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**Integration of Renewable Energy Sources into Electrical
Distribution Networks**

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Dedication

With deep gratitude and sincere words, I dedicate this humble work at the end of my studies to:

☞ To my dear and respected parents:

No words of dedication can truly express the depth of my attachment, love, and gratitude toward you. I offer you this modest work as a token of appreciation for all the sacrifices and great kindness you have always given me. I hope that one day I will be able to repay even a small part of everything you have done for me.

☞ To my dear brothers and sisters:

Youssef, Amal, Rachid, Siham, and Sofiane, and especially the youngest and closest to my heart, Asmaa. I also extend my gratitude to my sisters-in-law, Aya and Maryam, who have always been like sisters to me. Thank you for your continuous support, your love, and your encouragement, which have been a true source of strength throughout this work.

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Words cannot fully express how grateful I am to you. Thank you for always being there whenever I needed support, motivation, and encouragement. Thank you for all the special moments we shared together, moments that will never be forgotten. Thank you for your presence in my life, for your kind soul, and for every single thing you have done for me. I could not find a better opportunity than this to express part of my gratitude and affection toward you, because there are so many feelings inside me that words cannot describe. And from this place, I promise you that we will build a life together.

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Mohammed allouche

Dedication

Not all achievements are measured by degrees and certificates; some are measured by the amount of hardship a person hides behind a smile, and by the number of times they came close to giving up but still chose to continue the journey.

To the soul of my beloved father, may he rest in peace, whose presence is gone but whose impact remains forever. I wished for his presence in this moment more than ever, to witness the result of years of hard work. Your place will always remain محفوظاً in my heart, and this achievement will always carry a part of you.

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To everyone who believed in me, supported me, and stood by my side throughout these years, I dedicate this humble work to you. It was written through hardship, completed with hope, and achieved thanks to those who stood beside me.

To all of you...I dedicate the fruit of my efforts and the pride of this important stage of my life.

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Praise be to God, who granted us success and guidance, gave us strength and perseverance, and helped us accomplish this work after a long journey of effort and learning. Today, we present the fruits of our knowledge and hard work, which have finally come to completion.

These are our humble words, addressed to everyone who opens this dissertation, hoping that each reader may benefit from its content, appreciate what it offers, and provide constructive criticism where needed.

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To our beloved parents, no words are sufficient to describe the depth of our gratitude and love for your endless support, sacrifices, and encouragement.

Finally, we wish continued success and prosperity to all of us and to everyone who contributed to this achievement.

Thank you all.

ملخص

نظرًا للنمو السكاني، والتطور الاقتصادي، ومتطلبات الحياة العصرية، يشهد الطلب العالمي على الطاقة الكهربائية زيادة ملحوظة. ولمواجهة هذا التزايد، يتجه مشغلو شبكات التوزيع بشكل متزايد إلى دمج مصادر التوليد الموزع (DG) غير أنه من أجل تقليل خسائر القدرة الفعالة وتحسين ملف الجهد، يجب التخطيط بدقة لمواقع وأحجام وحدات التوليد هذه. في هذه المذكرة، يُقترح تطبيق خوارزمية الخفاش (Bat Algorithm - BA)، وهي إحدى الخوارزميات الميتاهيوريستية الحديثة، لحل مشكلة التحسين هذه. وقد تمت صياغة مسألة الإدماج الأمثل لمصادر التوليد الموزع بالاعتماد على ثلاثة أهداف رئيسية، تتمثل في: تقليل خسائر القدرة، وتحسين ملف الجهد، وتعزيز استقرار الشبكة. وقد تم التحقق من فعالية المنهجية المقترحة من خلال تطبيقها على شبكة التوزيع القياسية IEEE ذات 33 عقدة، حيث أكدت النتائج المتحصل عليها الكفاءة العالية لخوارزمية الخفاش في تحقيق الأهداف المرجوة.

الكلمات المفتاحية

التوليد الموزع، خوارزمية الخفاش، تحسين شبكات التوزيع، تقليل خسائر القدرة، تحسين ملف الجهد، استقرار الشبكة، شبكة IEEE ذات 33 عقدة.

Abstract

Due to population growth, economic development, and the increasing demands of modern life, the global demand for electrical energy is experiencing a significant rise. To address this challenge, distribution network operators are increasingly integrating Distributed Generation (DG) into their systems. However, to minimize active power losses and optimize the voltage profile, the location and size of these generation units must be carefully determined. This thesis proposes the application of the Bat Algorithm (BA), a recent metaheuristic optimization technique, to solve this optimization problem. The optimal integration of distributed generation is formulated as a multi-objective problem based on three main objectives: reducing power losses, improving the voltage profile, and enhancing network stability. The proposed approach is validated on the standard IEEE 33-bus distribution system. The obtained results clearly demonstrate the effectiveness of the Bat Algorithm in achieving the desired objectives and improving the overall performance of the distribution network.

Keywords

Distributed Generation, Bat Algorithm, distribution network optimization, power loss reduction, voltage profile improvement, network stability, IEEE 33-bus system.

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Acronyms and Abbreviations

HT — High Voltage
HTB — High Voltage Category B
HTA — High Voltage Category A
BTB — Low Voltage Category B
BTA — Low Voltage Category A
TBT — Very Low Voltage
SONELGAZ — National Electricity and Gas Company
OSE — Electricity System Operator
SCADA — Supervisory Control And Data Acquisition
AIE — International Energy Agency
GED — Distributed Energy Generation
LP — Linear Programming
NLP — Non-Linear Programming
GA — Genetic Algorithm
ACO — Ant Colony Optimization
ABC — Artificial Bee Colony
SFLA — Shuffled Frog-Leaping Algorithm
CSA — Cuckoo Search Algorithm
PSO — Particle Swarm Optimization
BA — Bat Algorithm
p.u — Per Unit

Nomenclature

S_{Base} — Base power

V_{Base} — Base voltage

R_i — Resistance of branch i

X_i — Reactance of branch i

P_G, Q_G — Active and reactive power generated at the source node

P_{Li}, Q_{Li} — Active and reactive power demanded at node i

$P_{(loss,i)}, Q_{(loss,i)}$ — Active and reactive power losses of line i

$P_{(PVS_i)}, Q_{(PVS_i)}$ — Active and reactive power generated by the i -th PVS

$P_{(PVS_i)}^{Min}, Q_{(PVS_i)}^{Min}$ — Minimum active and reactive power generated by the i -th PVS

$P_{(T, Loss, wo)}$ — Total active power loss in the base case

V_i — Voltage at node i

$V_{(min,i)}, V_{(max,i)}$ — Minimum and maximum voltage at node i

V_{ref} — Reference voltage

VD — Voltage deviation

S_{li} — Apparent power transmitted in line i

S_{li}^{max} — Maximum apparent power transmitted in line i

N_b — Total number of network branches

N_n — Total number of loads in the network

$NPVS$ — Total number of photovoltaic sources

X^T — System state variable vector

K_V — Voltage penalty factor

K_S — Power penalty factor

$H(V)$ — Penalty function for node voltage violations

$H(S)$ — Penalty function for line power flow violations

F_{Obj} — Objective function

General Introduction

The electrical power distribution sector is undergoing rapid and profound transformations driven by the continuous growth in energy demand, the global shift toward the utilization of renewable energy sources, and the technical challenges associated with enhancing the efficiency and reliability of electrical networks. In this context, Distributed Generation (DG) has emerged as one of the most promising solutions for improving the performance of distribution systems by locating generation sources closer to consumption centers, thereby reducing power losses, improving power quality, and enhancing voltage stability.

However, the integration of distributed generation units into distribution networks can only achieve its expected benefits when their locations and capacities are optimally determined, taking into account the operational characteristics of the network and the technical constraints imposed upon it. Consequently, advanced optimization techniques based on intelligent algorithms have gained significant attention due to their proven effectiveness in solving complex, nonlinear, and multi-objective optimization problems.

This dissertation aims to investigate the impact of the optimal integration of distributed generation sources and the structural reconfiguration of electrical distribution networks through the application of the Bat Algorithm (BA) to the IEEE 33-bus test system, which is widely recognized as a benchmark model in scientific research. The study formulates a multi-objective optimization problem focused on minimizing active power losses, improving voltage stability, and enhancing the overall operational efficiency of the distribution network.

This research is of particular importance in light of the growing transition toward smart grids and sustainable power systems. Its findings provide both scientific and practical contributions to the development of effective strategies for integrating renewable energy sources and improving the performance of modern electrical distribution networks.

Chapter 1

General Overview of Electrical Networks and Distributed Generation (DG)

1.1 Introduction

Electrical power network constitute the essential infrastructure responsible for delivering electricity from generation facilities to end users. In Algeria, electric power systems operate using a three phase alternating current with a standard frequency of 50 Hz. These networks are composed of a large number of interconnected elements, including generators, transformers, transmission and-distribution lines, protection devices, and-control equipment [1]

The liberalization of electricity markets, growing environmental concerns associated with global-climate-change, and rapid technological-advancements in renewable-based distributed-generation have significantly-transformed-power-systems, particularly distribution-networks. Traditionally, distribution-systems-were-designed-solely to transfer-electrical-energy in a one-way direction, from the transmission grid to medium- and low-voltage-consumers. Consequently, they were not originally intended to accommodate local generation units connected directly to the network.

The contribution of distributed energy resources is expected to continue increasing in the coming years. While this evolution offers numerous benefits, it also introduces several technical challenges for existing distribution infrastructures. These include impacts on system stability, complications in protection coordination, voltage regulation issues, and greater complexity in maintaining acceptable voltage profiles throughout the network.

To address-these challenges, utility-companies and regulatory authorities-are-undertaking initiatives-aimed at upgrading-electrical-infrastructures, with particular-emphasis on distribution-systems. The objective is to enhance network-operation, reliability, and security. One of the most-promising-solutions is the deployment of Distribution Smart Grid technologies. These advanced networks-incorporate-modern-communication platforms, intelligent monitoring-devices, and sophisticated-management techniques that facilitate the integration of renewable energy-sources while-improving the overall efficiency and performance-of the electrical system [2].

This chapter begins with an overview of conventional electrical power networks, followed by a more detailed presentation of distribution systems and their main characteristics. It then introduces the concept of smart distribution grids, discussing their definition, key features,

objectives, and the various functions associated with intelligent power networks. Finally, the chapter examines the different categories of distributed generation according to the energy source employed and their capability to supply active and reactive power.

1.2 Electrical Power System Structure

An electrical power system refers to the complete infrastructure involved in the generation, transmission, and delivery of electricity. It encompasses power plants as well as the transmission, sub-transmission, and distribution networks responsible for transferring electrical energy from generating stations to end users [3].

Electricity generation is traditionally based on dispatchable primary energy resources such as fossil-fuel thermal power stations, nuclear plants, and hydroelectric facilities. These installations generally employ large-scale generating units capable of adjusting their output according to operational, economic, and security requirements. Power systems are designed and operated to withstand severe disturbances without leading to widespread blackouts or cascading failures that could affect interconnected networks. In addition, they must ensure the rapid restoration of service following major incidents or equipment outages [4].

In conventional power systems, electricity is delivered to consumers through a hierarchical network structure. Energy is transmitted over extra-high-voltage (EHV) networks ($U_n > 50$ kV), then supplied through medium-voltage (MV) systems (1 kV $< U_n < 50$ kV), and finally distributed to customers via low-voltage (LV) networks ($U_n < 1$ kV). High-voltage transmission networks are generally interconnected in a meshed configuration to guarantee reliability and continuity of supply in the event of component failures. Conversely, medium and low-voltage distribution systems have historically been designed as passive networks, with little or no local generation and limited active load participation. These systems are usually operated using radial configurations, which simplify protection coordination and improve operational robustness.

Because of this architecture, electrical power traditionally flows in a single direction, from generating units toward consumers. The secure operation of the system requires a continuous balance between generated power and customer demand. Consequently, power production must be monitored and adjusted in real time to accommodate load variations while complying with the operational constraints established by the transmission system operator. This

vertically integrated structure offers several advantages, including lower operating costs, shared reserve capacity among generating units, improved efficiency of large-scale power plants, and enhanced system reliability through reduced failure risks [5].

The organization of transmission and distribution networks can be classified according to voltage levels, as illustrated in Figure 1.1.

