High Voltage Transmission System Planning for a Southern African Regional Grid

By

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DEDICATION

This thesis is dedicated to my children Mvelo, Ntsika, Mpilwenhle, and Sethabile Ndlela.

Lastly, I gratefully dedicate this thesis to God Almighty, my source of wisdom, knowledge, and insight, in gratitude for his faithful assistance in completing this thesis.

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ABSTRACT

It is proposed to use highly complex power system controllers to integrate African power grids into super-grids capable of accepting high levels of renewable energy penetration while maintaining power quality, active and reactive power flow, voltage, and power system stability. The proposed super-grid is built with ultra-high voltage direct current (UHVDC) and flexible AC transmission systems (FACTS), as well as dedicated AC and DC interconnectors with intelligent system applications, to create a Smart Integrated African Super-Grid. DC interconnectors will divide the continent's power grid into five substantial asynchronous portions (regions). Asynchronous segments will restrict AC fault propagation across segments while permitting power interchange between various regions of the super-grid, with minimal difficulties for grid code unification or harmonization of regular design regimes across the continent, as each segment retains its autonomy. A Smart African Integrated Electrical Power System Super-Grid powered by these technologies is critical to Africa's long-term economic growth and development; it is built on the foundation of green energy and harnesses over 200GW untapped potential of Africa's clean renewable hydro-electric, solar-PV, and wind power as part of a vast energy mix comprised of conventional and alternating energy resources. The proposed Super-Grid will power Africa's emerging economy and serve its 1.3 billion people by facilitating electricity trading and power exchange between regional power pools and countries. This study focuses on the development of the Southern African Power Pool (SAPP), into a robust Southern Africa regional grid (SARG), and prospects for a Smart Integrated African Super Grid.

The Southern African countries have the potential to have a reliable, sustainable, and efficient electrical power grid; thus, the use of renewable energy is strongly encouraged, as is upgrading the existing AC grid, including encouraging power interconnections to exchange power more specifically for long-distance transmission networks when transmitting bulk power using High Voltage Direct Current (HVDC) and installing suitable FACTS controllers to maximize power transfer. Thus, the modernization of the traditional Power Grid into a Smart Grid will enable two-way digital communication technology by providing utilities with real-time, precise data on electricity demand, power outages, and quality of supply. This study develops a load flow model for a robust Southern African Regional Grid, and introduces a number of power interconnections for power exchange in the Southern African Regional Grid, to increase grid reliability, and reduce electrical losses. This load flow analysis was carried out using DIgSILENT PowerFactory. Results obtained from varying the load and observing the generator and transmission lines for different scenarios, using HVDC, and HVDC transmission links with FACTS controllers, are discussed and presented. This study is valuable as we seek to enable all SAPP countries to interchange power more efficiently, especially those who lack access to electricity.

DECLARATION 2-PUBLICATIONS

This research work resulted in the following publications:

[1] N. W. Ndlela and I. E. Davidson, "Power Planning for a Smart Integrated African Super-Grid," in *2022 30th Southern African Universities Power Engineering Conference (SAUPEC)*, Durban, South Africa, 25-27 Jan. 2022: IEEE, pp. 1-6, doi: 10.1109/SAUPEC55179.2022.9730631.

[2] N. W. Ndlela and I. E. Davidson “Reliability and Security Analysis of The Southern Africa Power Pool Regional Grid.” In *Proceedings 2022 IEEE PES/IAS Power Africa Conference*, Kigali, Rwanda, 22 – 26 August 2022.

[3] N. W. Ndlela and I. E. Davidson “Load Flow Analysis of the Southern African Power Pool Interconnections using High Voltage Alternating Current, High Voltage Direct Current, and Flexible AC Transmission System.” In *Proceedings 2022 IEEE PES/IAS Power Africa Conference*, Kigali, Rwanda, 22 – 26 August 2022.

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LIST OF ABBREVIATIONS

A	Amps
AC	Alternating Current
ACFTA	Africa Continental Free Trade Area
CAPP	Central African Power Pool
COUE	Cost of Unserved Energy
DC	Direct Current
DVR	Dynamic Voltage Restorers
EAPP	Eastern African Power Pool
EENS	Expected Energy Not Served
EIA	Energy Information Administration
FACTS	Flexible AC Transmission System
GDP	Gross Domestic Product
GHG	Greenhouse gas
GW	Gigawatts
HV	High Voltage
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current

Hz	Frequency
ICT	Information Communication Technology
IEA	Information Energy Agency
IPPs	Independent Power Producers
km	Kilometre
kV	Kilovolts
kWh	Kilowatt-hours
LCC	Line Commutated Converter
MW	Megawatts
NAPP	Northern African Power Pool
PEs	Power Electronics
PLL	Phase-Locked-Loop
PCC	Point of Common Coupling
PU	Per Unit
PV	Photovoltaic
P-V Curves	Power Voltage Curves
PWM	Pulse width Modulation
Q-V Curves	Reactive Voltage Curves
QOS	Quality of Supply
RE	Renewable Energy
ROW	Right-of-Way
SADC	Southern African Development Community
SAPP	Southern African Power Pool

SCADA	Supervisory Control and Data Acquisition
SCFCL	Superconducting Fault Current Limiters
SSA	Sub-Saharan Africa
SS	Substation
STATCOM	Static Compensator
ST	Sub-Transmission
SVC	Static Var Compensator
TCR	Thyristor Controlled Reactor
Tx	Transmission Line
Xfmr	Transformer
TSC	Thyristor Switched Capacitor
UHV	Ultra High Voltage
UPFC	Unified Power Flow Controller
VSC	Voltage Source Converters
UHVDC	Ultra High Voltage Direct Current
WAPP	Western African Power Pool

CHAPTER 1 INTRODUCTION

1.1 Background

Africa is made up of 54 countries with five power pools: Northern, Central, Western, Eastern, and Southern African Power Pools. These power pools are primarily designed to operate the power system in their respective regions in Africa, resulting in increased levels of interconnection and power exchange [1]. According to the International Energy Agency (IEA), Africa is currently facing numerous challenges in the electricity sector. approximately 600 million people in Sub-Saharan Africa (SSA) still lack access to electricity, and those who do have access to electricity experience power outages more frequently [2-6]. Africa's low energy consumption levels contrast sharply with its availability of renewable energy resources. The continent possesses the world's largest renewable energy resources, and energy-bearing materials, with a renewable energy potential adequate to cover the continent's future energy, needs as shown in Figure1.1 [7].

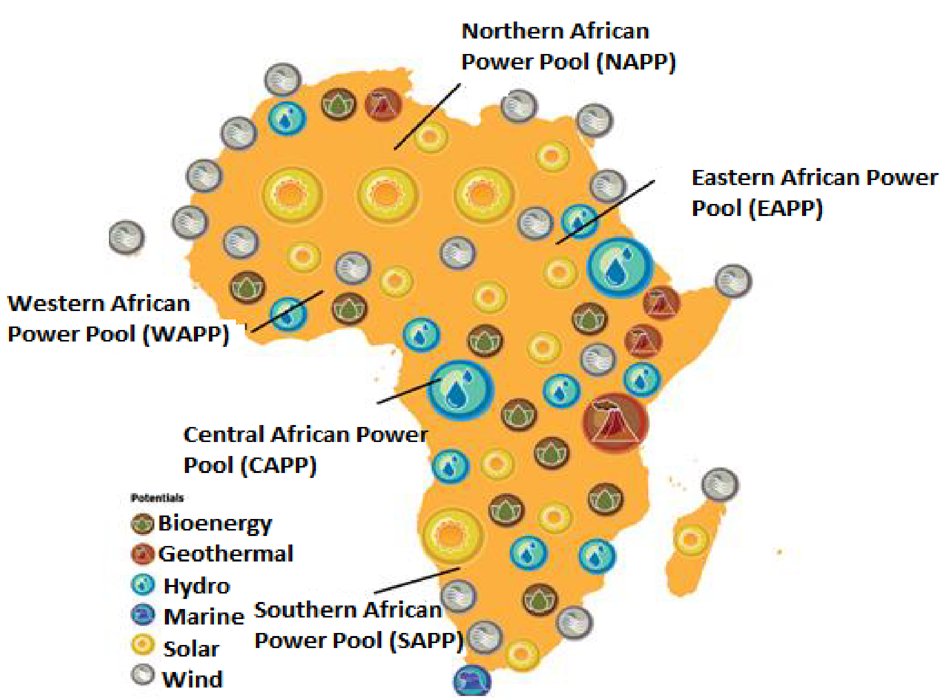


Figure 1. 1 Five Africa's Regional Pool and Renewable Potential in Africa [7].

The existing regional power pools in Africa are represented in Figure 1.2, which is separated into five asynchronous regions [8]. The goals of regional power integration are to encourage power exchange among member countries, export power to other regions experiencing energy shortages, invest in low-cost power facilities, and offer customers reliable and affordable electricity [6, 9].

Figure 1. 2 Africa's Regional Power Pool: NAPP, SAPP, WAPP, EAPP, and CAPP [8].

Electric energy is the most widely used source of energy because it is easily transported at a low cost and with high efficiency [10]. Africa is known as the continent with the greatest availability of renewable energy, specifically solar energy (thermal and photovoltaic), coal, and wind energy [11, 12]. It is also known as the continent with the least access to electricity, with approximately 43% of the population lacking access to grid electricity [13].

Global gross installed power generation capacity increased from 3000GW to around 3750GW in 2000 and was predicted to reach 6000GW by 2020 [9, 14]. Africa, which comprises approximately 13% of the world's population, accounts for approximately 2% of global economic production. Africa's real Gross Domestic Product (GDP) as a percentage of global GDP has remained stable at roughly 2% since 1970 and is likely to remain stable through 2020 [9]. Africa's population has risen dramatically from 364 million in 1970 to 1.3 billion in 2020, with a projected increase to 2.0 billion by 2050, making it the world's largest labor pool. According to the IEA, more than US$250 billion in extra investment in electricity generation, transmission, and distribution will be needed by Africa to guarantee universal access to electricity [3, 9]. Distribution and transmission in the majority of countries are extremely vulnerable and overburdened; there is an urgent need for investment to strengthen and expand the power transmission and distribution systems [15, 16].

The Africa Continental Free Trade Area (ACFTA) provides the potential for the establishment of an African continent-wide electricity market. This market has the potential to promote competent infrastructure growth and symbiotic power trading among Africa's five regional electric power pools, an Africa Union strategy for equitable growth and long-term development with the general objectives which include [17]:

- Establish a unified and liberalized market for goods and services.
- Enable free movement of people and investment to strengthen economic integration and encourage inclusive and sustainable socio-economic growth.
- Resolve the issues of various and overlapping memberships and accelerate regional and continental integration.
- Establish the framework for a continental customs union.
- Encourage industrial growth and strengthen member nations' economic competitiveness.

The AFCFTA creates a greater potential to expand Africa's access to power. Cross-border power trade in Africa has the ability to reduce electricity costs, improve supply reliability and security, expand customer choice, and increase renewable energy generation integration [18].

This study focuses on the Southern Africa regional grid and hence SAPP. SAPP has a lot to be concerned about when it comes to electricity usage, particularly when it comes to supplying developing countries. There is an urgent need to examine the current architecture of electrical power systems in SAPP countries in order to ensure that they deliver sufficient, sustainable, and reliable electricity [19]. In addition, electricity demand is increasing daily as a result of population growth in Southern African countries, and inadequate infrastructure [4, 20, 21]. Nearly 600 million people in SSA are still lacking electricity access [22-24]. Those who have access to electricity frequently experience power outages This is due to infrastructural breakdowns and capacity limitations as a result of the generation fleet's expansion being unable to keep pace with demand growth [2]. Figure 1.3 illustrates the total installed capacity and population of each pool in the African region, as obtained from [1, 3, 25-27].

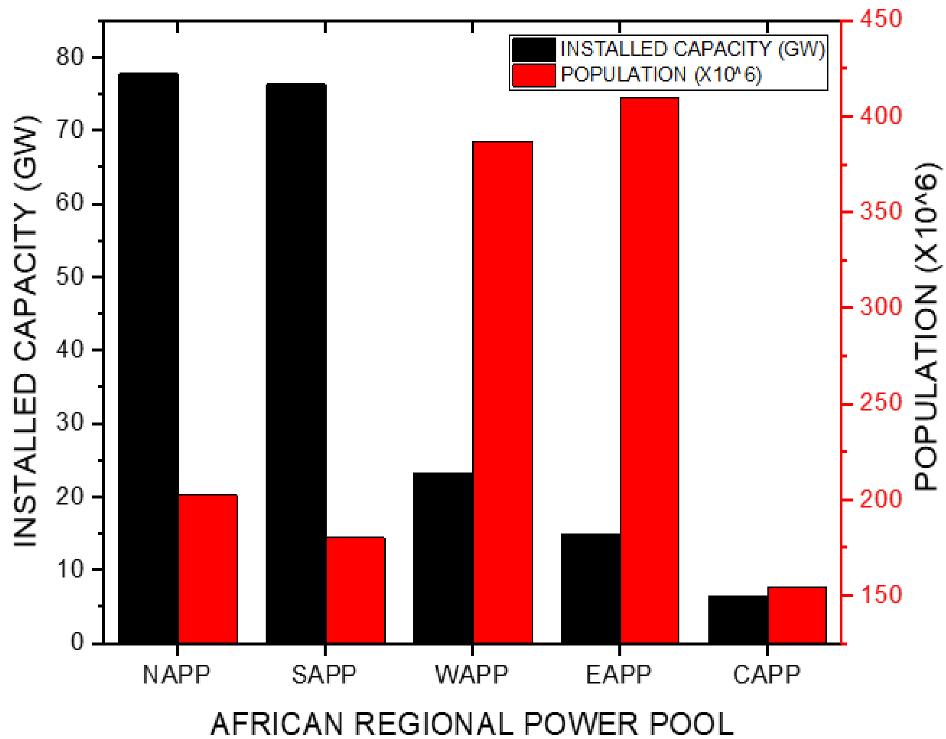


Figure 1. 3 Installed capacity & population for five African power pools.

The projected Southern African power planning plan would focus on the reliable alternative of transmitting electricity through the use of suitable HVDC and FACTS devices and power exchange in the Sothern Africa region, with a focus on developing countries such as Lesotho, which has roughly 45% access to electricity, Mozambique, which has 29% access to electricity, and Malawi, which has 11% access to electricity [28]. With the goal of importing electricity from nations such as South Africa, which has roughly 95% electrical access, Swaziland, for instance, imports the majority of its electricity from South Africa and Mozambique [3]. additionally, by using renewable energy to generate electricity The environment will be kept clean, and electricity will be provided at a reduced rate [29].

Africa's population is currently at 1.33 billion people, with an installed capacity of around 200GW as shown in Figure 1.3, Eastern African Power Pool (EAPP) has the majority of the population on the African continent with not adequately installed capacity to meet the countries population, whereas NAPP has the largest installed capacity to provide 100% access to the NAPP as shown in Figure 1.3.

1.2 Problem statement

The issue is an insufficient national electricity supply to fulfill demand. This is mostly due to the need for extensive unscheduled maintenance at Eskom's aged coal-fired power plants [30]. The figures for power outages in the Southern African region have increased significantly over the past decade as a result of several aspects, including member countries' insufficient electrical power supply systems; load expansion in areas that were inadequately planned for; and rapid population growth and economic expansion, making it challenging for each Southern African country to satisfy peak demand within its borders [31]. According to [3] electricity access in SSA is 43% with more than half of the countries in the region falling below this average [32]. This study simply proposes increased generation (from coal, hydro, uranium, wind, solar, nuclear, diesel and gas) and delivery capacity to meet customer needs across the region, while increasing investment in clean energy sources.

The goal is that by developing a regional power grid that absorbs large quantities of Renewable Energy (RE) generation, as part of the energy mix, and with interconnections for power exchange, the Southern Africa region will be better served. The analysis of this study describes how to increase grid reliability by managing voltages with an SVC, It also discusses an efficient technique for optimizing SARG power transfer over long-distance bulk power transportation through HVDC-LCC.

1.3 Aim of the study.

This study aims to increase access to electricity in the Southern African region through the development of a robust Southern African Power Grid by increasing the number of power interconnections with HVDC and FACTS devices where necessary.

1.4 Objectives of the study.

- Determining the Southern Africa power plant portfolio and High Voltage transmission infrastructure for the creation of load flow modeling using the DigSILENT PowerFactory software
- To identify the existing power interconnection across the region and introduce possible power new interconnection, by utilizing HVDC technologies and FACTS devices to enhance power delivery capacity across the region.
- To improve the existing traditional electrical power system by making it smarter and more efficient through the application of appropriate technologies, such as FACTS devices and HVDC links in conjunction with the HVAC transmission line.
- Modeling of the Southern African Regional grid using HVAC, with HVDC interconnection where there are greater losses, including FACTS devices for voltage instability where necessary to optimize power flow in the Southern African region and enhance the performance of existing power interconnection.

1.5 Motivation

Every aspect of human development is dependent on a reliable and stable energy supply system [9]. Due to that, a constant supply of reliable, sustainable, and sufficient electric power in the Southern African region is required, and that is possible by first looking at the security status of the regional power network. This information is extremely useful to gather methods to improve the current situations and to brand provision for future amplification where necessary.

To ascertain the Southern African region's security condition, a load flow study of the Southern African grid model will be performed. DIgSILENT PowerFactory is planned to play a significant part in this research by assessing load flow using HVAC with FACTS devices where necessary and HVDC transmission lines over long distances to exchange electricity within the Southern African region. This will then enable 100% access to all developing countries whilst maintaining grid reliability.

1.6 Hypothesis

The hypothesis of this research will be to modify the SARG and increase the number of power interconnections, which will lead to increased electricity access in the region. The development of grid reliability and electricity enhancement through the use of modern technology such as HVDC and FACTS devices.

1.7 Research question

The following research questions will be addressed in this study:

- What is the current level of access to electricity in each Southern African country?
- What is the current installed capacity in Southern Africa??
- What is the imbalance between supply and demand for electricity in Southern Africa?
- What are some feasible solutions for enhancing power transfer?
- What will be the reduction losses In the SARG due to the use of HVDC lines for long-distance power transfer carrying bulk power?
- What are the possible solution to minimize voltage instability

1.8 Research contribution

This SARG will include all the Southern African countries and will explore for alternative solutions to enhance power generation where appropriate, as well as apply all available technologies to increase the SARG transfer capabilities and power stability, This study is aiming to provide 100% electricity access to Southern African countries.

1.9 Delimitations and Limitations

This study focuses on the existing and possible new high-voltage SARG transmission network to exchange power, and the possible effective solution to enhance power transfer and make the grid more robust.

1.10 Organization of the thesis

This thesis is divided into six chapters:

Chapter 1 - introduction, background, problem statement, the significance of this study, and the motivation for conducting it.

Chapter 2 – Literature review and introduction of modernization of the traditional power system or smart grids.

Chapter 3 - discusses the SARG's history, connections, and power exchange.

Chapter 4 - details the step-by-step methodology used to approach the Southern African power interconnection.

Chapter 5: contains the obtained SAPP simulation findings, while

Chapter 6: the conclusion and future work.

CHAPTER 2 LITERATURE REVIEW

This chapter provides an overview of the most cost-effective solution for bulk power transmission lines over large distances for power exchange between Southern African countries. Overhead transmission (Tx) lines are significantly less expensive than an underground system. Thus the popular overhead Tx lines are HVAC which results in losses proportional to the distance traveled, and HVDC, which results in minimal losses over long distances when carrying bulk power. HVDC is designed by converting AC power to DC power which provides improved active and reactive power compensation during electrical power transmission over a large distance. In case of voltage instability, the use of FACTS devices, which is a combination of shunt and series converters, improves voltage stability by controlling some of the reactive power in HVAC. The purpose of this project is to develop a load flow model for the future SARG using the aforementioned technologies to ensure the SARG is reliable, sustainable, sufficient, and secure.

2.1 HVAC Technologies

Bulk energy transmission and connectivity are possible via HVAC or HVDC lines [33, 34]. HVAC has historically been the primary transmission system, owing to the early discovery of AC transformers, which enabled the transmission of HVAC over longer distances with reduced losses [35], The history of what is now referred to as alternating current transmission began in 1911 with the commissioning of the 110 kV line connecting Lauchhammer and Riesa, Germany. Since then, rated AC voltages for transmission lines have continually increased, reaching 1200 kV for ultra-high voltage (UHV) systems [36]. The goal of AC grids has constantly been to provide low-cost, disruption-resistant results. The AC power grid is intrinsically susceptible to environmental disturbances, However, over the last decade, the development of power electronics (PEs) and variations in load and generator characteristics have established a game-changer at an extraordinary rate [37, 38].

The primary objective of HVAC and HVDC transmission lines (TL) is to carry bulk power. Due to AC transmission lines having a large capacitance, voltage regulation becomes a major issue [39]. For both AC and DC TLs, the voltage of the TL is inversely proportional to the transmission line's losses [40].

The transmission network's primary objective is to transfer electricity from generating power stations located in various locations to the distribution system, which ultimately supplies the load. Choosing the voltage and conductor size is primarily determined by weighing ZI^2 losses, audible noise, and radio interference against the investment's fixed costs. For TL operating at voltages more than 69kV, 88kV, 115kV, 132kV, 138kV, 161kV, 230kV, 275kV, 345kV, 400kV, 500kV, and 765kV line to line, 50Hz frequency is utilized as the standard frequency [10].

2.1.1 Limitations of HVAC

- Line compensation required
- Skin effect and losses
- Distance limitation
- Regulation issues such as frequency and voltage
- Asynchronous connection
- Reactive power and impedance
- Frequent tripping [33, 37].

2.1.2 Conditions of HVAC Power interconnections

- Same frequency
- Same phase angle
- Same voltage

Traditionally, voltage stability in HVAC and HVDC systems has been researched for simple power system models However, in the literature, stability indices have only been examined for each unique technology. The traditional approaches for calculating the stability margin of an HVAC system rely on QV and PV curves. These curves can be used to determine steady-state voltage stability indices such as reactive power margin, point of collapse, and voltage stability factor [41].

2.2 HVDC Technology

Due to its numerous advantages, including long-distance transmission, high capacity, no synchronization, and broader application scope, HVDC transmission technology has been widely adopted [42, 43]. Because of their technological and economic exceptionalism over HVAC systems for long-distance transmission, HVDC systems are becoming increasingly important in long-distance transmission. HVDC is preferred for overhead point-to-point transmission projects beyond 300–800 km, as well as cable-based interconnection or grid integration of remote offshore wind farms located over and above 50–100 km[35, 43-45].

Table 2. 1 HVAC & HVDC Economical Power transfer over Transmission distance [36].

System	Voltage/ Current	Economical power transfer	Transmission distance
AC	500kV	1000MW	300-500 km
AC	1000kV	5000MW	1000-2000 km
DC	$\pm$500kV	3000MW	500-1500 km
DC	$\pm$800kV/5000A	8000MW	1000-2000 km
DC	$\pm$800kV/6250A	10000MW	1000-2000 km
DC	$\pm$1100kV/5000A	11000MW	1500-3000 km

Table 2.1 above compares the economic power transfer of HVAC and HVDC over a transmission distance, stating that for a 500kV AC system, the economic power transfer is 1000MW over a distance of approximately 500km, whereas, for a 500kV DC system, the economic power transfer is 3000MW over a distance of 500km-1500km [46].

