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ACE-ESD AFRICAN CENTER OF EXCELLENCE IN ENERGY FOR SUSTAINABLE DEVELOPMENT

TITLE: OPTIMAL PLACEMENT OF STATIC VAR COMPENSATORS (SVC$_S$) FOR VOLTAGE PROFILE IMPROVEMENT IN 220KV NETWORK OF RWANDA

Dissertation Number:

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MASTER OF SCIENCE IN ELECTRICAL POWER SYSTEM

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I. ABSTRACT

A 220KV Transmission Line network in Rwanda have a problem of high voltage drop due to long distance from one Substation to another, high loading of substation and few reactive power control that Levels lead to decrease of efficiency and stability of electrical Power System.

To improve voltage stability and efficiency of Rwanda's 220kV transmission network there is a need of Flexible AC Transmission System (FACTS) Devices. Stability in Power system are crucial for ensuring a reliable electricity supply in response to growing demand. Voltage instability and reactive power imbalance are significant challenges that can cause voltage drops, increased power losses, and potential system failures. FACTS Devices are widely recognized as effective solutions for enhancing voltage stability, improving power factors, and optimizing reactive power compensation.

For Voltage profile improvement on 220KV Transmission network in Rwanda, Static Var Compensators (SVCs) is proposed among other Flexible AC Transmission System (FACTS) Devices due to its Faster response on voltage fluctuations by injecting or absorbing reactive Power in network , reduce transmission Lines Losses by maintain voltage levels within optimal limits and SVCs are reliability proven in high voltage networks.

The aims of the optimal placement of SVCs within Rwanda's high-voltage network is to mitigate voltage fluctuations and enhance overall grid performance. Using advanced power system analysis tools, such as Newton-Raphson load flow analysis, sensitivity analysis, and optimization techniques like dig silent Power Factory, the most effective locations for SVC deployment are recognized.

The research findings indicate that optimal placement of SVCs at critical buses with high voltage drop within the 220kV network improves voltage profiles and reduces transmission losses. Simulation results show that optimized SVC placement leads to more stable voltage levels, better system reliability, and improved reactive power balance. Furthermore, SVCs implementation helps mitigate voltage collapse risks. This study provides valuable insights for Rwanda's power utilities and policymakers, supporting strategic grid reinforcement plans to accommodate future electricity demand growth. The proposed solution enhances grid stability and contributes to a sustainable and robust power infrastructure in Rwanda.

Key Words: Flexible AC Transmission System (FACTS) Devices; Static Var Compensators(SVCs); Efficiency, Dig silent power Factory software.

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III. NOMENCLATURE LIST

- SVC : Static Var Compensator
- GA – Genetic Algorithm
- PSO : Particle Swarm Optimization
- kV – Kilovolt
- MW – Megawatt
- MVAR – Megavolt-Ampere Reactive
- FACTS – Flexible AC Transmission Systems
- VPI – Voltage Profile Improvement
- RPF – Reactive Power Flow
- VSI – Voltage Stability Index
- OLTC – On-Load Tap Changer
- PF – Power Factor
- TCSC :Thyristor Controlled Series Capacitor
- IEEE – Institute of Electrical and Electronics Engineers
- NRLF – Newton-Raphson Load Flow
- TSO – Transmission System Operator
- STATCOM :Static Synchronous Compensator
- PSS/E – Power System Simulation for Engineering
- RURA – Rwanda Utilities Regulatory Authority
- REG Rwanda Energy Group
- EDCL Energy Development Corporation Limited

IV. LIST OF FIGURES

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V.APPROVAL AND CERTIFICATION

This thesis titled “OPTIMAL PLACEMENT OF STATIC VAR COMPENSATORS (SVC) FOR VOLTAGE PROFILE IMPROVEMENT IN 220KV NETWORK OF RWANDA”, submitted by Engineer Patrick RIMENYANDE, in partial fulfillment of the requirement for the degree of MASTER OF SCIENCE IN IN ELECTRICAL POWER SYSTEM at *the African Centre of Excellence in Energy for Sustainable Development* (ACE-ESD) Cohort 5, has been examined and approved by the undersigned.

We Certify that this work is the result of the candidate’s independent research efforts and meets the required academic and ethical standards.

Supervisor’s Names: A/Professor Kizito NKURIKIYEYEZU
Co-Supervisor’s Names : A/Professor JMV BIKORIMANA

VI. DECLARATION

I hereby declare that this thesis is my original work and has not been submitted for a degree at University of Rwanda or any other universities. All sources of materials used in this work have been properly acknowledged in light format.

Name of candidate: RIMENYANDE Patrick

Digitally signed
by Patrick
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Date:
2025.10.07
16:51:30 +02'00'

Signature

This thesis has been submitted for examination with my approval as a university advisor

A/Professor Kizito NKURIKIYEYEZU **Signature**

Dissertation Advisor

VII. ACKNOWLEDGEMENTS

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CHAPTER 1

1.0. INTRODUCTION

1.1. Background

With the loading increasing of existing power transmission systems, Voltage stability and the risk of voltage collapse have become significant challenges in power system planning and operation. The shift toward a deregulated power market has further contributed to the overloading of certain transmission corridors, increasing the strain on the network and raising concerns about system reliability. The application of Flexible AC Transmission System devices to ameliorate Power transmission also involves reactive power control/voltage stability issues. In everyday operation of power system, preventing "loss of voltage control", instability requires sitting additional capacitors or SVCs to maintain reactive reserves on generators, SVCs or synchronous condensers that otherwise exhaust reactive reserves and lose voltage control.[1]

Flexible AC transmission systems (FACTS) are important in decreasing system losses and voltage variations with maximizing transmission line loading. The best size and location determine how much these controllers can enhance transmission network performance. Moreover, FACTS devices are expensive, so optimal sizing is very important.[2] As a result, the required number and capacity of compensating devices used can reduce the overall cost of the system. However, determining optimal locations and sizes for these devices in massive electrical systems can be challenging because it is a highly nonconvex and nonlinear problem.[3]

Voltage stability and profile management in Rwanda are critical in ensuring reliable operation of electrical power systems, particularly in high voltage networks like the 220 kV network. Static Var Compensators (SVCs) and shunt Reactor must be installed to help stabilize the network from reactive Power.[4] will be used to enhance voltage stability by dynamically adjusting reactive power. The optimal placement of SVCs plays a crucial role in improving voltage profiles and system reliability. This research proposal aims to investigate the optimal placement of SVCs in a 220 kV network to achieve enhanced voltage profile management**.**

Modern power systems, besides classic generating units, consist of many renewables . There are also a lot of different devices based on power electronics, an example being Flexible Alternating Current Transmission System (FACTS) devices[5]. At the moment, FACTS devices are used as the most advanced reactive energy compensation devices . They are also used to solve various problems in the power system such as power system stability, power transfer capacity, voltage profile, power system efficiency, and so on. This paper, in general, deals with one of the most used types of FACTS devices, known as SVC devices (Static Var Compensator).[6]

1.2 Problem statement

The Power system in Rwanda a problem of high voltage deviation due to long distance of transmission Line and high loading that leads to decrease of stability and efficiency of electrical power System and some electrical equipment fail and resulted the blackout.[4]

The perfect location of Static Var Compensators (SVCs) is crucial for enhancing voltage stability and improving the voltage profile in a 220 kV network. In modern power systems, maintaining stable voltage levels is paramount to ensuring reliable operation and mitigating voltage deviations that can lead to equipment damage and operational inefficiencies. However, determining the strategic locations for SVC installation within the network remains a complex optimization problem due to the network's size, topology, and varying load conditions.

This research aims to address the following key challenges:

1. **Optimization of SVC Placement:** Developing algorithms and methodologies to identify the perfect locations for SVC connection in a 220 kV network to minimize voltage deviations and improve overall voltage profile.
2. **Impact of Network Topology:** Investigating how the network topology influences the effectiveness of SVC placement strategies, considering factors such as line impedance, load distribution, and generation patterns.
3. **Dynamic Load Conditions:** Assessing the dynamic response of SVCs under different load scenarios and developing adaptive control strategies to optimize their performance in real-time.

To determine the optimal locations for SVCs based on voltage stability, two methods are employed: modal analysis and the genetic algorithm. The results from both methods are shown to be similar; however, modal analysis alone cannot determine the optimal placement of SVCs, as their required sizes remain unknown. To address this limitation, the genetic algorithm is used to determine the appropriate SVC sizes. Additionally, to maximize the benefits of FACTS devices, the effectiveness of SVCs in damping inter-area oscillations (within the frequency range of 0.1–2 Hz) is analyzed, with the selection of proper control signals playing a crucial role.

1.3. Research Objectives

- **To assess the voltage drop profile of the existing 220 kV network**: This involves studying voltage variations and identifying critical nodes where voltage stability is a concern.
- **Find optimal placement of SVCs into 220kV** : Develop accurate models that represent the behavior and characteristics of SVCs, considering their impact on voltage stability and reactive power compensation.

- **To assess the impact of SVC placement on voltage profile improvement**: Evaluate the effectiveness of the proposed placement strategies through simulation studies and compare the results with baseline scenarios.

1.5 Scope And Limitations

It is essential to define what aspects the study will cover and what factors might constrain its conclusions. Here's a breakdown of scope and limitations of the research:

1.5.1 Scope

- ➢ Network Size and Configuration: The study will focus on a specific 220 kV network or a representative model. It will consider the network's topology, including the number and configuration of substations, transmission lines, and connection points.
- ➢ Optimization Algorithms: Research will involve developing or utilizing optimization algorithms to determine the optimal placement of SVCs. This could include heuristic methods, mathematical programming approaches, or machine learning techniques tailored to the problem.
- ➢ Impact Assessment: The study will assess the impact of SVC placement on voltage stability and profile improvement. It will analyze factors such as voltage deviations, stability margins, and reactive power flow dynamics.
- ➢ Dynamic Load Scenarios: Research will consider dynamic load scenarios to evaluate how SVCs perform under varying operational conditions. This includes peak demand periods, low-load conditions, and transient events.
- ➢ Control Strategies: The study may explore control strategies for SVCs to optimize their performance in real-time, including reactive power control algorithms and coordination with other network devices.

