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

Dissertation Title: Impact of Prosumer integration at 15kV Busbar of distribution Substations in City of Kigali (Case study: Nzove and Gahanga Substations).

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Date: October 7, 2025

Declaration

I declare that this Dissertation contains my own work except where specifically acknowledged, and it has been passed through the anti-plagiarism system and found to be compliant and this is the approved final version of the thesis.

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Date of Submission: ……../……./2025

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

Supervisor: Associate Professor JMV BIKORIMANA

Signature:

Acknowledgement

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Abstract

The increasing global emphasis on Renewable energy has catalyzed the integration of distributed energy resources into national grid with prosumers (individuals or entities that can both consume and produce energy) emerging as key players in this transition[1]. This thesis explores the impact of prosumer integration on the grid in Rwanda for 15kV Bus of Nzove and Gahanga distribution Substations in Kigali as case study, a country striving to improve electricity access to all cells by 2029 through sustainable energy solutions.[2]

This thesis is structured for three specific objectives that are to assess the current configuration of distribution substations within City of Kigali, to propose the integration of prosumers at distribution substations to enhance loading status of power transformers at these Substations and the overall performance of the grid to support the increment of customer connection and lastly, analyze the Impact of Prosumers integrated at 15kV busbar for the above said selected distribution substations.

This thesis aims to provide network awareness configuration in City of Kigali at Distribution Substation level, propose strategic prosumer integration to enhance loading status of Power transformers and voltage level at Kigali distribution substations and visual scenario of loading status of power transformer at distribution substation and line voltage at sending end once prosumer is integrated for that specific substation using DigSilent Power Factory software.

Results show that Prosumer integration improve a lot of grid performance and provide an opportunity to increase the costumer connectivity and reduce burden of government in energy investment as big customer can locally produce to their need and export the surplus for others to use.

Keywords: Prosumer, distribution Substation, DigSilent Power Factory, Renewable Energy integration, power transformer and distributed energy resources.

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List of Abbreviations

EV: Electric Vehicle

PV: Photovoltaic

RE: Renewable Energy

REG: Rwanda Energy Group

V2G: Vehicle to Grid

DER: Distributed Energy Resources

Chapter 1. Introduction

1.1 Background

The global energy landscape is undergoing a profound transformation driven by the need to reduce carbon emissions and promote sustainable energy solutions [1], [3]. Many countries are shifting towards renewable energy sources such as solar, wind, and hydropower to meet energy demands in an environmentally friendly manner. However, the integration of these renewable sources presents significant challenges to grid stability due to their intermittent nature and limited storage capacity [4], [5]. As a result, innovative solutions are required to balance energy supply and demand, enhance grid reliability, and optimize energy infrastructure.

A promising concept emerging from this transition is that of prosumers (individuals or entities that both produce and consume energy). Prosumers typically generate electricity using small-scale renewable energy systems, such as rooftop photovoltaic (PV) installations, and may supply surplus energy back to the grid [6]. Technologies such as Vehicle-to-Grid (V2G), which allows electric vehicles (EVs) to discharge energy into the grid during high demand periods, further highlight the potential of prosumers to act as decentralized energy contributors [7], [8].

In Rwanda, the government has set ambitious energy goals, including providing electricity access in all cells of the country by 2029 [2]. The Rwanda Energy Group (REG) is spearheading these efforts through the adoption of renewable energy technologies, such as solar PV systems and microgrids [9]. Additionally, emerging initiatives involving e-mobility companies indicate that V2G technology could play a role in Rwanda’s future energy landscape. However, Rwanda’s power system faces significant challenges, including the need for advanced net metering mechanisms to facilitate energy exchange between prosumers and the grid, and solutions to manage voltage stability and frequency regulation under fluctuating energy flows.

The increasing involvement of prosumers offers opportunities to address these challenges and enhance grid stability, especially during peak and off-peak periods. However, the impact of widespread prosumer integration into Rwanda’s power system remains largely unexplored. A comprehensive evaluation of how prosumer activities such as energy production, consumption, and storage affect grid performance is essential to optimize Rwanda’s energy infrastructure for the future.

This thesis aims to analyze the effects of prosumer integration on the 15kV bus of Kigali’s distribution substation and provide strategic proposal of prosumer integration for energy policymakers and stakeholders. The research will focus on improving loading status of power transformers and bus voltage at Nzove and Gahanga distribution substation located in City of Kigali using DIGSILENT POWERFACTORY software for visual insight provision.

1.2. Problem Statement

Despite Rwanda's admirable efforts to achieve universal electricity access and promote renewable energy usage, significant challenges remain in the effective integration of prosumers into the national grid. Recently, a study of grid connected PV prosumer to support smart city development in Rwanda has been made where shown that a solar PV microgrid designed for Ayabaraya village can be a prosumer [10]. However, the behavior of the grid in response to the contribution of prosumers, is not well understood. Hence this research on impact analysis of integrated prosumer to distribution substation within city of Kigali provides a comprehensive scenario of what would happen when prosumers are integrated.

1.3. Objective of the study

1.3.1 Main Objectives

The main objective of this thesis is to analyze the effects of integrating prosumers on distribution Substation of Rwanda Energy Group (REG) located in City of Kigali. This includes modifying the existing distribution Substation by allowing big customer with local power generation to feed back their surplus into the grid to enhance loading status of power transformers at distribution Substation and the overall performance of the grid to support the increment of customer connection.

1.3.2 Specific Objectives

Specific objectives of this research are described below:

1. Assess the Current configuration of distribution substations within City of Kigali.
2. Propose the integration of prosumers at distribution substations to enhance loading status of power transformers at these Substations and the overall performance of the grid to support the increment of customer connection.
3. Analyze the Impact of Prosumers integrated at 15kV busbar for the selected distribution substations.

1.4. Scope

This research focuses on the impact prosumers integration can have on the loading status of power transformer found at distribution substation within city of Kigali due to time constraint and the urbanization of the region compared the rest of the country.

In addition to that, the analysis done at substation level with one potential prosumer integrated despite numerous potential prosumers found on one feeder to ease assessment and avoid grid instability. For that reason, although the integration at all substations is proposed only two prosumers, Skol Industry and Master steel industry at Nzove and Gahanga Substation respectively will be considered for impact analysis and discussions.

Moreover, despite that the impact of prosumer integration benefited by the network due to the existence of distribution substations interconnection to avoid complexity and inaccurate discussions only direct distribution substations assessed in this thesis and the rest are recommended as future works to be done.

1.5. Justification

The justification for this research lies in its potential to significantly contribute to Rwanda's goal of achieving universal electricity access and promoting sustainable energy practices. As Rwanda aims for providing electricity access in all cells of the country by 2029[2]. By understanding the role of prosumers in the national grid and the proper prosumer integration can help mitigate the challenges associated with renewable energy sources, such as intermittency and storage issues[4]. This research provides valuable insights into optimizing the contributions of prosumers, leading to a more stable and resilient energy system.

1.6. Expected outcomes.

The expected results of this research include the following:

1. Network awareness configuration in City of Kigali at Distribution Substation level.
2. Strategic Proposal of prosumer integration to enhance loading status of Power transformers and voltage level at Kigali distribution substations.
3. Visual scenario of loading status of power transformer at distribution substation and line voltage at sending end once prosumer is integrated for that specific substation.

1.7 Thesis Organization

This thesis is structured into six chapters to systematically address the research on the impact of prosumer integration at the 15kV busbar of distribution substations in the City of Kigali, with a focus on the Nzove and Gahanga substations. Chapter 1: Introduction provides the background, problem statement, objectives, scope, justification, and expected outcomes, setting the context for the study. Chapter 2: Literature Review explores the role of prosumers in modern energy systems, grid stability challenges in developing countries, and Rwanda's energy sector, while identifying gaps in existing research. Chapter 3: Methodology outlines the research approach, including data collection from the Rwanda Energy Group (REG), system design, and simulation using DigSilent PowerFactory to evaluate grid performance under various prosumer integration scenarios. Chapter 4: Designing and Modeling details the existing network configuration of Kigali's distribution substations and proposes prosumer integration at the 15kV busbar, focusing on voltage stability and transformer loading. Chapter 5: Results and Discussion presents and analyzes the simulation results, highlighting the impact of prosumers on grid performance, including load flow, voltage stability, and overloading. Finally, Chapter 6: Conclusion and Recommendations summarizes the findings, provides actionable recommendations for prosumer integration, and suggests future research directions. The thesis concludes with a References section listing all cited sources and an Appendix containing additional technical details and supporting data.

Chapter 2. Literature review on distributed generation and prosumers.

The transition from centralized to decentralized power generation has led to the rise of Distributed Generation (DG), which involves small-scale renewable energy sources such as solar PV, wind turbines, and fuel cells. DG enhances energy efficiency, reduces transmission losses, and improves grid resilience. Alongside this, prosumers entities that both produce and consume electricity have become key players in modern power systems. With advancements in smart grids and bidirectional power flow, prosumers can integrate renewable energy into the grid, participate in electricity markets, and contribute to overall energy security[11], [12].

Despite these benefits, prosumer integration presents challenges related to grid stability, power quality, and regulatory frameworks, particularly in developing countries like Rwanda. Technical barriers such as voltage fluctuations, frequency instability, and limited grid infrastructure hinder widespread adoption. While some countries have successfully implemented net metering and peer-to-peer (P2P) energy trading, Rwanda still faces gaps in policy design, energy storage solutions, and advanced control strategies[13]. This chapter explores the evolution of prosumers, their impact on grid stability, and the key research gaps in integrating distributed generation into Rwanda's energy network.

2.1 Evolution of Prosumers in Distributed Generation

The energy sector has undergone a significant transformation in recent decades, shifting from centralized power generation to decentralized and consumer-driven models. Distributed Generation (DG) involves small-scale power production near consumption points, reducing transmission losses and enhancing grid resilience. Initially, power systems operated in a unidirectional manner, with utilities generating electricity and consumers passively receiving it. However, advancements in renewable energy technologies, energy storage, and smart grid systems have enabled the rise of prosumers entities that both produce and consume electricity[14], [15].

Prosumers play a crucial role in modern energy systems by integrating renewable energy sources such as solar photovoltaic (PV), wind, and battery storage into the grid. This paradigm shift is largely driven by falling costs of solar panels, increased efficiency of battery storage, and the need for energy independence. In many developed and emerging economies, regulatory frameworks, such as net metering and feed-in tariffs, have encouraged prosumer participation, allowing them to sell excess power back to the grid. Rwanda has recognized the potential of prosumer-based energy systems in achieving its national electrification goals, reducing dependency on centralized generation, and improving energy reliability[16].