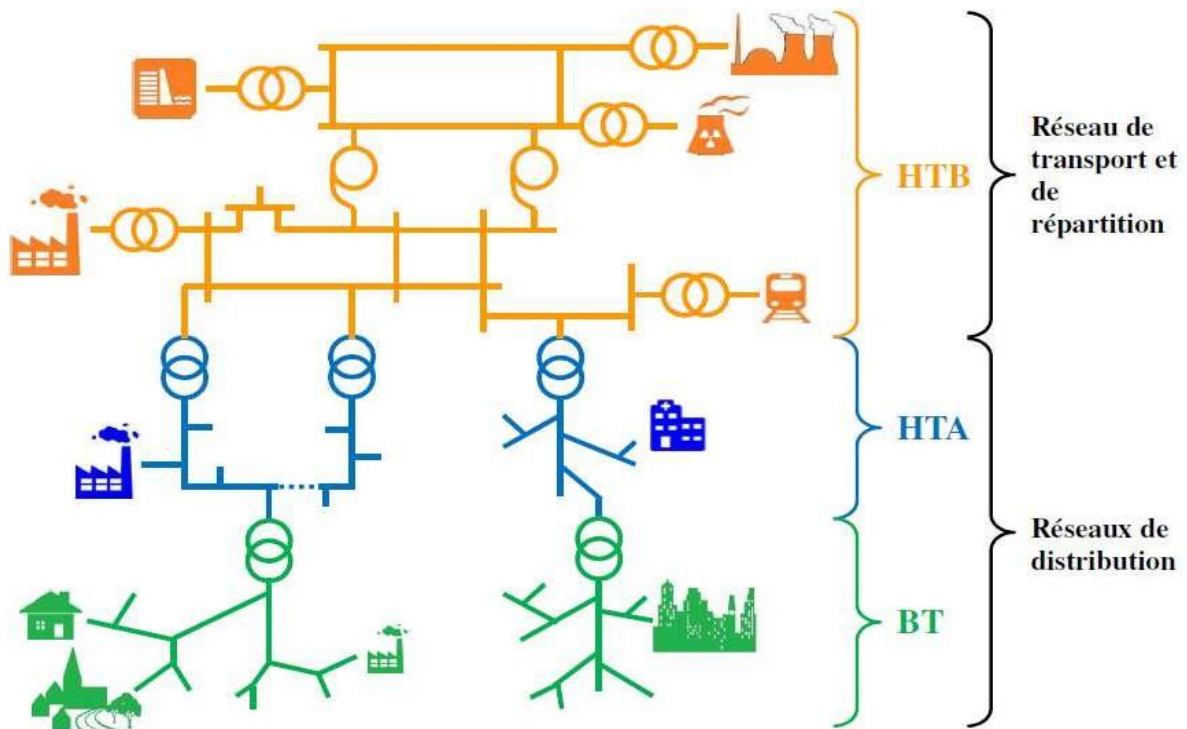


Figure 1.1: Organization of Electrical Power Networks According to Voltage Levels [15]

Concerns related to global climate change, has significantly transformed modern power systems. These changes are particularly evident in distribution networks due to the rapid growth of distributed generation resources. The integration of decentralized generation has led to the emergence of a new network architecture in which small- and medium-scale generating units are connected directly to distribution systems. The installation of these resources at medium-voltage (mv) and low-voltage (lv) levels has considerably altered the traditional hierarchical organization of power systems. As a result, power no longer flows exclusively from higher voltage levels toward end users. Instead, electricity can circulate in multiple directions, including between distribution feeders and, under certain operating conditions, from lower voltage levels back toward upstream networks. Consequently, distribution systems are evolving from passive infrastructures into active and dynamic networks [6].

Furthermore, the development of new large-scale power plants and the expansion of high-voltage transmission infrastructures have become increasingly challenging because of high investment costs, limited availability of suitable land, and growing public opposition to such projects. For these reasons, the deployment of alternative and decentralized generation technologies has been strongly encouraged. The main driving factors include:

- The progressive depletion of fossil fuel reserves, which have traditionally served as the primary energy source for conventional thermal power stations;
- International environmental commitments, particularly those inspired by the Kyoto Protocol, which promote the increased use of renewable and sustainable energy resources for electricity production;
- Public concerns regarding the safety, environmental impact, and long-term management of nuclear energy facilities;
- The significant ecological and social consequences associated with the construction of large dams and reservoirs for hydroelectric power generation, which can substantially affect local ecosystems and communities.

In addition, locating generation facilities close to consumption centers improves the ability to supply critical loads during major disturbances or emergency situations. At the same time, numerous small-scale electricity generation technologies have reached a sufficient level of technological maturity, making their widespread deployment within modern electrical networks both technically feasible and economically attractive [4, 7].

1.4 Distribution Networks

1.4.1 General Technical Characteristics

Distribution networks form the most critical part of the electrical power system, as they represent the final interface supplying the majority of end users. They typically operate at voltage levels below 50 kV, corresponding to the medium-voltage (MV) and low-voltage (LV) domains. In Algeria, standard MV distribution voltages are 10 kV and 30 kV. These voltage levels provide an effective technical compromise that helps reduce voltage drops along feeders, limit the number of primary substations (HV/MV connection points), and mitigate the technical, economic, and safety constraints associated with higher voltage operation.

In most cases, distribution networks are operated using a radial configuration. This topology simplifies protection schemes since power flows are predominantly unidirectional, from the HV/MV substations toward MV/LV transformers and final consumers. Such an arrangement facilitates fault detection and isolation, improves system maintenance operations, and enables easier energy metering at supply points. Backup or interconnection schemes between primary substations are also implemented to enhance supply reliability and reduce the number of customers affected during outage conditions [6].

1.4.2 Operational Schemes

1.4.2.1 HV/MV Substation (Bulk Supply Substation)

Distribution networks are supplied through HV/MV substations (bulk supply substations), which in their initial configuration consist of a single transformer fed by a high-voltage (HV) incoming line (HT1) and connected to one or two busbar systems (Figure 1.2.a). In a second development stage, as demand increases, a second transformer is installed to operate alongside the first one, forming a transformer pair commonly referred to as a half-bus arrangement. On the MV side, an additional busbar is introduced to feed the various outgoing distribution feeders.

Under normal conditions, the transformers operate in a radial mode. However, in the event of a failure, one transformer can be isolated and the load transferred to the remaining unit, provided that its loading does not exceed approximately 50% of its rated capacity under standard operating conditions (Figure 1.2.b). These substations are typically also connected to a second HV incoming line (HT2), known as a “backup or reserve line,” to enhance supply reliability.

In the final configuration stage, a third transformer and sometimes more is added, often connected in a double-infeed arrangement (Figure 1.2.c). The MV feeders are organized by half-bus sections according to their technical characteristics (overhead or underground lines) and according to the similarity of their load profiles, which is related to the type of customers

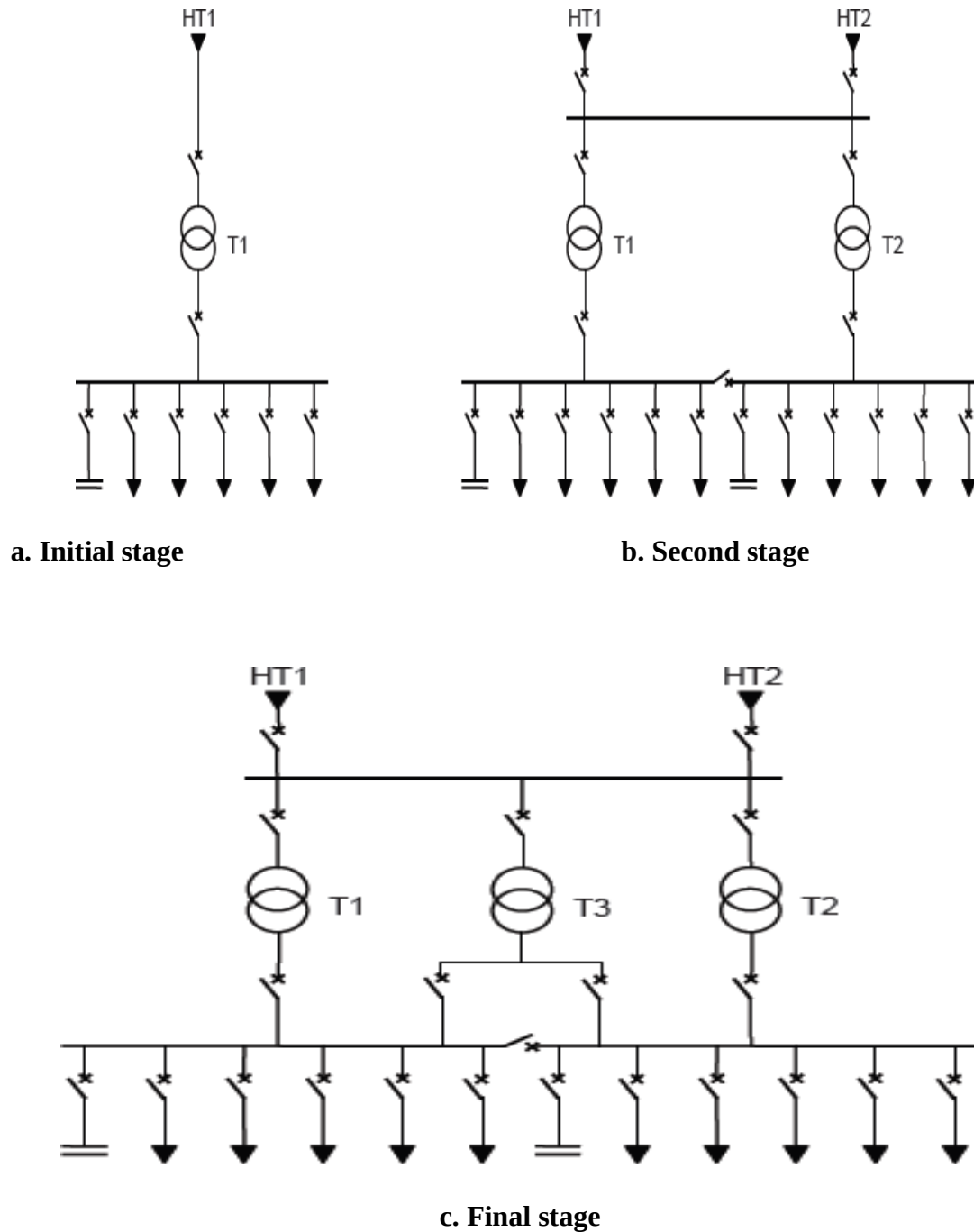


Figure 1.2: Schematic Diagram of HV/MV Substations (Bulk Supply Substations)

1.4.2.2 MV Lines and Feeders

In sparsely populated rural areas, distribution systems are mainly composed of overhead lines arranged in simple radial feeders (Figure 1.3), which are generally more economical than underground cable installations. The design of such networks is primarily constrained by the maximum allowable voltage drop, due to the considerable distance between the supply point and the end consumers. Voltage levels decrease gradually along the feeder as a result of line impedance and connected load demand (Figure 1.4).

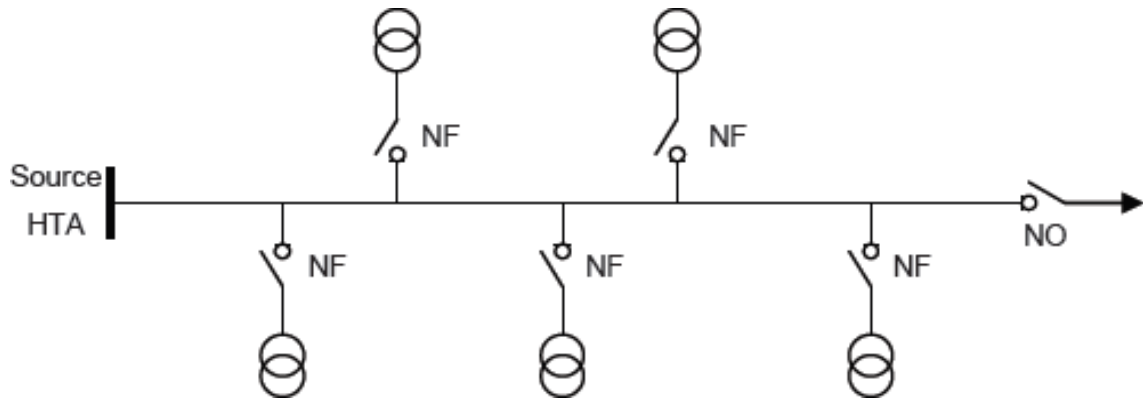


Figure 1.3: Radial Feeder Configuration Diagram

Where: NF and NO represent, respectively, normally closed switch and normally open switch.

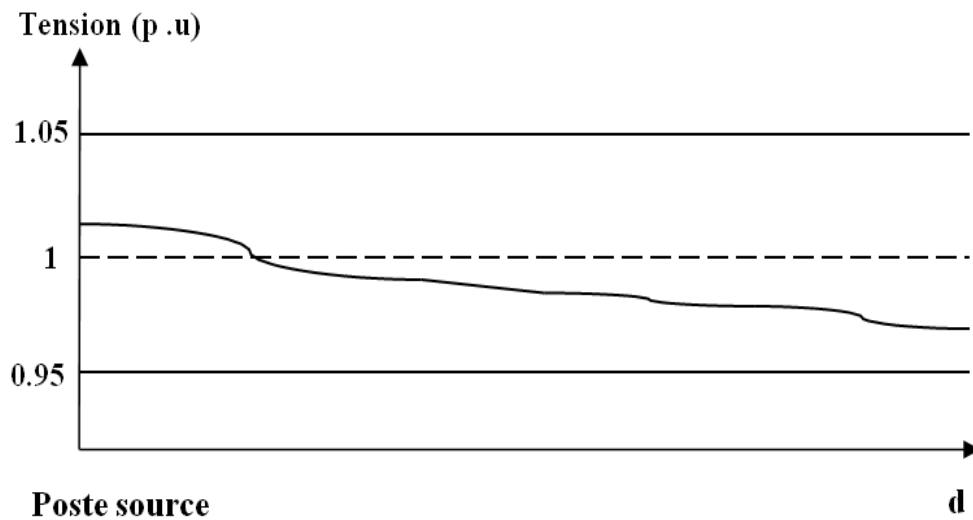


Figure 1.4: Voltage Variation Along an MV (HTA) Feeder

In urban or densely loaded mixed areas, distribution networks are mainly composed of underground medium-voltage (MV/HTA) cables arranged in double-feeder configurations (Figure 1.5) or ring-main (open-loop) systems. Compared to overhead lines, these underground networks are less affected by voltage drops due to their shorter lengths and their electrical characteristics, including higher homopolar capacitance.