1.5.2 Limitations

- ➢ Geographic and Environmental Challenges: Rwanda's varied topography, including mountainous regions and remote areas, can affect the installation and maintenance of SVCs.
- ➢ Infrastructure Limitations: Rwandan power infrastructure, including transformers, Transmissions Line, Protection Equipment and substations, are outdated and insufficiently developed to support the integration of advanced equipment like SVCs.
- ➢ Data Availability and Accuracy: Limited availability and accuracy of network data, load profiles, and equipment specifications may restrict the precision of the optimization and analysis.
- ➢ Limited Network Interconnections: Weak or insufficient network interconnections can affect the effectiveness of SVCs, leading to underperformance performance

1.5.3 Dissertation Outline

- Introduction Provides background, problem statement, research objectives, questions, significance, and scope.
- Literature Review Covers power system stability, SVC functions, past studies on SVC placement, and research gaps.
- Methodology Explains research design, data collection, network modelling, optimization techniques, and evaluation metrics.
- Case Study: 220kV Network of Rwanda Analyses Rwanda’s power grid, voltage stability issues, load flow analysis, and SVC placement strategy.
- Results and Discussion Presents the impact of SVC placement on voltage profile, network stability, and comparative analysis of methods.
- Conclusion and Recommendations Summarizes key findings, contributions, practical recommendations, limitations, and future research directions.
- References

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

This chapter discussed on basic concepts of SVCs, advantages, Functionality, their types and Characteristic and area of application, reviews existing research on the optimal placement of SVCs, examining methodologies, case studies, and optimization techniques relevant to the 220kV network of Rwanda. The need for advanced voltage control strategies is increasingly important due to the growing electricity demand and integration of renewable energy sources in modern power systems.

In power Systems, the heavy loading conditions and energy disruption cause instability and voltage collapse. Fortunately ,the voltage at load buses can be regulated by SVC. with increment of reactive load, the susceptance of the SVC and the amount of reactive power provided from the SVC also increased automatically ,in order to keep balance of the reactive power in the network.[7]

Voltage stability is a key factor in power system operation, affecting system reliability and efficiency. Unstable voltage profiles can lead to voltage collapse, blackouts, and reduced power quality. The increasing demand for electricity in Rwanda necessitates advanced reactive power compensation solutions, such as SVCs, to maintain voltage levels and prevent system instability. Recent studies emphasize the role of FACTS devices in enhancing the robustness of power grids, particularly in developing economies where grid infrastructure is often constrained.

SVCs are flexible AC transmission system (FACTS) devices used to regulate voltage by dynamically adjusting reactive power. Their application enhances power transmission efficiency, minimizes voltage fluctuations, and improves overall system performance. Various studies have explored the role of SVCs in different network configurations, highlighting their advantages over traditional reactive power compensation techniques such as capacitor banks.

2.2 Functionality and Components of SVCs

Static Var compensator are shunt connected static generators absorbers whose outputs are varied so as to control voltage of the electric Power System's operate by dynamically controlling the reactive power injected into the system using thyristor-controlled reactors (TCR) and thyristor-switched capacitors (TSC). These components enable rapid response to voltage fluctuations, making SVCs more effective than fixed compensation methods also SVCs maintain stable voltage levels in high-voltage power systems, especially those with fluctuating loads or long transmission lines, by dynamically adjusting the balance of reactive power.

The SVC is connected to a coupling transformer that is connected directly to the ac bus whose voltage is to be regulated They can rapidly switch capacitors on and off or vary the current in an inductor to provide either inductive or capacitive reactive power, ensuring a smooth, continuous adjustment of the system's reactive power.[8]

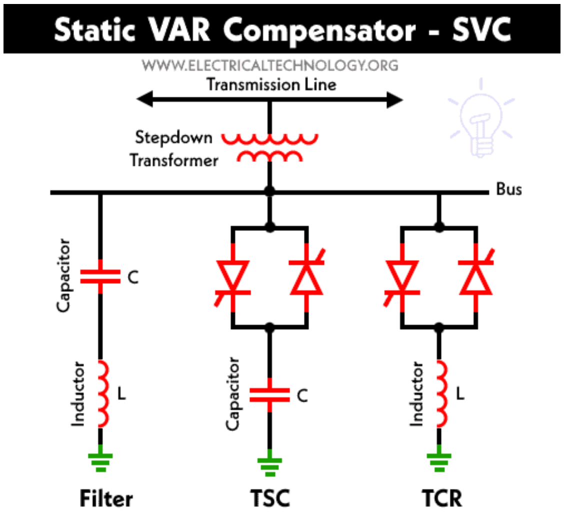


Figure 1:SVC Power Factor Correction

Figure 2:SVC Power Delivery Projects Grid Solutions

2.3 Advantages of SVCs

Static VAR Compensators (SVCs) can provide faster and efficient voltage regulation, making them essential for maintaining stability in power transmission networks. They are dynamically controlling reactive power, SVCs help in reducing voltage fluctuations and improving power factor, leading to a more stable and efficient system. also, they minimize transmission losses by injecting or absorbing reactive power locally, preventing excessive power flow through the transmission lines, which can cause inefficiencies and instability. Their ability to quickly respond to changes in system conditions makes them highly effective in enhancing the reliability of high-voltage networks.

Static Var Compensator (SVCs) also, improving power transfer capability and overall grid reliability. By optimizing voltage levels, they help avoid voltage collapse and enhance the dynamic stability of the system, ensuring a steady and uninterrupted power supply. SVCs also help in mitigating system disturbances such as flicker, harmonics, and unbalanced loads, which are common in high-demand areas compared to more advanced FACTS devices like the Unified Power Flow Controller (UPFC), SVCs are more cost-effective, require less maintenance, and can be easily integrated into existing transmission networks**,** making them a practical solution for improving voltage regulation in modern power systems

2.4 Review of Optimal SVC Placement Methodologies

2.4.1 Analytical Methods

Early research focused on analytical approaches for SVC placement, using load flow analysis to determine suitable locations. These methods provide fundamental insights but are limited in handling large-scale networks and complex constraints.

2.4.2 Optimization Techniques

There are some Technique proposed for optimal SVC placement in Power System:

- First method is modal analysis, which identifies weak buses based on the system's voltage stability margin. This method analyzes the participation factors of different buses in the critical modes of voltage instability, helping engineers determine potential locations for SVC deployment but does not determine the optimal size of the SVC, making it necessary to combine it with other techniques.

- Optimal power flow (OPF)-based placement, which integrates SVC placement within the broader optimization of the power system's operational parameters. OPF techniques use mathematical programming and artificial intelligence-based approaches to optimize voltage profiles while considering system constraints such as line limits, generator capabilities, and cost-effectiveness.

- Particle Swarm Optimization (PSO) Methods ,This methods consider multiple objectives, such as minimizing voltage deviations, reducing power losses, and improving overall system stability. By simulating various placement scenarios, these algorithms can identify the most effective locations and appropriate SVC sizes for voltage regulation. Additionally, **sensitivity analysis** is often applied to assess how different buses respond to reactive power compensation, further refining the placement strategy.
- Mixed-Integer Programming (MIP): A mathematical optimization technique used to determine the most cost-effective SVC placement while satisfying system constraints.

2.4.3 Machine Learning and AI in SVC Placement

Recent advancements in machine learning and artificial intelligence have introduced data-driven approaches to optimize SVC placement. These methods leverage historical data and predictive modelling to enhance decision-making processes.

2.5 Basic concepts

Static Var Compensators (SVCs) are crucial devices in modern power systems used to regulate voltage and improve voltage stability. They provide reactive power support to the network, which helps maintain voltage levels within acceptable limits. An SVC can quickly inject or absorb reactive power, which makes it an effective tool for addressing voltage fluctuations and enhancing overall system stability. It regulates voltage and stabilizes the system.[9]

Optimizing the placement of SVCs involves determining the most effective locations and capacities for SVC units to achieve desired voltage profile improvements. This process requires a balance between enhancing voltage stability and managing costs.

2.6 SIMILAR WORKS

Optimal Placement of FACTS Devices in Power Systems for Voltage Stability Improvement: This body of work delves into the strategic placement of Flexible AC Transmission System (FACTS) devices, including Static Var Compensators (SVCs), to bolster voltage stability within power systems. Researchers have employed various optimization algorithms such as Genetic Algorithms (GA) and Particle Swarm Optimization (PSO) to pinpoint the most effective locations for these devices. Detailed simulations of power networks form the crux of these studies, providing critical insights into the impact of FACTS devices on voltage profiles and overall system stability. This research is particularly relevant as it highlights methodologies and algorithms that could be directly applied to the optimal placement of SVCs in a 220KV network.

Dynamic Voltage Stability Enhancement Using SVC and STATCOM: A Comparative Study: This comparative study scrutinizes the performance of SVC and Static Synchronous Compensator (STATCOM) devices in enhancing dynamic voltage stability. By examining different scenarios and configurations within high-voltage networks, the research utilizes simulation tools to evaluate the effectiveness of each device. Additionally, it often incorporates cost-benefit analysis to substantiate the selection of one device over the other. The findings from this study underscore the advantages of SVCs in voltage stability improvement, providing comparative data that can be instrumental in justifying the focus on SVCs for the proposed research.[10]

Optimal SVC Placement Using Particle Swarm Optimization for Voltage Stability Enhancement in Power Systems: This research leverages Particle Swarm Optimization (PSO) to identify optimal locations for SVCs within power systems, with the primary goal of enhancing voltage stability and minimizing transmission losses. Through extensive simulations and case studies on various power networks, the study demonstrates the efficacy of PSO in solving the optimization challenge. This research is particularly pertinent as it offers a detailed example of employing PSO for optimal SVC placement, which can be adapted for the specific context of a 220KV network.[11]

Voltage Profile Improvement in Power Systems Using Genetic Algorithm-Based SVC Placement: This study explores the application of Genetic Algorithms (GA) to optimize SVC placement for voltage profile enhancement. It presents a comprehensive methodology that includes developing a fitness function, which considers factors like voltage stability, system losses, and investment costs. The research also features practical case studies and simulation results, making it highly relevant. This proven approach to using Genetic Algorithms for SVC placement can be tailored to meet the unique requirements of a 220KV network.[12]

Enhancing Voltage Stability in Power Systems Through Optimal Placement of SVC Using Differential Evolution Algorithm: This paper investigates the use of the Differential Evolution Algorithm (DEA) for the optimal placement of SVCs, focusing on voltage stability improvement and system loss reduction. The research includes a detailed description of the algorithm, simulation setups, and results from various test cases. This study introduces another optimization technique that could be considered for the proposed research, offering alternative methods and comparative results.

Several case studies have been conducted on optimal SVC placement:

- IEEE Test Systems: Many studies validate their methodologies using IEEE 14-bus, 30-bus, and 57-bus test systems. These test cases provide standardized benchmarks for evaluating optimization techniques.

- Regional Power Grids: Research on African power networks, including Kenya and South Africa, highlights unique challenges in SVC deployment, such as network constraints and economic considerations.
- Rwanda’s Power Network: Limited studies exist on SVC placement in Rwanda’s 220kV network, necessitating further research. The expansion of Rwanda's power grid and increasing reliance on renewable energy sources underscore the need for an optimized approach to reactive power compensation.