Table 2.2 compares AC and DC technologies from a technological, economic, and social perspective [47]. Despite obvious technological differences, this qualitative data illustrates the discrepancy between social repercussions and line cost. From a technical perspective, a cheaper approach may have greater social ramifications, which may lead to a greater economic impact on the project, difficulties, slowdowns, or even cancellation. The data presented in Table 2.2 is also independent of line length.

Table 2. 2 transmission line technologies comparison [36].

Name	AC Cable	AC OHL	VSC HVDC	LCC HVDC

Cost	High	Low	High	Medium
Losses	Low	Low	Medium+	Medium
Power reversal	Swiftly	Swiftly	Swiftly	Slow
Modeling approach	Low	High	Low (if cable)	Low (if cable)
Grid interconnections	Synchronous	Synchronous	Any	Any
Reactive power control	No	No	Yes	Yes
Power Oscillation damping	No	No	Yes	Limited
Active power control	No	No	Yes	Yes

The overall amount of HVDC and HVAC transmission is depicted graphically in Figure 2.1 (a), and it is determined by economic and technical aspects such as cost and transmission line distance. Furthermore, the station cost, line cost, and losses are shown in figure 2.1 (B) [35].

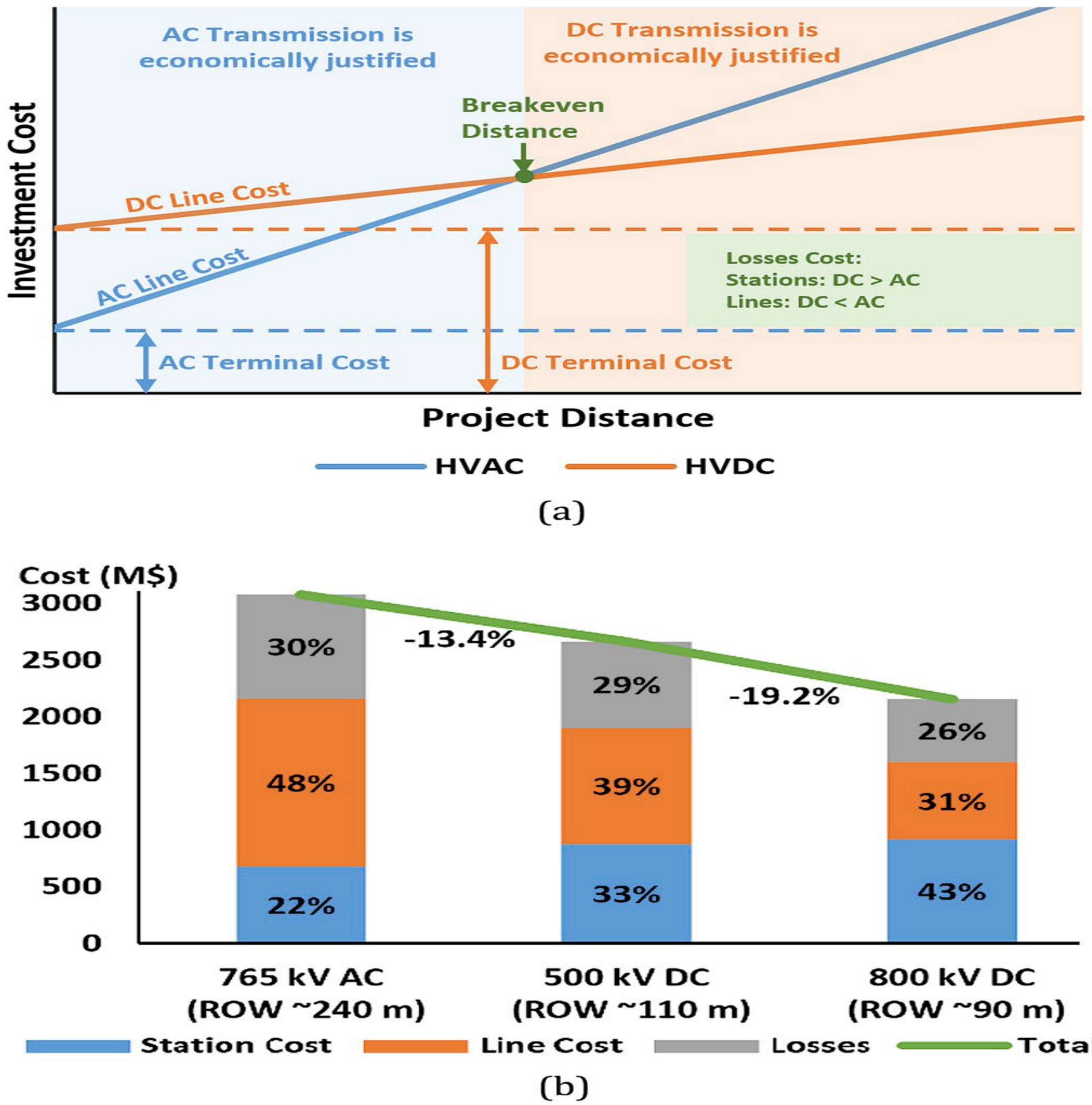


Figure 2. 1 HVAC vs. HVDC cost comparison: (a) qualitative breakeven distance assessment. (b) Cost and ROW estimation for a generic 6000 MW transmission for 2000 km [35].

2.2.1 HVDC Features

Connecting HVDC links to AC grids always necessitates the use of rectifiers/inverters. This is required for converting the AC voltage to a steady DC voltage and back to an AC voltage. Rectifiers/inverters are described as converters. Typically, the decision to choose HVDC over HVAC is encouraged by the benefits afforded by HVDC links as shown in Figure 2.2 [48].

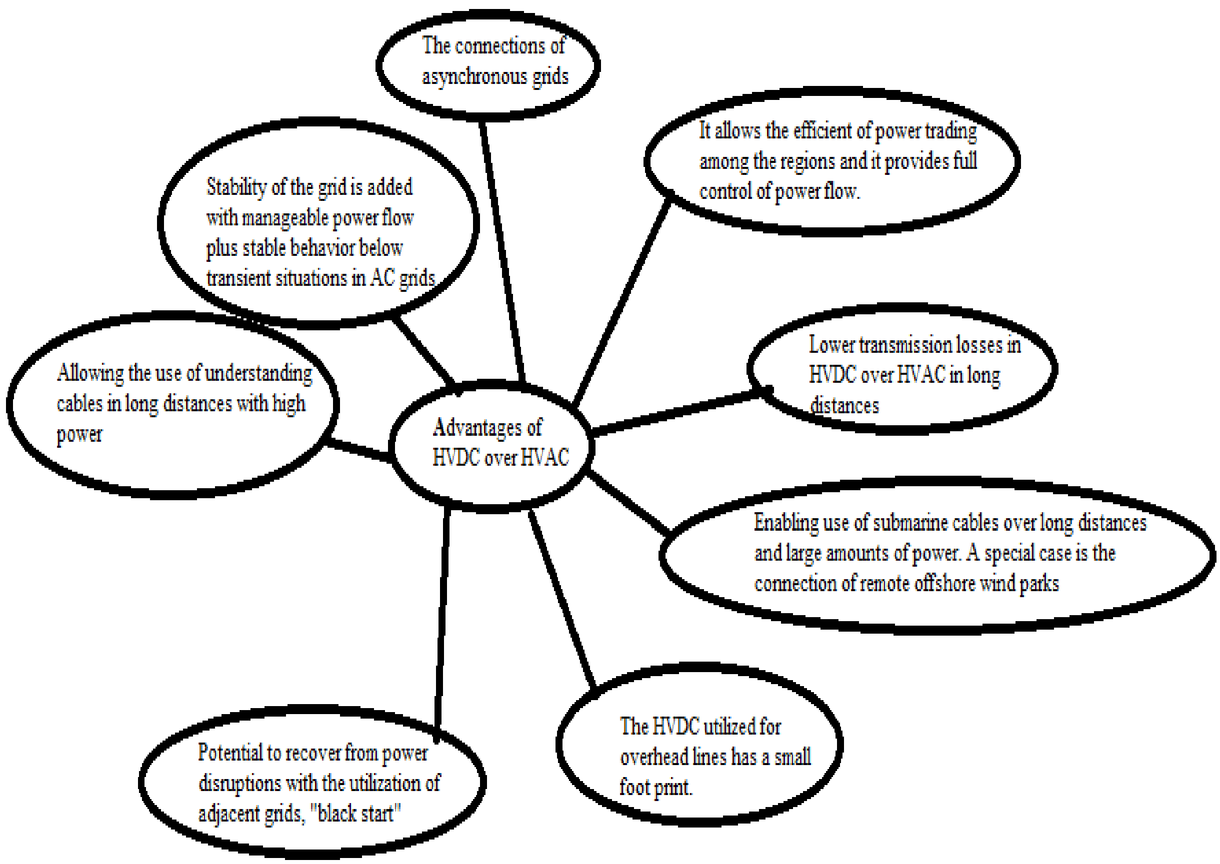


Figure 2. 2 Advantages of HVDC over HVAC

2.2.2 Types of HVDC

Typically, HVDC systems are bipolar or monopolar in configuration. Bipolar configurations are significantly more expensive to implement than monopole configurations since they require two ground-isolated lines and at least two converters for each terminal. However, due to the double power injection, this design provides benefits in terms of system protection and redundancy. Transformers that connect the AC grid to the converters are either of distinct groups or have two windings in bipolar topology [49, 50]. Generally, the configurations of both transformers for harmonic reduction will be different. Typically, one transformer is connected grounded-star to the delta transformer, while the other is connected to the grounded-star-star. Due to the improved flexibility provided by the bipolar arrangement, it is expected to be the preferred configuration for potential HVDC grid development [51]. With bipolar support, the DC grid can be configured in a variety of ways, including bipole with metallic return and bipole with the ground return [50], the common HVDC transmission configurations are shown in Figure 2.3.

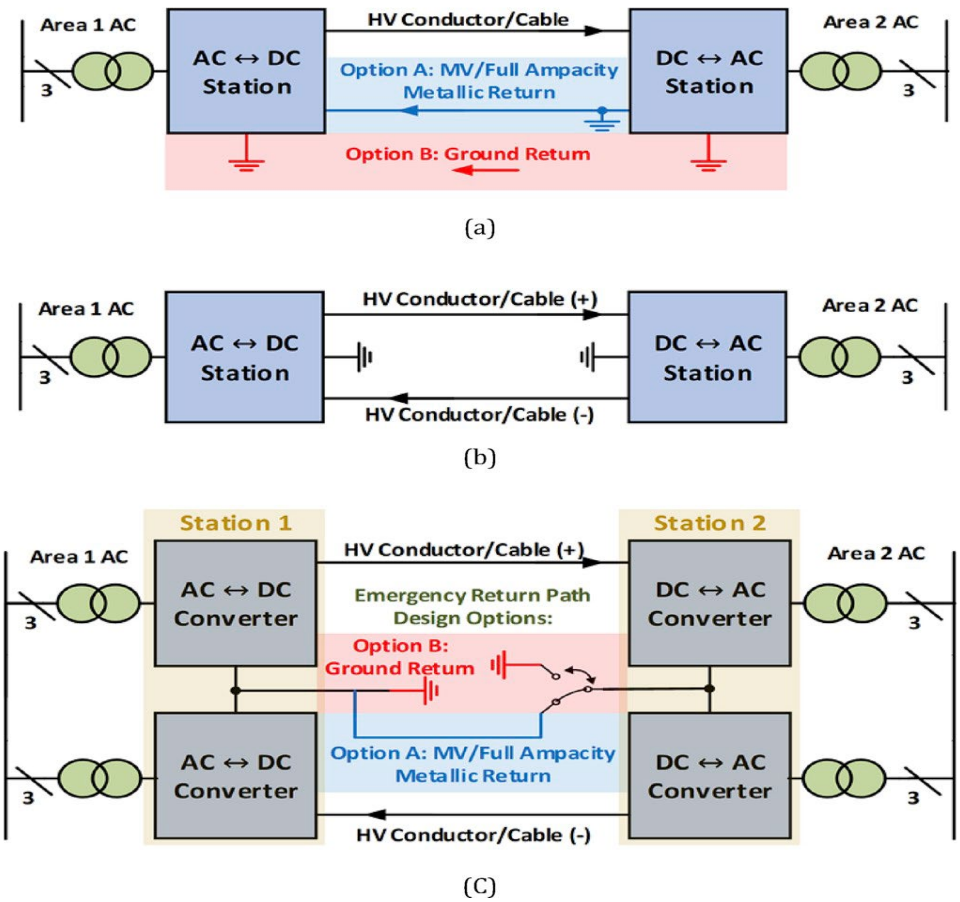


Figure 2. 3 typical HVDC Transmission configurations: a) Monopole with Metallic and earth electrode returns. b) symmetrical monopole. c) Bipole with both return possibilities [35].

a. Line Commutated Converter (LCC) HVDC transmission

As the name says, LCC converters function in accordance with the specifications of the AC transmission line. Their switching frequency is identical to that of the line (50–60 Hz). Gate control signals are applied to direct their working mode (i.e. rectifier/inverter) depending on the thyristor firing angles (ideally: 0-90° for rectifier mode and 90-180° for inverter mode), as well as to regulate power quality[35]. Figure 2.4 is the configuration of the LCC-HVDC scheme and Table 2.2 is the function of all the components of the LCC HVDC.

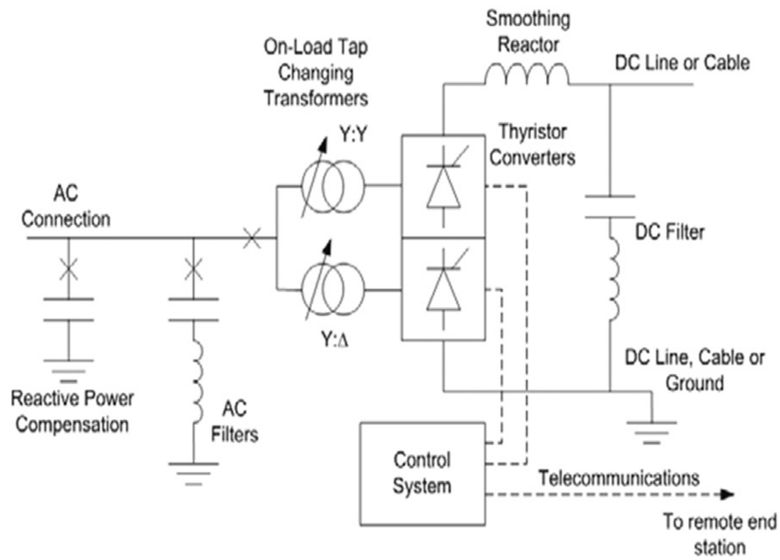


Figure 2. 4 LCC-HVDC system component [52].

Table 2. 3 Function of LCC-HVDC components [53].

component	***Function***
LCC Converters	• Heart of the system • Thyristor valves are the primary component.
AC filters	• Preventing current harmonics generated on the AC side of HVDC converters from entering the AC network, or at least decreasing them to a sufficient level
DC Filters	• Minimizing the ripple on the DC voltage • In charge of interferences near the DC line • They are required when the transmission medium is an overhead line, but not when using subterranean cables or back-to-back transmission.
Reactive Power Compensation	• Improving system stability and enhanced power availability

Transformers	• Connecting the AC network to the valve bridges and adjusting the AC voltage level Each converter requires the use of three transformers.
Control System	• It consists of two converters, one for managing the DC voltage and the other for controlling the DC current. • Obtaining the desired voltage and current combination

b. Voltage Source Converters (VSC) HVDC transmission

A voltage source converter grid is capable of independently controlling reactive and active power and requires fewer circuits to transmit the same amount of power. A DC grid is advantageous for enhancing the fault-ride-through capability and overall performance of an AC system [54].

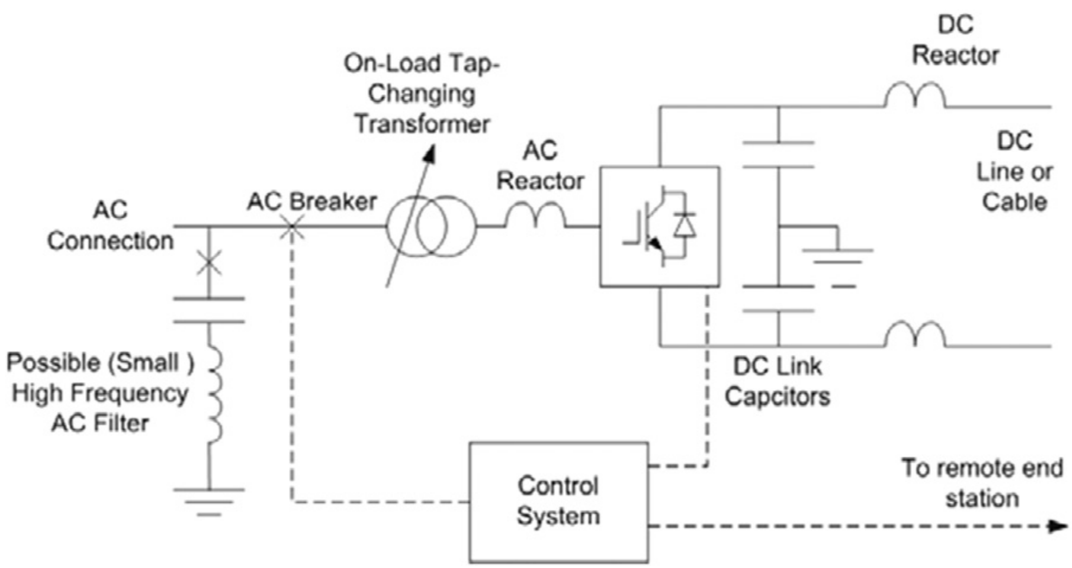


Figure 2. 5 VSC-HVDC system components [52].

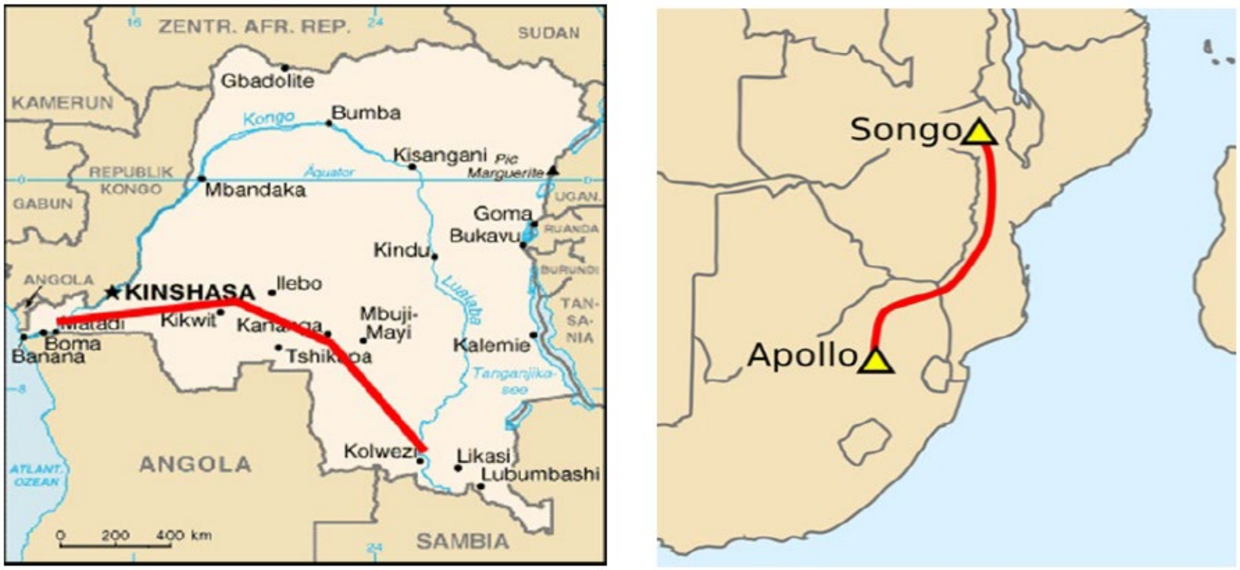
Table 2.3 below presents the components of VSC HVDC and the function of each component [55, 56].

Table 2. 4 Function of VSC-HVDC components [52].

Components	***Functions***

VSC Converters	• Heart of the system • IGBT valves are the main component.
Transformers	• controlling the AC voltage to the DC voltage level
Control System	• Independent control of active and reactive power. It is composed of a more powerful vector controller.
DC Capacitors	• Dropping voltage ripple on the DC side (as in LCC-HVDC transmission through DC filters) • Offering energy storage and the ability to regulate power flow. Their dimensions are determined by the needed DC voltage.
AC Filters	• Function identical to that found in LCC-HVDC systems. • However, no reactive power control is required. • Additionally, on the AC side, the current harmonics are linked to the Pulse Width Modulation (PMW) frequency. • In comparison to LCC, there are fewer filters.
Phase Reactors	• Currents control between active and reactive power • Minimize the AC's high-frequency harmonics.

There are existing HVDC lines such as Cahora Bassa Hydroelectric Generation Station, located at the Cahora Bassa Dam in Mozambique, which imports energy to Johannesburg (Apollo), as indicated in Figure 2.6(b), to supply South Africa's grid via an LCC-based HVDC power transmission system with thyristors as switching devices [57]. This is one of the world's extant HVDC point-to-point interconnections The first HVDC link between Gotland and the Swedish mainland was successfully commissioned in 1954 [58]. And The Inga–Shaba Extra HVDC (EHVDC) Intertie, seen in Figure 2.6(a), is a 1,700 km (1,100 mi) long HVDC overhead electric power transmission line [59].



(a) Inga–Shaba EHVDC (b) Cahora Bassa-Apollo HVDC

Figure 2. 6 illustrates the HVDC power transmission line between the Inga–Shaba EHVDC in the Democratic Republic of the Congo and (b) the Cahora Bassa Hydroelectric Generation Station at the Cahora Bassa Dam in Mozambique and Apollo in Johannesburg, South Africa [50].

2.2.3 Recent HVDC installations

Table 2. 5 HVDC Line Commutated Converter.

HVDC / Project name	***Location***	***Characteristic***			
		(MW)	***(KV)***	***Year***	***(km)***
Italy - Greek	Italy	500	±400	2001	200
Netherlands-Norway	Europe	*700*	±450	2008	580
Italy-Sardinia	Italy	2X500	±500	2011	435
UK - Netherlands	Europe	1000	±400	2011	260
Jinpin – Sunan	China	7200	±800	2012	2093
Mundra – Haryana	India	2500	±500	2012	960
Rio – Madeira	Brazil	800	100	2012	B-B
Rio – Madeira	Brazil	2x3150	±600	2013	2375
Xiluodu – Guangdong	China	6400	±500	2013	1251
Nuozhadu – Guangdong	China	5000	±800	2013	1451
NZ Inter-Island 3		1200	±350	2013	571
Southern Hami – Zhengzhou	China	8000	±800	2014	2200

Biswanath – Agra	India	6000	±800	2014	1728
Xiluodu- Zhejiang	China	8000	±800	2014	1688
Finland-Estonia	Finland	650	±450	2014	196
Zhundong – Sichuan*	China	10000	±1100	2015	2600
Italy-Montenegro	Italy		±500	2017	433
North-East Agra	India	6000	±800	2017	1728
Nelson River Bipole 3	Canada	2000	±500	2018	1324

Table 2. 6 HVDC – Voltage Source Converter.

