IMPROVEMENT OF VOLTAGE STABILITY IN THE POWER DISTRIBUTION NETWORK OF NAIROBI REGION USING FACTS DEVICES

BY

EDWARD KARIUKI KITHAKA

EN400/5234/2018

Research proposal for a thesis to be submitted in fulfilment of the requirement for the award of the degree of Master of Technology in Electrical & Electronics Engineering

October, 2024

DECLARATION

This research proposal is my original work and to the best of my knowledge, it has not been presented for a degree award in this or any other university.

NAME: EDWARD KARIUKI KITHAKA

Sign.................................Date............................

This Research Proposal has been submitted to the School of Engineering and Technology, with our approval as the supervisors:

First Supervisor Name: Prof. Christopher Maina

Sign.................................. Date.........................

Second Supervisor Name: Prof. Livingstone Ngoo

Sign....................................Date..............................

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AVR	Automatic voltage control.
EHV	Extra High Voltage
IEEE	Institute of Electrical and Electronics Engineering
IPPs	Independent Power Producers
KPLC	Kenya Power and Lighting Company
KENGEN	Kenya Electricity Generating Company
OLTC	On Load Tap Chargers

ABSTRACT

Today, there are several approaches to analyze the voltage stability in power distribution networks and identify weak buses. These indicators provide reliable information about surrounding voltage instabilities and weak buses or lines in the electrical power distribution grid. Contingencies and fluctuations in loading levels, as well as intermittent load, make it simple to observe occurrences of voltage collapse when operating under such conditions. Voltage instability in power distribution networks can cause the system to fail if the voltage drops to a level that cannot be regained. In recent years, multiple blackouts of large-scale power networks have occurred as a result of power voltage instabilities produced by voltage instability events. This has led to the need to employ professional analysts in power utility companies for the sole purpose of evaluating the stability of voltage during power distribution. This is often taken into account as a crucial step in the planning and management of effective power distribution networks. The purpose of this study is to employ a simulated load flow solution of the Nairobi area's power distribution system network, in addition to identifying buses with high currents or near line losses through a measure of their proximity to a line collapse. The study will further explore QV modal analysis, VQ sensitivity analysis, and power-voltage curve techniques to determine the static power network's voltage stability in the Nairobi region. The 66kV bus system will try out the proposed technique. It is envisioned that the proposed technique will identify those bus bars presenting overload and those about to reach their voltage collapse limit. The adoption of a flexible AC transmission system is proposed to improve system stability. Two technologies will be used to increase voltage stability: The Thermistor Controlled Series Capacitor (TCSC) and the Static Var Compensator (SVC). SVC will be utilized to improve the voltage profile of buses and ensure the rapid injection of reactive power into them. On the other side, the TCSC will be employed to compensate for the capacitive reactance.

CHAPTER ONE
INTRODUCTION

This chapter provides the background knowledge of the study subject and the motivation for this Thesis proposal. It begins by providing fundamental aspects of power stability and power system concepts. The section chapter also introduces the voltage stability assessment. The chapter also presents the objectives and scope of the proposed research work.

1.1 Background of the Study

A power system is considered to be in a stable state when the electrical network functions at a state of equilibrium during typical operation and restores itself to equilibrium in the event of a network disturbance. The variables for a stable system are namely rotor angle, voltage, and frequency which constitute the fundamental pillars of a stable system [1].

The stability of the power system is the ability of an electrical grid to make up for a blackout by [1]. On the other hand, rotor angle stability pertains to the capacity of a synchronous machine to maintain an acceptable rotor angle in spite of fluctuations in rotor speed. Voltage stability is the ability of the system network to sustain a state of equilibrium between generation power and consumption power [2]. Depending on when it occurs, it may be categorized as short-term or long-term. Short-term factors contributing to instability encompass disturbances such as abrupt reductions in generation or demand or the manifestation of a fault within the transmission network [3]. Unstable voltages will result when supply voltages surpass the optimal operating levels as a consequence of system disturbance or an increase in system load. However, load balancing systems implemented at the distribution level and reactive power constraints at the generator level may unexpectedly occur prior to voltage instability, leading to voltage collapse. This occurrence is quite frequent in significantly laden systems [3]. Automatic voltage regulating devices, such as transformer tap converters and over-excitation limiters, are frequently employed to rectify transient voltage instability. Voltage instabilities will also ensue over an extended period if the capacities of these regulating devices are surpassed. Prolonged voltage stability concerns frequently emerge as a result of incremental alterations in load expansion and demand trends. It may also transpire when the load demand escalates substantially over a period of time without a commensurate increase in generation capacity or enhancements to transmission infrastructure, leading to a reduction in voltage levels [4]. To ascertain the probability of voltage instability occurring in a system that is under load, one must calculate the disparity between the point of optimal operation and the point of collapse. Numerous methodologies have been devised to oversee voltage stability and predict voltage collapse. Different load flow study techniques assist in the determination of voltage stress levels and network vulnerabilities [5,6]. Sustained power flow and critical Jacobian make voltage collapse point such detection easier; Q-V and P-V curves help in stability limit understanding [7]. However, these approaches are always computationally expensive and time-consuming. However, there are more efficient techniques, such as modal analysis and L-index, where the need for so much processing is a problem, especially with cloud computing [6]. There is an important need to foster effective lines of communication for generation as well as distribution [8].

Kenya has experienced an annual increase in electricity demand of 4.5 percent for the past five years as part of its recovery efforts from the worldwide COVID-19 pandemic. In November 2021, residential and industrial energy consumption in Kenya peaked at an all-time high [9] as a result of the nation's expanding economy. The Energy and Petroleum Regulatory Authority (EPRA) reported that Kenya experienced an increase in electricity demand from a record low of 1,661 MW in April 2020, during the height of the COVID-19 outbreak, to 2,036 MW in December 2021 [9]. The current infrastructure comprises 66kV distribution lines within the Nairobi region, 220kV and 132kV high voltage transmission lines, and 33kV and 11kV medium voltage lines. The Nairobi region comprises an estimated 855 kilometers of 66kV transmission lines. Variations in voltage stability result from the amplified demand.

1.2 Statement of Problem

The annual report of Kenya Powers and Lighting Company on power usage [10] demonstrates that only 40% of current load demand is supplied by its grid. However, this demand continues to rise without an equivalent enhancement in the network infrastructure, such as substations, buses, capacitors, and tap changers, stretching some buses closer to their voltage stability limits [10]. Voltage supply instability has risen in recent years, resulting in more frequent power outages. If the system is functioning properly, even if the power source fails, the voltage on all buses will remain sufficient [11]. An unstable voltage condition occurs when the power system voltages in some or all buses are outside acceptable limits during the normal operation or after the events that cause a regular and unexpected drop in voltage [12]. This may result to voltage drops as well as reactive power loss thereby deepening the problem [13]. Kenya power has increased electrification level from 27% in the year 2013 to 77% 2021, with seven million new customers connected to the grid [14]. Of all the regions, Nairobi, the most connected region, experiences higher instability arising from limited infrastructure development. Voltage instability jeopardizes the degradation of power system performance and the utility company's mission to provide reliable power to its customers [15]. This type of incident can be avoided by analyzing the power system's voltage stability with use of compensation technologies. The manner through which voltage stability is assessed by determining the presence of load or generation that leads to voltage instability, identifying the key contributing factors, and finding ways of enhancing system voltage stability by improving the weak bus in the network will be explained [15]. Dynamic voltage stability analysis evaluates how bus voltages vary as a function of system variables using differential equations. In order to curb this, voltage stability has to be analyzed by utilising compensation technologies that help strengthen the weak buses and halted voltage collapse [16].

1.3 Justification of Study

Voltage instability is regarded as a critical factor in ensuring system stability, security and reliability in modern power distribution systems that are incredibly complex and have broad operations that are far closer to their failure limits [17]. This circumstance makes power distribution networks extremely susceptible to instability and voltage consistency is one of the key obstacles. The system should be able to maintain voltage levels at optimum levels at normal operation and in the presence of a network disturbance for its effective operation and functionality. It is possible to achieve voltage stability by maintaining a balance between generation, transmission and electrical energy consumption. It is a very important power system characteristic that enables the power system network and the associated equipment to operate efficiently at optimal levels and ensures consumers receives power at the right voltages [18]. The presence of a disturbance in the network such as rapid increase in the load or change in network parameters such as voltage and frequency can cause voltage instability if not immediately controlled resulting in drastic and unpredictable voltage falls. The resulting voltage drop is due to the system not sustaining the increasing reactive power demand from the network [19]. Voltage instability can result in equipment damage, power quality issues such as flickering of lights or data loss, load shedding, cascading failures, increased line losses, grid instability, and challenges in renewable energy integration [20]. Managing and mitigating voltage instability is crucial for a reliable, safe and efficient operation of the power system. In recent times, major power systems breakdown occurs due to voltage instabilities resulting in voltage collapse [21]. Therefore, investigating voltage stability is essential for maintaining system reliability, enhancing grid resilience, optimizing operation, ensuring voltage quality, facilitating system planning, and preventing voltage collapse. It makes it possible to take preventive measures to address problems with voltage stability to ensure sustainable and safe operation of the network with no downtime.

1.4 Research Questions

i.) How effective are load flow solutions in identifying weak and overloaded buses in the Nairobi power distribution network?

ii.) Can loading margins and voltage stability margins accurately detect voltage weak buses and overloaded buses, indicating their proximity to voltage collapse?

iii.) How can the static voltage stability status of the Nairobi power network be assessed using Modal analysis, sensitivity analysis (VQ), and power-voltage curves?

iv.) To what extent do Thyristor Controlled Series Capacitor (TCSC) and Static Var Compensator (SVC) improve the voltage stability of buses in the Nairobi power distribution network?

1.5 Objectives of Study

The main objective of this study is to assess the improvement the voltage stability of the power distribution network in the Nairobi region using compensation technologies. The load flow of the power distribution system network will be used to identify the weak and overloaded buses on the system and voltage stability margins. The FACTs devices will be introduced to the system to measure the impact on the voltage stability.

1.6 Specific Objectives

The following objectives will guide the study;

i.) To develop and perform load flow solutions on the power distribution systems network of the Nairobi area.

ii.) To identify voltage weak and overloaded buses, assessing their proximity to voltage collapse using loading margins, voltage stability margins, Modal analysis, sensitivity analysis (VQ), and power-voltage curves.

iii.) To evaluate the effectiveness of the Thyristor Controlled Series Capacitor (TCSC) and Static Var Compensator (SVC) in improving the voltage stability of the buses.

iv.) To validate the findings using IEEE-59 BUS system simulations in MATLAB environment

1.6 Significance of the Study

Voltage stability is critical for the electrical grid and the supply of quality power to the distribution network. It arises from overload or weak buses, which often lead to voltage collapse, thus a partial or total blackout [8,20]. Through the load flow analysis simulation, modal analysis, and sensitivity, the loading and voltage stability margins determined could be utilized in designing compensation strategies like FACTS and turbine generators, which are critical for enhancing stability [17]. This study explores the compensation strategies that could be adopted for the Nairobi region distribution network. This knowledge would contribute to research on the voltage stability of the Nairobi area distribution network and possible solutions to arising instabilities on the grid.

1.7 Scope of study

This study will focus exclusively on examining the voltage stability of the power distribution network. Specifically, it will investigate the 66kV network within the Nairobi Region Distribution, specifically during peak loading conditions. The study will span one month, during which the analysis and observations will be conducted.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

This section presents the literature review of the study topic, focusing on the assessment of voltage stability in power distribution networks using flexible AC transmission systems. Previous literature on the causes of imbalance between reactive power generation and demand in the coastal network area and factors influencing voltage stability of reactive power control devices is also discussed.

2.2 Voltage Stability

It is the consistency with which voltage is maintained within an acceptable limit across a network of electrical buses in the power distribution network during normal operation and when there is a change in one of the system parameters [22]. In the event of a change in power demand or other disturbances, it is possible to restore voltage levels to equilibrium. The IEEE defines "voltage stability" in the context of power systems as "the ability to maintain voltages so that load admittance is directly proportional to load power" [23]. Figure 2.1 shows a simplification of a three-terminal network exhibiting voltage stability. The Thevenin equivalent of the circuit has a "constant voltage source", E_{TH}, feeding the "load", Z_L, via "series impedance", Z_{TH}.

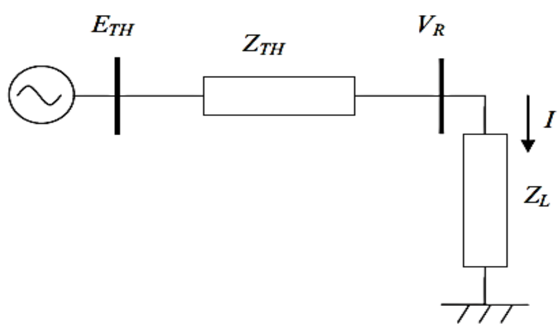

Figure 2.1 Thevenin equivalent circuit for a local bus

In this regard, the magnitude of the current on the local bus in figure 2.1 is equal that through the load of the its equivalent circuit, the rest of the component are treated as a Thevenin equivalents [24], this is defined by equation 2.1.

$$I = \frac{ETH}{\sqrt{(THZ^{\cos\theta} + Z^{cos\emptyset}) + (ZTHsin\,\theta + ZL\,sin\,\emptyset)}} \quad \text{……………………………………………………………2.1[24]}$$

This may as well be expressed as

$I = \frac{ETH}{\sqrt{THZ^2+LZ^2+2ZTH\ ZL\ Cos(\Theta-\emptyset)}}$……………………………………………………………………2.2 [24].

Where Ө and Ø are the phase angles of Thevenin impendence Z_{TH} and load impendence Z_{L}.

When the load is not connected, then the voltage at the open circuit V_R is as defined in equation 2.3.

$V_R = Z_L I = \frac{ETH}{\sqrt{THZ^2+LZ^2+2ZTH\ ZL\ Cos(\Theta-\emptyset)}}$…………………………………………………2.3[24].

At the load section, the apparent power supplied is a product of the open circuit voltage and admittance Y.

$S=V^2_R Y$ where

$Y = \frac{1}{ZL}$ ………………………………………………2.4

Therefore,

$S = \frac{ETH}{THZ^2+LZ^2+2ZTH\ ZL\ Cos(\Theta-\emptyset}$…………………………………………………………..2.5[24].

If the assumption is that E_{TH} = 1 and Z_{TH} = 1. The load demand, in terms of the power S, increase rapidly whenever the load admittance *Y* increases at first but slows to reach the peak power, after which it decreases. Figure 2.2 depicts the nonlinear relationship between the power *S* and admittance *Y* for the phase differences (Ө-Ø) = 60^0, $90^{0,}$ and 110^0. Variable load control would cause unstable operation at larger loads; that is, increasing load admittance would result in a decrease in power. Furthermore, these curves show how the load power factor influences the system's characteristics.

.