2.7 Summary of Previous Works and Their Gaps

Previous research on the optimal placement of FACTS devices, including Static Var Compensators (SVCs), has primarily focused on enhancing voltage stability and minimizing power losses within power systems. Studies have utilized various optimization algorithms, such as Genetic Algorithms (GA) and Particle Swarm Optimization (PSO), to determine the most effective locations for these devices. Comparative studies between SVCs and other devices like Static Synchronous Compensators (STATCOM) have highlighted the benefits of SVCs in dynamic voltage stability improvement, often backed by cost-benefit analyses.[13] Additionally, research employing Differential Evolution Algorithms (DEA) and Genetic Algorithms has demonstrated the potential of these methods in achieving optimal SVC placement, with practical case studies validating their efficacy. However, despite these advancements, several gaps remain. Many studies focus on theoretical models and simulations without extensive real-world application or validation in 220KV networks. The impact of network-specific characteristics, such as load variations and integration of renewable energy sources, is often underexplored. Moreover, comprehensive strategies that combine both placement and sizing of SVCs to maximize cost-effectiveness and system performance are relatively scarce. Addressing these gaps in the proposed research will provide a more holistic and practical approach to optimizing SVC placement in a 220KV network, enhancing both voltage stability and overall system reliability.

2.8. Justification for the Current Study

Existing research demonstrates various methodologies for SVC placement, yet there is a gap in literature focusing on Rwanda’s 220kV network. This study aims to address this gap by evaluating optimal placement techniques tailored to Rwanda’s power system. Additionally, the study will explore the cost-benefit analysis of implementing SVCs in Rwanda’s national grid.

2.9. Challenges in SVC Implementation

The Implementation of Static Var Compensator (SVC) in a 220kV Power System comes with many challenges like High initial cost is a major concern, as SVCs require significant investment in equipment, installation, and maintenance.

SVCs require complex system integration, as they must be properly coordinated with existing power grid components, protection schemes, and control systems to ensure smooth operation without causing instability.

Static Var Compensators (SVCs) generation of harmonics, that can affect to power quality . SVCs, particularly those using thyristor-controlled reactors (TCRs), can introduce harmonic distortions into the network, potentially affecting other connected equipment. To avoid those issues, additional filtering equipment are needed that increase complexity and cost at the same time.. Furthermore, space constraints can be an issue in urban areas due to lack of where land availability, making it difficult to install the necessary equipment.

Static Var Compensators require continuous monitoring and control to ensure the SVC operates efficiently and responds quickly to system disturbances. For long period of time, components are aging, especially the thyristors, capacitors, and reactors. This can impact reliability of power, necessitating regular maintenance and potential replacements. Apart from these challenges, SVCs is essential solution for improving voltage stability, reactive power management, and overall power system performance in high-voltage networks.

2.10. Conclusion on Literature Review

A thorough literature review indicates the significance of SVCs in voltage profile improvement. The integration of advanced optimization techniques will be instrumental in determining the optimal SVC placement for Rwanda's 220kV network. The findings from this study will contribute to the body of knowledge and provide practical recommendations for Rwanda's power infrastructure development. Future research should focus on integrating AI-based models for real-time voltage control and exploring cost-effective solutions for developing regions.

The review also highlights that the integration of SVCs must be tailored to the specific characteristics of the local power system. In the context of Rwanda, where the power infrastructure is rapidly expanding to meet growing demand, optimal deployment of SVCs can play a pivotal role in ensuring voltage stability and improving power quality. The existing literature underscores the importance of conducting load flow analyses and system simulations to identify weak buses and critical nodes in the network where SVC placement would yield maximum benefit.

In conclusion, the optimal placement of SVCs in Rwanda's 220kV network is not only feasible but essential for the sustainable development of the national grid. Leveraging modern optimization techniques and aligning with the unique grid conditions will ensure efficient use of SVC technology. Future research should focus on real-time data application, hybrid optimization methods, and integration of renewable energy sources to further enhance system performance and resilience

CHAPTER 3: RESEARCH METHODOLOGY

3.1. Introduction

This chapter outlines the methods, materials, and equipment used in the study to determine the optimal placement of Static Var Compensators (SVCs) for voltage profile improvement in the 220kV network of Rwanda. The methodologies employed ensure replicability and adherence to industry standards.

3.2. Research Approach

This study employs a combination of analytical modeling and optimization techniques to determine the most effective SVC placement. The methodology follows these key steps:

1. **Data Collection:** use Rwanda's 220kV transmission network data, including line impedances, bus voltage levels, load demands, Transmission line Length, Conductor size and generation capacities.
2. **Network Modeling:** Creating a simulation model of the power system using industry-standard software. Develop a single-line diagram of the network and model it in power system simulation software such as PSS/E, MATLAB/Simulink, or Dig SILENT Power Factory.
3. **Performance Evaluation and Validation:** Conduct post-installation power flow simulations to compare voltage profiles before and after SVC placement. Assess the impact of SVCs on system stability, transmission losses, and reactive power compensation. Validate the results against IEEE standard benchmarks and ensure compliance with Rwanda Utilities Regulatory Authority (RURA) grid codes**.**

3.3 Data Collection

The data required for this Project are sourced from:

- Rwanda Energy Group (REG) reports and grid operation data.
- IEEE test systems for validation purposes.
- Load flow and voltage stability reports from prior studies.

The data collected includes:

- Voltage profiles across different buses.
- Load demand of substation (Peak Load).
- Transmission line parameters, including, Length of transmission Line from substation to substation, Conductor size, impedance and reactance.

3.4 Network Modelling

The 220kV power network of Rwanda is modelled using Digsilent power Factory. Key aspects of the modelling process include:

- Representation of transmission lines, generators, transformers and loads.
- Implementation of load flow analysis using Newton-Raphson
- Incorporation of SVC models to assess their impact on voltage regulation.

4. Validation and Benchmarking

The results obtained from the study are validated against:

- IEEE 14-bus and 30-bus standard test systems.
- Previous research studies on FACTS device optimization.
- Industry recommendations for reactive power compensation.

Benchmarking ensures that the proposed methodology aligns with established industry standards and best practices.

5. Equipment and Software Used

The study relies on the following tools and software:

- **Dig silent power factory:** For conducting load flow analysis and evaluating voltage stability by integrating reactive power absorbers in model.
- **MATLAB Simulink:** Used for modeling and simulating the power system. Also used in production of graphs.
- **PSS/E (Power System Simulator for Engineers):** For validating system performance and stability.

The use of these tools ensures accuracy and reliability in the study’s findings.

6. Conclusion

This research methodology Guarantee a systematic and replicable approach to optimizing SVC placement. The integration of multiple optimization techniques enhances the accuracy and reliability of the findings, contributing valuable insights for Rwanda's power network improvement. The study's experimental procedures and validation steps ensure the applicability of the proposed optimization strategy in real-world scenarios. The results obtained will serve as a foundation for further research on FACTS devices in power systems.

Furthermore, the use of advanced optimization techniques, including Load flow Analysis, presents an opportunity for future enhancements in voltage stability analysis. By incorporating adaptive and real-time decision-making approaches, future studies can further refine the methodology to improve grid resilience and operational efficiency. The findings from this study can be extended to similar Power networks in other developing countries facing voltage stability challenges.

CHAPTER 4. RESULTS & SIMULATION

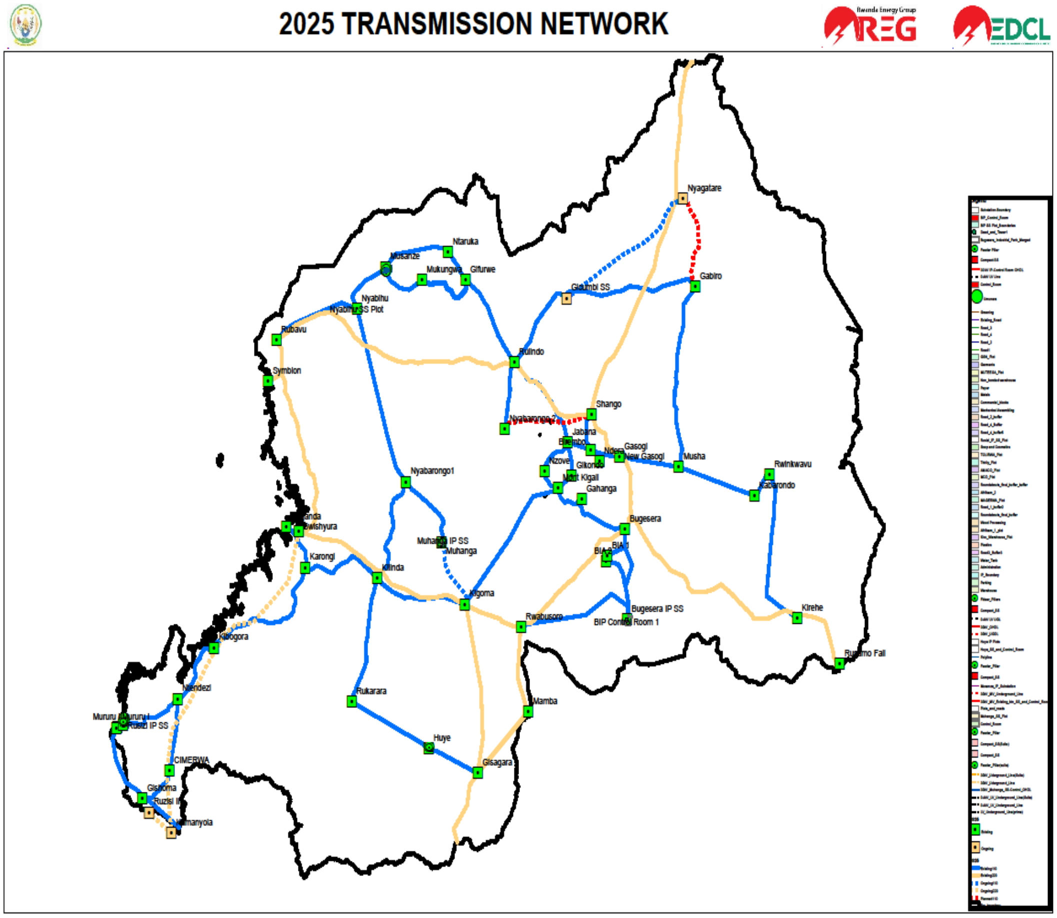
4.1 Data Used in Simulation

In this part ,the data that are used in simulation and design are categorized and summarized according to their types.

4.1.1 Rwandan Transmission Network 2025

The below Rwanda Electrical network map indicate existing 110KV and 220KV transmission Line, connected substations and extension needed in future . These data are used to construct a 220KV Transmission model.

Figure 3: Rwanda Transmission Network 2025[4]



4.1.2 High Voltage Transmission Length

Table 1. contains the Length data used to design and simulation of transmission with connected load for each substation.