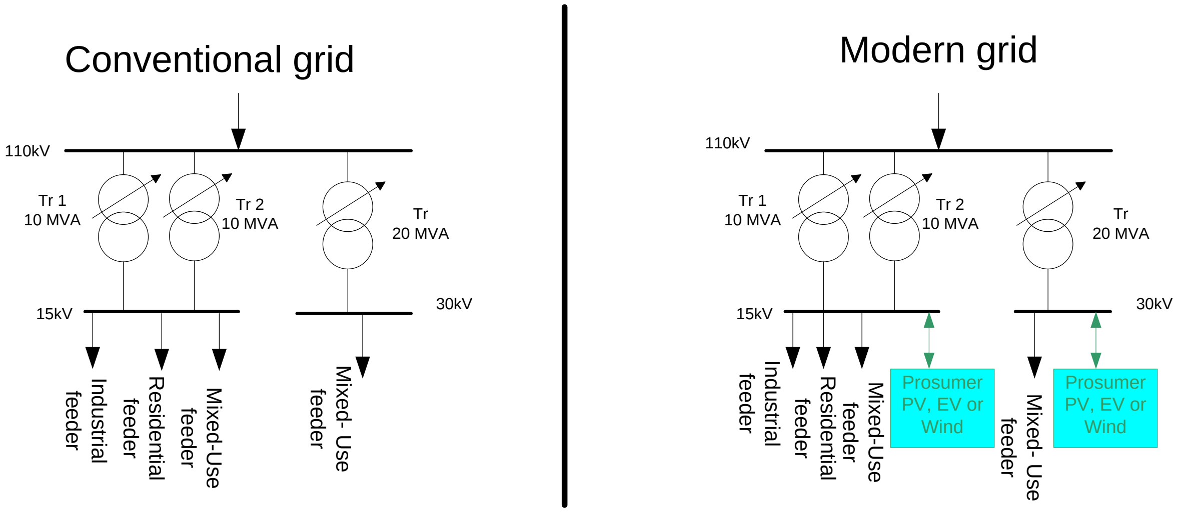


Figure 1: Conventional grid and Modern grid

Figure 1 shows the comparison between conventional grid and modern grid that significantly present great energy transition whereby prosumers penetration is making unidirectional power flow systems to bidirectional power flow systems with several benefits as shown by figure8 and 9 in this thesis.

2.2 Prosumers in Distributed Generation and Grid Stability

The integration of prosumers into power systems presents both opportunities and challenges. On one hand, prosumers enhance grid resilience by reducing reliance on centralized power plants, enabling localized energy generation, and mitigating transmission losses. On the other hand, their participation introduces complexities in power system operation, especially regarding grid stability, voltage regulation, and frequency control[17].

One of the key benefits of prosumer integration is its ability to support peak load demand by injecting power into the grid during high-demand periods, reducing strain on conventional power plants[16]. Additionally, advanced prosumer models leverage demand-side management (DSM) strategies, where electricity consumption is dynamically adjusted based on grid conditions. Technologies like Vehicle-to-Grid (V2G) systems, where electric vehicles (EVs) act as mobile storage units, further enhance grid flexibility[18].

However, challenges arise due to the intermittent nature of renewable energy sources. Solar and wind power fluctuate based on weather conditions, potentially leading to grid instability if not properly managed[19]. Voltage fluctuations, reverse power flow, and protection coordination issues require sophisticated control mechanisms, such as Model Predictive Control (MPC) and Advanced Distribution Management Systems (ADMS), to optimize energy dispatch and ensure reliability[19], [20]. Countries with well-established smart grid infrastructure have successfully integrated prosumers, demonstrating that proper regulatory policies and real-time monitoring systems can mitigate these challenges[18] as per below figure.

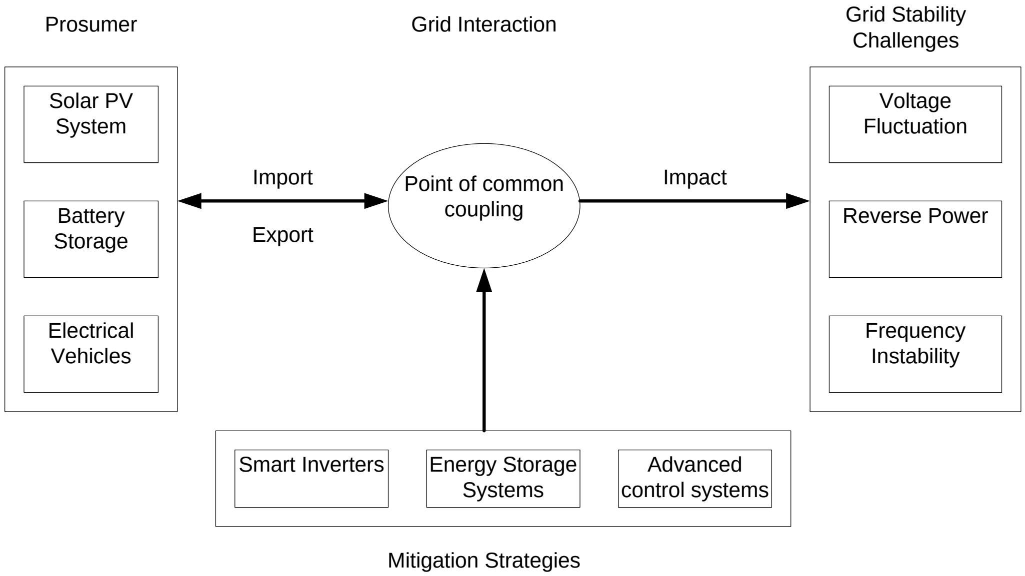


Figure 2: Prosumers in Distributed Generation and Grid Stability

2.3 Research Gaps Related to Prosumers in Distributed Generation in Rwanda

Despite the promising role of prosumers in improving energy access and stability, Rwanda still faces several challenges in their effective integration into the national grid. Research gaps are tabulated below.

Table 1:Key research gaps for prosumers in Rwanda.

Research Gap	Key Issues	Impact	Potential Solutions
1. Regulatory Framework	• Underdeveloped net metering policies Lack of compensation mechanisms Insufficient financial incentives	• Discourages investment in prosumer technologies Creates market uncertainty Slows adoption rates	• Develop comprehensive prosumer regulations Implement clear net metering policies Establish fair compensation mechanisms
2. Grid Infrastructure Limitations	• Grid designed for unidirectional power flow Voltage fluctuations at distribution substations	• Reduces grid adaptability Creates technical challenges Limits prosumer capacity	• Upgrade distribution infrastructure Implement real-time grid monitoring Reinforce critical substations
3. Transformer Loading Research	• Limited studies on prosumer impact Insufficient data on transformer lifecycle Inadequate thermal stress analysis	• Unknown effects on maintenance schedules Potential premature equipment failure Inefficient grid operations	• Conduct dedicated transformer impact studies Analyse thermal stress patterns Develop adaptive maintenance schedules
4. Energy Storage Integration	• Unexplored BESS integration Lack of economic feasibility studies Limited technical implementation frameworks	• Inability to balance intermittent generation Reduced grid stability Missed opportunity for demand management	• Assess BESS economic feasibility Develop storage integration roadmaps Pilot storage projects at key substations
5. Optimization Strategies	• Lack of prosumer control strategies Limited penetration level simulations Insufficient use of modelling tools	• Suboptimal prosumer contributions Unknown impact at higher penetration levels Limited predictive capability	• Develop substation-level control strategies Use DigSilent/MATLAB for simulation Model different penetration scenarios

2.4 Conclusion

The integration of prosumers into distributed generation networks represents a significant step toward achieving sustainable and resilient power systems. As Rwanda aims to improve energy accessibility and stability, prosumers offer a viable solution for reducing grid dependence, enhancing energy security, and supporting peak demand periods. However, their integration requires strong regulatory frameworks, advanced control mechanisms, and infrastructure upgrades to ensure stability and efficiency[13], [17], [18].

Addressing the research gaps identified in this chapter will be critical in shaping future policies and technical strategies for prosumer-driven energy systems in Rwanda. The next chapter will explore the methodological approach used to assess the impact of prosumers on distribution substations in Kigali, focusing on transformer loading, 15kV bus voltage on Nzove and Gahanga distribution substations.

Chapter 3. Methodology

This chapter discusses the systematic approach undertaken to analyze the effects of prosumer integration on 15kV Busbar at distribution substation in city of Kigali. This study specifically focuses on both power transformers and 15kV busbar at Nzove and Gahanga distribution substations in Kigali due to time constraint, city's high urbanization and energy demand. The methodology is structured to ensure a comprehensive understanding of the substation's behaviour under prosumer influence. The approach includes data collection from reliable sources, the design and modelling of the power system using DIGSILENT POWERFACTORY, and the simulation of various scenarios to evaluate grid performance. This chapter also concludes with how the discussion of simulation results was made.

