OPTIMIZATION OF DISTRIBUTED GENERATION BASED ON PV SYSTEMS IN RWANDA ELECTRICAL NETWORK

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DECLARATION

I, the undersigned, declare that the dissertation I have submitted for the University of Rwanda or any other higher education institution is my own original work.

I certify that this dissertation comprises all of my original work, with the exception of those sections where I have clearly acknowledged the source. It has also undergone an anti-plagiarism check and been confirmed to be in compliance.

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DEDICATION

To the Almighty God,
To my wife UWAJENEZA Yvonne,
To my daughter KUBWIMANA IYIZIRE Edwige
To my son KUBWIMANA SANDWA Eloi
To my father late BIZIMANA Sebastien
To my mother MUKAGASANA Tharcille
To my brothers and sisters
To my relatives
To my friends

This work is dedicated.

ACKNOWLEDGEMENT

In the realization of this dissertation, there is a collective effort of various people to whom I owe my earnest appreciation. I owe a commitment of acknowledgment to all of those who, in different ways, have made this work possible. I would love to expand numerous appreciations to those who helped me on this long journey.

First of all, I would like to specify my ardent appreciations to the Almighty God who walked with me all through this travel. Without the perpetual assistance and shield of my Lord, I should not achieve the blessed end of this dissertation.

Much appreciation goes particularly to my Supervisor, Dr. IYAKAREMYE Jean de Dieu, for the guidance that he gave me when I was conducting my dissertation and for his continuous support, and inspiration.

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ABSTRACT

For active power loss decrease and voltage profile improvement, the application for best-located and best-sized distributed generation remained important while planning for power system enhancement. This research aimed to determine the optimal placement and the optimal size of PV-based DGs on Rwanda electrical distribution network. First, the whole Rwanda distribution network was studied to identify the feeder with the highest power losses and that feeder was taken it as a case study. Butare feeder located on Kigoma Substation in the Southern province of Rwanda was found to have the highest power losses.

Second, the Simulations were carried out on the Butare feeder distribution network, and the data from the feeder distribution network were processed with help of ETAP software to identify weak buses (WBs) i.e., buses whose voltages were beyond permissible limits. Third, the best locations for the best-sized PV-based DGs were found in the proximity of the feeder WBs. The particularity of the research relied on employing WB and WIA approaches for location and size selection criteria respectively. Forth, after connecting PV-based in the feeder distribution network, the simulated results were discussed by observing the effect of DG on Rwanda distribution network in terms of power loss decrease and voltage profile improvement. The simulated results demonstrated the effectiveness of the suggested approach gives better performance for the distribution network. The results revealed a considerable minimization of active power losses on the distribution network (i.e. from 1.112MW to 0.475MW) and improvement of the voltage profile of 17 weak buses whose voltages were below permissible limits and the voltage profile were highly improved on Rubona bus (i.e. from 0.91 to 1). Therefore, to optimize the Butare distribution network using a PV-based DG network, PV systems would be 30% PL and would be located at identified WBs.

Keywords: Distributed generation, voltage profile, optimal placement and sizing, penetration level, PV systems, power loss decrease and voltage profile improvement

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LIST OF ACRONYMS AND ABBREVIATIONS

AC: Alternating Current

DC: Direct Current

DG: Distributed generations

EMS: Energy Management System

EMTP: Electromagnetic Transients Program

EPS: Electrical Power System

ETAP: Electrical Transient and Analysis Program

HOMER: Hybrid Optimization Model for Energy Resources

PSS/E: Power system simulator for Engineering

GPS: Globe Positioning System

HV: High voltage

IEC: International Electrical Commission

IEEE: Institute Electrical and Electronics Engineer

IES: integrated energy systems

MT: Micro turbine

MV: Medium voltage

NR: Newton Raphson

PV: Photovoltaic

REG: Rwanda Energy Group

RTDS: Real Time Digital Simulator

SCADA: Supervisory Control and Data Acquisition

SEGIS: Solar Energy Grid Integration Systems

SPSO: Selective particle swarm optimization

VMF: Voltage Magnitude and Frequency

RDS: radial distribution system

PDS: Power distribution system

WB: Weak Bus

CO_2: Carbon dioxide

AAB: Arrete bus

CDB: Credo Hotel bus

RUSB: Rusatira bus

RBNB: Rubona bus

BADB: Bandagure bus

MBZB: Mbazi bus

NDRB: Ndora bus

NURB: NUR bus

GKNB: Gikonko bus

MUSHB: Musha bus

MBWB: Mugombwa bus

GSB: Gisagara bus

KGB: Kigoma bus

GB: Gitwe bus

BHB: Buhanda bus

KRB: Karambi bus

DB: Douane bus

MMB: Murama bus

KMB: Kamegeri bus

RWB: Rwinyana bus

MWB: Mwendo bus

MPB: Mpanga bus

NDRB: Ndora bus

MYB: Muyunzwe bus

RMBB: Ramba bus

RPHB: RP/IPRC Huye bus

BUB: Butansinda bus

MPB: Mpanga bus

GASB: Gasoro bus

NYM: Nyamuyaga bus

BGEB: Bigega bus

Bus 81: Huye bus

DEFINITION OF KEY TERMS

ETAP: The Electrical Transient Analyzer Program is a software tool used by power system engineers to develop and analyze electric power systems models.

DG: Distributed generations are small power generations that are connected to the electrical network installed closer to the end users.

Carbon dioxide: is a gas whose each molecule is made up of one carbon atom to two oxygen atoms and acts as a greenhouse gas.

Distributed generation: Diverse technologies used to produce electricity close to or at the point of usage.

A PV cell: a type of electronic device that produces electricity when exposed to sunlight

Substation: a link between transmission and distribution systems that reduces the transmission lines' voltage to a level appropriate for the distribution system and controls the flow of electricity in different directions

A bus bar: any conducting material used to transport electricity from the incoming feeders to the outgoing feeders

Bus: a graph node of a single-line diagram at which voltage, current, power flow, or other quantities are to be evaluated, and this may correlate to the actual busbars in a substation.

Load: any device that uses electricity in the form of electrical current to produce another form of energy among heat, light, or work.

Power plant: an industrial facility that uses primary energy to produce electrical energy.

Power generation: expression used for the various technological methods used to produce electricity

Power transmission: the large-scale transfer of electrical energy from a generating power plant, to a substation.

Power distribution: the last phase of an electrical power system which consists of supplying electricity to the load and transporting electricity from the transmission lines to the loads in each individual customer's residence.

CHAPTER ONE: GENERAL INTRODUCTION

The need for electrical energy is vital for the advancement, and way of life quality of any country's citizens. After power generation, its distribution to the clients is vital. In any case, all electrical energy produced by electrical plants may not reach its destination but, a portion of it is lost in power lines. As seen, power losses and voltage drops increase within the distribution network as long as clients are located in zones distant from the starting point of the feeder at the substation. In this study, PV-based DGs were proposed to overcome those issues. This chapter will deal with the background of the study, the problem statement, the purpose of the study, the research objectives, the research questions, the scope of the study, the expected outcomes, and the significance of the study.

1.1 Background of the study

In the past, distributing electricity from electrical power plants to consumers required extensive power lines. Because they are good conductors, the resistance of those electrical power lines will rise as they get longer [1]. Electric current passing between two buses causes power losses in the power lines, which results in a voltage drop that lowers the voltage level of the receiving bus to that of the sending bus. The electrical current flowing through power lines and their resistance both contribute to power losses and voltage drops in the lines [2][3].

Navani referred to "power losses" as the difference between the amount of electricity generated in the power plants and that used by the consumers as measured over time by energy meters [4].
The authors, Serebrisky and Mercado, divided power losses between technical and non-technical power system losses. Power lines may experience fixed or variable technical losses. Transformer core losses and the corona effect in power lines are the two main causes of fixed technical losses. Fixed losses depend on line quality and are expected to be constant, therefore voltage variation from the nominal value is reduced because they are in proportion to the square of the voltage but, independent of power flow [5].

Numerous strategies have been put forward to reduce active power losses and enhance voltage profiles in power lines while taking into account the current flowing through the lines and their resistance.

Both reducing the resistance of the power lines and reducing the electric current flowing through them are suggested approaches [6].

1.2 Statement of the Problem

Electricity is generated far from end users in many countries’ electrical power systems by various generating power plants including thermal, hydro, and solar power plants, among others. To reach its destination, the electricity must travel many kilometers across many areas, causing significant power losses and voltage drops in electrical power systems due to the huge current flowing within power and resistance of the same line caused by load variations in power lines.

The impact of higher power system losses is significant. First, those losses can cause undesirable overheating in power lines, reducing transmission line efficiency. Second, a considerable amount of useful power is lost on the way without reaching its destination and finally, causes the operating cost of electric utilities to increase resulting in a high cost of electricity.

There are various methods to overcome those problems. In transmission systems, on one side, the voltage from electrical power plants is stepped up by the power transformer and the current will be reduced, on the other side, the resistance can be reduced by shortening transmission lines with the building of new substations and lines bifurcation. In distribution networks, power losses and voltage drops in distribution lines are overcome by reducing the amount of electric current flowing through the distribution lines and also by minimizing the resistance of distribution lines reducing in the feeder length.

In this research, the problem of power losses and voltage profile in distribution lines was studied and, to deal with these issues, we can reduce the amount of electric current flowing through the distribution lines by introducing DGs into distribution systems.

DG can provide several benefits, which include power loss decrease and voltage profile enhancement. Energy efficiency is improved by producing electrical energy in smaller quantities nearer to end users, minimizing the need for new transmission investments [7].

Installation DG offers various advantages for the distribution network in the sense of operation, such as reduced power loss and thereby improved efficiency, enhanced voltage against voltage drops in long power lines, but also increased power reliability. However, these extreme benefits are only realized when DG is installed in the appropriate location and with the appropriate capacity; otherwise, the inaccurate position and size of the DG may cause so many technical issues [8].

1.3 Purpose of the study

Distribution losses in the electrical distribution network in Rwanda electrical grid presents a significant effect on the electricity generated and customers' electrical appliances. This study proposes a solution to decrease real power losses. This decrease in power loss affects the improvement of the power quality and reduces the pollution of the environment. The results found in this study may be used by planners and operators of REG to install optimally PV-based DG in the current electrical distribution network to reduce the losses and to enhance the voltage profiles of the Rwanda's electrical distribution network in Rwanda grid.

1.4 Research objectives

1.4.1 Main Objective

The main objective of this dissertation is to optimize the distributed generation based on PV systems on Rwanda's electrical distribution network to minimize active power losses and to improve the voltage profiles on the chosen feeder.

1.4.2 Specific Objectives

To realize the main objective, the specific objectives of this dissertation are summarized below:

- To assess the areas of Rwanda's electrical distribution network with poor voltage profiles and high active power losses, and to select the feeder with the highest power losses and use it as a case study.