Table 1: Existing transmission links[4]

No	Line kV	Description	Length_KM
1	110	Birembo-Gasogi	8.67
2	110	Birembo-Shango	9.59
3	110	Bugarama-Gishoma	12.27
4	110	Bugesera-Bugesera IP	23.10
5	110	Gabiro-Musha	45.96
6	110	Gahanga-Bugesera	17.31
7	110	Gasogi-Musha	17.48
8	110	Gifurwe-Mukungwa (Double Circuit)	18.46
9	110	Gikondo-MountKigali	5.22
10	110	Gikondo - Jabana I	8.36
11	110	Jabana I-Birembo	6.97
12	110	Jabana I-Jabana II	1.29
13	110	JabanaI-Rulindo	25.73
14	110	Kabarondo-Rwinkwavu	7.25
15	110	Karongi-Kibuye	12.41
16	110	Karongi -Kibogora	39.20
17	110	Kibogora-Ntendezi	18.46
18	110	Kibuye-KivuWatt	1.21
19	110	Kigoma-Kilinda	27.45
20	110	Kilinda-Karongi	25.11
21	110	Kilinda-Nyabarongo	27.85
22	110	Kilinda-Rukarara	31.29
23	220	Mamba-Rwabusoro	21.54
24	110	MontKigai-Kigoma	40.33
25	110	MontKigali-Gahanga	9.64
26	110	MontKigali-Jabana	17.25
27	110	Mururu II-Mururu I	0.37
28	110	Musha-Kabarondo	23.35
29	110	Ndera cut-In cut-out	2.14
30	110	Ntaruka-Gifurwe	8.51
31	110	Ntendezi-Bugarama	17.62
32	110	Ntendezi-Mururu II	20.89
33	220	Rubavu-Goma Border	7.01
34	220	Rubavu - Bwishyura/Kibuye	57.54
35	110	Rulindo-Gabiro	63.86
36	110	Rulindo-Gifurwe	24.93
37	220	Rwabusoro-Bugesera SS	40.64

No	Line kV	Description	Length_KM
38	220	Shango - Rubavu	106.11
39	220	Shango -Mirama(Up to Uganda Border)	92.01
40	110	Mukungwa-Nyabihu	28
41	220	Rusumo-Bugesera-Shango	117.651
42	220	Kigoma-Gisagara-Burundi Border	64
43	220	SPLK Evacuation Line	4.5

4.2. Rwandan 220 KV Network topology

This section, modelling the existing 220KV Transmission network, including all generation Plant, Substation and transmission line with existing data. The figure.4 below indicating all 220KV Transmission Line of all countrywide and connected substation.

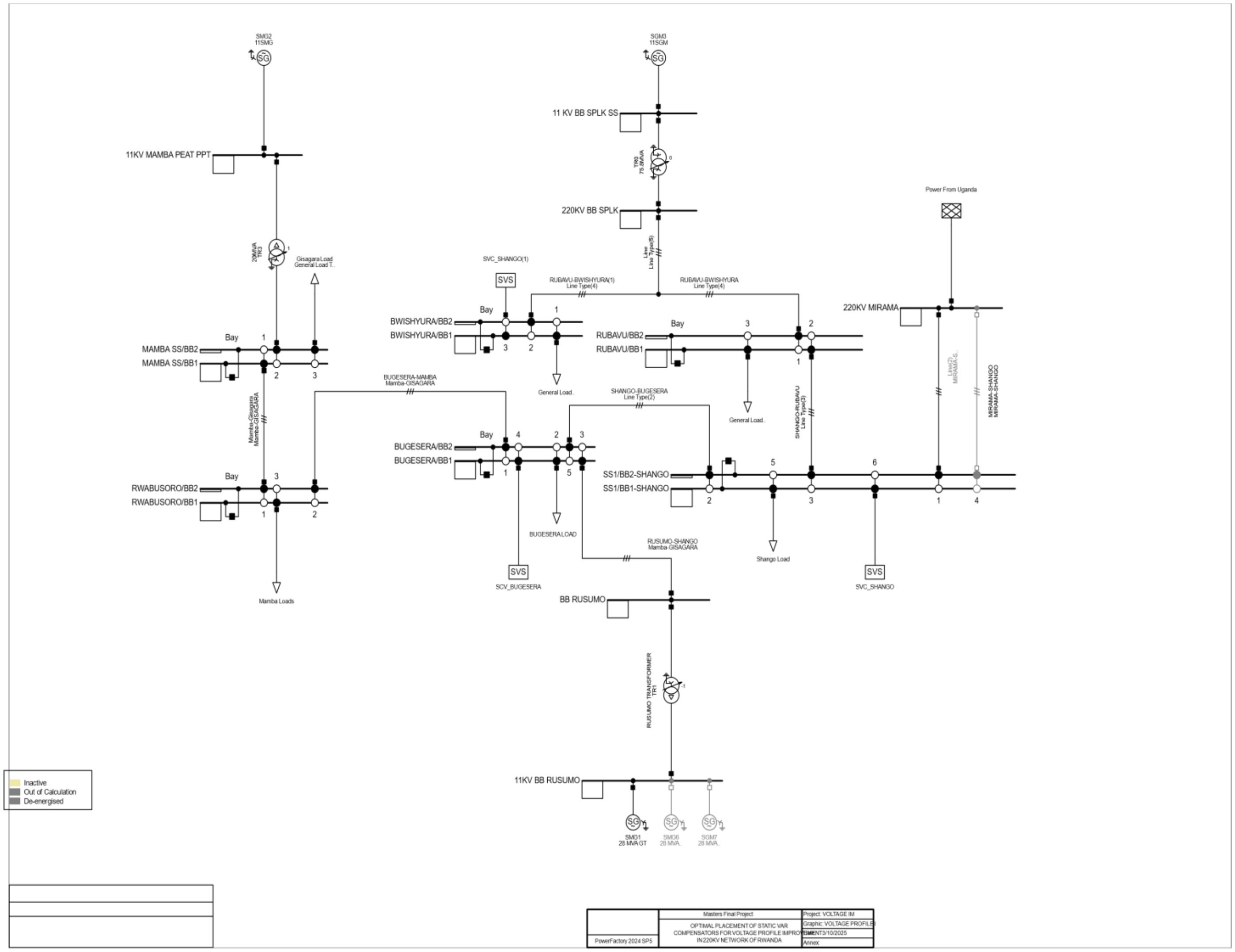


Figure 4: Rwandan 220KV Network topology

4.3. 220KV Transmission Modeling and Simulation.

To select the optimal location for a Static Var Compensator (SVC) in a 220kV network using an IEEE bus model, power engineers use optimization algorithms to identify the bus that, when equipped with an SVC, best improves voltage stability and reduces power losses. This process involves creating an objective function that balances objectives like voltage deviation reduction and power loss minimization then using methods like Particle Swarm Optimization (PSO) to find the best SVC location and size. Key steps include identifying weak buses, evaluating system performance under various contingencies, and simulating the SVC's impact on the network[14]

This section including the modelling and simulation of each transmission line and Substation with existing Characteristics such us, Conductors Size, Conductor characteristic , Line Impedance, 220KV Transmission Line length between two substation, Generation Capacity, Load connected to substation and Transformer size.