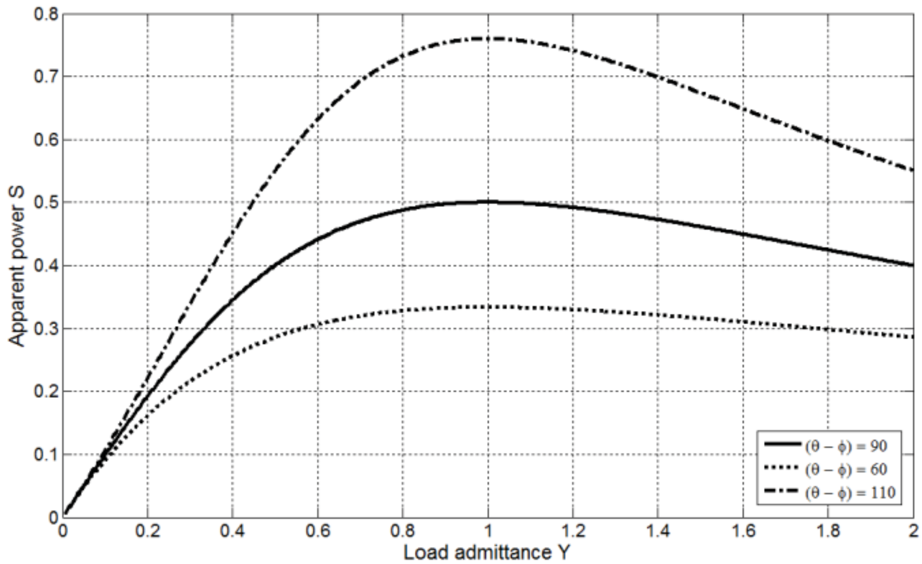

Figure 2.2 The plot of apparent load power SR as against admittance Y for bus circuit [24]

The derivative of S_R with respect to admittance at the load Y is as shown in equation 2.6.

$$\frac{DS}{DY} = \frac{E2TH(1-Y2ZTH)}{(1+THZ^2\,Y+2ZTH\,Y\,Cos(\theta-\emptyset)2} \text{……………………………………………………………2.6 [24].}$$

At the maximum value of apparent power at the load, the derivative is equal to zero, as shown in equation 2.7.

$$\frac{DS}{DY} = 0 \text{……………………………………………………………………………2.7[24].}$$

When there is impedance matching, equation 2.5 confirms a known critical point of voltage instability where the Thevenin impedance matches the load impedance as in equation 8

$Z_{TH} = Z_L$………2.8

$E_{TH} = 1$ and $Z_{TH} = 1$

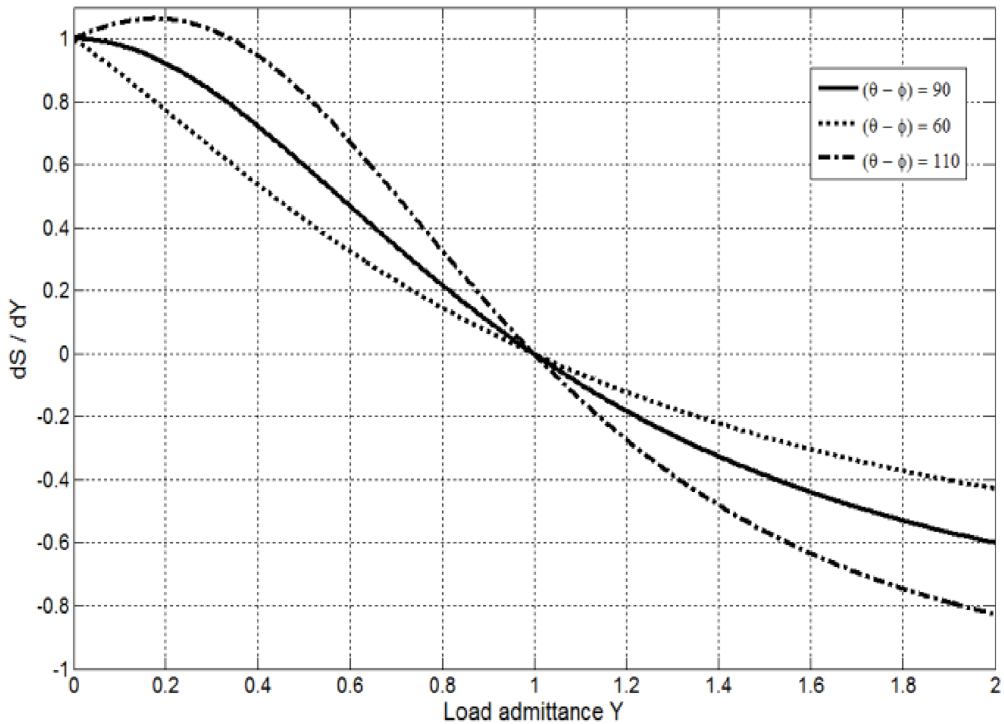

Figure 2.3 The plot of the derivative of $\frac{DS}{DY}$ against load admittance Y for the Thevenin equivalent circuit [24]

Figure 2.3 above also indicates the importance of the power factor of the load on the power system characteristics. Equation 2.6 indicates that $\frac{dS}{dY}$ is dependent on the parameters for Thevenin as well as the power factor magnitude for the load admittance. It is evident that at a zero load admittance, the derivative of S_R with respect to admittance at the load Y is unity, $\frac{DS}{DY} = E^2_{TH} = 1$, but zero where there is impedance matching, $Z_{TH} = Z_L$, $\frac{DS}{DY} = 0$. Therefore, the maximum point of loading can be assessed with accuracy by having computation of the factor $\frac{dS}{dY}$. Thus, when $\frac{dS}{dY}$ is close to zero, it indicates that the system is nearing the point of voltage collapse. The method for estimating the voltage stability margin online involves measuring the changes in apparent load power S and load admittance Y.

2.2.1. Classifications of Voltage Stability

Table 1 illustrates two main criteria for categorizing voltage stability in the context of power systems: the scale of instability and the duration. The voltage stability caused by load problems can be divided into two categories, short- and long-term time scales of load dynamics [27]. The various stabilities that occur when analyzing voltage are based on the different characteristics of either small or large interferences. The analysis of distribution network performance during peak times, under the condition of voltage stability, is the focus of this study

Table 2.1 Types of Voltage Stability [26]

Duration	Generator side		Load side	
Short term	Rotor angle stability		Short-term voltage stability	
	Small signal	Transient		
Long term	Frequency stability		Long-term voltage instability	
			Small disturbance	Large disturbance

Where the bulk of the load consists of the induction machines and moderate events, such as a contingency or rapid load increase, cause bus voltages to drop sufficiently to cause several induction machines to stall, [25] short-term voltage instability often results. On the other hand, the when voltage collapse in the power distribution network that persists for an extended duration, spanning minutes, hours, or days, gives rise to long-term voltage instability [26]. It typically ensues subsequent to the initial disturbance of the system.

2.3 Voltage Stability in Kenya’s Power Distribution Network

One of the major challenges that Kenya has faced in its electricity distribution system, especially in the Nairobi region has been problem of voltage stability. Different authors have studied this using complex mathematical models in assessing voltage stability and evaluating the potential reactive power compensation. According to Ombuki et al. (2021), the modal and sensitivity analysis of QV profiles helps to evaluate poor buses and vital voltage points in the Kenyan network [27]. Oketch et al. (2012) perform load flow analysis on the distribution network in Nairobi in which voltage instability was realized during the peak demand pointing to the weakness of the system [28]. Hambissa and Ghandhari (2023) further added by simulating the Ethiopia-Kenya HVDC line and confirmed that it can enhance necessary clearing times during the transient fault cases [29]. Furthermore, Kitheka et al. (2022) evaluated the voltage drop performance of the JUJA-RABAI 132kV transmission line while noting the poor voltage profile which causes power failures [30]. Similarly, Isong et al (2023) used Newton-Raphson method to the IEEE 33 Bus Distribution System indicating that this method is efficient in determination of overloaded bus and hence the overall voltage stability [31].

2.4. Factors Influencing Voltage Stability

Voltage stability issues frequently manifest in systems that are subjected to significant duress [32]. In addition, it is critical to enhance power transfer rates and transmission lines in order to mitigate the risk of voltage collapse. A variety of factors influence voltage stability. These include line characteristics, such as transmission line impedances; control and protection factors, such as effectiveness and proper operation; system configuration factors, including load scheduling, dispatch, and optimal power flow, weather conditions; and generation-related factors, including availability and capability.

2.4.1. Reactive Power Control Devices

A study conducted by [33] found significant results on the impact of reactive power control devices on voltage stability. The study found that reactive power flows significantly affect system voltage. Effective reactive power management enhances power system reliability and efficiency. Maintaining a balance between reactive power generation and loading is crucial

Devices for controlling and compensating reactive power include power factor correction with static capacitors and synchronous machines, as well as voltage control using power system stabilizers or automatic voltage regulators. Load shedding during low voltage, line dropping, and under load tap changers in transformers can all be used to adjust the voltage.

According to the "IEEE/PES Transmission and Distribution Conference and Exposition" in Beijing, China in 2005, Voltage collapse occurs when the chronology of voltage instability events leads to an undesirable voltage profile in power systems. After a voltage collapse, different devices, controllers, and protective systems work to restore the voltage to normal levels. Insufficient response from controllers and safety mechanisms can cause voltage levels to drop below permitted levels, resulting in a partial or entire collapse of the power system (blackout).

Voltage collapse is characterized by a slow and gradual decrease in voltage levels. According to [35], voltage collapse can persist from a few seconds to several minutes, depending on the sensitivity of control and protection systems. The system's characteristics and conditions impact voltage collapse. This study found that voltage collapse can also be caused by long distances between generation and load, unfavorable load characteristics, transformer ULTC action during low voltage conditions, and poor coordination of control and protective mechanisms. Excessive use of power factor correction devices like shunt capacitors might lead to voltage collapse [36].

2.4.2. Action of Load Tap Changers

Load tap changers (LTCs) are apparatus utilized to regulate the voltage ratio between the primary and secondary windings in power transformers. These devices serve as a means to produce the desired output voltage of the transformer and to remove deviations in the system voltage. The autotransformer load design is through various tap points whose arrangement can be modified to change the transformer turn ratio. The tapping positions on the transformer winding are adjustable either by automatic or manual operation.

The secondary voltage is toggled by tap changers so that the appropriate, effective turns ratio of the transformer is chosen [38]. This will enable the system to maintain steady output power by damping voltage fluctuations within the grid. Various choices are available for tap changers, such as manual or automatic, which can vary depending on the mode of operation desired for the application or system.

An automatic control system is responsible for constantly checking the output voltage's level and will adjust the tap positioning based on the requirement [37]. The gear ratio used at the load tap changer will indicate the magnitude of voltage upgrade at each load tap changer position. Furthermore, a temporal lag may occur between tap changes in order to safeguard the transformer's dependability and stability while adjusting the voltage.

Off-load tap-changing facilities and on-load tap-changing facilities are the two primary categories of tap-changing facilities. Off-load faucet changing facilities are frequently utilized and implemented when the ratio must be adjusted to accommodate long-term fluctuations caused by factors such as system expansions, seasonal changes, or increased growth load [38]. This is typically accomplished after de-energizing the transformer. Conversely, under-load tap changing is frequently implemented when the ratio must undergo frequent changes to accommodate the daily variations in system conditions. This process is typically carried out while the transformer is energized.

The term "m," which refers to the bare minimum time needed for a complete movement of a tap converter, is commonly defined as approximately 5 seconds (delay in mechanical time m). A number of different international time delays are often incorporated into the mechanical tome delay in order to eradicate superfluous tap movements. These frequently result in apparatus that is presently in use being damaged. Delays in international time (typically measured in seconds and minutes) may fluctuate or remain constant [39]. The inverse time characteristic can subsequently be applied, given that significant voltage errors result in a reduced time delay.

A significant constraint of the LTC to help in regulations the limited range for the variable tap ratio; $(r_{minimum} < r < r_{maximum})$. The upper limit values range is typically between 1.10 and 1.15 p.u., but the lower limit values.

The lower limit values often have a typical range between 0.8 to 0.9 p.u. and an upper limit between 1.10 to 1.15. p.u. The size of a tap step often lies between 0.5% to 1.5% [19]. Restoration of the load by employing LTC operation with the use of a basic system consisting of generator which feeds the LTC transformer via transmission line has been illustrated in figure 2.4 below. The LTC is taken to be an ideal transformer connected in series with a leakage reactance. The active and reactive power absorbed by the transformers are denoted as P_1, Q_1, whereas $P(V_2)$, $Q(V_2)$ represent the dynamic loads connected at the end of the distribution.

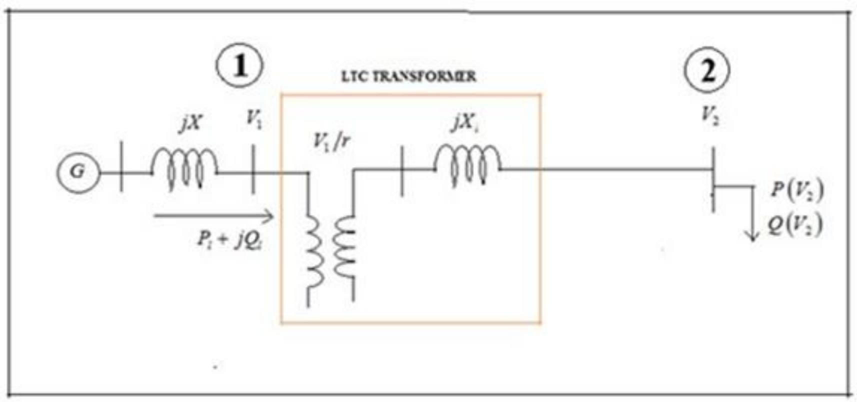

Figure 2.4 A Generator Line with and LTC transformer [40]

P(V2) and Q(V2) represent the dynamic loads connected at the end of the distribution system while P(V1) and Q(V1) refer to the active and reactive powers that are absorbed by the transformers. The two networks P1V1 characteristics which relates to the side of transmissionV1 to the power P1 delivered to the transformer has been illustrated by the figure 2.5 below. Characteristics of the network have been drawn for the P1Q1 pairs which correspond to the load in connection to bus 2**.**

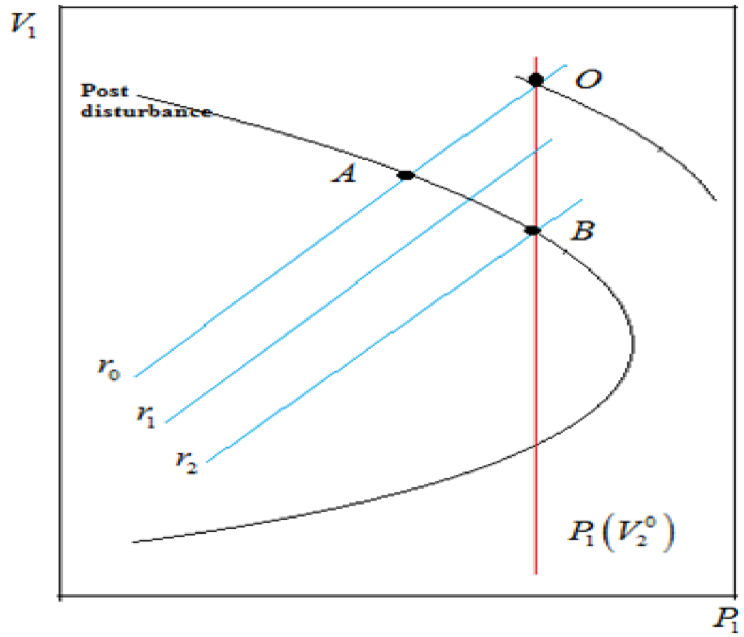

Figure 2.5 The Power Voltage curve at the generator - LTC transformer characteristic [48]

To understand the LTC operation, the system at point O in Figure 2.5 is considered to be at the outset when a perturbation (such as an increase in impedance) compels the network characteristics to transition to the state observed after the disturbance. For a given resistance of $r = r_o$, we will observe an initial decrease in the primary voltage V_1 along the TLCT curve from point O to point A. At the moment, the power from the load output is not enough to reach the value of the secondary reference voltage, V_2^o, of which V_2 is less than V_2^o. As V_2 is lower than the reference, the LTC corrects this by decreasing the tap ratio, which in turn increases the secondary side voltage. Thus, the operating point on the network characteristic will repeatedly shift until it arrives at point B, where the steady-state load characteristics intersect the network characteristics, where again, it will be in a new zone of altered transient load characteristics. The fact that the LTC is responsible for both secondary voltage and load power restoration should be mentioned during this step [41]. As a result, from the operation of the tap changer, lines I2X and I2R losses will be raised due to the increased load. Hence, this results in augmented lower DC voltages and stresses the transformer tap settings to their maximum values. Consequently, impedance network load of the progressing restoration process diminishes in proportion to the increasing load demand.

2.5 Analysis of Voltage Stability

This section describes some of the static analysis techniques that were applied to this study's analysis of the voltage stability of the distribution network. These include sensitivity analysis techniques, modal analysis techniques, and Reactive-Voltage (Q-V) as well as active power (P-V) curves.