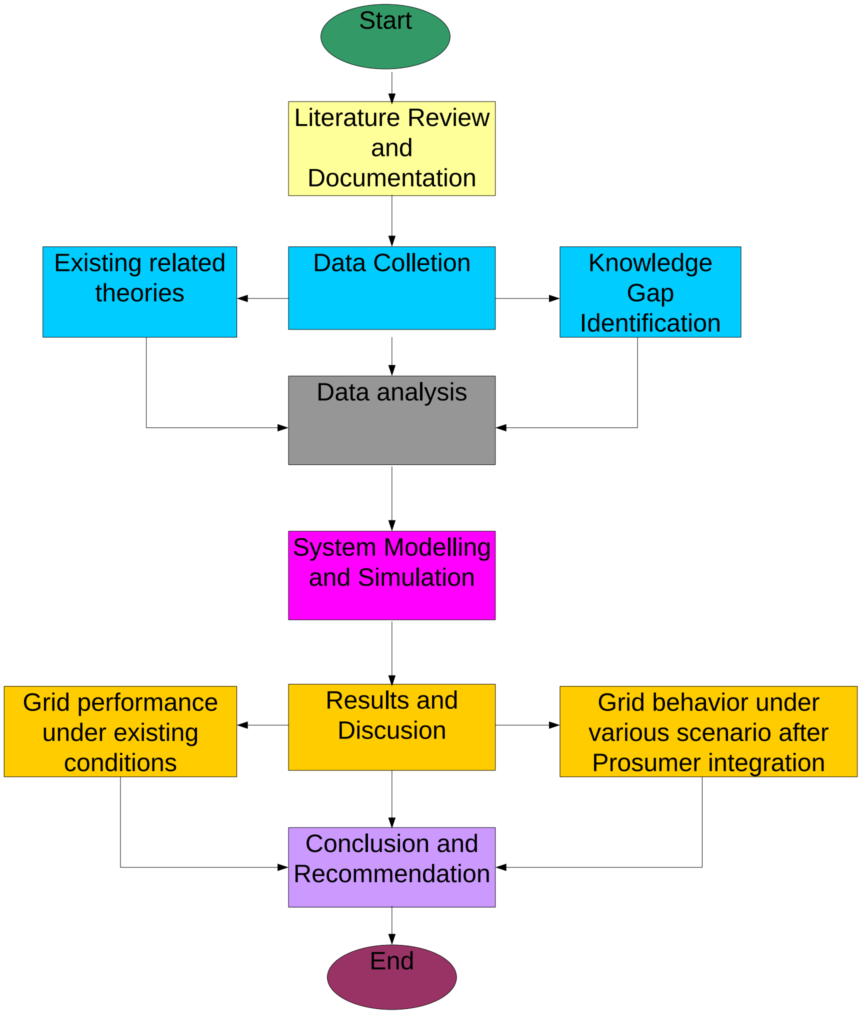


Figure 3: Methodology flow chart

3.1. Data Collection

In this thesis, data collected in two categories as below discussed.

3.1.1. Primary Data Collection

Data was obtained directly from Rwanda Energy Group (REG). The collected information includes transformer ratings, feeder loading status, distribution network configurations, and historical energy consumption data for Kigali's substations.

Below table provides basic information for distribution substation configuration used in this thesis. Whereby, 8; 110/15kV distribution substations, Power transformers and feeder are allocated accordingly.

Table 2: Distribution Substation located in City of Kigali

Substation Names	Number of installed	Voltage levels	power transformers capacities	Outgoing Feeders for MV busbar
Jabana 1	2	100/15kV	10 MVA each	Kigali
				Rutongo
				Utexrwa
				Deutch Welle
				Sucrerie
Nzove	1	100/15kV	20 MVA	Abatoire1
				Abatoire2
				Skol
Mt. Kigali	2	110/15kV	20 MVA	Nyamirambo
				Rebero
		110/30kV	20MVA	Kanazi
				Kiyumba

Gahanga	1	110/15kV	20 MVA	Master Steel
				Pylon 20
Gikondo	3	110/15kV	15 MVA each	Kigali Sud
				Kigali Nord
				Kimihurura
				Pompage Merdien
				Sonatube
				Gikondo Haut
				Nyarurama
				PI
				Kic-P20
				NECC1
				NECC2
Gasogi	1	100/15kV	20 MVA	Nyagasambu
				Masaka
				Mulindi
				Inyange
				Rusororo
				Rutunga
Ndera	1	110/15kV	20 MVA	Free Zone
				Rubungo
				Gikomero
Birembo	1	110/15kV	20 MVA	Kibagabaga-Remera
				Kibagabaga-Nyarutarama
				Kinyinya
				Rubungo 1
				Rubungo 2

3.1.2. Secondary Data Collection

Secondary data are sourced from academic literature, government reports, and international case studies on prosumer integration and grid stability. These resources provide insights into global best practices and technical parameters, such as load patterns, and transformer performance under distributed generation scenarios.

3.2. Design and Modelling

The power system model was designed using DIGSILENT POWERFACTORY (Electrical Transient Analyzer Program), which is well-suited for analysing power distribution networks and assessing grid stability. The design process involves the below steps:

3.2.1. System Representation

A single-line diagram of the selected distribution network in Kigali was developed. The diagram to include key components such as transformers, feeders, busbars, loads, and PV system as prosumers representation.

3.2.2. Input Parameters

Data collected from REG are input to DIGSILENT POWERFACTORY model, including transformer ratings, feeder names from distribution Substation, 110kV lines interconnecting substations. Prosumers are modelled as PV system that generates more compared to the feeder of connection. Loading parameters are P and Q as data type accepted by the software.

3.2.3. Scenario Development

Multiple scenarios were created to evaluate the impact of prosumer integration. These scenarios will include different levels of prosumer penetration (e.g., 10%, 30%, 50% and 100%).

The DIGSILENT POWERFACTORY model will serve as the foundation for simulations, enabling detailed analysis of transformer loading, voltage profiles, and power flow under each scenario.

3.3. Simulation

The simulations were conducted using DIGSILENT POWERFACTORY's load flow analysis module. The objective is to assess the effects of prosumer integration on power transformer loading and 15kV bus in the selected substation (Nzove and Gahanga).

- **Load Flow Analysis**

Load flow simulations analyzes the power distribution network under each scenario. This has identified the loading status of transformers, voltage level at 15kV busbar. Special attention was given to demonstration both the loading status of power transformers and 15kV bus voltage level due to prosumer integration.

3.4. Result Discussion

The simulation results are analyzed to assess the implications of prosumer integration. The discussion focused on the impact of prosumer energy on distribution power transformer loading and Voltage deviations caused by prosumer generation.

3.5 Evaluation Metrics and Penetration Scenarios

To evaluate the impact of prosumer integration on Kigali's distribution substations, the following performance indices were used:

- **Transformer Loading (%):**

$$\text{Loading Index} = \left(\frac{\text{Sactual}}{\text{Srated}}\right) \times 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(1)}$$

This index shows how heavily a transformer is loaded under different scenarios. Reductions in loading indicate load sharing by prosumers.

- **Bus Voltage Deviation (kV):**

Voltage at the 15kV bus was monitored to observe the effect of distributed energy injection. A value closer to 15kV is considered ideal.

The penetration scenarios were selected based on a progressive and practical simulation approach used in several power system impact studies:

- 10%: Represents initial or pilot-level adoption.
- 30%: Simulates moderate adoption.
- 50%: Tests aggressive integration.
- 100%: A worst-case/full-saturation stress scenario.

This range provides a comprehensive performance spectrum allowing policymakers to anticipate effects at different adoption stages.

Chapter 4. Designing and modelling of distribution substations with prosumer integration.

This chapter focuses on designing the power distribution system model for the study area (Distribution Substations in City of Kigali) and simulating the impact of prosumers these substations using DIGSILENT POWERFACTORY software. The design process involves defining the network structure, assigning collected operational parameters for the distribution transformers and feeders, and integrating prosumer systems into the model.

4.1. Kigali Distribution Substation Network Configuration

Below is the existing Kigali distribution substation network configuration that provides a pictorial view of the current network before the integration of Prosumers.

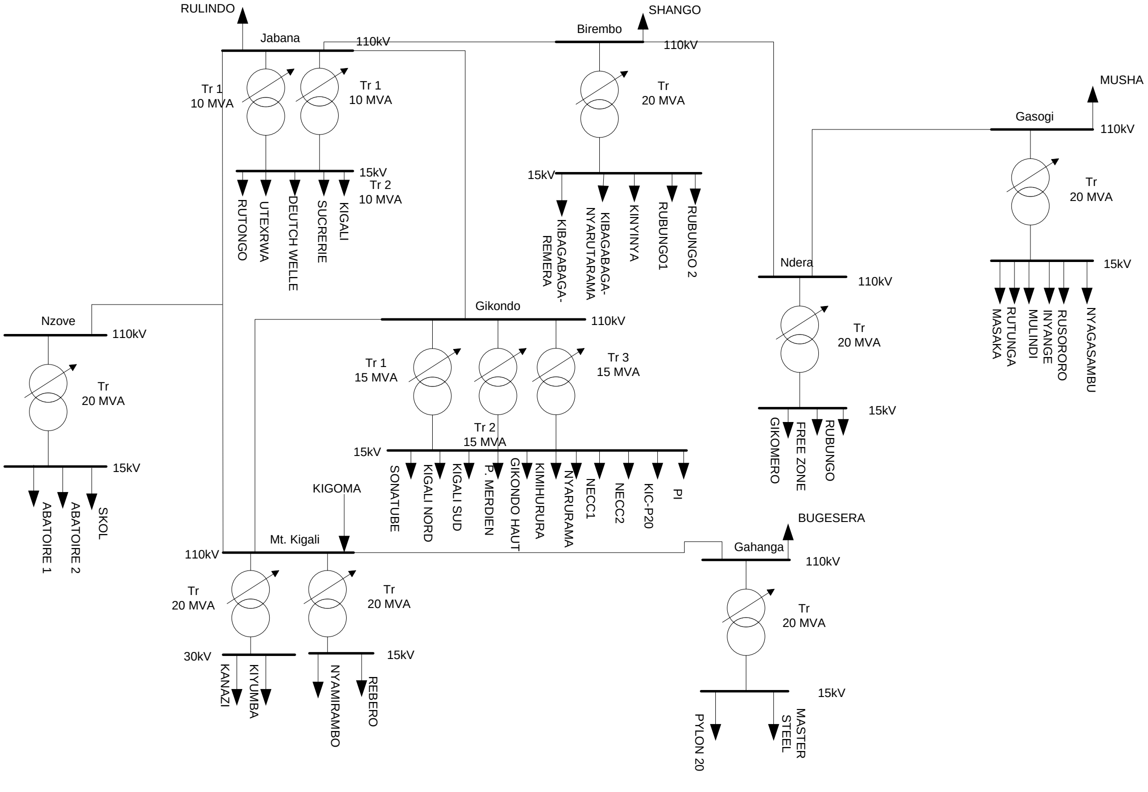


Figure 4: Existing distribution substation configuration in city of Kigali

Figure 4, shows the existing distribution substation configuration with all outgoing feeders that were not detailed as their real length is hard to be determined hence makes feeder parameters unknown due to variation in conductor size where for instance a feeder comes from a substation with ACSR 240/40mm2 and different T-offs connected to it are of 35/6mm2, 70/12mm2, 120/20mm2 or underground extension made with either 50mm2, 70mm2, 95mm2,120mm2 or 240mm2 however for this thesis feeder loads are going to assigned to P and cos φ for simulation purpose.

