UNIVERSITY of RWANDA COLLEGE OF SCIENCE AND TECHNOLOGY ACE-ESD AFRICAN CENTER OF EXCELLENCE IN ENERGY FOR SUSTAINABLE DEVELOPMENT

DETERMINATION OF THE OPTIMAL CURRENT DURING PEAK HOURS FOR AN OFF-GRID PV- DIESEL HYBRID SYSTEM USING NON-LINEAR PROGRAMMING: CASE OF NURU POWER PLANT IN GOMA

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Declaration

I declare that this dissertation is the result of my own work except where especially acknowledged, and has not been submitted for any other degree at University of Rwanda or any other institution. It has been passed through the anti-plagiarism system and found to be compliant and this is approved final version of the thesis.

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Date : 09-11-2021

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Date : 10/11/2021

Dedication

To my brothers and sisters : MUMBERE Laurent, KAMBALE Jean de Dieu, KASEREKA Gislain, KAHINDO Elizabeth and MATHE Bernadette.

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Abstract

This study proposes a model that determines the optimal current in transmission and distribution lines while taking into account load demand. The optimal current is determined for power losses minimization in transmission lines during the highest load demand hours**.** This problem is formulated as a quadratically constrained quadratic problem and solved using Quadratic Constrained Quadratic Program (QCQP) solver. NURU power plant in Goma has been taken as a case study to demonstrate the effectiveness of the power losses optimization model developed. The technique consisted of controlling the current to be maintained at its optimal level through the transmission lines, considering the power at the distribution side and the power generated. The results show that the optimization model developed in this study reduces peak hours power losses by 77%.

Key words

Hybrid system;

Nonlinear programming ;

Optimal Current ;

Peak hours;

Quadratic Constrained Quadratic Program.

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List of symbols

A	Ampere
CO_2	carbon dioxide
GW	Gigawatt
K	Kelvin
Kg	Kilogram
Km	Kilometer
kV	Kilovolt
kVA	kilovolt-Ampere
kW	Kilowatt
kWh	kilowatt-hour
m	Meter
MW	Megawatt
MWh	megawatt-hour
MWh/y	megawatt-hour per year
NOx	Nitrogen oxide
tCOeq	tonnes of carbon dioxyde equivalents
Ω	Ohm
Ω.m	Ohm-meter
W	watt.

List of Acronyms

AC : Alternative Current
a.m. : Ante meridium
a-si : Amorphous silicon
CdTe : Cadmium Telluride
CIGS : Copper Indium Gallium Selenide
CSP : Concentrating solar power
C-si : Monocrystalline Silicon
DC : Direct Current
DOD : Depth of Discharge
DRC : Democratic Republic of Congo
ESMAP : Energy Sector Management Assistance Program
FACTs : Flexible Alternative current Transmission system
GHG : Greenhouse Gas
GaAs : Gallium Arsenide
HRESs : Hybrid renewable energy systems
NLP : Nonlinear Programming
p.m : Post meridium
Poly-si : Polycrystalline silicon
PSO-TS : Particle Swarm Optimization method and the Tabu-Search technique
PV : Photovoltaic
QCQP : Quadratic Constrained Quadratic Program
SHC : Solar heating and cooling
SSA : Sub-Saharan Africa
STATCOM : Static Synchronous Compensator
WOA : Whale Optimization Algorithm

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1 INTRODUCTION

1.1 Background

Though Sub-Saharan Africa (SSA) has tremendous renewable energy potential, the population of SSA countries, compared to emerging countries from other regions in the world, has the least access to electricity. According to the World Bank reports, electricity access in SSA dropped from 67% in 2010 to 54% in 2019 due to population growth. This shows that electrification lags behind population growth in many countries, singularly in countries like the Democratic Republic of the Congo (DRC), Nigeria, and Malawi. For DRC, for example, only about 19 % of its population has access to electricity [1].

Solar is one of the major sources of electricity generation in DRC, with average daily irradiation of 3.5 to 5.5 kWh/m^2 (as shown in Figure 1.1). According to the International Renewable Energy Agency, DRC had 20 MW of installed PV capacity at the end of 2020. One among PV plants commissioned in 2020 is a 1.3 MW off-grid PV-battery storage hybrid plant in Goma. The plant consists of 4,000 panels, each being capable to produce 335 W [2], and the batteries which enable continued supply of energy to the population after sunset. It also features several backup generators of nearly 364 kW as the total capacity. Electricity from this plant is distributed directly to the population via a mini-grid equipped with transformers and a transmission line. Figure 1.2 shows the NURU solar off-grid hybrid plant in Goma.

Goma is the capital, in the eastern part of DRC, of North Kivu province, with area of 75.72 km^2. It is located next to Rwandan city of Gisenyi, on the northern shore of Lake KIVU.

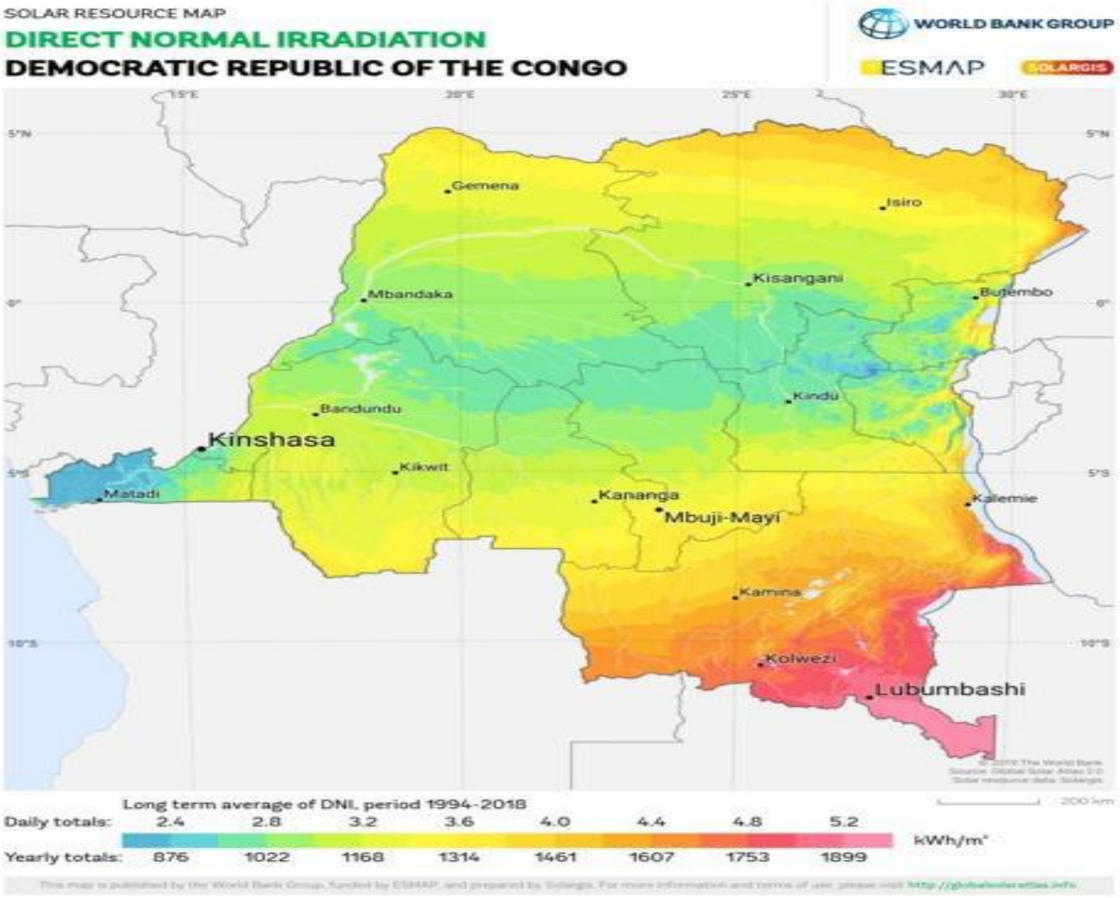

Figure 1.1: The map and data for Democratic Republic of Congo[1]

Figure 1.2. NURU solar power plant in Goma city of the DRC.