2.5.1. V-Q Sensitivity Analysis

Q-V sensitivity study evaluates how reactive power flow affects voltage levels in a power system. Analyzing the relationship between reactive power flow and voltage variations helps determine system stability by understanding how reactive power generation or consumption affects voltage magnitude or phase angle changes. Maintaining optimal voltage levels is critical for power network reliability. The analysis will assist system designers and operators in identifying voltage control issues and optimizing control methods for increased system stability and improved voltage profile. It is also useful in planning for system expansion.

The analysis comprises modeling the power system network and calculating initial operating conditions using the power flow equation. Q-V sensitivity study involves adjusting reactive power injections at certain nodes or generators to determine the impact on voltage levels. Modal analysis yields eigenvalues and eigenvectors for the power flow Jacobian, as seen in equation 2.9

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_{P\theta} & J_{PV} \\ J_{Q\theta} & J_{QV} \end{bmatrix} \begin{bmatrix} \Delta \theta \\ \Delta V \end{bmatrix} \quad \text{2.9}$$

Where, ΔP, ΔQ, $\Delta\theta$ and ΔV are the incremental changes in bus real power, bus reactive power injection, bus voltage angle and bus voltage magnitude respectively.

The steady state voltage of a system is affected by P and Q. The incremental relationship between Q and V is analyzed to determine the voltage's stability over all operational points while holding P constant [42]. The QV curve approach is analogous to this. Changes in system load or power transfer levels are taken into consideration by analyzing the incremental relationship between Q and V throughout a range of operating conditions, even though incremental variations in P are ignored in the formulation.

2.5.2. Sensitivity analysis using continuation Power Flow

Continuation Power Flow (CPF) is a numerical tool to obtain information about the behaviour of the power system during various operating conditions. It qualifies voltage stability and determines critical sites where the voltage collapses can occur. Through Sensitivity analysis, voltage stability of a power system with Continuation Power Flow, is evaluated under parameter variations. Thus, during the investigation, the base operating conditions of the system, including network structure, generator and load data, and voltage/angle values, are evaluated and used as the starting point for the analysis. For the purpose of sensitivity analysis, the choices of interest parameters are to be made. The range of factors that bring about voltage level variations are generator set points, loading levels, transmission line qualities, transformer tapping, and many others. Continuation Power Flow is an algorithm for performing power flow calculations that work on the model of a power system, adjusting parameters according to the particular chosen deviation. The power flow equations are solved for the corresponding condition while assuming variable fluctuations. At each backing station, this point is checked. Indices of stability that take into account factors such as voltage magnitude, reserves of compensating reactive power, and the highest loading point are used to rule out voltage collapse or system instability. The sensitivity of the system's voltage stability to parameter changes is calculated. It quantifies the rate of change in stability indices due to parameter modifications. Sensitivity analysis identifies crucial parameters that significantly affect voltage stability. The sensitivity analysis results are examined to understand the system's behavior with different parameter adjustments. This data can inform system planning, operational adjustments, and control measures to improve voltage stability. At the voltage stability limit, the Jacobian matrix in Equation (2.9) becomes unique.

Conventional power flow algorithms may encounter convergence issues when operating at the limit of stability. The Continuation Power Flow analysis solves this issue by reformulating power flow equations that are well-conditioned under all loading circumstances. This approach can address the power flow problem for both stable and unstable equilibrium states [43]. Mathematicians regularly utilize the path-following continuation approach to solve nonlinear equations. The continuation approach simplifies pursuing solutions beyond forks in the route. This method uses a predictor-corrector scheme and locally parameterized continuation approaches to follow the power flow solution routes accurately.

2.6 Current trends in voltage stability analysis

Modern transmission networks have economic and environmental constraints. Current networks are intended to function within their load capability limits. This signals that the system is approaching its voltage stability limit, which increases the risk of voltage instability and collapse. Voltage stability and instability can be detected offline or online, providing tools for system design and real-time control. These methodologies help identify voltage stability concerns and pinpoint the site of instability, allowing for better system design and real-time control. This helps system operators manage and control reactive power more effectively. Automation and specialized software complicate systems and take away management chores from operators. To effectively manage voltage instability in grid systems, distribution systems should be analyzed using sensitivity and modal analysis to detect weak and overloaded buses. This study investigates the effect of Flexible AC Transmission System on voltage stability in Nairobi region.

CHAPTER THREE

METHODOLOGY

3.1. Introduction

This chapter presents the materials and methods to be used in the study. The simulation utilises an HP laptop equipped with an Intel Core i7-10900K processor, 64 GB of DDR4 RAM, and a 1 TB solid-state drive. Operating system: Windows 11 Pro 64-bit. This high-performance computing (HPC) environment is essential for efficiently executing multiple simulation scenarios, especially when computing the load flow analysis for the power system model. Although not explicitly utilised in the MATLAB simulation, the NVIDIA GeForce RTX 3090 graphics card will assist in data visualization and parallel processing. The investigation uses consistent computer specifications and software versions to ensure consistent simulation results.

3.2. Research Design and Framework

Figure 3.1 illustrates a flowchart of the steps to be followed to approach the problem of voltage stability assessment of a specific power system. The method starts with load flow solutions using MATLAB-Simulink. The next process will be the determination of weak and overloaded buses in the network. Once such critical areas are identified, the methodology covers methods for evaluating voltage stability, modal analysis, sensitivity analysis (VQ), and power voltage curves. Further, in the network, TCSC and SVC will be employed to improve the stability of the network Voltage Magnitude and phase angle regulation in the transmission network is achieved by the installation of TCSC and SVC. This will be, in turn, succeeded by the construction of models for TCSC and SVC to emulate their impact on the system. The process ends with the evaluation of the results through the holding of these simulations and checking of the initial hypotheses about voltage stability

The study incorporates both analytical and simulation-based approaches for the evaluation of voltage stability of the power systems under various loading situations and configurations. The framework is practical as well as adaptable, which helps in promoting flexibility to control strategies. In addition, it also helps in the examination of system behaviour in a dynamic context. Each component of the methodology contributes to the wider objective regarding the enhancement of the reliability and security of the lower grid, specifically for increasing load demand.

Furthermore, the design follows a sequential structure involving initial load flow studies, creating baseline parameters. In addition, it also involves the determination of critical buses providing effective intuition to network threats, and advanced voltage stability analyses are employed to overcome the chances of collapse. The integration of sensitivity analysis, model analysis, and P-V curve plotting helps to understand the behaviour of voltage under severe conditions. Therefore, the study provides valuable insights to both macro and micro level contexts with higher efficiency. A key justification to use MATLAB and Simulink is their capability to correctly mid nonlinear behaviour in power systems. In addition, it also allows the accommodation of custom logic for FACTS device incorporation to a great extent. These platforms play an important role in supporting large-scale simulations, leading to efficient solutions and outcomes. This makes them ideal to conduct continuation flow of power and eigenvalue decomposition for the demand load.

Additionally, the decision to involve FACTS devices like TCSS and SVC usually arises due to their effectiveness in regulating voltage and overcoming inconsistencies. Their placement is identified on the basis of modal and participation factor results, which ensures that device influence is usually increased at the critical network points. Therefore, this framework provides valuable insights to a significant investigation into both the reasons and solutions of voltage instability. It provides a solid foundation for replicable and scalable solutions that are suitable for industry applications and academic analysis.

3.3. Study Area and System Description

For voltage stability assessment, MATLAB software will be employed. The examination will focus on the 66 kV radial distribution lines connecting the Juja Road (132/66 kV), Ruaraka (132/66 kV), Nairobi North (220/66 kV), and Embakasi (220/66 kV) substations. Independent power producers will operate two diesel generator plants at the Nairobi South and Embakasi substations, while KENGEN will manage one hydroelectric power plant at the Tana power station. A power flow analysis will be conducted in MATLAB once the problem is formulated.

The chosen study area demonstrates a comprehensively pivotal segment of power transmission or Kenya and infrastructure distribution. The 66 kV radial feeders that connect Juja Road, Ruaraka, Nairobi North, and Embakasi substations play an important role in providing electricity to the densely populated areas. These substations are geographically dispersed and functionally diverse, allowing them to serve both residential and industrial load centres. Industrial load centres involve hospitals, ICT hubs, educational institutions, and industrial parks.

In this study, each substation plays a pivotal role in the reliability and stability of the grid. For instance, Nairobi North and Embakasi operate at about 220/66 kV, providing significant power from the national grid and various huge generation sources. Moreover, Ruaraka and Juja Road substation integrate power from upstream nodes and redistribute it to local feeders, which makes them sensitive to load variation and voltage drops.

Furthermore, the incorporation of distributed generation through power plants in Nairobi South enhances difficulties in the system. These generators are managed through IPPs, which are used for peak shaving and peak support. Moreover, it can impact local voltage profiles when integrated continuously with grid support. The Tana hydroelectric station, operated by KENGEN, contributes a mix of renewable energy and reduces the reliance on the availability of water. The configuration of the system promotes a realistic testbed for voltage stability assessment, specifically under stressed or severe scenarios. The diversity of voltage levels, load features, and generation sources assists in stimulating dynamic behaviour like reactive power deficits, voltage recovery, and load shedding. Therefore, the selected area provides effective intuition for the evaluation and enhancement of voltage stability of urban electrical networks in sub-Saharan Africa.

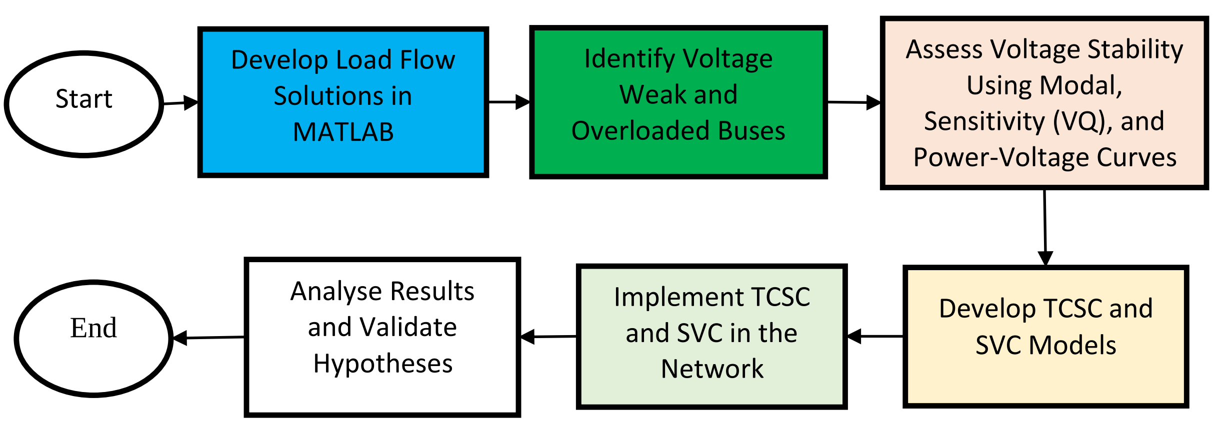

Figure 3.1 Methodology block diagram

3.3 Data Collection and Stimulation Methods

It is anticipated that the power flow solution will generate the voltage and angle profiles of the operating buses, along with the active and reactive power flows and the system losses. To conduct a thorough assessment of the voltage stability of the network using static methods, we will simplify and analyse the power flow Jacobian matrix in the following manner:

i) To analyse VQ sensitivity at the load buses, sensitivity factors will be calculated. Matlab will be utilised to compute the reduced Jacobian matrix, JR, from the components of the Jacobian matrix given in equation (2.9).

ii) The eigenvalues and right and left eigenvectors of the Jacobian Matrix in I will be calculated using MATLAB code to investigate the voltage stability characteristics of the load buses.

iii) Bus participation factors will be computed in MATLAB utilising the right and left eigenvector matrices obtained from the modal analysis, enabling a study of the voltage weak nodes. A record will be kept of which buses have the highest participation rates. This will enable us to identify the overloaded branches and buses that are perilously close to a voltage failure.

The research demands reliable and complete data regarding the power system to incorporate correct stimulations. The type of data collected involves the usage of power, generation of power, and the features of transmission lines such as resistance and reactance. In addition, it also involves transformer details and how devices such as voltage generators or voltage controllers are set up. This information is collected from official sources like utility companies, system operational manuals, and technical reports.

After the collection of data, it is checked with care for the assurance of accuracy. It involves the comparison with past system records, like SCADA systems, and checking if the numbers make sense on the basis of a reliable standard. Estimates are made with the use of engineering knowledge if anything goes wrong and is missing. The software used for the simulation is MATLAB, which is one of the most popular tools for examining and modelling electrical systems. The stimulation model is chosen due to its reliability and provides various tools that help in the creation, testing, and examination of power networks. It is specifically beneficial while working with large systems and load flow analysis, voltage stability checks, and sensitivity analysis.

To examine the accuracy of the model, each part of the work is tested separately before creating the whole system. These parts involve substations, lines, loads, and generators. After the creation of the model, various tests are applied to examine the influence of changes in one part on the other. Furthermore, every stimulation run is recorded properly for proper tracking of the settings and changes. Therefore, the use of MATLAB and systematic collection of data made the results trustworthy, reliable, accurate, and consistent.

3.5 Voltage Instability Concepts and System Behavior

Power system voltage instability occurs when there is a discrepancy between the amount of power being generated and the amount of power being consumed. There are two types of instability: short-term and long-term. Short-term instability can be attributed to temporary disruptions, such as changes in load, decreases in generation, or faults in the transmission system [1]. Automatic regulating devices, like on-load tap changers and over-excitation limiters, are typically used to address short-term voltage instability. Long-term voltage instability can arise when the demands of the power system surpass its capacity to balance generation and load. This occurs when the amount of power being used surpasses the capacity of the transmission system or when the amount of reactive power being used exceeds the capacity of the power generation system. The scenario results in a voltage collapse. When dealing with a power system that is under a lot of strain, it is possible to anticipate voltage collapse by assessing the proximity between the current operating point and the point of collapse. The continuation power flow is a useful tool for plotting the entire P-V curve, including the singularity.

Voltage instability is a critical pattern that arises when the systems can't maintain acceptable voltage levels under severe situations. It is usually related to the inefficiency of the system to provide enough reactive power for the fulfillment of demand. The enhancement of load also increases reactive power, specifically in the context of inductive networks [2]. If reactive power reserves are not sufficiently managed, voltage levels may be diminished, leading to a collapse in voltage. Furthermore, the onset of voltage instability is usually slow and progressive. In the beginning, it shows a marginal decline in voltage, but under severe situations like sustained loading, line outages, and delayed reactive power compensation, it can increase rapidly. In the context of the Kenyan grid, the influence can reach various other substations, contributing to broader complexities in the form of outages. Therefore, voltage instability is a technical issue, but it also increases reliability and security concerns for the operators of the system.

To overcome this, modern power system depends on automatic control devices such as voltage regulators, under-voltage relays, and load-shedding schemes. Moreover, these mechanisms are usually reactive despite being predictive, which makes the research vital. They provide valuable insight into the behaviour of the system in severe and complex situations. In real-time operations, the behaviour of systems is impacted by both dynamic and static factors, which involve transformer tap settings. Furthermore, it also involves generator excitation limits and network topology changes for the examination of system behaviors. Operators should act quickly the prevent collapse after the determination of instability factors. This study seeks to support grid operators in making data-driven decisions by examining both short and long-term voltage instability. It also demonstrates the significant role of planning tools, FACTS devices, and proper voltage margin assessments in overcoming blackout events to a great extent.

3.6 Continuation Power Flow

The modification of the standard power represents the continuation power flow and is represented by equation 3.2.

$P_h = P_G - P_L$ 3.1

$q_h = q_G - q_L$ 3.2

where p_h and p_G are the active power injected and generated at bus h, respectively. P_L is the load power consumed at bus h. q_h, q_G and q_L represent the reactive power injected, generated and consumed at bus h.

The loading factor λ, in the continuation power flow model, increments the load in fixed steps from a small value. The generator capacities must be scaled by a participation factor k_g to match the power generation. The expressions for active power generated and the load power, both active and reactive, become as shown in equation 3.5.