For distribution loading status of different feeders for Kigali Substation, the following formula was used.

$$Q = P * \tan\left(Cos^{-1}(P.f)\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Where, P is Active Power in MW, Q is Reactive Power in Mvar and P.f is the Power factor.

Table below shows Kigali Substations loading status excluding Kiyumba and Kanazi feeders from Mt. Kigali Substations and data for Mach 2024 are used for simulation.

Table 3: Kigali Substations loading status excluding Kiyumba and Kanazi feeders from Mt. Kigali Substations

PERIOD				**Jan-24**		**Feb-24**		**Mar-24**		**Apr-24**	
Distribution Substation	**Existing Tr (MVA)**	**Feeder Names**	**Feeder Type (Power factor)**	**P(MW)**	**Q(MVar)**	**P(MW)**	**Q(MVar)**	**P(MW)**	**Q(MVar)**	**P(MW)**	**Q(MVar)**
Birembo	**1x20**	Kibagabaga-Nyarutarama	Residential (0.95)	3	0.99	2.9	0.95	4.8	1.58	2.81	0.92
		Kibagabaga-Remera	Residential (0.95)	4	1.31	1.3	0.43	4.1	1.35	2.47	0.81
		Rubungo1	Mixed use (0.9)	5.2	2.52	5.3	2.57	7.6	3.68	4.75	2.30

		Kinyinya	Residential (0.95)	4.69	1.54	5.1	1.68	7.67	2.52	4.40	1.45
S/Total				16.89	6.36	14.6	5.63	24.17	9.13	14.43	5.48
Gahanga	**1x20**	Master Steel	Industrial (0.85)	4.5	2.78	4.83	2.99	4.57	2.83	4.58	2.83
		Pylon 20	Industrial (0.85)	4.72	2.92	5.16	3.19	5.34	3.31	4.31	2.67
S/Total				9.22	5.70	9.99	6.18	9.91	6.14	8.89	5.50
Gasogi	**1x20**	Inyange	Industrial (0.85)	1.72	1.06	1.84	1.14	1.99	1.23	1.69	1.05
		Rusororo	Residential (0.95)	1.55	0.51	1.62	0.53	1.61	0.53	1.49	0.49
		Mulindi	Mixed use (0.9)	4.49	2.17	3.89	1.88	3.88	1.88	3.97	1.92
		Masaka	Residential (0.95)	3.62	1.19	3.89	1.28	3.88	1.28	3.77	1.24
		Rutunga	Residential (0.95)	0.52	0.17	0.65	0.21	0.69	0.23	0.55	0.18
		Nyagasambu	Residential (0.95)	0.85	0.28	0.85	0.28	0.91	0.30	0.77	0.25
S/Total				12.75	5.38	12.74	5.32	12.96	5.45	12.24	5.13
Gikondo	**3x15**	Kicukiro PLN 20	Mixed use (0.9)	1.34	0.65	7.17	3.47	6.51	3.15	7.18	3.48
		Gikondo Haut	Residential (0.95)	1.96	0.64	1.84	0.60	0.00	0.00	0.00	0.00
		Kigali North	Mixed use (0.9)	5.10	2.47	5.90	2.86	6.76	3.27	6.48	3.14
		Kigali South	Mixed use (0.9)	5.49	2.66	5.09	2.47	5.62	2.72	5.20	2.52

		Kimihurura	Residential (0.95)	5.67	1.86	2.79	0.92	5.57	1.83	4.08	1.34
		Nyarurama	Residential (0.95)	0.38	0.12	0.38	0.12	0.39	0.13	0.40	0.13
		Ministerie1	Mixed use (0.9)	0.00	0.00	0.07	0.03	0.07	0.03	0.07	0.03
		Ministerie2	Mixed use (0.9)	5.82	2.82	6.06	2.93	5.76	2.79	4.98	2.41
		Parc Industrial (0.85)e	Industrial (0.85)	0.21	0.13	0.10	0.06	0.13	0.08	0.00	0.00
		Sonatube	Industrial (0.85)	1.34	0.83	1.33	0.82	1.39	0.86	1.48	0.92
		Pom. Merdien	Mixed use (0.9)	2.18	1.06	2.07	1.00	3.06	1.48	2.03	0.98
S/Total				29.49	13.24	32.81	15.28	35.27	16.34	31.90	14.95
Jabana	**2x10**	D.Welle	Mixed use (0.9)	2.05	0.99	2.1	1.02	2.21	1.07	2.10	1.02
		Kigali	Residential (0.95)	1.76	0.58	3.65	1.20	3.86	1.27	5.45	1.79
		Rutongo	Residential (0.95)	4.48	1.47	4.8	1.58	4.94	1.62	4.47	1.47
		Sucrerie	Industrial (0.85)	0.58	0.36	0.5	0.31	0.11	0.07	0.05	0.03
		Utexerwa	Industrial (0.85)	4.06	2.51	3.88	2.40	3.97	2.46	4.12	2.55
S/Total				12.93	5.91	14.93	6.51	15.09	6.49	16.19	6.86
Mt. Kigali	**1x20**	Nyamirambo	Residential (0.95)	5.28	1.74	5.36	1.76	5.23	1.72	5.76	1.89

		Rebero	Residential (0.95)	1.6	0.53	1.53	0.50	1.53	0.50	1.59	0.52
S/Total				6.88	2.27	6.89	2.26	6.76	2.22	7.34	2.41
NDERA	**1x20**	Rubungo	Residential (0.95)	4.8	1.58	2.29	0.75	2.57	0.84	2.50	0.82
		Free zone 1	Industrial (0.85)	9.4	5.82	8.84	5.47	8.76	5.42	9.37	5.80
		Gikomero	Residential (0.95)	2.38	0.78	2.16	0.71	2.19	0.72	2.19	0.72
S/Total				16.58	8.18	13.29	6.93	13.52	6.98	14.06	7.34
NZOVE	**1x20**	Abattoir 1	Industrial (0.85)	5.16	3.19	5.20	3.22	5.31	3.29	3.50	2.17
		Abattoir 2	Industrial (0.85)	5.3	3.28	1.74	1.08	3.25	2.01	3.22	1.99
		Nzove	Mixed use (0.9)	6.4	3.10	6.54	3.17	6.74	3.26	6.86	3.32
S/Total				16.86	9.57	13.48	7.47	15.30	8.56	13.58	7.48
Kigali Total	**185 MVA**			**121.60**	**56.61**	**118.74**	**55.58**	**132.98**	**61.31**	**118.63**	**55.15**

4.2 Network Configuration with integration of DER (Prosumer) at 15 KV buses

Figure 5 is the existing distribution network configuration with proposed prosumer integration at 15kV Busbar.

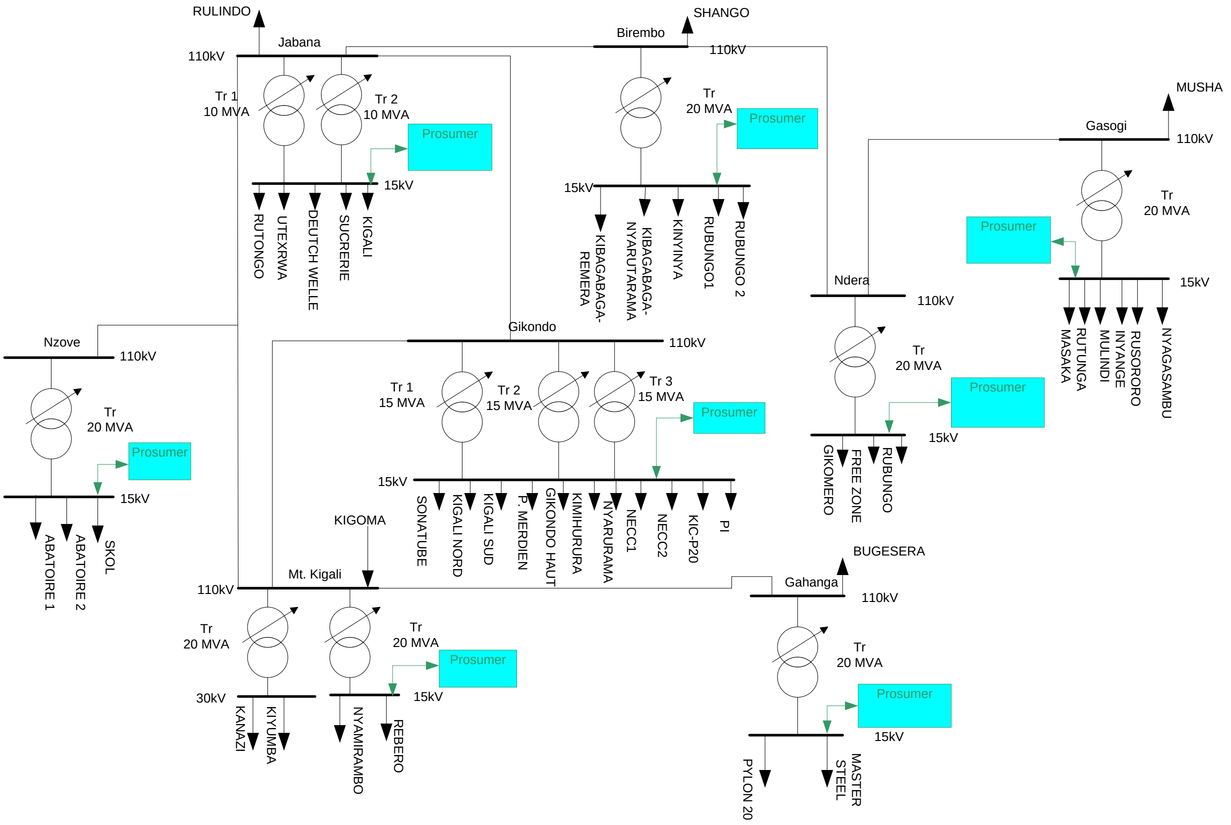


Figure 5: Distribution Substation in city of Kigali with proposed Prosumer integration

The integration of prosumer at 15kV busbar will enhance grid performance and allow connectivity increase to other customers while the prosumer himself/ herself will benefit based on the exchange. i.e when $E_{import} > E_{export}$, the prosumer incurs costs, while the reverse gains credits.

4.3. Network configuration with integration of DER (Prosumer) at selected 15 KV busbar.

Figure 6 shows the existing distribution network configuration with prosumer integrated at selected 15kV Busbar, which is our case to model, simulate and discuss the results.