HVDC / Project name	***Location***	***Characteristics***			
		(KV)	**Year**	**(MW)**	**(Km)**
Germany - Europe	Germany	±150	2009	400	200
Namibia - Zambia	Namibia	±350	2010	300	951
Potrero Hill - Pittsburg	USA	±200	2010	400	85
East-West	UK	±200	2012	500	261
France - Spain	France	±320	2013	1000	65
Denmark-Norway	Norway	±500	2014	700	244
Sweden - Norway	Swedish	±300	2014	1440	190
BorWin2	Germany	±300	2015	800	200
DolWin1	Germany	±320	2015	800	165
HelWin1	Germany	±250	2015	576	130
HelWin2	Germany	±320	2015	690	130
Germany–Germany	Germany	±320	2016	900	135
Caithness—Moray Link3	UK	320	2018	1200	160
Netherlands-Denmark	Denmark	±320	2019	700	329
Belgium - UK	Europe	±400	2019	1000	140
Norway-Germany		±525	2020	1400	623
Pugalur Thrissur HVDC	India	±320	2021		165
Zhangbei DC Grid Project	China	500	2021	3000	495
Rudong OffshoreWind Connector	China	400	2022	1100	100
Sheyang OffshoreWind Connector	China	250	2022	1100	83

2.2.4 HVDC drawbacks

HVDC is one intelligent approach for transmitting large amounts of renewable energy over a long distance. However protection of HVDC continues to be a challenge, and superconducting fault current limiters (SCFCL) provide an intriguing perspective, even if genuine superconducting tapes are not currently intended to function at voltages more than 100kV [60]. There are additional difficulties, such as managing power flow and direct voltage, as well as achieving rapid control and protection [61]. Furthermore, DC switchgear has its restrictions and is more expensive than AC ones [62]. In order to transfer electricity at high voltages and distribute it at low voltages, DC voltage cannot be directly stepped up or down [63]. It requires supplementary equipment such as a rectifier and inverter

2.3 FACTS Technology

FACTS devices are recognized to increase the effectiveness of an AC system by offering speed and flexibility, transmission line phase angle, and reactances in the line [64]. FACTS devices encompass all controllability compensation devices employing power electronics [36]. FACTS is a term that refers to a power electronic-based system that is used to give control over one or more AC transmission system characteristics in order to boost stability and power transfer capabilities. This research will demonstrate the feasibility of utilizing one of these technologies. The Unified Power Flow Controller (UPFC) is a more adaptable and FACTS device that is used to improve the system's power operation and delivery. It is capable of managing a variety of factors such as line flows and bus voltage [65].

This approach makes use of the HVAC system's flexibility to improve load flow at the receiving end of the transmission, which is why it is termed a FACTS [66].

Below are the different types of FACTS which are:

a. Shunt Connected FACTS Controllers.
b. Series Connected FACTS Controllers.
c. Series-Shunt Connected FACTS Controllers (UPFC) [65].

FACTS devices such as Static Var Compensator (SVC), Static Compensator (STATCOM), and dynamic voltage restorers fall under these categories of FACTS controllers.

2.3.1 Static Var Compensator

SVC, as a shunt device, allows dynamic voltage control with fast adjustable reactive shunt compensation via high-speed thyristor switching/controlled reactive devices [67]. Figure 2.7 illustrates the SVC model. It is composed of a harmonic filter and a static variable system consisting of a thyristor-controlled reactor (TCR), a thyristor-switched capacitor (TSC), and a mechanically switched capacitor. SVC regulates the voltage by regulating the reactive power generated into or absorbed from the power system (through TSC or TCR). The TSC responds in a stepped manner, whereas the TCR responds in a smooth or continuously varying manner [68].

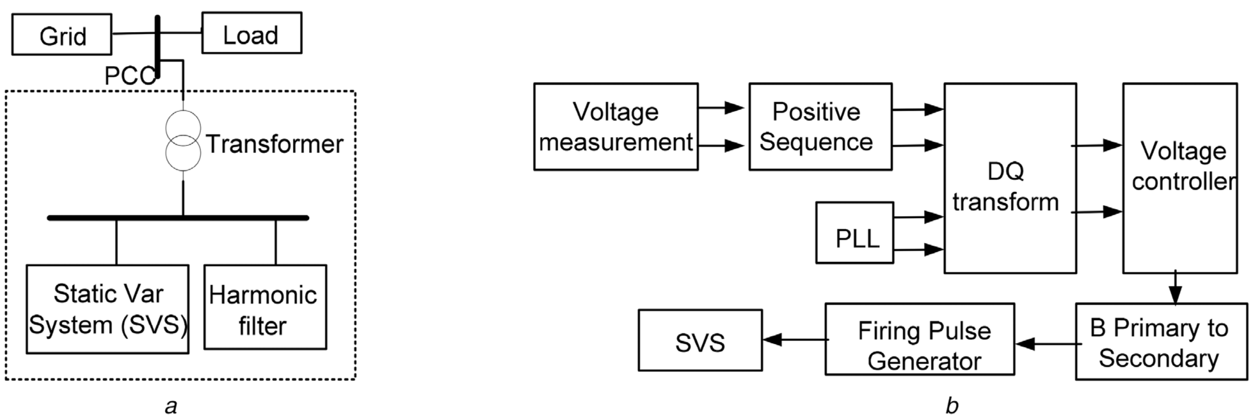


Figure 2. 7 SVC Model. a) Configuration, b) Block Model [67].

2.3.2 Static Compensator

STATCOM, which is a shunt connected to the alternating current power system, regulates the voltage by altering the amount of reactive and active power communicated between the power system and the voltage-sourced converter (VSC). STATCOM's model is depicted in Figure 2.8, and it comprises primarily of a power transformer, a VSC on the secondary side of the transformer, and a DC capacitor that serves as an energy storage device [69]. The VSC has a multipurpose topology that can be utilized for a variety of functions, including voltage regulation and reactive power compensation, power factor correction, and harmonic suppression [70].

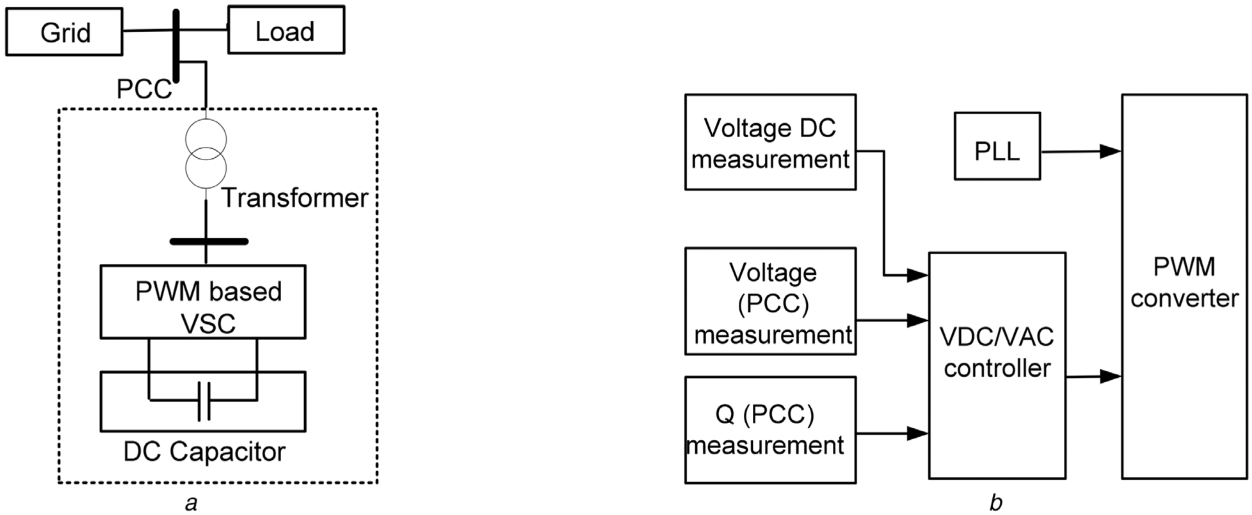


Figure 2. 8 STACOM Model. a) Configuration, b) Block Model [67].

2.3.3 Dynamic Voltage Restorers (DVR)

The DVR, which is connected in series with the grid, is capable of shielding delicate loads from voltage changes or disturbances via a VSC that injects a dynamically controlled voltage in series with the supply voltage via transformers for load voltage correction. DVRs can be utilized to alleviate critical PQ disturbances such as voltage sags with suitable control architecture [71]. Figures 2.9 a) and b) illustrate the modeling of DVR. The work develops a PI-based control technique for the goal of mitigating voltage sag, as illustrated in Figure 2.9 c). The control structure comprises a current controller based on PI and a feedback voltage controller based on PI, as well as an appropriate time delay function. The controller signals Pmr and Pmi are modulation indices that will be used by PWM VSC to determine the real and imaginary components of the AC-side voltage [67, 72].

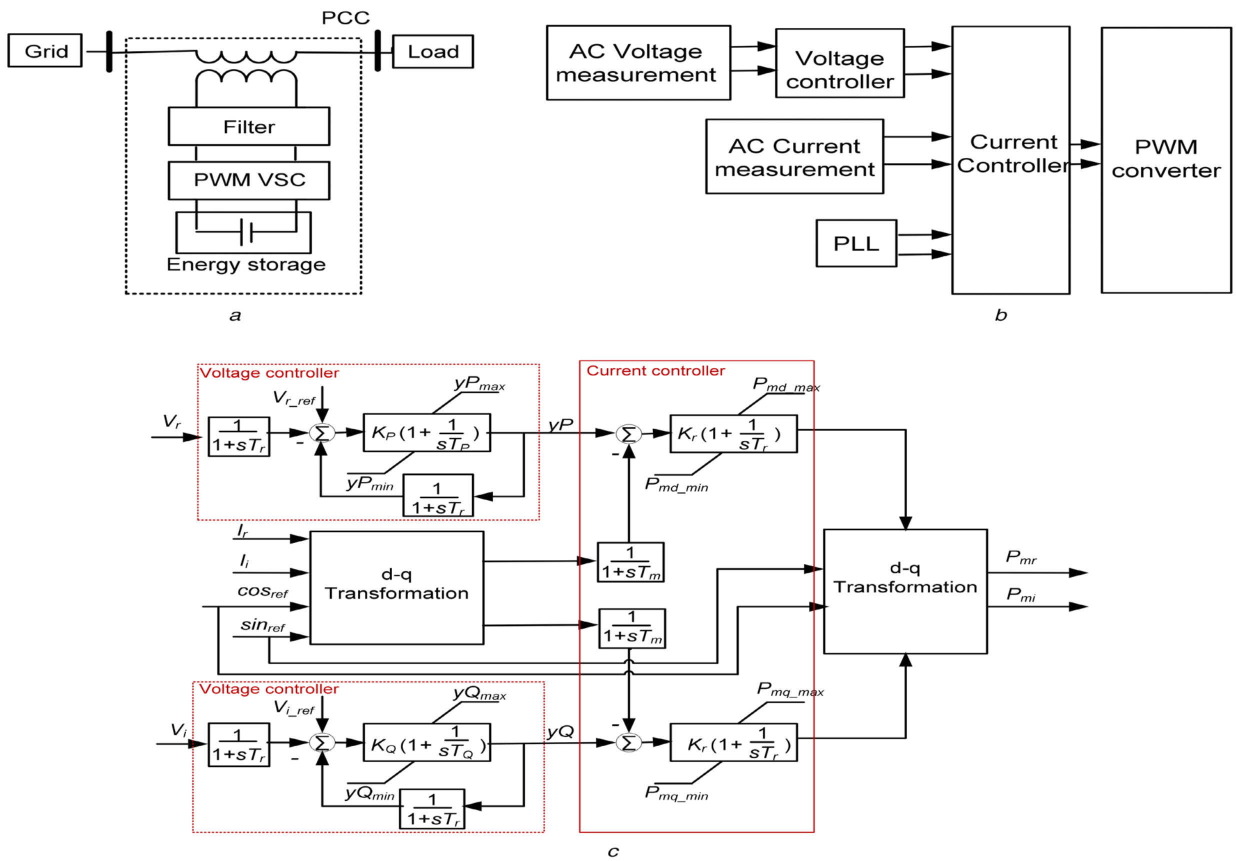


Figure 2. 9 DVR Model and Voltage / Current Controllers. a) Configuration, b) Block Diagram, c) DVR Voltage / Current controller [73].

2.4 Power System Reliability and Security

Many households, industries, and national economies today rely on an uninterrupted power supply to survive. Electric equipment, for example, can save lives in hospitals. In transportation, electricity is utilized in signaling, important to traffic control. In the metal processing industry, power outages can cause solidification in smelters, resulting in significant financial losses. The loss of electricity is unbearable in many critical functions [74-76]. A power system's reliability is a measure of the grid's or network's ability to withstand network shocks, which are unanticipated network interruptions such as a generator trip or a quick load spike, as well as other unpredictable network events. Security and system stability must be maintained at all times. This concept was termed operational reliability of power systems by the Northern America Electric Dependability Corporation. There is an urgent need to meet the expanding demand for electricity, and each grid must be reliable. There are the following features of a reliable grid network [77, 78]:

• The system's busbars must have an acceptable voltage.

• No overloading of system components such as transformers, generators, or transmission lines.

• At all times, its generating capacity must exceed the load requirements.

• Capability to maintain stability in the event of a short circuit

• The ability to maintain stability in the event of a loss of a generator

Frequent blackouts or power outages are a clear indication of an insecure electric grid [79, 80]. While connected power grids are widely acknowledged to be tremendously secure and reliable, their complexity implies that unexpected occurrences such as inadequate connections, human error, malfunctions, or a failure in the protective strategy may occur, resultant in a cascade of equipment [81].

2.5 Thermal Overload Violation/ MVA Line Limit

Under normal operating conditions, the busbar voltages should remain within the following range, as illustrated in Figure 2.10

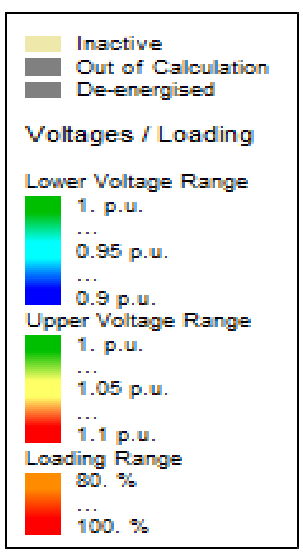


Figure 2. 10 Voltage limits and thermal loading limit.

For lower voltage range is when the voltage is < 0.95p.u and for upper voltage is when the voltage is > 1.05 p.u and the maximum thermal loading range should be in the range of 80% - 100%

2.6 Smart Grid

The term "smart grid" refers to an electrical system that incorporates numerous modes of operation and energy conservation measures, such as smart appliances, energy-efficient resources, smart meters, and renewable energy sources. The smart grid has several critical components, including electronic power conditioning, electricity distribution, and distribution control [54]. Smart Grid is about much more than information technology and smart meters [82, 83]. A Smart Grid is an electrical system that is capable of intelligently integrating the actions of all users linked to it — generators, consumers, and those who do both – to deliver sustainable, economic, and secured electricity efficiently [84]. A sophisticated SAPP grid must include sophisticated energy management tools, condition monitoring equipment such as phase measurement units (PMUs), protection through state estimation tools, ICT - information and communication technology - capabilities, and innovative technologies such as self-healing and efficiency gains [85].

Table 2. 7 Traditional Power Systems vs Smart Grids [85].

Features	Current grid	Smarts grid
Collaborating actively along with energy users	Homogeneous consumers, no collaboration	Customers are knowledgeable, engaged, and proactive in controlling their energy use, consumption, and resources.
Energy generation and storage compatibility	The dominance of primary sources of generation	Focus on distributed generation and renewable energy
Flexible work arrangements in the event of a natural or man-made disaster	Extreme vulnerability	Adaptability and rapidity
Optimized operating costs and efficiency	Integration with operating system data is limited.	Complete integration with network parameter information
Reaction to disruptions	The goal is to keep the system from sustaining more damage. The emphasis is on the protection of the resources required to repair the system.	Automatically detects problems and takes appropriate action. The emphasis is on prevention and minimizing the customer's influence.

Energy quality	Concentrating on the outage. Low degree of accountability for energy quality	Energy quality is a critical aspect of the quality/price relationship.
New products, services and markets	Markets for wholesale goods are small and poorly integrated, limiting consumers' capabilities.	The wholesale market is mature and well-integrated. The expansion of new power markets

The traditional architecture of the power sector is built on centralized electricity distribution technologies and a limited amount of automated facility control. Electricity is generated in large-scale power plants and transmitted across extensive distances to users. While massive resources are required for reconstruction, all of these issues can be resolved with smart grids [86, 87]. Furthermore, the principal characteristics of the smart grid are listed in [88].

2.6.1 Smart grid features

As per [88]. The following are some of the various technology solutions that are frequently explored when developing a smart grid strategy to increase the grid's reliability, environmental sustainability, safety, economics, security, and efficiency.

- Information and Communications Integration (ICT)
- Distributed Energy Resources (DER)
- Distribution Management System/Distribution Automation (DMS)
- Transmission Enhancement Applications (TA)
- Demand Response (DR)
- Asset/System Optimization (AO)
- Customer Side Systems (CS)
- Advanced Metering Infrastructure (AMI)

A smart grid is not a standalone system; it mixes numerous technologies. By judiciously combining these technologies, it also considers and can deliver a variety of different economic and environmental benefits.

- Enhanced Reliability
- Enhanced resource utilization

- Better integration of plug-in hybrid electric vehicles (PHEVs) and renewable energy
- lowered operating expenses for utilities
- Efficiency and conservation improvements.
- Lower greenhouse gas (GHG) and other emissions [89].

2.6.2 Smart grid benefits

- The reliability of the utility grid is improved by reducing power quality disturbances and again reducing concerns and the probability of widespread blackouts.
- Smart grids permit the improvements and efficiencies yet to be wished for.
- The electricity amount paid by consumers by applying downward pressure is reduced.
- Affordability is maintained better for energy consumers
- Consumers are supplied with useful information and it has a greater choice of supply
- It is integrating renewables or nonconventional Distributed Energy Resources (DERs).
- Security is improved by decreasing the concerns and probability of manmade attacks and natural disasters.
- Enable higher penetration of alternating power generation sources
- Injuries and loss of life are reduced from the utility grid-related events, leading to a reduction in safety issues.
- The overall efficiency is improved by reducing losses plus wastage of energy.
- The smart grid is supporting and promoting the deployment of more renewable DERs which provide cleaner power and reduce environmental pollution by decreasing the emission of greenhouse gases plus Carbon particulates [90].

2.7 Protection of the grid

Electrical power system growth is a challenge for electricity management systems in terms of ensuring reliable and secure operation [91, 92]. This condition necessitates the development of technologies that assist in visualizing and controlling electrical system variables through high-speed communications channels and precise data, allowing the grid operator to estimate the system's state in real-time using mathematical computations [93].

Advanced measurement technologies for the electrical system are critical for the development of smart grids. Numerous factors contribute to the tremendous difficulty and difficulty of developing wide-area monitoring systems. Several significant concerns include the following [94]:

- Data paucity
- Analysis of incomplete data
- Bandwidth requirements
- Sensor selectivity and intelligent data fusion
- Advanced sensing and metering
- Integrated communications across the grid

The technologies indicated above are to be employed in the projected Southern African grid to enhance grid resilience, hence improving electricity availability in underdeveloped countries.

With the use of power interconnections, this chapter focuses on the most efficient means of transmitting electricity with minimal losses. It also focuses on methods for ensuring the grid's reliability. The various techniques of transmitting power are explored, along with their benefits and drawbacks, in addition, various strategies for ensuring grid stability are examined, along with their benefits and drawbacks. The HVDC LCC is chosen for long-distance transmission lines carrying bulk electricity due to its long-distance advantages. The SVC is chosen in this work as one of the FACTS devices in order to reduce voltage instability and ensure grid reliability.

CHAPTER 3 DEVELOPMENT OF THE SOUTHERN AFRICAN POWER GRID

In developing a robust Southern Regional Electrical Power Grid, it is pertinent, to begin with, the existing Southern African Power Pool, its features, purpose, limitations, opportunities, and challenges. Figure 3.1 The Southern African region shows the connectivity of the Southern African Power Pool (SAPP) operating members in dark green (electrically integrated) and future connections of SAPP non-functioning members in light green (not electrically interconnected). Relative power system sizes for each country are also presented, scaled by circle size (based on annual domestic energy demand in 2016), with the dominant South African system clearly visible [95].

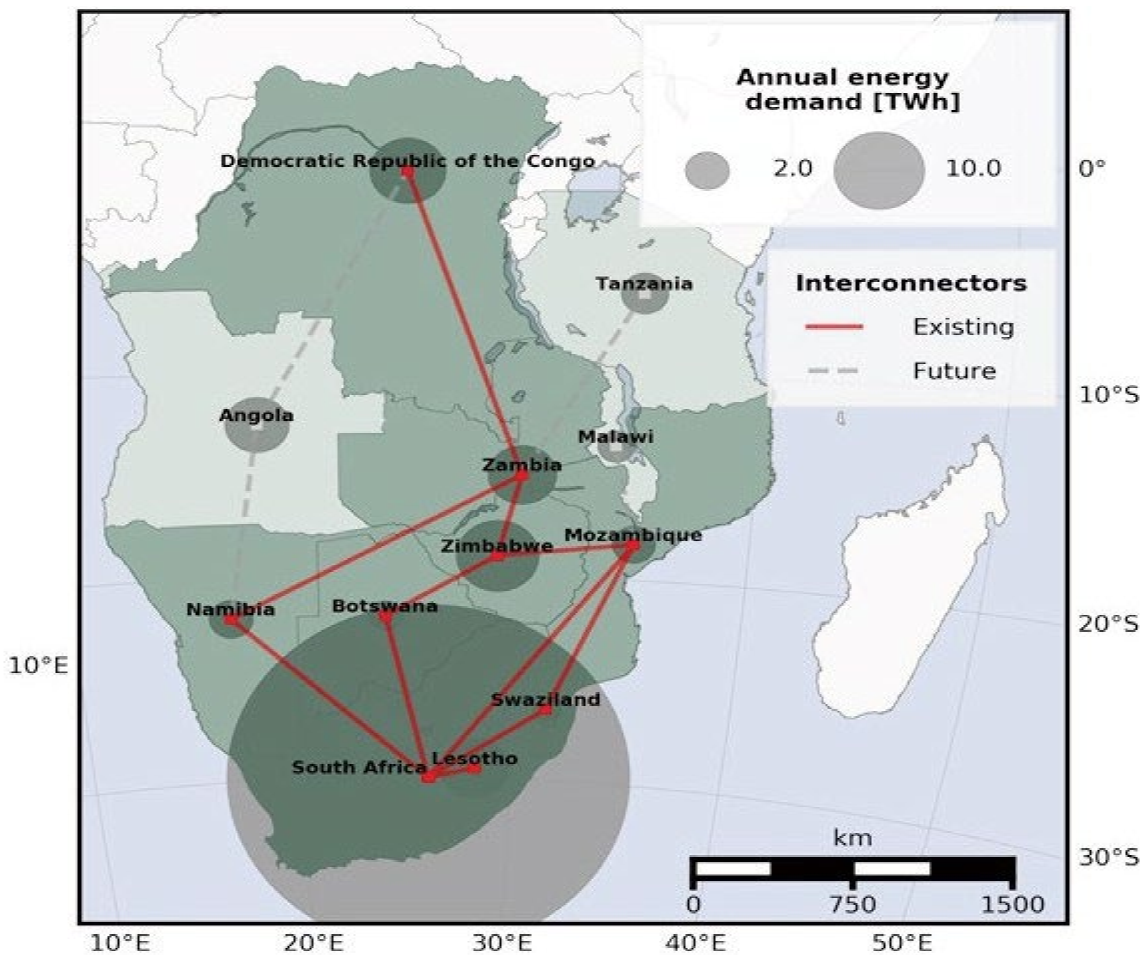


Figure 3. 1 Southern African Regional grid existing and future interconnection [95].