The main design constraint for underground distribution infrastructure is the maximum current carrying capacity of the cables, which becomes critical in areas with high load density where significant power demand must be supplied.

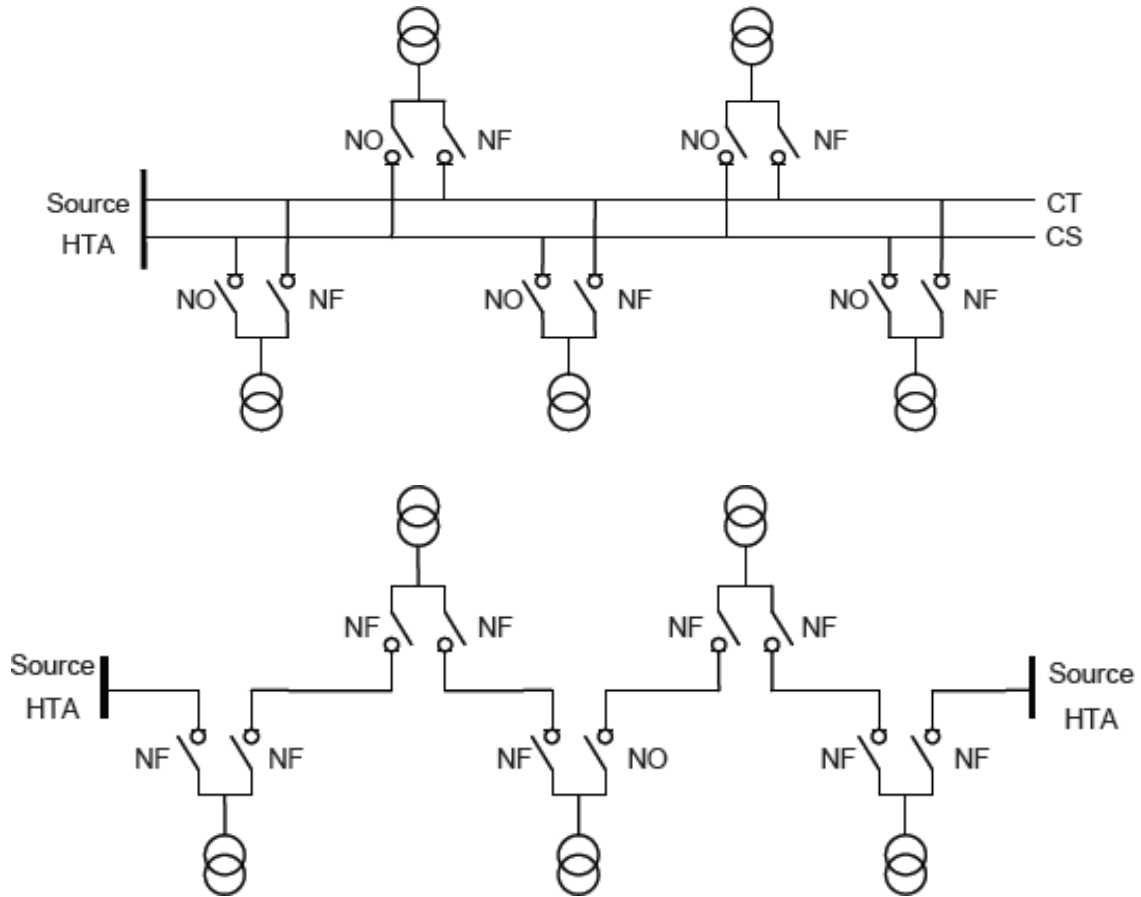


Figure 1.5: Double Feeder Configuration Diagram

Figure 1.8: Ring Main (Open-Loop) Configuration Diagram

CT and CS represent the working cable and the backup cable, respectively, ensuring service continuity in the event of a fault.

1.5 Distributed Generation and Its Impact on Distribution Networks

1.5.1 Definition of Distributed Generation

Since the early 1990s, the structure and operation of electrical power systems have been increasingly questioned due to economic, environmental, and political pressures. The slowdown in electricity demand growth has reduced the justification for large-scale

investments in centralized generation facilities. This situation is further reinforced by public acceptance issues: while consumers demand low-cost electricity, there is often strong opposition to the construction of large power plants in nearby areas. At the same time, growing environmental awareness has encouraged utilities and policymakers to promote decentralized electricity production, which is conceptually opposed to traditional centralized generation connected to the transmission grid [4].

Decentralized generation is primarily based on renewable energy sources and cogeneration technologies, aiming to improve overall energy efficiency and reduce environmental impact. This shift has led to the emergence of a new category of producers known as distributed generation (DG), which contributes to cleaner and more flexible energy systems.

The literature indicates that there is no single universally accepted definition of distributed generation. In some countries, it is defined according to the voltage level at which generation units are connected to the grid. In others, it is characterized by the fact that these units supply electricity directly to local loads. Another approach defines distributed generation based on specific technical attributes, such as the use of renewable energy sources, cogeneration systems, or non-dispatchable generation technologies, among others.

Distributed generation units differ from centralized power plants mainly in their smaller size and their typical connection to distribution networks rather than transmission systems [5]. They can be classified according to their rated capacity [7, 8]. In this context, micro DG units range from 1 W to 5 kW, small DG units from 5 kW to 5 MW, and medium DG units from 5 MW to 50 MW, typically connected to distribution networks. In contrast, large-scale centralized generation units generally range from 50 MW to 300 MW.

1.5.2 Types of Distributed Generation

Classifications of distributed generation are generally established based on the type of primary energy source used [4,5] as well as on the capability of the units to supply active and reactive power [9].

According to the energy source, distributed generation can be divided into two main categories: renewable energy sources and non-renewable energy sources.

The main renewable energy sources include:

- **Hydropower:** Hydroelectric plants operate by exploiting the gravitational potential energy of water from rivers, lakes, or dams. The generated power depends on both the water head and flow rate. In distributed generation applications, small hydropower plants (micro-hydro systems) are typically used, with power levels on the order of up to 5 MW. The main advantages of this technology are the availability of the primary energy source and the stability of electricity production. However, its main drawbacks include high initial investment costs and potential environmental impacts.

- **Wind energy:** Wind turbines convert the kinetic energy of wind into electrical energy through a rotor system connected to a gearbox and generator. This energy source has experienced significant growth due to technological advancements and its favorable environmental profile. Although investment costs can be high, especially for offshore installations, the primary energy is free and environmental impacts are relatively low.

- **Geothermal energy:** Geothermal systems utilize heat from underground water reservoirs, which can reach temperatures up to 350 °C in favorable locations. This heat can be extracted directly or used indirectly to produce steam, which drives conventional turbines in thermal power plants.

- **Solar energy:** Solar radiation can be converted either directly into DC electricity using photovoltaic systems, often used in isolated or off-grid applications combined with storage systems, or indirectly through solar thermal systems. In the latter case, solar energy is concentrated using mirrors or collectors to heat a working fluid, producing steam that drives turbines. Despite several available technologies, solar thermal power remains relatively limited in large-scale deployment.

- **Biomass:** Some thermal power plants use biomass-derived fuels as their primary energy source. Agricultural residues, municipal waste, biogas, and forestry by-products can be used to generate heat, which is then converted into electricity. This technology is increasingly applied in rural areas.

Two main types of non-renewable distributed generation technologies can also be identified:

- **Fossil fuel-based systems (gas, coal, oil):** These systems operate on the same principle as large thermal power plants. The combustion of fossil fuels produces heat, which is then converted into electricity. The main technologies include steam turbine plants, gas turbines, and internal combustion engines (diesel engines). These systems can also operate in cogeneration mode, simultaneously producing electricity and useful heat, achieving very high overall efficiency.

- **Hydrogen-based systems:** Fuel cells generate electricity directly from hydrogen and oxygen through an electrochemical process that is the reverse of water electrolysis. Although considered a promising future energy carrier, hydrogen is not naturally available in usable form and requires energy for production. The main technologies currently under development are PEMFC (Proton Exchange Membrane Fuel Cell) for low-power applications and SOFC (Solid Oxide Fuel Cell) for stationary cogeneration systems. However, these technologies remain expensive and are not yet widely deployed.

Distributed generation can also be classified into four categories based on the ability to supply active and reactive power:

- **Type 1:** Units capable of supplying only active power, such as photovoltaic systems, microturbines, and fuel cells, typically connected to the grid through power electronic converters/inverters.

- **Type 2:** Units capable of supplying both active and reactive power. This category includes systems based on synchronous machines, such as cogeneration units and gas turbines.

- **Type 3:** Units capable of supplying only reactive power. Synchronous compensators and similar devices operating at or near zero power factor are typical examples.

- **Type 4:** Units that supply active power while absorbing reactive power. Induction generators, commonly used in wind energy systems, fall into this category.

1.5.3 Impacts of Distributed Generation on Distribution Networks

Previous studies have shown that increasing penetration levels of distributed generation (DG) can significantly influence the future operation of distribution networks [10,11]. In

particular, the voltage profile of the system may be substantially altered by the presence of DG units [12], to the extent that voltage levels at certain buses may exceed their upper operational limits, even when acceptable values are maintained at the primary substation [13]. Protection coordination schemes may also be affected due to the contribution of DG to short-circuit currents downstream of protective devices, the possible reversal of power flow in certain feeders, and the reduction of fault clearing times [11].

On the other hand, DG installations located close to consumption points help reduce active power flows through the network, thereby decreasing transmission losses. However, many DG technologies rely on intermittent primary energy sources, such as wind and solar, which makes short-term power output difficult to predict [12]. As a result, these units cannot always guarantee a fixed power delivery or fully participate in energy markets based on available capacity [16].

The integration of DG into distribution systems can therefore have significant effects on overall system behavior, including power flow distribution, voltage regulation, reliability, and operational flexibility. The main impacts can be summarized as follows:

1.5.3.1 Impact on Power Flow

The integration of distributed generation (DG) changes the conventional operating behavior of distribution networks. Traditionally, most distribution systems are designed for unidirectional power flow, where electricity moves from the primary substation toward end users. The introduction of DG adds an additional generation source within the network itself.

When the power produced by a DG unit exceeds the local downstream demand, the surplus energy is exported back toward the upstream network, leading to a reversal of power flow direction. At certain points between the DG location and the primary substation, the net power flow may even become zero due to the balancing effect between local generation and load demand. Figure 1.6 illustrates the variation between maximum and minimum power flow levels in a distribution network, both with and without DG integration [17].

In a system without DG, the maximum power flow occurs during peak demand periods, while the minimum flow corresponds to low consumption periods. After the integration of DG, this behavior is reversed: maximum power flow is observed when demand is low, whereas minimum power flow occurs during peak load conditions. This change in power flow

characteristics is particularly important when analyzing voltage drop behavior and voltage regulation within distribution networks.

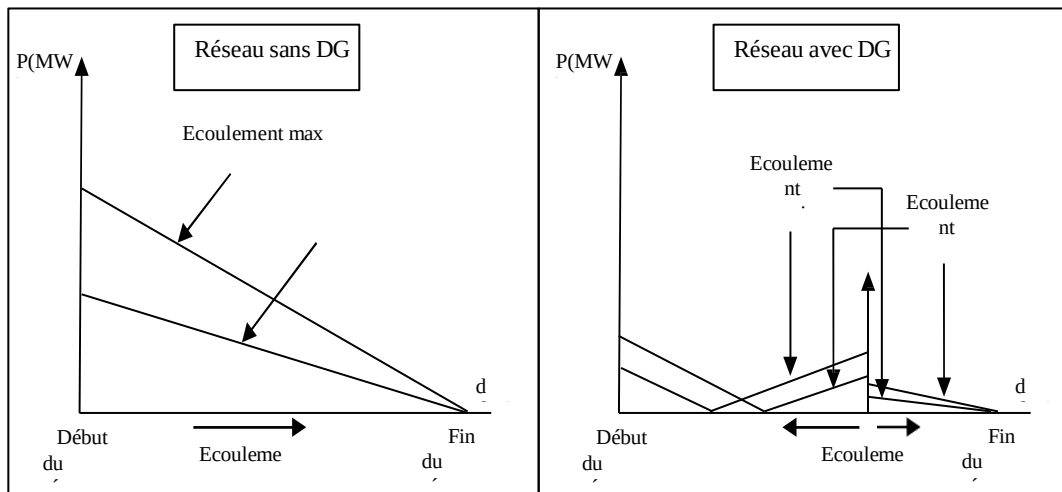


Figure 1.6: Impact of Distributed Generation on Power Flow

Figure 1.7 divides the distribution network into two main segments: section *ag*, which extends from the beginning of the feeder up to the location of the generator, and section *gc*, which runs from the generator toward the end of the network. In section *ag*, a zero-power point may appear, corresponding to the balance between the power supplied by the upstream grid and the power injected by the generator.