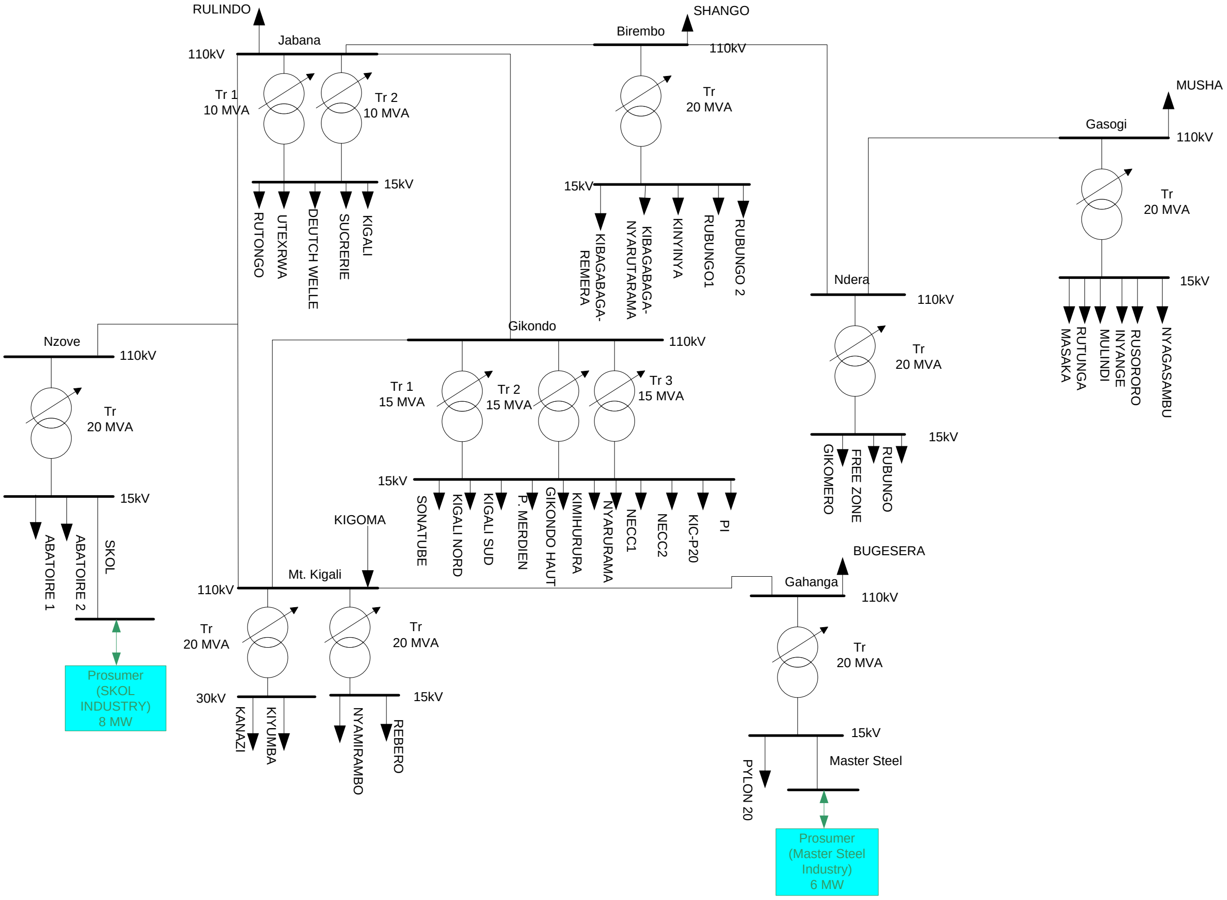


Figure 6:Distribution Substation in city of Kigali with Prosumer integrated at the selected busbar.

For our case study, only one potential prosumer on Skol feeder from Nzove substation which is Skol Industry and Master steel industry at Master steel feeder from Gahanga substation are going to be simulated to analyze their impact on their respective distribution substation.

4.4 Kigali Distribution substations Network with prosumer connected at selected bus in DIGSILENT POWEACTORY

Figure 7 is the screenshot of the Kigali Distribution substations Network with prosumer connected at selected bus in DIGSILENT POWEACTORY software that was built to undergo different scenario for impact assessment on direct substation after load flow.

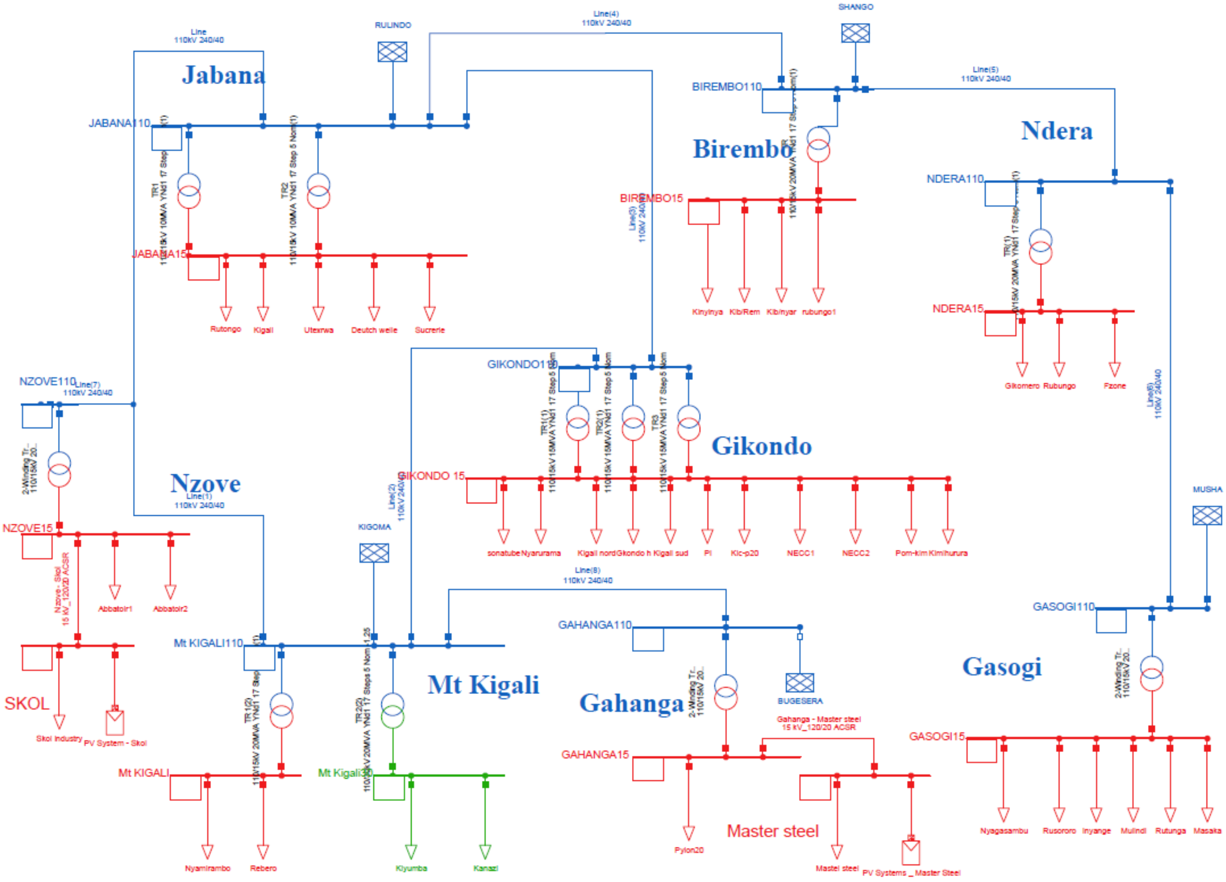


Figure 7: Kigali distribution substation with prosumer connected at Nzove and Gahanga Substation

In the next chapter, results found during load flow analysis are discussed to provide visual scenarios of what can happen when Prosumers are properly integrated to the national grid.

4.5 Assumptions for Prosumer Plant Design

Due to confidentiality restrictions on industrial energy production data, the prosumer plant capacities modeled in this study were derived from actual feeder loading data.

- Skol Industry (Nzove Substation): The Skol feeder, with an average demand of approximately 8 MW, was used as a proxy.
- Master Steel Industry (Gahanga Substation): The Master Steel feeder with a loading of around 6 MW was modeled similarly.

These values were used as base capacities for simulating four levels of penetration. The approach ensures simulations remain grounded in realistic scenarios while maintaining confidentiality.

Chapter 5. Results and discussion

This chapter provides both results and discussion of load flow analysis for this thesis to provide insights of what is improved when Prosumer are connected to 15kV Busbar at the selected busbar of both Nzove and Gahanga distribution substation within Kigali distribution network.

5.1. Results

The results shown below are for load flow analysis from DigSilent Powerfactory under different scenarios such as network without prosumer integration, with prosumer integrated with 10%, 30%, 50% and 100%. Result shown and discussed are Voltage bus and power transformer loading status.

5.1.1. Power Transformer loading status.

Both results for Gahanga and Nzove Power transformer loading status without prosumer integrated and with prosumer integrated at 10%, 30%, 50% and 100% are below shown in the figure.