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[1] Source : Global Solar Attlas 2.0, Solargis and The World Bank Group 2020.

1.2 Problem Statement

There is always a gap between energy generated and energy distributed to the final consumers. This gap is mainly due to the losses occurring in the transmission but also in the distribution system. The losses between the power plant and consumers can either be technical or non-technical and go up to 22 %. Therefore, it is necessary to reduce losses to the minimum for electric power to get to the consumers.

Technical losses are classified into two categories : variable and fixed technical losses. Fixed losses are steady and can be handled by replacing old and inefficiency equipment with efficiency equipment, while variable losses vary with the change of the amount of power flowing. Variable losses increase during the highest load demand hours (peak hours). It is therefore essential to control current flow during peak hours to minimize losses.

1.3 Objectives

1.3.1 Main Objective

The primary goal of this study is to determine the optimal current for power losses minimization in transmission lines, during the highest load demand hours.

1.3.2.The Specific Objectives

1. To explore the impact of power losses on the consumers,
2. To formulate a mathematical model of power losses,
3. To develop an optimization model which can help to minimize power losses during peak hours.

1.4 Scope of the study

This study focuses on minimizing variable technical losses occur during peak hours.

1.5 Expected Outcomes and Significance of the Study

1.5.1 Expected Outcome of the Study

The development of an optimization model for variable technical power losses, which takes current flow during peak hours into consideration.

1.5.2 Significant of the Study

1. This study will give a new perspective in reducing variable technical power losses.
2. Through this study, the benefits of optimization methods in reducing variable technical power losses will be emphasized.
3. The results of this study will provide information which can be used in the future work that will scrutinize the different advantages of optimization techniques in solving power losses problems.
4. This study will benefit power plant operators as its results may motivate them to use optimization methods to reduce power losses by controlling current flow.
5. This study will also give information about the relation between power losses and greenhouse gas emissions.

1.6 Thesis Outline

This study is organized as follows :

Chapter two provides literature on solar energy, photovoltaic system, electricity transmission and distribution, and optimization.

Chapter three presents the problem formulation and optimization modelling.

Chapter four presents the case study and simulation results.

Chapter five provides conclusion of the work done and offers suggestions for future work.

2 LITERATURE REVIEW

This chapter covers solar energy, photovoltaic system, electricity transmission & distribution, and optimization background.

2.1 Solar Energy

Solar energy is the most abundant source of energy on the planet, and an important part of our future sustainable energy. It can be captured and used in a variety of ways such as electricity generation, heating water for domestic, commercial, or industrial use, etc. [3].Solar energy has many advantages ; these advantages include [4] :

i. *Renewable Energy Source*

Solar energy is produced from a non-exhaustible resource. Its harvesting process does not cause harm to biological or climate systems.

ii. *Reduces Electricity Bills*

Using solar energy instead of non-renewable energy in buildings can help building owners to reduce their electricity bills significantly.

iii. *Low Maintenance Costs*

Solar panels do not require reguraly maintenance. Their maintenance is done annually, exceptionally when there is an urgent problem to be solved. Therefore, the maintenance costs are lower.

iv. *Technology Development*

Researchers and experts in the solar energy industry are working tirelessly to increase the efficiency of solar harvesting technologies. Studies have shown that nanotechnology will significantly increase solar panels' efficiency and substantially increase electricity production in the future.

Solar energy is harnessed using three primary technologies : (a) photovoltaic (PV), which convert directly light from the sun to electricity ; (b) concentrating solar power (CSP), using heat from the sun (thermal energy) to drive utility-scale, electric turbines ; and (c) solar heating and cooling (SHC) systems, that collect thermal energy for providing hot water and air heating or conditioning. This study focuses on solar energy harnessed using PV.

2.2 Photovoltaic System

Photovoltaic (often shortened as PV) combines two Greek words : **photo** which means light and **volt**, which refers to electricity. It is the process of converting light to electricity. PV components generate electricity directly from sunlight through an electronic process that occurs in semiconductor materials [6]. Figure 2.2 shows the basic operating principle of a solar cell. Solar cell is the basic unit of a photovoltaic module or panel.

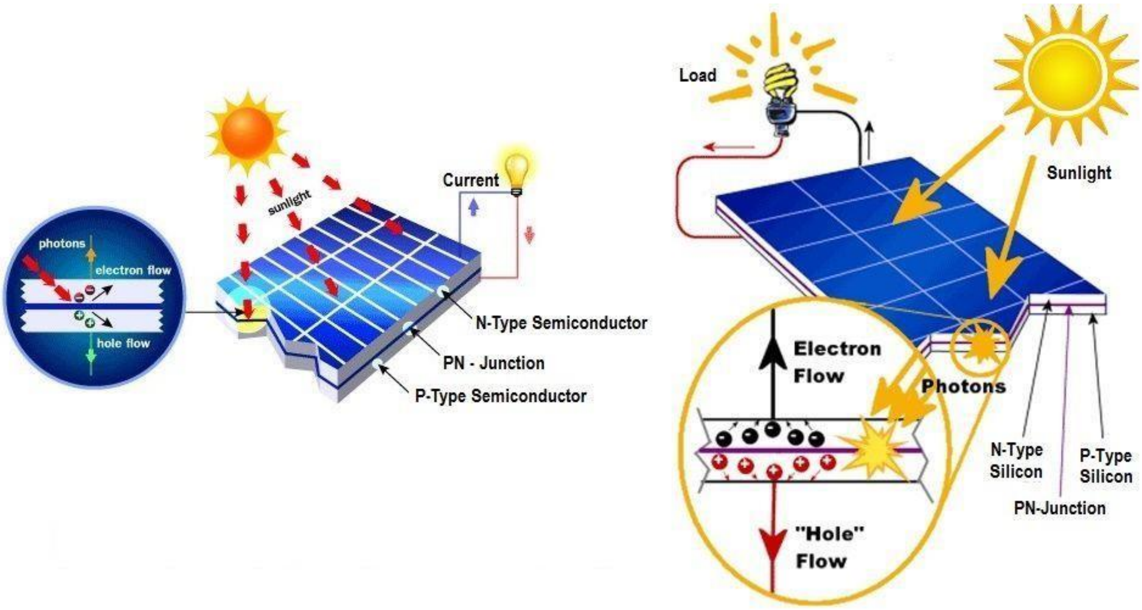

Figure 2.1: Basic operating principle of a solar cell[2].

Solar cells are mainly composed of two semiconductors : P-type and an N-type.These are joined together to create a p-n junction. The sunlight received on Earth particles of solar energy called photons. When sunlight is incident on solar cells, the energy from the photon is now transferred to an electron of the semiconducting material, causing therefore it to jump to a higher energy state known as the conduction band. These electrons are free to move through the material in their excited state in the conduction band, and this motion of the electron creates an electric current in the cell.

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[2] Source : Apogeeweb Semiconductor Electronic (https://www.apogeeweb.net/article/27.html)

PV cells are manufactured from many different materials and in different ways. Silicon (Si) is the most common material for commercial solar cell construction, but also other materials such as Gallium Arsenide (GaAs), Cadmium Telluride (CdTe), Copper Indium Gallium Selenide (CIGS), and Organic Solar Cells are used. There are different type of silicons and the way they are processed impact mostly the overall cost of production in the light to the electricity conversion efficiency of the module. The most known Silicon materials are [7] :

(a) *Amorphous*

Amorphous silicon (a-Si) is known as the non-crystalline allotropic form of the semiconductor silicon. It is the oldest and most mature type of silicon with an efficiency of between 5 - 7%.

(b) *Monocrystalline*

Monocrystalline silicon (c-Si or mono-Si) cells are referred to as silicon cells [8]. The entire volume of the cell is normally a single crystal of silicon. We have to denote that the efficiency of monocrystalline cells varies between 15 – 22%. This is the type of cell whose commercial use is more widespread in the world nowadays.