In contrast, in section *gc*, the power flow can be seen as the combined contribution of both the upstream network and the local generating unit. This means that the electrical energy in this part of the system is the result of the superposition of power coming from the main grid and that produced by the distributed generation source [17].

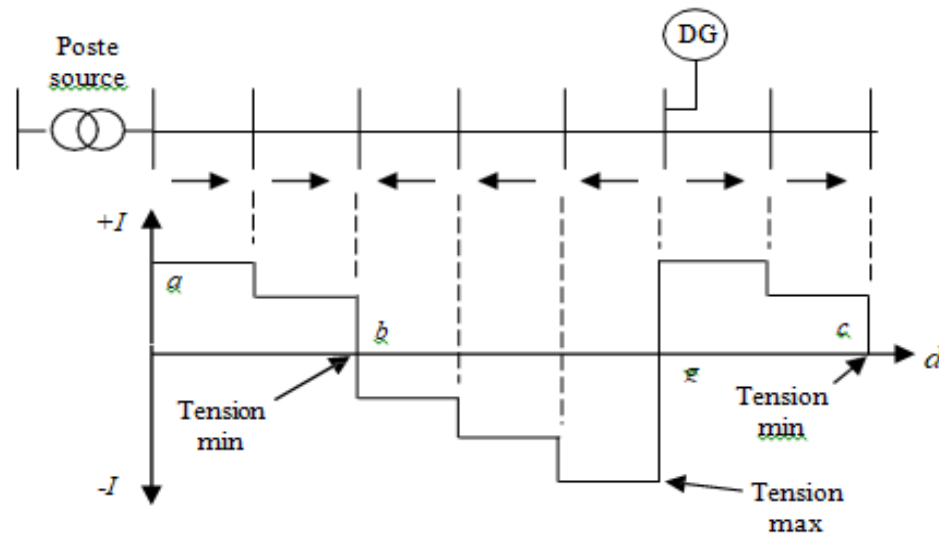


Figure 1.7: Example of Power Flow Under an Operating Condition

1.5.3.2 Impact on Voltage Profile and Stability

conventional feeder without DG, the voltage typically decreases progressively as the distance from the primary substation increases, as shown in Figure 1.8. However, the integration of one or more DG units can locally raise voltage levels at specific points along the network.

These local voltage increases may, under certain operating conditions, evolve into overvoltage situations that exceed permissible limits, especially during periods of low load demand [4]. In this work, the objective is to maintain network voltages within acceptable operating boundaries through the proper and optimal placement of DG units, in order to ensure a positive impact on both voltage profile and system stability.

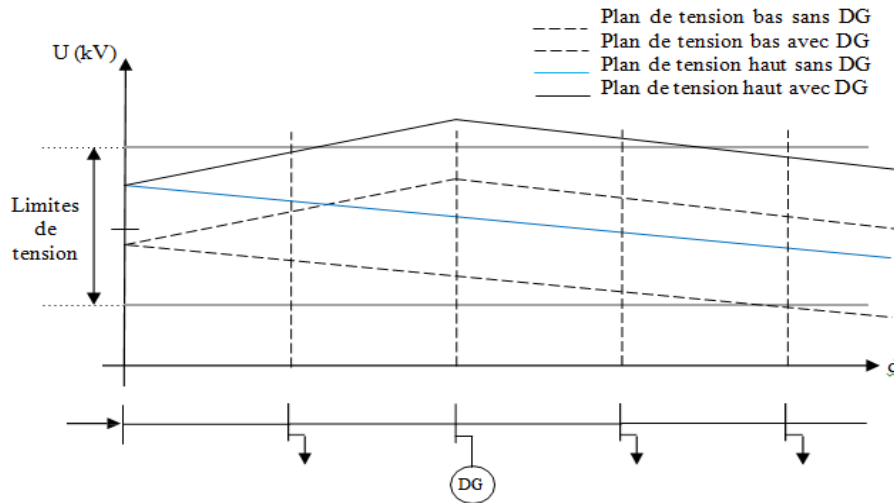


Figure 1.8: Network Voltage Variations With and Without DG

1.5.3.3 Impact on Power Losses

The integration of distributed generation units into distribution networks—originally designed to operate without any embedded generation other than that supplied from the primary substation—can significantly influence power flow behavior throughout the system.

Reducing Joule losses has become a key objective for distribution system operators [4]. Achieving lower losses contributes to reduced energy delivery costs, increases the available transmission capacity of distribution feeders, and improves the overall voltage profile [16]. Several studies [18,19] have investigated the impact of distributed generation penetration on system power losses. The modification of network operating conditions caused by the introduction of DGs affects various technical parameters, which are strongly dependent on both the location and the size of the installed generation units within the network.

1.5.3.4 Impact on System Stability

Distributed generation units may be based on either synchronous or asynchronous machine technologies. The integration of synchronous generators into the power network modifies the system's critical fault clearing time, which represents the maximum duration of a disturbance that the system can withstand without losing stability.

This alteration has a direct effect on the dynamic stability margin of the electrical system under study [20].

1.5.3.5 Impact on Protection Scheme

The connection of new generating units to the power system also alters short-circuit current levels, which in turn affects the setting and coordination of protection thresholds. These changes may lead to issues such as loss of selectivity, unwanted tripping of protection devices, or even blinding of the protection system, thereby compromising its proper operation [20]

1.5.3.6 Impact on System Observability and Controllability

Distributed generation units, especially those based on renewable and intermittent energy sources, are characterized by variability in their primary resources. This intermittency makes it difficult for the system operator to accurately estimate their output power and, consequently, the total power injected into the network [20].

1.5.3.7 Impact on Supply Continuity

Due to the same intermittent nature of these energy sources, the unavailability of distributed generation units during periods of system demand may lead to power shortages and potential service interruptions caused by insufficient generation capacity [20].

1.5.3.8 Impact on Power Quality

Asynchronous machine-based distributed generators typically absorb reactive power for magnetization purposes. During grid connection, they draw high inrush currents, which can contribute to voltage dips. In addition, the use of power electronic interfaces may increase harmonic distortion levels, negatively affecting the overall quality of supply delivered to consumers [20].

1.6 Conclusion

Distributed generation has introduced major changes in distribution networks by significantly modifying their operational behavior. Several benefits can be expected for consumers, producers, regulators, and society as a whole. However, a number of adverse impacts on the electrical network must also be considered.

In particular, the integration of distributed generation affects voltage profiles, voltage stability, and power losses in distribution systems. The purpose of the next chapter is to study power flow calculation methods based on identifying the network topology directly from its data

Chapter 2

Power Flow in Distribution Networks

2.1 Introduction

In the existing literature, several methods have been proposed for this purpose, which are generally grouped into two main categories:

- Newton-based approaches [20-24]
- Backward/Forward Sweep techniques [25-26]

Newton-based methods, including the Newton–Raphson algorithm and the Fast Decoupled Load Flow, are extensively applied in transmission system studies. They are well known for their strong convergence characteristics and numerical robustness in such networks. However, when applied to distribution systems, these methods may face convergence difficulties due to inherent features such as radial configuration, high R/X ratios, and unbalanced operating conditions [26,27].

On the other hand, Backward/Forward Sweep methods are specifically tailored for distribution networks. These methods operate through a two-stage procedure: first a backward sweep to compute branch currents, followed by a forward sweep to update bus voltages [28,29].

In this chapter, the latter approach is adopted to formulate and solve the power flow problem in a distribution network. The proposed technique is assessed in terms of performance using the IEEE 33-bus test system.

2.2 Per-Unit System:

The per-unit system is a normalized approach used in electrical engineering to express system quantities in a dimensionless form. It enables calculations that are independent of the actual voltage and power levels, by scaling all electrical variables relative to predefined base values. This representation greatly facilitates the comparison and analysis of different elements within a power network [30].

Considering a base power S_{base} in kVA and a base voltage V_{base} in kV, along with a resistance R measured in ohms (Ω), the per-unit resistance R_{pu} is obtained using the following relationship:

$$R_{pu} = R \frac{S_{Base}}{10^{-3} V_{Base}^2} \quad (2.1)$$

The normalized active and reactive load powers are obtained respectively using Equations (2.2) and (2.3):

$$P_{pu} = \frac{P}{S_{Base}} \quad (2.2)$$

$$Q_{pu} = \frac{Q}{S_{Base}} \quad (2.3)$$

2.3 Power Flow Calculation Model:

2.3.1 AC Power Flow Model:

Power flow analysis, also referred to as load flow computation, is a fundamental tool in the study and planning of electrical power systems. Its primary purpose is to evaluate system losses under different operating conditions while ensuring that all operational constraints of the network are properly satisfied.

In optimization-based studies, including the present work, power flow equations must be solved repeatedly for multiple scenarios. Therefore, the selected computational approach must be both fast and numerically stable, while maintaining sufficient accuracy to ensure reliable results.

The electrical operating state of the network is fully described by the voltage magnitudes and phase angles at all buses. These variables are obtained by solving a set of nonlinear algebraic equations derived from the AC power flow formulation, expressed as follows:

$$P_i = V_i \sum_{j=1}^{N_n} V_j (G_{ij} \cdot \cos \delta_{ij} + B_{ij} \cdot \sin \delta_{ij}) \quad (2.9)$$

$$Q_i = V_i \sum_{j=1}^{N_n} V_j (G_{ij} \cdot \sin \delta_{ij} - B_{ij} \cdot \cos \delta_{ij}) \quad (2.10)$$

Where:

P_i and Q_i denote the net injected active and reactive power at node i , respectively;

V_i is the voltage magnitude at bus i ;

δ_{ij} represents the phase angle difference between the voltage phasors V_i and V_j

G_{ij} and B_{ij} are the real (conductance) and imaginary (susceptance) components of the bus

admittance matrix;

N_n is the total number of buses in the network.

Distribution networks are characterized by operational and structural properties that are notably different from those of transmission systems. These include [31]:

- a predominantly radial or weakly meshed configuration,
- a relatively high resistance-to-reactance (R/X) ratio,
- a large number of nodes and branches,
- the presence of unbalanced loading conditions.

Due to these specific features, many conventional load flow techniques used in transmission systems become less effective when applied to distribution networks. Consequently, several specialized algorithms have been developed in the literature [32,33] to efficiently handle power flow analysis in such systems.

One of the most commonly adopted techniques is the Backward and Forward Sweep method [34], the principle and implementation of which are presented in the following section.

2.3.2 Backward and Forward Sweep Algorithm:

Over the past decades, numerous versions of the Forward/Backward Sweep method have been developed in the literature [35-37] to improve the efficiency of power flow analysis in distribution systems. These techniques ensure reliable convergence while eliminating the need to directly solve large nonlinear equation systems or handle computationally intensive matrix operations.

Compared with traditional approaches such as Gauss–Seidel or Newton–Raphson, the sweep-based method stands out due to its simplicity, fast execution, and reduced computational burden. It relies on an iterative procedure consisting of two main stages at each iteration:

Backward Sweep: computation of branch currents starting from the load injection currents using Kirchhoff's Current Law (KCL).

Forward Sweep: updating bus voltages by propagating voltage drops along the network from the slack (source) bus toward the end nodes.

Algorithm Procedure:

Step1:Calculation of Injection Currents

After importing network parameters and initializing bus voltages (typically assumed as 1 p.u.), the current injected at bus i is computed as follows:

$$I_i = \frac{S_i^*}{V_i^*} \quad (2.11)$$

Where:

S_i represents the complex conjugate of the load power at node i ;

V_i denotes the complex conjugate of the voltage at node i .

Step2:Backward Sweep

In this stage, branch currents are evaluated by performing a backward traversal of the network, beginning from the farthest (terminal) buses and progressing toward the slack (source) bus. The branch currents are obtained using the following relationship:

$$[J] = [BIBC][I] \quad (2.12)$$

Where:

BIBC refers to the Branch-to-Bus Injection Current matrix, which is composed solely of 0 and 1 elements and typically exhibits an upper triangular structure.

Step3:Forward Sweep

Beginning from the source (slack) bus, the node voltages are updated by propagating voltage drops along the network using the following expression:

$$V_{jr} = V_{js} - Z_j \cdot J_j, \quad j = 1, 2, \dots, N_b \quad (2.13)$$

Where:

j_s and j_r denote the sending and receiving nodes of branch i , respectively;

Z_j represents the series impedance associated with branch i .