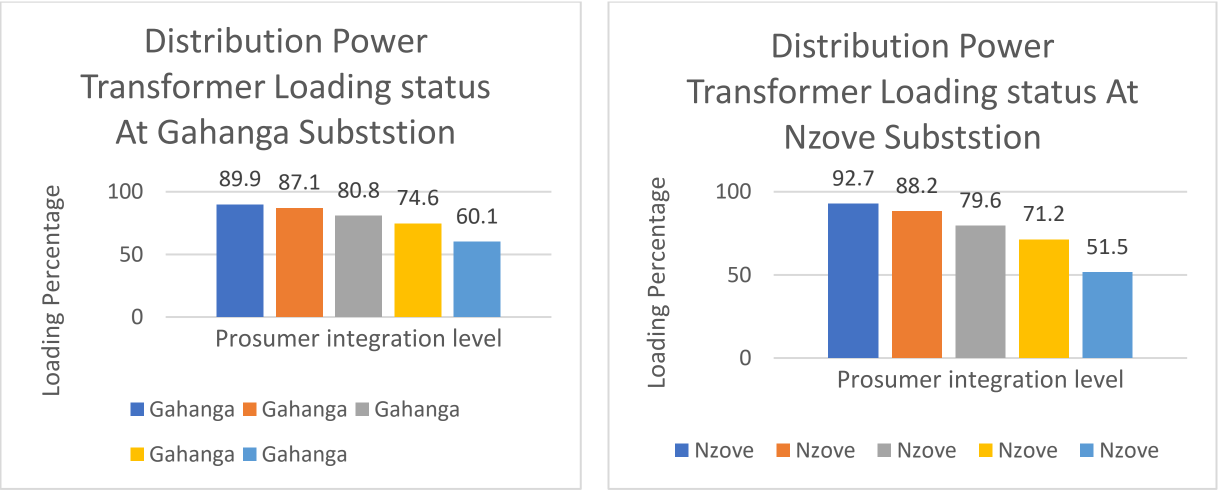
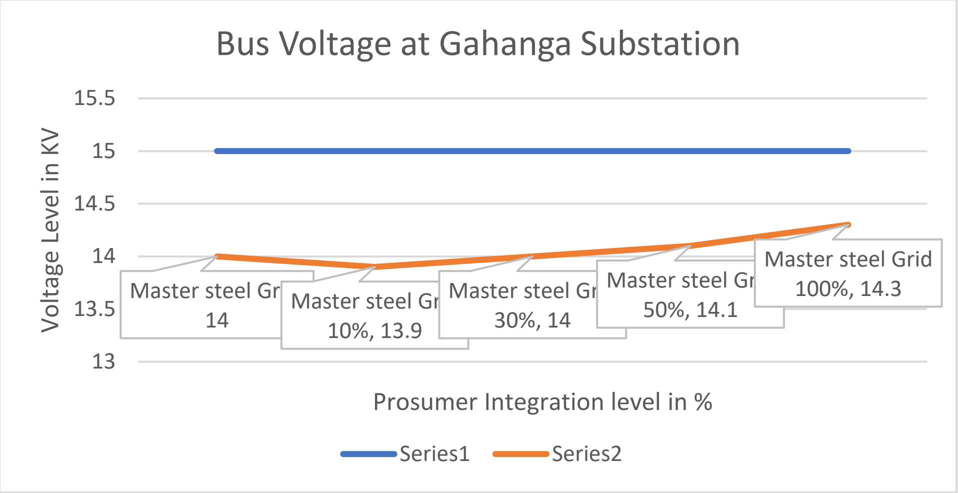


Figure 8: Power transformer loading status without prosumer and with prosumer integrated at different level.

5.1.2. Gahanga and Nzove 15kV Busbar Voltage status

Both results for Gahanga and Nzove 15kV Busbar Voltage without prosumer integrated and with prosumer integrated at 10%, 30%, 50% and 100% are below shown in the figure.



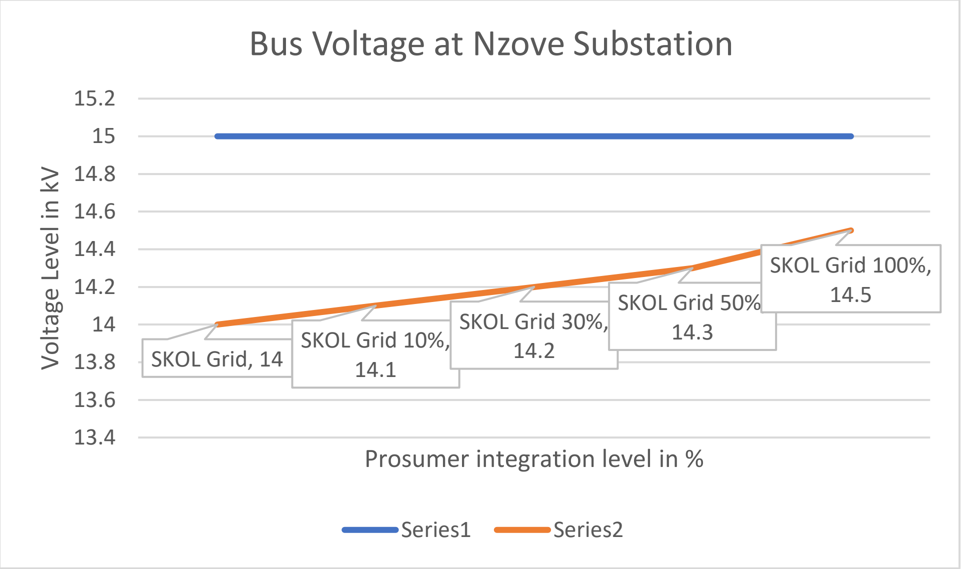


Figure 9: Busbar Voltage without prosumer and with prosumer integrated at different level.

5.2 Discussion

5.2.1 Interpretation of Simulation Results

The load flow simulations revealed that integrating prosumers significantly enhances operational performance. At Gahanga, transformer loading reduced from 89.9% to 60.1%; at Nzove, from 92.7% to 51.5%. Bus voltage improved from 14.0kV to 14.5kV at Nzove and from 13.9kV to 14.3kV at Gahanga.

These trends confirm that prosumer integration improves both transformer loading and voltage profiles.

5.2.2 Technical and Operational Challenges of Prosumer Integration

Despite the benefits, simulations revealed challenges:

- Overvoltage risks at high penetration levels.
- Reverse power flow impacts protection schemes.
- Transformer underutilization.
- Lack of energy storage to manage surplus.
- Grid design not suited for bidirectional flow.

These highlight the need for system upgrades and advanced controls.

5.2.3 Opportunities for the Rwandan Grid

The results reveal several strategic opportunities:

- Peak shaving during high demand.
- Deferred infrastructure upgrades.
- Supporting Rwanda’s 2029 electrification goals.
- Enabling local energy markets.
- Improving local energy resilience.

With supportive policies, prosumer integration can be a cornerstone of Rwanda's energy future.

Chapter 6. Conclusion and Recommendations

Chapter 6 is the last chapter of this thesis that provides both conclusion for work done and recommendations for future research work to be done within prosumer integration area.

6.1 Conclusion

The main purpose of this thesis was to analyze the effects of integrating prosumers on distribution Substation of Rwanda Energy Group (REG) located in City of Kigali. This includes modifying the existing distribution Substation by allowing big customer with local power generation to feed back their surplus into the grid to enhance loading status of power transformers at distribution Substation and the overall performance of the grid to support the increment of customer connection, whereby two potential prosumers (Skol and Master steel) penetrated their generations to the nearby substation (Nzove for skol and Gahanga for Master steel) and their impact to the grid performance have been investigated and simulated using DigSilent Powerfactory software.

From simulation results, it is evident that the distribution network performance had improved at the loading status of the power transformer at Gahanga and Nzove substations were improved depending on the level of prosumer penetration to the grid. The same applied to the Voltage at 15kV busbar in those distribution substations which showed a significant improvement to better optimize the existing infrastructure thus enhance energy access to expedite country goal for electricity access in all cells by 2029 and help the country to avoid urgent energy investment financial incentives to deal with the increasing energy demand while prosumers themselves get credits or incurs cost depending on the monthly net energy exchange.

Lastly, I conclude by saying, as the proposal of integrating prosumer to the national grid at the distribution substation level was provide in this thesis; REG in charge of energy and other energy stakeholders should work together toward universal electricity access by optimizing existing energy infrastructure through integrating potential prosumers countywide to the grid as this technology is significantly supporting in developed countries along the globe and provides solutions to renewable energy intermittency and storage issues.

6.2. Recommendations

Based on the findings of this research, the following recommendations are proposed to optimize prosumer integration and enhance grid stability in Rwanda:

- Distribution Substations need to be upgraded to handle bidirectional power flow.
- Prosumer integration studies at 30kV distribution substation is also required.
- Feed in Tariff that promotes time of use and net metering policy needs to be strengthened.
- Provision of battery energy storage systems (BESS) to store excess energy generated by prosumers during periods of high generation and release it during periods of high demand is needed.
- Advanced Distribution Management System (ADMS) to ensure network real time monitoring and control is needed.
- Study on socioeconomic impact of prosumer integration in needed.
- Development for standard protocol that governs prosumer interconnection is required.

Prosumer integration at the 15kV busbar of distribution substations in Kigali represents a significant opportunity to enhance grid performance, increase renewable energy adoption, and support Rwanda's energy transition. However, realizing these benefits requires strategic investments, policy reforms, and innovative solutions to address the challenges of grid instability and infrastructure stress. By implementing the recommendations outlined in this thesis, Rwanda will create a more resilient, sustainable, and inclusive energy system for the future.

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Appendix

- **Kigali distribution substation loading in DigSilent Powerfactory**

Table 4: feeder loading in DigSilent Powerfactory

Name	Grid	Terminal	Terminal	u, Magnitude	Active Power	Reactive Power	Apparent Power	Power Factor
		StaCubic	Busbar	p.u.	MW	Mvar	MVA	
Abbatoir1	Grid		NZOVE15	0.955	5.3	3.3	6.2	0.85
Abbatoir2	Grid		NZOVE15	0.955	3.3	2	3.8	0.85
Deutch welle	Grid		JABANA15	0.968	2.2	1.1	2.5	0.9
Fzone	Grid		NDERA15	0.964	8.8	5.4	10.3	0.85
Gikomero	Grid		NDERA15	0.964	2.2	0.7	2.3	0.95
Gkondo h	Grid		GIKONDO15	0.96	0	0	0	1
Inyange	Grid		GASOGI15	0.973	2	1.2	2.3	0.851
Kanazi	Grid		Mt Kigali30	1	0	0	0	1
Kib/Rem	Grid		BIREMBO15	0.951	4.1	1.4	4.3	0.95
Kib/nyar	Grid		BIREMBO15	0.951	4.8	1.6	5.1	0.95
Kic-p20	Grid		GIKONDO15	0.96	6.5	3.2	7.2	0.9
Kigali	Grid		JABANA15	0.968	3.9	1.3	4.1	0.95
Kigali nord	Grid		GIKONDO15	0.96	6.8	3.3	7.5	0.9
Kigali sud	Grid		GIKONDO15	0.96	5.6	2.7	6.2	0.9
Kimihurura	Grid		GIKONDO15	0.96	5.6	1.8	5.9	0.95
Kinyinya	Grid		BIREMBO15	0.951	7.7	2.5	8.1	0.95
Kiyumba	Grid		Mt Kigali30	1	0	0	0	1
Masaka	Grid		GASOGI15	0.973	3.9	1.3	4.1	0.95
Mastel steel	Grid		Master steel	0.931	4.6	2.8	5.4	0.85