- To simulate the power distribution network on the selected feeder, then figure out power losses and voltage profiles at the feeder buses
- To determine the best location and the best size for a PV-based DG on Rwanda's distribution network for chosen feeder
- To evaluate the impact of DG on the selected feeder on Rwanda's distribution network

1.5 Research questions

The following researches questions must receive an answer in order for the mentioned research objectives to be accomplished:

- What is the first feeder with the worst voltage profile and the biggest power losses?
- What buses have a bad voltage profile among those that are present on the selected feeder?
- What size and location would be optimal for a PV-based DG?
- How do the DGs affect the selected feeder in Rwanda's electrical network?

1.6 Scope of the study

This research is restricted to:

i. Rwanda's 30kV distribution network is located on the feeder with the biggest power losses.
ii. The usage of the Electrical Transient and Analysis Program (ETAP) for network simulation
iii. The application of DG based on PV systems for voltage profile improvement and power loss reduction on buses with poor voltage profiles at selected feeders.

1.7 Expected Outcomes and Significance of the Study

1.7.1 Expected Outcome of the Study

Since the study consists of PV based DG, this study will help:

- to reduce technical losses on the Rwanda electrical network on the selected feeder
- to improve the voltage profile of Rwanda electrical network the considered feeder
- to size the PV systems to be connected to the Rwanda electrical network

1.7.2 Significance of the Study

a) This study will help the country:

- To use the available generated electricity effectively
- To provide reliable electricity to the citizens
- To reduce harmful gas emissions

b) This study will help the electricity company:

- To reduce power losses in electrical distribution network
- The electricity cost will be reduced

c) This study will help the researcher:

- To contribute to the improvement of Rwanda electrical network and then to the development of the country
- To fulfill the requirements of obtaining the master's degree of Electrical Power Systems
- To enhance the knowledge and skills about conducting research.

CHAPTER TWO: LITERATURE REVIEW

In order to address concerns with power losses and voltage profiles in distribution systems, many scholars used various technology alternatives and techniques to assess distributed generations of renewable energy resources like solar energy, hydropower, and their hybrid topologies. This chapter covered the theoretical perspectives, different related publications, the research gaps in the literature identified by those works, and the ways in which this research effort will fill those gaps.

2.1 Theoretical perspectives

Theoretical perspectives go beyond simple opinions that someone possesses. Instead, they are structural explanations, or tools that have been researched and reviewed over time. These are theories are developed and applied via researches to understand the world in general and in this instance the ways in which families interact with, and experience the world.

2.1.1. DG Technologies

2.1.1.1 Micro turbine

A decentralized power source known as a microturbine (MT) can produce electricity by burning natural gas. Between 40KW and 1MW of electricity can be generated by MTs. They are also capable of simultaneously generating heat and power [9]. Since they are effective and available, MTs are pollution free. Microturbines are an excellent technique to produce electricity at a low cost because they also have low maintenance and running costs. The thermodynamic cycle governs how the microturbine system operates. Here, a centrifugal compressor system is presented. Compressed intake air is sent to the combustion chamber. There, compressed air that has been combined with oil burns while creating high-pressure combustion gases [10].

In the turbine, the high-pressure gas expands. An MT has an air-gas heat exchanger, or a heat exchanger warms compressed air before it enters the combustion chamber using the expanded gas. As a result, the combustion process consumes less fuel [11].

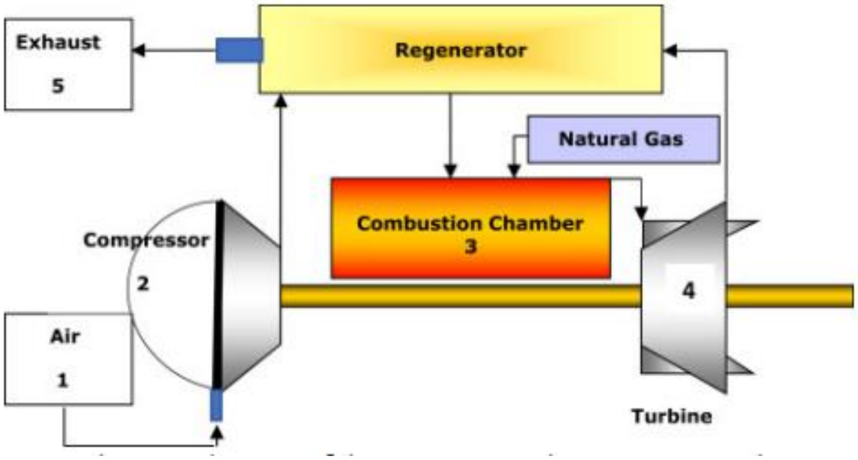

Figure 2. 1 Schematic diagram of micro turbine [12]

The fundamentals of MT design are the same as those of any other kind of gas turbine. However, MT has a significantly higher efficiency than a gas turbine. Some MTs can pre-heat the air utilized in the combustion chamber using exhaust heat. The MT output power can be anything between 30 kW and 500 kW. Expenses of using MT are higher than the costs of using reciprocating engines despite several advantages [13].

2.1.1.2 Reciprocating engines

A reciprocating engine is one of the distributed power generators that can be generated electricity with conversion efficiency is 28% to 43%. Burn natural gas and diesel to generate rotation from the piston and generate electricity. This piston can turn the shaft of a generator and produce electricity. The power range of the reciprocating engine is narrow (5kW to 20kW) and that power is used. Reciprocating internal combustion engines are the most popular prime mover for generating mechanical electricity in cogeneration plants. Since the use of CHP in integrated energy systems (IES) advances understanding to effectively manage increasing energy demand and climate change. The joint behavior of CHP with other elements in IES is essential.

One of the distributed power generators that may provide energy with a conversion efficiency of 28% to 43% is a reciprocating engine. Burning natural gas and diesel fuel causes the piston to rotate, producing power. This piston has the ability to propel a generator's shaft and generate power. The reciprocating engine's limited power range (5kW to 20kW) is utilized. The most common primary mover for producing mechanical electricity in cogeneration plants is reciprocating internal combustion engines. Since the integration of CHP into IES improves knowledge of how to successfully manage both the world's growing energy demand and climate change. The interaction of CHP with other IES components is crucial [14].

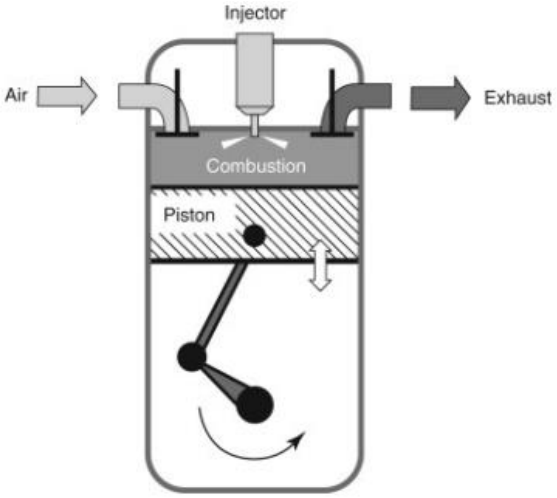

Figure 2. 2 Schematic showing reciprocating engine operation [15].

The heat and pressure produced during the combustion of fuel and air in reciprocating engines are converted into mechanical energy. Air from the intake manifold reacts with the fuel that is injected into the cylinder. As a result of the exothermic reaction, high-temperature, high-pressure gases are produced. These gases expand by pushing the piston downward, which generates rotational energy. Gases leave the cylinder and enter the exhaust system during the upward exhaust stroke[16].

2.1.1.3 Gas turbine

A gas turbine is a form of power generator burning natural gas to produce mechanical energy. This mechanical energy turns the generator turbine and the latter produces electricity. The electrical conversion efficiency of gas turbines is between 20% and 40%. Gas turbines (GT) are widely used for power generation due to their high thermal efficiency and low CO_2 emissions [17].

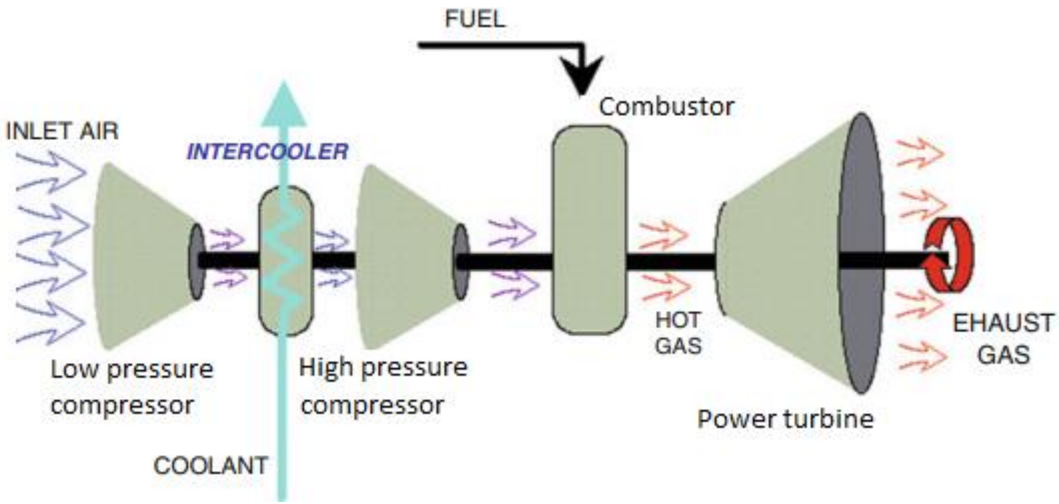

Figure 2. 3 Illustration of gas turbine with intercooling and combustor [18]

According to the gas turbine's basic operating concept, the air is first compressed by a compressor and heated by the fuel's combustion energy. The working gas is heated and pressed to high levels. Utilizing the interaction between the gas and the blades, the engine transforms the energy of the gas into the rotating energy of the blades. The air compressor, combustor, and turbine are the basic parts of both gas turbines. Due to the use of continuous combustion, gas turbines can manage higher gas flows than reciprocating internal combustion engines. The gas turbine is then a good choice for a high-power engine. This benefit is utilized by the jet engine, a type of gas turbine used in aircraft.

The gas turbine functions on the Brayton cycle concept, and the addition of a regenerator is one modification of this fundamental cycle. By recovering some of the energy from the exhaust gas, a gas turbine with a regenerator (heat exchanger) warms the air before it enters the combustor. The hot gas that results from this cycle is usually employed with low-pressure ratio turbines, and it is allowed to expand through a turbine to produce work [19].