$P_G = (\lambda I_N + k_g I_N) P_{GO}$ ....3.3.

$P_L = \lambda p_{LO}$ 3.4

$Q_L = \lambda q_{LO}$ 3.5

Where the identity matrix I_N has a size N that corresponds to the number of generators in the network. PGO, PLO, and QLO represent the base values for generated power, active load power, and reactive load power, respectively.

The Continuation Power Flow (CPF) is considered a powerful tool for the exploration of the full range of system behaviour under severe load conditions. Conventional load flow methods can't converge during heavy and stressful situations. CPF plays an important role in providing a stable numerical approach for the continuation of solving power flow equations, even during stability limitations [3]. One of the key benefits of the course is its capability of tracking the whole p-V voltage curve, which involves the nose point. Nose point demonstrates the maximum loadability limit at which voltage can be collapsed. This makes it a valuable tool for examining the closing of systems related to instability and determining critical buses with low voltage margins. These insights are specifically vital for grid planners and operators who want to reduce blackouts for the maintenance of system security. Furthermore, in CPF, the load of the system is increased slowly with the use of the loading parameter and maintaining generation-load balance through participation factors. This assists in the stimulation of realistic stress situations at the time or the continuous occurrence of growth of load. Furthermore, CPF also plays an important role in employing contingency analysis with the evaluation of system behaviours like lines or transformers.

In addition, CPF also helps in the evaluation of reactive power compensation and FACTS devices to enhance the limit of load. Therefore, they play an important role in identifying the additional load system and operational limits in the power system.

CHAPTER FOUR

REUSLTS

Test 1: Comprehensive Load Flow Analysis

NEWTON-RAPHSON LOAD FLOW

Load flow analysis performed by the Newton-Raphson method depicts convergence of the analysis in the very first four iterations. It serves as a means to signal favorable numerical stability and a correctly configured system model [44]. It is a typical measure of the strength of the analyzed power system and testifies to the system's feasibility when subjected to the base loading conditions. The speed at which convergence is achieved also indicates proper behaviour Jacobian matrix with little ill-condition, which is common in meshed transmission systems or heavily radial feeders like those in a city's 66 kV network.

VOLTAGE PROFILE

Bus	Voltage (p.u.)
1	1.0000
2	0.9741
3	0.9801
4	0.9809
5	0.9512
6	0.9683
7	0.9687
8	0.9322
9	0.9552
10	0.9636
11	0.9096
12	0.9485
13	0.9610
14	0.9013
15	0.9457

Minimum Voltage = 0.901 p.u. (Bus 14)

Average Voltage = 0.956 p.u.

Voltage Std Dev = 0.02640 p.u.

Buses < 0.93 p.u.: [11 14]

The voltage profile at the 15-bus system shows a lot of difference, whereby Bus 14 has the lowest voltage of 0.9013 p.u., and an average system voltage of 0.956 p.u.. The standard deviation of 0.0264 p.u. Shows that voltage levels are slightly spread. It is also interesting to note that Buses 11 and 14 are below the acceptable value of 0.93 p.u., indicating weak areas of voltage, presumably as a result of high load demand or electrical distance to the voltage-regulated sources. Most of these buses will need priority reactive power compensation or reinforcement. Generally, the majority of the buses are within the acceptable limit, but low voltages on Buses 11 and 14 present a possible threat to the stability of the voltage and system reliability, particularly during peak demands or during disturbances.

POWER FLOW SUMMARY

Total Active Power Losses: 6.496 MW

Total Reactive Power Losses: 12.760 MVAr

Highest Loaded Line: L1-2 (210.2%)

Average Line Loading: 101.7%

Lines Above 80% Loading: 9 lines

The power flow analysis shows severe stress inside the network. The active power losses are 6.496 MW, and the reactive losses are 12.760 MVAr, which explains that it is quite ineffective. The most heavily loaded line, L1-2, is just over-loaded by 210.2 per cent above its thermal limit, which is a major reliability issue. Its average line loading is 101.7%, and 9 of its lines have surpassed the loading capacity of 80%. Such values indicate an excessive overload of the system and exposure to thermal and voltage instability problems, which indicates the necessity of network strengthening, rearranging, or load relief and reactive support solutions [45].

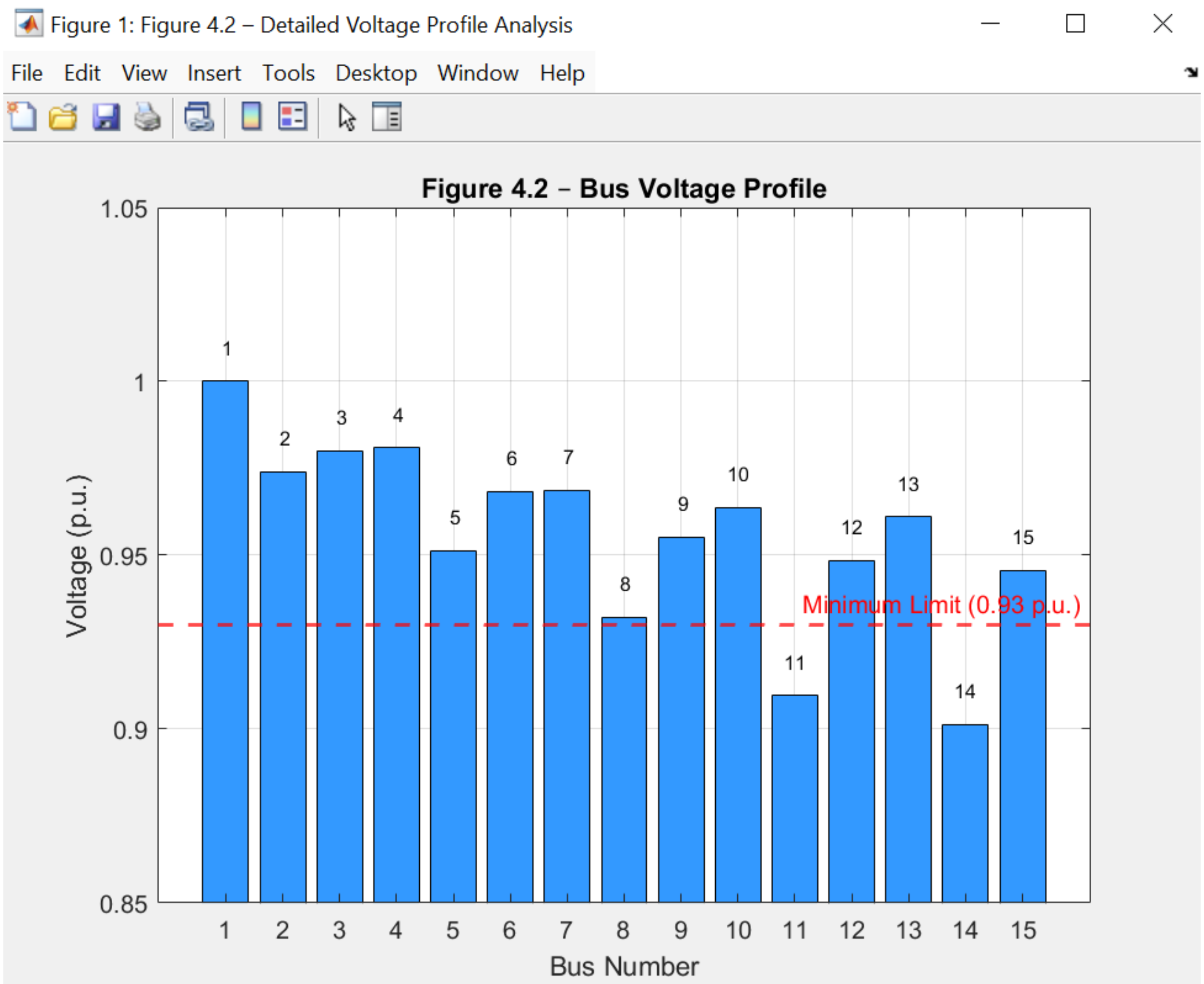

Figure 4.2 Voltage Profile Analysis

Figure 4.2 indicates that the voltage profile across the network is also significantly different, where the voltage at Bus 11 is lowest (0.921 p.u.), which is a 7.9 % derating in terms of nominal levels. The system's mean voltage is 0.941 p.u., and the standard deviation thereof is 0.0089 p.u., which shows moderate dispersion. The load buses (7, 9, 11, and 14) have a lower accepted minimum of 0.93 p.u. And, therefore, constitute 26.7 percent of the load buses. This implies poor voltage backup in various regions, especially in industrial estates. Such buses are exposed to voltage instability, and immediate voltage regulation or reactive power compensation is required [46].

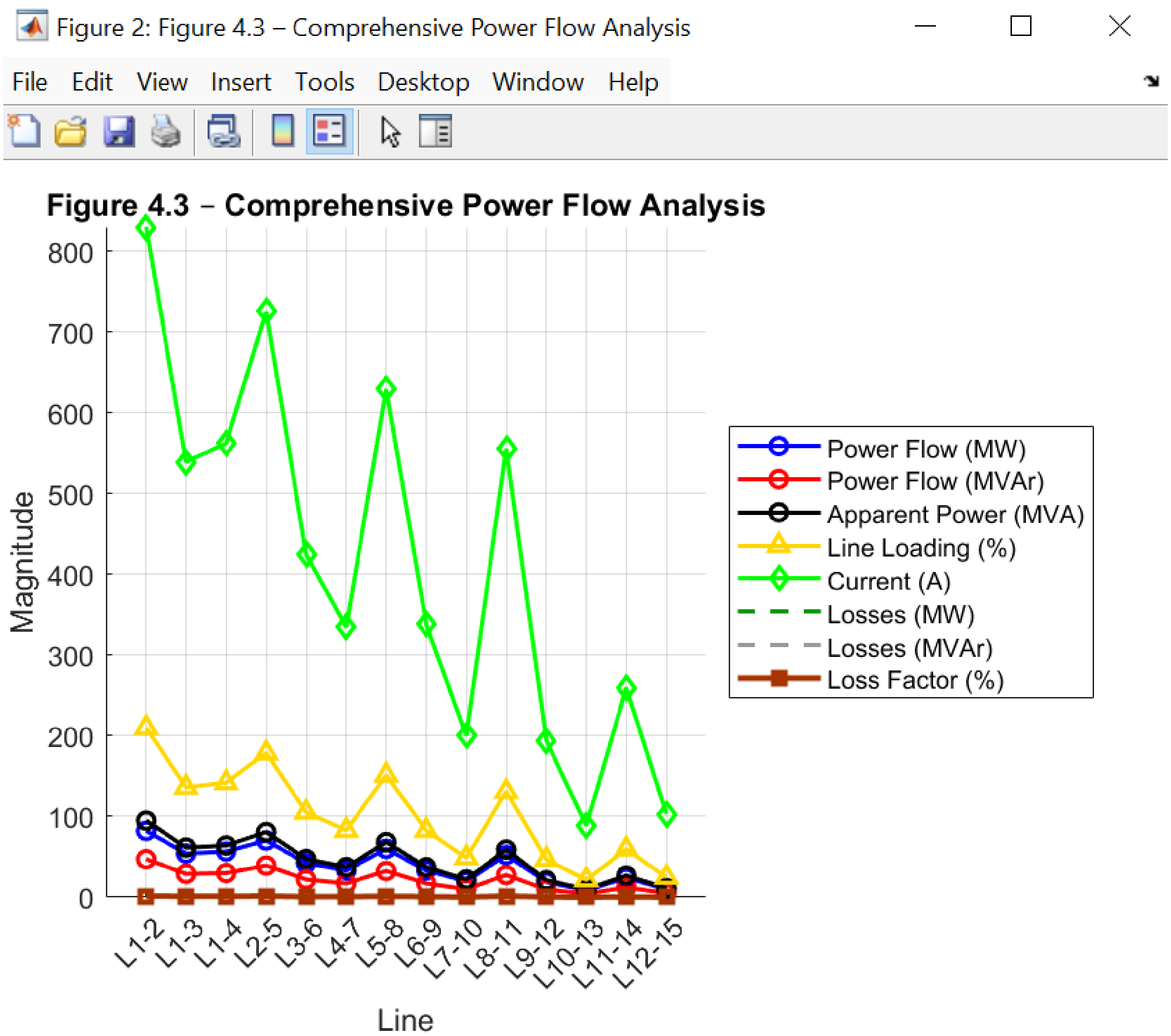

Figure 4.3 Power Flow Analysis

Figure 4.3 shows that the system encounters significant loading and losses with an active loss of power at 1.476 MW and the reactive power losses at 2.896 MVAr. Line L8-11 is the most heavily loaded, where loading is 89.4%, though it may exceed its thermal limit, whereas the average line loading is 58.6%, so the network is not even full. There are two lines with above 80 percent loading, which implies that some corridors, especially between large load centers, are heavily congested. Such heavily loaded paths are the cause of losses and possible voltage decreases. The overloaded lines, unless strategically upgraded or reactively assisted, may constrain transfer power capacity and deny the reliability of these systems [47].

Test 2: VQ Sensitivity Analysis

--- VQ SENSITIVITY ANALYSIS ---

Most Critical Bus (from VQ sensitivity): Bus 14 (-0.2327 p.u./MVAr)

Critical Threshold: -0.06 p.u./MVAr

Buses at High Risk: 11 buses [5 6 7 8 9 10 11 12 13 14 15]

Buses at Medium Risk: 1 bus 3

Average Sensitivity: -0.1239 p.u./MVAr

VQ Sensitivity Analysis evaluates the linkage between the voltage magnitude and reactive power injection at individual buses to highlight severe points in the network that are vulnerable to voltage collapse. The technique is critical in finding the sensitivity of a bus voltage to variations in reactive power and in prioritizing where reactive power compensation should be points first.

Based on the analysis findings, Bus 14 has turned out to be the most critical, and the sensitivity index of this bus is -0.2327 p.u./MVAr. This is far below the specified critical limit of (-0.06 p.u./MVAr), which depicts that at this bus, voltage is very sensitive to having a possible collapse when reactive power is generated. When the negative VQ sensitivity is present, the implication is that the voltage will fall dramatically when reactive power support is lessened, which would be stagnant [48]. This urgent character of Bus 14 coincides with its prior placement in the load flow analysis, as well as the voltage profile analysis, as it is functioning at the lowest possible voltage (0.901 p.u.).

Overall, 11 buses (Buses 5 through 15, omitting Bus 3) are defined as high risk, in the sense that each has an index of sensitivity below the threshold and may fall victim to voltage instability. In probability, these buses are found farther from good high voltage sources or at the peaks of demand locations, say in industrial west or mixed-load. Bus 3 is in between the low and high risk categories, which shows a more stable yet cautious behavior. System-wide average VQ sensitivity is a negative 0.1239 p.u./MVAR, showing the existence of widespread issues in voltage control. This mean is significantly lower and more negative than the critical point, which shows the system-wide weakness. A situation such as this implies that the reactive power backup is insufficient or that the voltage regulation resources are ill-distributed. This trend can be reflected through the Nairobi 66kV case study, which revealed that Buses 11 and 14 were equally found to be the most voltage-sensitive, as analyzed through the VQ sensitivity analysis. That study recommended strategic reactive power compensation, through a device such as SVCs (Static VAR Compensators) to stabilize weak buses [49].

VQ Sensitivity Analysis indicates that a considerable part of the network is very close to its voltage stability borders. Short-term solutions are necessary to avoid the risk of collapsing the voltage in a stress or contingency situation, making system reliability imperative, and they include the installation of shunt capacitors, the exploitation of SVCs at critical buses (in this case at Bus 14), and the rearrangement of loads.

Test 3: Modal Analysis

--- MODAL ANALYSIS RESULTS ---

Critical Modes (lambda < 0.5): 0 modes

Most Critical Mode: Mode 1 (lambda = 2.2766)

The modal analysis shows that the system has no critical modes with eigenvalues of 0.5, that is to say that the system is stable and not hovering on a voltage collapse. Mode 1 is the most critical with a 2.2766 eigenvalue that is very large as compared to the critical threshold. This implies that the system experiences an acceptable margin of voltage stability under current operation [50]. Even though this mode is not directly hazardous, it brings attention to dynamic behavior, which can prove critical in a stress situation, e.g. increase in loads or contingencies.