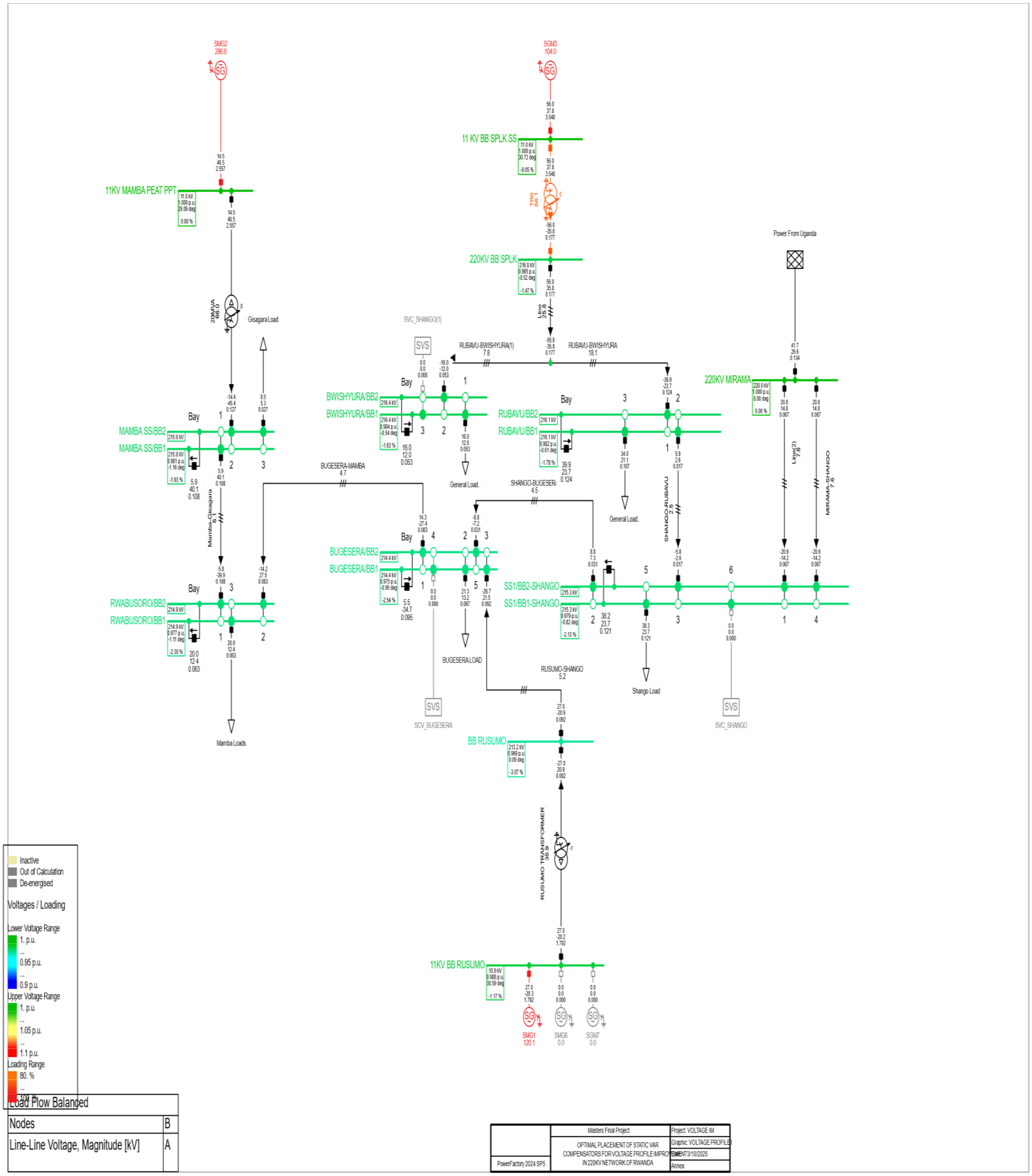


Figure 5:Modeling of Existing 220KV Transmission without SVC

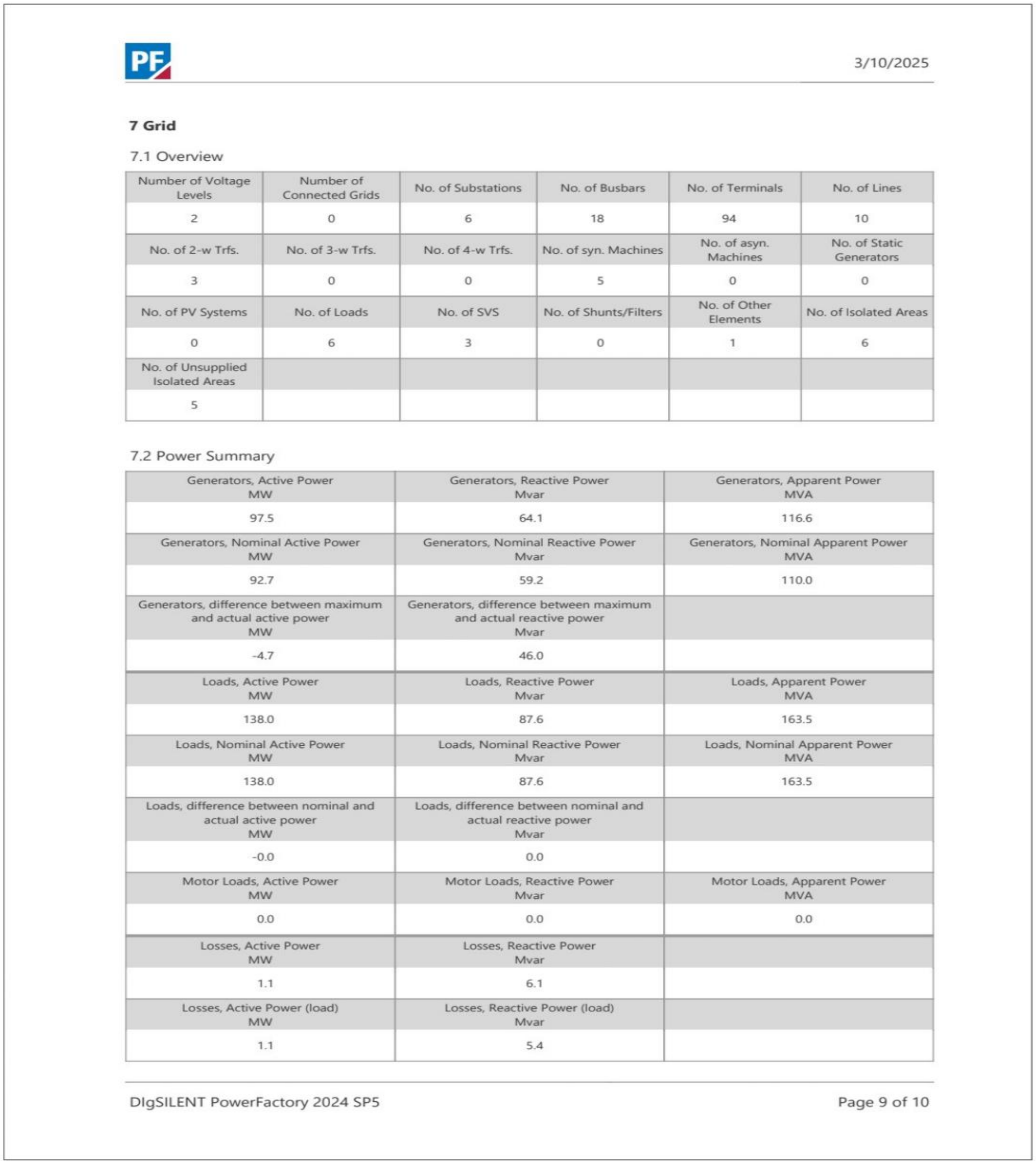
4.2.1. Voltage deviation in substation

In existing network there are Voltage deviation in many nodes due to long transmission Line, Line impedance and voltage drops due to resistance of conductors. The table below indicate each substation with voltage deviation. Table 2 summarized the voltage deviation level in each substation and percentage. Table 3 indicate the summary of Active and reactive Power losses with load and no load losses.

Table 2: Voltage deviation in Existing 220KV Switching Substation

No	SUBSTATION	Voltage Level	Voltage Deviation	Percentage Voltage deviation(%)
1	MIRAMA	220	0	0
2	SHANGO	215.3	4.7	2.1
3	BUGESERA	214.4	5.6	2.5
4	RWABUSORO	214.9	5.1	2.3
5	MAMBA	215	5	2.3
6	BWISHYURA	216.4	3.6	1.6
7	RUBAVU	216.1	3.9	1.8

Table 3:Grid Summary after simulation of 220KV Network without SVC



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7 Grid

7.1 Overview

Number of Voltage Levels	Number of Connected Grids	No. of Substations	No. of Busbars	No. of Terminals	No. of Lines
2	0	6	18	94	10
No. of 2-w Trfs.	No. of 3-w Trfs.	No. of 4-w Trfs.	No. of syn. Machines	No. of asyn. Machines	No. of Static Generators
3	0	0	5	0	0
No. of PV Systems	No. of Loads	No. of SVS	No. of Shunts/Filters	No. of Other Elements	No. of Isolated Areas
0	6	3	0	1	6
No. of Unsupplied Isolated Areas					
5					

7.2 Power Summary

Generators, Active Power MW	Generators, Reactive Power Mvar	Generators, Apparent Power MVA
97.5	64.1	116.6
Generators, Nominal Active Power MW	Generators, Nominal Reactive Power Mvar	Generators, Nominal Apparent Power MVA
92.7	59.2	110.0
Generators, difference between maximum and actual active power MW	Generators, difference between maximum and actual reactive power Mvar	
-4.7	46.0	
Loads, Active Power MW	Loads, Reactive Power Mvar	Loads, Apparent Power MVA
138.0	87.6	163.5
Loads, Nominal Active Power MW	Loads, Nominal Reactive Power Mvar	Loads, Nominal Apparent Power MVA
138.0	87.6	163.5
Loads, difference between nominal and actual active power MW	Loads, difference between nominal and actual reactive power Mvar	
-0.0	0.0	
Motor Loads, Active Power MW	Motor Loads, Reactive Power Mvar	Motor Loads, Apparent Power MVA
0.0	0.0	0.0
Losses, Active Power MW	Losses, Reactive Power Mvar	
1.1	6.1	
Losses, Active Power (load) MW	Losses, Reactive Power (load) Mvar	
1.1	5.4	

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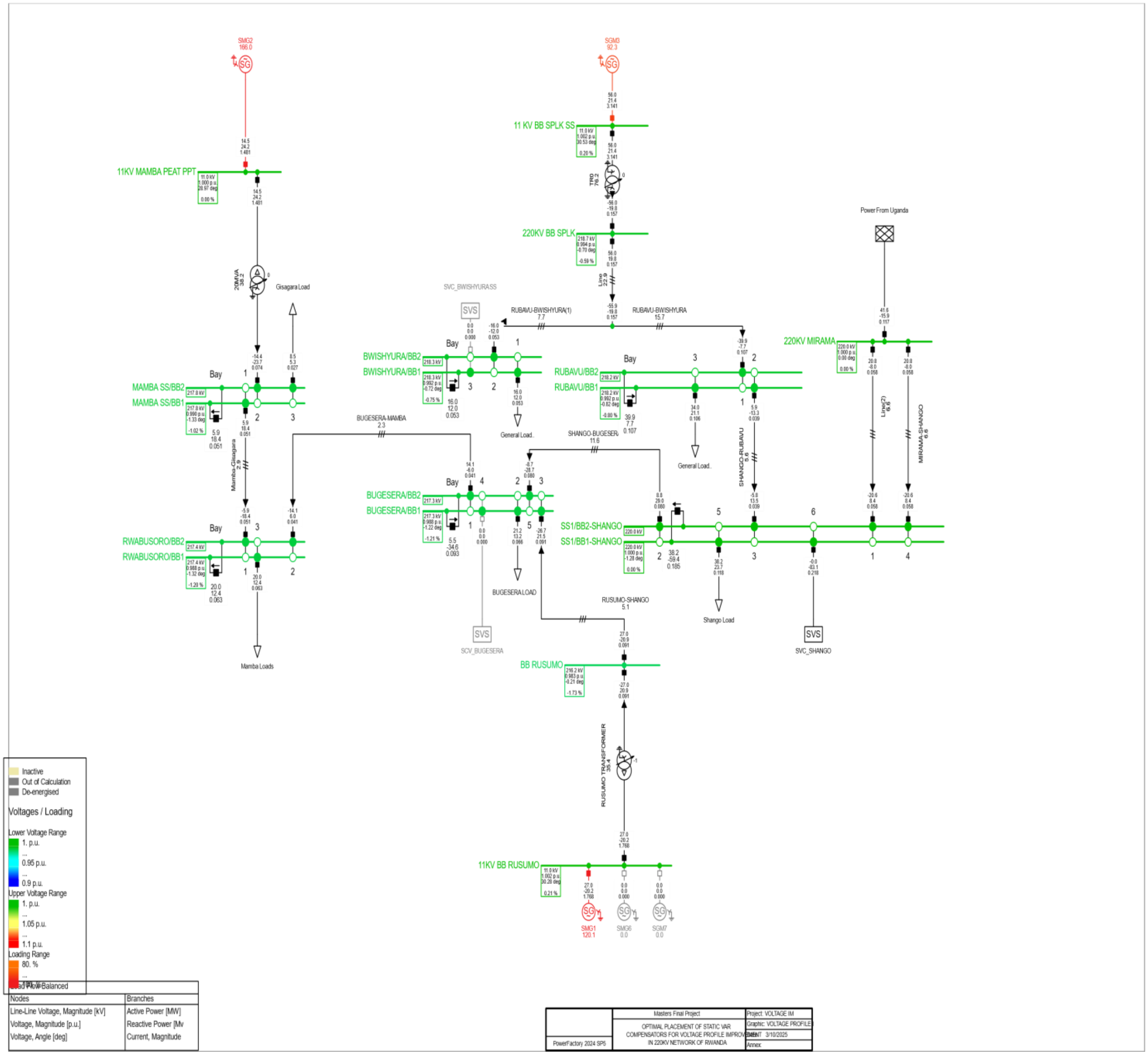
4.3. 220KV Transmission Modeling and Simulation with Static Var compensator installed

In this section, the existing 220KV network simulated by installing the Static Var Compensator on critical buses with High voltage deviation and checking the effect of SVCs in each substation

Figure 6:220KV Transmission Modelling and Simulation with SVC installed at SHANGO SS