2.1.1.4 Fuel Cells

Fuel cells produce electrical energy from chemical energy. Fuel cells have electrodes, and electrolytes, each of which has its own role. Fossil fuels are a major source of energy used around the world, yet they are a finite resource and have severe environmental impacts leading to climate change and some health issues. While various types of FC show promising properties for future use, there are also some environmental issues that need to be addressed. Although FC is considered more environmentally friendly than traditional power conversion systems, various types of FC still have distinct operational and environmental drawbacks. FC is considered to be more environmentally friendly and efficient. A major challenge for FCs is fuel procurement, including obtaining hydrogen for hydrogen FCs where hydrogen production has an environmental impact [20].

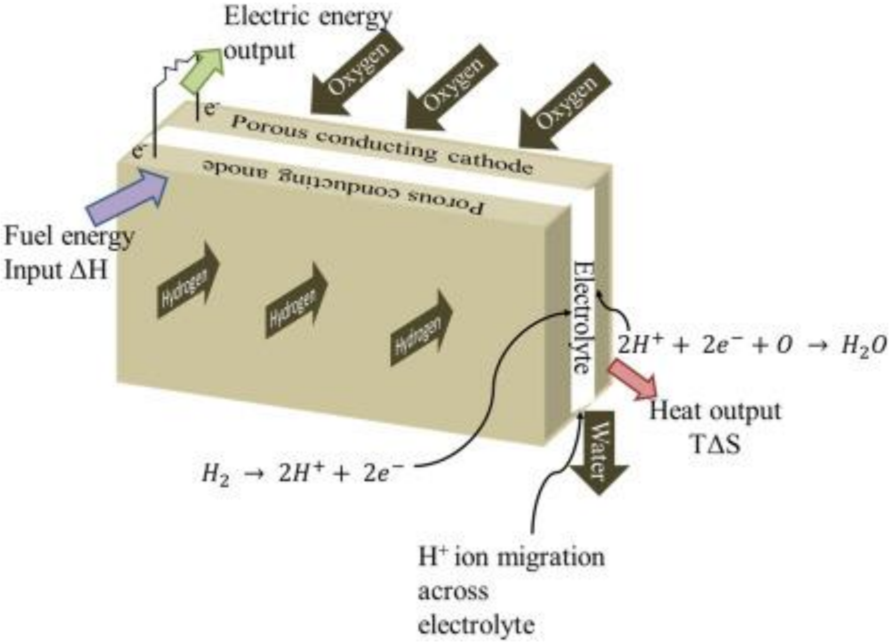

Figure 2. 4 Representation of Hydrogen-oxygen fuel cell operation [21]

The next generation of highly efficient, green energy systems is represented by fuel cells. A fuel cell is a device that produces electrical energy through an electrochemical reaction between an oxidant like oxygen and fuel like hydrogen. In contrast to a battery, fuel is continuously delivered to the cell in this system. Depending on the electrolyte used and the operating temperature, there are various types of fuel cells. Either mixed conductors or pure electronic conductors serve as electrodes [22].

2.1.1.5 Solar PV systems

Solar energy is a type of energy from the sun that can be converted into electrical energy using solar cells. This thematic issue on advances in solar energy conversion brings together experts in the field to discuss current research and future prospects in the field. Topics in this issue focus on, but are not limited to, fabrication, and advanced characterization of light conversion system components, materials, processes, and techniques [23].

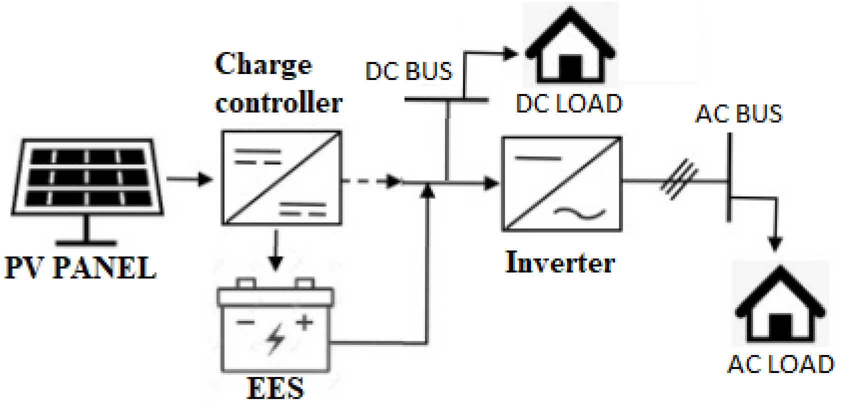

Figure 2. 5 Solar PV system [24]

DC loads can be directly powered by the electricity produced by the solar panels, or AC loads are supplied by converting the same electricity from DC to AC using a solar inverter. Solar PV systems come in a variety of sizes, from modest roof-mounted installations with a few panels and kilowatts of power to big installations with several megawatts of power that make use of massive arrays of solar panels [25].

2.1.1.6 Micro hydropower plant

Micro hydro power is one of the most effective ways to produce electricity through stand-alone electric power generation using renewable resources. MH generates electrical energy by converting the potential energy of moving water. After electricity production, the water can also be helpful for irrigation and other residential uses. Hydropower has made a mark on the production of electrical energy these days all over the world. Power plants that produce less than 100 kW of electricity are known as micro hydropower plants. Compared to fossil fuels, these small hydro plants are more reliable, cost-effective, and take up less land [26].

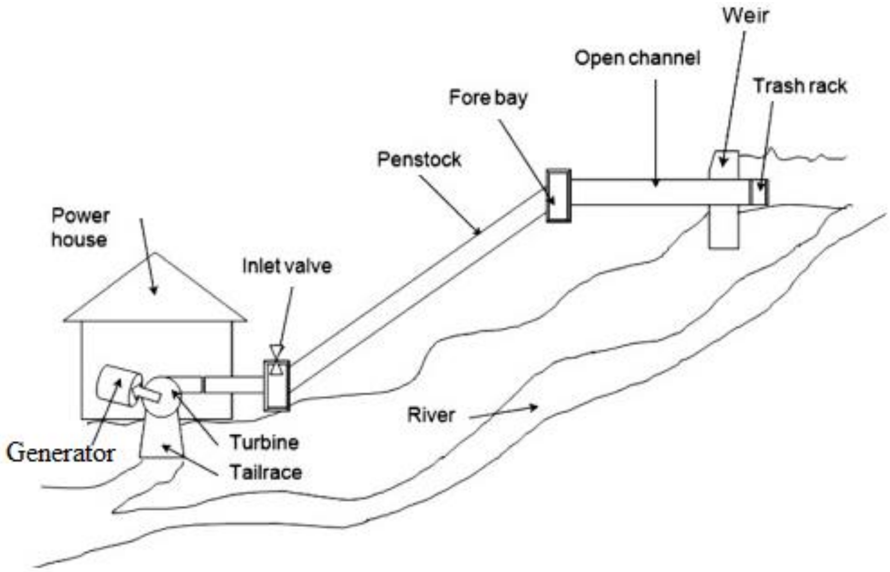

Figure 2. 6 Micro hydropower plant [27]

Micro-hydro has been used to generate electricity as a renewable energy DG. The absence of the need to build huge dams is the main benefit. The varying water flow is imposed by inconsistent rainfall. However, this causes these DGs to experience significant changes in a generation. It is clear that the dam, penstock, turbine, tailrace, generator, and auxiliary equipment make up the core elements of micro hydro. While the flow rate refers to the volume of water per unit of time, the head is the vertical distance through which the waterfalls. The electricity production from MHDGs depends on effective and well-placed types of equipment in combination with the proper head and flow rates. Due to frictional losses and turbine flaws, the efficiency of MHDG is often only approximately 50% [28].

2.1.1.7 Wind power system

Power Wind turbines are devices that convert air movement into mechanical energy and through generators convert this mechanical energy into electrical energy. There are two types: offshore wind turbines and onshore wind turbines. Wind turbines can generate up to 3MW of power, and wind turbines cannot be installed everywhere. Wind turbines also have a very high capital cost, but their operating costs are zero because the wind is their main source of power. This has several important implications.

1) Capital expenditures are important, but no decision, because operational costs must also be taken into account.

2) Since material costs change over time because we have found permanent magnets. Not sure about the Price trends influence decisions.

3) Which generator system is better since it depends on the location where the turbine is installed because the total energy generated depends on the wind speed?

4) System efficiency is important, but not the decision, because a system is less productive and a power supply with low energy cost is better [29].

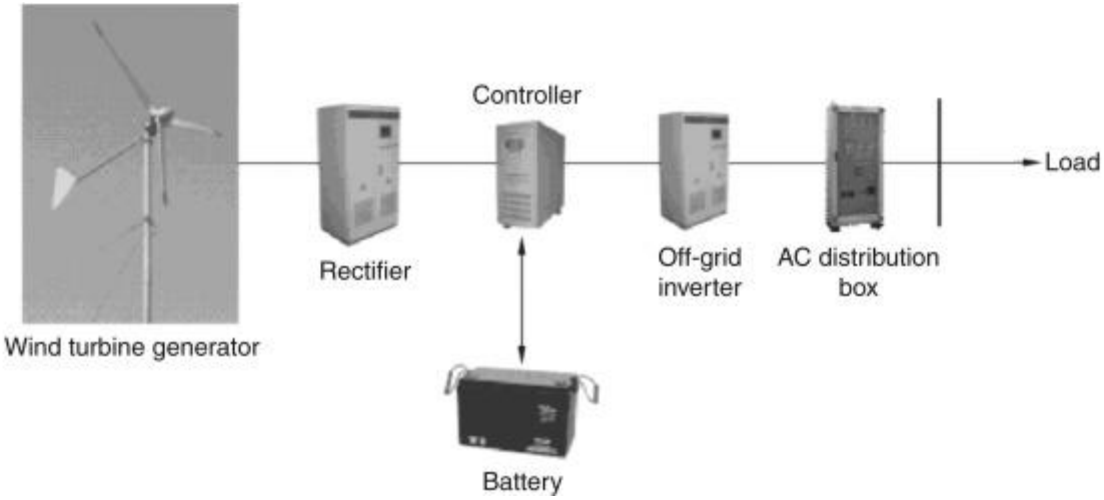

Figure 2. 7 Structure of wind power system [30]

To meet local demand, independent wind power systems are typically installed in remote off-grid areas. Such a system needs to be equipped with an energy storage system to address the fluctuation of wind-generated electricity. An autonomous wind power system is shown in Figure 2.7, with the key components being the wind turbine generator, rectifier, controller, battery, off-grid inverter, and AC distribution box. The rectifier converts the generator's alternating current first into direct current to charge the battery, then the inverter converts it back to alternating current to power AC loads [31].

2.1.2 Voltage profile in distribution systems

Bus voltage normally drops due to active power consumption; however this can be fixed by controlling line drop compensation on the transformers' under load tap changers. Voltage variances between two buses on each line segment are significantly smaller in distribution systems than the voltage on the outgoing bus [32].