Master Steel	Grid		GAHANGA15	0.955	4.6	2.8	5.4	0.85
Mulindi	Grid		GASOGI15	0.973	3.9	1.9	4.3	0.9
NECC1	Grid		GIKONDO15	0.96	0.1	0	0.1	0.919
NECC2	Grid		GIKONDO15	0.96	5.8	2.8	6.4	0.9
Nyagasambu	Grid		GASOGI15	0.973	0.9	0.3	1	0.95
Nyamirambo	Grid		Mt KIGALI	0.99	5.2	1.7	5.5	0.95
Nyarurama	Grid		GIKONDO15	0.96	0.4	0.1	0.4	0.949
PI	Grid		GIKONDO15	0.96	0.1	0.1	0.2	0.852
Pom-kim	Grid		GIKONDO15	0.96	3.1	1.5	3.4	0.9
Pylon20	Grid		GAHANGA15	0.955	5.3	3.3	6.3	0.85
Rebero	Grid		Mt KIGALI	0.99	1.5	0.5	1.6	0.951
Rubungo	Grid		NDERA15	0.964	2.6	0.8	2.7	0.951
Rusororo	Grid		GASOGI15	0.973	1.6	0.5	1.7	0.95
Rutongo	Grid		JABANA15	0.968	4.9	1.6	5.2	0.95
Rutunga	Grid		GASOGI15	0.973	0.7	0.2	0.7	0.949
Skol industry	Grid		SKOL	0.935	6.7	3.3	7.5	0.9
Sucrerie	Grid		JABANA15	0.968	0.1	0.1	0.1	0.844
Utexrwa	Grid		JABANA15	0.968	4	2.5	4.7	0.85
rubungo1	Grid		BIREMBO15	0.951	7.6	3.7	8.4	0.9
sonatube	Grid		GIKONDO15	0.96	1.4	0.9	1.6	0.85

- **Load flow analysis Without Prosumer integrated.**

Table 5: Busbar voltage results before prosumer integration

Name	Grid	Nom.L-L Volt.	Ul, Magnitude	u, Magnitude
		kV	kV	p.u.
GAHANGA15	Grid	15	14.3	0.955
Master steel	Grid	15	14	0.931
NZOVE15	Grid	15	14.3	0.955
SKOL	Grid	15	14	0.935

Table 6: Power distribution transformer loading results before prosumer integration

Name	Grid	Loading
		%
Nzove 110/15kV, 20MVA	Nzove	92.7
Gahanga 110/15kV, 20MVA	Gahanga	89.9

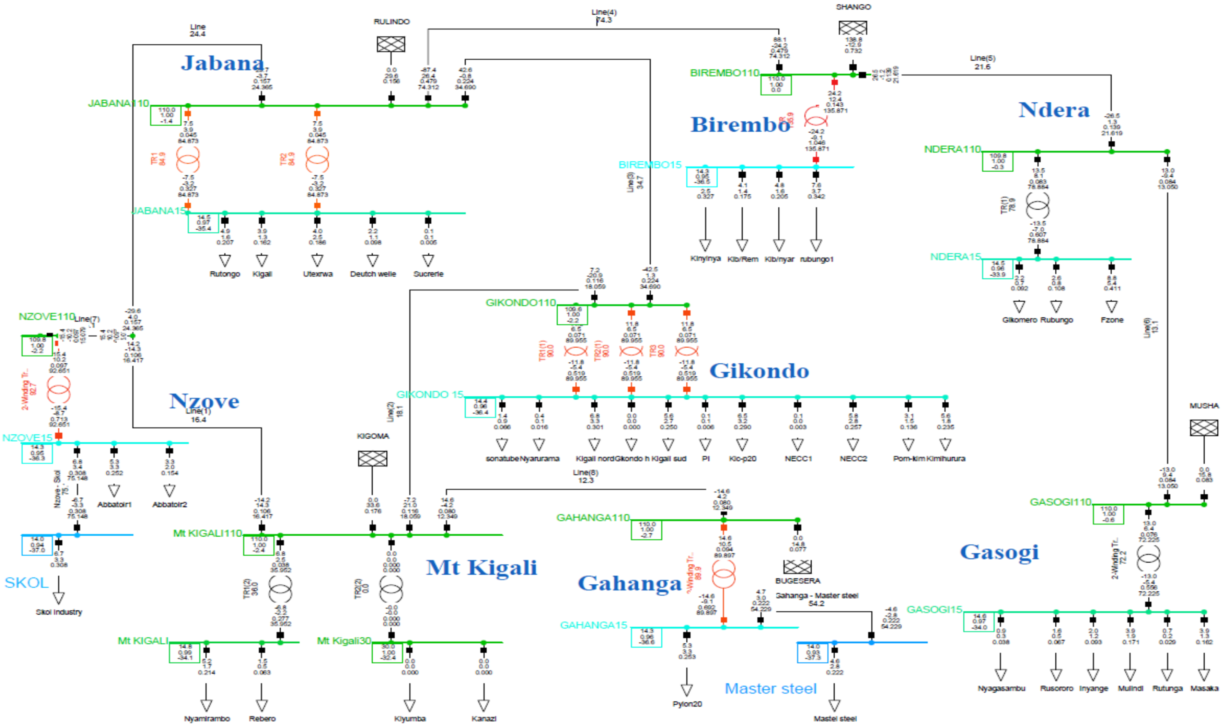

Figure 10: Load flow analysis before prosumer integration

- **Load flow analysis with 10% Prosumer penetration.**

Table 7: Busbar voltage results after 10% prosumer penetration

Name	Grid	Nom.L-L Volt.	Ul, Magnitude	u, Magnitude
		kV	kV	p.u.
GAHANGA15	Grid 10%	15	14.3	0.951
Master steel	Grid 10%	15	13.9	0.928
NZOVE15	Grid 10%	15	14.3	0.956
SKOL	Grid 10%	15	14.1	0.939

Table 8: Power distribution transformer loading results after 10% prosumer penetration.

Name	Grid	Loading
		%
Nzove 110/15kV, 20MVA	Nzove	88.2
Gahanga 110/15kV, 20MVA	Gahanga	87.1

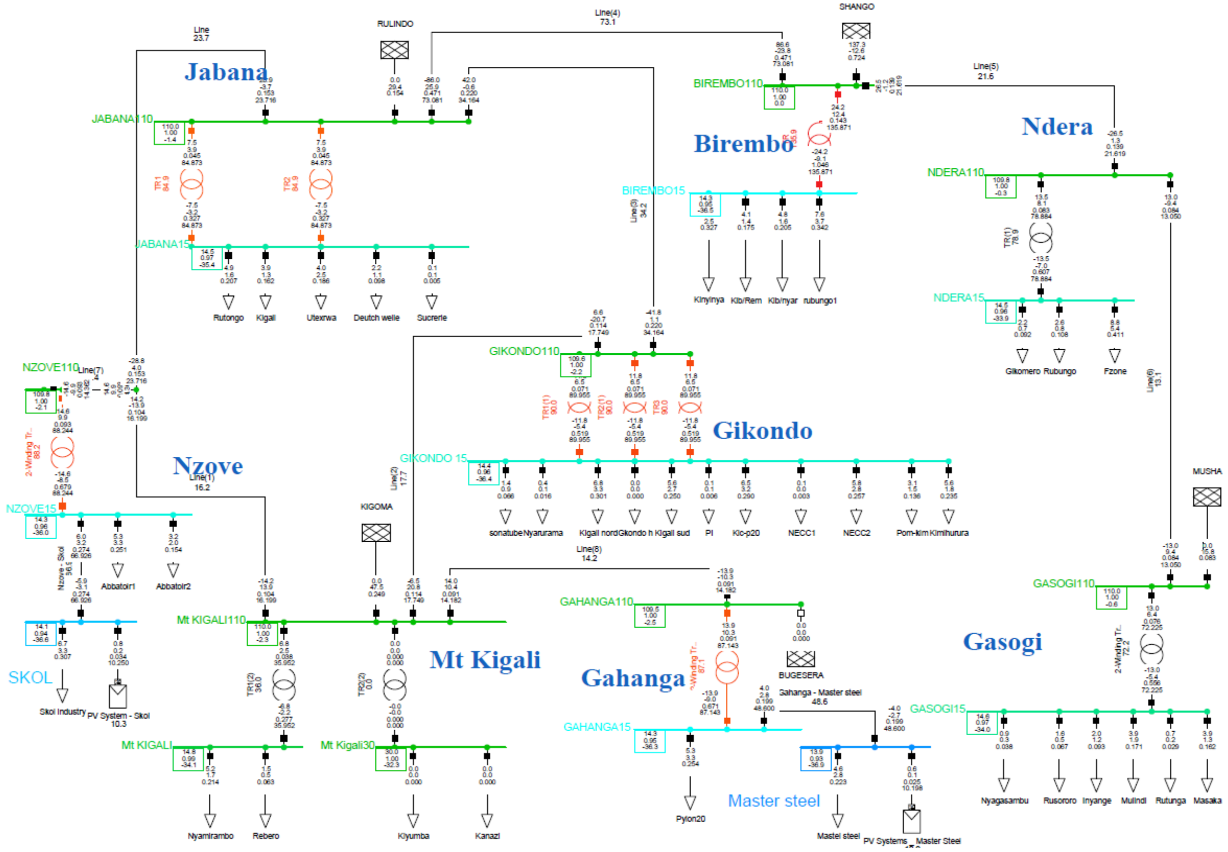

Figure 11: Load flow analysis after 10% prosumer penetration

- **Load flow analysis with 30% Prosumer penetration**

Table 9: Busbar voltage results after 30% prosumer penetration

Name	Grid	Nom.L-L Volt.	Ul, Magnitude
		kV	kV
GAHANGA15	Grid 30%	15	14.3
Master steel	Grid 30%	15	14
NZOVE15	Grid 30%	15	14.4
SKOL	Grid 30%	15	14.2

Table 10: Power distribution transformer loading results after 30% prosumer penetration.

