.2 % on Sotraki feeder. Figure 4.5 shows the change in percentage power loss reduction of both active and reactive power losses as the number of DGs is increased. As it should be expected scenario 1 (which allocate DGs in the ascending order of DSI) present for each number of DGs the highest percentage of power loss reduction.

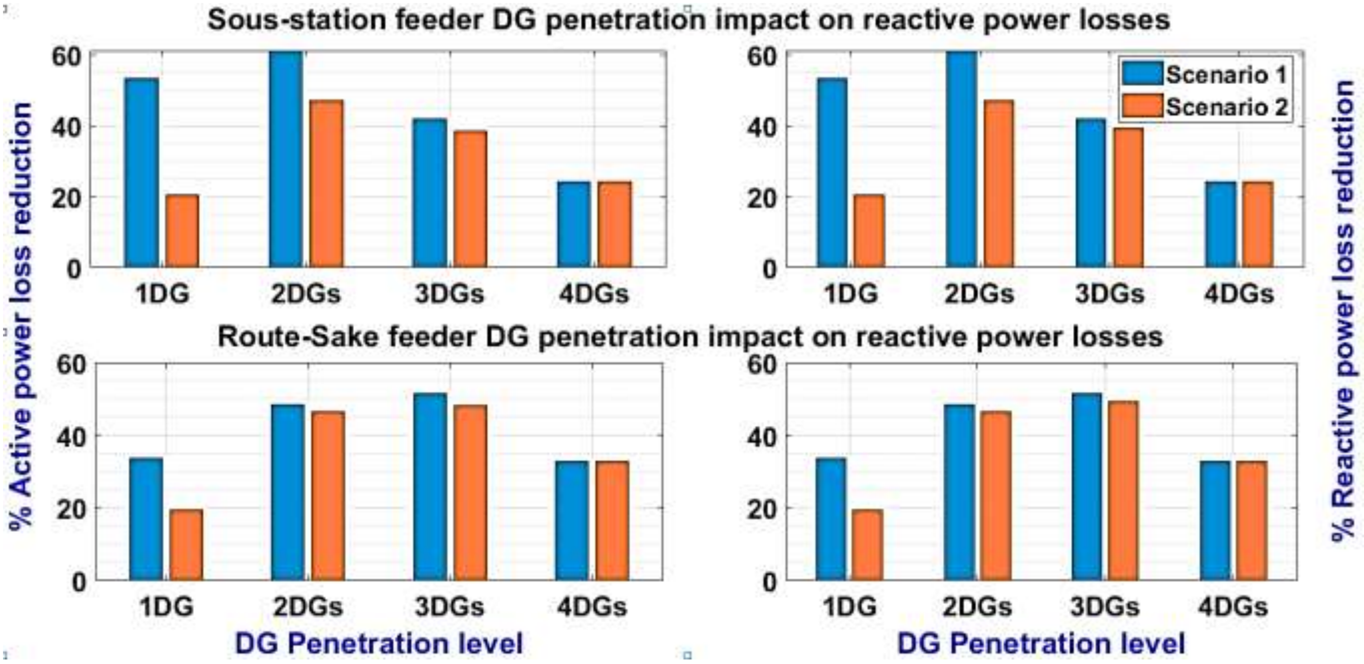

Figure 0.5 DGs penetration impact on power loss reduction

4.4.2 Effect on buss voltage profile

Effects of DGs penetration on voltage profile was investigated so as to figure out the change in buss voltage magnitude as the number of DGs is increased. Increasing the number of DGs leads to an increase in buss voltage. For both feeders, the lowest buss voltage is better when four DGs are optimally placed and sized. For the first scenario, the placement of a single DG brings the lowest buss voltage to the standard IEEE-1159 and ANSI-C84.1 on both feeders; which is not the case for the second scenario where it is necessary to place at least two DGs in order to obtain almost the same result. Table 4.7 gives the lowest voltage magnitude for each feeder with respect to the level of DG penetration.

Table 0.7 Lowest buss voltage for the two scenarios

Scenarios	Number of DGs	R-S feeder’s lowest bus voltage (p.u)	S-S feeder’s lowest bus voltage (p.u)
Scenario 1	Zero	0.8711	0.8674
	One	0.9136	0.9121
	Two	0.9399	0.9416
	Three	0.9599	0.9741
	Four	0.9706	0.9895
Scenario 2	Zero	0.8711	0.8674
	One	0.8904	0.8948
	Two	0.9046	0.9183
	Three	0.9232	0.9470
	Four	0.9706	0.9895

As our objective is to minimize power system losses, number of DGs is selected not by considering the highest voltage improvement, but by considering the highest power loss reduction. The fact is only one DG brings buss voltage in the range sets by standards. The three DGs chosen for Route-Sake feeder have brought the lowest buss voltage from 0.8711 p.u to 0.9599 p.u; thus, reducing the highest voltage drop from 12.9 % to 4% and this is an improvement of 10.2%. The two DGs chosen for Route-Sake feeder have brought the lowest buss voltage from 0.8674 p.u to 0.9416 p.u; thus, reducing the highest voltage drop from 13.26 % to 5.8 % and this is an improvement of 8.55 %.