The DG unit's potential assistance for raising the system voltage profile will be maximized by its ideal placement. Simulations are used to assess the DG placement, which offers the required amount of DG penetration's minimal voltage deviation. Consider a DG that could handle the entire load in the distribution system. The 100% DG penetration is what leads to such a situation. Maintaining voltages at all buses as close to 1.0 p.u. as possible is interesting. When the network operates with an acceptable voltage range of 1 ± 0.06, the DG cost is considerably decreased [33].

2.1.3. Power losses

Because of its proximity to the load, DG dramatically increases power losses. DG units are designed to be located in locations where they offer a greater reduction in power losses. To reduce those losses, this DG installation procedure is analogous to capacitor placement. The biggest differential is that capacitor banks only affect reactive power flow, but DG units can influence both dynamic and responsive control. The amount of DG was purposefully allotted in feeders with substantial losses [34]. Thus, by lowering line current, resistance, or both, line power losses can indeed be reduced. The Power line losses can be decreased as a result of the network's reduced current when DG is utilized to supply local the load. The location, the DG's capacity, the relative amount of the load, the network structure, and other factors can all affect how much loss the DG can add or minimize [35].

2.1.4 PV systems description

2.1.4.1 Advantages and disadvantages of PV systems:

Advantages:

PV systems have several advantages:

- Photovoltaic technology has eco-friendly properties as the products are eco-friendly, quiet, and do not harm the environment.
- PV systems can be autonomous systems that are they can function reliably without any supervision.
- There is no need of connecting PV system to another energy source or fuel supply.

- PV systems can be combined with other power supplies for getting a system with increased reliability.
- A PV system can withstand bad weather conditions such as snow and ice.
- PV systems do not use fossil fuels since fuel is plentiful and free.
- PV systems are highly reliable as there are no moving parts in the installation
- Modular system of solar panels allows for a variety of adaptable assemblies
- Eliminates the cost and risk of transporting fossil fuels.

Disadvantages:

Although PV technology has many advantages, it also has some drawbacks

- Solar module manufacturing is an advanced technology therefore; its cost is very high.
- The actual yield of solar modules is around 10-15%.
- The PV system is weather dependent that is, depends on the availability of sunlight
- The solar systems produce direct current and have to be converted into alternating current using a power inverter [36].

2.1.4.2 Components of photovoltaic Systems

1. PV cells

PV cells are made up of two semiconductor layers. One layer is positively charged, while the other is negatively charged. As the PV cell is exposed to enough sunlight, the negative layer of the photovoltaic cell absorbs photons and releases free electrons. These free electrons move naturally to the positive layer, resulting in a voltage differential. A variety of PV cells can be collected into modules, which can then be connected in any size array. Photovoltaic systems directly convert solar energy into electricity [37].

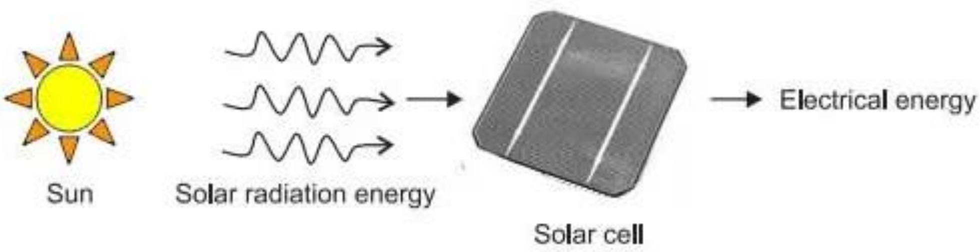

Figure 2. 8 PV Cell [38]

Individual solar cells are often connected in series in PV panels to increase the panel voltage. The electric properties of the cell may not match due to a variety of circumstances. To minimize the mismatch between cells strung in series, a panel is built from cells belonging to the same group. A bypass diode is placed over each of these subpanel strings, and it activates if the PV subpanel string's reverse bias exceeds the diode's forward voltage [39].

2. Battery storage technologies

For power systems that require energy storage, this contains any system that functions without being connected to the utility grid. The battery bank is also linked to the inverter, which supplies power to the AC loads. The battery bank is also linked to the inverter, which supplies power to the AC loads. When the system employs direct current loads, the battery bank is linked to a direct current load center. Its purpose is to store excess energy that will not be used directly. Batteries have the ability to resist charging and discharging to a specified value based on their capacities [40].

Figure 2. 9 Batteries for PV systems [41]

The flow of lithium ions between the positive and negative electrodes is the basis for the operation of lithium-ion (Li-ion) batteries. During charging mode, the positive electrode delivers lithium ions to the negative electrode through the use of the electrolyte as a means of ion mobility. When the battery is depleted, this phenomenon takes place in a reverse manner. Lithium-based materials, such as lithium iron phosphate and lithium manganese oxide, are used to make the positive electrode. The initial high cost of Li-ion batteries prevents their widespread adoption in grid storage systems [42].

3. Charge controller

The purpose of the charge controller in the system is to monitor the charging and discharging of the battery so that it is not damaged. It also serves as a link between other units of the system by maintaining the voltage and current flow within the required tolerances. Its role in the system is vital because the energy cost produced is influenced heavily by its quality [38].

In PV systems, charge controllers are essential for preventing battery damage from over-charging and over-discharging by regulating the current flowing to and from the batteries. In PV systems, they can also protect the appliances that are connected to the batteries. When the batteries in PV systems with single-stage controllers are charged up, the charging circle is turned off to safeguard the batteries. The control method predicts the full state of charge as the charge termination point and the battery's minimal state as the charging starting point [43].

3. Conversion system:

A power converter is equipment that is normally available between solar panels and load without storage with a continuous load. Since PV cells are a DC power source, it has to be converted into usable AC power using a power inverter. The inverter is usually combined with a rectifier that performs the transformation of alternating current into direct current and its role will be Charge the battery and provide the DC circuit of the installation in the case during long periods without the sun [44].

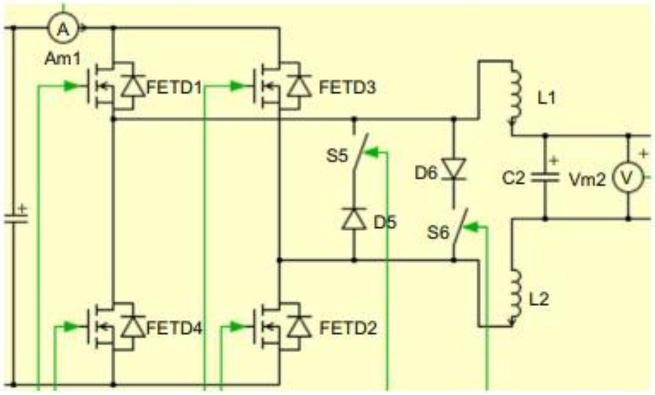

Figure 2. 10 Electronic circuit of power inverter [45]

In the past few decades, there have been about 4600 different types of PV inverters available on the markets. One-third of the global market for string inverters is made up of three phases. A very modest market share, in the range of 1%, is held by the smaller inverter, which has been available for the past 20 years to directly link a single PV module to the AC grid [46].

2.2. Related study

2.2.1 Distributed generation for power losses reduction and voltage profile improvement

Ekwue and Akintunde discussed how the distributed generation impacted distribution networks in their study [47]. To minimize power losses in the distribution systems, the distributed generation was proposed on a 15-bus distribution network. When a distributed generation was randomly placed at two different buses 2 and 4, technical losses were reduced from 0.06149MW to 0.03246MW and 0.02027MW, respectively, when a distributed generation was placed at bus 2 and bus 4. When a distributed generation was installed on bus 4, the voltage significantly improved, and technical losses were reduced. However, the discussed paper did not show the type of the DG to be used [47].

In the paper [48], Abiola et al, took a case study on the Ayepe 34 bus to target the optimal sitting and sizing of the DG using the Cuckoo Search Algorithm (CSA) in a real Nigerian power distribution network. The objective function was formulated using a weighting method, taking into account active power loss, and reactive power loss. The base case total loss of real power and total loss of reactive power were 0.762 MW, and 0.146 MVar, respectively. For a single DG unit, total active power loss, and total reactive power loss became 0.141 MW, and 0.027MVar respectively. However, this paper did not specify DG technology to deal with [48].

In [49], Nweke et al. investigated the use of distributed generation to reduce power losses in a 28-bus on Nigerian transmission network. The researchers determined the best size and position of a distributed generation in the power system. Six of the 28 buses had lower voltages, and a total active power loss of 92.7MW was calculated before introducing distributed generation. The size of a distributed generation at respective buses was determined using the optimal sizing equation of a distribution generation, and it was determined that load bus 17 (Abuja), whose DG is sized 0.18MW, corresponds to the least active power loss and was chosen as the optimal location of a distributed generation. However, the discussed paper did not mention the type of the DG to be connected optimally to the available distribution network [49].

Various works using NR to enhance voltage profile and minimize power loss were described. Furthermore, a modified algorithm was presented by researchers Ayodeji et al. in the paper [50], to address this issue and provide a more efficient PDS. The main objective of this study is to minimize the active power loss and improve the VP of the distribution system using the proposed SPSO method. Finally, a comparative analysis was presented between the proposed SPSO and existing distribution network reconfiguration (DNR) methods. The comparison results suggested SPSO was found to be more efficient in reducing system voltage deviation (VD) and power loss. However, the discussed paper did not plan the DG types to be used [50].

In their study [51], Duong Quoc et al. suggested placement of multiple Distributed Generator in Primary Distribution Networks for Loss Reduction. They determined the best size and location for four different DG types using an analytical method: the first DG provided both real and reactive power, the second provide only active power, and the third produced real power while absorbing reactive power and the fourth could only deliver reactive power. The effective power factor of DGs for minimizing power losses was found to be closer to the power factor of combined load in the respective system, as proved. However, the voltage profile effects of the various types of DGs were not evaluated and the types of DG were not specified in the study [51].

Another study [52] conducted by Najib et al. planned to identify the best location and size of distributed generation because trying to install distributed generation units in non-optimal locations and sizes could cause numerous challenges including voltage flicker, impacting the voltage state, system losses, harmonics, and voltage profile. The study minimized the real power losses and improved the voltage profile using the firefly algorithm. However, the discussed paper did not clarify the type of DG to be used [52].

In this work [53], Rao et al. aimed to minimized the power losses and improved the voltage profile of the distribution grid, a new approach was presented to solving the problem of distribution grid reconfiguration under distributed generation (DG) conditions. A sensitivity analysis was used to determine the best location for installing the DG unit. To examine the performance of the proposed method, different scenarios of DG placement and network reconfiguration were considered. This method was tested in 33-bus and 69-bus radial distribution systems with three different loads to demonstrate the performance and effectiveness of the proposed method, with good results. In this paper, the type of DG was not mentioned by researchers [53].