Convergence Criterion

The iterative process is continued until the change in bus voltages between two consecutive iterations falls below a specified tolerance value ε :

$$|V_i^{k+1} - V_i^k| < \varepsilon, \quad i = 1, 2, \dots, N_n \quad (2.14)$$

Loss Calculation:

Active power losses in each branch are given by:

$$P_{Loss,i} = R_i \cdot \frac{P_i^2 + Q_i^2}{|V_i|^2} \quad (2.15)$$

Total active power losses in the network:

$$P_{T,Loss} = \sum_{i=1}^{N_b} P_{Loss,i} = \sum_{i=1}^{N_b} R_i \cdot \frac{P_i^2 + Q_i^2}{|V_i|^2} \quad (2.16)$$

Reactive power losses in each branch:

$$Q_{Loss,i} = X_i \cdot \frac{P_i^2 + Q_i^2}{|V_i|^2} \quad (2.17)$$

Total reactive power losses in the network:

$$Q_{T,Loss} = \sum_{i=1}^{N_b} Q_{Loss,i} = \sum_{i=1}^{N_b} X_i \cdot \frac{P_i^2 + Q_i^2}{|V_i|^2} \quad (2.18)$$

2.3.3 Flowchart of the Forward/Backward Sweep Method:

The flowchart of the Forward and Backward Sweep algorithm is shown in Figure 2.1.

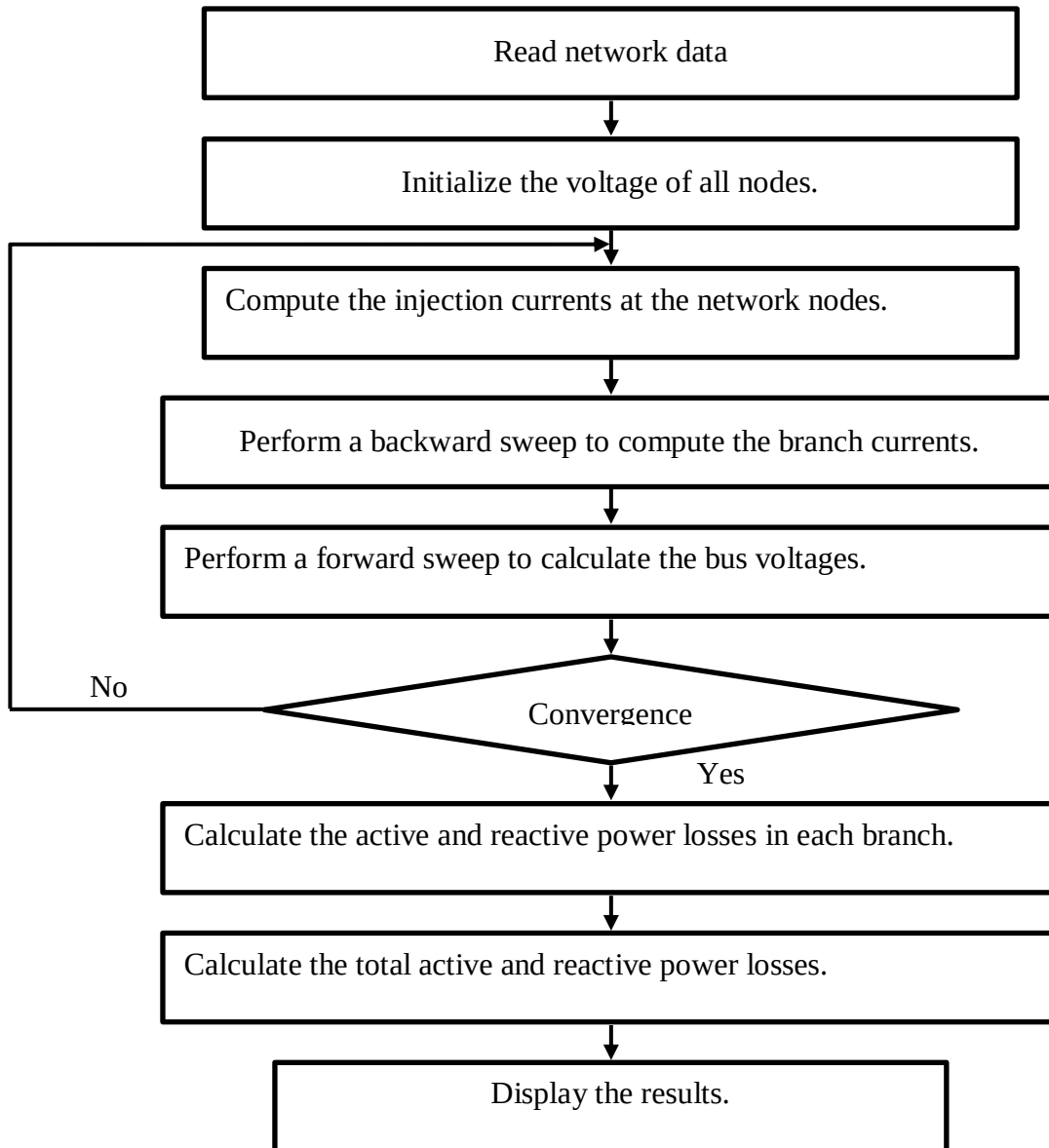


Figure 2.1 Flowchart of the Backward/Forward Sweep algorithm

2.4 Numerical Applications:

In order to assess the performance of the proposed power flow solution method, simulations are conducted on the IEEE 33-bus test system under different load levels and load types.

2.4.1 IEEE 33-Bus Test System:

Figure 2.2 shows the IEEE 33-bus distribution network. The main characteristics of this system are as follows:

- Number of buses: 33

- Number of branches: 32
- Number of open switches: 5
- Slack (reference) bus: 1
- Base power: 10 MVA
- Base voltage: 12.66 kV

The line and load parameters are provided in Appendix 1.

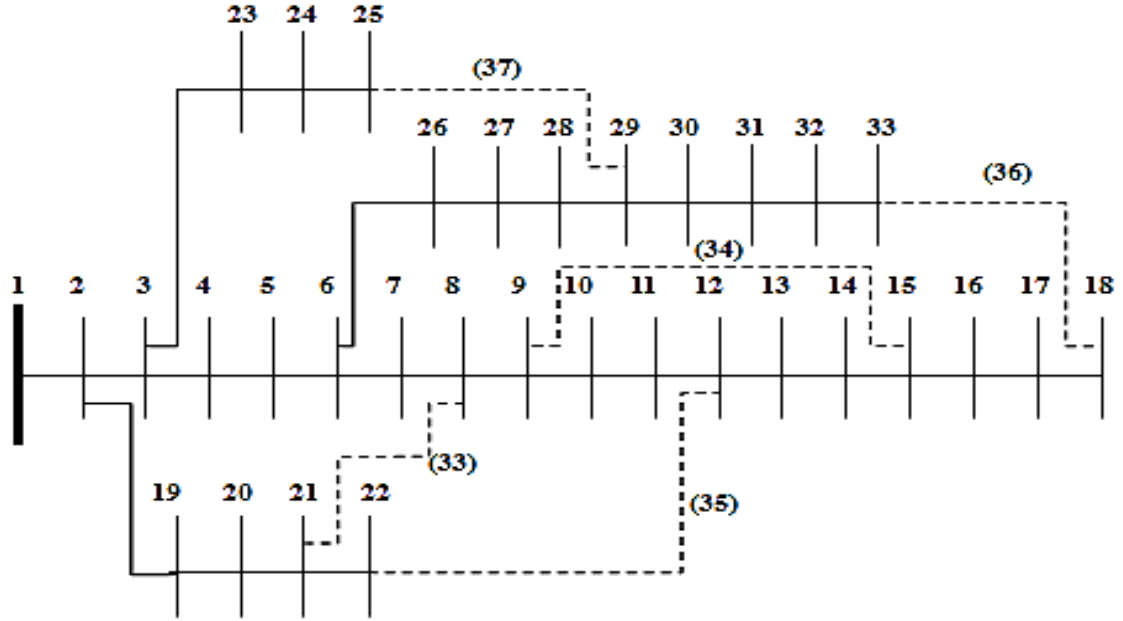


Figure 2.2: Simplified representation of the IEEE 33-bus distribution network

2.4.2 Power Flow Results:

The results presented in this subsection are obtained from simulations performed on the IEEE 33-bus distribution network. Table 2.1 lists the voltage magnitudes at each bus of the system, while Figure 2.3 illustrates the corresponding voltage profile along the network.

From the combined interpretation of Table 2.1 and Figure 2.3, it can be observed that the lowest voltage value occurs at bus 18, with a magnitude of 0.9130 p.u. This bus is located near the end of the main feeder. The noticeable voltage drop at this point indicates the importance of implementing suitable voltage control or compensation measures, especially for buses located far from the main substation.

Table 2.1: Power flow solution for the IEEE 33-bus distribution network

N,b	V_m	VSI
1	1	1
2	0,997	0,988086
3	0,9829	0,932245
4	0,9754	0,905002
5	0,968	0,877861
6	0,9496	0,81138
7	0,9462	0,801268
8	0,9413	0,784996
9	0,935	0,7642
10	0,9292	0,745394
11	0,9284	0,742815
12	0,9269	0,738019
13	0,9207	0,718431
14	0,9185	0,711552
15	0,917	0,707207
16	0,9157	0,702999
17	0,9136	0,696776
18	0,913	0,694952
19	0,9965	0,986045
20	0,9929	0,971879
21	0,9922	0,969204
22	0,9916	0,966716
23	0,9793	0,919811
24	0,9727	0,894809
25	0,9693	0,882836
26	0,9477	0,806675
27	0,9452	0,797964
28	0,9337	0,759356
29	0,9255	0,733295
30	0,9219	0,722361
31	0,9178	0,709388
32	0,9169	0,706654
33	0,9166	0,705785

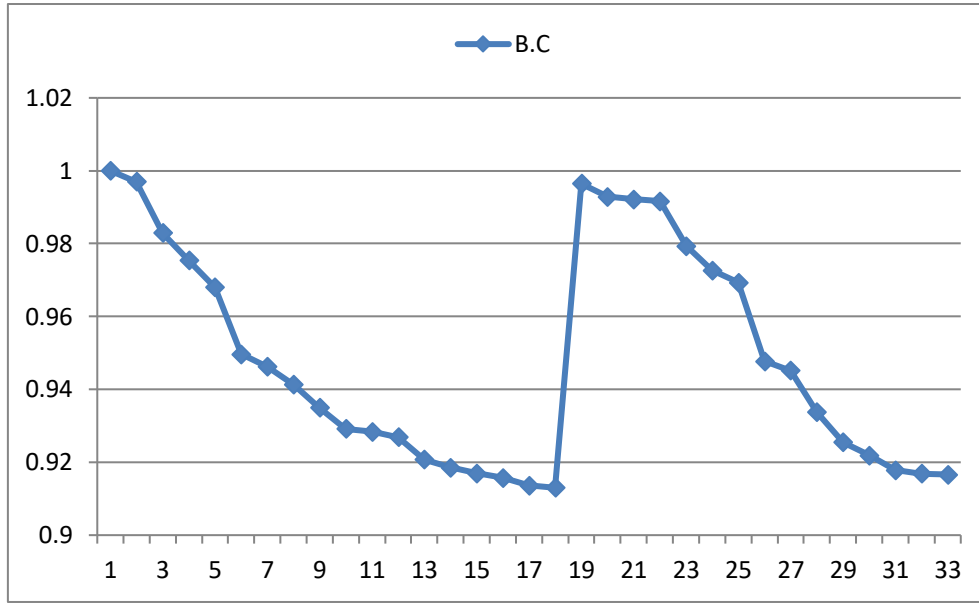


Figure 2.3: Voltage at each bus of the IEEE 33-bus distribution network

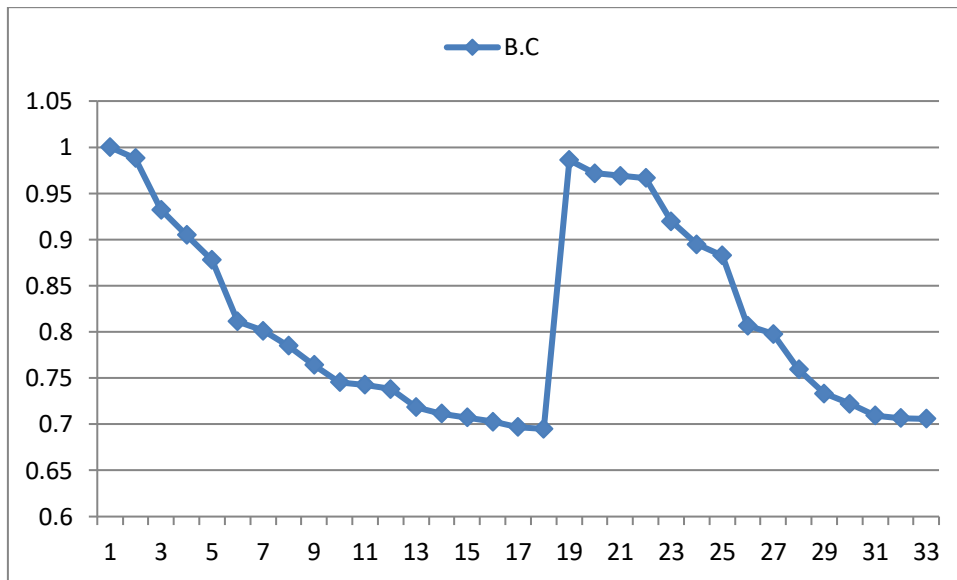


Figure 2.4: VSI at each bus of the IEEE 33-bus distribution network

The table(2.1) and figure(2.3),(2.4) show the voltage magnitudes and voltage angles at each bus.