Neglecting DSI when placing and sizing DG may lead to a pseudo-improvement of the buss voltage. Comparison between the two proposed scenarios shows that if we are financially limited, the buss which have the highest DSI should be the first to be considered when allocating DGs. Figure 4.6 illustrate the impact of both DG penetration and DSI on buss voltage. It can be seen that for each DG penetration level, scenario 1 always present a percentage of voltage improvement higher than scenario two.

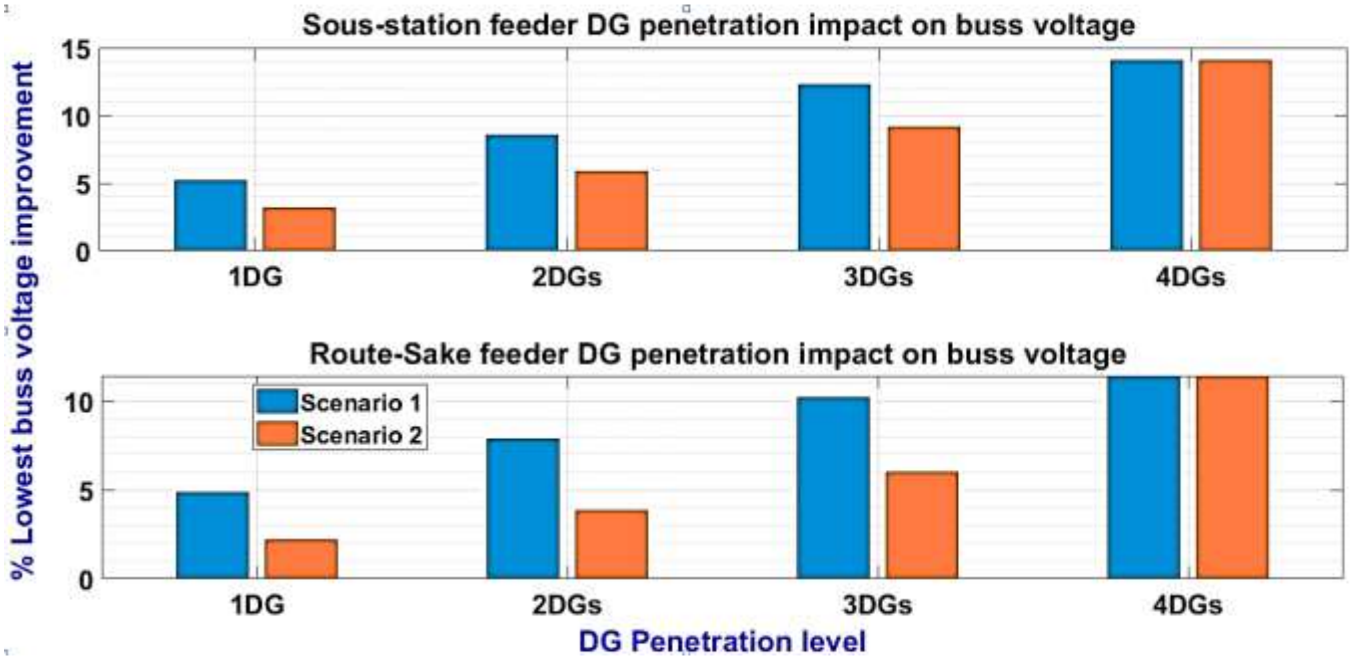

Figure 0.6 Impact of DSI and DG penetration on buss voltage

4.5. CHAPTER CONCLUSION

The chapter shows the simulation results starting by the existing power system for comparison purposes. Optimal placement and location of DGs could therefore be found by implementing the proposed method to the existing network and comparison with previous work results has been done. At the end, a DG penetration level analysis has been done so as to determine the limit for each selected feeder.

CHAPTER 5. CONLUSION AND RECOMMENDATIONS

5.1 CONCLUSION

In conclusion, this research work showed the formulation and implementation of a two steps algorithm to help in reducing system power losses and improving voltage profile by optimizing the location and size of DGs. Power loss reduction index was formulated and used as one of the input parameters in the FL-based first step of the proposed method while power loss minimization problem was solved for sizing DGs in the PSO-based second step. Discharging PSO from siting of DG results in fasten convergence and simulation time reduction. For Sotraki feeder 2 busses were chosen and for Route-Sake feeder 3 busses were chosen as optimal location of DGs. The results have shown that DG placement is more efficient than capacitor placement for the case studied. Indeed, the proposed method has presented the highest power loss reduction. The percentage active and reactive power loss reduction was 51.4% each for Route-Sake and 61.2% each for Sotraki feeder. The voltage profile which was out of standards before DG placement was generally improved with lowest buss voltage of 0.959 p.u for Route-Sake and 0.94 p.u for Sotraki feeder.