(c) *Polycrystalline*

Polycrystalline or multi-crystalline silicon (polysilicon or poly-Si) consists of several silicon crystals in a single PV cell. In order to form the wafers of a polycrystalline solar cell, several fragments of silicon are melted together. The polycrystalline cells have the efficiency varying between 15 – 17%.

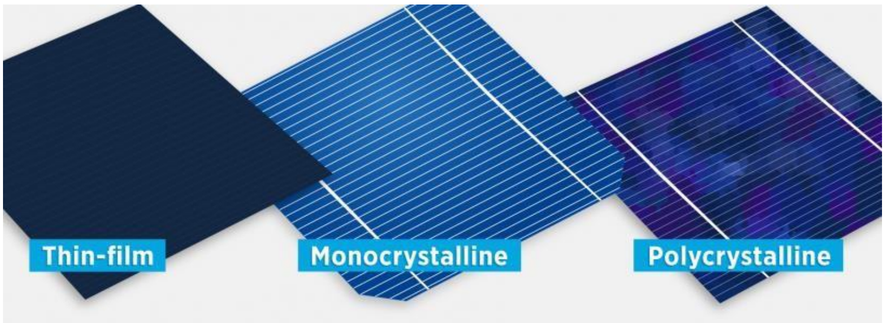

Figure 2.2: Silicon Solar Cell Material Silicon Solar Cell Material[3].

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[3] Source : Office of Energy efficiency & Renewable Energy , Solar Photovoltaic Cell Basics

2.2.1 PV major components

In photovoltaic systems, the major PV system components are PV array, Power Conditioning equipment (Inverter and charge controller), and Energy storage. The figure (2.3) shows important components of PV system for power generation.

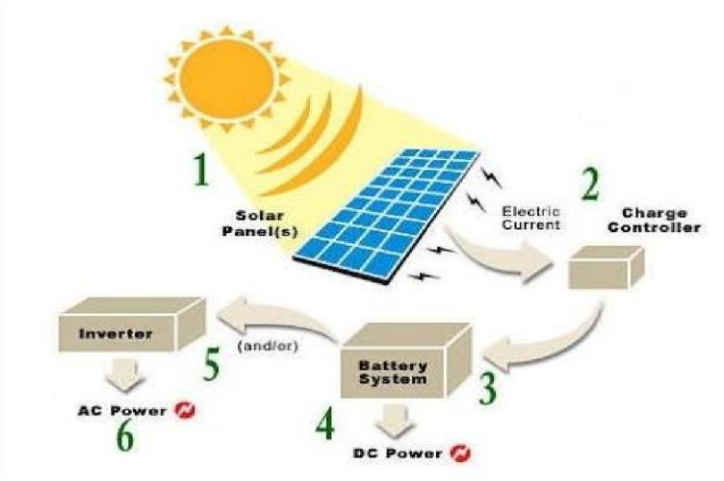

Figure 2.3: Components of PV system for power generation.

i) PV array

PV array is composed of an individual solar module. The solar module produces a small amount of electricity. When more than one solar module is connected, create a solar array. The purpose of a solar array in a PV system is to convert sunlight into Direct Current (DC) electricity.

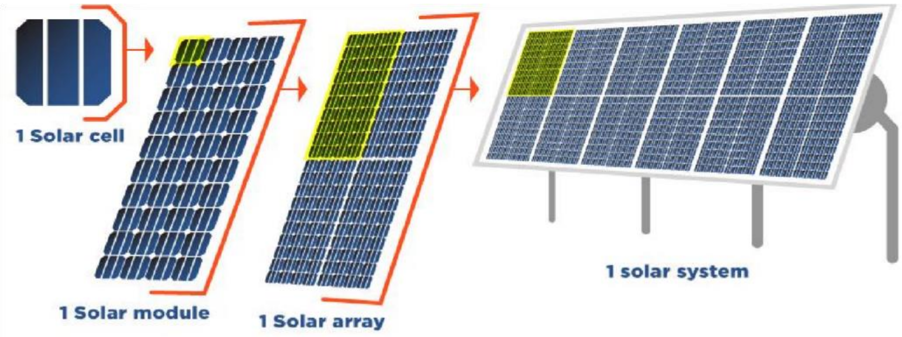

Figure 2.4: Solar Cell, module, array, and solar system[4].

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[4] Source : Solar Energy Home Systems (http://solarenergyhomesystems.com/solar.php)

ii) Power Conditioning Equipment

Power conditioning equipment consists of inverter and charger controllers. The function of the inverter is to convert the Direct Current (DC) into an Alternative Current (AC), which powers everything in our homes. Besides ensuring that the right amount of current is delivered to the battery, charge controllers also prevent the backflow of current from the battery to panels. During the nighttime, when the voltage of the battery is higher than that of solar panels, the current may flow in the opposite direction, which can damage solar panels.

iii) Energy Storage

Power is generated during the day when it is sunny. The generated energy can be used immediately or stored in batteries for later use, especially at night or on cloudy days. There are four major types of batteries used for storing electricity ; (a) Lead-acid, (b) Lithium-iron, (c) flow, and (d) Sodium nickel chloride. Due to their various advantages, lead-acid batteries are the most used batteries in PV systems. Some of the benefits of lead-acid batteries are; availability in many sizes, low cost, performance characteristics, and recyclability [8].

Battery should be size correctly in order to meet the load demand at the required time. The most imortant parameters to size PV system battery are;

- Norminal Voltage ;
- Energy demand ;
- Number of day of autonomy ;
- Depth of discharge ; and
- Efficiency.

The size of the battery in terms of energy storage can be estimated as follows :

$$\text{Battery Capacity(Ah)}=\frac{\text{Energy demand per day x Days of autonomy}}{\text{depth of discharge x Efficiency x Nominal Volts}} \quad (2.1)$$

where **Depth of Discharge** is the percentage of battery capacity that has been discharged.It is expressed as a percentage of maximum capacity (example 80%) ; the **nominal voltage** is the reference voltage of the battery in Volts ; **Days of autonomy** mean the number of days during which batteries would be large enough to supply continuously energy without charging, and the **Energy demand per day** is the energy consumption in kWh.

2.2.2 Types of PV Systems

PV systems vary from small size (that generates tens of kW) to large-based utility (that generates hundreds of MW) based on their applications. PV system can either be connected to the utility grid (grid-tie or hybrid systems) or disconnected from the grid (off-grid also known as stand-alone systems) [9].

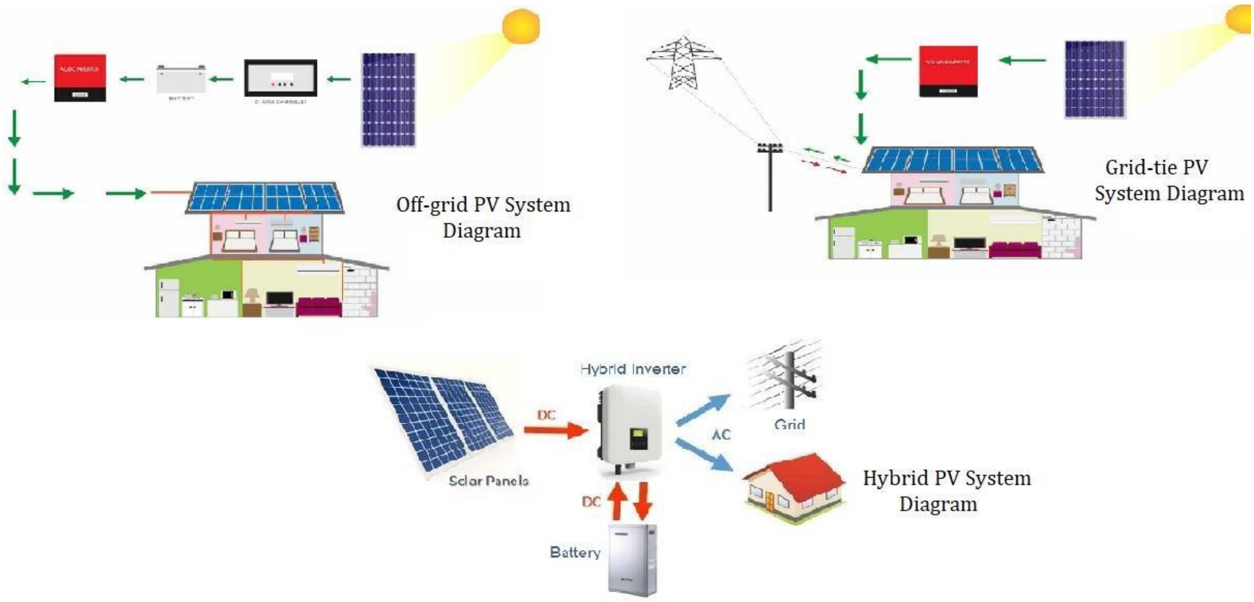


Figure 2.5: Types of PV systems.