3.1 Southern Africa overview

The 1992 Treaty that established Southern African Development Community (SADC) immediately resulted in a focus on regional resource management. In 1995, SAPP brought together member states' national power utilities, and a year later, SADC member states signed the SADC Protocol on Power [96, 97]. Southern Africa is the second of five power pools on the African continent which was established under the auspices of the SADC with the objective of providing a platform for regional resolutions to electricity generation and supply issues through coordinated preparation and the operation of regional power systems [98, 99]. The SAPP region is comprised of twelve countries: Angola, Botswana, Lesotho, Malawi Mozambique, Namibia, South Africa, Swaziland, Zambia, Zimbabwe, Tanzania (which is also part of the EAPP), and the Democratic Republic of the Congo (DRC), which is also part of the CAPP and EAPP [100].

Table 3. 1 Southern African countries and their installed capacity in MW [3, 25, 27, 101-104].

Country	Thermal	Gas	Hydro	Solar	Nuclear	Wind	Oil	Diesel	Total (MW)
South Africa	45489	2409	3393	2323	1840	2323			**57777.4**
Angola		243	5901.46	35			95	136	**6410.46**
Mozambique	800		2206	40					**3046**
Botswana	822			1.3				70	**893.3**
Lesotho			72.67	0.305					**73**
Malawi			370.35					36	**406.35**
Namibia	120		332	163				46.4	**661.4**
Swaziland			78.1						**78.1**
Zambia	405		2294.5	54				8.85	**2762.35**
Zimbabwe	1130		1140						**2270**
Total	**48766**	**2652**	**15788.48**	**2616.6**	**1840**	**2323**	**95**	**297.25**	**74378.36**

According to Table 3.1, Southern African countries currently have around 74GW of installed capacity, with South Africa supplying approximately 58GW [3, 27]. South Africa generates most of its electricity from coal and is the only SAPP country that offers nuclear electricity [95, 104].

Figure 3.2 below shows the Southern region's available resources, with thermal having the largest installed capacity, the majority of which is in South Africa, and oil having the least installed capacity [27, 104, 105].

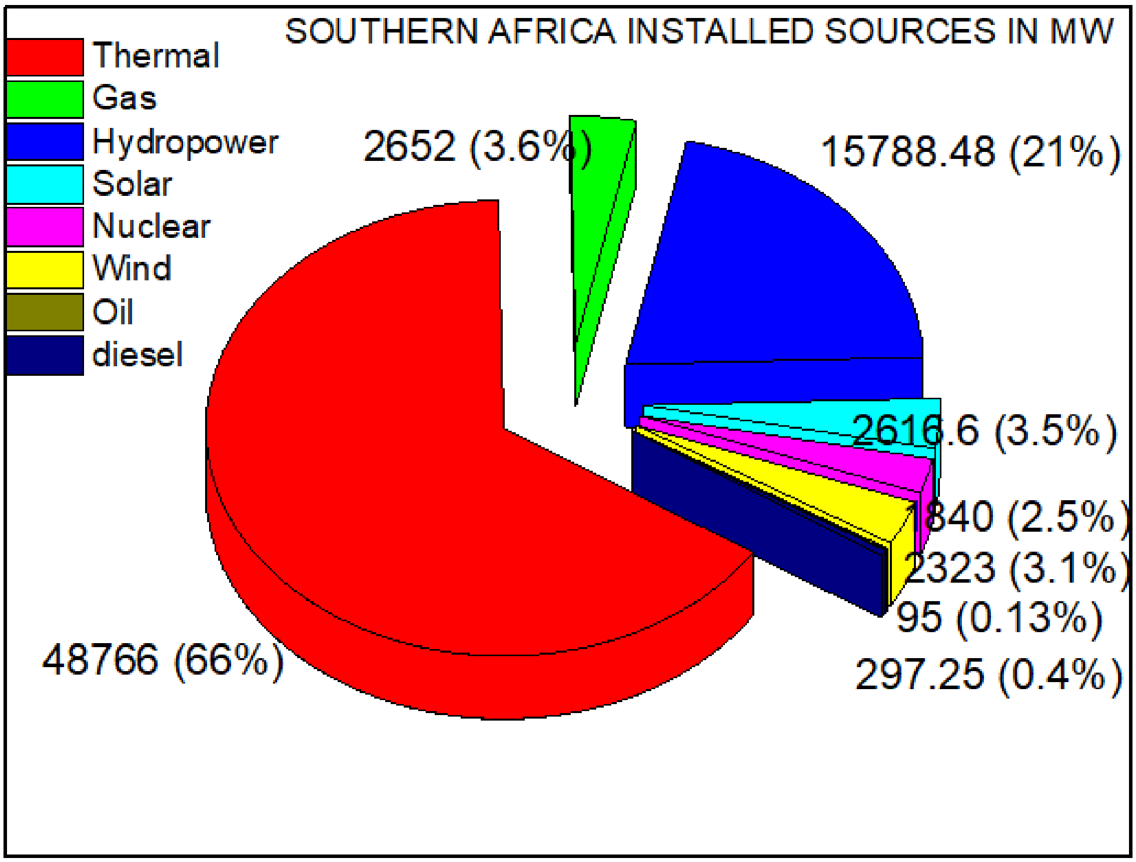


Figure 3. 2 The installed capacity in the Southern Africa Region.

Table 3.2 shows SAPP members and their power utilities, along with their population for each country, with South Africa having the most people and Swaziland having the least [3, 27].

Table 3. 2 Southern African Power Pool members with its utilities and their population.

SAPP MEMBERS	UTILITIES	Population (Million)
Angola	Empresa National de Electricidade (ENE)	31.85

Botswana	Botswana Power Corporation (BPC)	2.303
Lesotho	Lesotho Electricity Commission (LEC)	2.125
Malawi	Malawi Electricity Supply Commission (ESCOM)	18.64
Mozambique	Electricidade de Mozambique (EDM)	30.39
Namibia	Namibia power (NAMPOWER)	2.495
South Africa	Electricity Supply Commission (ESKOM)	58.65
Swaziland	Swaziland Electricity (SEC)	1.148
Zambia	Zambian Electricity Supply Corporation (ZESCO)	17.87
Zimbabwe	Zimbabwe Electricity Supply Authority (ZESA)	14.65

Figure 3.3 shows the population of each country in the Southern African region to show which country is most populated and which is less populated [3, 27, 101].

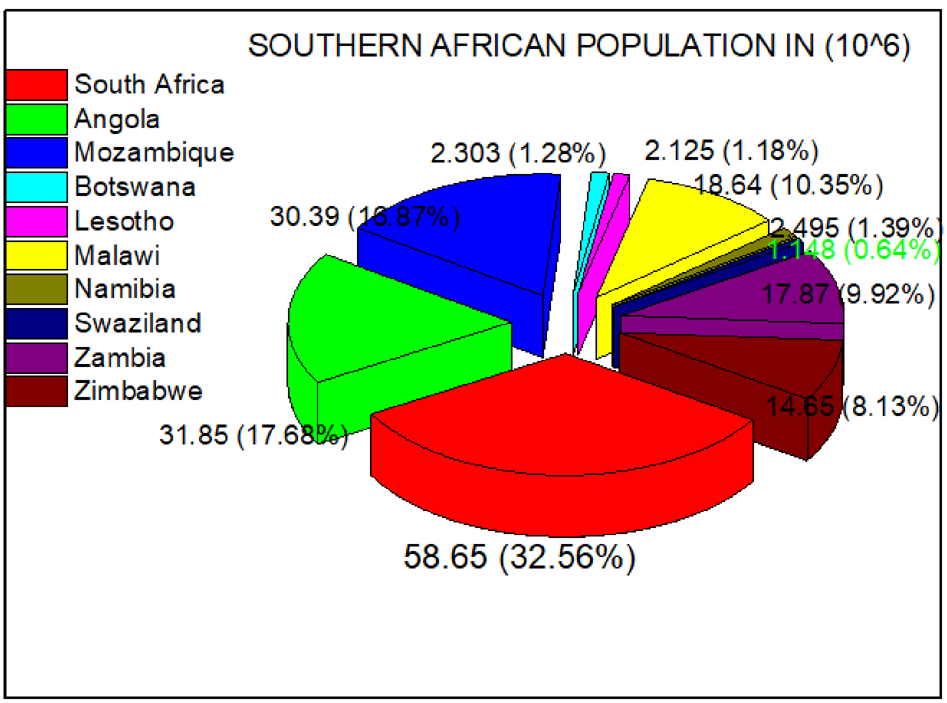


Figure 3. 3 Southern African Population in x10^6.

Table 3.3 compares installed capacity to power demand to determine which countries require greater power access, and present access to electricity is examined to determine the current level of power access.

Table 3. 3 SAPP countries installed capacity against their demand & current electricity access [3, 26, 27].

country	Installed capacity (MW)	Potential installed (MW)	Power demand (MW)	Current access (%)
South Africa	57777.4	67380	46678	95
Angola	6410.46	8289.26	3378.65	45
Mozambique	3046	9326.9	1650.5	29
Botswana	893.3	2228.3	702	56
Lesotho	73	2161.975	155	44.64
Malawi	406.35	1505.05	470	11
Namibia	661.4	686.4	600	56
Swaziland	78.1	87.1	223	87
Zambia	2762.35	4792.35	2300	31
Zimbabwe	2270	4207	2200	41.9

When producing electricity, some factors must be addressed, such as the environment's sustainability and the impact on the environment. Southern Africa has the potential to alleviate all of these energy problems if the necessary infrastructure is in place to utilize the continent's huge renewable energy resources. This strategy of utilizing renewable energy to provide sufficient electricity for Southern Africa is designed to provide essential social, economic, and environmental services without jeopardizing or impairing the viability of the region [11, 106].

This project examines Southern Africa's electrical energy resources, feasibility studies for interconnecting power systems, the existing status of the electric power factor, and the construction of a Southern Africa smart grid network in terms of interconnections. There are now thirteen (13) interconnection projects in the SAPP, including Mozambique-Zimbabwe-South Africa (MOZISA), which connects Mozambique, Zimbabwe, and South Africa. This project focuses on African power infrastructure and electricity exchange in the SAPP region, where there is considerable poverty and a scarcity of electricity infrastructure [97].

3.2 Southern Africa Countries

The purpose of Southern Africa is to provide a stable and cost-effective power supply to each country's consumers while maintaining appropriate use of natural resources and having a low impact on the environment [107]. Figure 3.4 represents a map of southern Africa with existing and prospective power interconnections as well as available hydro, pump storage, and thermal resources [108].

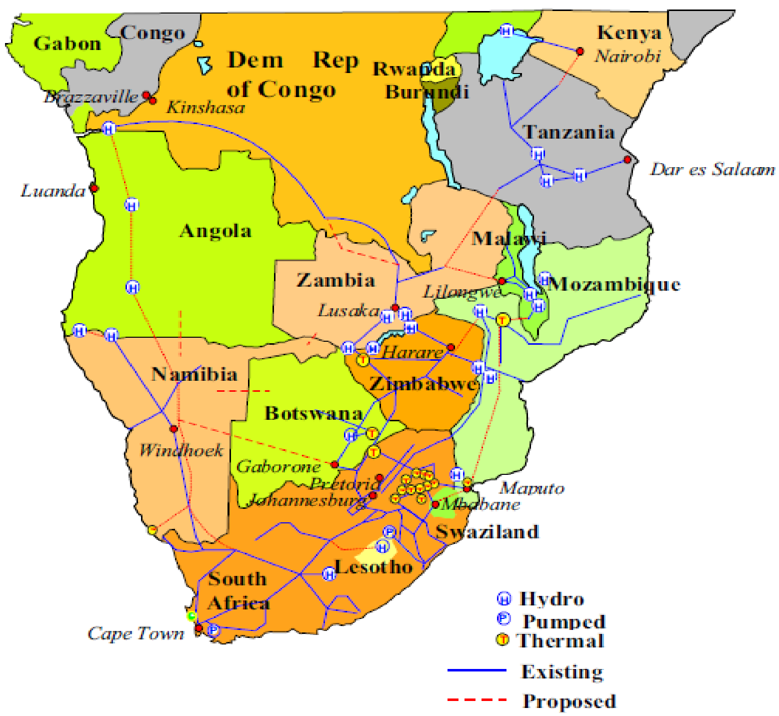


Figure 3. 4 Southern African Power Grid [109].

3.2.1 South Africa

Eskom supplies roughly 90% of South Africa's electricity, with the remaining 10% coming from Independent Power Producers (IPPs) and imports. South Africa had an installed capacity of around 53GW in 2017. Coal-fired electricity generation accounts for the majority of installed capacity in South Africa, accounting for 75% of installed capacity [110, 111]. Natural gas-fired open-cycle plants account for 4%, nuclear account for 4%, hydroelectric account for 7%, and non-hydro renewable energy accounts for 6%. South Africa intends to diversify its energy mix, thereby increasing energy security and attempting to eliminate environmental pollution [3]. Electric energy consumption totals 227.10 billion kWh per year, with an average of 3584 kWh consumed per capita [25]. Table 3.4 illustrates the South Africa power plant portfolio; it is vital to illustrate the South Africa plant portfolio because it contributes bulk power to both the SAPP grid and the projected Southern African grid [3, 27, 104].

Table 3. 4 South Africa power plant portfolio

Coal-fired plants	**Installed capacity (MW)**	**hydroelectricity**	**Installed capacity (MW)**
Arnot	2100	**Conventional hydro stations**	
Camden	1561	Gariep	360
Duvha	3600	Vanderkloof	240
Grootvelei	1200	**Pumped storage schemes**	
Hendrina	2000	Drakensberg	1000
Kendal	4116	Palmiet	400
Komati	1000	Ingula	1332
Kriel	2850	**Other hydropower Stations**	
Lethabo	3708	Colley Wobbles	42
Majuba	4110	Second Falls	11
Matimba	3990	First Falls	6
Matla	3600	Ncora	2.4
Tutuka	3654	**Other renewable energy stations**	
Medupi	4800	Sere Wind Facility	106
Kusile	3200		
Gas/ Liquid turbine stations		**Nuclear**	
Acacia	171	Koeberg	1840
Port Rex	171		
Ankerlig	1327		
Gourikwa	740		
Independent Power Producers (Solar & Wind)			5027
Total Installed Capacity (existing)			58108.4
Eskom Planned capacity additions (Kusile unit 5 & 6)			1600

3.2.2 Angola

Angola is regarded to be Africa's second-largest oil producer, after Nigeria. Angola's economy is heavily reliant on hydrocarbon extraction, rendering it vulnerable to crude oil price changes. Angola generated 10 billion kilowatt-hours (kWh) of power in 2016, largely through fossil fuel and hydroelectric sources. In 2016, only 35% of Angolans had access to electricity, leaving approximately 17 million people without access to electricity, the majority of whom live in rural areas. The electricity sector faces difficulties due to insufficient power generation, limited income protection due to the fact that more than 80% of users are not metered, and a shortage of highly skilled workers to manage electricity Networks [3, 103].

3.2.3 Mozambique

The International Energy Agency reports that 57% of the people living in urban regions of Mozambique have access to electricity however only about 15% of the rural area residents have access to power [112]. In the year 2015, the power generation was about 20 million megawatt-hours in Mozambique. And most of the electricity comes from hydropower which is 87% [113]. Mozambique's hydroelectric potential is projected to be 19000MW [114]. Mozambique has one of the largest hydro dams on the African continent, with an installed capacity of 2075MW, producing electricity for South Africa, Botswana, Mozambique, Zimbabwe, and the larger (SAPP) South African Power Pool. Only roughly 500 MW of the entire capacity is used in the country. EDM has 117MW, while IPP has 100MW and 175MW, respectively, and Aggreko has 65MW, which makes a total installed capacity of 2626MW in Mozambique [115]. The entire annual usage of electric energy is 11.57 billion kWh, with an average of 392 kWh per capita. The total amount of energy produced by electricity-generating plants is 18 billion kWh [25, 116].

3.2.4 **Botswana**

Botswana was previously recognized as a country that was heavily reliant on South African power but has since transitioned to producing the majority of its own [102, 117]. Botswana has Morupule plant A, which has a capacity of 600MW, and Morupule plant B, which has a capacity of 132MW [118]. Additionally, it has Matshelagabedi, which has a capacity of 70MW, and Orapa, which has a capacity of 90MW and is now owned by BPC, which brings the total installed capacity to 890MW [119]. The total annual usage of electric energy is 3.64 billion kWh, with an average of 1613 kWh per capita. The total amount of energy produced by electricity-generating plants is 3 billion kWh [25].

3.2.5 Lesotho

May 2020 development statistics provided by the World Bank from official sources, Lesotho's installed generating capacity is 0.08GW [120]. The total annual usage of electric energy is 9.04 billion kWh, with an average of 293 kWh per capita. The total amount of energy produced by electricity-generating plants is 10 billion kilowatt-hours (kWh) [25].

3.2.6 Malawi

Malawi's power system is one of the most brutally unnatural in Sub-Saharan Africa, with fewer than 10% of the 18 million-strong people connected to the grid. Around 80% of Malawians live in rural areas, while less than 1% have access to power [121]. Whereas the total installed capacity for electricity generation in Malawi's linked grid is around 362MW, 351MW of which is hydropower, and 11MW is reciprocating engines (diesel sets) [122]. The total annual usage of electric energy is 1.32 billion kWh, with an average of 73 kWh per capita. The total amount of energy produced by electricity-generating facilities is one billion kilowatt-hours (kWh) [25].

3.2.7 Namibia

Namibia was anticipated to be 508MW in the year 2012, according to the World Bank's compilation of development indicators derived from formally acknowledged sources. Namibia's total installed generation capacity actual value, estimates, projections, and historical statistics were sourced in May 2020 [123]. Several reforms were done by the electricity sector in Namibia targeted at IPPs to offer a stable investment climate. The total annual usage of electric energy is 3.89 billion kWh, with an average of 1589 kWh per capita. The total amount of energy produced by electricity-generating facilities is one billion kilowatt-hours (kWh) [25, 124].

3.2.8 Swaziland

The Swaziland Electricity Company has four hydroelectric facilities that generate 60.4MW of electricity and account for 15-17 percent of Swaziland's total energy consumption. Eskom of South Africa and EDM of Mozambique both import electricity to Swaziland, which is where they obtain the remainder of their power [125, 126]. The average yearly usage of electric energy is 1.43 billion kWh, with an average of 1259 kWh per capita. The total amount of energy produced by electricity-generating plants is 381 million kWh [25].

3.2.9 Zambia

Zambia's diverse electricity generation is mainly by hydropower. Large and mini-hydro stations account for 95% of installed capacity. Fossil fuels account for around 4% of the country's generation mix, which also includes diesel-powered mini-grids managed by ZESCO and Ndola Energy. The heavy fuel oil plant generates 50MW, whereas the Copper Belt Energy Consumption Corporation generates 80MW with six gas turbines [127, 128]. ZESCO now operates a total of 2493.5 MW of installed capacity through a variety of power plants [3]. The total annual usage of electric energy is 11.04 billion kWh, with an average of 636 kWh per capita. The total amount of energy produced by their electricity-generating plants is 12 billion kWh [25].

3.2.10 Zimbabwe

Zimbabweans are currently confronted with a lack of power, water, and money. For the past two decades, Zimbabwe has been unable to generate sufficient power, necessitating intervention from countries such as Mozambique, South Africa, the Democratic Republic of Congo, Namibia, and Zambia in 2000 and 2008. Zimbabwe now generates electricity from one hydropower plant and three coal-fired thermal power plants; however, there is a proposal to add 1600MW through solar, wind, biomass, mini-hydro, and geothermal sources [129, 130]. Kariba, Hwange, Harare, and Munyati currently generate 1200MW, while the country's demand is 1500MW; additionally, there is a projected plan to add 1000MW or more renewable energy by 2025 and 1600MW by 2030, utilizing renewable resources such as solar, wind, small hydropower, biomass, and geothermal [130]. The Hwange power station is having difficulty operating due to aging equipment, resulting in a production capacity of less than a quarter of its capacity [131].

Figure 3.5 demonstrates that there is a huge demand for power exchange, particularly in developing countries, and that power is unevenly distributed, causing most countries to struggle to achieve 100 percent energy access in their country.