The penetration level analysis revealed that there is a number of DGs we should not exceed for an optimal power losses reduction. As soon as the lowest buss voltage lies in the standards during the integration process, considering the optimal size of DGs at their respective site, their optimal number should no longer be dictated by their contribution in voltage improvement but by their power system losses reduction capacity. Indeed, the energy losses located at distribution system level constitute a considerable shortfall for the company in charge of the grid. For Route-Sake and Sotraki feeders, the efficient number of DGs was respectively 3 and 2. Above these numbers, power system losses started to grow (decrease in percentage power loss reduction) for both feeder but the voltage profile kept improving. If the integration is to take place over several years (which is generally the case due to economic and technical limits), DSI has to be considered as one of the key parameters while planning for integrating DGs for the first time in a distribution system.

Thus, the objectives of the research work were achieved successfully and DGs allocation and sizing using FL and PSO method was proved to be a better method for power loss reduction compare to capacitor placement using analytical method. The proposed method results also in more voltage profile improvement.

5.2 CONTRIBUTION TO KNOWLEDGE

The contribution of this work has different aspects depending on parties that play a role in the energy sector of Goma city. REI is a new concept in DRC in general and particularly Goma particularly in Goma. Studies in the integration field are very important so as to offer to energy decision-makers an increased knowledge of this new trend. Some of the direct benefits of this work include:

- This research work is a knowledge support on power loss reduction for distribution companies working in Goma city. This reduction in loses will enable them to avoid some of the penalties and compensations they incur and hence result to an improvement in their profit margins.
- The research work will also ensure that they improve the voltage levels at the consumers to the required limits. This will enable the DISCOs to avoid the costs incurred during compensation of spoilt customer equipment due to voltage deviations outside the acceptable limits. As a result, this makes the companies more economical and reliable in operation
- The work will help the power companies incorporate small-sized green energy sources to their networks easily and more reliably. This is of much importance due to the changing attention in power production with the shifting in green energy.

Other parties will also benefit substantially from this research work. An example of this is the end customers who will feel secure knowing that they are operating their machines with stable voltage profiles. All these benefits relate back to the country’s economy and thus the whole community.

5.3 RECOMMENDATIONS FOR FUTURE WORKS

1. The objective function could be improved by transforming it into a multi-objective function so as to take into consideration other system parameters like cost, stability issues.

2. A part from Solar power plant, other type of DGs could be incorporated in the future works so as to compare their effectiveness in power system losses reduction.