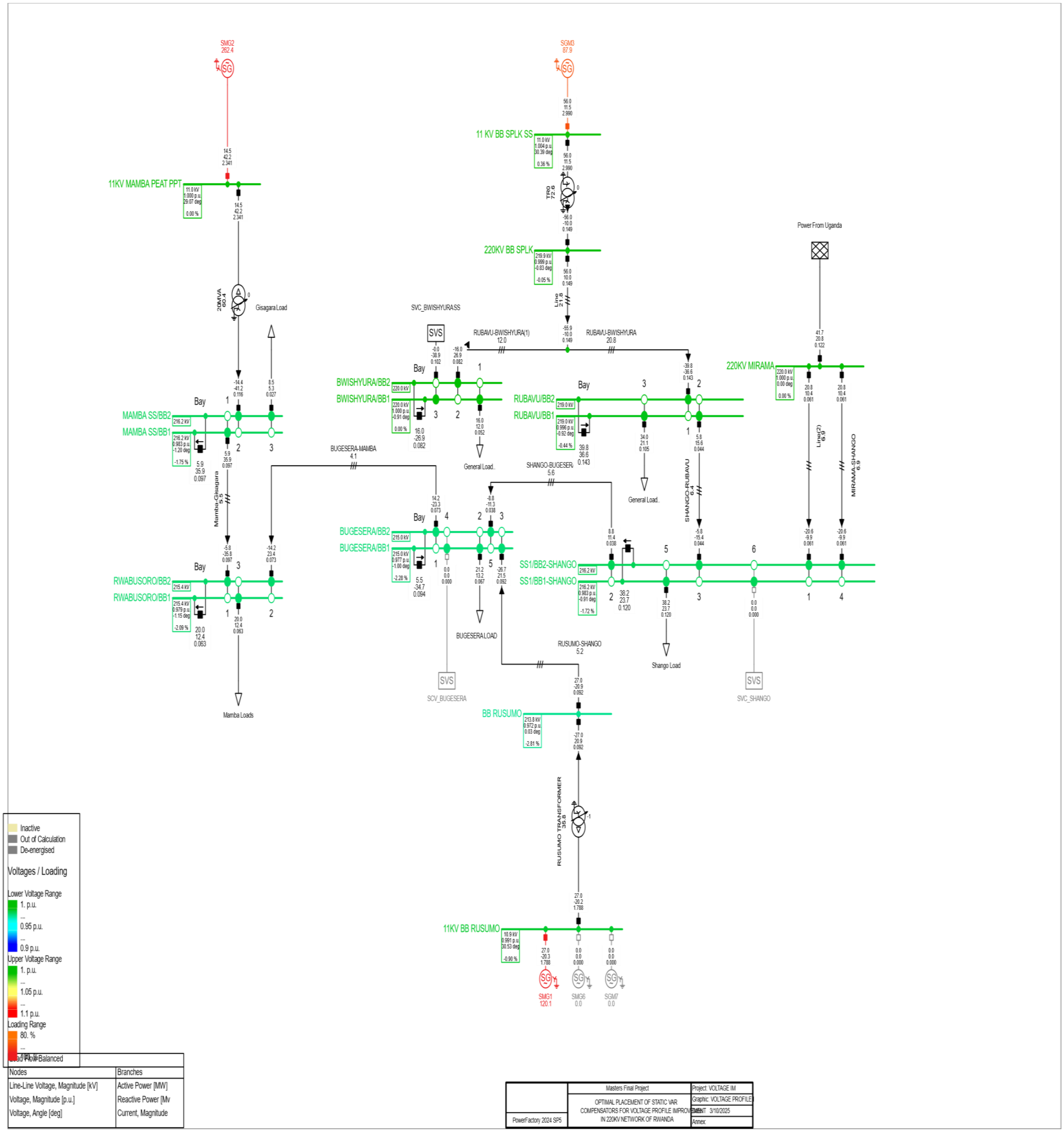


Figure 7:220KV Transmission Modelling and Simulation with SVC installed at BWISHYURA SS

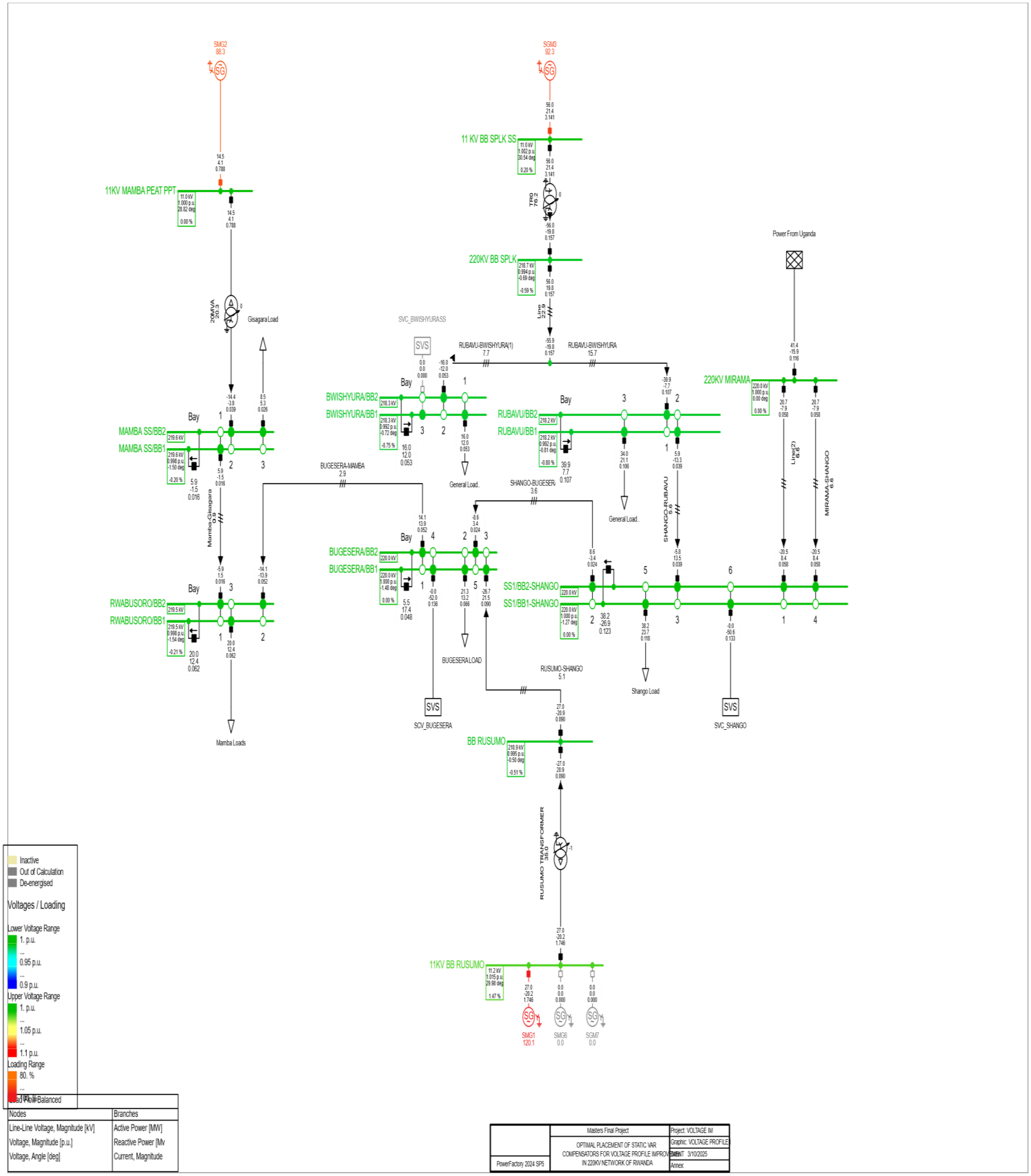


Figure 8:220KV Transmission Modelling and Simulation with SVC installed at SHANGO&BUGESERA SS

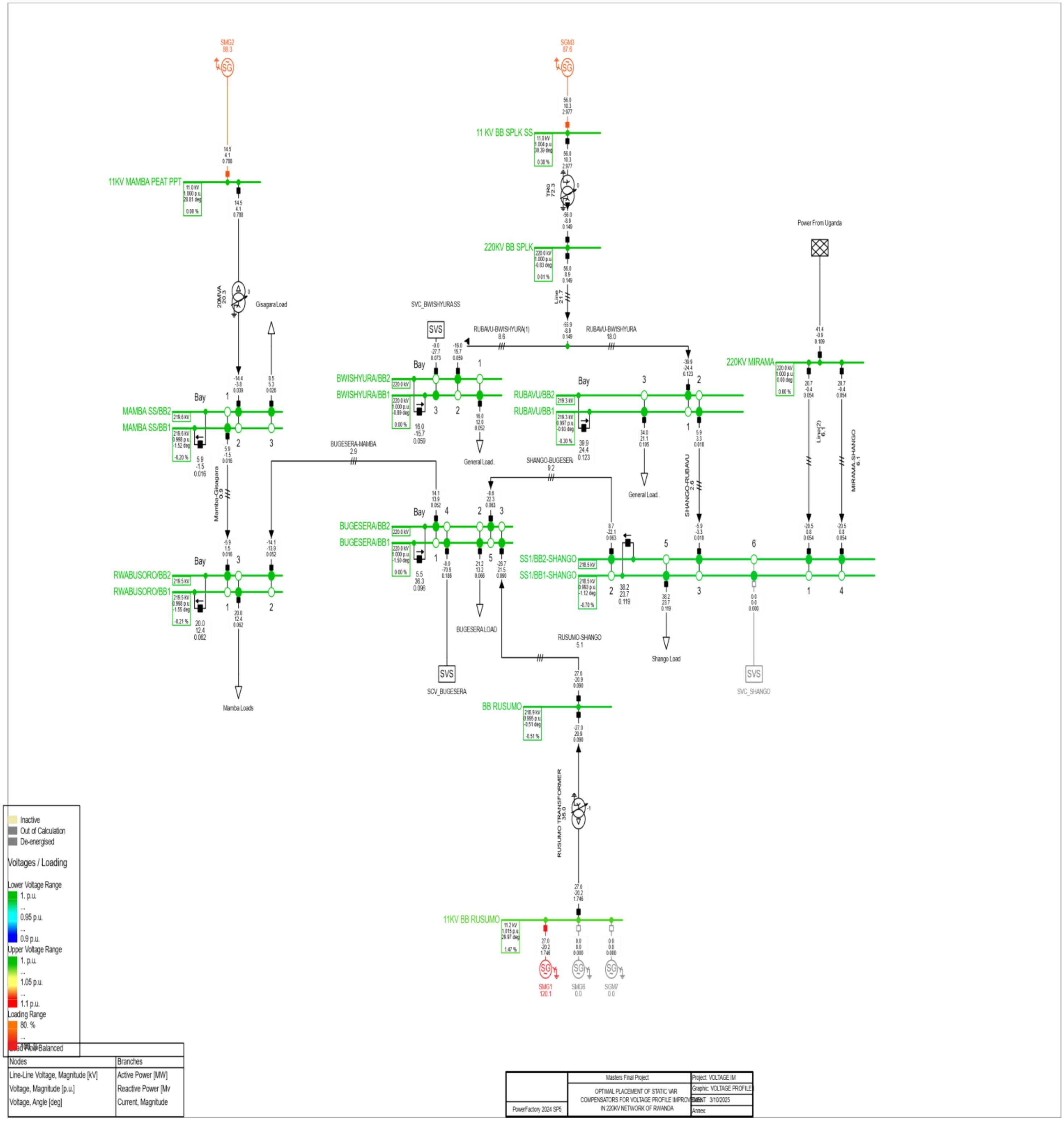


Figure 9:220KV Transmission Modelling and Simulation with SVC installed at BUGESERA &BWISHYURA SS.