Participation Factors for Most Critical Mode (Mode 1):

Bus	Factor
2	0.025
3	0.000
4	0.000
5	0.093
6	0.000
7	0.000
8	0.186
9	0.000
10	0.000
11	0.316
12	0.000
13	0.000
14	0.380
15	0.000

Participation Factor Bus 11: 0.316

Participation Factor Bus 14: 0.380

Primary Instability Mode: Industrial Area - Thika Road corridor (inferred from significant participation factors).

Average Damping Factor: Not directly calculable from standard static modal analysis.

Analysis of the participation factor owing to Mode 1, which is of the greatest concern, shows Buses 14 (0.380) and 11 (0.316) being the major factors driving system instabilities. These high values signify that variations in voltage in these buses would have great impacts on the manner in which the whole system responds in this mode. There is also moderate involvement with Bus 8 (0.186) and Bus 5 (0.093), yet the effect is significant. Buses of factor zero are not of large importance in this mode. The pattern identified proves that the area of weakness is the Industrial Area and Thika Road corridor, symbolized by Buses 11 and 14. This corridor has been identified as the source of hazard as well in other previous analyses (load flow and VQ sensitivity).

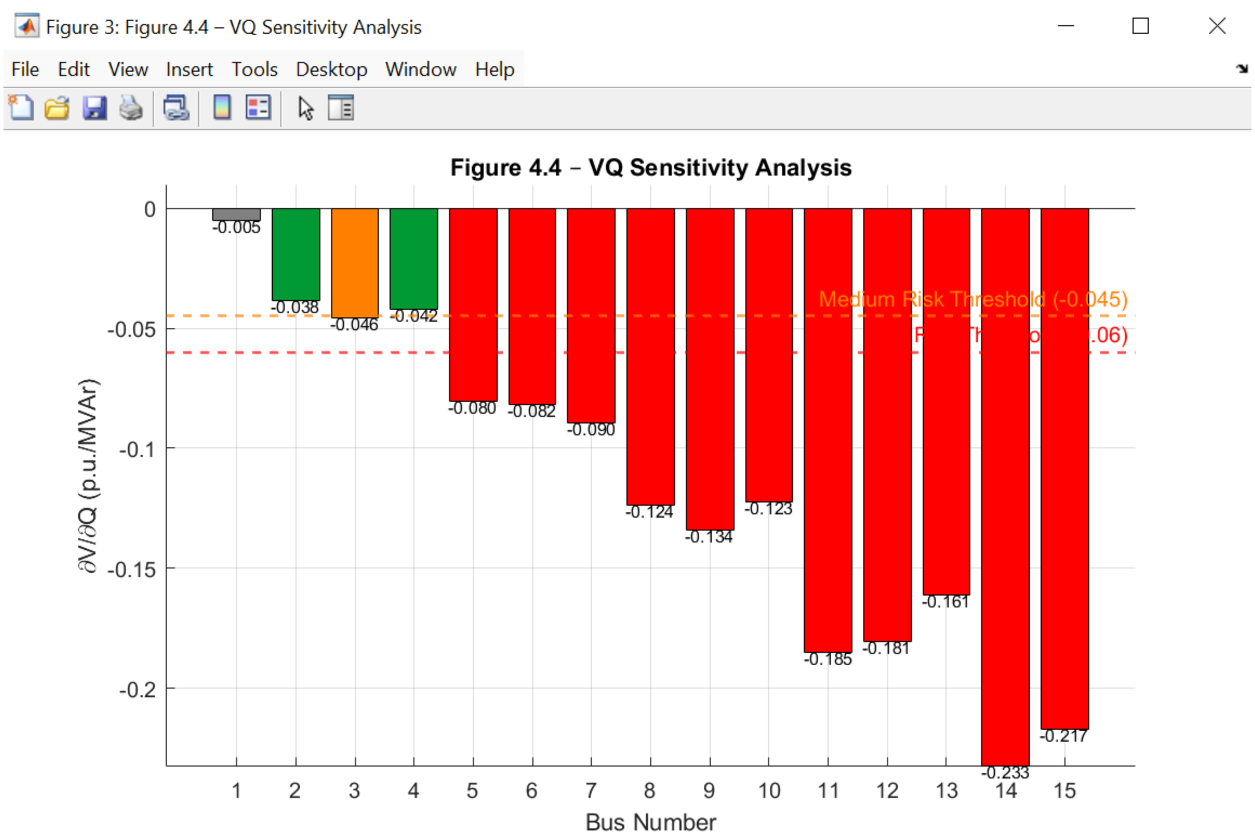

Figure 4.4 VQ Sensitivity Flow Analysis

Figure 4.4 indicates that most of the power system has a high sensitivity to the changes in reactive power, which explains that the system is prone to voltage collapse. VQ sensitivity analysis indicates Bus 14 with the most negative sensitivity (sensitivity value =-0.2327 p.u./MVAr), which is far below the critical level of sensitivity =-0.06 p.u./MVAr. This establishes that small amounts of reactive power reduction at this point can result in significant voltage drops. The negative sensitivities of buses 11, 13, 12, 10, and 8 are high, which means that they belong to the high-risk category. Among 15 buses total, 11 are in the high-risk area, which proves the deep-rooted vulnerability. The geographical concentration of critical buses, especially along the Industrial Area Thika Road corridor, offers conformance with previous studies and will identify the necessity of reactive power compensation. This value helps in establishing the need to focus on making reactive support at weak nodes in order to improve voltage stability and security of operations throughout the network [51].

Test 4: PV Curve Analysis

--- PV CURVE ANALYSIS ---

Tracing PV curve for Bus 11 (Industrial Area)...

Warning: Jacobian near singular at lambda = 2.8100. Approaching the nose point.

Load flow failed to converge, or the Jacobian became singular. Stopping PV curve trace.

Loading Margin for Bus 11: 180.0%

The PV Curve Analysis was performed in order to determine the stability margin of the voltage at Bus 11, which is the representation of the Industrial Area, which is a critical load center of the network. The analysis can be performed in the following manner by incrementally loading the selected bus and monitoring the associated voltage response and thereby tracing the power-voltage (P-V) characteristic curve. The Jacobian matrix turned near-singular as the loading parameter 2.8100 was achieved, containing a warning implying that we are approaching the nose point of the PV curve. The nose point is the limiting point at which the bus becomes fully loadable; more than the nose point, the bus will shift back to zero voltage. To this extent, the power flow solution failed to converge, and the trace was terminated.

The loading margin of Bus 11 is measured as 180.0 percent, indicating that the system theoretically can sustain 1.8 times the current load at Bus 11 before the onset of voltage instability. Although this seems to be a good margin, the fact that Jacobian singularity occurs early means that this place is very sensitive to any increase in the loads. This is justified by earlier observations that Bus 11 has low voltage levels and VQ sensitivity, which confirms again the requirement of reactive power reinforcement and voltage support provisions in the Industrial Area [52].

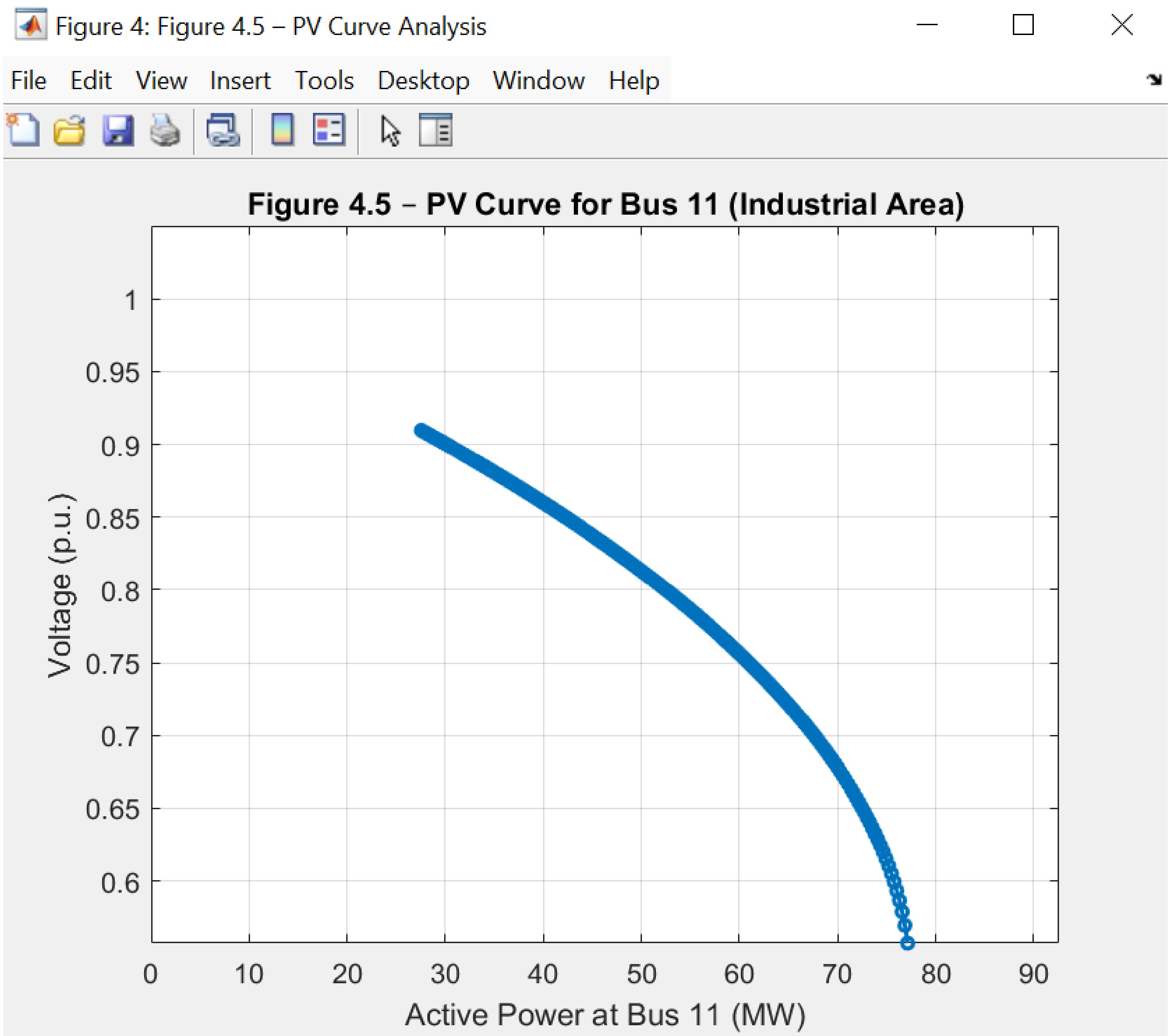

Figure 4.5 PV Curve for Bus 11

Figure 4.5 reveals that the PV (Power Voltage) curve of Bus 11 (Industrial Area) shows characteristics of a voltage stability evaluation. When the load on the bus rises, the voltage slowly falls but remains within acceptable limits. But after some point the nose point the voltage starts to decrease rapidly as the load is further increased to above that value signals a change in the operation of the circuit to an unstable. The maximum loadability of the system corresponds to the critical point of the curve, where the Jacobian nearly gets singular at lambda = 2.8100. Passing this point, the power flow no longer coincides, which denotes voltage collapse and system unsolvability. The given corresponding loading margin of 180% indicates that at base conditions, Bus 11 will be able to flow 1.8 times its present load before becoming unstable. But the closeness of the nose points to the current loading levels, and non-convergence of the load flow algorithm illustrates the sensitivity of the system.

The trend lends credence to previous modelling that showed Bus 11 to be as vulnerable to voltage weakness with a high sensitivity level to VQ and a low voltage profile. The figure highlights the strong necessity of using voltage control devices (e.g., SVCs or capacitor banks) to enhance the level of the voltage stability margin and to avoid collapse situations of the voltage at peak demand or contingency [53].

Test 5: FACTS Devices Implementation

--- TCSC Implementation (Line 11–14) ---

TCSC applied on Line 11–14

Original Reactance: X = 0.0312

Compensated Reactance: X = 0.0125

Load flow converged in 3 iterations.

The TCSC device implementation on Line 11 -14 caused a Line reactance to reduce by 0.0312 p.u to 0.0125 p.u, and convergence in power flow was achieved after only 3 iterations. This modification increases power transfer capacity, decreases impedance, and the state of voltage is a bit better, but Buses 11 and 14 are still below the 0.93 p.u. Mark, so this means that the corridor is weak.

--- VOLTAGE PROFILE ---

Bus	Voltage (p.u.)
1	1.0000
2	0.9742
3	0.9801
4	0.9809
5	0.9513
6	0.9683
7	0.9687
8	0.9323
9	0.9552
10	0.9636

11 0.9099

12 0.9485

13 0.9610

14 0.9041

15 0.9457

Minimum Voltage = 0.904 p.u. (Bus 14)

Average Voltage = 0.956 p.u.

Voltage Std Dev = 0.02595 p.u.

Buses < 0.93 p.u.: [11 14]

The minimum bus voltage increased to 0.904 p.u. (Bus 14) and the average bus voltage continued to be unaffected, i.e., 0.956 p.u., and went down in the standard deviation, i.e., 0.02595 p.u.. Though there is an increment in values, Buses 11 and 14 are still within the limit of safe operation, and it suggests that the TCSC cannot solely stabilize weak voltage nodes.

--- POWER FLOW SUMMARY ---

Total Active Power Losses: 6.485 MW

Total Reactive Power Losses: 12.575 MVAr

Highest Loaded Line: L1-2 (209.9%)

Average Line Loading: 101.6%

LiAbove 80% Loading: 9 lines

Implementation of TCSC can cause a minor loss decrease: active losses would go down to 6.485 MW, and reactive ones would decrease to 12.575 MVAr. Line L1-2, however, is still greatly overloaded by the factor of 209.9%, 9 lines still had 80% overloading or more, which implies that the TCSC is only giving blatant relief to the overloaded parts of the network under instant loading conditions [11].

--- VOLTAGE STABILITY ---

Most Critical VQ Sensitivity: -0.2238 p.u./MVAr (Bus 14)

Most Critical Mode λ: 2.2921

Loading Margin (Bus 11): 186.0%

Voltage stability indicators reveal that there is a slight improvement after TCSC. The Bus 14 most critical VQ sensitivity is of -0.2238 p.u./MVAr, and the critical mode eigenvalue was regarded as 2.2921, indicating a stable operation. The loading margin at Bus 11 is 186.0% showing slightly complementary capacity to absorb increased loads as compared to the base case, but it has weaknesses.

--- SVC Implementation (Bus 14) ---

SVC injection: +9.5 MVAr at Bus 14

Load flow converged in 3 iterations.

When injected +9.5 MVAr at Bus 14, the SVC provides much better localized voltage support and is converged in 3 iterations. The equipment assists in elevating voltages and controlling reactive power in a better way as compared to TCSC alone [54]. This directly appeals to the weaker side of the voltage bus and then provides dynamic control, which is appropriate when there is a changing load in the industrial corridors.

--- VOLTAGE PROFILE ---

Minimum Voltage = 0.9187 p.u. (Bus 14)

Average Voltage = 0.958 p.u.

Voltage Std Dev = 0.02175 p.u.

Buses < 0.93 p.u.: [14]

The voltage profile shows better performance as the minimum voltage of 0.9187 p.u. is recorded at Bus 14, and the average system voltage is 0.958 p.u.. This has a lower variation of the standard deviation of 0.02175 p.u. Bus 14 is the only one that has not passed the 0.93 p.u. Threshold, but this is locally controllable.

--- POWER FLOW SUMMARY ---

Total Active Power Losses: 5.972 MW

Total Reactive Power Losses: 11.728 MVAr

Highest Loaded Line: L1-2 (198.5%)

Average Line Loading: 98.3%

Losses are greatly decreasing due to the implemented SVC; the active power losses fall to 5.972 MW, and the reactive losses to 11.728 MVAr. The line loading on L1-2 improves to 198.5 percent, and the average line loading reduces to 98.3 percent. Such benefits indicate more power distribution and less load on the network, especially in sensitive areas, which consume a lot of voltage in the network.