Researchers Evans and Stephen, applied an adaptive neural fuzzy logic technique to optimize the position and size of the DGs in the study [54]. A 24-bus radial distribution was used to demonstrate this process and is properly positioned and sized at the optimum location which reduces power loss and also improves the voltage profile at the buses. The percentage reduction in power loss at the buses was 48.96% cumulative for ANN, while the adaptive neural fuzzy logic technique is 49.21%. The voltage configuration of the networks after optimizing the position and size of the DGs by adaptive neural fuzzy logic technique was also significantly improved, with the lowest bus voltage increasing from 0.9284 to 1.05pu [54].

2.2.2 PV systems for rural electrification

For the purpose of evaluating the viability of a Wind-PV hybrid system for the local generation of electrical energy to supply rural areas in the country's eastern province where there is enough sunlight and high-speed wind, Emmanuel et al. conducted a research study on rural electrification in Rwanda in [17]. The system was simulated using HOMER software. A cost-effective hybrid system for supplying energy to rural communities was created as a consequence of the research for a model community of 200 families with a secondary and primary school, a health facility, and an office building for the government. In order to improve people's lives, this study suggested developing an effective and affordable hybrid power system. However, the PV system is not used in this research as PV-based DG [55].

Jeannine developed a photovoltaic system for electrifying rural areas as part of the project [56] . Since transmission lines are expensive and electricity from the national grid is so far away from the destination, her project's main objective was to demonstrate how a photovoltaic system can solve the electricity issue in rural areas of Rwanda, particularly in the Bugesera District. PV systems are an alternative plan because they are inexpensive and efficient power systems for supplying electricity to various households and public services. Instead of extending the use of electricity from the national grid, this study sought to boost system efficiency and cost. However, the author did not use the power system as PV-based DG [56].

In research [57], Odax analyzed the power system options for rural electrification in Rwanda to offer a hybrid power system based on the best combination of renewable energy resources available in rural areas of Burera District to meet the electricity demand in an affordable and sustainable way using simulation using HOMER software. This study encouraged a hybrid renewable energy system; effective and affordable to address the electricity shortage in the Burera district. The author concluded that the hydro-wind hybrid system was not practical due to our nation's unfavorable location near the equator for wind, so he opted for a system combining hydro and batteries-diesel generators as a storage medium [57].

According to the papers cited above, some researchers discussed about introduction of DG in various power systems while others uses solar PV systems for rural electrification mention. As no researcher discussed about the types of DG to be used and no researcher proposed the use of PV systems as DG to overcome the issues of power loss in distribution networks and poor voltage profile, however, to the best of my knowledge, the integration of PV-based DG can solve problems in Rwanda electric distribution network to minimize power losses in distribution lines and improve the network's voltage profile.

CHAPTER THREE: METHODOLOGY

The tools and systems that were used for the study were discussed in this chapter. Mathematical models and simulation were examples of the above. First, data on Rwanda distribution buses were collected from REG and modeled using ETAP software. Buses with high power losses and voltage drops were identified, and the best PV-based DG location and size were determined.

3.1 Power flow analysis

The Newton Raphson (NR) technique was used to study the power flow of the feeder distribution network under consideration. NR was governed by the power flow formulae below. With PV-based DG present at candidate busbars for the installation, equation 3.1 expressed the active power flow equations.

$$P_i = P_{DGi} - P_{Di} = \sum_{k=1}^{n} |V_i||V_k| (G_{ik} \sin\theta_{ik} + G_{ik} \sin\theta_{ik}) \quad \text{…..……………………………} \quad \textbf{Equation 3. 1}$$

Where

V_i : Voltage at bus i

V_k : Voltage at bus k

V_{ik} : Voltage between buses i and k

P_i : Real power injected at bus i

P_{DGi} : Real power supplied by DG at bus i

P_{Di} : Real power demand at bus i

G_{ik} : Real part of matrix’s demand at bus ikth element

B_{ik} :Imaginary part of matrix’s demand at bus ikth element

θ_{ik} : Voltage angle difference between busbars i and k

n: number of total number of busbars in t

3.2 Active Power Loss of distribution system

The total active power loss for an electrical distribution network with a specific number of power lines can be calculated using equation 3.2. The power line x, of the resistance R and current Ii flowing through it was considered. In equation 3.3, the active power loss brought on by a line was expressed.

$P_{loss}(total) = \sum_{1}^{k} P_k$ ……………………………………… **Equation 3. 2**

Where

P_k : Active power loss in distribution lines

$P_k = I_i^2 \times R$ ……………………………………………… **Equation 3. 3**

where R wass the resistance of the distribution line between two buses
and I_i and could be expressed as:

$I_i = V_i \sum_{j=0}^{n} Y_{ij} - \sum_{j=1}^{n} Y_{ij} V_j$ ………………………………….. **Equation 3. 4**

Where V_i : voltage at busbar i

V_j : Voltage at busbar j

Y_{ij} : Admittance of the distribution network between buses i and j

3.3 Busbar Voltage Profile

The distribution network's limits for busbar voltage profile change were selected to be 5% and was expressed in p.u as described in Equations 3.5 in order to analyze the change in busbar voltage profiles before and after integrating the distributed PV-based DG into the distribution network.

$0.95 \le V_i \le 1.05 p.u$ ………………………………… **Equation 3. 5**

3.4 Methodology approach

To minimize power losses on power lines and improve the voltage profile of distribution grids, PV-based DGs were considered in this section. The data used in the study were secondary data as they have already been collected by REG and, as they dealt with numbers, quantitative methods were used.

3.4.1 Determination of the feeder as a case study in the Rwanda distribution network

Our research's first objective was to assess the areas of Rwanda's distribution network that had larger power losses and lower voltage profiles. We then chose the feeder with the largest power losses and used it as a case study. Various feeders for different substations in all hubs of the electrical distribution network were studied, and feeders with higher power losses and poor voltage profiles were located, using data about power distribution from REG websites. The feeder with the greatest power losses was chosen as the case study among those feeders.

3.4.2 Model the electrical distribution network of the case study

The second objective discusses how to model the power distribution system on the chosen feeder and then determine power losses and voltage profile at weak busbars. This objective was achieved by using data collected from REG about selected feeder. Those data were mainly, feeder capacity, feeder voltage, loading at each transformer, input and output voltages of all transformers resistance and reactance of distribution lines. The provided data were computed by using ETAP software for identifying total load, power losses, and voltage profile at busbars.

3.4.3 Determine the optimal placement and size of PV based DG in the Rwanda electrical network for the chosen feeder.

Determining the best location and size of a PV-based DG for the selected feeder in the Rwanda distribution network was the third objective of the dissertation. To reach the objective, two issues had to be resolved: first, the optical placement on the selected feeder must be decided; second, the optimal size must be decided. Utilizing an integration approach, the PV-based DG was optimally sized and situated at weak buses (WBs) where the voltage profile was below the permitted limits.

3.4.3.1 Approach for DG location

The WB was used to determine the best location for DG on a proposed feeder. To select the best busbar for PV-based DG location, the WB approach depended on the deviation of busbar voltage magnitude boundaries. However, the WB strategy places PV-based DG on busbars whose voltage magnitude exceeds the guidelines established in Equation 3.5. These busbars were referred to in this study as weak busbars because of voltage variations. Initial voltage magnitudes of busbars in the feeder distribution network were obtained by modeling the load flow without integrating any DG station as the base case.

3.6.3.2 Approach for DG Size Selection

3.6.3.2.1 DG penetration level

Based on busbar voltage deviations, the size of PV-based DG stations to be installed on weak buses was chosen as a portion of the system's overall demand. Equation 3.6 is used to determine the total size of PV base DG stations as a share of the overall system demand.

$$DG_{size}(total) = \frac{P_L \times P_{load}(total)}{100\%} \quad \text{...} \ \textbf{Equation 3. 6}$$

Where:

$DG_{size}(total)$: the total size of DG to be installed in MW

P_L: DG penetration level total demand of distribution network

$P_{load}(total)$: Total active power of connected load

The size, nature, and placement of DG had the single greatest impact on the network; and the penetration level is an indicator that showed how local generation capacity stacks up against a certain distribution network's demand [58].

2.6.3.1.1 Integration approach (IA)

In accordance with the magnitude of the DG to be shared between busbars, two types of IA were considered: the normal integration approach (NIA) and the weighted integrated approach (WIA).

a) Normal Integration approach (NIA)

The NIA was taken into account when the distribution network of the feeder under consideration evenly distributed the entire size of DG among its weak busbars. As a result, the DG size for each weak busbar was the same across all weak busbars and was calculated using the equation. 3.7.

$$DG_{size}(NIA) = \frac{D_{size}(total)}{k} \quad \text{....................................} \ \textbf{Equation 3. 7}$$

Where:

$DG_{size}(NIA)$: Size of DG for each weak bus

k: total number of weak busbars the feeder distribution network

b) Weighted integration approach (WIA)

The WIA approach differed in the generating capacity of power installed on weak buses depending on the voltage magnitude deviation. The more the voltage curve of a busbar deviated from the limits of equation 3.4, the higher was the installed power compared to other busbars, as formulated in equation 3.8.

$$DG_{size}(WIA) = D_{size}(total) \times \frac{D_k}{D_{total}} \quad \text{...} \textbf{ Equation 3. 8}$$

Where:

$DG_{size}(WIA)$: Size of each DG Station in according in WI

D_k: Deviation of kth busbar's voltage magnitude

D_{total}: Total deviation of all weak busbars

k: number of weak busbars

3.4.4 Effect of DG on the Rwanda electrical network specifically on the chosen feeder.

The fourth objective was to look at how DG affected the selected feeder in Rwanda's electrical distribution network. This objective was accomplished by choosing the optimal placement and size for my DG, which gave the best outcomes when simulated using the ETAP program.

3.5 Data collection technique

To collect data for the Rwanda distribution electrical network on the feeder taken as the case study were gathered for this study from REG. The survey was in the form of a questionnaire, and it will be finished by the office in charge.

3.6 Methods of analysis

3.6.1 Data reparation

Before analyzing data, the preparation of them was needed. In this section, the questionnaires were recuperated and the researcher collected and consolidated them from REG into one table.

3.6.2 Analysis software

In this dissertation, the collected data from REG were analyzed after being prepared. The ETAP software was used to simulate and analyze how PV-based DG can contribute in distribution network so as to control the voltage and decrease the power losses. ETAP, as a powerful software, was used to perform simulations, analysis, and design of Power systems because of its very large capabilities like load flow analysis, stability of power systems, cable ampacity study, and so on.

3.6.3 Procedure analysis

Six different Penetration Level (PL) scenarios were taken into consideration in order to evaluate the advantages of integrating distributed PV systems. The base case, in which no PV-based units were connected to the distribution network, was first taken as a reference. Then, to choose the size and candidate busbars for PV-based placement, the WB technique was used. Following the identification of WB, the various PLs' PV-based sizes were established. Following that, the PL of PV systems were increased from the previous five examples by 10, 20, 30, 40, and 50%. Equation 3.8 was used to calculate the size of each PV systems to be installed on WBBs for all PL scenarios, and simulations were executed by using corresponding MW sizes for each P.