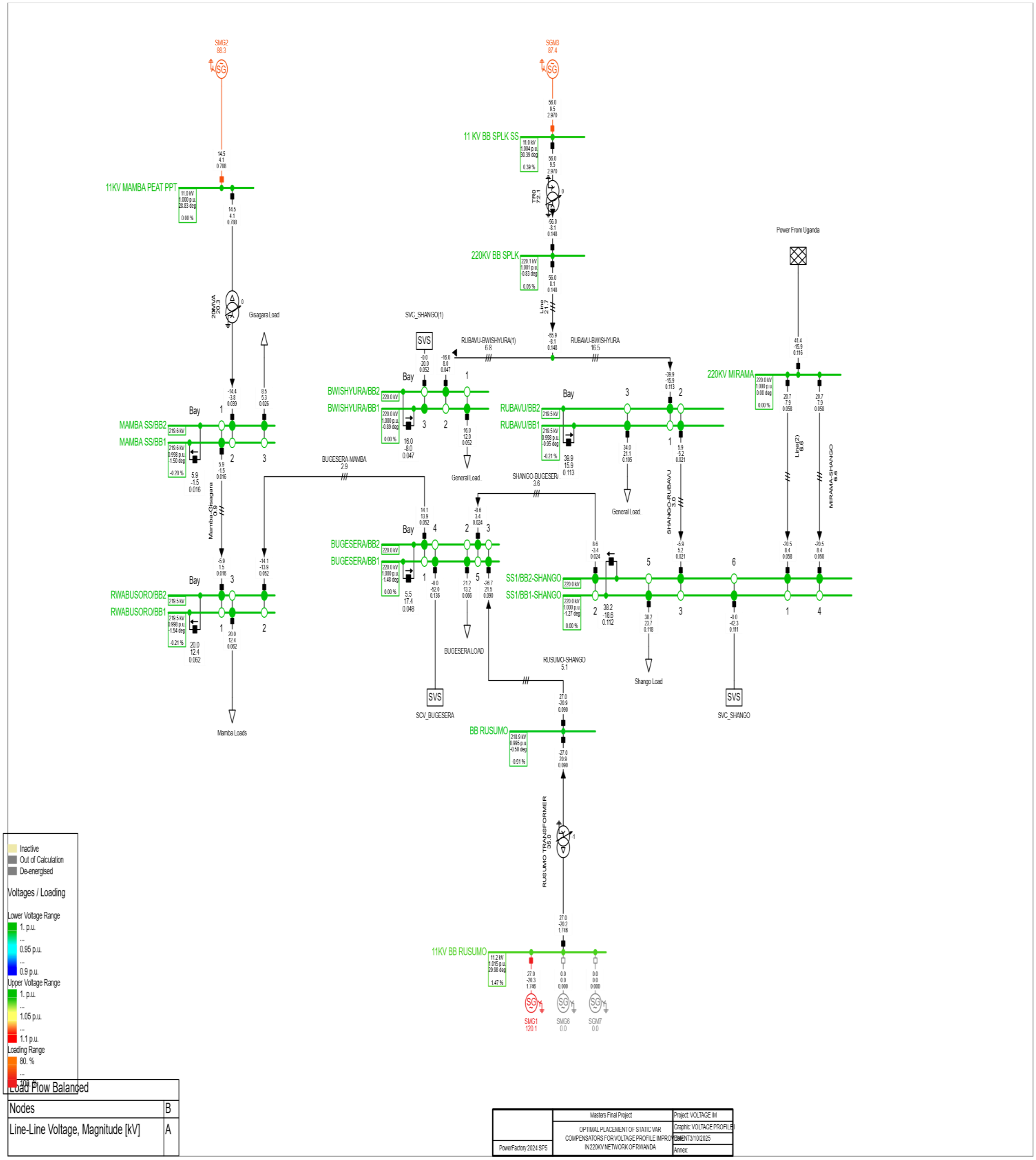


Figure 10:220KV Transmission Modelling and Simulation with all SVC installed

4.3.2 Analysis of the effect of SVC in 220KV Network.

Scenario 1. Simulation of existing 220KV network without SVC there are much voltage deviation in all switching Substation as indicated in table2.voltage deviation reach up 5.6KV and table 5.show the load losses of 1.1MW active power and 6.1MVAR reactive Power.

Scenario 2. Simulation of existing 220KV Network with SVC connected in one of three Substation (Shango, Bwishyura and Bugesera SS). The voltage deviation at Substation where SVC Connected improved but other Substation voltage change is small.

Scenario 3. Simulation of existing 220KV Network by connecting SVC to two Substation among Three. The Voltage improved in two Substation with SVC and small impact on remain Substation .

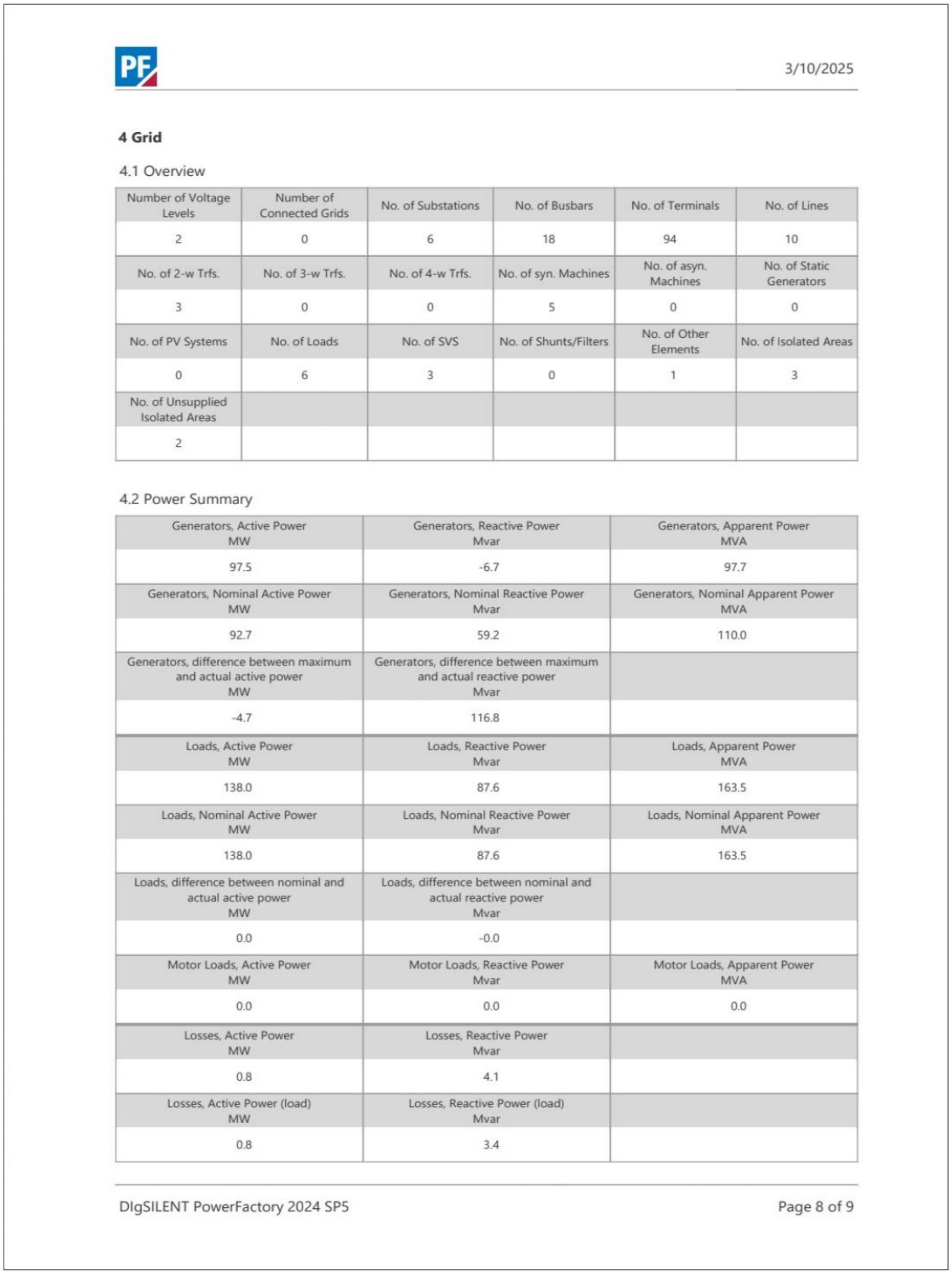
Scenario 4. Simulation of 220KV existing network by installing SVC to Shango, Bugesera and Bwishyura Substations. After connecting SVC to those three substation, the Voltage Profile improve as indicated in Table 4.comparing the voltage deviation with and without SCV. And Figure 10. Show Load losses reduced to from 1.1MW to 0.8MW and from 6.1 to 3.4MVAR compared with network without SVCs.

In Table4 . indicate the voltage deviation; the Maximum voltage deviation is 5.6 KV in Bugesera substation when no SVC installed at any Substation. But after connecting the SVC, the maximum voltage deviation decreased up 0.5 KV and losses decreased.

Table 4:Voltage deviation with SVC installed.