Name	Grid	Loading
		%
Nzove 110/15kV, 20MVA	Nzove	79.6
Gahanga 110/15kV, 20MVA	Gahanga	80.8

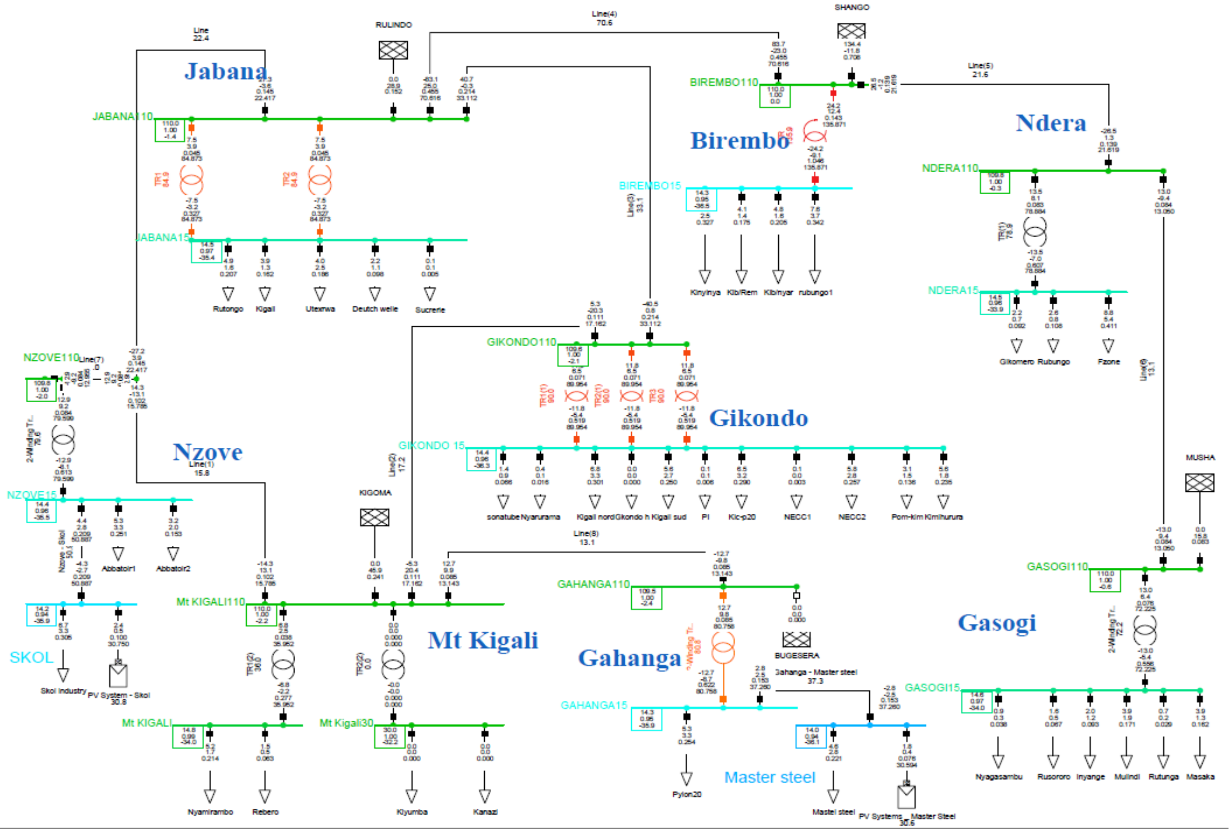

Figure 12:Load flow analysis after 30% prosumer penetration

- **Load flow analysis with 50% Prosumer penetration**

Table 11: Busbar voltage results after 50% prosumer penetration

Name	Grid	Nom.L-L Volt.	Ul, Magnitude
		kV	kV
GAHANGA15	Grid 50%	15	14.3
Master steel	Grid 50%	15	14.1
NZOVE15	Grid 50%	15	14.4
SKOL	Grid 50%	15	14.3

Table 12: Power distribution transformer loading results after 50% prosumer penetration.

Name	Grid	Loading
		%
Nzove 110/15kV, 20MVA	Nzove	71.2
Gahanga 110/15kV, 20MVA	Gahanga	74.6

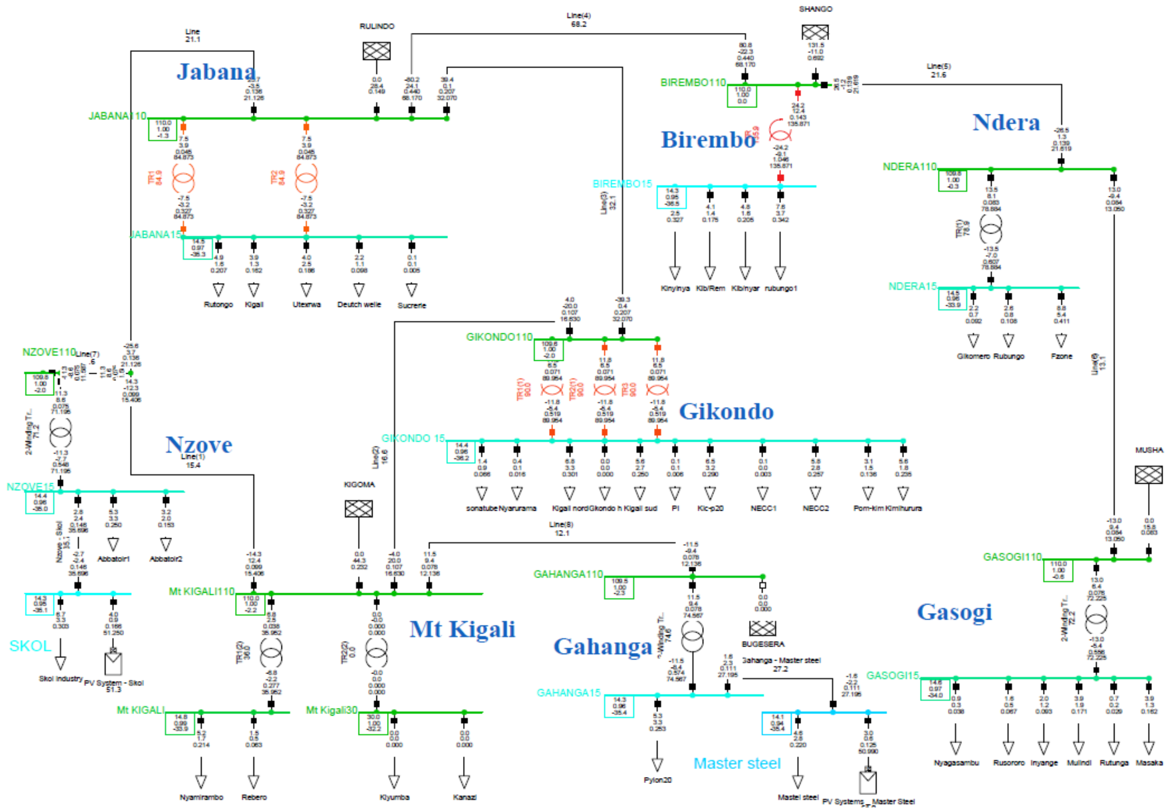

Figure 13: Load flow analysis after 50% prosumer penetration

- **Load flow analysis with 100% Prosumer penetration**

Table 13: Busbar voltage results after 100% prosumer penetration

Name	Grid	Nom.L-L Volt.	Ul, Magnitude
		kV	kV
GAHANGA15	Grid 100%	15	14.4
Master steel	Grid 100%	15	14.3
NZOVE15	Grid 100%	15	14.5
SKOL	Grid 100%	15	14.5

Table 14: Power distribution transformer loading results after 100% prosumer penetration.

Name	Grid	Loading
		%
Nzove 110/15kV, 20MVA	Nzove	51.5
Gahanga 110/15kV, 20MVA	Gahanga	60.1

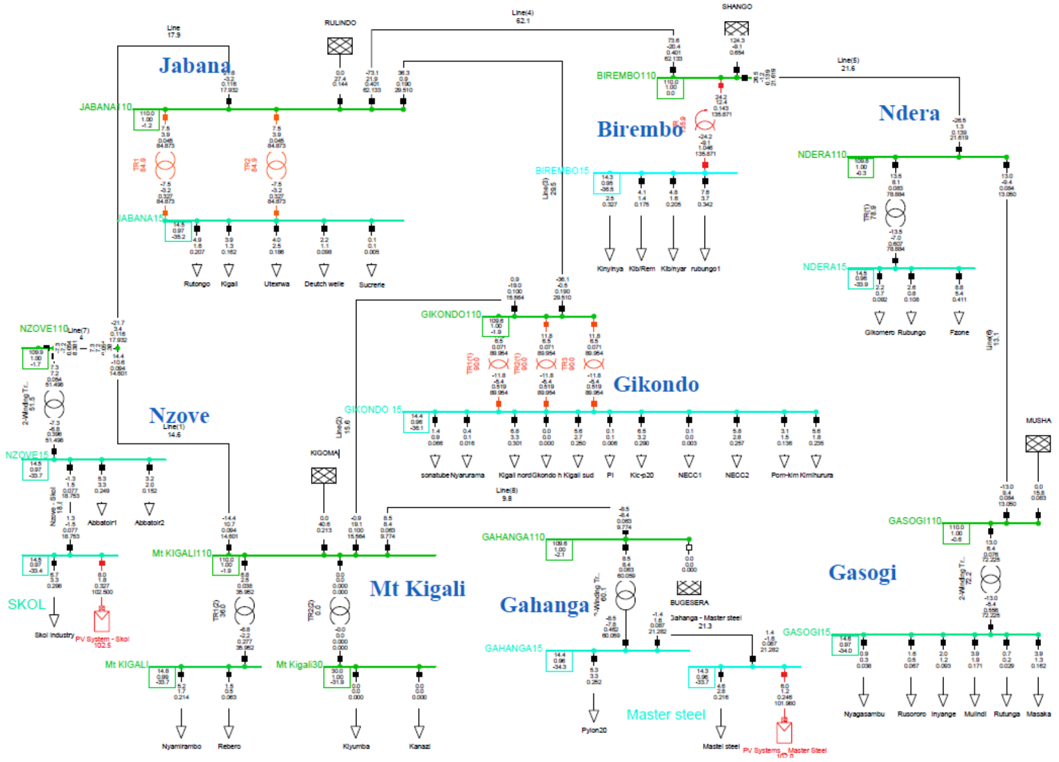

Figure 14: Load flow analysis after 100% prosumer penetration