i) Off-grid PV system

An Off-Grid PV System is a PV system wholly detached from the utility grid. Going off the grid means completely disconnecting your home from the mains electricity grid and powering your home by using solar energy only. An off-grid PV system must have a battery to store enough energy during a sunny day and use the excess power at night and on cloudy days. Off-grid PV systems are primarily used in remote locations in rural areas.

ii) Grid-Connected PV system

The grid-Connected PV system is the PV system connected to the utility grid. The inverter provides the electricity directly to the households/buildings and the utility grid when the electricity produced is more than the households/building demand. If the households/building demand is higher than what the solar system produces or when there is no sunlight, the households/buildings use the electricity from the grid. The biggest challenge of an on-grid system is that it does not supply electricity during the grid outage. One of the advantages of a grid-tie system over an off-grid system is that your house/building will always have power.

iii) Hybrid PV system

Hybrid PV system combines solar energy with another source of energy such wind, solar, hydro, or diesel generator. The hybrid system can also be referred to as a grid-tie system with a storage battery. In hybrid PV systems, solar power is the priority, and other sources fill the gaps. The most common hybrid systems are PV diesel and PV wind hybrid systems. Figure 2.6 shows the PV-diesel hybrid system connection structure.

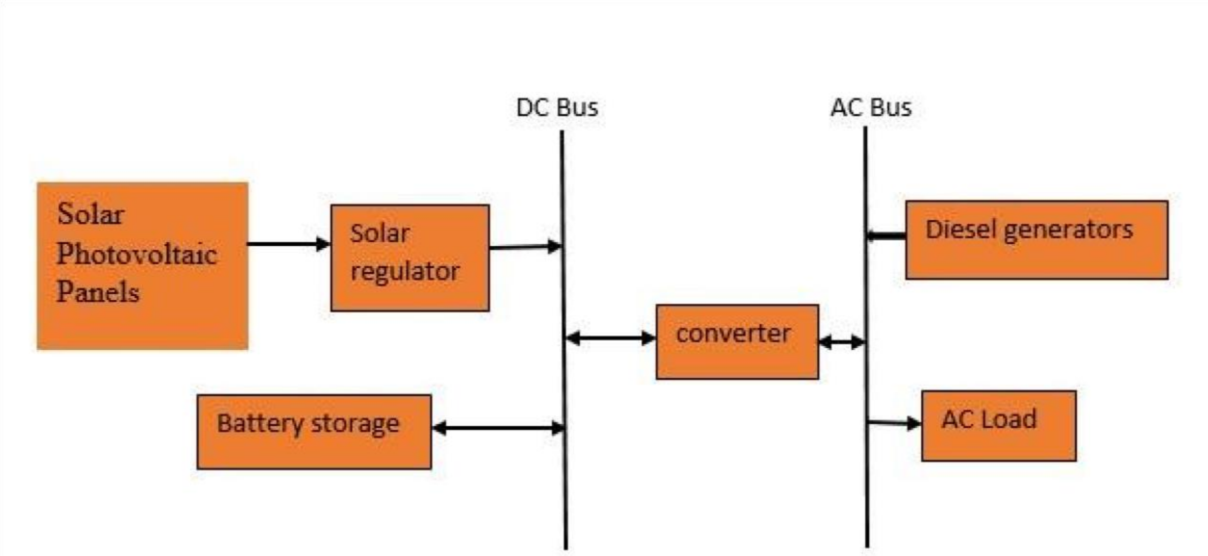


Figure 2.6 A PV-Diesel hybrid system.

2.2.3 PV System Sizing

Before designing a PV system for a home or commercial building, the designers need to know the type of system they want to size, how much energy is being used (energy demand), the amount of sunlight available, and estimate the system losses. PV system sizing is mathematically expressed as[10]:

$$PV system\ size = \frac{\frac{Energy\ demand}{Annual\ full\ sun\ hours}}{efficiency} \quad (2.2)$$

Energy demand (in W or kW) can be estimated using different approaches, including appliance labels, empirical measurement/direct measurement, or electric bills. Full sun hours refer to the solar insolation which would be received by a particular location if the sun were shining at its maximum value for a certain number of hours. Solar panels do not deliver 100% of the power listed on the manufacturing sheet. This is mostly due to some losses caused by wiring mismatch, direct current conversion to the alternating current through inverter, dust, and temperature. Therefore it is essential to take into consideration the efficiency when sizing PV.

2.3 Electricity Transmission and distribution

Power plants are usually located far from homes and businesses that need electricity. Thus, the electricity produced had to be transported and distributed to consumers. The transmission of electricity from power generation to consumers goes through different stages; these stages are called transmission and distribution systems. Figure…. shows the power transmission and distribution process.

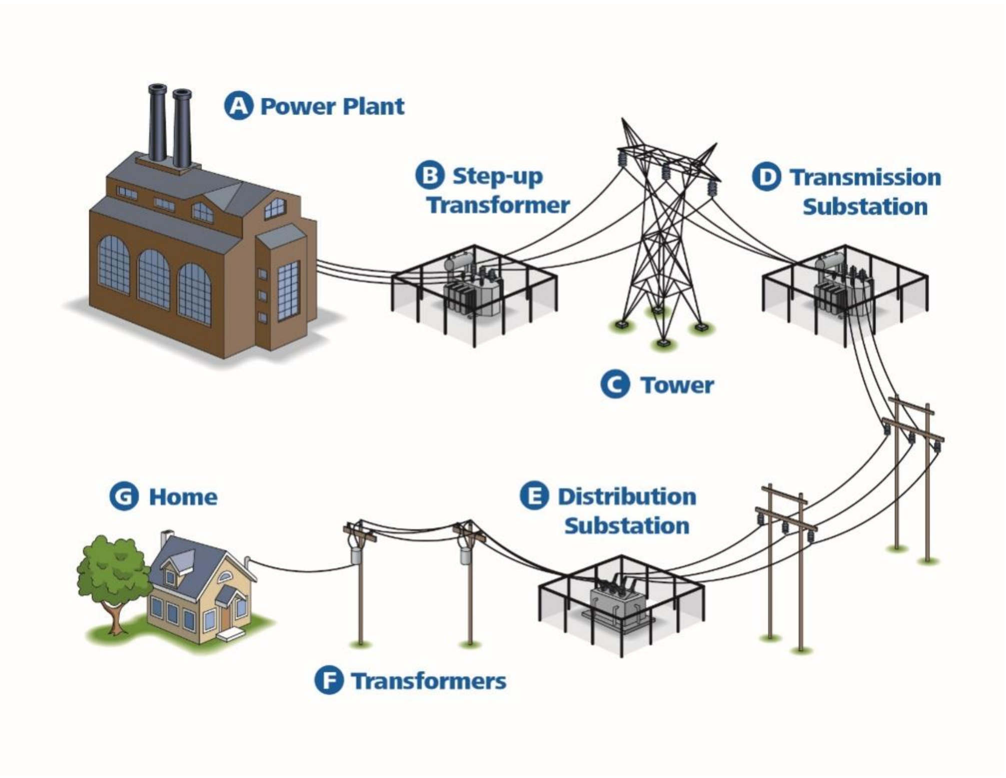


Figure 2.7 Power transmission and Distribution Process.