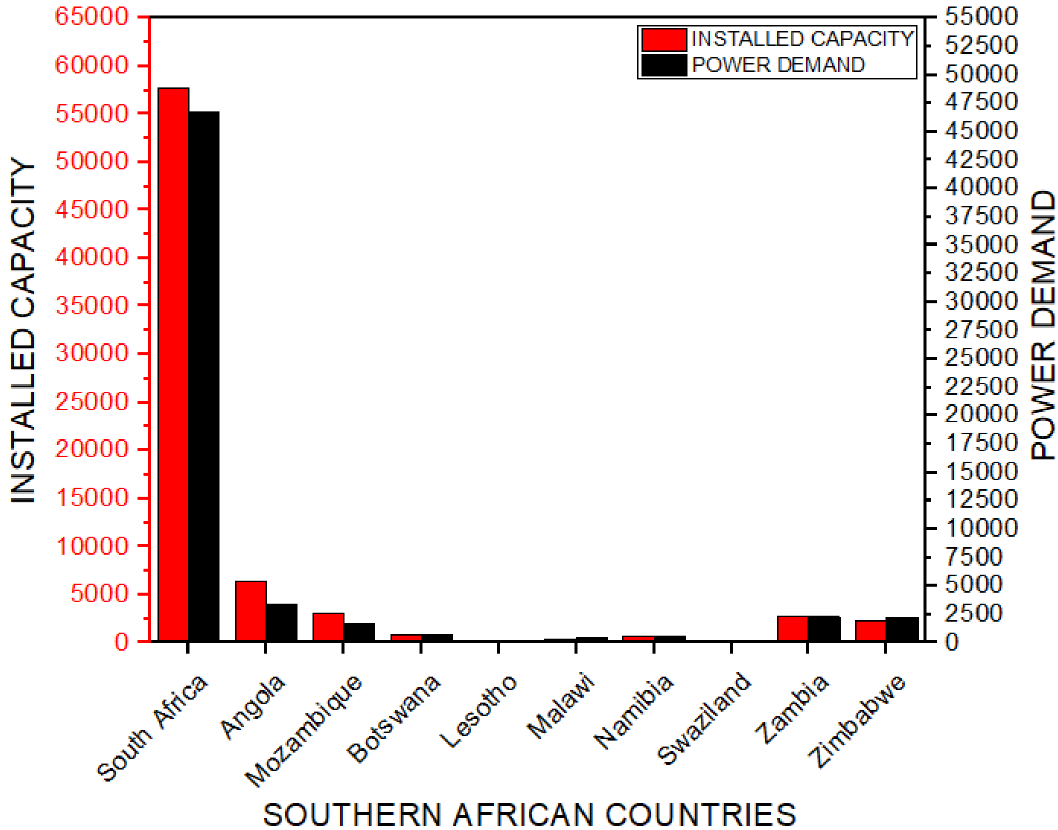


Figure 3. 5 Installed capacity and Power demand of each Southern African country.

3.3 SAPP Interconnections

To ensure network efficiency over increasingly great distances, power pools were formed and interconnections were developed. SAPP participants were granted equal rights and obligations and promised to behave in solidarity without taking advantage of one another [96]. SAPP regulates electricity trading by interconnecting neighboring countries' high-voltage transmission networks and promoting a fair and competitive market [97]. Due to the population growth in Southern Africa, there is an urgent need to raise the electrical supply due to the population and also to modernize the electrical power infrastructure in order to enhance electricity generation. Even with existing infrastructure, operating a power system on a big linked system becomes significantly more complicated, resulting in power loss, voltage instability, and unreliable power system operation [132]. When transmitting electricity over longer distances, switching HVAC to HVDC is more efficient and cost-effective. for spans greater than 500 kilometers, DC lines are more advantageous since they have no reactance and can transfer more power per conductor size than AC lines [10].

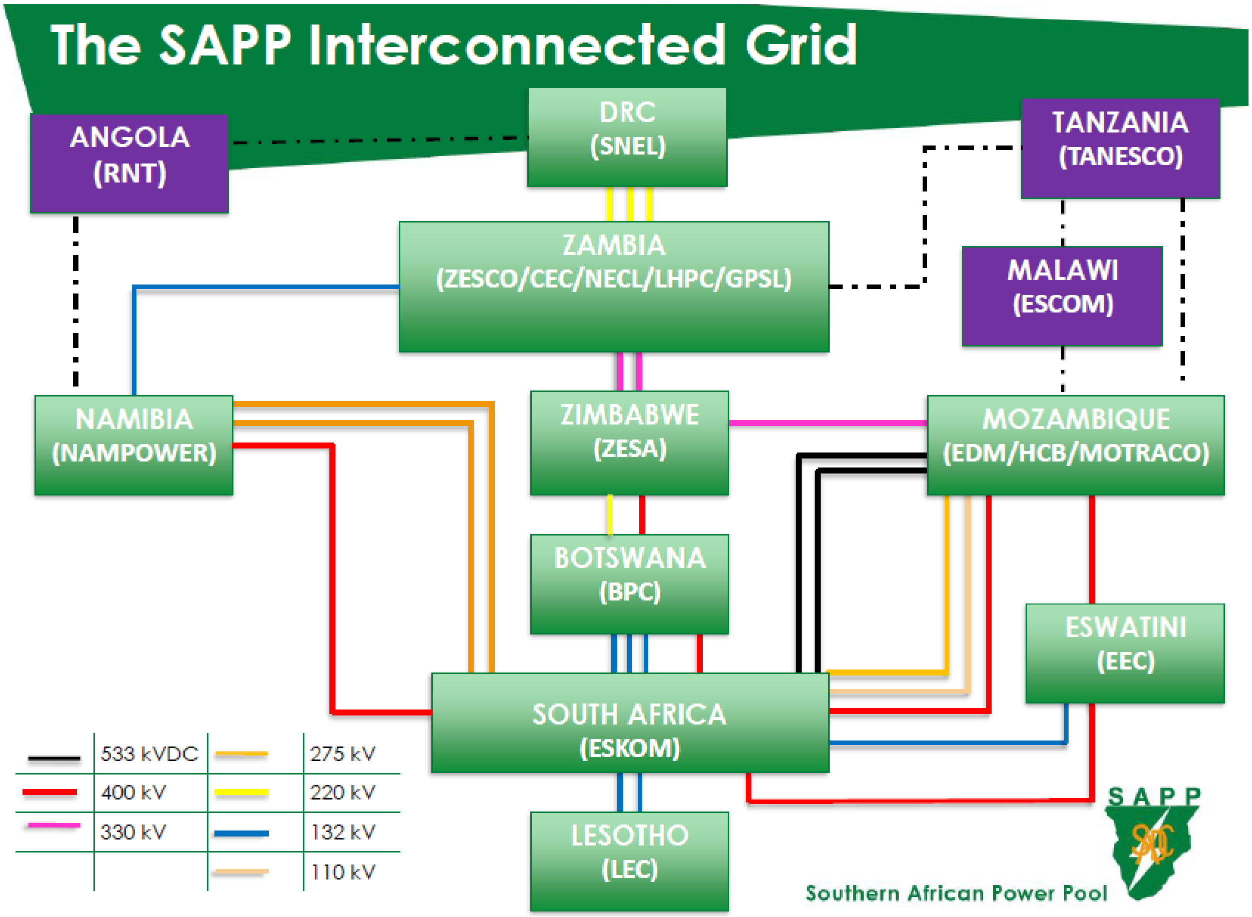


Figure 3. 6 SAPP Existing power interconnections (2022) [133].

3.4 SAPP Existing interconnections

The first exchange occurred in 1960 between the Democratic Republic of Congo (DRC), Zambia, and Zimbabwe; in 1970, an interconnection between Mozambique and South Africa was established; in 1995, an interconnection between Botswana and South Africa was established; and in 1995, Zimbabwe and South Africa were connected through a 400kV link. Currently, Tanzania, Angola, and Malawi do not have any interconnections with other countries, but new electricity lines are planned, and thus are expected to do so [2, 72].

Electricity is generated at the power plant's generating station and distributed to various types of customers via transmission lines; the voltage is stepped up at the transmission Sub-station that is located at the generating station for transmission purposes and then stepped down after it has been transmitted to a lower voltage which is then transformed and distributed, and maybe further stepped down at specific points along the utility distribution lines, and the issues related to the power grid are listed below.

- Limited delivery systems

The existing electricity delivery uses SCADA which is restricted to limited bandwidth and comparatively slow data transmission rate that mostly requires some seconds or more to react to an alarm or changing of the system and again there is no visibility in the distribution network underneath the substation.

- High cost of power outages and power quality interruption

Every year, there are numerous power outages and interruptions across Africa, resulting in significant economic loss, particularly for companies that rely on high-quality power

- inefficiency at managing peak load

Electricity demand changes constantly, as the costs are associated with meeting these demands. For the existing grid, supply must continually fluctuate to meet demand, and the power grid must maintain a buffer of surplus supply, resulting in lower efficiency, greater costs, and higher emissions [89].

3.4.1 SAPP future interconnections

According to the most recent data from SAPP, electricity demand in SAPP countries is expected to increase from 57784 MW to 77654 MW between 2017 and 2025, assuming a compound annual growth rate of 2.9 percent. Between 2017 and 2022, an additional 28773 MW of generation capacity is anticipated to be commissioned to fulfill future demand. Thus, new cross-border lines are being planned to improve the capacity of the SAPP region and boost electricity commerce between the SAPP countries. SAPP has 13 high-priority projects that will require about USD4 billion in investment [27]. The following is a summary of some upcoming SAPP transmission projects, eleven priority transmission projects are being implemented in the SAPP region. These projects seek to establish new power corridors to spur industrial development and strengthen the region's energy security without overburdening the region's existing transmission network. One of the most significant projects is the Zambia–Tanzania–Kenya (ZTK) interconnection, which intends to connect EAPP with the SAPP. [134].

Table 3. 5 Planned SAPP Interconnection projects [134-136].

Project	**Technical parameters**	**Expected commissioning / Status**
Angola-Namibia interconnector (ANNA)	400kV, 360km	2025
Botswana-South Africa Interconnector (BOSA)	400kV	2024
Kolwezi-Solwezi (DRC-Zambia) Interconnector	330kV	Implementation
Malawi-Tanzania Interconnector	400kV	NA
Malawi-Zambia Interconnector	400kV, 286km	NA
Mozambique-Malawi Interconnector (MOMA)	400kV, 218km	2023
Mozambique-Tanzania Interconnector (MOTA)	400kV, 700km	NA
Mozambique-Zambia Interconnector	400kV, 368km	NA
Mozambique-Zimbabwe-South Africa Interconnector (MOZISA)	400kV, 935km	2022
Zambia-Tanzania-Kenya Interconnector (ZTK)	400kV, 2302km 330kV, 373km	implementation
Zimbabwe-Zambia-Botswana-Namibia Interconnector (ZIZABONA)	330kV, 408km	completion
Mozambique – Malawi Interconnector (Tete – Phombeya)	220kV, 200km	N/A

3.5 SAPP Power Exchange

The current electricity trade between these nations is governed by bilateral agreements [137]. SAPP is credited with being Africa's first organized international power pool, through which the southern African countries' national energy firms cooperate to meet the needs of the SADC. SAPP now has ten member countries collaborating to promote electricity commerce and power pooling for more affordable and reliable power, particularly for developing countries [138]. From 2004 to 2016, SAPP added 15468 MW of new generation capacity, resulting in a yearly average of approximately 1291 MW of new generation capacity. In 2016, SAPP's installed generation capacity was 61894 MW and its operating generation capacity was 46959 MW, and 52542 MW in demand and reserve power. Between 2015 and 2016, the SAPP region added 1864 MW of additional generation capacity [3, 27]. Additionally, a significant interconnection project in the transmission section was commissioned in 2015, namely the 220 kV DRC – Zambia interconnector. The 220kV double-circuit, 142-kilometer interconnector will be erected parallel to the current single-circuit line built in the 1950s, with an overall length of about 51 km in Zambia and 91 km in the DRC. This link improved capacity transfer by 240 MW between the two countries, significantly increasing North-South trade in the SAPP region [139].

3.6 Current SAPP Grid

The theft and vandalism of electricity infrastructure is causing SAPP member utilities to lose millions of dollars. The decline in economic activity in numerous SAPP nations as a result of COVID-19 restrictions exacerbated this difficulty [140].The current electricity grid contributes significantly to the greenhouse or global warming effect, which has an environmental impact, due to the use of fossil fuels, particularly coal. Renewable energy is eager to provide another source of energy that is pollution-free, environmentally friendly, and technologically advanced. There is a strong focus on renewable energy, especially solar and wind energy, which offers power without contributing to Carbon Dioxide emissions [141]. Generally, today's transmission and distribution networks are characterized as dumb systems due to their inability to respond intelligently to the data required for modern grid functioning. Again, the current power infrastructure is incapable of providing adequate service in terms of energy efficiency, security, and dependability, or of integrating renewable energy on a large enough scale to meet clean energy demand [142]. That is why the introduction of the smart grid addresses all of these issues by encouraging energy saving, increasing reliability, and controlling power more effectively and efficiently. The smart grid consists of centralized large power plants and distributed energy generators that enable bidirectional power flow and information exchange. It is defined as a two-way power communication system that enables the creation of an automated and energy-efficient advancing energy delivery network. Meanwhile, power flows in just one direction in the existing power system, from the generation station to the customers via the transmission and distribution networks. Generally, the smart grid is a combination of technologies that enable an electricity network to be more accessible, flexible, economical, and reliable [143].

CHAPTER 4 MATHEMATICAL MODELING AND DEVELOPMENT OF SARG

As a result of higher trading volumes, extra sub-markets for electricity trade, and greater membership, the SAPP has matured through time with increased trading volumes, additional sub-markets for electricity trade, and expanded membership [95, 144]. The Southern African region now has 74.4GW of installed capacity, compared to an unevenly distributed demand of around 58GW. This chapter presents detailed mathematical modeling of the Southern African Regional grid load flow analysis using HVAC with FACTS devices and an HVDC transmission line.

4.1 Power system components modeling

The power system is mostly known to dwell much on the ways of generating electricity from the power station, transmitting electricity through overhead lines, and distributing electricity to consumers [10]. With the objective of transmitting power to developing countries, this project focuses on the generating and transmission aspects. The following components are employed in this research to demonstrate the prospective outcomes of power exchange across the Southern African region.

4.1.1 Generators

The generators are applied in this research to demonstrate the amount of accessible power in the Southern African region and from which types of resources. In general, huge amounts of power are created by three-phase synchronous generators. Generators are treated as sources of both reactive (MVAr) and actual power (MW). Typically, the controlled operation of a synchronous generator is modeled in load flow calculations. The basic notion of a controlled synchronous machine modeled for load flow analysis is shown in Figure 4.1.

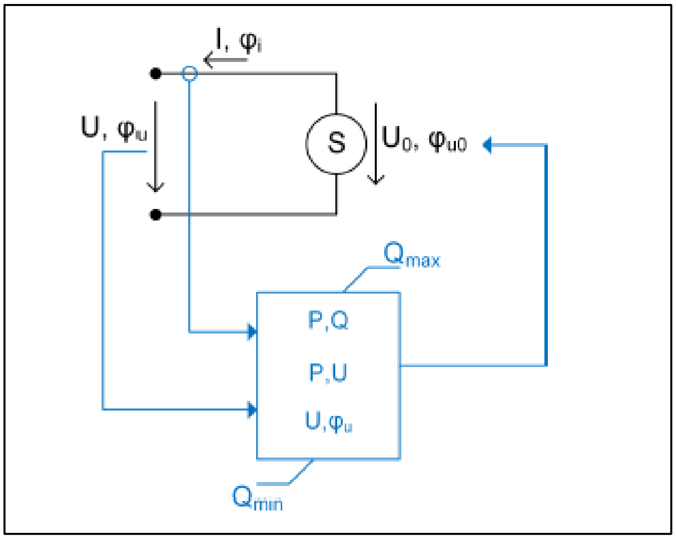


Figure 4. 1 Controlled Synchronous generator

Constant V, voltage Q-droop, Const. Cosphi, Const. Q, Q(P)-Characteristics, and Voltage iq-Droop are the six local controllers for synchronous generators offered by DigSilent PowerFactory. In this project Const. V and Const. Q is used, whereas Constant V is typically used for large synchronous generators at large power plants that operate in voltage control mode ("PV" mode), while Const. Q is typically used for smaller synchronous generators (PQ Mode). With this type of control, the active and reactive power of the generator can be specified [145]. Additionally, there is a reference machine, which serves as a slack bus for conserving reserve power.

4.1.2 Transmission modeling

The transmission network is fundamentally represented by the Y-Bus (Admittance Matrix), which is composed of several transmission system components. The impedance (Z) and admittance (Y), where Z equals the sum of the resistor (R) and the reactance (X), and Y equals the sum of the susceptance (B) and conductance (G), respectively [10]. Because admittance is the mathematical inverse of impedance, their relationship is given in the equation below

$$Z = R + jX \tag{4.1}$$

$$Y = G + jB \tag{4.2}$$

$$Y = \frac{1}{Z} = \frac{1}{R+jX} = \left(\frac{R}{R^2+X^2}\right) + j\left(\frac{-X}{R^2+X^2}\right) \tag{4.3}$$

Whereby

$$G = \left(\frac{R}{R^2 + X^2}\right) \quad and \quad B = \left(\frac{-X}{R^2 + X^2}\right) \tag{4.4}$$

Transmission lines, transformers, switching shunts (capacitors/reactors), line shunts, and bus shunts are all modeled using the admittance matrix. The matrix contains all of the system's interconnections between buses. The Y-Bus is an n by n matrix, with n being the number of buses in the system. The bus shunts (B and G) represent a fixed impedance/admittance at the bus. B Shunt implies an impedance MVar injection. G Shunt is an impedance MW absorption. The impedance parameters for a transmission branch (line or transformer) include series resistance per unit, series reactance per unit, shunt charging per unit, and shunt conductance per unit.

A temperature dependency can be specified for a line type through the conductor material listed below [146].

- Aluminium ($\alpha = 0.00403$ 1/K)
- Copper ($\alpha = 0.00393$ 1/K)
- Aldrey ($\alpha = 0.00360$ 1/K)
- Aluminium-Steel ($\alpha = 0.00403$ 1/K)
- Aldrey-Steel ($\alpha = 0.00360$ 1/K)

with a coefficient of temperature α or with resistance at max. operating temperature ($t\max$ in degC and $rline_{t\max}$ in Ohm/km)

below is the equation to calculate the resistance of the line

$$R_1^{'} = rline \cdot (1 + \alpha \cdot (temp - 20) \tag{4.5}$$

The following formula is used to determine the line's loading:

$$loading = \max\left(\frac{|I_{busi}|}{I_{nom(busi)}}, \frac{|I_{busj}|}{I_{nom(busj)}}\right) \cdot 100 \ \ [\%] \tag{4.6}$$

The losses of the lines are calculated as follow

$$Losses = (P_{busi} + P_{busj}) \cdot 1000 \quad [kW] \tag{4.7}$$

4.1.3 Busbars and thermal loading modeling

Bus bars are a type of conductor that collects electricity from entering feeders and distributes it to outgoing feeders; consequently, it is an electrical junction where all incoming and outgoing electrical currents meet. The bus bars operate under particular voltage restrictions. Transformers, generators, and line thermal loads must be between 80% and 100% as shown in Table 4.1 [147].

Table 4. 1 Network condition modeling

Network condition	**Voltage limit**
System healthy	0.95 – 1.05 p.u.
Lower voltage range	≥ 0.95 p.u.
Upper voltage range	≤ 1.05p.u.
Thermal loading	80% - 100%

4.1.4 Loads modeling

In the case of an HV system, the phrase 'load' might refer to complete MV feeders, while in the case of an MV system, it refers to LV feeders [148]. The load is employed in this design to indicate the demand of each country in the Southern African region, The load parameters were stated as the country's load demand as real Power (P)

Load modeling in a steady-state has a constant impedance (Z), current (I), and power (P), hence a combination of three quantities, real and reactive power, must be supplied for each load. The load will vary in this design to analyze the performance of load flow across the Southern African countries. The equation is utilized with the general load type model.

$$S_{ls} = P_{Spec} + jQ_{Spec} \qquad (4.8)$$

4.1.5 Transformers modeling

The load in the transformer should not exceed 100% of its thermal limit at any operating conditions.

4.1.6 Circuit Breakers

The corroding capability of circuit breakers must meet the maximum fault levels of the system, as well as other factors required for the safe and secure operation of the system.

4.2 Prerequisites for SAPP planning.

SAPP has established system planning standards that must be followed throughout the inter-utility planning procedure and that will also apply to the model development and simulation of the Southern Africa Region project. This system planning has been established to meet the minimal standards of SAPP and to assure the reliable, efficient, and economical transfer of electrical power from generators to load centers. In any situation, the transmission system may evolve for several reasons, including but not limited to the one listed below:

- Reconfiguration, decommissioning, and improvement of the present network.
- The addition of new transmission substations or the upgrading of an existing transmission system's interconnection.
- Modifications to customer requirements or network configurations.
- The accumulated effect of several of the above-mentioned developments.

4.2.1 The preparation phases

The following planning method will be followed, which is segmented into the following major activities:

- Identifying the problem.
- Formulation of possible options to achieve the requirement.
- Analysis of these alternatives to guarantee compliance with accepted technological constraints and justifiable supply-chain reliability and quality criteria.
- Costing of these alternatives using approved methods.
- Choosing the best option.
- Creating a business case for the best solution based on the agreed-upon reasoning criteria.
- Request permission for the preferred option and the start of execution.

4.2.2 Criteria for transmission design

The Transmission Planning Criteria establishes the principles that will be used to plan for the short, medium, and long term. The fundamental objective of transmission planning is to ensure the continued stability of the bulk transmission system in the event of the most likely system disruptions. The transmission network is responsible for ensuring the continued supply of electricity to customers.

4.2.3 The concept for transmission design

The interconnected transmission system must be capable of operating reliably under a wide range of expected system conditions while remaining within the thermal, voltage, and stability limits specified for the equipment and electric system in this requirement. Electric power systems must be designed to resist emergencies and interruptions due to maintenance. Risks and repercussions should be assessed for extreme event scenarios that gauge the robustness of the electric system.

4.2.4 Transmission Planning Principles

The purpose of transmission planning is to assure the development of a reliable, efficient, and cost-effective electricity transmission infrastructure for the long-term benefit of transmission users and the country. The planning procedure includes the use of technical reliability criteria, economics, and coordination with generation and distribution functions, as well as transmission operations, maintenance, and protection, Information Communication and Technology (ICT), strategic aspects, as well as environmental concerns.

4.3 Power station integration

When interconnecting power plants, the following network redundancy standards must be met:

4.3.1 Power plants with a capacity of less than 1000 MW

a) With all connecting lines operational, the power station's total output shall be capable of being transmitted to the system under any load state. If the local region is reliant on the power station for voltage support, a minimum of two lines shall be connected.

b) Following the successful clearance of a single-phase fault, transient stability must be maintained.

c) If only a single line is used, it must be capable of being switched to alternate busbars and bypassed at both ends of the line.

4.3.2 Power plants with a capacity of more than 1000 MW

a) With one connecting line out of service, the power station's overall output must be transmitted to the system for any system load disorder.
b) With the two most severe line interruptions, it should be possible to transfer to the system the total output of the power station minus its smallest unit.
c) The smallest unit installed at a power plant may only be directly connected to the transmission system and centralized dispatched.

Transient stability can be sustained with a three-phase line or busbar fault that was cleared during normal protection times while the system was in good health and under the most demanding power station loading situation; a single-phase fault that was resolved within "bus strip" timings, the system remained healthy and the most onerous power plant loading situation remained; a single-phase fault that is cleared within standard protection times, resulting in one line being out of service and the power plant being loaded to its ordinary accessibility. The cost of maintaining transient stability liabilities incurred by the generator if the System Operator determines that the best option is to install unit or power station equipment.

Busbar designs must allow for the use of alternative busbars. Furthermore, feeders must be capable of bypassing. The busbar configuration must ensure that no more than 1000 MW of generation is lost due to a single constraint. In order for the System Operator to successfully integrate new power stations, specific details per unit and power station are requested.

When integrating a nuclear facility or off-site power supply to a nuclear facility, The degrees of redundancy and/or reliability and quality of the transmission system and off-site power supply standards stipulated in its nuclear operating license or by the country's National Nuclear Regulator must be adhered to.