Table2;2 : Active and reactive power losses in the branches of the IEEE 33-bus network

N,b	PI	QI
1	12,23532917	6,341092
2	51,79389998	26,38525
3	19,90504997	10,13554
4	18,70144008	9,523736

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5	38,25058322	33,01826
6	1,914654173	6,329178
7	4,83873072	1,599103
8	4,180598007	3,003707
9	3,561341678	2,524212
10	0,553916543	0,183285
11	0,881229948	0,291228
12	2,688294293	2,097883
13	0,729202037	0,959897
14	0,356974087	0,317762
15	0,281475714	0,205545
16	0,251648953	0,336012
17	0,053140081	0,041667
18	0,16092023	0,153527
19	0,832186785	0,749899
20	0,100761216	0,117719
21	0,043635354	0,057694
22	3,18153324	2,174519
23	5,143934794	4,061533
24	1,287396979	1,007348
25	2,601851099	1,324541
26	3,328713772	1,695335
27	11,30052191	9,96471
28	7,834168447	6,824063
29	3,895252887	1,984537
30	1,593803791	1,57493
31	0,213169102	0,248496
32	0,013171533	0,020475

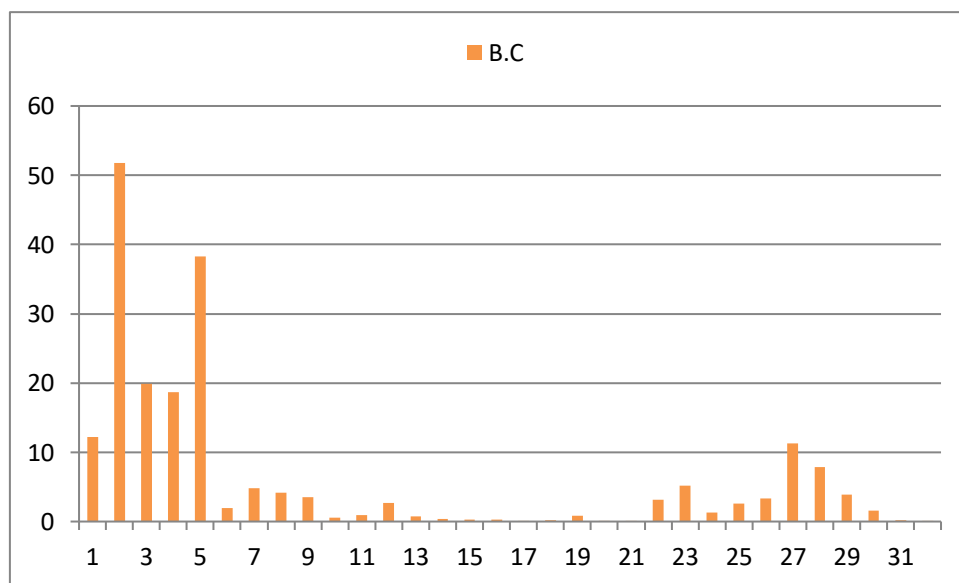


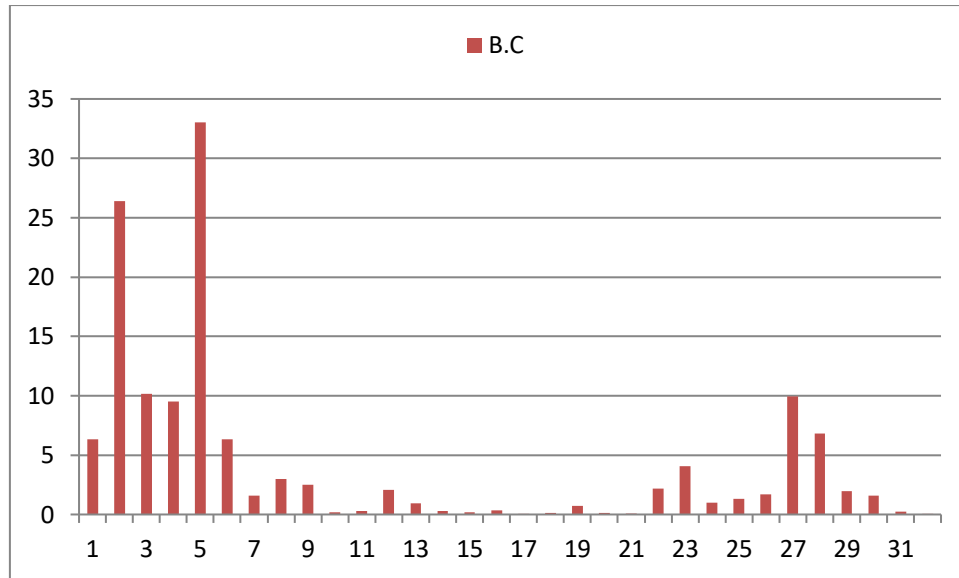
Figure 2.5: Pertes de puissance active dans les branches**Figure 2.6: Pertes de puissance réactive dans les branches**

figure (2.5) and (2.6) the corresponding table represent the **voltage profile** at all buses. The minimum voltage value is **0.9134 p.u.**, which is observed at **Bus 18**.

2.5 Conclusion

This chapter has focused on the analysis of power flow in electrical distribution systems. Initially, the main models used to represent network components—such as lines, loads, and sources—were presented. After that, a well-established iterative technique widely reported in the literature, the Backward/Forward Sweep method, was introduced, as it is particularly suitable for radial distribution networks.

This approach operates through two main stages: a backward sweep stage used to compute branch currents, followed by a forward sweep stage used to update the voltage magnitudes at all network buses.

Finally, the proposed method was tested on the IEEE 33-bus distribution system in order to demonstrate its accuracy and effectiveness.

Chapter 3

Optimal Placement of DGs in the Distribution Network

3.1 Introduction:

The continuous increase in electricity consumption has led to major changes in the operation and structure of modern distribution systems. These developments are mainly motivated by the necessity to modernize electrical infrastructures in order to satisfy evolving energy demands and environmental considerations. Consequently, considerable efforts are being directed toward the integration of distributed energy resources into power networks.

In contrast to the conventional centralized generation approach, where electricity is produced by large power plants connected to transmission systems, distributed generation is based on smaller generating units installed near load centers. This transformation particularly affects distribution systems, which have become a key environment for the deployment of renewable energy technologies and intelligent grid solutions [37].

Despite its numerous advantages, the widespread integration of distributed generation into distribution networks may create several operational issues, including variations in voltage profiles, modifications in power flow behavior, and possible impacts on network stability and reliability [38]. For this reason, efficient optimization and control techniques are required to ensure secure and reliable system operation.

Within this framework, the present chapter investigates a distribution network equipped with DGs. The main purpose is to identify the optimal locations and suitable sizes of DGs by applying an efficient metaheuristic optimization technique known as the Bat Algorithm (BA).

3.2 Effect of Distributed Generation Integration on the Structure of Distribution Networks

To ensure that the integration of Distributed Generation (DG) units into distribution systems is technically efficient and economically beneficial, special attention must be given to the selection of their installation sites and generation capacities. The determination of optimal locations and appropriate sizing should take into account the electrical properties of the network as well as its operating constraints.

3.2.1 Placement of Distributed Generation Units

Distributed Generation (DG) sources should be installed according to a well-planned strategy to improve the overall efficiency of the electrical network. Proper integration can contribute to lowering transmission expenses, decreasing line power losses, and reducing the reactive power required from the main substation. Therefore, identifying the most suitable locations for DG units within the distribution system is necessary to maintain bus voltages within permissible ranges while achieving minimum energy losses.

3.2.2 Sizing of Distributed Generation Units

The uncontrolled integration of Distributed Generation (DG) units can negatively affect both the power loss level and the voltage behavior of the distribution system. Inappropriate sizing of these units may lead to operational imbalances and reduced network performance under varying load conditions.

To prevent such issues, the injected power of each DG source must be carefully determined in order to maintain a proper balance between local production and consumer demand. Consequently, this study focuses not only on identifying the most appropriate installation locations for DG units, but also on determining their optimal generation capacities to guarantee reliable and efficient operation of the distribution network.

3.3 Bat Algorithm (BA)

The Bat Algorithm (BA) is a metaheuristic optimization technique inspired by the echolocation capability of microbats in nature. This algorithm was introduced by Dr. X. Yang in 2010 [20].

To formulate the optimization process, X. Yang simplified the natural behavior of bats according to the following assumptions [20]:

- Every bat uses echolocation to explore its environment, allowing it to estimate distances and identify the position of obstacles as well as prey.
- Bats move randomly in the search space with a velocity v_i at a position x_i . They operate within a frequency range between f_{min} and higher frequencies while adjusting their wavelength λ and loudness A_0 during the search process. In addition, bats can automatically

modify both the pulse emission rate $r \in [0,1]$ and the operating frequency depending on how close they are to the target solution.

- The sound loudness is assumed to decrease progressively during the search process within the interval $A \in [A_0, A_{min}]$

A. Motion of Virtual Bats

In numerical simulations, artificial bats are considered as search agents. At each iteration t , specific update rules are applied to modify their positions x_i and velocities v_i within the multidimensional search domain. The updated position x_i^{t+1} and velocity v_i^{t+1} at iteration t are expressed as follows:

$$f_i = f_{min} + (f_{max} - f_{min})\beta \quad (3.1)$$

$$v_i^t = v_i^{t-1} + (x_i^t - x^*)f_i \quad (3.2)$$

$$x_i^t = x_i^{t-1} + v_i^t \quad (3.3)$$

The parameter $\beta \in [0,1]$ represents a random vector generated according to a uniform probability distribution. The term x^* corresponds to the current global optimum, identified as the best solution among all candidate solutions produced by the n bats.

The quantity λf_i defines the increment applied to the bat velocity, whereas the frequency f_i controls the adjustment of the movement speed while the parameter λ remains unchanged. The admissible range of f_i depends on the nature of the optimization problem, including its scale, domain, and specific characteristics. At the beginning of the algorithm, each bat is assigned an initial frequency randomly chosen within the interval $[f_{min}, f_{max}]$

To enhance local exploration, whenever one of the current best solutions is identified, a neighboring solution is generated for each bat through a random walk process.

$$x_{new} = x_{old} + \varepsilon A^t \quad (3.4)$$

Here, $\varepsilon \in [-1,1]$ denotes a random value, whereas A^t corresponds to the mean loudness of all bats during the current iteration.

The mechanism used to update the positions and velocities of bats is comparable to the procedure adopted in the conventional Particle Swarm Optimization (PSO) algorithm. Because the movement of search agents is maintained within a controlled range, the Bat Algorithm can be considered as an effective hybrid approach that combines swarm intelligence techniques with local exploitation strategies. This balance is mainly governed by the loudness parameter and the pulse emission rate.

B. Loudness and Pulse Emission Rate

Furthermore, the loudness A_i and the pulse emission rate r_i are continuously adjusted throughout the iterative process. In general, as a bat approaches its target, its loudness gradually decreases, whereas the pulse emission rate tends to increase. For this reason, the loudness parameter can be effectively used to regulate the search behavior of the algorithm. Once the loudness reaches the minimum threshold $A_{\min}$, the bat is considered to have located its prey and consequently stops producing sound pulses.

The mathematical expressions below illustrate the updating process of the loudness A_i and the pulse rate r_i during successive iterations.

$$A_i^{t+1} = \alpha A_i^t \quad (3.5)$$

$$r_i^{t+1} = r_i^0 [1 - \exp(-\gamma t)] \quad (3.6)$$

Where α and γ are constant parameters. The coefficient α plays a role comparable to the cooling factor used in the Simulated Annealing method. For all parameter values satisfying $0 < \alpha < 1$ and $\gamma > 0$ the following condition is obtained:

$$A_i^t \rightarrow 0 \text{ et } r_i^t \rightarrow r_i^0 \text{ lorsque } t \rightarrow \infty \quad (3.7)$$

The determination of suitable parameter values generally involves a trial-and-error process. Different loudness levels and pulse emission rates are assigned to the bats in order to enhance the exploration capability of the algorithm. These parameters are updated only when a better solution is obtained, indicating that the bats are progressing toward the global optimum.