Electricity produced at the power plants is increased to higher voltages through a step-up transformer (position B in Figure…) before it is carried into the transmission lines. The stepping-down transformer (Position F in Figure…) lowers the voltage in distribution lines to meet customer levels.

2.3.1.Power losses

There are mainly two types of losses in transmission lines : Technical losses and non-technical losses. Radiation loss, conductor loss, dielectric heating loss, coupling loss and corona loss are technical losses, and power theft, metering inaccuracies are non-technical losses**.**

The resistance of the materials themselves to the flow of electricity is reflected by a larger share labeled "resistive" or "copper" losses. Core losses are typically 25 to 30 percent of total distribution losses, and do not increase (or decrease) with changes in load but they are largely influenced by the characteristics of the steel laminations used to manufacture the core of transformers. Resistive losses, contrariwise, are analogous to friction losses in the lines and transformers. The increasing of loads leads to the fact that the wires (including those in the transformers) get hotter, the material becomes more resistive, and line losses increase. The current on a line increases exponentially resistive losses. Power losses can be contained in a reasonably short period of time, this has been established by many studies. So the important thing is to know which solution to apply in order to reduce as much as possible losses and therefore to get high electricity to be distributed.

With Joule Effect, the power losses can be written as follows:

$$P_L = I^2 R, \qquad (2.2)$$

Where P_L = Power losses (Watt),

I = Current (A),

R = Resistivity (Ω).

Considering reactance, let's call Z the impedance of the whole transmission line. It follows that the formula (2.2) can be rewritten as :

$$P_L = I^2 Z \qquad (2.3)$$

2.4 Optimization

Optimization is defined as a method used to solve the conflicts of a decision situation so that the decision variables take the best possible value (optimal value). Optimization is used in various disciplines, including energy, physics, biology, engineering, economics, and business. The main components of the optimization problem are objective function, design variables, and constraints.

i. Objective function

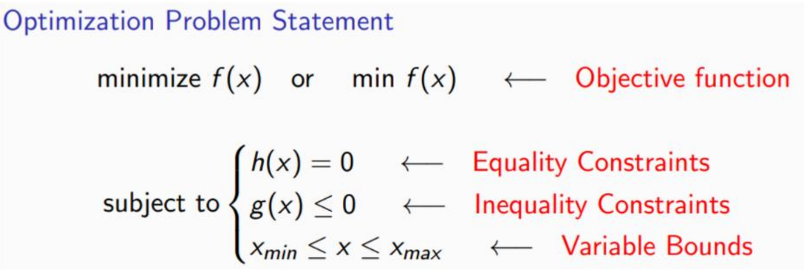
The first step in designing an optimization problem is to determine the objective of the problem. The objective function is the scalar that is to be maximized or minimized. It is generally given as an explicit function or must be the result of a complex computational procedure. With respect to the objective function, the optimization problems are classified by determining how the function depends on the design variables (linear, quadratic, or non-linear).

ii. Design Variables

Design variables called also decision variables and in certain circumstances, controlled variables, are the parameters that need to be determined to achieve the best optimal solution under given constraints.

iii. Constraints

In optimization, constraints are the mathematical equations that the solution must satisfy. There are two main constraints in optimization; equality and inequality. A constraint is called equality constraint when the mathematical equation is limited to being equal to a fixed quantity. It is called inequality constraints when the function is required to be greater than or equal to a certain quantity.



Optimization Problem Statement

$$\text{minimize } f(x) \quad \text{or} \quad \min f(x) \quad \longleftarrow \quad \text{Objective function}$$

$$\text{subject to} \begin{cases} h(x) = 0 & \longleftarrow \quad \text{Equality Constraints} \\ g(x) \leq 0 & \longleftarrow \quad \text{Inequality Constraints} \\ x_{min} \leq x \leq x_{max} & \longleftarrow \quad \text{Variable Bounds} \end{cases}$$

2.4.1 Classification of optimization problem

The optimization problem can be classified based on the type of objective function (linear or non-linear), constraints (constrained or unconstrained), nature of design variables (continuous or discrete), data used (deterministic or stochastic), and time (static and dynamic) [11]. Figure 2.6 presents the classification of optimization problems.

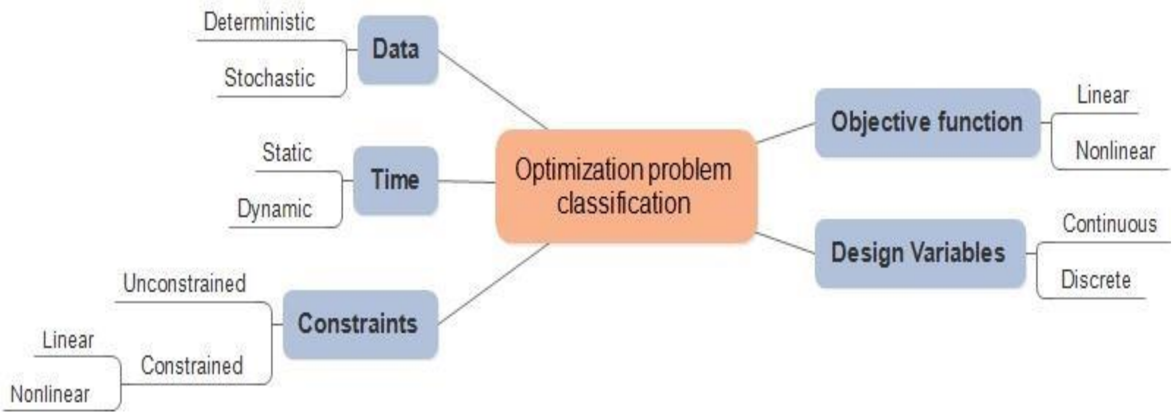


Figure 2.8 Classification of optimization problems.

(a) Linear and Non-linear Models

The decision variables are always multiplied by constants and added together for the objective function and the constraints of an optimization model. If an optimization model is not linear, then it is a non-linear model.

(b) Integer and Non-integer Models

If one or more decision variables must be discrete, the optimization model is an integer model. If all the decision variables are free to assume fractional values (continuous values), it follows that the optimization model is a non-integer model.

(c) Static and Dynamic Models

A static model is one in which the decision variables do not involve sequences of decisions over multiple periods, while a dynamic model is a model in which the decision variables do involve sequences of decisions over multiple periods.

(d)Deterministic and Stochastic Models

By supposing that for any value of the decision variables, the value of the objective function is known with certainty when the constraints are satisfied or not, this is a deterministic model. If not, then it is a stochastic model.

2.4.2 Application Area of optimization in power systems.

The optimization is needed in power systems for Planning, Operation and control.In planning, optimization techniques are used to design power plant that meet the demand at the optimal cost. For operation, for example, the optimization is applied for optimal power flow for power system analysis, scheduling and energy management. Optimization techniques are used in power system to ensure that the power generated matches the demand.

2.5 Related works

The optimization of power losses is not a new concept in research and Engineering. There are many authors who have worked on it, everyone with his methodological approach according to the goal to achieve, or the function to be optimized. Many studies have been conducted on the power losses optimization of different power systems Table (2.1) presents some of the research conducted on power losses optimization.

Table 2.1. Summary of the research conducted on power losses optimization.