4.4 HVAC Load flow solution using Newton Raphson's Method

The Newton Raphson method is preferred due to its ability to solve non-linear equations. The basic principle of power flow obtained from Newton Raphson method research is the magnitude and phase angle (V & δ) of the voltages flowing through all buses on the system, as well as the reactive and real power (Q & P) flowing in each line. This method solves power flow by first evaluating the system's data, obtaining the known and unknown variables in the system, which totally depends on the type of bus, which are slack bus, PQ bus, which is a load bud, and PV bus, which is a generator bus, as shown in Table 4.2 [10].

Table 4. 2 Specifications of different bus

Bus type	**Specified**	**Not specified**
Slack	$V = 1.0 p.u.$	& δ = 0.0
PQ bus	P, Q	δ, V
PV bus	P, V	δ, Q

The Newton Raphson algorithm was used in this investigation to examine load flow in a system.

$$S_i = V_i \sum_{j=1}^{n} Y_{ij}^* V_j^* = \sum_{j=1}^{n} |V_i||Y_{ij}| \angle \left(\delta_i - \delta_j - \theta_{ij}\right) \quad (4.9)$$

Whereby

$$Y_{ij} = |Y_{ij}| \angle \theta_{ij}, V_i = |V_i| \angle \delta_i and V_j = |V_j| \angle \delta_j \quad (4.10)$$

This formula is used to compute the actual and reactive powers of each bus in a power network [10].

$$P_i = \sum_{j=1}^{n} |V_i||V_j||Y_{ij}| \cos\left(\delta_i - \delta_j - \theta_{ij}\right) \quad (4.11)$$

$$Q = -\sum_{j=1}^{n} |V_i||V_j||Y_{ij}| \sin(\delta_i - \delta_j - \theta_{ij}) \quad (4.12)$$

Thermal loading is calculated by dividing the load current by the rate current.

$$thermal.loading = \frac{Iload}{Irated} X100\% \quad (4.13)$$

Whereby the load current per phase

$$I_l = \frac{S^*_{l3\phi}}{3V^*_l} \quad (4.14)$$

4.5 HVAC Load Flow Analysis with FACTS Devices

Numerous methods for assessing power system stability and load flow have been proven. It is necessary for the investigative process of system performance, stability improvement, and optimal system operation under given limits. It is critical to optimize the placement and sizing of FACTS controllers in order to reduce power system contingencies. In this study, the Static Var System is used as a FACTS device to control some of the reactive power and increase system stability.

The various control combinations define how the SVS's internal admittance is computed. Only one admittance value is determined for balanced load flow. All three admittances are estimated for unbalanced load flow. The current for balanced operation is then computed using the equation below:

$$i = j.y_{svs}.u \quad (4.15)$$

Whereby i is the current , and y_{svs} is the admittance and u is the voltage. When the Balanced Control option is enabled on the basic data page in DigSilent PowerFactory, all three admittances are equal. If the control is set to Unbalanced Control, all admittances are computed separately based on the control mode selected on the load flow page and the general parameters of the load flow command.

When executing load flow, three control options are available: no control, reactive power control, and voltage control. Of these three control options, voltage control was applied in this study, whereby the SVS can be configured to maintain a specified setpoint for either the local voltage at its terminal or the voltage on a remote busbar. This was done to manage the voltage instability in busbars by managing some of the reactive power with SVC.

4.6 Load flow analysis with HVDC transmission line

Due to the rate of change in the Southern African region's growing population, there is a great need for electricity to meet the growing demand. The Southern African electrical infrastructure requires a fundamental upgrade of the current electrical network to interconnect the transmission system that will connect different Southern African countries for power exchange. As previously stated, when transporting bulk power over longer distances, HVDC is the most cost-effective and efficient alternative with lower losses than HVAC. HVDC (LCC) is utilized to support HVAC on longer distances conveying bulk electricity for the reasons of lower cost, minimal losses, and greater power transfer capabilities, as well as mesh connecting of transmission systems among different Southern African countries. Below are the basic calculations for LCC HVDC

The DC Current for the HVDC LCC link is as follows:

$$I_{dc} = \frac{V_{dc}\cos\alpha - V_{dc}\cos\delta}{R_l + R_r + R_i} \quad (4.16)$$

Whereby V_{ac} is the ac voltage, V_{dc} is the dc Voltage, I_{dc} is the dc current, α is the firing angle, δ is the extinction delay angles, R_l is the resistor from the loop, R_r is the resistor from the rectifier and R_i is the resistor from the inverter

The line to line voltage is used to determine the optimum no-load DC voltages per bridge on connection sides 1 (rectifier) and 2 (inverter).

$$V_{dc} = \frac{3\sqrt{2}}{\pi} V_{ac} \quad (4.17)$$

4.7 Power transfer capability

Transfer capability is a measure of an interconnected system's ability to reliably transport electricity from one location to another through all transmission circuits connecting those areas under specified system conditions. Additionally, the capability of transfer is directional in nature.

Several critical points of transfer ability analysis are summarized below:

System conditions - For the analysis period, baseline system requirements are recognized and modeled, including estimated customer demand, generation dispatch, system configuration, and planned power transfers.

Critical contingencies - Transfer capacity assessments consider both generation and transmission system contingencies to determine which facility failures are the most restrictive to the transfer under consideration.

System limits - The transmission network's transfer capability may be restricted by thermal, voltage, stability, or contractual constraints.

4.7.1 PV curves

PV curves are critical for analyzing power system voltage stability. By increasing the power demand of user-selected loads until the load flow calculation no longer converges, the PV Curves calculation identifies the critical point of voltage instability; that is, until the steady-state limit is reached.

4.7.2 Criteria for maximum power transfer

When the power transfer over a power corridor surpasses one of the four conditions listed below, the maximum power transfer is determined:

a) Unless agreed upon by utilities, For system health conditions, any busbar voltage that falls below 0.95 pu.
b) The power flow on the corridor outweighs 95% of the maximum power transfer on the PV curve at the corridor's knee position (Pmax).
c) The reactive power in the affected area exceeds 90 percent of the reactive capacity of the locally installed SVCs and/or generators, requiring a minimum 10 percent reactive reserve on the SVCs and/or generators.
d) Without transformer tap changer action, the voltage drop for a 5% increase in load exceeds 5%.

4.8 Standardization of equipment

Reference IEC standards or equivalents. International Standards should be followed while purchasing equipment.

4.9 Criteria for economic justification

Transmission projects should be chosen based on the one with the lowest life cycle cost when comparing multiple options. In accordance with authorized investment criteria, a detailed techno-economic review should be carried out.

4.9.1 Investment criteria for networks

When the required development meets the technical and investment conditions indicated in this section, the entity/utility must invest in the transmission system.

The entity/utility must identify and convey all implications as soon as possible so that budgeting and execution of related changes may be planned.

Any of the investing criteria listed below, each of which is appropriate in different circumstances, can be used.

Unless otherwise specified by plant life or project life expectancy, calculations will be based on a typical project life expectancy of 25 years.

The following essential economic parameters will be taken into account:

- Rate of discount
- Cost of Unserved Energy
- Additional characteristics provided by SAPP

4.9.2 Criteria for the lowest economic cost

These criteria will apply in the following instances:

- When investments are made to improve supply reliability and/or quality in order to meet the restrictions or objectives.
- Determining and/or validating the desired level of network or equipment redundancy.

The method necessitates calculating the cost of inadequate network services. These expenses include the costs of:

- Interruptions
- Load shedding
- Network restrictions
- Poor supply quality (QoS).

The equation to satisfy the least-cost investment criterion is as follows:

The value of improving QoS to customers > the cost of providing improved QoS to the service provider.

As a result of this calculation, if the value of improved QoS to the customer is less than the price to the service provider, the service provider should avoid investing in the proposed project (s). The investment choice is then postponed to maximize economic gain.

This indicates that the following criteria must be met:

"COUE yearly value (US$/kWh) x annual decrease in expected energy not served (EENS) to customers (kWh) > annual cost of reducing EENS to the service provider (R)"

The reduction in EENS is estimated probabilistically using the investments' benefits.

The cost of unserved energy (COUE) is based on the type of load, the duration, and frequency of interruptions, the time of day they occur, whether advance notice is given, The indirect harm caused to customer start-up costs, and the accessibility of customer backup generation.

CHAPTER 5 SARG NETWORK CONSTRUCTION AND POWER FLOW MODELING

5.1 Design and construction of networks

The SARG network model was created using DigSILENT PowerFactory. The Newton-Raphson method is used by PowerFactory to solve nonlinear equations. Early data for the model's construction came from the websites of Eskom, SAPP, and the Energy Information Administration (EIA). Each country has its own network, which includes accessible resources such as thermal, hydroelectric, solar, diesel, wind, oil, and nuclear that are used as generating stations (GS) to generate electricity within their borders. These countries were then connected via existing and proposed electricity interconnections using transmission voltages of 110kV, 132kV, 220kV, 275kV, 330kV, and 400kV to form the Southern African Regional grid network. The approach outlined below was used to construct the Southern African grid model. The analysis was done under the assumption of 100% generation plant availability.

- The single-line diagrams of Southern African regional member states were created using DIgSILENT PowerFactory.
- Using the raw data gathered, the data requirements for every component, Among the input devices are power transformers, transmission lines, generators, loads, and reactors.
- The individual models are then interconnected to form a single network, with each country characterized as a substation in the Southern African regional mega Grid.
- The thermal rankings of the elements and the voltage ratings of the busbars are determined in DIgSILENT PowerFactory in accordance with the Southern African regional standards.
- The voltage levels in the models are examined to ensure that all networks are connected to transmit electricity; the voltage levels are shown in seven colors ranging from 11kV to 400kV.

Figure 5.1 shows the grid voltage levels ranging from 11kV to 400kV as presented in each model to demonstrate voltage connectivity in the substation.

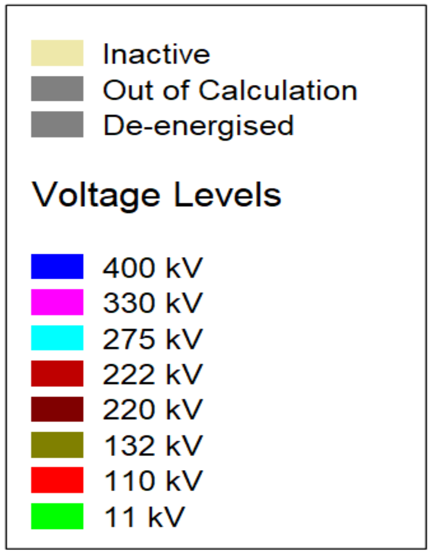


Figure 5. 1 SAPP Grid voltage levels

Figure 5.2 shows the Lesotho SS with two power interconnections between South Africa and Lesotho is shown as 2 X Tweesprut - Maseru TL. Lesotho generates electricity from hydropower and solar power within the country which is also shown in the DigSilent PowerFactory model.

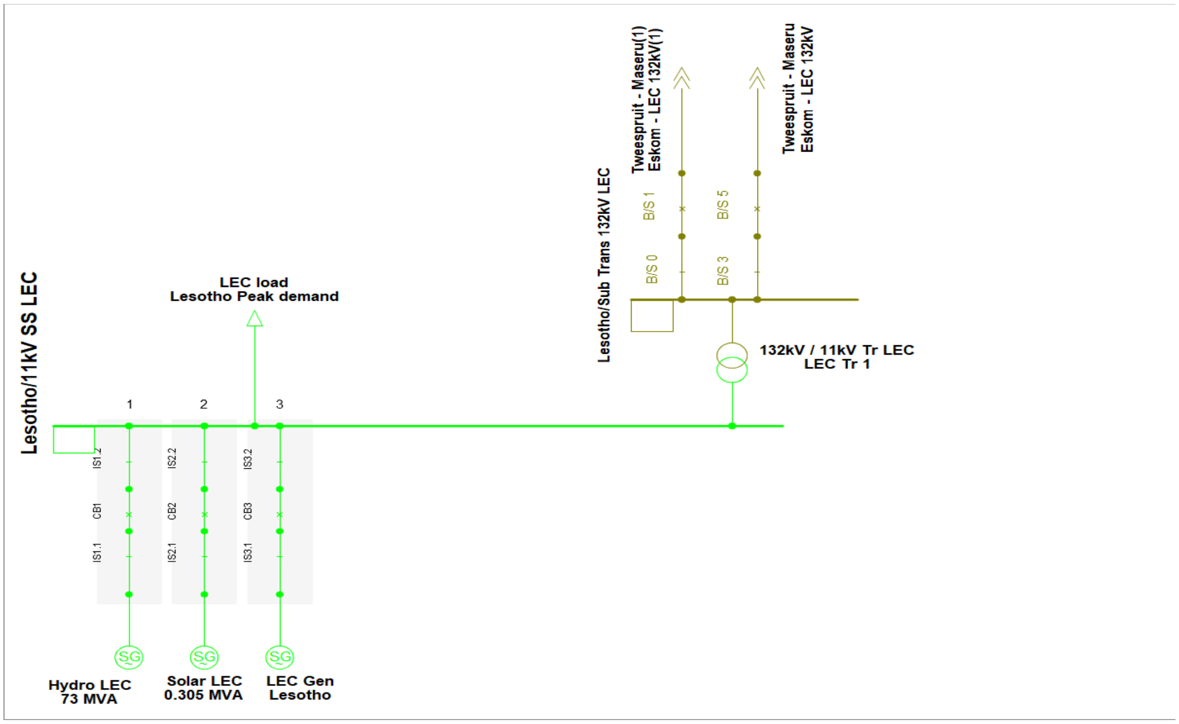


Figure 5. 2 Lesotho (SEC) HV Power network.

Figure 5.3 depicts the Swaziland power utility . Swaziland obtains electricity from hydropower. Swaziland has three existing interconnections for power exchange, which are Normandie–Nhlangano TL, Camden-Edwaleni TL, and Edwaleni II–Maputo TL.

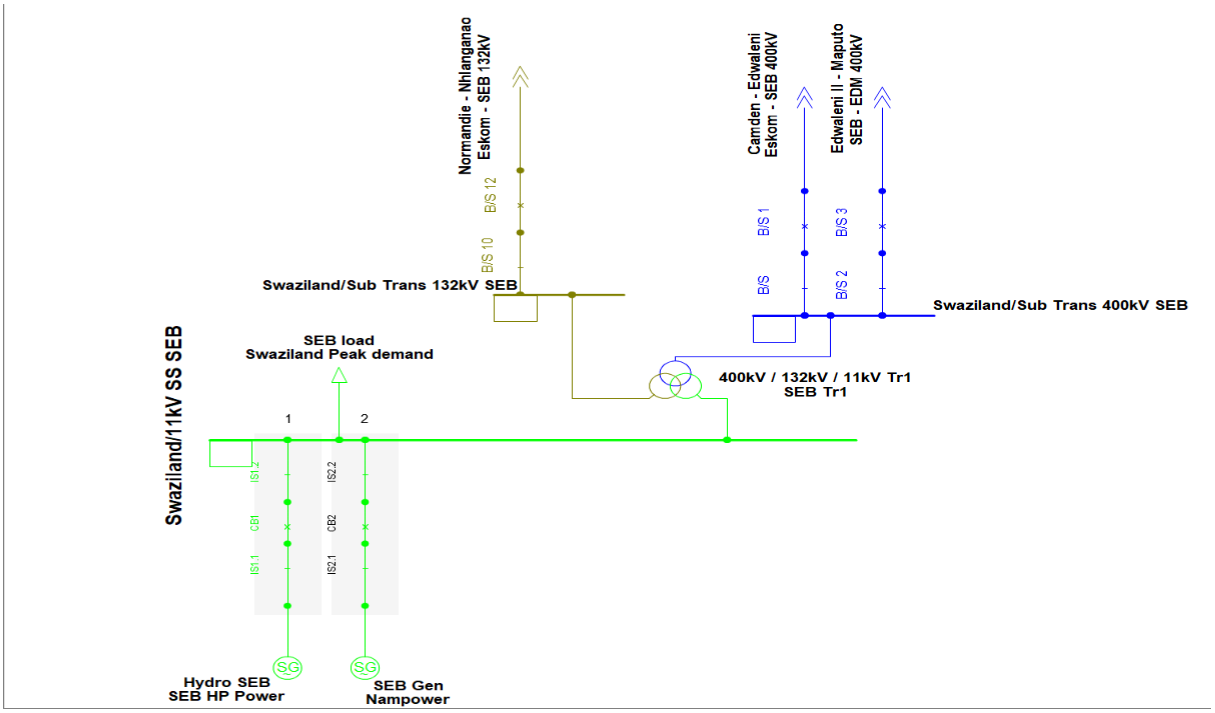


Figure 5. 3 Swaziland (SEB) HV Network grid.

Figure 5.4 illustrates the South African network grid. South Africa obtains the majority of its electricity from Eskom, which is largely coal-based. South Africa has 15 existing power interconnections, as displayed in Fig 5.4. Botswana, Swaziland, Lesotho, Mozambique, and Namibia are all interconnected to South Africa.

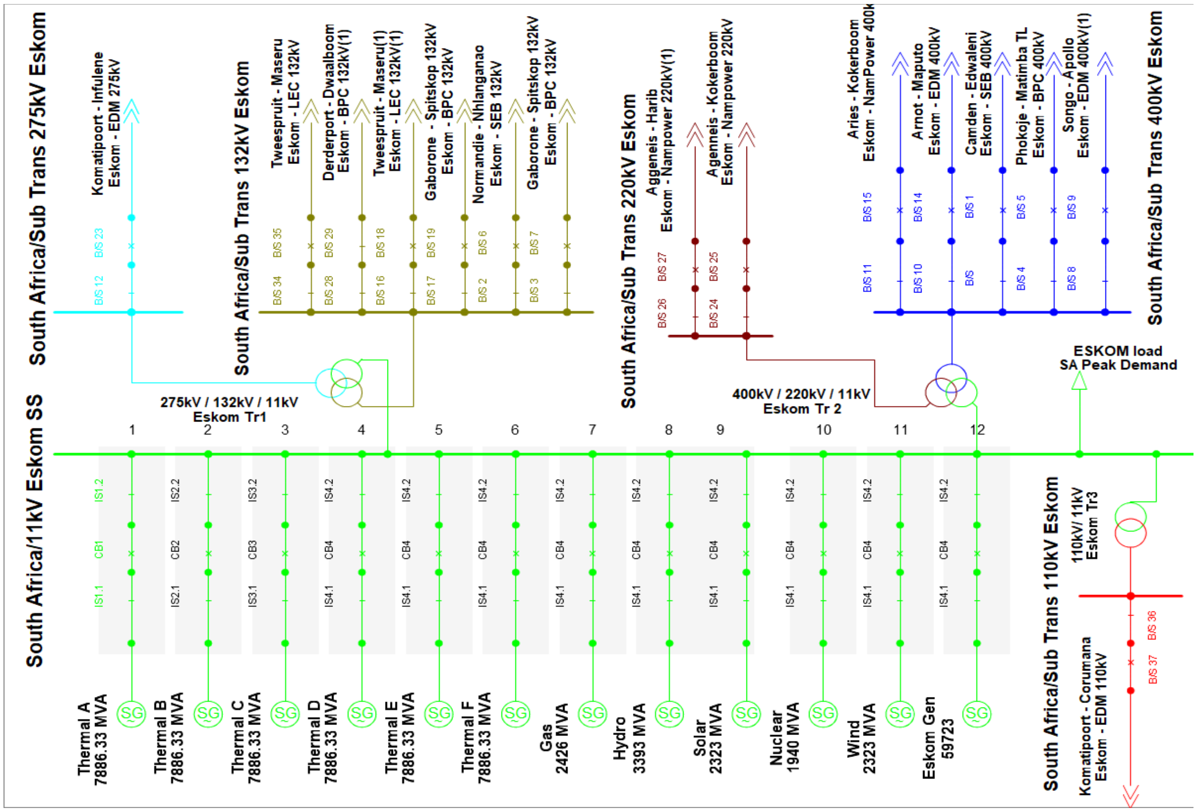


Figure 5. 4 South Africa (Eskom) HV Grid network.

Figure 5.5 portrays the Mozambique SS; Mozambique generates electricity from coal, hydro, and solar power; Mozambique obtains the majority of its power from the EDM power utility as previously noted. Mozambique currently has power interconnections with Swaziland, South Africa, and Zimbabwe. These interconnections are displayed in Fig 5.5, along with one proposed interconnection, the Malawi-Mozambique TL, which is also included in this project.