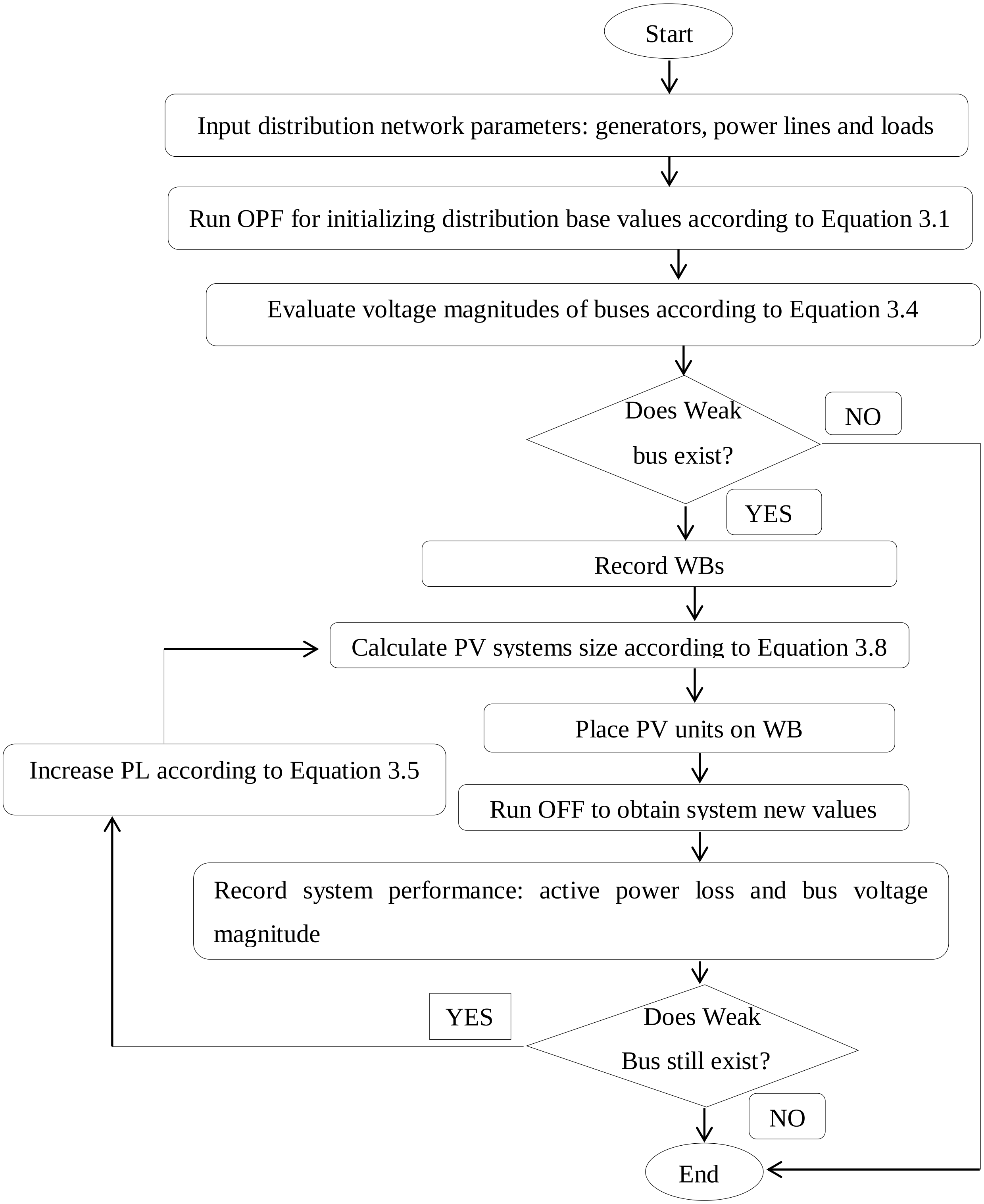

Figure 3. 1 Distribution network flowchart

CHAPTER FOUR: RESULTS SIMULATION AND DISCUSSION

The results related to the study's research objectives were presented in this chapter. A case study distribution feeder was first selected. Second, ETAP software was used to analyze and simulate the case study data in order to determine the performance of the distribution network in terms of active power loss and voltage profile. Third, the best site for weak buses was identified, and size PV-based DG calculations were made. In order to assess the impact of PV-based DG at the appropriate WBB, the DN was simulated.

4.1 Choice of the case study

In the "Rwanda Electricity Distribution Master Plan" report, REG assessed various electrical losses in MW and per unit voltage of each feeder of all substations in all provinces and Kigali City. Power losses and per unit voltage for each feeder of each substation for the Southern hub were shown in table 4.1. The Butare feeder, which had a 1.6MW capacity and among other feeders of the same region, it had the largest voltage drop (0.8p.u.) and maximum power losses, as presented by Kigoma Substation, according to the data in the table [59].

Table 4. 1 Active power losses and minimum voltage in Southern Province [59]

Low flow result for medium voltage network				
Substation	Feeders	Load (MW)	Losses (MW)	Minimum voltage (p.u)
Mont Kigali	Kiyumba	3.7	0.04	0.97
Kigoma Substation	Butare	13.6	1.58	0.80
	Gatumba.	4.91	0.18	0.94
	Ntongwe	5.25	0.32	0.91
Rukarara (II)	Rukarara (II)	8.04	0.36	0.92
Total for all substations		35.55	2.47	

A table 4.2 discussed power losses and per unit voltage for every feeders of each substations for Eastern hub. According to data given in the table, Musha Substation presented the Akagera feeder, the feeder (1.3MW) with the highest power losses and largest voltage drop (0.6p.u) among all feeders of the same hub [59].

Table 4. 2 Active power losses and minimum voltage in Eastern Province [59]

Low flow result for medium voltage network				
Substation	Feeders	Load (MW)	Losses (MW)	Minimum voltage (p.u)
Mont Kigali	Kanazi	7.06	0.5	0.86
Gabiro Substation	Kiziguro	2.65	0.03	0.97
	Ngarama	0.92	0.01	0.99
	Nyagatare	5.81	0.33	0.97
Kabarondo	Zaza	5.21	0.27	
Musha Sustation	Karenge	2.39	0.20	0.86
	Redmi	0.29	0.01	0.99
	Rwamagana	2.89	0.14	0.92
	SteelRwa	3.81	0.07	0.97
	Akagera	2.49	1.30	0.57
Total for all substations		35.96	2.91	

Table 4.3 listed the power losses and per unit voltage for each feeder of each substation for the Kigali hub. The Rutongo feeder had the largest power losses of all the feeders in the same hub, with a capacity of 0.22 MW and a voltage drop of 0.89 p.u [59].

Table 4.4 displayed the power losses and per unit voltage for each feeder of each substation for the Northern Hub. The Byumba feeder, with a capacity of 0.15 MW and a maximum voltage drop of 0.95 p.u was a feeder that was part of the Rulindo Substation [59].

Table 4. 3 Power losses and p.u minimum voltage in Kigali Province [59]

Low flow result for medium voltage network				
Substation	Feeders	Load (MW)	Losses (MW)	Minimum voltage (p.u)
Birembo Substation	Gikomero	1.15	0.009	0.988
	Kibagabaga	1.41	0.022	0.978
	Remera	1.08	0.099	0.987
	Kinyinya	2.40	0.073	0.96
Gahanga	Master Steel	0.68	0.004	0.993
	Pylon 20	0.45	0.002	0.994
Gasogi Substation	Inyange	1.97	0.058	0.951
	Kabuga	1.95	0.062	0.951
	Kanombe	5.06	0.159	0.936
Gikondo Dispatching	Gasogi	3.39	0.094	0.948
	Gikondo (Haut)	1.54	0.005	0.993
	Kimuhurura	0.82	0.038	0.999
	Nyarurama	0.49	0.001	0.998
	Industrial	0.96	0.004	0.994
	Kigali North	5.46	0.197	0.944
	Kigali South	3.705	0.064	0.974
Jabana I (Substation)	Rutongo	2.742	0.217	0.892
	Deutch Welle	0.919	0.013	0.983
	Kigali	4.358	0.095	0.957
	Sucrerie	0.613	0	1
	Utexirwa	2.867	0.063	0.97
Mont Kigali Substation	Kanazi	0.224	0	0.999
	Kiyumba	0.21	0	1
	Nyamirambo	1.686	0.01	0.989
	Nyarurama	0.714	0.007	0.988
Ndera	KSEZ1	3.13	0.034	0.979
Nzove Substation	Abattoir	0.088	0	0.999
	Skol	2.92	0.034	0.975
Total for Kigali Substations		53.004	1.274	

Table 4. 4 Power losses and p.u minimum voltage in Northern Province [59]

Low flow result for medium voltage network				
Substation	Feeders	Load (MW)	Losses (MW)	Minimum voltage (p.u)
Camp Belge Substation	Gisenyi	9.403	1.086	0.999
	Kinigi	1.064	0.004	1
	Prime Cement	1.44	0.002	0.996
Gifurwe Substation	Gakenke	0.589	0.004	1.002
	Kirambo	0.525	0.001	0.996
	Ntaruka	0.064	0.1135	1
Mukungwa HPP	Remera	0.333	0.1135	1.019
Remera SS	Janja	0.362	0.004	1.019
Mukungwa HPP	Ruhengeri / Camp Belge	0.882	0.11	1.01
Ntaruka HPP	Ruhengeri	0.486	0.001	0.996
	Cyanika	0.528	0.001	0.997
Rulindo Substation	Base	0.738	0.003	0.995
	Byumba	4.373	0.149	0.952
	Gasiza	0.595	0.001	0.997
	Musasa	0.936	0.007	0.99
Total for Northern Substations		22.318	1.6	

Power losses and the unit voltage for each feeder of each substation for the Southern hub were detailed in Table 4.5. The Rubavu Substation contains the Rubavu Feeder, which among other feeders of the same hub had the largest power losses (0.215MW) and voltage drop (0.996p.u) **[59]**.

Table 4. 5 Power losses and p.u minimum voltage in Western Province [59]

Low flow result for medium voltage network				
NORTHERN HUB (961 Transformer considered)				
Substation	Feeders	Load (MW)	Losses (MW)	Minimum voltage (p.u)
Gihira	Goma	6.071	0.059	0.996
Karongi Substation	Gisovu	0.272	0.001	1.017
	Kibuye	3.574	0.1	0.968
	Mugonero	0.437	0.001	1.016
Kibogora Sustation	Nyamasheke	0.541	0.001	0.997
	Rwanika	0.669	0.002	0.996
Kilinda Substation	Birambo	0.443	0.001	0.998
	Hospital	0.032	0	1
Mururu1	Mashyuza	2.741	0.061	0.969
Mururu2	Shagasha	2.469	0.01	0.993
Ntendezi Substation	Kibogora	0.554	0.001	0.999
	Mururu1	0.638	0.002	0.998
Nyabarongo HPP (Substation)	Nyabarongo (Auxiliary)	0.12	0	1
Rubavu	Rubavu	5.234	0.215	0.996
Total for Western Substations		23.795	0.454	

According to the report, Table 4.6 showed the overall losses for each province. The Southern Province had the second-largest losses (2.5MW), proceeded by the Eastern Province, which had the biggest losses (2.9MW) [59].