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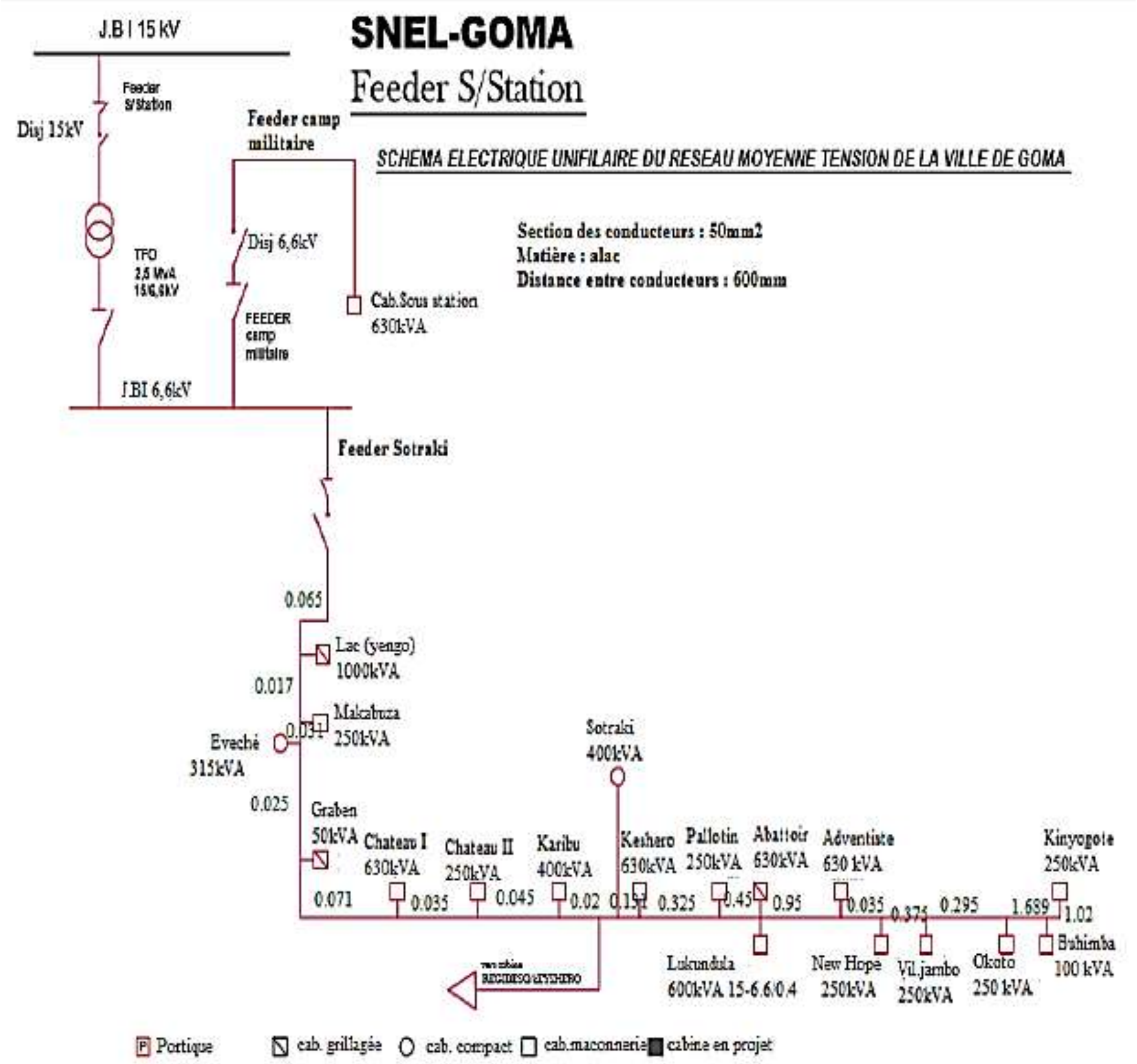
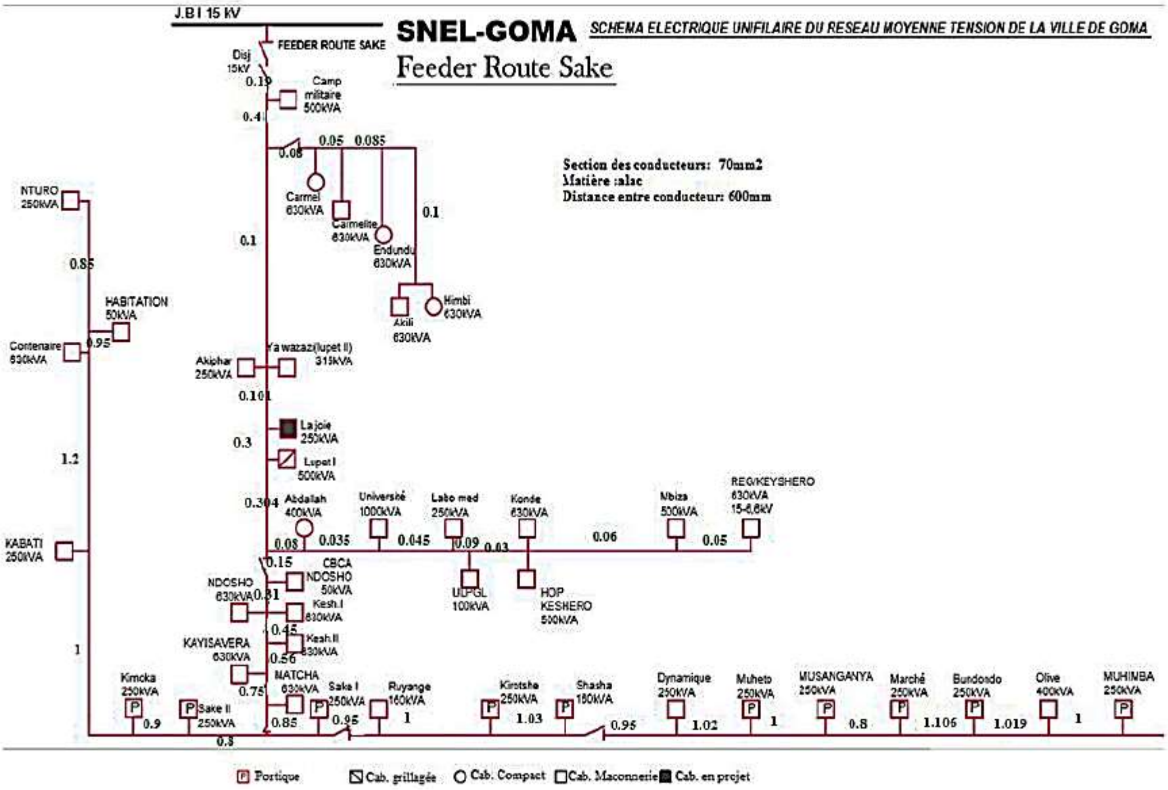
APPENDIX 1: Sotraki feeder single phase diagram, buss load and line length