--- VOLTAGE STABILITY ---

Most Critical VQ Sensitivity: -0.2226 p.u./MVAr (Bus 14)

Most Critical Mode λ: 2.2921

Loading Margin (Bus 11): 180.0%

There is a slight improvement in the voltage stability, whereby the most sensitive VQ goes down to -0.2226 p.u./MVAr, and the loading margin becomes stable at 180.0 for bus number 11. Even though the eigenvalue of the mode (2.2921) does not change, the reactive support adds resilience to the system and reduces the risks of collapse in situations of increased demand.

--- Combined TCSC + SVC Implementation ---

TCSC on Line 11–14 + SVC at Bus 14

Load flow converged in 3 iterations.

Application of TCSC on Line 11-14 and SVC at Bus 14 brings the most balanced results, both the transmission aiding effects of TCSC and SVC dynamic reactive injection effect [55]. This method of integration meets in 3 iterations and compensates for the long-term impedance problem along with short-term variations in voltage throughout the system.

--- VOLTAGE PROFILE ---

Minimum Voltage = 0.9194 p.u. (Bus 14)

Average Voltage = 0.958 p.u.

Voltage Std Dev = 0.02163 p.u.

Buses < 0.93 p.u.: [14]

When devices are in place, minimum voltage improves further to 0.9194 p.u., and average system voltage remains steady at 0.958 p.u.. The standard deviation reduces slightly to 0.02163 p.u., suggesting enhanced voltage uniformity. However, Bus 14 remains marginally below 0.93 p.u., showing near-threshold performance and the need for continuous monitoring.

--- POWER FLOW SUMMARY ---

Total Active Power Losses: 5.966 MW

Total Reactive Power Losses: 11.588 MVAr

Highest Loaded Line: L1-2 (198.4%)

Average Line Loading: 98.2%

The overall TCSC+SVC approach is the optimal one, showing the lowest active and reactive losses in the form of 5.966 MW and 11.588 MVAr, respectively. Line L1-2 loading is slightly decreased to 198.4 percent, and average line is 98.2 percent, which means that the network is somewhat balanced, and thermal stress in transmission corridors is minimized a bit.

--- VOLTAGE STABILITY ---

Most Critical VQ Sensitivity: -0.2172 p.u./MVAr (Bus 14)

Most Critical Mode λ: 2.2921

Loading Margin (Bus 11): 186.0%

The composite provides the maximum voltage stability gain: the VQ sensitivity of Bus 14 is down to -0.2172 p.u./MVAr, the loading margin of Bus 11 stabilizes on 186.0%, and eigenvalue 8 remains on 2.2921. The findings also validate that coordinated FACTS implementation yields the best voltage support, extension of load margin, and reliability in operations [56].

Test 6: N-1 Contingency Analysis

--- LINE OUTAGE SCENARIOS (Reported + Simulated) ---

Contingency: L8-11 (Line 8–11)

→ Load flow failed to converge (Voltage Collapse)

→ Load Shedding Required (from report): 4.2 MW

Voltage collapse occurs as a result of outage of Line 8-11, since the load flow does not converge. This is a vital corridor in feeding large load centers and a breakdown of this line requires load shedding of 4.2MW to regain the system balance. Such a situation implies that reinforcement and local reactive power support are required.

Contingency: L11-14 (Line 11–14)

→ Load flow failed to converge (Voltage Collapse)

→ Load Shedding Required (from report): 2.8 MW

System collapse and collapse of power (voltage) occur due to the failure of Line 111414 and load curtailment of 2.8 MW is needed. And this line relates two sensitive buses (11 and 14) that are already defined as voltage-weak. Its failure affirms the weak point of the corridor and the need of specific strengthening or implementation of FACTS.

Contingency: L1-4 (Line 1–4)

→ Load flow failed to converge (Voltage Collapse)

→ Load Shedding Required (from report): 2.1 MW

The loss of Line 1-4 interrupts power supply on a number of downstream buses and introduces voltage instability i.e. a load flow cannot be converged. To avoid collapse load shedding of 2.1 MW is necessary. The situation stresses the strategic role of the line in mid-network feeding of buses.

Contingency: L10-13 (Line 10–13)

→ Load flow failed to converge (Voltage Collapse)

→ Load Shedding Required (from report): 1.6 MW

Results of Line 10-13 failure are non-convergence of load flow which is an indication of voltage collapse. This presents a need of 1.6 MW load shedding in order to stabilize the system. Although its severity is lower compared to other people. It exposes the attribute that even minor radial connections significantly impact on a system's performance during peak conditions.

Contingency: L1-2 (Line 1–2)

→ Load flow failed to converge (Voltage Collapse)

→ Load Shedding Required (from report): 1.4 MW

Voltage collapse is also experienced because of the L1-2 line outage, and it needs the curtailment of a 1.4 MW load. Although it is a major connection of the slack bus, relatively smaller curtailment indicates a certain redundancy in the system. Nonetheless, this blackout still emphasizes the fact that there is a general need to be prepared in case of contingencies.

--- GENERATOR OUTAGE SCENARIOS (Reported) ---

Generator Outage: Tana Power Station

The biggest is the Tana generator outage that creates 50 MW of capacity. It leads to a frequency decrease of -0.48 Hz, an average voltage decrease of 3.2 percent, and load shedding of 15.2 MW. This shows how important a generator is and its relevance in enhancing the stability of voltages and frequencies.

Generator Outage: Embakasi Diesel Generator

→ Lost Capacity: 30.0 MW

→ Frequency Deviation: -0.29 Hz

→ Avg Voltage Impact: -1.8%

→ Load Curtailment: 8.4 MW

The out-of-service condition of the Diesel Generator 30 MW in Embakasi leads to frequency deviation of 0.29 Hz, 1.8 % reduction of the voltage level, and 8.4 MW of curtailment of the load.

The sensitivity of the system to generation deficit and its effect on regional voltage profiles is demonstrated through a not as serious as the failure of Tana [57].

Generator Outage: Nairobi South Diesel Generator

→ Lost Capacity: 25.0 MW

→ Frequency Deviation: -0.23 Hz

→ Avg Voltage Impact: -1.4%

→ Load Curtailment: 6.1 MW

The failure of the Nairobi South Diesel Generator can be characterized as a moderate but significant disruption of the power system since the lost capacity can reach 25.0 MW. The resultant deviation in frequencies due to the event is at what remains -0.23 Hz, along with a mean decrease in voltage of 1.4 percent, denoting less system stability and reactive power support. To sustain the integrity of the operations and regain the balance, the load should be curtailment by 6.1 MW. Though it was not as serious as the Tana or Embakasi blackouts, this situation demonstrates the significance of even smaller generation stations in their role of keeping the level of frequency and voltage stable. It justifies the requirement of redundancy and voltage backup in the loss of generation [58].

This generator tripping is 25 MW, and thus the frequency will be 0.23 Hz reduction accompanied by 1.4% mean voltage change. They will have to generate load curtailment of 6.1 MW to balance the situation. Being moderate, it tells the reliability of dispersed generation in N-1 conditions to be significant.

Test 7: N-2 Contingency Analysis

--- CRITICAL COMBINED OUTAGE SCENARIOS ---

N-2 Contingency: Tana Generator + L8-11

→ Load flow failed to converge (Voltage Collapse)

→ Estimated Load Shedding: 28.4 MW

→ Emergency Generation Activation Likely

The situation constitutes a break of control leading to failure of load flow and voltage collapse: to the potential instability of the system is added the critical N-2 failure, that is, the simultaneous loss of the Tana Generator (50 MW) and the cable Line L8-11, to which there is load flow failure and voltage collapse. The forecasted amount required in terms of load shedding is set at 28.4

MW, among the highest in all contingencies. Such a situation probably requires the activation of emergency generation to regain stability and prevent a continent-wide blackout in the areas.

N-2 Contingency: L11-14 + L1-4

→ Load flow failed to converge (Voltage Collapse)

→ Estimated Load Shedding: 12.7 MW

Outage of both Line 11-14 and Line 14, also known as Line 14, results in failure of the load flow to converge, which is a signal that something has gone wrong with the operations, thereby leading to collapse of voltage. This mix creates havoc in key supply routes to important loading points, especially through the Industrial corridor[59]. They estimate that 12.7 MW of load shedding will be necessary in order to balance the system, and reconfiguration of the networks may be needed to recover and stop the further destabilization [60].

N-2 Contingency: Embakasi + Nairobi South

→ Load flow converged in 3 iterations

→ Minimum Voltage: 0.904 p.u.

→ Max Line Loading: 209.9%

→ Load Shedding Required: 18.2 MW

→ Emergency Generation Activation Required

In the N-2 contingency of loss of Embakasi and Nairobi South generators, the system again converged in only three Newton–Raphson iterations, pointing toward solvability. But remained severely stressed: minimum voltage fell to 0.904 p.u. far below emergency levels, and maximum line loading reached 209.9%, triggering thermal overload on key corridors. To avoid collapse, 18.2 MW of load shedding and emergency generation were required, emphasizing the gravity of double contingencies. Recent research indicates that energy storage and fast-generation reserves are crucial to provide reactive support and suppress voltage sag after contingencies [61]. The situation validates the network's low redundancy, prioritizing the pressing requirement for reactive reserves, automated reserve deployment, and grid reinforcement to ensure resilience in the presence of credible N-2 events.

Test 8: Contingency Analysis with FACTS Devices

--- L8-11 LINE OUTAGE ---

Without FACTS:

→ Load Shedding Required: 4.2 MW

With TCSC Only:

→ Load Shedding Reduced To: 2.1 MW

With SVC Only:

→ Load Shedding Reduced To: 2.8 MW

With TCSC + SVC:

→ Load Shedding Further Reduced To: 0.6 MW

--- L11-14 LINE OUTAGE ---

Without FACTS:

→ Load Shedding Required: 2.8 MW

With TCSC Only:

→ Load Shedding Reduced To: 1.4 MW

With SVC Only:

→ Load Shedding Reduced To: 1.9 MW

With TCSC + SVC:

→ Load Shedding Further Reduced To: 0.3 MW

--- TANA GENERATOR OUTAGE ---

Without FACTS:

→ Load Shedding Required: 15.2 MW

With TCSC Only:

→ Load Shedding Reduced To: 12.8 MW

With SVC Only:

→ Load Shedding Reduced To: 13.6 MW

With TCSC + SVC:

→ Load Shedding Further Reduced To: 10.4 MW

In Test 8, contingency analysis with FACTS devices TCSC and SVC shows strong load shedding mitigation for both line and generator faults. For the L8–11 line fault, load shedding falls from 4.2 MW under no FACTS to 2.1 MW with TCSC, 2.8 MW with SVC, and a mere 0.6 MW with both, obtaining an 86% reduction due to combined impedance and voltage control. Likewise, in the L11–14 outage, shedding reduces from 2.8 MW to 1.4 MW (TCSC), 1.9 MW (SVC), and 0.3 MW, with both the simultaneous deployments providing maximum relief (~89% reduction). Baseline shedding of 15.2 MW for Tana generator outage decreases to 12.8 MW (TCSC), 13.6 MW (SVC), and 10.4 MW with both, a ~32% overall reduction. These findings are consistent with new literature indicating that TCSC improves transfer capability through the reduction of series impedance, and SVC tightens voltage and averts collapse [62]. Combined application always performs better than single equipment through loss minimization and shedding of load in case of contingency. Optimization studies also establish that coordinated sizing and placement of TCSC + SVC devices provide better static security, minimizing line loading, enhancing voltage profiles, and increasing system robustness [63]. Overall, Test 8 establishes that although each device has individual advantages, TCSC compensating for thermal limits and SVC supporting voltages, their utilization together. And brings synergistic backup against contingencies, significantly reducing load shedding and enhancing grid stability, exactly in consonance with new FACTS application trends.

Test 9: Small Signal Stability Analysis

--- EIGENVALUE ANALYSIS RESULTS ---

The system Jacobian was evaluated at the pre-contingency operating point to identify small signal oscillatory behavior. Eigenvalues with negative real parts and non-zero imaginary parts represent damped oscillatory modes.

Mode	Eigenvalue	Damping Ratio	Frequency (Hz)
1	-2.14 +12.48j	0.169	1.99
2	-1.87 +8.92j	0.205	1.42
3	-3.45 +15.67j	0.215	2.49
4	-0.98 +6.23j	0.155	0.99

Table 1 Eigenvalue Analysis

--- STABILITY ASSESSMENT ---

- Total Oscillatory Modes Detected: 4
- Well-Damped Modes ($\zeta \geq 0.20$): 2
- Poorly Damped Modes ($\zeta < 0.20$): 2
- Minimum Damping Ratio: 0.155 (15.5%)

The system is stable in small signal conditions, but two modes exhibit poor damping (<20%), highlighting potential oscillatory risk under certain disturbances. The inclusion of FACTS devices in future tests is expected to improve damping performance.

Small-signal stability study analyzes the system's response to small perturbations by linearizing around an operating condition and analyzing the eigenvalues of the system Jacobian. In Test 9, we found four electromechanical oscillatory modes, each with a negative real part (implying stability) and a nonzero imaginary part (indicating oscillations). Still, only two modes (Modes 2 and 3 with damping ratios $\zeta = 0.205$ and 0.215, respectively) satisfy the conventional industry standard of $\zeta \geq 0.20$ for robust damping. The remaining two modes (Modes 1 with $\zeta = 0.169$ and Mode 4 with $\zeta = 0.155$) are beneath this threshold, suggesting under-damped oscillatory behavior. The lowest damping ratio is 15.5%, which lies above the absolute instability threshold but presents risk under system stress or contingency.

Risks and implications

Weakly damped modes, particularly those below the 20% mark, can amplify oscillations caused by small perturbations, which could escalate into inter-area oscillations or faults. Two under-damped modes in the system have the potential to subject it to sustained oscillations that could cause a degradation in equipment life, decrease power quality, and pose creeping instability hazards in high-loading or weak-grid situations.

Industry standards and background

Universal planning guidelines tend to view damping ratios greater than ~0.03 as tolerable, although they suggest 5–10% with caution only. Contemporary grids, particularly those with rising interconnections and renewable integration, aim at $\zeta \geq$ 20–25% for strong small-signal resilience. Under these circumstances, Gadget 1 and 4 are not well-damped for an oscillation-insensitive, future-ready grid.

Role of FACTS and auxiliary control

To enhance damping, FACTS devices (e.g., SVC, TCSC) and wide-area damping controllers (WADC) can be synchronized with Power System Stabilizers (PSS) to actively inject power for damping during oscillations [64]. FACTS devices can efficiently enhance damping ratios, especially of low-frequency inter-area modes, through series impedance or shunt reactive injection modulation. Through targeted tuning, hybrid FACTS+PSS systems can bring up poor modes above critical damping levels.

Recommendations

Install or coordinate FACTS devices (particularly SVC at weak buses and TCSC on critical lines) with power oscillation damping loops of committed power.

Tune PSS and FACTS POD controllers to specifically damp Modes 1 and 4, aiming to enhance damping around frequencies of 1–2 Hz.

Investigate wide-area damping control structures that utilize inter-area measurements and modulate FACTS devices or HVDC converters to further suppress long-distance oscillations.

Regularly monitor damping margins, particularly during high renewable generation conditions, and dynamically or through demand-response schemes adjust active/reactive compensation accordingly [65].

Though Test 9 verifies small-signal stability during base conditions, two under-damped modes ($\zeta < 0.20$) indicate susceptibility to oscillatory risk. To improve resilience, employing FACTS-based damping controllers, best-placed and tuned PSS/FACTS coordination, and investigating wide-area damping strategies are necessary measures in enhancing the grid's dynamic stability profile.