Authors	Publication year	Model/techniques used	Analysis Metric (and results if any)	References
Faishal Islam Bappy, Md Jahirul Islam, Amit Kumer Podder, et al.	2019	HOMER and HELIOSCOPE softwares	The analysis metric consists here of Hybrid renewable energy systems (HRESs) as analysis metric, to be designed for successfully meeting the electrical energy demand of a sophisticated load profiling area with minimum cost [13]. This study found that PV-diesel based micro-grid system proved	[12]

			to be the most suitable choice having comparatively lower NPC ($3.62M), lower initial cost ($0.83M), lower system losses, moderate CO_2 emission along with better excess electricity profile (4142kWh/year).	
Sovann Ang, Uthen Leeton, Thanatchai Kulworawanichpong, and Keerati Chayakulkeeree,	2018	Whale Optimization Algorithm	Here, the analysis metric is power loss to be mimized. WOA spent the less to reach the optimal solutions when compared to other algorithms in regarding of computational time effort[13]. As a result, the power loss was improved with 6.92% reduction with WOA of the entire system.	[13]
Zahir Sahli, Abdellatif Hamouda, Abdelghani Bekrar and Damien Trentesaux	2018	Particle Swarm Optimization method and the Tabu-Search technique	The analysis metric is the voltage deviation. The PSO-TS algorithm has reduced the voltgage deviation from the initial state at 1.1521 p.u to 0.0866 p.u, representing a reduction of 92.48% [14].	[14]
Helge Urdal, Richard Ierna, Andrew J. Roscoe	2018	Comparison using Grid Forming.	The Analysis metric here is the stability of power hybrid systems operating close to 100% penetration of power electronic, which interfaced power sources[15]. The results demonstrated high	[15]

			converter penetration typically(65-70%) at synchronous area level could a type of super synchronous instability.	
M.Maheshkumar	2016	Use of FACTS devices	The use of FACTS devices such as STATCOM, as result found, can help in the better utilization of a network operating under normal conditions[16].	[16]
Omorogiuwa Eseosa, Oboma S.O	2015	Nonlinear Program (NLP) Optimization Technique	The analysis metric here is total cost to be reduced and the validity of the proposed method is illustrated by its application to a wide spectrum of actual transformers, of different power ratings and losses, resulting to optimum design with an average cost saving of 9.1%[17].	[17]

3 PROBLEM FORMULATION AND OPTIMIZATION MODELLING

3.1 Problem Formulation

Technical losses are classified into two categories : variable and fixed technical losses. Fixed losses are steady and can be handled by replacing old and inefficiency equipment with efficiency equipment, while variable losses vary with the change of the amount of power flowing. Generally, variable losses increase during the highest load demand hours (peak hours). It is therefore essential to control current flow during peak hours to minimize losses.

This study proposes an optimal power losses model that determines the optimal current for power losses minimization during peak hours while taking into account load demand.

3.2 Optimization formulation

The model formulated optimally determines the current flow at each evaluating interval. The optimization problem is described in the following subsections :

3.2.1 Design Variable

The design variable of the power losses optimization problem is the current flow in transmission lines, from the generation side to the distribution side. Let's denote *I(t)* the current flow at time t, where t = 1,2,3,...N. N is the evaluation period, and t is the sampling interval. The decision variable of the optimization problem is given as

$$X = [I(1), I(2), \ldots\ldots I(N)]^T (3.1).$$

3.2.2 Objective function

The objective of this study is to determine the optimal current that can allow operators to minimize power losses by controlling the power flow from the consumers side. The objective problem can be formulated into an optimization problem as

$$\text{Min } P_{L.} \qquad (3.2)$$

By using Joule effect, the power losses ($P_{L)}$ can be expressed as

$$P_L = \sum_{t=1}^{N} I^2(t)\, R\ , \ (3.3),$$

where I(t) is the current flow at time t, and R is the resistivity of cables in Ohm(Ω).

3.2.3 Constraints.

i) Boundary constraint :

$$I_{min} \leq I(t) \leq I_{max} \tag{3.4}$$

The constraint (3.4) indicates that the current flow is a continuous value bounded between minimum current flow (I_{min}) and maximum current flow (I_{max}).

ii) Power losses

$$\sum_{t=1}^{N} P_L(t) \leq \sum_{t=1}^{N} 6\% \, P_G(t) \tag{3.5}$$

The constraint (3.5) indicates that the sum of power losses should be less than or equal to 6% of the sum of power generated.

iii) Loads

$$\sum_{t=1}^{N} [P_G(t) - P_L(t)] \geq \sum_{t=1}^{N} P_D(t) \tag{3.6}$$

The constraint (3.6) shows that the sum of power generated minus the sum of power losses should be greater than or equal to the sum of power demand at time t.

3.3 Solution Methodology

This problem is formulated as a quadratically constrained quadratic problem. The power losses optimization problem is solved using QuadraticConstrained Quadratic Program (QCQP) available in the MATLAB interface OPTI toolbox. The Quadratic Constrained Quadratic Programing is a Nonlinear programming technique and its solver offers a solution to problems of the form:

$$\min_x \frac{1}{2} X^T H x + f^T x \tag{3.7}$$

$$\text{subject to} \begin{cases} Ax \leq b, \\ Aeq\, x \leq beq, \\ lb \leq x \leq ub, \\ X^T Q x + l^T x \leq r. \end{cases}$$

where H, A, Aeq and Q are matrices, and f, b, beq, lb, ub, l and x are vectors, and r is a scalar. Quadratic Constrained Quadratic Program solves problems in MATLAB as follows :

Opt=opti(‘qp’,H,f,’ineq’,A,b,’lb’,lb,’qc’,Q,l,r)

[x; fval ; exiflag ; info] = solve(Opt).

4 CASE STUDY AND SIMULATION RESULTS

4.1 Case study

The optimization model formulated is applied to the NURU power plant as the case study to evaluate its effectiveness. The power plant has 4000 Monocrystalline photovoltaic (PV) modules of 335 W each. The installed capacity of the NURU power plant is 1.3 MW, but currently is only producing 1.079 MW due to technical losses. The installation is equipped with ten batteries for a total capacity of 2.2 MWh for storing the electricity. The stored electricity is used by the loads once there is no irradiance or no sunshine available. The power plant is also equipped with several backup Diesel generators. Power consumed by end-users of the NURU power plant is generally from the PV-Battery hybrid system, and diesel generators produce electricity when the high demand has to be satisfied at time. The table (4.1) shows the power consumption (loads)

Table 4.1. Power demand during the day

Time of the day	Loads Demand(MW)
8 AM	0.7553
9 AM	0.80925
10 AM	0.83083
11 AM	0.8632
12 AM	0.91715
1 PM	1.00347
2 PM	1.02505
3 PM	1.02505
4 PM	0.91715

5 PM	0.8632

The current in transmission lines is determined according to the formula

$$P = \sqrt{3}\ VI\cos\varphi. \qquad (4.1).$$

where P = power consummed

V= voltage in transmission line (11 kV)

I = the current through transmission lines

Cosφ = power factor. Let's consider power factor equal to 0.8.

The target is to apply the formulated optimization model to reduce losses as much as possible therefore to get maximum power at distribution side.

For transportation of power, NURU power plant has 33 km as the length of the line and uses cables of 75 mm^2 of section.

With POUILLET law,

$$R=\rho\frac{L}{S} \qquad (4.2)$$

where R= Resistor (Ω),

ρ= resistivity (Ωm),

L= length (m),

S= section (m^2).

An empirical formula gives at 300 K, the resistivity of 28.10^{-9} Ωm, it follows that

$$R= 28.10^{-9}\ \Omega m\ \text{x}\ \frac{33\ km}{75\ \text{mm2}}$$

$$= 28.10^{-9}\ \Omega m\ \text{x}\ \frac{33x10^{3}\ m}{75x10^{-6}\ m^{2}}$$

$$= 12.32\ \Omega.$$

The upper bounded current for our formulation model is determined as :

$I_{max}=\frac{1.222\ \text{MW}}{\sqrt{3}\ \text{x11 kVx0.8}}$from the formula (4.1).

$I_{max}=\frac{1222}{15.242}$

$I_{max} = 80.18329$ A

where 1.222 MW is the power at distribution side when power losses are evaluated at 6% of power generated.

With Quadratic Constrainted Quadratic Program, the objective function

$$\text{Min } P_L=\sum_{t=1}^{N} 12.32 I^2(t)$$

Linear part $f^T x = 0$, and

$$\text{Quadratic part } \frac{1}{2} x^T H= \sum_{t=1}^{N} 12.32 I^2(t) \qquad (4.3).$$

$$\text{Subject to} \begin{cases} 0 \le I(t) \le 80.183\ A \\ \sum_{t=1}^{N} P_L(t) \le 0.06 \sum_{t=1}^{N} P_G(t) \\ \sum_{t=1}^{N} [P_G(t) - P_L(t)] \ge \sum_{t=1}^{N} P_D(t) \end{cases} \qquad (4.4).$$

The purpose being to control the current when there is high demand, this is made every one hour. It follows that the controls of current flow are done at 1 p.m. up to 3 p.m., therefore N=2.