APPENDIX 2: Route-Sake feeder single phase diagram, buss load and line length



APPENDIX 3: Matlab codes for the research work

Main MATLAB program for Route-Sake feeder

```
% Main program for Optimal DG placement and sizing for Route Sake Feeder
clear all; close all; clc
%line impedance calculation

ro=2.82e-8;%resistivity
D=60e-2; %distance between to conductors
s=70e-6;%section
d=sqrt((4*s)/pi);%diameter
mi = 4*pi*1e-7;% air permeability
f=50;% frequence
w=2*pi*f; %pulsation
Uref= 15000;
Sref= 1500*1e3;
Zref=(Uref^2)/Sref;
Iref= Sref/(sqrt(3)*Uref);
r=d/2;% conductor radius
t=[0.19; 0.4; 0.103; 0.1; 0.3; 0.3; 0.15; 0.3; 0.45; 0.56;
   0.47; 0.75; 0.85; 0.95; 1; 1.03; 0.95; 1.02; 1; 0.81; 1.06; 1.019;
   1; 0.08; 0.05; 0.085; 0.1; 0.08; 0.035; 0.045; 0.09; 0.03;
   0.06; 0.05; 0.8; 0.9; 1; 1.2; 0.95; 0.085]*1e3;%longueurs des troncons.
N=40;%number of branches
NCi=N;
R=zeros(N,1);
L=zeros(N,1);
for n=1:1:N
    R(n,1)= (ro*t(n))/s; %resistance
    L(n,1)=(mi/pi)*(1/4+ log(D/r))*t(n);%inductance
end
R2=R;
X2=L*w;
Z = (R2+ X2*1i)/Zref;
% BIBC matrix

BIBC=zeros(N,N);

for n=1:N
    if n<2
      for o=1:N
            BIBC(n,o)=1;
      end
    end
    if n>=2 && n<=6
        for o=2:23
            if o>=n
                BIBC(n,o)=1;
            end
        end
        for o=28:N
                BIBC(n,o)=1;
        end
    end
    if n>=7 && n<=12
        for o=7:23
            if o>=n
                BIBC(n,o)=1;
            end
        end
        for o=35:N
```

```
            BIBC(n,o)=1;
        end
    end
    if n>=13 && n<=23
        for o= 13:23
            if o>=n
                BIBC(n,o)=1;
            end
        end
    end
   if n>=24 && n<=27
       for o=24:27
           if o>=n
               BIBC(n,o)=1;
           end
       end
   end
   if n>=28 && n<=34
       for o=28:34
           if o>=n
               BIBC(n,o)=1;
           end
       end
   end
   if n>=35
       for o=35:N
           if o>=n
               BIBC(n,o)=1;
           end
       end
   end
end
BIBC;

BCBV=zeros(N,N);
for n=1:N
    if n<=23
      for o=1:23
        if o<=n
            BCBV(n,o)=Z(o,1);
        end
      end
    end
    if n>=24 && n<=27
        for o=1:2
            BCBV(n,o)=Z(o,1);
        end
        for o=24:27
            if o<=n
                BCBV(n,o)=Z(o,1);
            end
        end
    end
    if n>=28 && n<=34
         for o=1:6
            BCBV(n,o)=Z(o,1);
        end
        for o=28:34
            if o<=n
                BCBV(n,o)=Z(o,1);
            end
        end
    end
    if n>=35 && n<=40
```

```
         for o=1:12
            BCBV(n,o)=Z(o,1);
        end
        for o=35:40
            if o<=n
                BCBV(n,o)=Z(o,1);
            end
        end
    end
end
BCBV;


phi=31*pi/180;
Sload=[500 0 565 250 500 0 50 1260 630 630 630 0 250 160 250 160 250 250 250 250 250
400 250 630 630 630 1260 400 1000 250 100 1130 500 630 250 250 250 630 50
250]*1e3/Sref;
P=Sload*cos(phi);
Q=Sload*sin(phi);

%---------------------------FUZZY LOGIC SECTION---------------------------
%-------------------------------------------------------------------------

%load flow base case
[ DV, V1, B1 , Sl,V2 , Ii ] = loadflowdg( N, NCi, BIBC, BCBV, Q, P, Z );
% PLbase=real(Sl);

[ PLI ] = PowerLossIndex( N, NCi, BIBC, BCBV, Q, P, Z );
%load flow Compensated case
% P2=zeros(length(Sload));
% [ DVcom, V1com, Bcom, Slcom, V2com ] = loadflowdg( N, NCi, BIBC, BCBV, Q, P2, Z );
% PLcom=real(Slcom);

% Fuzzy logic for DG placement
[ DSI, CandBuss ] = Candidatebus( PLI , V2 );

DSI;
CandBuss;

% ---------------------------PSO SECTION----------------------------------
%------------------------------------------------------------------------

% PSO parameters
% LB=0;
LB=zeros(1, length(CandBuss));
%Lower bound of the variable
% UB=1.5;
UB=ones(1, length(CandBuss))*1.5;
%Upper bound of the variable
m=length(CandBuss); %number of variable
n=350; %Population size
wmax=0.9; %inertia weight Maximum
wmin=0.4;  %inertia weight Minimum
c1=2; c2=2;  %acceleration factors


for i=1:20     %loop for maximum run
    % Initialization of position and velocity
    for j=1:n
        for k=1:m
            pos(j,k)=LB(1,k)+rand()*(UB(1,k)-LB(1,k));
        end
```

```
    end
    vel=0.1*pos;

    %Function evaluation

    for t=1:n
        Objective(t,1) = Fitness( N, NCi, BIBC, BCBV, Q, P, Z , pos(t,:), CandBuss );
    end

    pbestval=Objective;
    pbest=pos;    %initial pbest

    [fminval, index]=min(Objective);
    gbest=pbest(index,:);  %initial gbest

    % ********** PSO Routine  **********

      for q=1:n
          w=wmax-(q/Maxiter)*(wmax-wmin);
       for j=1:m
         %Update velocity
        vel(q,j)=w*vel(q,j)+ c1*rand()*(pbest(q,j)-pos(q,j))+c2*rand()*(gbest(1,j)-
pos(q,j));

        %update position
        pos(q,j)=vel(q,j)+pos(q,j);

        %handling boundary constraints
        if pos(q,j)<LB(j)
            pos(q,j)=LB(j);
        elseif pos(q,j)>UB(j)
            pos(q,j)=UB(j);
        end

       end

               Objective(q,1) = Fitness( N, NCi, BIBC, BCBV, Q, P, Z , pos(q,:),
CandBuss );
               if Objective(q)<pbestval(q)
                   pbest(q,:)=pos(q,:);
                   pbestval(q)=Objective(q);
                   if pbestval(q)< fminval
                       gbest=pbest(q,:);

                   end
               end
        gbest*Sref;
     end

    F_ans(i)= Fitness( N, NCi, BIBC, BCBV, Q, P, Z , gbest, CandBuss );
    F_gbest(i,:)=gbest;
end

[minLoss, bestRUN]= min(F_ans)
DGsize=F_gbest(bestRUN,:)*Sref

Pdg=P;
for i=1:length(CandBuss)
    Pdg(CandBuss(i))=Pdg(CandBuss(i))-(DGsize(i)/Sref);
end
```

```
[ DV1dg, V1dg, B1dg , S1dg,V2dg , Iidg ] = loadflowdg( N, NCi, BIBC, BCBV, Q, Pdg, Z
);
```