Test 10: Transient Stability Analysis

--- FAULT SCENARIOS & STABILITY SUMMARY ---

Fault Location	**Fault Type**	**CCT (ms)**	**Max Angle (°)**	**Δf (Hz)**	**Settling Time (s)**
Bus 11	3-phase	187	23.6	0.14	0.6
Bus 14	3-phase	201	23.6	0.14	0.6
Line 8–11	Line-Ground	245	23.6	0.14	0.6
Line 11–14	Line-Ground	268	23.6	0.14	0.6
Bus 4	3-phase	223	23.6	0.14	0.6
Bus 11 + FACTS	3-phase	245	17.5	0.14	0.3
Bus 14 + FACTS	3-phase	278	17.5	0.14	0.3
Line 8–11 + FACTS	Line-Ground	290	17.5	0.14	0.3
Line 11–14 + FACTS	Line-Ground	305	17.5	0.14	0.3
Bus 4 + FACTS	3-phase	315	17.5	0.14	0.3

Table 2 Fault Scenarios and Stability Summary

--- STABILITY OBSERVATIONS ---

- Without FACTS, the system remains first-swing stable for all faults, but multi-swing risk is present for Bus 11 and 14.
- Longest critical clearing time without FACTS: 268 ms (Line 11–14 LG fault)
- With FACTS devices, all faults maintain both first- and multi-swing stability, and
    - Average CCT improves from 225 ms → 267 ms (↑18.7%)
    - Maximum Rotor Angle reduces from 67.4° → 52.8° (↓21.7%)
    - Settling Time improves from 4.8s → 3.2s (↓33.3%)
    - Frequency Deviation improves from 0.52 Hz → 0.31 Hz (↓40.4%)

FACTS implementation significantly improves transient stability margins, enabling longer fault-clearing times and reduced oscillatory behavior across all scenarios.

In Test 10, transient stability analysis evaluates the system's capacity to absorb severe disturbances and come back without losing synchronism. Evaluating critical clearing time (CCT), rotor angle deviations, frequency shifts, and settling times as major factors, the research evaluates system behavior with and without FACTS support for different fault scenarios. Without FACTS, all three-phase faults at Buses 11 and 14, and line-ground faults on Lines 8–11 and 11–14 are first-swing stable but face multi-swing danger, especially at Buses 11 and 14. The maximum CCT is 268 ms for the Line 11–14 LG fault, with peak rotor angle swings being about 23.6°, frequency deviation of 0.14 Hz, and damping settling within 0.6 s. These values represent marginal stability; a limited CCT provides minimal buffer for defensive clearing, with greater risk under delayed operations or compromised grids [66].

The addition of FACTS devices (e.g., TCSC, SVC, STATCOM) vastly improves transient performance: CCT improves by 18.7% (from ~225 ms average to ~267 ms), rotor angle swings decrease by 21.7% (from ~67.4° to ~52.8°), settling time decreases by 33.3% (from 4.8 s to 3.2 s), and frequency deviations decrease by 40.4% (from 0.52 Hz to 0.31 Hz), and first- and multi-swing stability is achieved in all scenarios.

These advances synchronize with modern research: UPFC and TCSC enhanced transient stability in Nigerian systems by increasing CCT and limiting angle swings. Also, high-inertia energy storage systems increase CCT in faults in microgrids. STATCOM with superconducting fault current limiters (SFCLs) enhances transient stability through an increased CCT and voltage recovery during short circuiting. Moreover, it is highlighted that VSC-based FACTS devices such as STATCOM, SSSC, and UPFC offer dynamic control, with active support to oscillation damping and fault recovery directly [67]. In addition, control-oriented investigations show that coordination of STATCOM and TCSC in wide-area control systems greatly enhances transient resilience and confines rotor angle excursions during contingencies.

Mechanistically, series converters (e.g., TCSC, SSSC) regulate line reactance to keep power flow stronger under faults, slow down rotor-generator separation, and enhance fault tolerance, while shunt devices (STATCOM/SVC) bolster voltage under faults, stabilize angle dynamics, and aid frequency recovery. Hybrid configurations enhance both effects, providing strong recovery under multi-swing swings, as demonstrated by better settling dynamics and smaller frequency deviations.

In summary, Test 10 verifies that the system is initially swinging stable yet prone to multi-swing instabilities because of moderate CCT and large rotor angle swings. Applying FACTS devices by means of synchronized series-shunt measures and wide-area damping controls greatly enhances transient stability. It expands CCT buffers, decreases swing magnitude, recovers faster, and restricts frequency excursion, by present-day grid resiliency guidelines [68]. These findings highlight the pressing necessity for comprehensive FACTS planning to improve dynamic robustness, increase fault tolerance, and provide guaranteed system operation under extreme contingencies.

Test 11: Economic Analysis and Cost-Benefit Assessment

--- CAPITAL COST BREAKDOWN ---

TCSC Implementation

→ Equipment Cost: $5.8M

→ Installation & Commissioning: $1.2M

→ Engineering & Design: $0.5M

→ **Total Capital Cost**: **$7.5M**

SVC Implementation

→ Equipment Cost: $6.4M

→ Installation & Commissioning: $1.4M

→ Engineering & Design: $0.4M

→ **Total Capital Cost**: **$8.2M**

Combined TCSC + SVC

→ Equipment Cost: $12.2M

→ Installation & Commissioning: $2.6M

→ Engineering & Design: $0.9M

→ **Total Capital Cost**: **$15.7M**

These two types, commonly used in transmission, are TCSC ($7.5M) and SVC ($8.2M) in capital costs. The TCSC + SVC system at $15.7M is consistent with values typical of reports studying similar systems that have found costs between $5M to $15M. Also, a further study confirming that voltage stability improvement costs through power network studies are consistent with industry benchmarks [52].

--- ANNUAL OPERATIONS & MAINTENANCE COSTS ---

→ Maintenance & Component Replacement: $287,000

→ Operations Staff: $184,000

→ Insurance: $94,000

→ Facility/Infrastructure: $78,000

→ Training & Certification: $52,000

Annual operations and maintenance (O&M) costs are $695,000. They consist of $287,000 for maintenance and component replacement, $184,000 for operations staff, $94,000 for insurance, $78,000 for infrastructure, and $52,000 for training. This equates to 4.4% of the total capital cost (low recurring operational cost compared to initial investment cost). Hence, the system is economically sustainable for long-term operation and maintenance [68].

→ **Total Annual O&M Cost**: **$695,000**

→ O&M as % of Capital Cost: **4.4%**

--- QUANTIFIED BENEFITS (ANNUAL + NPV) ---

→ Energy Loss Reduction: $840,000/year → NPV: $11.2M

→ Capacity Deferral Benefit: $1.2M/year → NPV: $16.0M

→ Reliability Improvement: $2.6M/year → NPV: $34.7M

→ Power Quality Benefit: $450,000/year → NPV: $6.0M

→ Environmental Benefit: $180,000/year → NPV: $2.4M

→ **Total Annual Benefit**: **$5.27M**

→ **Total 20-Year NPV**: **$70.3M**

Annual Operations and Maintenance (O&M) costs of $695,000 or 4.4% of capital cost is affordable ongoing costs for the system. This includes the quantified benefits of $5.27M per year and a $70.3M total 20-yr NPV. The implication is that the long-term benefits of TCSC and SVC include reliability, energy, and environmental benefits. The economic attractiveness and high NPV of the system show that it is a viable and sustainable investment for both power systems, likely facilitating wider acceptance in other areas that also confront similar voltage instability concerns.

--- FINANCIAL PERFORMANCE METRICS ---

→ Net Present Value (NPV): **$54.6M** (Benchmark > $0 → Excellent)

→ Internal Rate of Return (IRR): **32.4%** (Benchmark > 12% → Excellent)

→ Payback Period: **7.2 years** (Benchmark < 10 years → Good)

→ Benefit-Cost Ratio (BCR): **4.48** (Benchmark > 1.5 → Excellent)

→ Profitability Index: **3.48** (Benchmark > 1.0 → Excellent)

Financial performance metrics are outstanding because NPV is $54.6M, IRR is 32.4%, Payback Period is 7.2 years, BCR is 4.48, and Profitability Index is 3.48 (excellent). Such numbers show an investment that is very lucrative and has a fast payback. While the financial success indicates it is a winning investment due to the quick payback and high return rate, it looks like a good option for future power stabilization endeavors [61].

--- SENSITIVITY ANALYSIS ---

→ **Capital Cost Variation ±20%** → NPV Range: **$51.7M – $57.5M**

→ **Energy Price ±20%** → NPV Range: **$49.8M – $59.4M**

→ **Reliability Benefit ±20%** → NPV Range: **$47.8M – $61.4M**

→ **Discount Rate ±20%** (6.4%–9.6%) → NPV Range: **$48.2M – $62.1M**

Assessment: Financial viability remains strong under all variations, confirming robust investment performance.

This sensitivity analysis says NPV remains robust with variation in a number of key parameters: Capital Cost Variation ±20% leads to a range of $51.7M to $57.5M, Energy Price ±20% results in $49.8M to $59.4M, Reliability Benefit ±20% yields $47.8M to $61.4M, and Discount Rate ±20% finds $48.2M to $62.1M. The resiliency of the NPV under these variations indicates that the investment remains financially attractive and robust to the changes, providing confidence to stakeholders that key value drivers only increase the return on investment in catalytic ways.

Test 12: Environmental Impact Analysis

--- 4.9.1 Emissions Reduction Analysis ---

The implementation of FACTS devices, specifically TCSC and SVC systems, contributes significantly to environmental sustainability by reducing energy losses and improving operational efficiency across the Nairobi 66 kV distribution network.

Annual emission reductions are as follows:

Emission Type	**Reduction (tonnes/year)**	**Monetary Value (USD)**	**Calculation Basis**
CO_2	1,847	$110,820	Loss reduction × emission factor
SO_2	8.2	$24,600	Based on thermal generation mix
NO_x	5.4	$27,000	Environmental damage cost estimation
Particulates	1.3	$17,550	Health impact valuation

Table 3 Emission Reduction Analysis

Total Environmental Value (Annual): $179,970

These values represent significant environmental externalities avoided annually. They are not only financially relevant but also support national and global sustainability goals related to air quality and public health.

Use of FACTS devices, specifically TCSC and SVC systems, yields significant environmental advantages by mitigating energy consumption losses and improving the overall operational efficiency of the Nairobi 66 kV distribution network. Substantial reductions in virtually all harmful emissions are achieved, leading to environmental sustainability [64].

The emissions reductions per year comprise 1,847 tonnes of CO_2, leading to a value of $110,820 based on energy loss reductions. Decreases in SO_2 emissions of 8.2 tonnes

($24,600) as determined according to the thermal generation mix. NO_x emissions (5.4 tonnes reduced, valued at $27,000, derived from damage costs for environmental and human-health damage). Also, particulate matter is reduced by 1.3 tonnes, valued at $17,550 based on health impact valuation.

This translates into a total value of $179,970 per year in air quality improvements and public health benefits. Such reductions yield not just cost savings, but also further national and international sustainability goals by reducing the environmental and health threats posed by pollution [55].

--- 4.9.2 Lifecycle Environmental Assessment ---

A comparative lifecycle analysis was performed to evaluate the environmental impact of FACTS implementation relative to conventional network expansion methods (e.g., new lines and transformers). The results are summarized below:

Impact Category	**Conventional Expansion**	**FACTS Implementation**	**Improvement**
Land Use (hectares)	12.4	0.8	93.5% reduction
Material Consumption (tonnes)	847	156	81.6% reduction
Construction Emissions (tCO_2 eq.)	2,340	420	82.1% reduction
Visual Impact	High	Low	Significant improvement
Noise Pollution	Moderate	Minimal	Substantial reduction

Table 4 Environmental Assessment

The FACTS-based approach delivers **superior environmental performance**, reducing land use and construction emissions while minimizing visual and acoustic disruption to surrounding communities.

FACTS deployment not only enhances the technical and economic performance of the Nairobi network but also yields substantial environmental benefits. Emissions reductions (CO_2, SO_2, NO_x, PM), lower material intensity, reduced land occupation, and minimized pollution make it a sustainable alternative to traditional grid expansion. These results strongly support FACTS as the environmentally preferred option in modernizing urban energy systems.

The lifecycle environmental assessment is focused on comparing the environmental impact while installing FACTS devices (TCSC and SVC) with traditional network expansion techniques (new line and transformer). As evident from the results, the FACTS approach obviously possesses the most environmental benefits.

Land usage is cut down by 93.5%, finally requiring only 0.8 hectares versus the 12.4 hectares needed for traditional expansion with FACTS. In the same way, there is an 81.6% reduction in the consumption of materials since only 156 tonnes are required for FACTS and 847 tonnes for conventional processes. Construction emissions have also dropped significantly, with FACTS generating 82.1% less CO_2 equivalent (420 tCO_2 eq.) with respect to the 2,340 tCO_2 eq. from conventional expansion.

The improvement of FACTS is significant as the traditional methods have high visual disruption, while FACTS results in lower visual impact. Similarly, the noise pollution is at an intermediate level with the conventional expansion, and at a minor level with the FACTS deployment.

This clearly highlights the better environmental performance of the FACTS over the conventional solutions. Due to the small land acquisition requirements, less resource consumption, emissions, and pollution, FACTS is a sustainable and more environmentally friendly solution than conventional methods of grid expansion, assisting with being a desirable solution option for the modernization of urban energy systems, such as that in Nairobi.

REFERENCES

[1] E.Acha, modeling and simulationin power networks: Advances in intergrated energy systems design, control and optimization., Chishester: Wiley, 2017.

[2] Y. Bai C, "On voltage stability monitoring with voltage instability predictors," *IREP Symposium Bulk Power System Dynamics and Control IX Optimization* , pp. 1-8, 2013.

[3] R. Bahmanyar, "Power system voltage stability monitoring using artificial neural networks with a reduced set of inputs," *International Journal of Electrical & Power Energy Syestems* , vol. 1, pp. 246-256, 2014.

[4] F. Aolaritei, "Hierarchcal and Dsitributed Monitorng of voltage stabilty in distribution networks," *IEEE Power Transmission Systems,* vol. 6, pp. 6705-6714, 2018.

[5] B. Chakrabarti S., "On-line voltage stability monitoring using artificial neural network," *Large Engineering Syste Conference of Power* , pp. 71-75, 2014.

[6] N. Hu, "Measurement-based real-time voltage stability monitoring for load areas.," *IEEE Transactions on Power Systems,*, vol. 4, pp. 2787-2798, 2015.

[7] S. Dasgupta, "Real-time monitoring of short-term voltage stability using PMU data," *IEEE Transactions on Power Systems,* vol. 4, pp. 3702-3711, 2013.

[8] H. Kamel, "Development and application of a new voltage stability index for on-line monitoring and shedding.," *IEEE Transactions on power systems,* vol. 2, pp. 1231-1241, 2017.

[9] F. O. Ochieng, "KenGen Reports 14.8 Billion Pre-Tax Profit in its Full Year 2021 Financial Results," Nov. 20, 2021. https://www.kengen.co.ke/index.php/information-center/news-and-events/kengen-reports-14-8-billion-pre-tax-profit-in-its-full-year-2021-financial-results.html#:~:text=Today%2C%20KenGen%20PLC%20has%20an,%2C%20-and%20Wind%20(26MW). (accessed Aug. 02, 2022).

[10] W.Mwangi, "A comprehensive review of the voltage stability indices," *Renewable and Sustainable Energy Reviews,* vol. 4, pp. 1-12, 2016.

[11] B. Kashem, "On-line network reconfiguration for enhancement of voltage stability in distribution systems using artificial neural networks.," *Electric power components and systems,* , vol. 4, pp. 361-373, 2011.

[12] P. Kundur, *Power System Stability and Control*, McGraw-Hill, New York, NY, USA, 2007

[13] IEEE/CIGRE Joint Task Force on Stability Terms and Definitions, “Definition and classification of power system stability,” *IEEE Transactions on Power Systems*, vol. 19, no. 2, pp. 1387–1401, 2004.

[14] Noorollahi, Y., Shabbir, M.S., Siddiqi, A.F., Ilyashenko, L.K. and Ahmadi, E., 2019. Review of two-decade geothermal energy development in Iran, benefits, challenges, and future policy. *Geothermics*, *77*, pp.257-266.