Table 4. 6 Losses in Rwanda distribution network [59]

Region (Hub)	Losses in (MW)	% Contribution
Kigali	1.274	14.63
North	1.6	18.37
South	2.474	28.41
East	2.906	33.37
West	0.454	5.21
Total	8.708	100

The Butare feeder at the Kigoma substation exhibited the largest power losses of 1.6 MW and the highest voltage drop of 0.8 p.u voltage, according to the results of power losses and voltage profiles from the Southern provinces, as shown in Table 4.7.[59]

Table 4. 7 Feeders with highest power losses per hub [59]

Substation	Feeder	Load in MW	Power losses	p.u voltage
Kigoma	Butare	13.632	1.578	0.801
Musha	Akagera	2.491	1.301	0.567
Jabana I	Rutongo	2.742	0.217	0.892
Rulindo	Byumba	4.373	0.149	0.952
Rubavu	Rubavu	5.234	0.215	0.996

Power losses and the unit voltage for each feeder of each substation for the Southern hub were summarized in Table 4.5. The Rubavu Substation included the Rubavu Feeder, which among other feeders of the same hub had the largest power losses (0.215MW) and voltage drop (0.996p.u) [59].

4.2 Model of Butare feeder

The Kigoma substation with Butare as a case study wad selected to evaluate the optimization of PV-based DG on Rwanda's electrical network. The substation had four feeders, including the Butare, Gatumba, Ntongwe, and Kigoma auxiliary feeders. Butare had the most amount of power losses out of all the feeders in Rwanda's distribution system. The Butare feeder started at a 110/30kV distribution transformer on the Kigoma substation, as shown in Table 4.8. The cumulative loss on the Butare feeder was 1.6 MW, about 14 MW and 30 kV, respectively, are peak demand and the feeder bus voltage. There were 127 buses overall, 72 of which are load buses, and 126 branches. Each load bus had a transformer rating of 15kVA, 25kVA, 50kVA, 100kVA, 160kVA, 200kVA, 250kVA, 315kVA, and 400kVA. Additionally, a 415V/240V step-down transformer was present on each load bus. To provide electricity to customers who are spread across the districts of Gisagara, Huye, Nyanza, and Ruhango.

Table 4. 8 Description of Butare distribution feeder

Substation transformer	110/30kV
Total number of buses	127
Number of load buses	72
Number of branches	126
Peak load	20MW
Transformer ratings in the feeder	15kVA, 25kVA, 50kVA, 100kVA, 160 kVA, 200kVA, 250 kVA, 315 kVA, 400 kVA

The Butare distribution feeder's lengths of distribution lines were shown in Table 4.9, and each line was terminated by a bus that was connected to one or more distribution transformers.

Table 4. 9 Lengths of Butare feeder power lines

SN	ID	Length (km)	SN	Line	Length (km)
1	AAL	4.9	18	KBL	3.3
2	BADL	1.8	19	KGM1L	4.3
3	BGEL	2.6	20	KML	1.2
4	BHL	3.2	21	KRL	1.5
5	BUL	3.5	22	KYL	4.9
6	CDOL	0.7	23	MBWL	7.8
7	CHUL	1.5	24	MBZL	5.3
8	CWL	2.5	25	MGZL	8.1
9	DUL	2.9	26	MML	2.9
10	GASL	3.4	27	MPL	5.4
11	GISL	14.8	28	MTL	1.1
12	Gitwe	12.7	29	MTML	1.7
13	GKML	3.9	30	MUGL	4.7
14	GKNL	3.2	31	MUGL9	6.7
15	GTL	3.3	32	MUSL	8.4
16	HYL	13.4	33	MWL	3.5
17	HYL2	1.1	34	MYL	5.9

Figure 4.1 showed an ETAP software model of a Butare feeder. The distribution network data for the chosen feeder was entered into the ETAP software to evaluate an initial NR power flow; power loss, and the voltage profile at each bus, which led to the creation of the base case model.

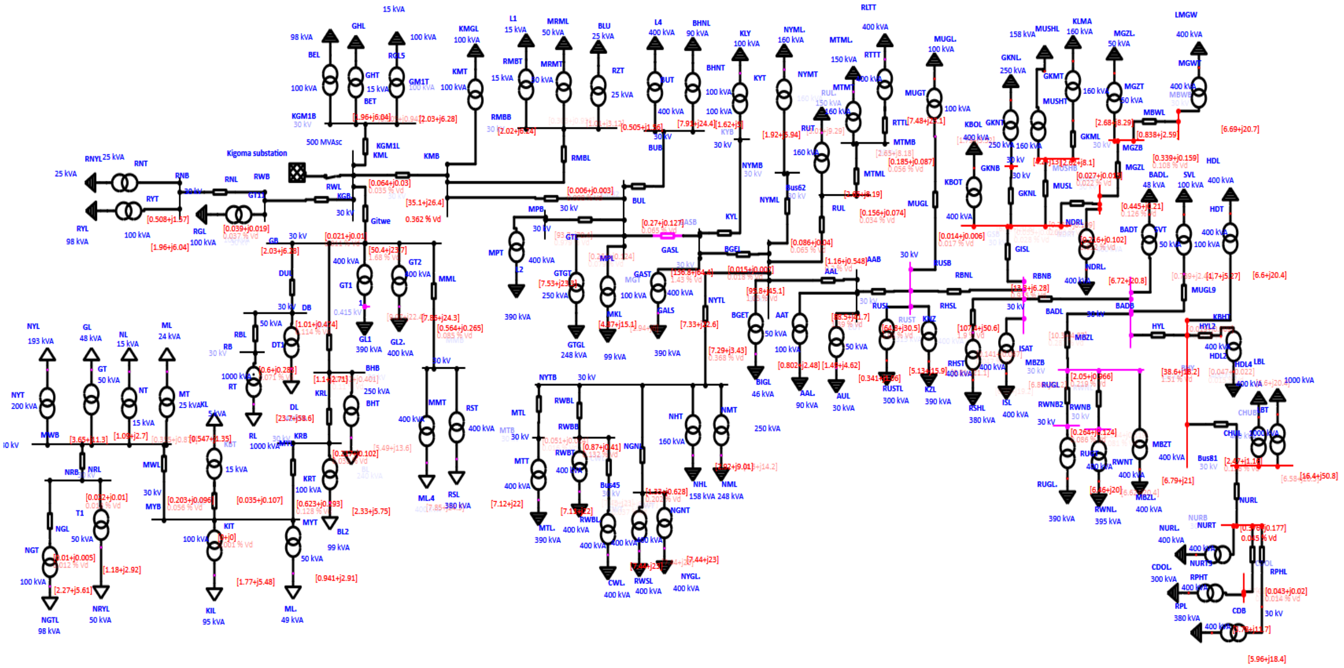

Figure 4. 1 Model of Butare distribution feeder

Case 1: Base Case model

In case 1, the distribution network of the Butare feeder was simulated and examined using ETAP software without the usage of DG. The results of the voltage profiles on weak buses WBs, thus, those whose voltage was below acceptable thresholds, are shown in Table 4.9. To accommodate the DG that would be injected into the feeder distribution network, WBs were preferable choices. The values that were currently available can be used to calculate the p.u. voltage deviation for each bus and the total voltage deviation was found to be 1.494p.u.

Table 4. 10 Voltage deviation for weak busbars

SN	Bus ID	% Voltage	MW Loading	p.u voltage	p.u VD
1	CDB	89.88	0.214	0.899	0.101
2	NURB	89.88	0.762	0.899	0.101
3	Bus81	89.93	1.745	0.899	0.101
4	BHY	90.06	2.31	0.901	0.099
5	MBWB	90.66	0.285	0.907	0.093
6	MGZB	90.76	0.321	0.908	0.092
7	MUSHB	90.83	0.228	0.908	0.092
8	GKNB	90.89	0.179	0.909	0.091
9	NDRB	90.89	0.609	0.909	0.091
10	GSB	90.92	1.303	0.909	0.091
11	RWNB2	91.26	0.282	0.913	0.087
12	RWNB	91.27	0.286	0.913	0.087
13	MBZB	91.35	0.858	0.914	0.087
14	BADB	91.57	3.317	0.916	0.084
15	RBNB	91.86	5.215	0.919	0.081
16	RUSB	93.76	5.926	0.938	0.062
17	AAB	94.79	6.086	0.948	0.052

Table 4.10 showed that the overall load is 13.094 MW. The DG size was chosen with several penetration levels, ranging from 10% to 50% with an increment of 10% between adjacent penetration levels. Thus, the penetration levels for 10%, 20%, 30%, 40%, and 50% were 1309.8kW, 2619.5kW, 3929.3kW, 5239.0kW, and 5239.0kW, respectively. According to WIA, the PV-based DG sizes on individual WBs that were to be injected were determined and are shown in table 4.11.