The general pseudo-code of the Bat Algorithm (BA) is presented as follows:

Objective Function: $f(x)$, with $x=(x_1, \dots, x_d)^T$

1. Initialize the population of bats x_i their corresponding velocities v_i , for $i=1,2,\dots,n$
2. Assign a pulse frequency f_i to each bat position x_i .
3. Initialize the pulse emission rate r_i and the loudness A_i .

While ($t < \text{maximum iteration number}$)

- Produce new candidate solutions by modifying the frequencies and updating both velocities and positions according to Equations (3.1), (3.2), and (3.3).
- **If** ($\text{rand} > r_i$)
 - Choose one solution among the current best solutions.
 - Generate a local candidate solution around the selected best solution x^* using Equation (3.4).
- **End If**
- **If** ($\text{rand} < A_i$ and $f(x_i) < f(x^*)$)
 - Accept the newly generated solutions.
- **End If**
- Update and identify the current best solution x^* .

End While

Display the final results corresponding to the optimal solution x^* .

End of Algorithm

3.4 Formulation of the Optimization Problem

4.3.1 Objective Functions

In this study, we define the location and capacity of the Distributed Energy Management Systems (DEMs) to be placed in the distribution network with the objective of minimizing active power losses and voltage deviations and maximizing the voltage stability index, detailed below:

4.3.1.1 Minimizing Active Losses

Power losses in a distribution network are one of the key parameters that determine the costs of electricity supply and the network's technical problems. This objective aims to minimize the total active losses of the network. The DEM connected to the network should be able to reduce active losses without causing a problem. Total active losses can be calculated using the following equation:

$$P_{T, Loss} = \sum_{i=1}^{N_b} P_{Loss}(i) \quad (4.7)$$

. The first objective function can be expressed as follows:

$$F_{Obj1} = \min \left(\frac{P_{T, Loss}}{P_{T, Loss, wo}} \right) \quad (4.8)$$

Where $P_{T, Loss, wo}$ represents the total active power loss of the base case (before the integration of DG units).

4.3.1.2 Voltage Deviation Minimization

Bus voltage is one of the most important indicators used to assess power quality in a distribution system. An improved voltage profile can be achieved by minimizing the deviations of load bus voltages from the nominal value of **1.0 p.u.** Therefore, this objective aims to reduce the overall voltage deviation throughout the network. The voltage deviation can be calculated using the following equation :

$$VD = \sum_{i=1}^{Nb} (V_i - V_{ref})^2 \quad (4.9)$$

Where

- V_i the voltage magnitude at bus i ;
- V_{ref} is the reference voltage, equal to **1.0 p.u.**

The second objective function can be expressed as follows:.

$$F_{Obj2} = \min \left(\frac{VD}{VD_{wo}} \right) \quad (4.10)$$

Where VD_{wo} represents the voltage deviation of the base case (without DG integration).

4.3.1.3 Voltage Stability Index Maximization

The Voltage Stability Index (VSI) can be calculated using Equation (4.11). Subsequently, the objective of maximizing the Voltage Stability Index can be converted into a minimization problem by employing Equation (4.12) .

$$VSI_j = |V_i|^4 - 4 \times (P_j X_i - Q_j R_i)^2 - 4 \times (P_j R_i + Q_j X_i) \times |V_i|^2 \quad (4.11)$$

$$\max(VSI_j) = \min \left(\frac{1}{VSI_j} \right) \quad (4.12)$$

Finally, the third objective function can be formulated as follows:

$$F_{Obj3} = \min \left(\frac{VSI_{wo}}{VSI_j} \right) \quad (4.13)$$

Where VSI_{wo} represents the Voltage Stability Index of the base case (without DG integration).

4.3.2 Overall Objective Function

The overall objective function is formulated using the weighted-sum approach as follows:

$$MOF = \min(w_1 \times F_{Obj1} + w_2 \times F_{Obj2} + w_3 \times F_{Obj3}) \quad (4.14)$$

Where w_1 , w_2 , and w_3 are the weighting factors. In this study, the values of w_1 , w_2 , and w_3 are set to 1, 0.65, and 0.35, respectively [92].

The process of determining the optimal configuration of the distribution network and the best placement of DG using metaheuristic optimization techniques can be summarized as follows:

Step 1: Import and prepare the data of the distribution system.

Step 2: Perform an initial power flow study based on the original network configuration and calculate the total power losses.

Step 3: Set the control parameters of the chosen optimization algorithm.

Step 4: Generate an initial population randomly, where each individual represents a possible solution defined by DG locations and sizes, $P0=[X1,X2,...,Xi]$, and initialize the iteration counter $t=0$.

Step 5: Execute the power flow calculation for each candidate solution and evaluate the corresponding objective function.

Step 6: Verify that all solutions satisfy network operational limits and security constraints after the load flow analysis.

Step 7: Produce new candidate solutions following the rules of the selected metaheuristic method, then return to Step 5.

Step 8: Continue iterating Steps 5 to 7 until the predefined maximum number of iterations is reached.

Step 9: Identify the best solution obtained and present the final results, including DG locations, DG ratings, total system losses, and voltage profile performance.

5 Applications:

The optimization of the network structure, particularly the optimal allocation and sizing of DG, is carried out using the Bat Algorithm (BA) as a metaheuristic optimization technique. The method is implemented in the MATLAB programming environment, and its effectiveness is tested using the standard IEEE 33-bus distribution system as a benchmark case.

5.1 Results and Discussion:

The optimal integration of Distributed Generation (DG) into the IEEE 33-bus distribution network will be carried out according to the following scenarios:

- Case 1: Without DG integration;
- Case 2: With the integration of one DG unit;
- Case 3: With the integration of two DG units;
- Case 4: With the integration of three DG units.

The results presented in Table 3.1 clearly demonstrate the effectiveness of Distributed Generation (DG) integration in improving the performance of the distribution network. Compared to the base case, the optimal placement and sizing of DG units lead to significant reductions in active power losses, improved voltage profiles, and enhanced system stability.

In the base case, the network exhibits active power losses of 0.2027 MW, a voltage deviation of 0.117 p.u., and a stability index of 0.6950 p.u.. After the installation of a single DG unit at bus 6 with an optimal capacity of 3.3134 MW, the active power losses decrease to 0.1114 MW, corresponding to a reduction of approximately 45.0%. Simultaneously, the voltage deviation is reduced to 0.01640 p.u., while the stability index improves to 0.8538 p.u., indicating a considerable enhancement in network performance.

When two DG units are installed at buses 7 and 10 with capacities of 1.4580 MW and 1.0337 MW, respectively, the active power losses further decrease to 0.0972 MW, representing a reduction of about 52.1% compared to the base case. The voltage deviation

remains low at 0.01770 p.u., and the stability index reaches 0.8260 p.u., confirming the positive contribution of multiple DG installations to the system operation.

The most favorable results are obtained with the integration of three DG units located at buses 16, 9, and 30, with capacities of 0.4472 MW, 0.9158 MW, and 1.2680 MW, respectively. Under this configuration, the active power losses are reduced to 0.0853 MW, corresponding to an overall reduction of approximately 57.9%. In addition, the voltage deviation reaches its minimum value of 0.00595 p.u., reflecting a highly improved voltage profile across the network. The stability index also attains its highest value of 0.9187 p.u., demonstrating a substantial improvement in the network's voltage stability.

Table 3.1 : Optimization results for DG allocation and sizing

	Location	Capacity (MW)	PL (MW)	VD (p.u)	SI (p.u)
C.B	-	-	0,2027	0,117	0,6950
1-DG	6	3,3134	0,1114	0,01640	0,8538
2-DG	7	1,4580	0,0972	0,01770	0,8260
	10	1,0337			
3-DG	16	0,4472	0,0853	0,00595	0,9187
	9	0,9158			
	30	1,2680			

Overall, these results confirm that the optimal allocation of DG units can effectively minimize power losses, improve voltage regulation, and enhance system stability. Furthermore, the progressive improvement observed when increasing the number of DG units highlights the importance of proper DG placement and sizing in achieving optimal distribution network performance.

Table and figure (4.1) respectively represent the voltage profile at each studied bus before network reconfiguration and after network reconfiguration in the presence of distributed generation sources (DGs).

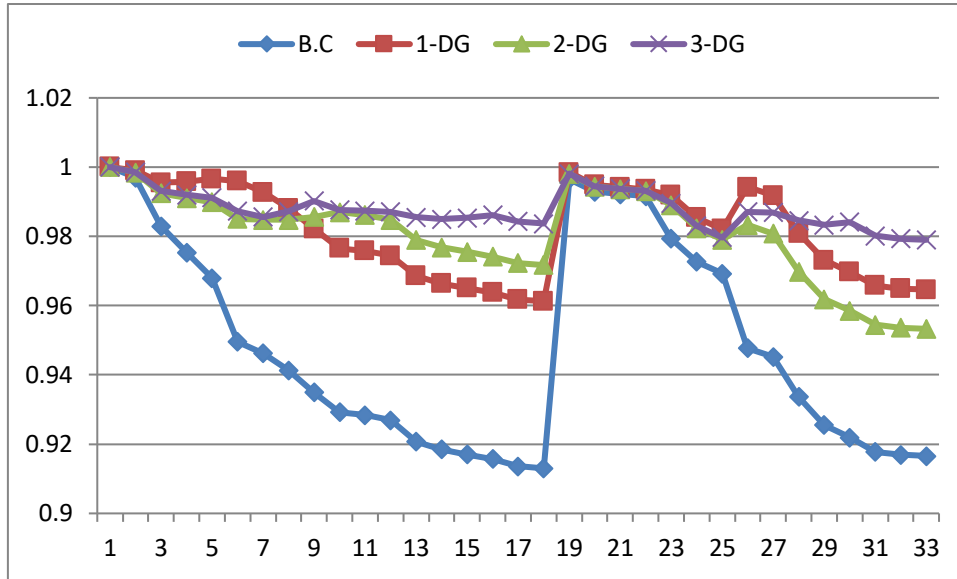


Figure 3.1: Voltage magnitude of the IEEE 33-bus system

Table 3.2 : Voltage amplitude values of the IEEE 33-bus system

N,b	B.C	1-DG	2-DG	3-DG
1	1	1	1	1
2	0,997	0,999	0,9985	0,9986
3	0,9829	0,9955	0,9925	0,9931
4	0,9754	0,9958	0,9911	0,992
5	0,968	0,9966	0,9899	0,9912
6	0,9496	0,996	0,9851	0,9873
7	0,9462	0,9927	0,9848	0,9856
8	0,9413	0,9881	0,9848	0,9872
9	0,935	0,9822	0,9856	0,9902
10	0,9292	0,9766	0,987	0,9877
11	0,9284	0,9758	0,9862	0,9874
12	0,9269	0,9744	0,9848	0,9871
13	0,9207	0,9686	0,979	0,9855
14	0,9185	0,9664	0,9768	0,985
15	0,917	0,9651	0,9755	0,9853
16	0,9157	0,9638	0,9742	0,9862
17	0,9136	0,9618	0,9723	0,9843
18	0,913	0,9613	0,9718	0,9837
19	0,9965	0,9985	0,998	0,9981
20	0,9929	0,9949	0,9944	0,9945
21	0,9922	0,9942	0,9937	0,9938
22	0,9916	0,9936	0,9931	0,9932
23	0,9793	0,9919	0,989	0,9896
24	0,9727	0,9854	0,9824	0,983
25	0,9693	0,9821	0,9791	0,9797

26	0,9477	0,9942	0,9833	0,9871
27	0,9452	0,9918	0,9808	0,9869
28	0,9337	0,9809	0,9698	0,9846
29	0,9255	0,9731	0,9619	0,9833
30	0,9219	0,9697	0,9585	0,9841
31	0,9178	0,9658	0,9545	0,9802
32	0,9169	0,9649	0,9536	0,9793
33	0,9166	0,9646	0,9533	0,979

Table(3.2) and figure (4.2) respectively represent the Voltage Stability Index profile at each studied bus, before network reconfiguration and after network reconfiguration in the presence of distributed generation sources (DGs).