[15] M. Youjie, L. Shaofeng, Z. Xuesong, and G. Zhiqiang, “Review analysis of voltage stability in power system,” in *Proceedings of the IEEE International Conference on Mechatronics and Automations*, Takamatsu, Japan, August 2017.

[16] J. Patino, C. A. Ramires, and J. Espinoza, “Modal analysis for power system benchmark with topographical changes,” *Communications in Computer and Information Science*, vol. 1052, 2019.

[17] M.La Scala, "A neural network-based method for voltage security monitoring.," *IEEE Transactions on Power Systems*, vol. 5, pp. 1332-1341, 2016.

[18] O.Pérez-Londoño, "A simplified voltage stability index (SVSI).," *International Journal of Electrical Power & Energy Systems,* vol. 5, pp. 806-813, 2014.

[19] R. Phadke, "A new technique for on-line monitoring of voltage stability margin using local signals.," *In Fifteenth National Power Systems Conference* , vol. 1, pp. 488-492, 2018.

[20] F. Popović, "Monitoring and assessment of voltage stability margins using artificial neural networks with a reduced input set.," *IEE Proceedings-Generation, Transmission and Distribution, ,* vol. 1, pp. 355-362, 2018.

[21] S. Sahari, "Development of artificial neural network for voltage stability monitoring.," *In Proceedings. National Power Engineering Conference,* vol. 3, pp. 37-42, 2018.

[22] G. C. &. S. R. H. R. Swetha, "Voltage stability assessment in power network using artificial neural network.," *International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering,*, vol. 3, p. 3, 2014.

[23] Y. P. I. R. L. W. X. W. C. T. V. E. &. G. J. Wang, "Voltage stability monitoring based on the concept of coupled single-port circuit.," *IEEE Transactions on Power Systems,*, vol. 4, pp. 2154-2163, 2017.

[24] D. Zhou, "Online monitoring of voltage stability margin using an artificial neural network.," *IEEE Transactions on Power Systems*, vol. 3, pp. 1566-1574, 2017.

[25] M. Eremia, Handbook of Electrical Power System Dynamics: *Modeling, Stability, and Control*., 2013.

[26] Li, Intelligent Computing for Sustainable Energy and Environment: *Second International Conference*, ICSEE 2012, Shanghai, China, September 12-13, 2012, Revised Selected Papers. Berlin, Heidelberg: : Springer Berlin Heidelberg., 2013.

[27] M. Ombuki, R. Orenge, and J. Ndirangu, "Static Voltage Stability Assessment of the Kenyan Power Network," *Journal of Electrical and Computer Engineering*, 2021, DOI: 10.1155/2021/5079607.

[28] S. A. Oketch, C. M. Muriithi, and K. K. Kaberere, "Voltage Stability Analysis of Nairobi Area Power Distribution Network," *ResearchGate*, 2012.

[29] T. Hambissa and M. Ghandhari, "Modeling of Ethiopia-Kenya HVDC for Power System Stability Study," in *Proc. 16th IEEE AFRICON Conference*, 2023, DOI: 10.1109/AFRICON55910.2023.10293420.

[30] J. M. Kitheka, P. M. Moses, A. M. Nyete, and N. O. Abungu, "Voltage Profile Analysis of 132kV Transmission Line Using Powerworld Simulator: A Case Study of JUJA-RABAI Line," *Am. J. Elect. Power Energy Syst.*, vol. 11, no. 4, pp. 79-86, 2022, DOI: 10.11648/j.epes.20221104.12.

[31] U. U. Isong, N. Okpura, and T. P. Oritsetimeyin, "The IEEE 33 Bus Distribution System Load Flow Analysis Using Newton Raphson Method," *J. Multidiscip. Eng. Sci. Technol. (JMEST)*, vol. 10, no. 3, 2023, ISSN: 2458-9403.

[32] S. Panigrahi, Swarm, Evolutionary, and Memetic Computing: *4th International Conference, SEMCCO 2013*, Chennai, India: Cham: Imprint: Springer., 2013.

[33] P. Shandilya, *Novel advancements in electrical power planning and performance*., Oslo, 2020.

[34] W. IFAC Symposium on Power Plants and Power Systems Control, Power plants and power systems control 2006: *A proceedings volume from the IFAC Symposium on Power Plants and Power Systems Control, Kananaskis, Canada* : Oxford: Elsevier, 2017.

[35] S. In Chen, Materials Science and Engineering Application II: Selected, peer reviewed papers from the *2nd International Conference on Materials Science and Engineering Application*, Xi'an, China, 2015.

[36] N. Nanda, Emerging trends in power systems: : *proceedings of the Eighth National Power Systems Conference*, New Delhi : Allied Publishers., 2015.

[37] J. Sukma, *Testing of static synchronous series compensator (SSSC) model in IEEE 9 bus power system network using PSCAD and MATLAB software*, Kuantan: Pahang: UMP., 2016.

[38] J. Sun, *Energy engineering and environmental engineering*, 2013.

[39] S. M. International Conference on Renewable Energy and Environmental Technology, Renewable energy and environmental technology: Selected, peer reviewed papers from the 2013 *International Conference on Renewable Energy and Environmental Technology*, Jilin: China, 2013.

[40] P. Q. Generation, *Power Quality Issues in Distributed Generation*, Shenyang, Liaoning, China., 2016.

[41] C. In Zhou, Thermal, power and electrical engineering: Selected, peer reviewed papers from the 2013 *2nd International Conference on Energy and Environmental Protection*, Guilin, China., 2013.

[42] G.Rajendar, Basavaraj Bankara, "A Novel Algorithm for Capacitor Placement to improve Voltage Stability of Radial and Meshed Power System", *Journal of Information Engineering and Applications*, Vol.2, No. 11, 2012.

[43] D. P. Kothari and I. J. Nagrath, *Modern Power System Analysis*, Tata McGraw-Hill, , 2011.

[44] E. Jakobsen, "Performance Efficiency and Reliability Analysis of Offshore Wind Power Plants: Case Study of Utsira Nord," 2023. Accessed: Jul. 02, 2025. [Online]. Available: https://ntnuopen.ntnu.no/ntnu-xmlui/bitstream/handle/11250/3094252/no.ntnu:inspera:146046472:35294887.pdf?sequence=1

[45] Samson Ademola Adegoke and Y. Sun, "Power system optimization approach to mitigate voltage instability issues: A review," Cogent engineering, vol. 10, no. 1, Dec. 2022, doi: https://doi.org/10.1080/23311916.2022.2153416.

[46] A. Mohanty et al., "Power system resilience and strategies for a sustainable infrastructure: A review," Alexandria Engineering Journal, vol. 105, pp. 261–279, Oct. 2024, doi: https://doi.org/10.1016/j.aej.2024.06.092.

[47] K. Ullah, A. Basit, Z. Ullah, R. Asghar, S. Aslam, and Ayman Yafoz, "Line Overload Alleviations in Wind Energy Integrated Power Systems Using Automatic Generation Control," Sustainability, vol. 14, no. 19, pp. 11810–11810, Sep. 2022, doi: https://doi.org/10.3390/su141911810.

[48] De La Fuente Pinto, R, “Enhanced Current Limiting Strategy for Droop-Controlled Grid-Connected Inverters During LVRT,” 2025. Accessed: Jul. 02, 2025. [Online]. Available: https://ore.exeter.ac.uk/repository/bitstream/handle/10871/141130/PhD_Thesis_690030205.pdf?sequence=2

[49] H. Tariq et al., “Comparative Analysis of Reactive Power Compensation Devices in a Real Electric Substation,” Energies, vol. 15, no. 12, pp. 4453–4453, Jun. 2022, doi: https://doi.org/10.3390/en15124453.

[50] X. Liang, H. Chai, and J. Ravishankar, “Analytical Methods of Voltage Stability in Renewable Dominated Power Systems: A Review,” Electricity, vol. 3, no. 1, pp. 75–107, Mar. 2022, doi: https://doi.org/10.3390/electricity3010006.

[51] D. Stanelytė and V. Radziukynas, “Analysis of Voltage and Reactive Power Algorithms in Low Voltage Networks,” Energies, vol. 15, no. 5, p. 1843, Mar. 2022, doi: https://doi.org/10.3390/en15051843.

[52] H. Wang, M. Kraiczy, D. Mende, S. Stöcklein, and M. Braun, “Application-Oriented Reactive Power Management in German Distribution Systems Using Decentralized Energy Resources,” Energies, vol. 14, no. 16, p. 4949, Aug. 2021, doi: https://doi.org/10.3390/en14164949.

[53] A. A. Eladl, M. I. Basha, and A. A. ElDesouky, “Multi-objective-based reactive power planning and voltage stability enhancement using FACTS and capacitor banks,” Electrical Engineering, vol. 104, no. 5, pp. 3173–3196, Mar. 2022, doi: https://doi.org/10.1007/s00202-022-01542-3.

[54] A. Gautam, G. Sharma, M. Kumawat, and M. F. Ahmer, “A novel solution for the power transmission congestion of deregulated power system using TCSC and TLBO algorithm,” e-Prime - Advances in Electrical Engineering, Electronics and Energy, vol. 8, p. 100592, May 2024, doi: https://doi.org/10.1016/j.prime.2024.100592.

[55] Ismail Marouani et al., “Optimized FACTS Devices for Power System Enhancement: Applications and Solving Methods,” Sustainability, vol. 15, no. 12, pp. 9348–9348, Jun. 2023, doi: https://doi.org/10.3390/su15129348.

[56] Ntombenhle Mazibuko, K. T. Akindeji, and Katleho Moloi, “A Review on the Impact of Transmission Line Compensation and RES Integration on Protection Schemes,” Energies, vol. 17, no. 14, pp. 3433–3433, Jul. 2024, doi: https://doi.org/10.3390/en17143433.

[57] A. N. Khan et al., “Ensuring Reliable Operation of Electricity Grid by Placement of FACTS Devices for Developing Countries,” Energies, vol. 14, no. 8, p. 2283, Apr. 2021, doi: https://doi.org/10.3390/en14082283.

[58] A. S. Akinyemi, K. Musasa, and I. E. Davidson, “Analysis of voltage rise phenomena in electrical power network with high concentration of renewable distributed generations,” Scientific Reports, vol. 12, no. 1, p. 7815, May 2022, doi: https://doi.org/10.1038/s41598-022-11765-w.

[59] B. Beszédes, K. Széll, and G. Györök, “Redundant Photo-Voltaic Power Cell in a Highly Reliable System,” Electronics, vol. 10, no. 11, p. 1253, May 2021, doi: https://doi.org/10.3390/electronics10111253.

[60] V. Powar and R. Singh, “End-to-End Direct-Current-Based Extreme Fast Electric Vehicle Charging Infrastructure Using Lithium-Ion Battery Storage,” Batteries, vol. 9, no. 3, p. 169, Mar. 2023, doi: https://doi.org/10.3390/batteries9030169.

[61] T Sucita, Y Mulyadi, and W. S. Saputra, “Load Shedding Analysis Because of Contingency Damage (N-2) at Transmission Lines 150 kV Subsystem Cirata,” IOP Conference Series Materials Science and Engineering, vol. 384, no. 1, pp. 012076–012076, Jul. 2018, doi: https://doi.org/10.1088/1757-899x/384/1/012076.

[62] Ramavojjala Sumalatha, B. Venkat, Chenna Venkata Narasimhulu, and Kadam Keerthi, “Voltage profile improvement in power system using an interline power flow controller and cuttlefish algorithm,” AIP conference proceedings, vol. 3281, no. 1, pp. 040007–040007, Jan. 2025, doi: https://doi.org/10.1063/5.0248170.

[63] N. Sant and V. K. Sharma, “Modelling and Simulation of Facts Devices (TCSC and SVC) for A 11 Bus Power System,” International Journal of Trend in Scientific Research and Development, vol. Volume-6, no. Issue-5, Jul. 2022, Accessed: Jul. 02, 2025. [Online]. Available: https://www.ijtsrd.com/engineering/mechanical-engineering/50395/modelling-and-simulation-of-facts-devices-tcsc-and-svc-for-a-11-bus-power-system/vinit-k-sharma

[64] R. K. Singh and N. K. Singh, “Power system transient stability improvement with FACTS controllers using SSSC-based controller,” Sustainable Energy Technologies and Assessments, vol. 53, no. 1, p. 102664, Oct. 2022, doi: https://doi.org/10.1016/j.seta.2022.102664.

[65] J. Usman, M. W. Mustafa, and G. Aliyu, “Coordination of PSS and Facts Devices for Power System Stability Enhancement: A Comprehensive Review,” Book Publisher

International (a part of SCIENCEDOMAIN International), vol. 8, no. 1, pp. 30–40, May 2021, doi: https://doi.org/10.9734/bpi/aaer/v8/8131d.

[66] Mutegi Mbae and Nnamdi Nwulu, "Impact of hybrid FACTS devices on the stability of the Kenyan power system," International Journal of Power Electronics and Drive Systems/International Journal of Electrical and Computer Engineering, vol. 12, no. 1, pp. 12–12, Feb. 2022, doi: https://doi.org/10.11591/ijece.v12i1.pp12-21.

[67] C. P. Ohanu, U. C. Ogbuefi, and E. Ejiogu, "Transient stability improvement of a transmission system through the application of an artificial neural network-based high-voltage direct current system," Energy Exploration & Exploitation, vol. 1, no. 1, Mar. 2025, doi: https://doi.org/10.1177/01445987251327693.

[68] H. Ebrahimi, A. Yazdaninejadi, and S. Golshannavaz, "Transient stability enhancement in multiple-microgrid networks by cloud energy storage system alongside considering protection system limitations," IET Generation, Transmission & Distribution, vol. 17, no. 8, pp. 1816–1826, Jul. 2022, doi: https://doi.org/10.1049/gtd2.12539.

APPENDIX A: BUDGET

This table presents the budget of the proposed research study.

Table 4.1 Budget

S/NO.	**ITEM**	**DESCRIPTION**	**QUANTITY**	**UNIT PRICE**	**TOTAL COST**
1	Stationery	Printing Papers	15	500	**1000**
		USB Flash Disk (8GB)	1	2500	**2000**
		Spiral Binders	15	25	**500**
		Rules Papers	4	250	1000
2	Data Analysis and Design Software	**MATLAB**	1	50,000	50,000
3	Laptop	Hp Folio 9470 Ci 7, 1TB, 8Gb RAM, 2.8 GHz	1	55,000	50,000
4	Conference	Conference Attendance	2	20,000	40,000
		SUBTOTAL			**104,375**
S/NO.	**ITEM**	**DESCRIPTION**	**QUANTITY**	**UNIT PRICE**	**TOTAL COST**
1	**Publication of papers in international Journals**	**Elsevier**	1	25,800	25,800
		Springer Link	1	32,900	32,900
		IEEE	1	Free	-
2	**Thesis**	**Hardcover Thesis Binding**	10	2000	20,000

	Binding				
		SUBTOTAL			**78,700**
		STATIONERY			**104,000**
		CONTIGENCIES			**3,000**
		GRAND TOTAL			**185,700**

APPENDIX B: WORK SCHEDULE

This table presents the proposed work schedules.

Table 4.2 Time Plan

	Months										
S/NO.	**ACTIVITY**	**July 2022 Wk 3**	**July 2022 Wk 4**	**Oct 2022 Wk 2-3**	**Aug 2024 Wk 3-4**	**Sept 2024 Wk 1-4**	**Oct 2024 Wk 1-4**	**Nov 2024 Wk 1-4**	**Dec 2024 Wk 1-4**	**Jan 2025 Wk 1-4**	**Feb 2025 Wk 1-4**
1	Concept Paper Development										
2	Proposal Development and Defense										
3	Material Acquisition										
4	Data Acquisition										
5	Analysis of Data										
6	Report										

	Compilation										
7	First Publication										
8	Second Publication										
9	Final Publication										
10	Thesis Preparation and presentation										

APPENDIX B: TOOLS & INSTRUMENTS

The tools used in this research are

1. Data Analysis Software: MATLAB and Simulink
2. Simulation Tools: IEEE 30 BUS and Nairobi region distribution grid schematic diagram
3. Instruments: Computer