No	SUBSTATION	Voltage With SVC	Voltage Deviation	Percentage Voltage deviation (%)
1	MIRAMA	220	0	0
2	SHANGO	220	0	0.0
3	BUGESERA	220	0	0.0
4	RWAB	219.5	0.5	0.2
5	MAMBA	219.6	0.4	0.2
6	BWISHYURA	220	0	0.0
7	RUBAVU	219.5	0.5	0.2

Table 5:Grid Summary after simulation of 220KV Network after installation of SVCs



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4 Grid

4.1 Overview

Number of Voltage Levels	Number of Connected Grids	No. of Substations	No. of Busbars	No. of Terminals	No. of Lines
2	0	6	18	94	10
No. of 2-w Trfs.	No. of 3-w Trfs.	No. of 4-w Trfs.	No. of syn. Machines	No. of asyn. Machines	No. of Static Generators
3	0	0	5	0	0
No. of PV Systems	No. of Loads	No. of SVS	No. of Shunts/Filters	No. of Other Elements	No. of Isolated Areas
0	6	3	0	1	3
No. of Unsupplied Isolated Areas					
2					

4.2 Power Summary

Generators, Active Power MW	Generators, Reactive Power Mvar	Generators, Apparent Power MVA
97.5	-6.7	97.7
Generators, Nominal Active Power MW	Generators, Nominal Reactive Power Mvar	Generators, Nominal Apparent Power MVA
92.7	59.2	110.0
Generators, difference between maximum and actual active power MW	Generators, difference between maximum and actual reactive power Mvar	
-4.7	116.8	
Loads, Active Power MW	Loads, Reactive Power Mvar	Loads, Apparent Power MVA
138.0	87.6	163.5
Loads, Nominal Active Power MW	Loads, Nominal Reactive Power Mvar	Loads, Nominal Apparent Power MVA
138.0	87.6	163.5
Loads, difference between nominal and actual active power MW	Loads, difference between nominal and actual reactive power Mvar	
0.0	-0.0	
Motor Loads, Active Power MW	Motor Loads, Reactive Power Mvar	Motor Loads, Apparent Power MVA
0.0	0.0	0.0
Losses, Active Power MW	Losses, Reactive Power Mvar	
0.8	4.1	
Losses, Active Power (load) MW	Losses, Reactive Power (load) Mvar	
0.8	3.4	

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4.4 Comparison of 220KV Network With and Without SVCs

Table 6. Shows the comparison of Voltage Level and Voltage deviation when Static Var Compensators connected to substation and when no Reactive Power compensator installed . Also, table 3 indicates the advantages of using Static Var Compensator in Voltage profile improvement by reducing the Voltage deviations and increasing stability.

Table 6: Voltage Deviation in 220KV Substation with installed SVCs.

No	SUBSTATION	VOLTAGE WITHOUT SVC	VOLTAGE WITH SVC	VOLTAGE DEVIATION	Percentage Voltage Deviation(%)
1	MIRAMA	220	220	0	0.0
2	SHANGO	215.3	220	0	0.0
3	BUGESERA	214.4	220	0	0.0
4	RWAB	214.9	219.5	0.5	0.2
5	MAMBA	215	219.6	0.4	0.2
6	BWISHYURA	216.4	220	0	0.0
7	RUBAVU	216.1	219.5	0.5	0.2

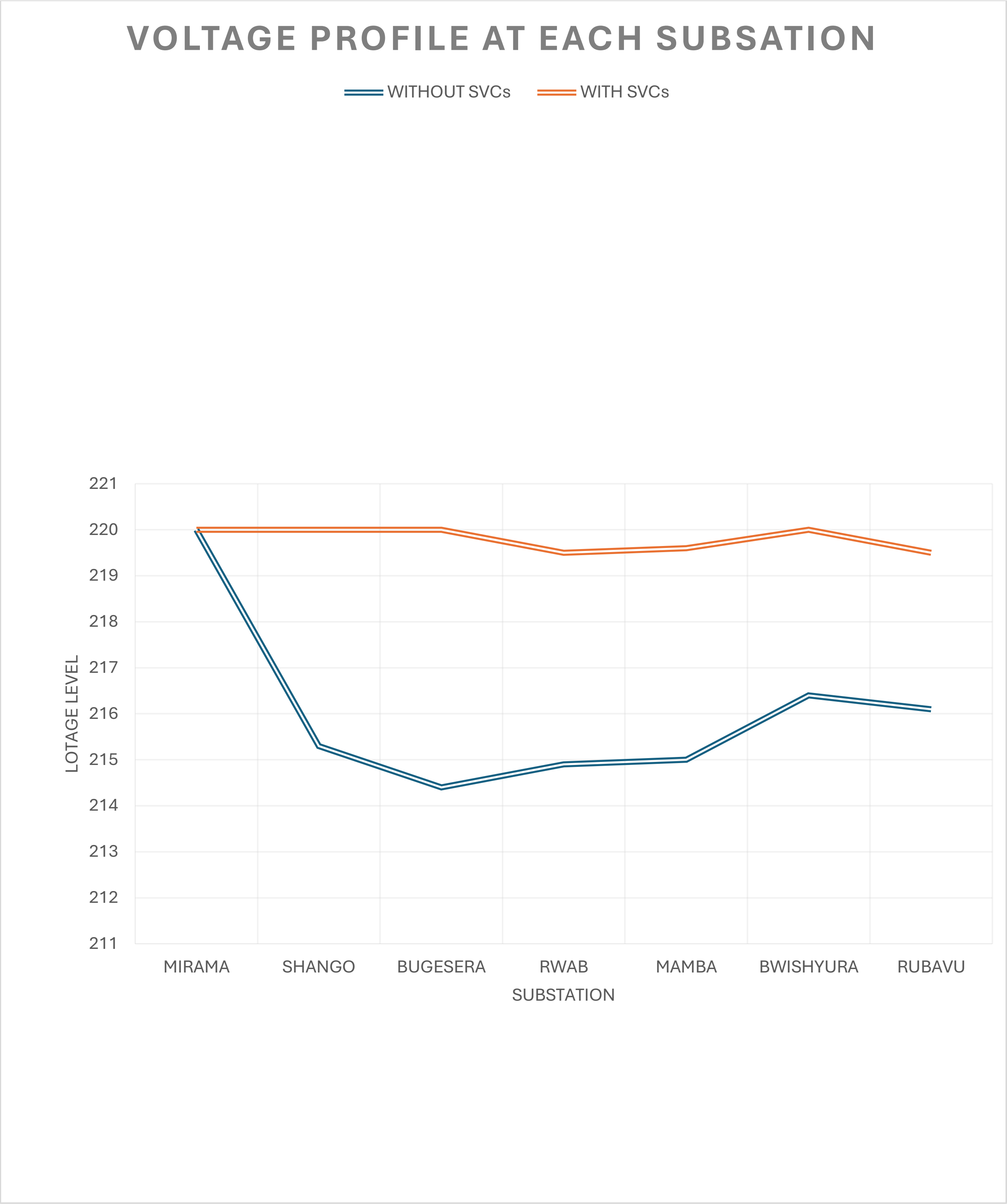

Figure 11:Voltage Profile improvement after applying SVCs.

CHAPTER5. CONCLUSIONS AND RECOMMENDATIONS

In This Chapter of Summary of results and analysis ,the data used in network modelling and simulation and results obtained after simulation are provided. Results are analyzed on Static Var Compensators (SVCs) installed in 220KV Network. Through detailed simulations and analyses, it has been demonstrated that strategically placing SVCs at specific nodes or Substation reduce voltage fluctuations and improve overall system stability. The optimal placement not only mitigates voltage sag and swell but reduce the Load losses in 220KV Network, leading to improved efficiency in power transmission. The findings underline the importance of considering both electrical load patterns and network topology when determining SVC locations, which contributes to more resilient and reliable grid operations.

Furthermore, the study reveals that the optimal placement of SVCs can result in substantial economic benefits by reducing transmission losses and minimizing the need for additional infrastructure investments. By optimizing the voltage profile, utilities can defer costly upgrades and enhance the performance of existing assets.

From the result obtained in Table 6, it indicate that the present analysis technique have advantage and in reduction of voltage drop in high voltage transmission Line and connected Substations. The SVCs generate the reactive power and compensate the voltage drops.

This study has successfully investigated the optimal placement of Static Var Compensators (SVCs) in the 220kV network of Rwanda to improve the voltage profile and enhance overall power system stability. Through a comprehensive analysis using power system simulation tools and optimization techniques, the research identified strategic locations where SVC installation yields the most significant voltage stability improvements.

One of the key observations from the simulations is that SVCs, when optimally placed, help in regulating reactive power flow, thereby maintaining voltage levels within acceptable range. This, minimizes the risk of voltage collapse and blackout and ensures a more resilient power system capable of handling demand variations and contingencies.

But also, some limitations must be acknowledged. This study focuses on static load conditions, whereas every day, power systems experience dynamic fluctuations. Future research should incorporate real-time load variations, dynamic simulations, and hybrid compensation solutions that integrate SVCs with other Flexible AC Transmission System (FACTS) devices for more comprehensive grid optimization.

In conclusion, the optimal placement of SVCs in Rwanda’s 220kV network offers a viable and effective solution for voltage profile improvement. The implementation of these findings can significantly enhance grid performance, reduce transmission losses, and support the nation’s growing electricity demand. Policymakers and grid operators are encouraged to consider the study’s recommendations for a more stable and efficient power system.

5.1. **Recommendations for further work**

After analyzing the results of this studies on the optimal placement of Static Var Compensators (SVCs) for voltage profile improvement in the 220kV network of Rwanda there is recommendation that need to be tipped out for the researchers and read in energy field.

For the future researchers they should conduct additional aspects such cost analyzes, and compare SVCs with other Flexible AC Transmission System and refine the findings.

For the reader and Utility decision makers . I would like to recommend them to implement the above developed model to increase voltage Stability to avoid any fluctuations caused by poor voltage.

5.2 Further Works

This study focused on SVCs, other Flexible AC Transmission System (FACTS) devices such as Static Synchronous Compensators (STATCOMs), Thyristor-Controlled Series Capacitors (TCSCs), and Unified Power Flow Controllers (UPFCs) may offer different benefits. Future research should compare the performance, cost-effectiveness, and suitability of these devices in the context of Rwanda's 220kV network.

This study primarily examined steady-state voltage profiles. Future research should include dynamic and transient stability assessments to evaluate how SVCs perform under fault conditions, sudden load variations, and other grid disturbances. This would provide a more comprehensive understanding of their effectiveness in maintaining grid stability.

The current study employed optimization algorithms for SVC placement. Future work could explore advanced techniques such as Artificial Intelligence (AI) and Machine Learning (ML) to enhance decision-making processes. AI-driven models can predict optimal placements based on historical grid performance data and real-time conditions.

While technical feasibility is crucial, the economic implications of SVC deployment should also be evaluated. Future studies should conduct cost-benefit analyses to determine the financial viability of SVC installations, considering capital investment, maintenance costs, and the economic impact of improved voltage stability.

The findings of this study were derived from simulations. To validate these results, real-world implementation and experimental case studies should be conducted. Pilot projects within Rwanda's 220kV network could provide practical insights into the effectiveness of SVCs under actual operating conditions.

By addressing these areas, future research can build upon the current findings to further enhance the efficiency, reliability, and economic feasibility of reactive power compensation in Rwanda's 220kV transmission network.

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