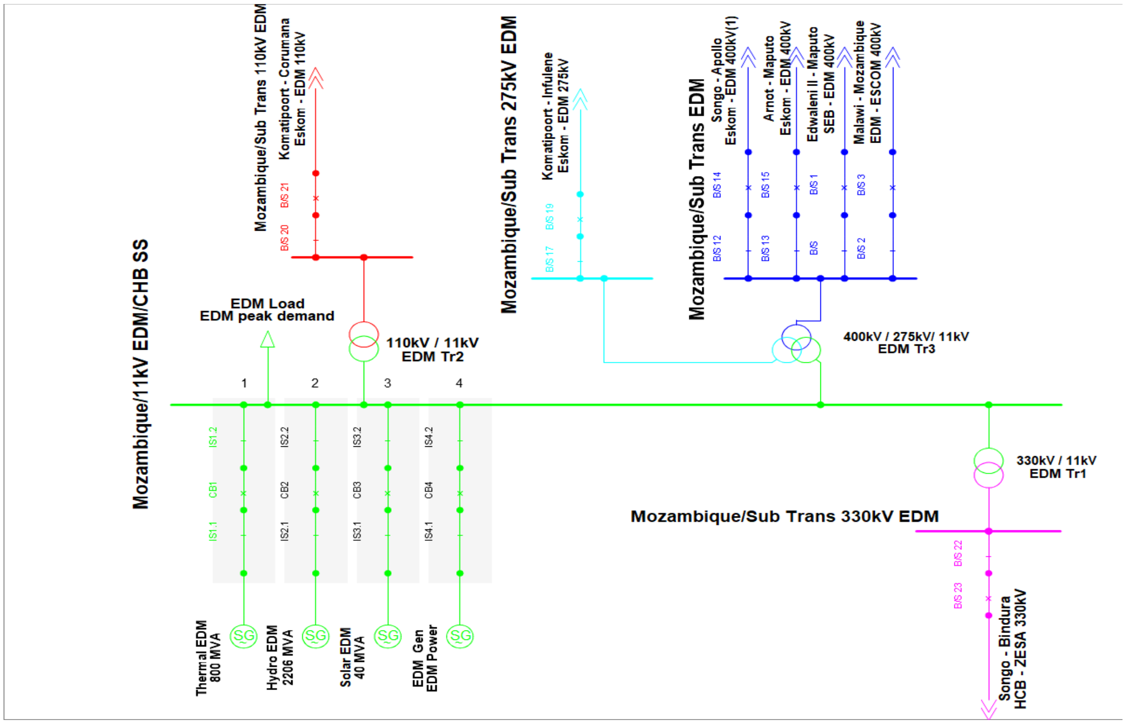


Figure 5. 5 Mozambique (EDM) HV Power Network

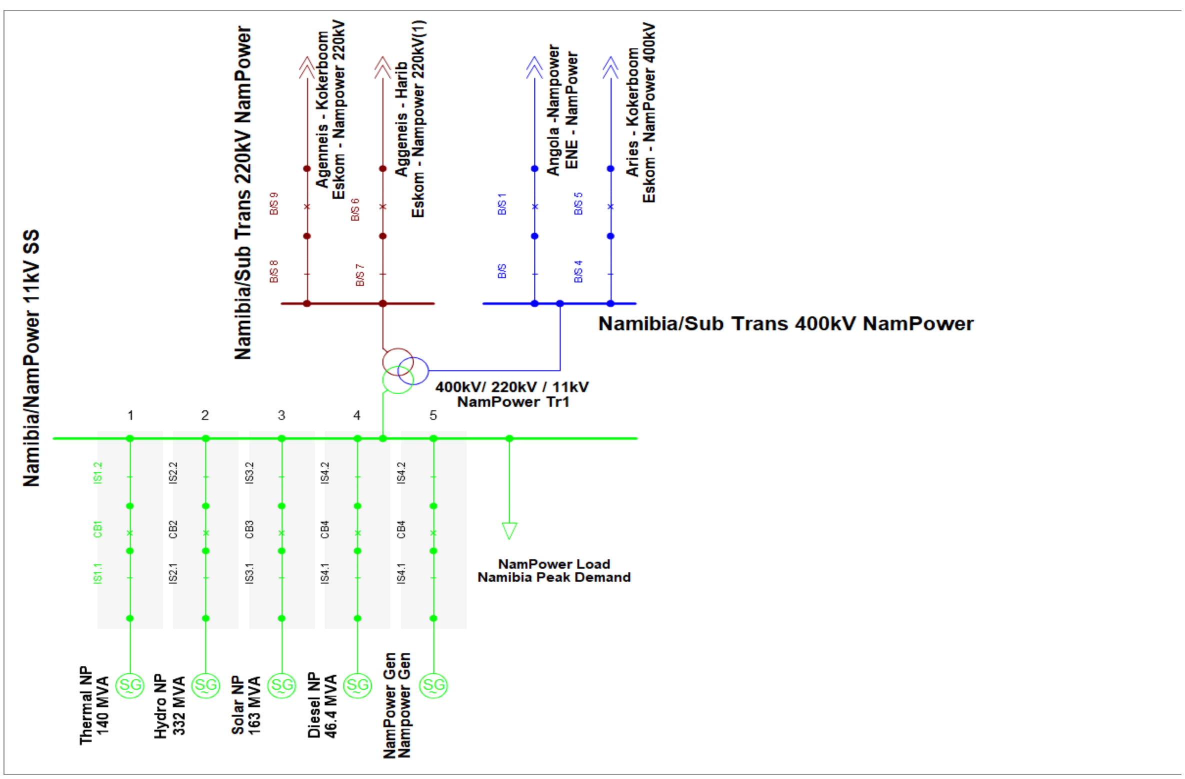


Figure 5. 6 Namibia (NamPower) HV Power Grid.

Figure 5.6 shows the Namibia SS. Namibia has Nampower as the utility that generates electricity using thermal, hydro, solar, and diesel sources. Namibia is currently connected to South Africa via the SAPP, and there is also a proposed interconnection between Namibia and Angola; these interconnections are shown in Figure 5.6.

Figure 5.7 shows the Angola HV power network. Angola's utility is ENE. Angola is not presently connected to the SAPP grid; nevertheless, there is a proposed interconnection between Angola and Namibia, which is also included in this project as shown in Figure 5.7.

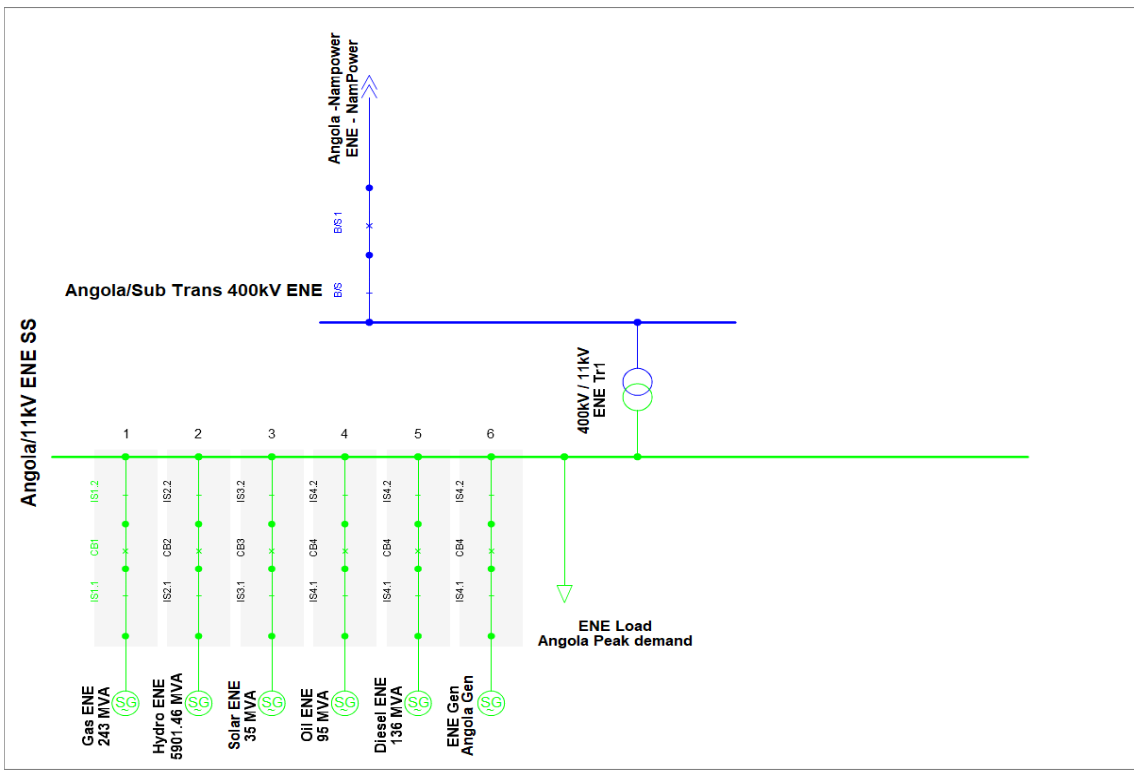


Figure 5. 7 Angola (ENE) HV Power network.

Figure 5.8 illustrates the Zambia SS, with ZESCO operating as the country's power utility. Zambia is currently only connected to Zimbabwe in the SAPP, however, a proposed interconnection between Malawi and Zambia is included in this research.

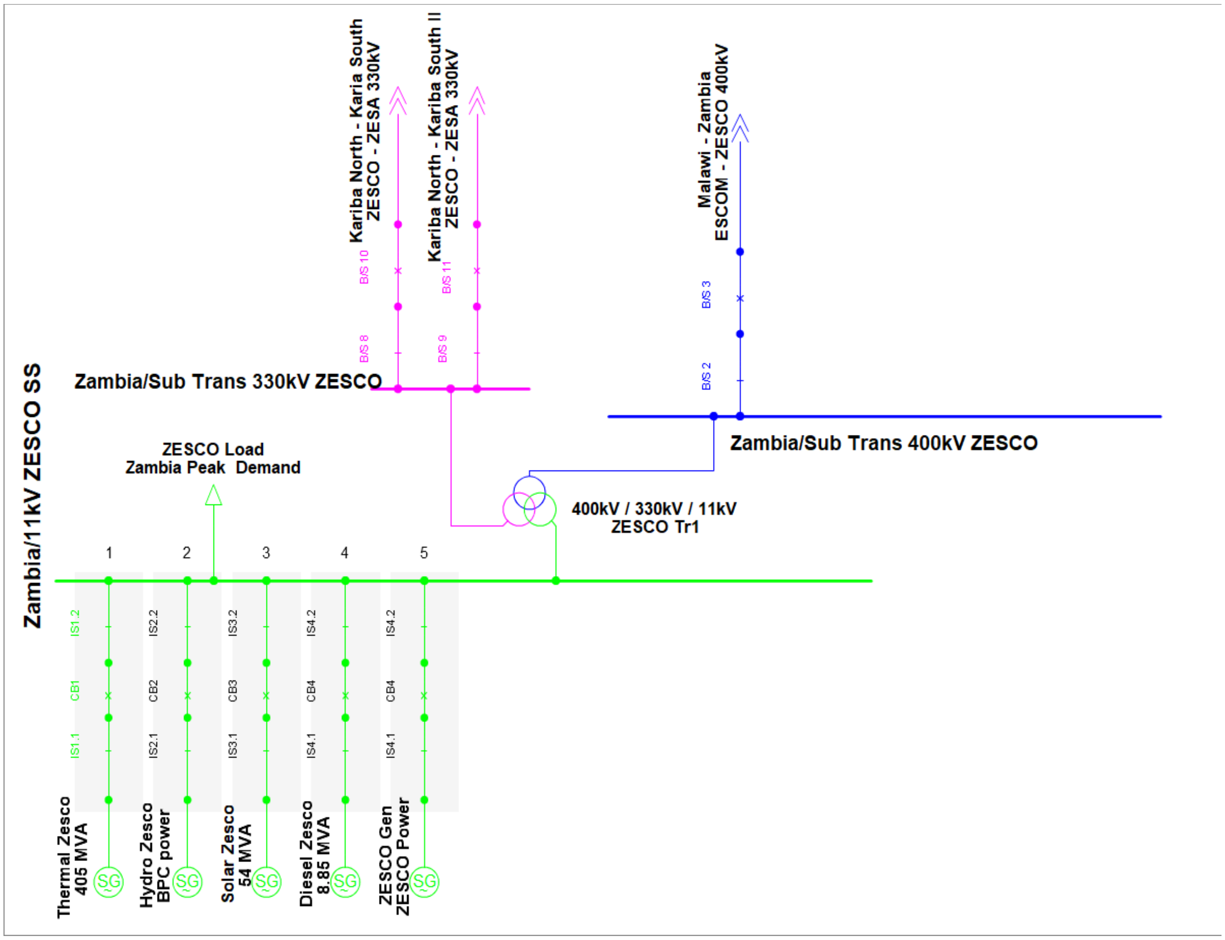


Figure 5. 8 Zambia (ZESCO) HV Power Grid.

Malawi does not have any existing power interconnections to any Southern African countries, but there are two proposed interconnections, Malawi-Mozambique and Malawi-Zambia, which are both included in this research with the aim of power exchange in Malawi. Malawi has Escom as its electricity utility, producing electricity from hydropower and diesel power as shown in Figure 5.9

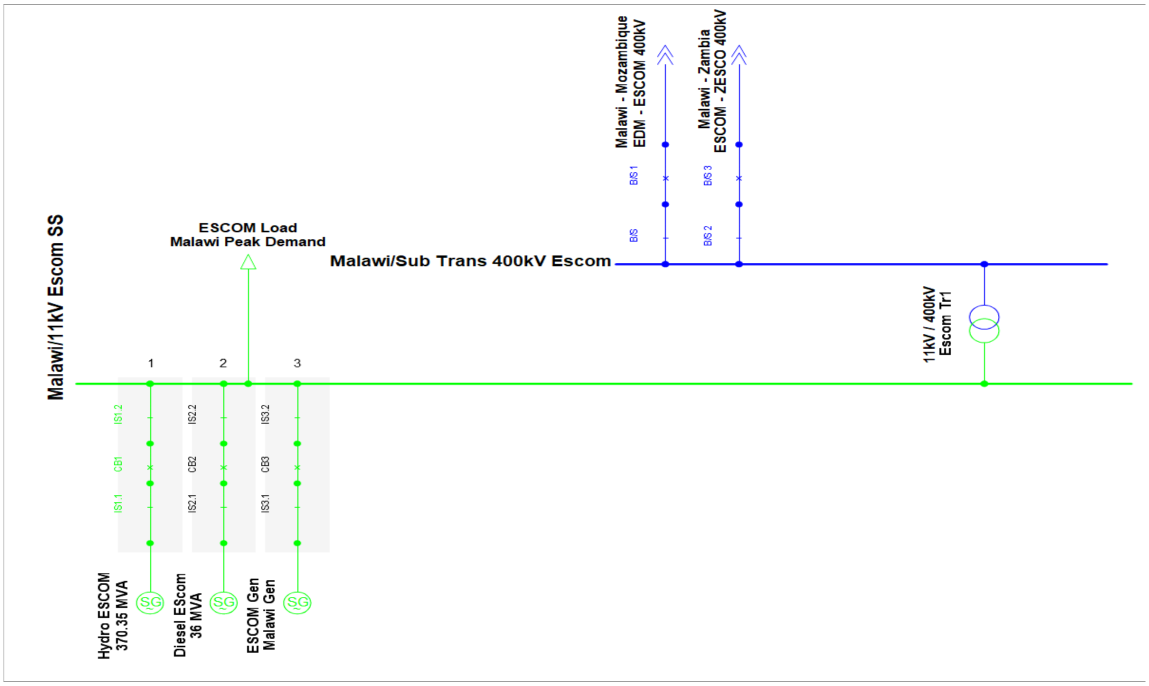


Figure 5. 9 Malawi (Escom) HV Power Grid.

Botswana's high-voltage network is displayed in Figure 5.10. Botswana has BPC as their utility that generates electricity using thermal, solar, and diesel sources. Botswana is currently connected to the SAPP grid through South Africa and Zimbabwe; these interconnections are utilized in this research to facilitate power exchange.

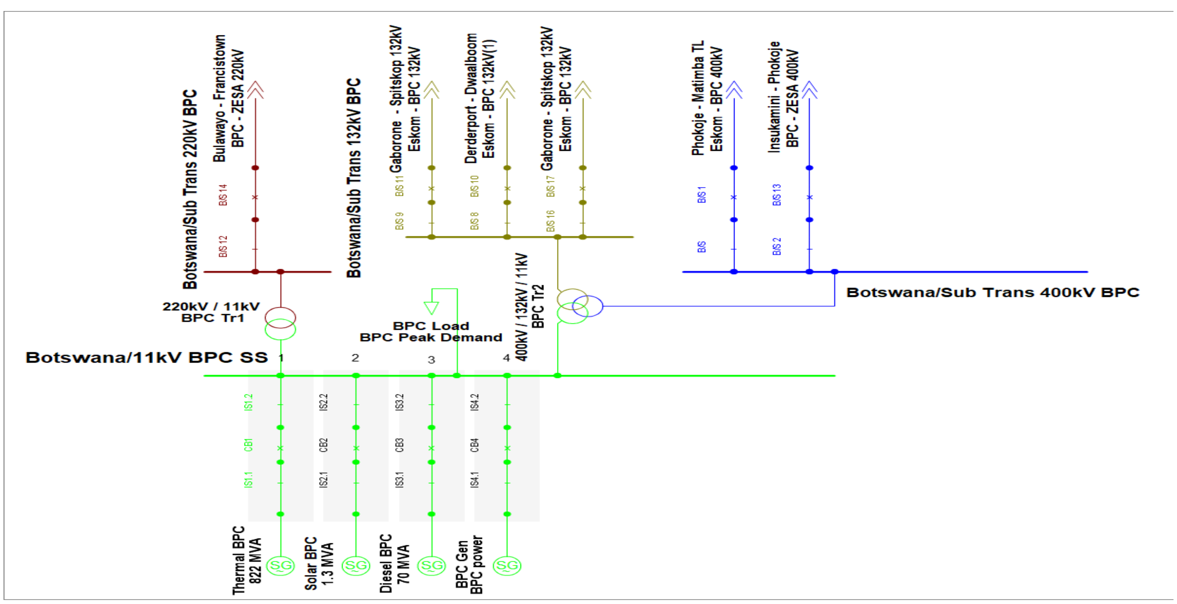


Figure 5. 10 Botswana (BPC) HV Network.

Figure 5.11 represents the Zimbabwe HV network grid. Zimbabwe produces the majority of its electricity from the ZESA electricity utility, which generates power from thermal and hydropower sources. Zimbabwe is currently interconnected with Zambia, but there is also a proposed interconnection included in this project, as portrayed in Figure 5.11.

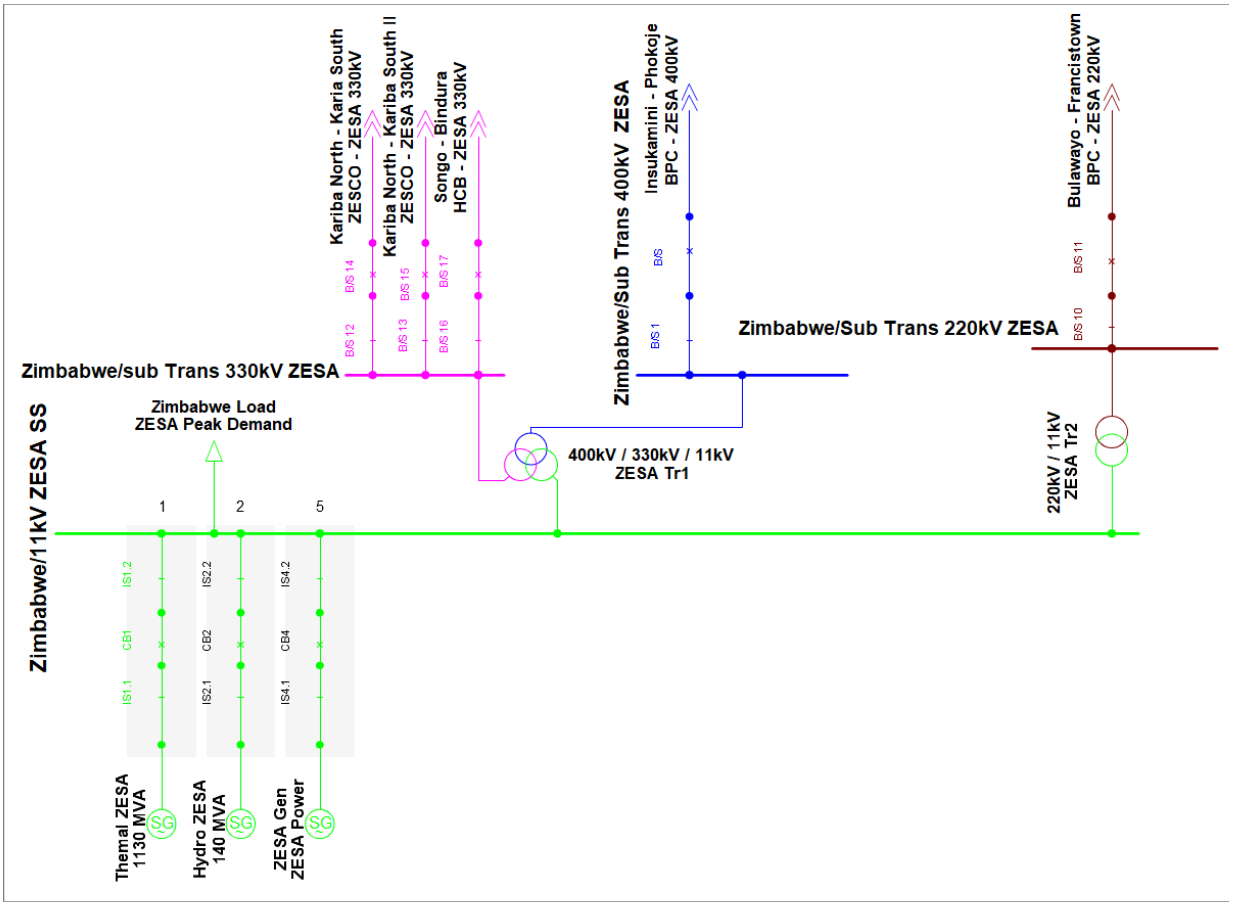


Figure 5. 11 Zimbabwe (ZESA) HV Network Grid.

Figure 5.12 shows a network model of all Southern African countries interconnected together to form a single mega station; the color variation represents the voltage levels in the substation.

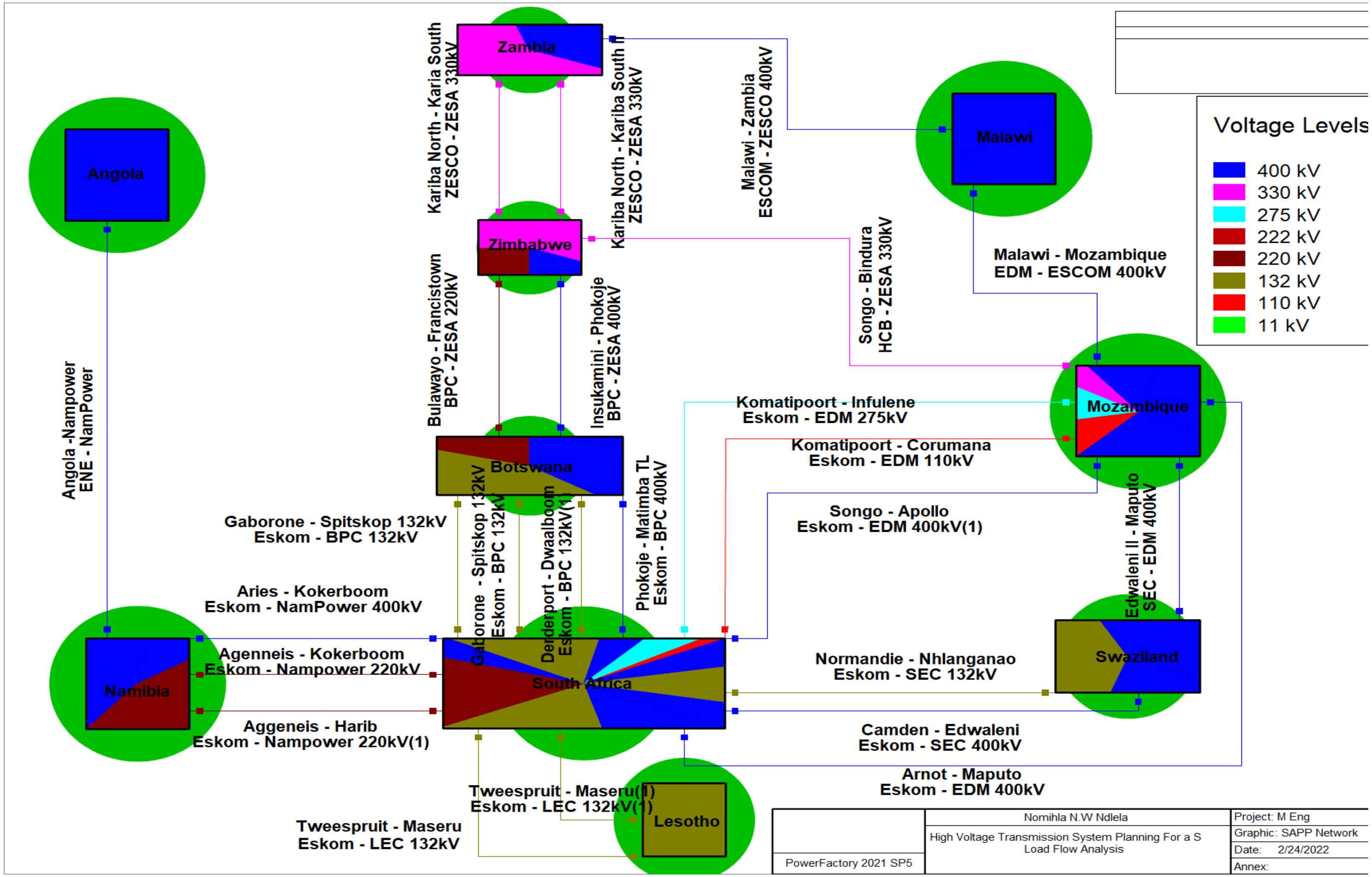


Figure 5. 12 Southern Africa Network Model

5.2 Individual Southern African country network model

The model was initially simulated without power connectivity to see if they would be able to generate enough power within their respective countries.