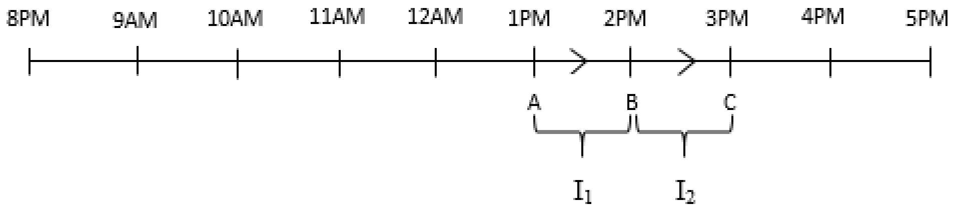


Figure 4.1 Time of control of current flow.

The formulas (2.2) and (4.1) show that the objective function, in terms of the design variable, is subject to

$$\begin{cases} 0 \le I_{(t)} \le 80.183\ A \\ 12.32\ (I_1^2 + I_2^2) - 914.52(I_1 + I_2) \le 0 \\ 12.32\ (I_1^2 + I_2^2) - 15242(I_1 + I_2) \le -3.1\ MW \end{cases} \qquad (4.5)$$

where3.1 MW is the sum of power demands from 1 p.m. up to 3 p.m.

4.2 Simulation Results

Results show that the optimal currents are 70 A between 1 p.m and 2 p.m and 80 A between 2 p.m and 3 p.m., and the optimum power losses is 139.0241 kW. The optimal currents and power losses are shown in Figure 4.2. Compared to the baseline (without optimization), the optimization model reduces power losses from 605.53 kW to 139.024 kW

There is a connection between power losses and Greenhouse Gas Emissions. In order to meet the load demand, the power losses of PV are compensated with diesel generators. Diesel generators, unfortunately, produce carbon dioxide (CO_2), Nitrogen oxide (NOx), and particulate matters. Considering the European average of evaluation of global warming, 1 kW produces 0,45 kg CO_2 eq. Based on the power losses to be reduced, the optimization model developed will reduce 1,199.71 tonnes of CO_2 in a year.

The figure 4.3 shows cleary the difference of power losses before optimization and after optimization.