Main matlab program for Sotraki feeder

```
%backward forward method
clear all; close all; clc

ro=2.78e-8;
D=60e-2;
s=50e-6;
d=sqrt((4*s)/pi);
mi = 4*pi*1e-7;
f=50;% frequence
w=2*pi*f; %pulsation
Uref= 6600;
Sref= 1000*1e3;
Zref=(Uref^2)/Sref;
Iref= Sref/(sqrt(3)*Uref);
r=d/2;
l=[0.065; 0.017; 0.031; 0.025; 0.071; 0.035; 0.045; 0.02; 0.131; 0.325; 0.450; 0.95;
0.035; 0.375; 0.295; 1.689; 1.02]*1e3;%longueurs des troncons.
N=17;
NCi=N;
R=zeros(N,1);
L=zeros(N,1);
for n=1:1:N
    R(n,1)= (ro*l(n))/s;
    L(n,1)=(mi/pi)*(1/4+ log(D/r))*l(n);
end
R2=R;
X2=L*w;
Z = (R2+ X2*1i)/Zref;

BIBC=zeros(N,N);
for n=1:1:N
    for o=1:1:N
       if o==n || o>=n+1
       BIBC(n,o)=1;
       end
    end
end
BIBC;

BCBV=zeros(N,N);

 for n=1:1:N
     for o=1:1:N
        if o==n || o<=n-1
            BCBV (n,o)= Z(o,1);
        end
    end
 end
BCBV;
Ni=8;

phi=31*pi/180;
S1=[1000 250 315 50 630 250 400 400 630 250 1230 630 400 250 250 100 250]*1e3/Sref;
P=S1*cos(phi);
Q=S1*sin(phi);
```

```
%---------------------------FUZZY LOGIC SECTION---------------------------
%-------------------------------------------------------------------------

%load flow base case
[ DV, V1, B1 , S1,V2 , Ii ] = loadflowdg( N, NCi, BIBC, BCBV, Q, P, Z );

[ PLI ] = PowerLossIndex( N, NCi, BIBC, BCBV, Q, P, Z );

% Fuzzy logic for DG placement
[ DSI, CandBuss ] = Candidatebus( PLI , V2 );

DSI;
CandBuss;

% --------------------------PSO SECTION----------------------------------
%------------------------------------------------------------------------

% PSO parameters

LB=zeros(1, length(CandBuss));
%Lower bound of the variable
% UB=1.5;
UB=ones(1, length(CandBuss))*2;
%Upper bound of the variable
m=length(CandBuss); %number of variable
n=300; %Population size
wmax=0.9; %inertia weight Maximum
wmin=0.4;  %inertia weight Minimum
c1=2; c2=2;  %acceleration factors

for i=1:20     %loop for maximum run
    % Initialization of position and velocity
    for j=1:n
        for k=1:m
            pos(j,k)=LB(1,k)+rand()*(UB(1,k)-LB(1,k));
        end
    end
    vel=0.1*pos;

    %objective Function evaluation

    for t=1:n
        Objective(t,1) = Fitness( N, NCi, BIBC, BCBV, Q, P, Z , pos(t,:), CandBuss );
    end

    pbestval=Objective;
    pbest=pos;    %initial pbest

    [fminval, index]=min(Objective);
    gbest=pbest(index,:);  %initial gbest

    % ********** PSO Routine  **********

      for q=1:n
          w=wmax-(q/Maxiter)*(wmax-wmin);
       for j=1:m
         %Update velocity
        vel(q,j)=w*vel(q,j)+ c1*rand()*(pbest(q,j)-pos(q,j))+c2*rand()*(gbest(1,j)-
pos(q,j));
```

```
        %update position
        pos(q,j)=vel(q,j)+pos(q,j);

        %handling boundary constraints
        if pos(q,j)<LB(j)
            pos(q,j)=LB(j);
        elseif pos(q,j)>UB(j)
            pos(q,j)=UB(j);
        end

       end

               Objective(q,1) = Fitness( N, NCi, BIBC, BCBV, Q, P, Z , pos(q,:),
CandBuss );
               if Objective(q)<pbestval(q)
                   pbest(q,:)=pos(q,:);
                   pbestval(q)=Objective(q);
                   if pbestval(q)< fminval
                       gbest=pbest(q,:);

                   end
               end
        gbest*Sref;
     end


    F_ans(i)= Fitness( N, NCi, BIBC, BCBV, Q, P, Z , gbest, CandBuss );
    F_gbest(i,:)=gbest;
end

[minLoss, bestRUN]= min(F_ans)
DGsize=F_gbest(bestRUN,:)*Sref

Pdg=P;
for i=1:length(CandBuss)
    Pdg(CandBuss(i))=Pdg(CandBuss(i))-(DGsize(i)/Sref);
end
[ DV1dg, V1dg, B1dg , S1dg,V2dg , Iidg ] = loadflowdg( N, NCi, BIBC, BCBV, Q, Pdg,
```