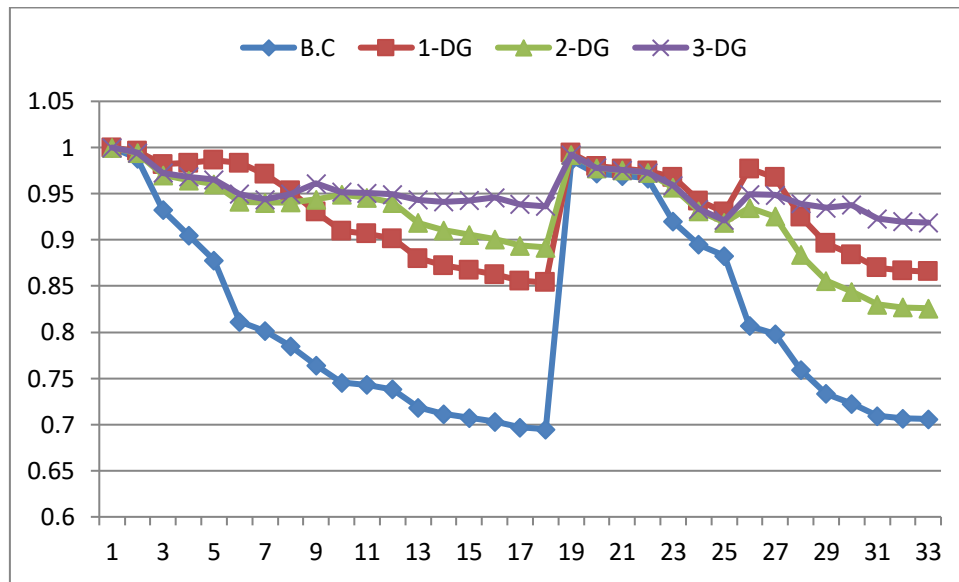


Figure 3.2:Profil de VSI

Table 3.3 : VSI values of the IEEE 33-bus system

N,b	B.C	1-DG	2-DG	3-DG
1	1	1	1	1
2	0,988086	0,996	0,9941	0,9945
3	0,932245	0,9817	0,9701	0,9724
4	0,905002	0,9834	0,9646	0,9683
5	0,877861	0,9865	0,9602	0,9653
6	0,81138	0,9833	0,9412	0,9495
7	0,801268	0,9711	0,9402	0,9437
8	0,784996	0,9532	0,9406	0,9496
9	0,7642	0,9303	0,9437	0,961
10	0,745394	0,9096	0,9488	0,9516

11	0,742815	0,9067	0,9458	0,9507
12	0,738019	0,9014	0,9404	0,9493
13	0,718431	0,8798	0,9183	0,9434
14	0,711552	0,8722	0,9105	0,9412
15	0,707207	0,8674	0,9056	0,9426
16	0,702999	0,8627	0,9008	0,9458
17	0,696776	0,8558	0,8938	0,9386
18	0,694952	0,8538	0,8917	0,9365
19	0,986045	0,9939	0,992	0,9924
20	0,971879	0,9797	0,9778	0,9782
21	0,969204	0,977	0,9752	0,9755
22	0,966716	0,9745	0,9727	0,973
23	0,919811	0,9681	0,9566	0,9589
24	0,894809	0,9424	0,9311	0,9333
25	0,882836	0,9302	0,9189	0,9211
26	0,806675	0,977	0,9348	0,9494
27	0,797964	0,9675	0,9254	0,9487
28	0,759356	0,9251	0,8839	0,9393
29	0,733295	0,8963	0,8558	0,9346
30	0,722361	0,8842	0,8439	0,9377
31	0,709388	0,8698	0,8299	0,9229
32	0,706654	0,8668	0,8269	0,9197
33	0,705785	0,8658	0,826	0,9187

Tables(3.3) and figure (4.3) respectively represent the active power losses at each branch, before network reconfiguration and after network reconfiguration in the presence of distributed generation sources (DGs).

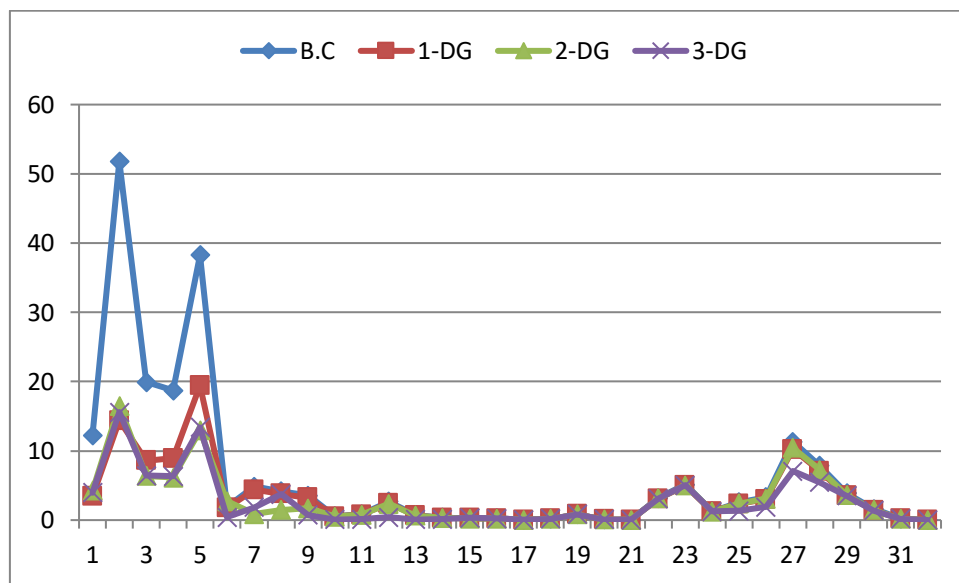


Figure 3.3: Active power losses in each branch before and after reconfiguration

Table 3.4 :Active power losses in each branch of the IEEE 33-bus distribution network before and after reconfiguration

N,b	B.C	1-DG	2-DG	3-DG
1	12,23532917	3,4095	4,2423	3,9851
2	51,79389998	14,3554	16,5212	15,5963
3	19,90504997	8,5823	6,357	6,4254
4	18,70144008	8,9305	6,1476	6,3123
5	38,25058322	19,4301	12,9485	13,4014
6	1,914654173	1,7332	2,7071	0,4133
7	4,83873072	4,3769	0,8963	1,8409
8	4,180598007	3,778	1,4757	3,7195
9	3,561341678	3,2175	1,7213	0,7576
10	0,553916543	0,5003	0,4897	0,1075
11	0,881229948	0,7958	0,7789	0,1492
12	2,688294293	2,4271	2,3753	0,4029
13	0,729202037	0,6583	0,6442	0,1126
14	0,356974087	0,3222	0,3153	0,1497
15	0,281475714	0,254	0,2485	0,2997
16	0,251648953	0,227	0,2222	0,2168
17	0,053140081	0,0479	0,0469	0,0458
18	0,16092023	0,1603	0,1604	0,1604
19	0,832186785	0,8289	0,8296	0,8295
20	0,100761216	0,1004	0,1005	0,1004
21	0,043635354	0,0435	0,0435	0,0435
22	3,18153324	3,1	3,1188	3,1151
23	5,143934794	5,0118	5,0424	5,0363
24	1,287396979	1,2542	1,2619	1,2604
25	2,601851099	2,3522	2,4075	1,3521
26	3,328713772	3,0087	3,0795	1,8836
27	11,30052191	10,2119	10,4529	7,0471
28	7,834168447	7,0787	7,2459	5,469
29	3,895252887	3,5192	3,6024	3,5197
30	1,593803791	1,4392	1,4734	1,3971
31	0,213169102	0,1925	0,1971	0,1868
32	0,013171533	0,0119	0,0122	0,0115

Table(3.4) and figure (4.4) respectively represent the reactive power losses at each branch, before network reconfiguration and after network reconfiguration in the presence of distributed generation sources (DGs).

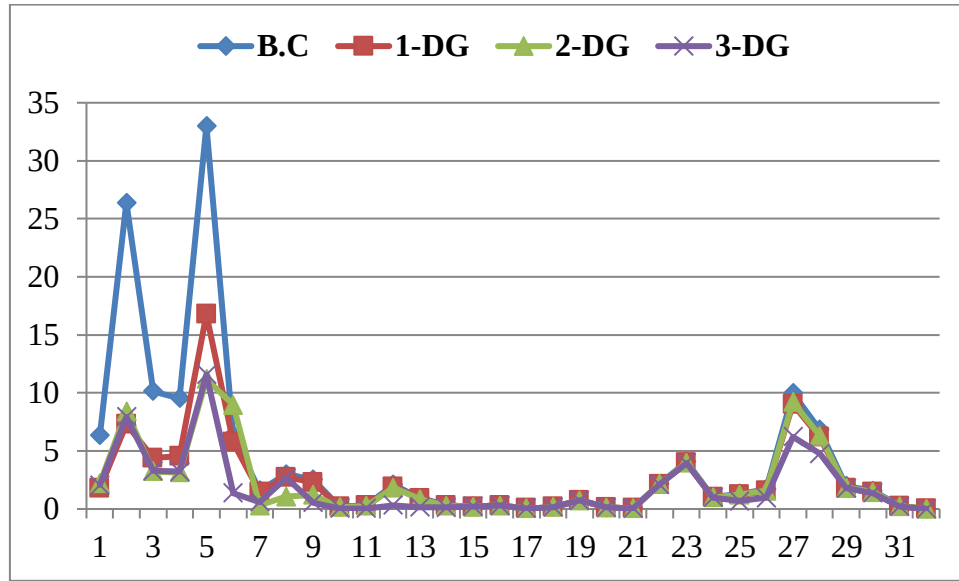


Figure 3.4: Reactive power losses in each branch before and after reconfiguration

Table 3.5 : Reactive power losses in each branch of the IEEE 33-bus distribution network before and after reconfiguration

N,b	B.C	1-DG	2-DG	3-DG
1	6,341092	1,767	2,1986	2,0653
2	26,38525	7,313	8,4164	7,9452
3	10,13554	4,3701	3,2369	3,2718
4	9,523736	4,5479	3,1307	3,2146
5	33,01826	16,7723	11,1773	11,5682
6	6,329178	5,7295	8,9486	1,3664
7	1,599103	1,4465	0,2962	0,6084
8	3,003707	2,7144	1,0603	2,6724
9	2,524212	2,2805	1,22	0,537
10	0,183285	0,1656	0,162	0,0356
11	0,291228	0,263	0,2574	0,0493
12	2,097883	1,8941	1,8536	0,3144
13	0,959897	0,8665	0,848	0,1482
14	0,317762	0,2868	0,2806	0,1332
15	0,205545	0,1855	0,1815	0,2189
16	0,336012	0,3032	0,2966	0,2895
17	0,041667	0,0376	0,0368	0,0359
18	0,153527	0,1529	0,1531	0,153
19	0,749899	0,7469	0,7476	0,7475
20	0,117719	0,1172	0,1174	0,1173

21	0,057694	0,0575	0,0575	0,0575
22	2,174519	2,1188	2,1316	2,1291
23	4,061533	3,9572	3,9813	3,9766
24	1,007348	0,9814	0,9874	0,9862
25	1,324541	1,1975	1,2256	0,6883
26	1,695335	1,5323	1,5684	0,9593
27	9,96471	9,0048	9,2173	6,214
28	6,824063	6,166	6,3116	4,7639
29	1,984537	1,7929	1,8353	1,7932
30	1,57493	1,4221	1,4559	1,3806
31	0,248496	0,2244	0,2297	0,2178
32	0,020475	0,0185	0,0189	0,0179

Table (3.5) presents a comparison of the results obtained by the BA with those obtained by other methods. Analysis of these results shows that the BA algorithm achieved the lowest values for both power losses (0,0853 MW) and voltage deviation (0,00595 p.u).

Table 3.6: Results obtained by BA compared to IMOHS and PSO

	Location	Capacity (MW)	PL (MW)	VD (p.u)	SI (p.u)
BA	16	0,4472	0,0853	0,00595	0,9187
	9	0,9158			
	30	1,2680			
IMOHS [39]	11	0.9250	103.360	0.0124	0.9208
	16	0.8630			
	32	1.2000			
PSO [40]	8	1.1770	105.300	0.0335	0.9256
	13	0.9820			
	32	0.8290			

3.6 Conclusion

Throughout this chapter, we have presented a method for optimizing the allocation and sizing of DGs in distribution networks using the Bat Algorithm (BA). Subsequently, we evaluated the performance of the BA algorithm through simulations in comparison with other well-known algorithms.

The simulation results demonstrated that optimizing the allocation and sizing of DGs enhances system performance by simultaneously optimizing active power losses, voltage deviation, and voltage stability, all aggregated into a single objective function.

General Conclusion

The optimal integration of distributed generation (DG) units, combined with the structural reconfiguration of distribution networks, has become a strategic lever to maximize the technical and operational efficiency of contemporary power systems.

To validate the rigor of the applied approach, numerical simulations were tested on the IEEE 33-bus benchmark network, an essential reference in the scientific literature for evaluating the robustness of optimization algorithms. The allocation and sizing of these generation units were resolved through the implementation of the Bat Algorithm (BA). This optimization problem was formulated as a multi-objective framework simultaneously aiming to minimize active power losses, maximize the voltage stability index (VSI), and mitigate voltage drops at critical nodes. The operational results demonstrate that a judicious allocation of these distributed resources leads to a significant improvement in the voltage profile and a drastic reduction in line losses. Furthermore, the BA algorithm exhibited notable computational superiority compared to the performance of several metaheuristics documented in previous works.

The findings of this study open promising research perspectives. It would be particularly valuable to expand the current objective function into a holistic optimization that encompasses techno-economic and environmental variables. Moreover, designing advanced optimization variants notably by hybridizing the BA with artificial intelligence paradigms such as artificial neural networks or reinforcement learning would represent a major breakthrough to enhance the dynamism, accuracy, and convergence of solutions in the face of real-time load fluctuations.

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