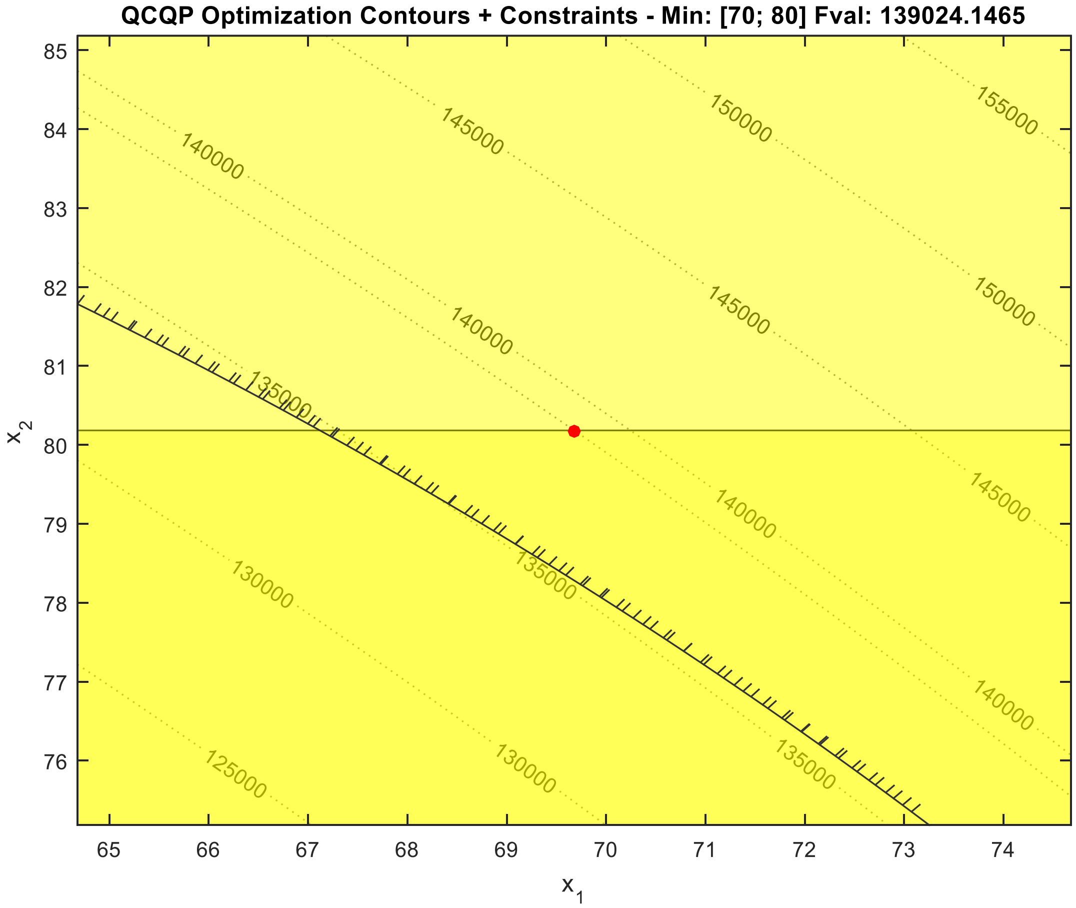


Figure 4.2 Simulation results

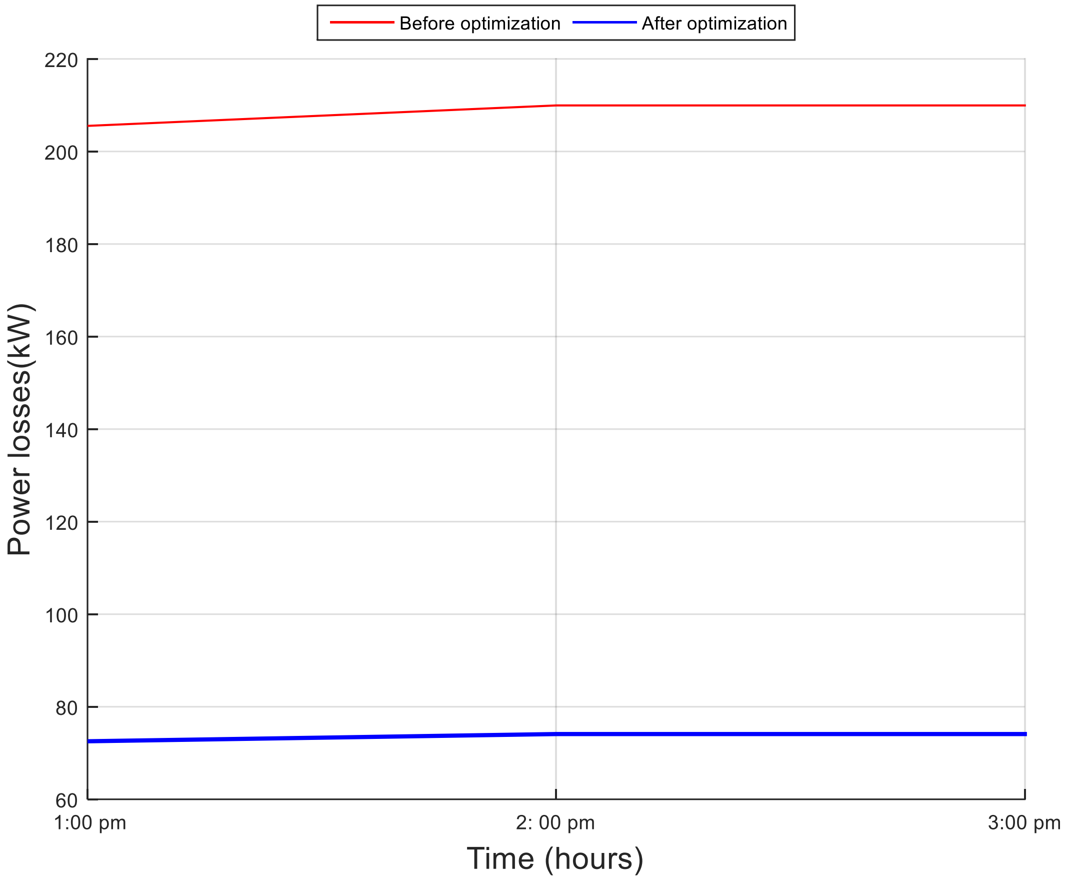


Figure 4.3 Comparison of power losses before optimization and after optimization

5 CONCLUSION AND FUTURE WORK

5.1 CONCLUSION

In this study, an optimal power losses model for off-grid PV system is formulated to determine the optimal current. The purpose is to minimize Power losses in transmission and distribution lines and to reduce the use of diesel generators during peak hour demand. Power losses due to high peak demand can be minimized by maintaining the current at its optimal level, the fact which allows to control power flow from consumers. A case study carried out shows that, per day, the optimal power losses model formulated would save up 77% of losses and 153.15 kg of CO_2 during peak hours. This model can be applied to other power plants. Based on the simulation results, it is concluded that power losses should be minimize not only to meet load demand but also to reduce greenhouse gas emissions.

5.2 FUTURE WORK

The future work will consist of :

a) Collecting data for non peak and peak hours, it means from 8 a.m. up to 5 p.m for my case study, in order to formulate a power losses optimization model which takes in account the variation of the demand during the day and therefore to minimize losses of the whole system.

b) Formulating an optimization model of two or more than two design variables and to solve the problem using other different techniques of optimization.

c) Comparing results of different solvers in order to propose the best solver of optimization problems, after collecting data for normal period and for peak hours and after designing the optimal model with more than two design variables. All this, for reducing as much as possible the dependance of diesel generators.

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Appendix 1

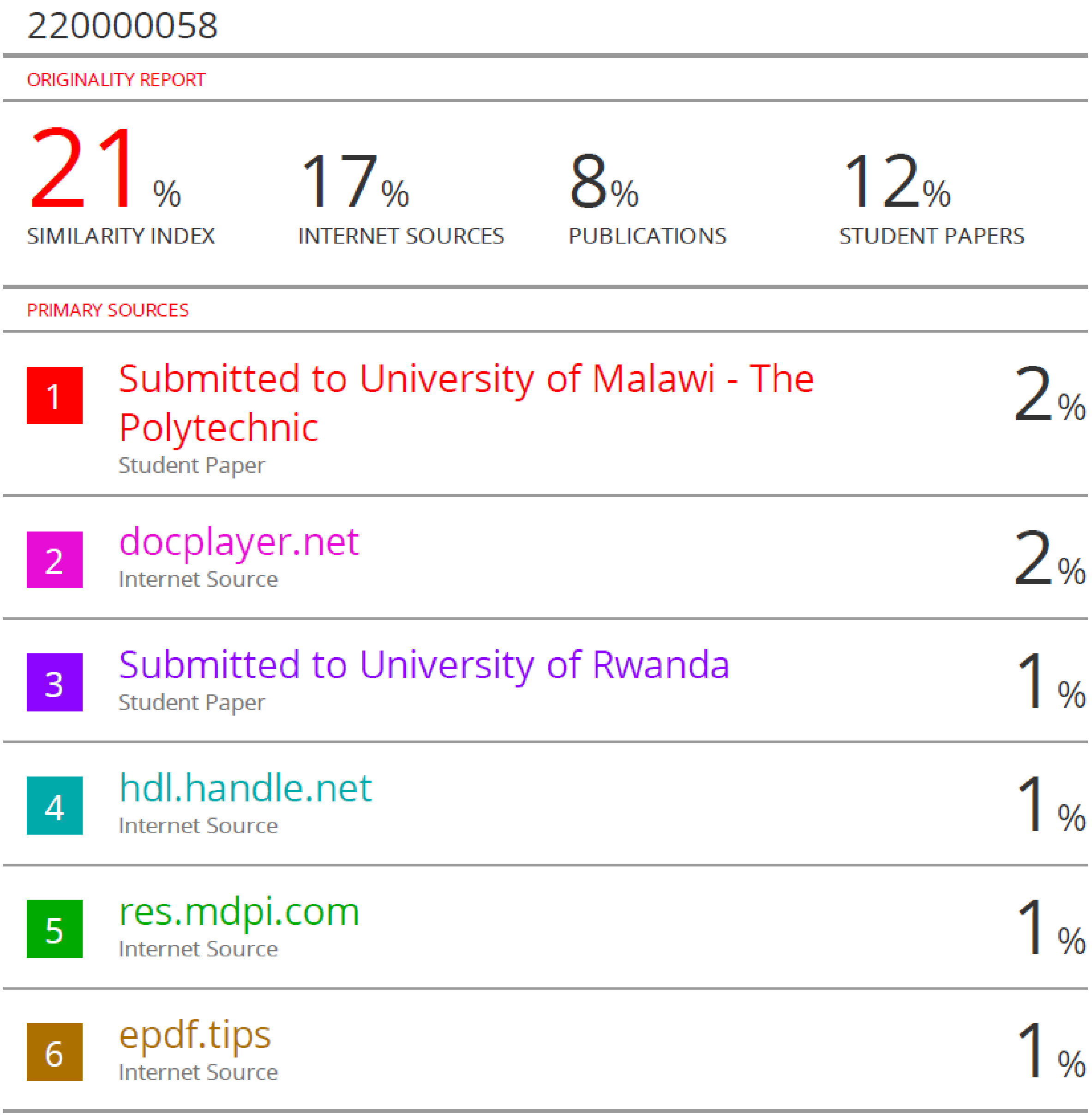
For getting the results, here below is the code for running the simulation.

```
%Objective
H=24.64*eye(2);        %Objective Function(min0.5x'Hx+f'x)
f=[0 0]';
%Linear Constraints
A=[1,0;0,1];           %Linear Inequality constraints(Ax<=b)
b=[0;0];
lb=[0;80.183];     %Bounds on x (lb<=x)
%Quadratic Constraints
Q={[12.32 0;0 12.32]
%Quadratic inequalities(x'Qx+l'x<=r)
[12.32 0;0 12.32]};
l=[[-914.52;-914.52],[-15242;-15242]];
r=[0;-3053570];
%Create OPTI object
Opt=opti('qp',H,f,'ineq',A,b,'lb',lb,'qc',Q,l,r);
%Solve the QCQP problem
[x,fval,exitflag,info]= solve(Opt);
%Plot Solution
plot(Opt)
```

Appendix 2

For getting graph of comparison of power losses before optimization and after, the below code has been plotted.

```
%Plot of graphs
t=[1 2 3];
x=[0.057 0.057 6.28];
y=[1.369 1.369 1.369];
z=[2.510 2.510 2.510];
figure
hold on
plot(t,x,'r',t,y,'b',t,z,'y','linewidth',1)
ylim([60,215])
xlim([1,3])
ylabel('Power losses(kW)','Fontsize',15); xlabel('Time (hours)','Fontsize',15)
legend('Before optimization','After optimization')
title('Comparison of power losses before and after optimization','Fontsize',15)
a=[1 2 3];
f=[205.53 209.95 209.95];
plot(a,f,'r','linewidth',1)
plot(t,x,'r',t,y,'b',t,z,'y','linewidth',2)
ylim([60,215])
xlim([1,3])
ylabel('Power losses(kW)','Fontsize',15); xlabel('Time (hours)','Fontsize',15)
legend('Before optimization','After optimization')
title('Comparison of power losses before and after optimization','Fontsize',15)
a=[1 2 3];
f=[72.54 74.1 74.1];
plot(a,f,'b','linewidth',2)
```



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