Sub-program for load flow calculation

```
function [ DV, V1, B1 , Sl,V2 , Ii ] = loadflowdg( N, NCi, BIBC, BCBV, Q, P, Z )
Ni=15; %number of itaration
V=zeros(N+1,Ni);
V(1:N+1,1:Ni)=1;%bus voltage initialization
DV1=zeros(N+1,Ni);
I=zeros(NCi,Ni);
B=zeros(N,Ni);
Sl=zeros(N,1);
for k=1:Ni-1
    for j=1:NCi
        I(j,k)= conj((P(1,j)+Q(1,j)*1i)/(V(j+1,k)));
    end
    for l=1:N
   B(l,k)=BIBC(l,:)*I(:,k);
    end
    for n=2:N+1
   DV1(n,k)=BCBV(n-1,:)*B(:,k);
    end
    for o=2:N+1
```

```
   V(o,k+1)=V(1,Ni)+DV1(o,k);
    end
end
DV=DV1(1:N+1,Ni-1);
V1=V(1,Ni)-(DV1(1:N+1,Ni-1));
V2=V(1,Ni)-(DV1(2:N+1,Ni-1));
Ii=I(1:NCi,Ni-1);
B1=B(1:N,Ni-1);
% Power loss calculation
   for n=1:N
    Sl(n,1)=Z(n,1)*abs(B(n,Ni-1))^2;
   end
end
```

Sub-program for PLI calculation

```
function  PLI  = PowerLossIndex( N, NCi, BIBC, BCBV, Q, P, Z )
%Base case
PLI=zeros(NCi,1);
[ ~ , ~ , ~ , Sl, ~ , ~ ] = loadflowdg( N, NCi, BIBC, BCBV, Q, P, Z );
PLbase=sum(real(Sl));
%power loss reduction for each node
PLi=zeros(NCi,1);
Pc=P;
for i=1:NCi
    if i==1
      Pc(i)=0;
      [ ~ , ~ , ~ , Sl, ~ , ~ ] = loadflowdg( N, NCi, BIBC, BCBV, Q, Pc, Z );
      PLi(i)=PLbase-sum(real(Sl));
    end
    if i>1
      Pc(i-1)=P(i-1);
      Pc(i)=0;
      [ ~ , ~ , ~ , Sl, ~ , ~ ] = loadflowdg( N, NCi, BIBC, BCBV, Q, Pc, Z );
      PLi(i)=PLbase-sum(real(Sl));
    end
end
PLi;
PLmax=max(PLi);
PLmin=min(PLi);

% PLI computation
for i=1:NCi
    PLI(i)=(PLi(i)-PLmin)/(PLmax-PLmin);
end
PLI;
end
```