Table 4. 11 Butare Feeder distribution load

SN	ID	kW
1	AAL.	69.17
2	AUL	23.71
3	BADL.	34.23
4	BEL	83.14
5	BHNL	74.83
6	BIGL	36.33
7	BL	195.5
8	BL2	80.36
9	BLU	21.03
10	CDOL.	210.2
11	CWL.	310
12	DL	39.11
13	GALS	313.1
14	GHL	12.7
15	GKNL.	175
16	GL	38.93
17	GL1	318
18	GL2.	327.6
19	GTGL	204.7
20	HDL	274.9
21	HDL2	274.8
22	HDL4	274.1
23	ISL	286
24	KBOL	280.2
25	KIL	77.74
26	KL	4.33
27	KLMA	111.8
28	KLY	80.07
29	KMGL	84.13
30	KZL	291.2
31	L1	12.62
32	L2	321.9
33	L4	329.5
34	LBL	685.3
35	LMGW	278.6
36	MBZL.	282.9
37	MGZL.	34.9
38	MKL	81.73
39	ML	19.47
40	ML.	39.99
41	ML.4	327.1
42	MRML	42.06
43	MTL.	304
44	MTML.	117.7
45	MUGL.	74.46
46	MUSHL	110.6
47	NDRL.	280
48	NGTL	79.28
49	NHL	123
50	NL	12.12
51	NML	193
52	NRYL	40.38
53	NURL.	273.8
54	NYGL.	309.8
55	NYL	157.5
56	NYML.	125.2
57	RGL	84.72
58	RGL5	84.68
59	RL	810.3
60	RLTT	311.6
61	RNYL	21.16
62	RPL	261.3
63	RSHL	272.7
64	RSL	312.2
65	RUGL.	275.9
66	RUL.	117.8
67	RUSTL	224.5
68	RWBL.	310.3
69	RWNL.	279.1
70	RWSL	309.8
71	RYL	83.12
72	SVL	71.02
Total load		13094.02

Table 4. 12 Size of PV-based DG for each WB

			Sizes of PV-based DG to be injected in Distribution system				
SN	Bus ID	p.u VD	for 10% PL	for 20% PL	for 30% PL	for 40% PL	for 50% PL
1	CDB	0.101	88.7	177.4	266.1	354.8	443.5
2	NURB	0.101	88.7	177.4	266.1	354.8	443.5
3	Bus81	0.101	88.3	176.5	264.8	353.0	441.3
4	BHY	0.099	87.1	174.2	261.4	348.5	435.6
5	MBWB	0.093	81.9	163.7	245.6	327.4	409.3
6	MGZB	0.092	81.0	162.0	242.9	323.9	404.9
7	MUSHB	0.092	80.4	160.7	241.1	321.5	401.8
8	GKNB	0.091	79.8	159.7	239.5	319.4	399.2
9	NDRB	0.091	79.8	159.7	239.5	319.4	399.2
10	GSB	0.091	79.6	159.2	238.7	318.3	397.9
11	RWNB2	0.087	76.6	153.2	229.8	306.4	383.0
12	RWNB	0.087	76.5	153.0	229.5	306.1	382.6
13	MBZB	0.087	75.8	151.6	227.4	303.2	379.1
14	BADB	0.084	73.9	147.8	221.7	295.5	369.4
15	RBNB	0.081	71.3	142.7	214.0	285.4	356.7
16	RUSB	0.062	54.7	109.4	164.1	218.8	273.4
17	AAB	0.052	45.7	91.3	137.0	182.6	228.3

Case 2: Injection of DG in Butare distribution network

To obtain the new parameters and compare them to the base case, PV-based DGs were placed on WBs for each PL after determining the size of the PV-based DGs for the selected PL as shown in Figure 4.2. So, on each of the available weak buses, and the PV-based DGs were individually administered with 10% PL. The distribution network's behavior in the presence of distributed generation was then, predicted using simulations to determine the voltage profile and power losses. For all PLs of PV units, the same procedure was applied.

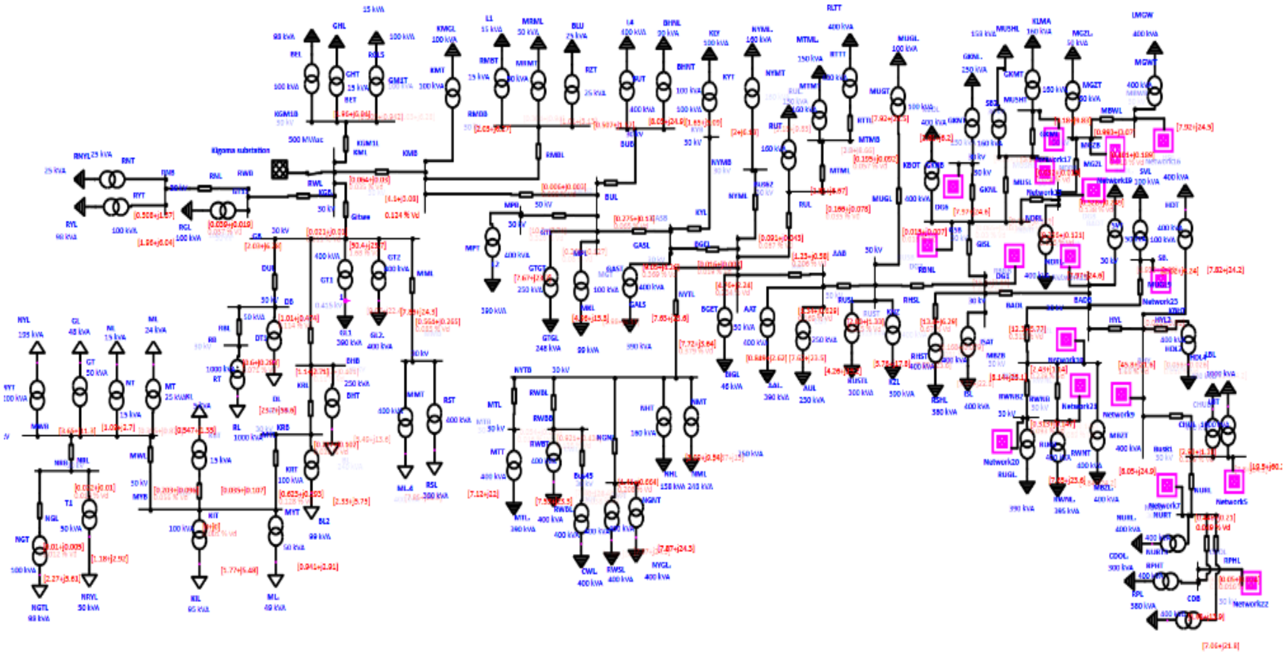

Figure 4. 2 Butare distribution feeder with PV-based DG penetration

Voltage deviation for the buses under consideration was given in Table 4.12, following the application of PV-based DGs equals PL of 10%, 20%, 30%, 49%, and 50% of to the appropriate WBs in comparison to the Butare feeder base case.

Table 4. 13 Bus Voltage after PV-based DG of various PL

Bus	Base case	10% PL	20% PL	30% PL	40% PL	50% PL
CDB	89.65	97.84	97.84	99.94	99.8	97.84
NURB	89.66	97.85	97.85	99.95	99.81	97.85
Bus81	89.7	97.9	97.9	99.94	99.8	97.9
BHY	89.83	98.04	98.04	99.96	99.48	98.04
MBWB	90.43	98.69	99.55	99.71	99.55	99.55
MGZB	90.54	98.81	99.67	99.83	99.67	99.8
MUSHB	90.6	98.88	99.74	99.9	99.74	99.49
NDRB	90.66	98.95	99.81	99.96	99.81	99.6
GKNB	90.67	98.95	99.84	99.84	99.84	99.56
GSB	90.69	98.98	100.84	100.84	99.84	99.59
RWNB	91.04	99.36	99.36	99.82	99.59	99.36
MBZB	91.12	99.45	99.45	99.91	99.68	99.45
BADB	91.34	99.69	99.69	99.69	99.92	99.69
RBNB	91.63	100	100	100	100	100
RUSB	93.52	99.33	99.33	99.33	99.33	99.33
AAB	94.55	99.12	99.12	99.12	99.12	99.12
BGEB	96.02	98.95	98.95	98.95	98.95	98.95
MWB	97.99	97.99	97.99	97.99	97.99	97.99
BHB	98.21	98.21	98.21	98.21	98.21	98.21

Depending on various penetration levels, the active power losses varied according in Table 4.13.

Table 4. 14 Effect of PV-based DG on real power in Butare feeder distribution network

	BASE CASE	**PV-BASED DGs**			
Power in MW	0% PL	20% PL	30% PL	40% PL	50% PL
Load	13.435	14.735	14.864	14.848	14.732
Generation	14.557	15.272	15.339	15.331	15.271
Loss	1.122	0.537	0.475	0.483	0.539

4.3 Impact of PV-based DG on Butare distribution feeder

4.3.1 Active power loss reduction

The total active loss of the Butare feeder distribution network was calculated for each of the analyzed situations. After each PL of PV-based-DG with their respective sizes, the NR power flow was carried out to estimate the overall active power losses in the feeder distribution network.

The investigation revealed that the addition of PV-based DGs to the electrical distribution network reduced the network's active power loss. Figure 4.2 showed the active power loss of the network for various PLs. When PV-based DGs of 10% PL were injected into the respective weak buses, the highest active power loss in the base case, where no PV-based DGs were included in the network, was reduced to 0.55MW. When the PL increased, the active power loss was further reduced. According to Table 4.13, the network's active power loss was lowest at 30% PL. Therefore, the WBs on the Feeder distribution network was the best locations for PV-based DGs.

4.3.2 Bus voltage profile improvement

Similar to the base case, the voltage profiles of WBs for various PLs were examined. Weak voltages were found to be improved by adding PV-based DGs to the distribution network compared to the initial scenario. The voltage profiles of the network's buses were shown in Figure 4.12 while accounting for each PL in contrast to the base scenario. As shown in Equation 3.5, all WB voltage profiles deviated from their theoretical boundaries in the base case presented by Figure 4.1. It was significant to observe that as PL increased, the magnitudes of the voltage at the WBs gradually increased and approached 0.95p.u.

The location of PV-based DGs on WBs decreased the amount of electric power to travel longer distances (to other feeder buses) to meet their demand, which increases the efficiency of the feeder as a whole. The most significant profile improvement was seen in the Rubona (RBNB) bus, where the voltage magnitude improved from 0.937 to 1 p.u.

CHAPTER FIVE: CONCLUSIONS AND RECOMMENDATIONS

5.0 Introduction

This chapter discussed the important research assistances and effects of the dissertation. The scope of the future research in this domain was once again proposed at the end of this chapter.

5.1 Conclusions

DG was offering progressively attention electrical power source as an alternative to centralized generating power plants. In optimal injection of DG into distribution networks raised practically, many benefits on the functioning of power distribution networks.

This dissertation aimed to determine practical problems of power losses and poor voltage profile and proposes solution to integrate the PV-based DG on Rwanda distribution network. The study was practically carried out in 30kV feeders in Rwanda electrical grid.

In this dissertation, opportunities for distributed power generation close to electrical load were evaluated. We chose a case study of Butare feeder in 110/30kV Kigoma substation located in Southern province of Rwanda, to study the effect of PV based DG on the feeder. The study showed the presence of meaningful minimization of power losses and improvement voltage profiles within the feeder. The results show that PV-based DG could minimize power losses and improve voltage profile of the Butare feeder.

Both optimal location and size of PV-based DG had to be to be considered carefully to benefit from DG introduction at maximum rate.

The obtained results showed that the voltage of the buses increased around 8% and the power losses in the feeder distribution network was reduced from 1.112 MW to 0.475 MW with the PV-based DGs of 30% PL.

5.2 Recommendations for further studies

The Rwandan government was given recommendations in this research on how to make use of the availability of solar renewable energy to lower greenhouse gas emissions. In order to promote future and beneficial research on Rwanda's electrical grid, recommendations were made to Rwanda Energy Group (REG) to give new updates. In order to assist research about Rwanda's electrical power systems and aid in the country's electrification, it was also advised that REG make relevant data about the country's electrical grid available.

This analysis would be expanded to include other feeders in Rwanda's distribution networks in further research. It was recommended to other researchers that other optimization procedures could be used to carry out the optimization process and it would be possible to expand the DG allocation problem to optimize DG reactive power.

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