Sub-program for selecting candidate busses (FL section)

```
function [ DSI, CandBuss ] = Candidatebus( PLI  , V )

Vabs=abs(V);
%Fuzzy logic section
range=[0 1];
fuzy_struct= newfis('FES'); %Generate new fuzzy
% input variable power loss index
L=[0 0 0 0.3];
LM=[0 0.3 0.3 0.5];
```

```
M=[0.3 0.5 0.5 0.7];
HM=[0.5 0.7 0.7 1];
H=[0.7 1 1 1];


fuzy_struct = addvar(fuzy_struct,'input','PLRI',range);
fuzy_struct = addmf(fuzy_struct,'input',1,'L','trapmf',L);
fuzy_struct = addmf(fuzy_struct,'input',1,'LM','trapmf',LM);
fuzy_struct = addmf(fuzy_struct,'input',1,'M','trapmf',M);
fuzy_struct = addmf(fuzy_struct,'input',1,'HM','trapmf',HM);
fuzy_struct = addmf(fuzy_struct,'input',1,'H','trapmf',H);
figure,plotmf(fuzy_struct,'input',1);

%second inputvariable Voltage index
range=[0.8 1];
L=[0.8 0.8 0.83 0.86];
LM=[0.84 0.87 0.87 0.90];
M=[0.88 0.91 0.91 0.94];
HM=[0.92 0.94 0.94 0.97];
H=[0.95 0.97 1 1];

fuzy_struct = addvar(fuzy_struct,'input','VI',range);
fuzy_struct = addmf(fuzy_struct,'input',2,'L','trapmf',L);
fuzy_struct = addmf(fuzy_struct,'input',2,'LM','trapmf',LM);
fuzy_struct = addmf(fuzy_struct,'input',2,'M','trapmf',M);
fuzy_struct = addmf(fuzy_struct,'input',2,'HM','trapmf',HM);
fuzy_struct = addmf(fuzy_struct,'input',2,'H','trapmf',H);
figure,plotmf(fuzy_struct,'input',2);

%output variable  DG suitability index
range=[0 1];
L=[0 0 0 0.3];
LM=[0 0.3 0.3 0.5];
M=[0.3 0.5 0.5 0.7];
HM=[0.5 0.7 0.7 1];
H=[0.7 1 1 1];

fuzy_struct = addvar(fuzy_struct,'output','DSI',range);
fuzy_struct = addmf(fuzy_struct,'output',1,'L','trapmf',L);
fuzy_struct = addmf(fuzy_struct,'output',1,'LM','trapmf',LM);
fuzy_struct = addmf(fuzy_struct,'output',1,'M','trapmf',M);
fuzy_struct = addmf(fuzy_struct,'output',1,'HM','trapmf',HM);
fuzy_struct = addmf(fuzy_struct,'output',1,'H','trapmf',H);
figure,plotmf(fuzy_struct,'output',1);

%add fuzzy rules
rule_mat=[1 1 2 1 1
    1 2 2 1 1
    1 3 1 1 1
    1 4 1 1 1
    1 5 1 1 1
    2 1 3 1 1
    2 2 2 1 1
    2 3 2 1 1
    2 4 1 1 1
    2 5 1 1 1
    3 1 4 1 1
    3 2 3 1 1
    3 3 2 1 1
    3 4 1 1 1
    3 5 1 1 1
    4 1 4 1 1
```

```
    4  2  4  1  1
    4  3  3  1  1
    4  4  2  1  1
    4  5  1  1  1
    5  1  5  1  1
    5  2  4  1  1
    5  3  3  1  1
    5  4  2  1  1
    5  5  2  1  1
    ];

fuzy_struct=addrule(fuzy_struct,rule_mat);
showrule(fuzy_struct);

%Fuzzy inference calculations
Inputs= [PLI Vabs];
FIC=evalfis(Inputs, fuzy_struct)

%ranking all busses
[RFIC, BussNo]=sort(FIC, 'Descend');

DSI=[RFIC , BussNo];
CandBuss=find(FIC>=0.45);

end
```

Sub-program for fitness determination

```
function Objective = Fitness( N, NCi, BIBC, BCBV, Q, P, Z , gbest, CandBuss )

for i=1:length(CandBuss)
    P(CandBuss(i))=P(CandBuss(i))-gbest(i);
end
[ ~ , ~ , B1 , S1 , V2 , ~ ] = loadflowdg( N, NCi, BIBC, BCBV, Q, P, Z );
P;
Ploss=real(S1);
abs(V2);
%constraints formulation
% Con=[];
Con1=abs(V2);  % votltage constraint
Con2=abs(B1); %current constraint
Vmax=1.01; Vmin=0.96;
Bmax=5; Bmin=0;
for i=1:length(Con1)
    if Con1(i)>=Vmax || Con1(i)<=Vmin
        Pen(i)=1;
    else
        Pen(i)=0;
    end
end
for i=1:length(Con2)
    if Con2(i)>=Bmax || Con2(i)<=Bmin
        Pen(i)=Pen(i)+1;
    else
        Pen(i)=Pen(i)+0;
    end
end
```

```
Penalty=10000000;
Objective=sum(Ploss)+Penalty * sum(Pen);

end
```

Appendix 4: Turnitin certificate of originality

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