Figure 5.13 shows the LEC substation with a peak demand of 155MW. The Lesotho countries produce power from two sources, hydropower and solar power, producing 70.3 MW, which is insufficient to meet the Lesotho demand and requires an additional 84.7 MW.

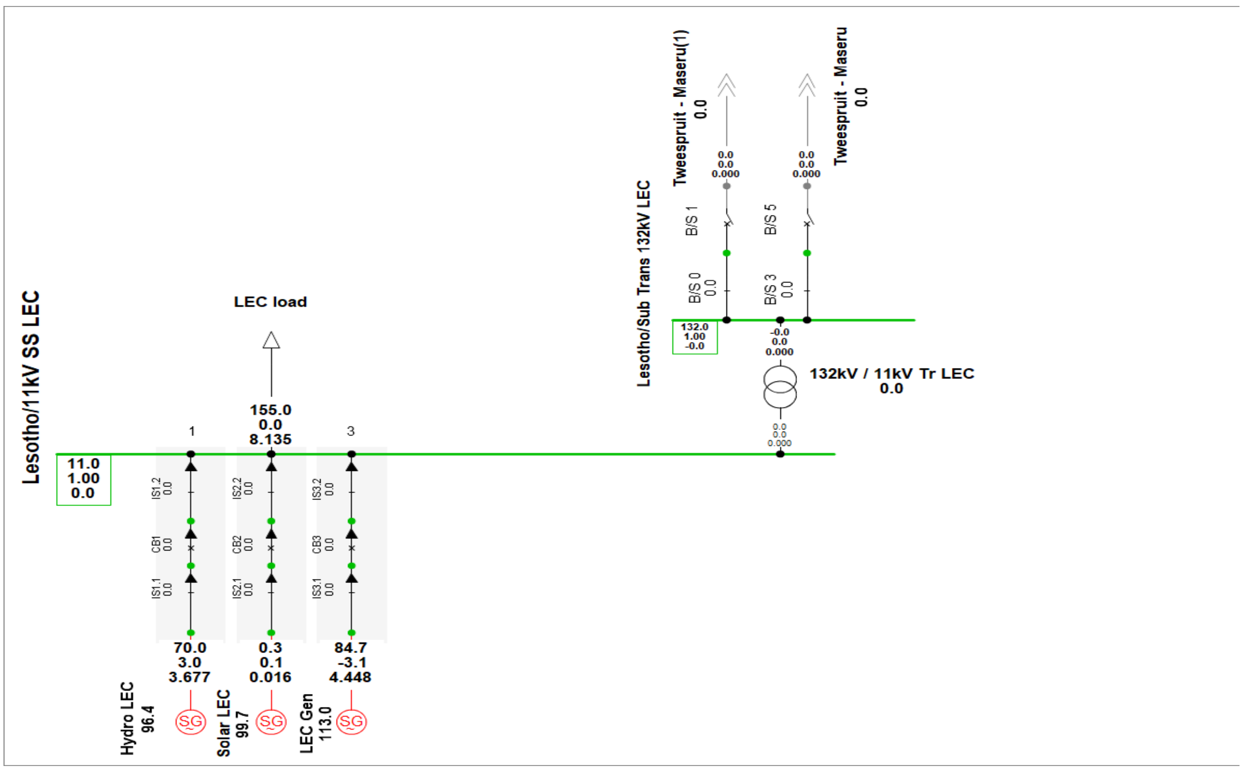


Figure 5. 13 Simulation results of Lesotho (LEC) SS HV Network.

Figure 5.14 shows the Swaziland (SEB) SS, which has a peak demand of 223 MW from a single hydropower substation with roughly 70 MW but still requires 153 MW or more to supply enough power for Swaziland.

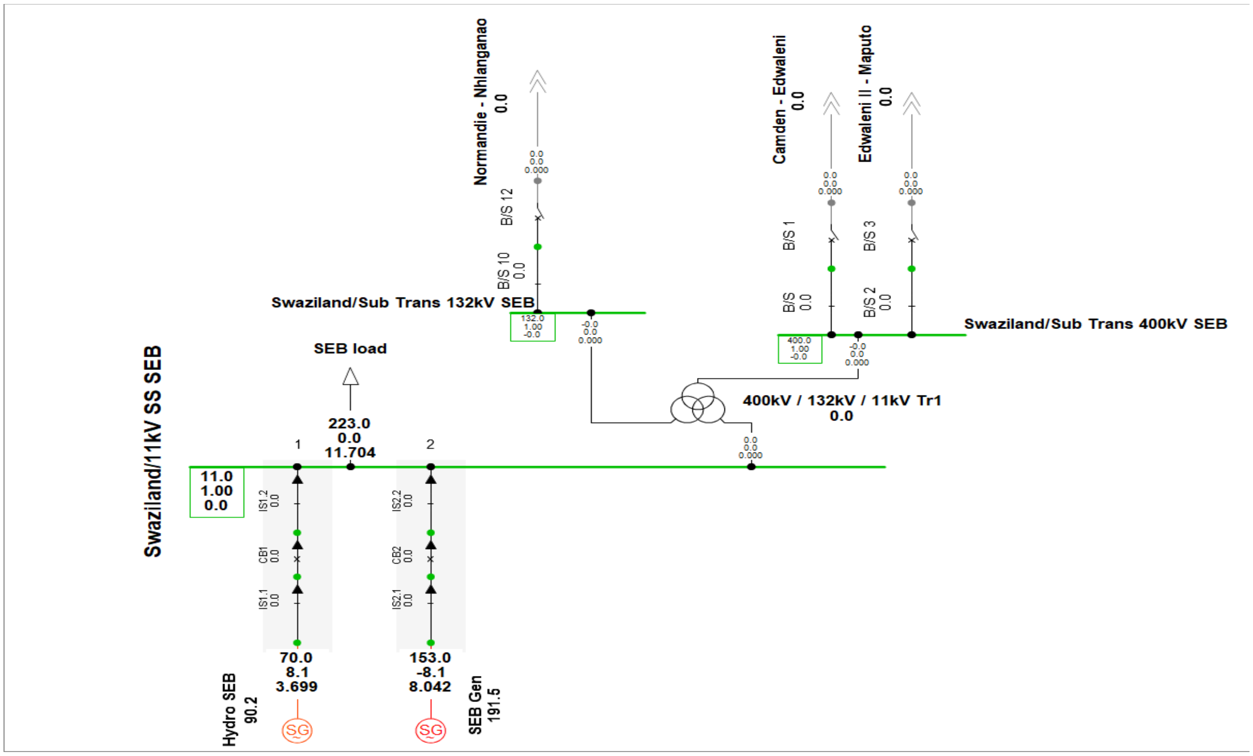


Figure 5. 14 Simulation result of Swaziland (SEB) HV Network

Figure 5.15 represents South Africa's power grid with a peak demand of 46678 MW. South Africa generates electricity using a variety of resources, as depicted in the figure, and it also has an excess of 12402 MW that may be exchanged with other countries.

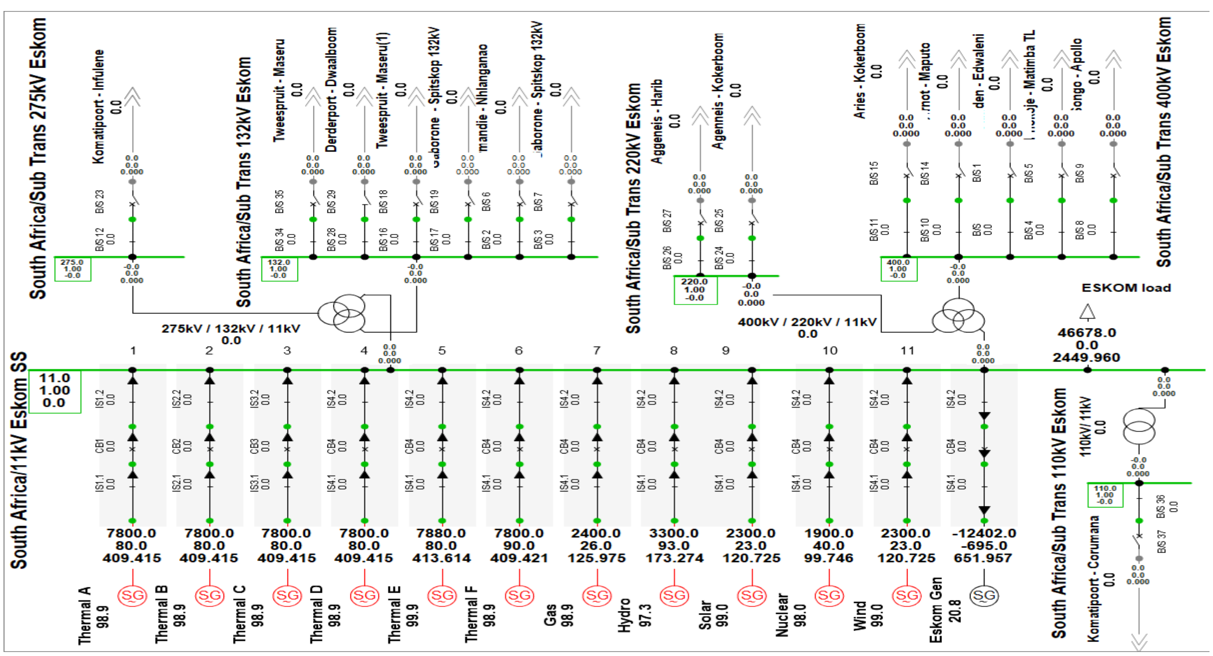


Figure 5. 15 Simulation results of South Africa (Eskom) HV Power network.

Figure 5.16 represents the simulation findings for Mozambique (EDM), which has an installed capacity of 3046MW and a demand of 1651MW, leaving the country with1286 MW of excess capacity.

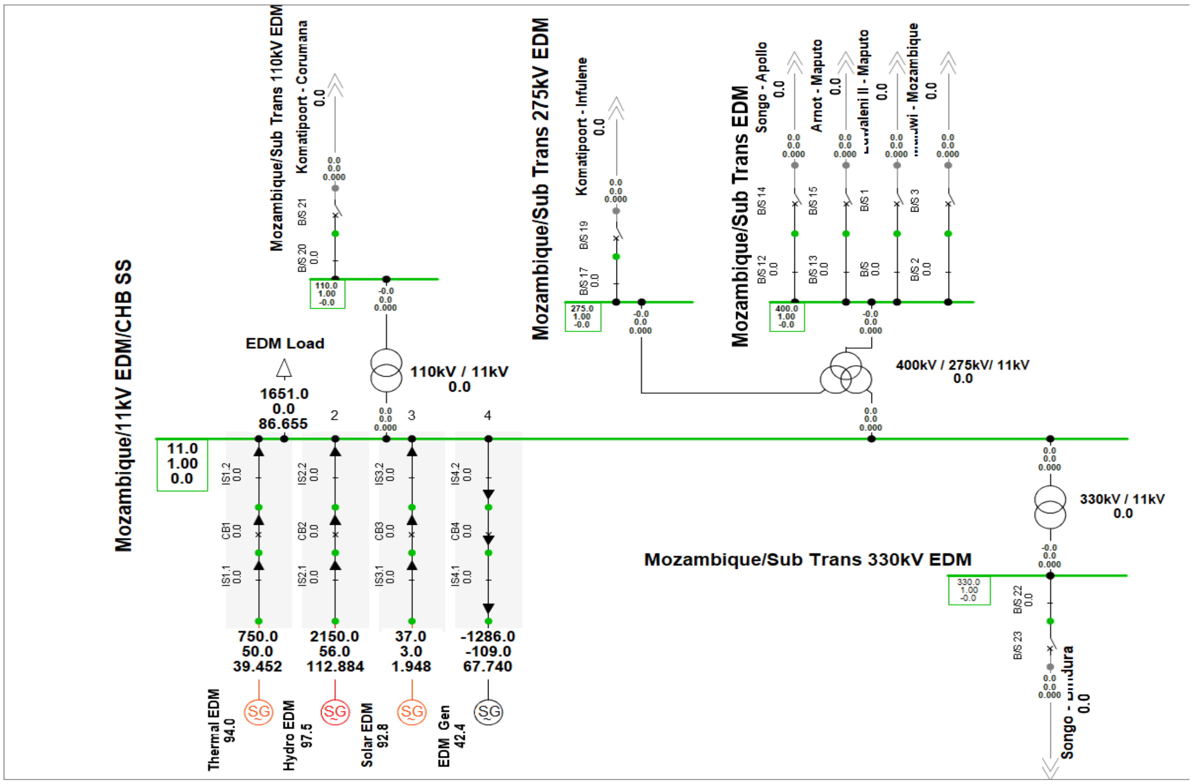


Figure 5. 16 Simulation results of Mozambique (EDM) HV Grid network.

Figure 5.17 shows Namibia's high-voltage power network with a peak demand of 600MW and an installed capacity of roughly 620MW; hence, Namibia's current access rate is approximately 56%.

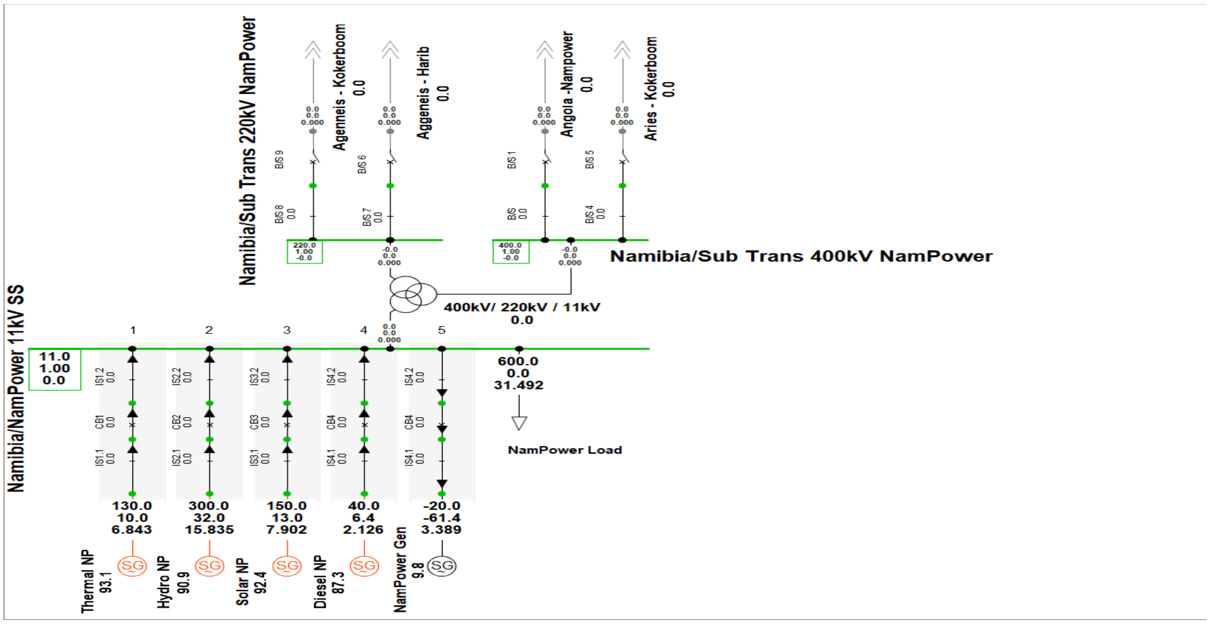


Figure 5. 17 simulation results of Namibia (Nampower) HV Power Grid.

Figure 5.18 represents Angola's (ENE) high-voltage network, which is not currently included in SAPP. Angola has an installed capacity of 6410MW, which is sufficient to meet the country's current energy consumption of 3379MW. Angola currently has a 45 percent electricity access rate.

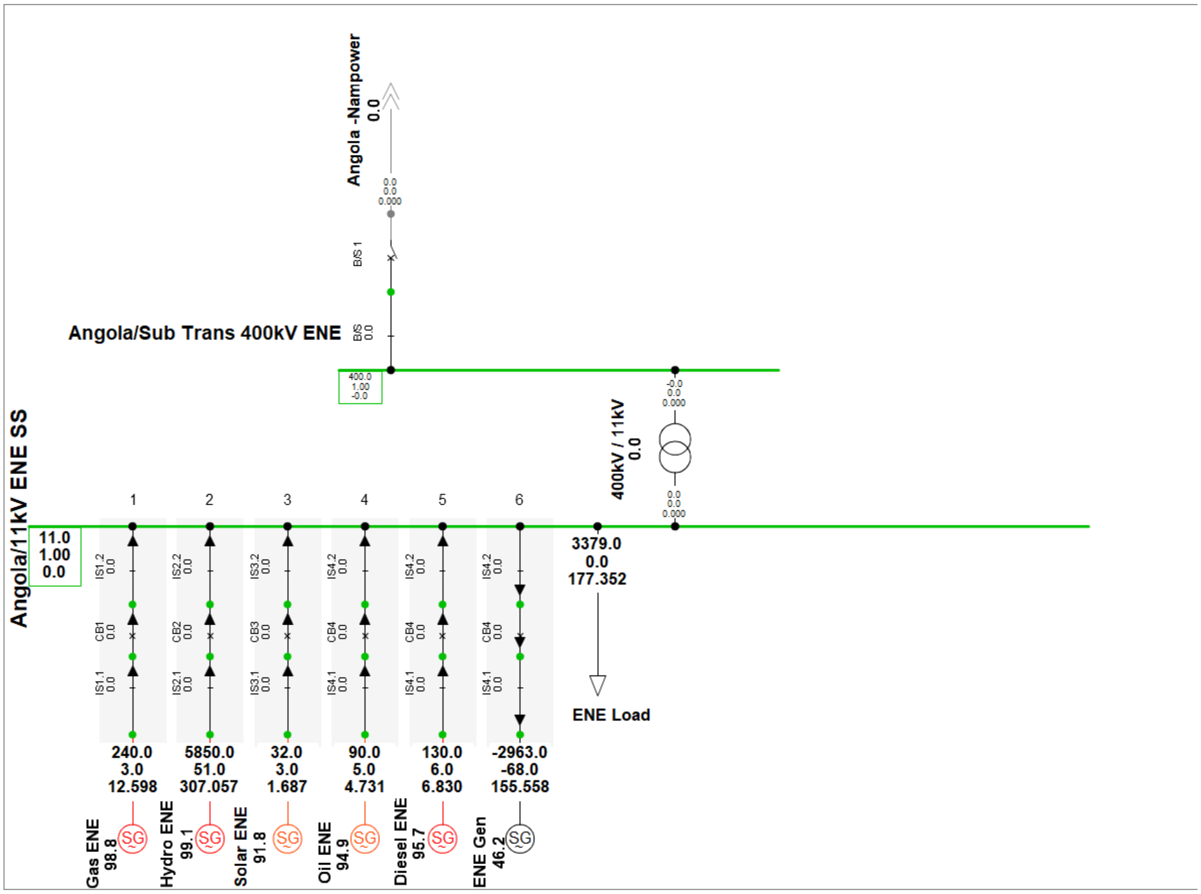


Figure 5. 18 Simulation results of Angola (ENE) HV Network.

Zambia has an installed capacity of 2763MW from thermal, hydropower, solar, and diesel sources and is required to meet a demand of 2300MW as shown in Figure 5.19. However, due to numerous constraints, Zambia currently has 31% access to electricity.

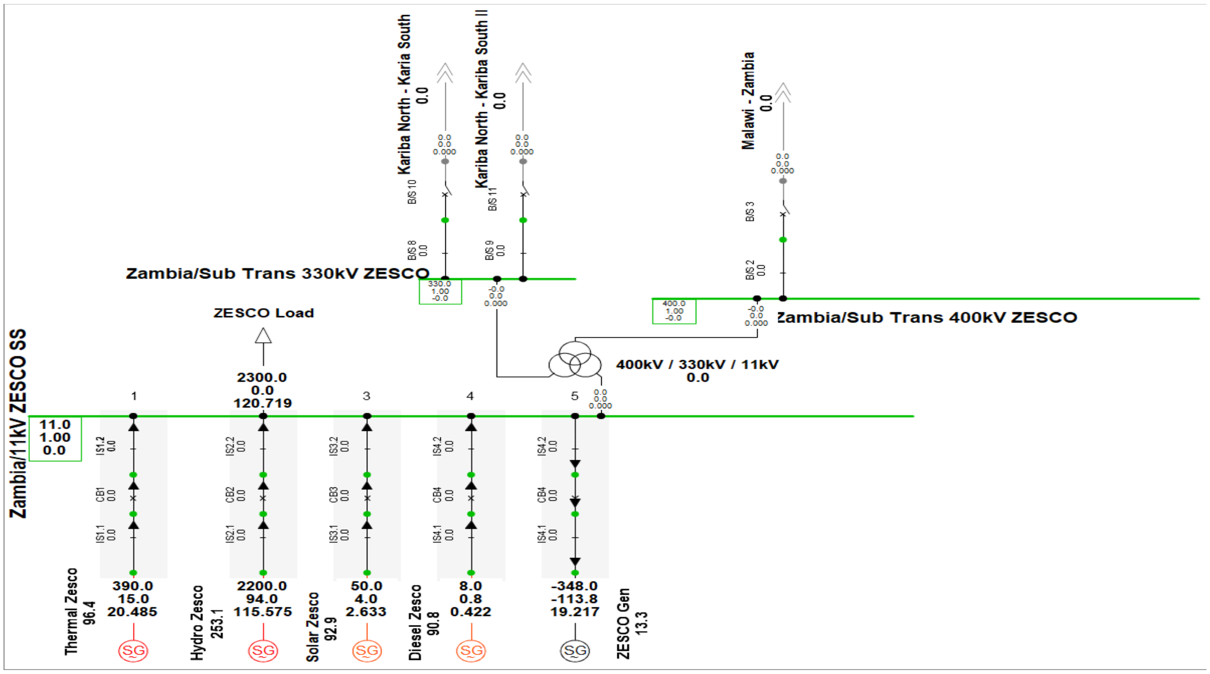


Figure 5. 19 simulation results of Zambia (ZESCO) HV Network.

Malawi's HV network is shown in Figure 5.20; with a peak demand of 470 MW, Malawi needs an additional 76 MW to generate sufficient power. Malawi generates power using hydropower and diesel Power stations.

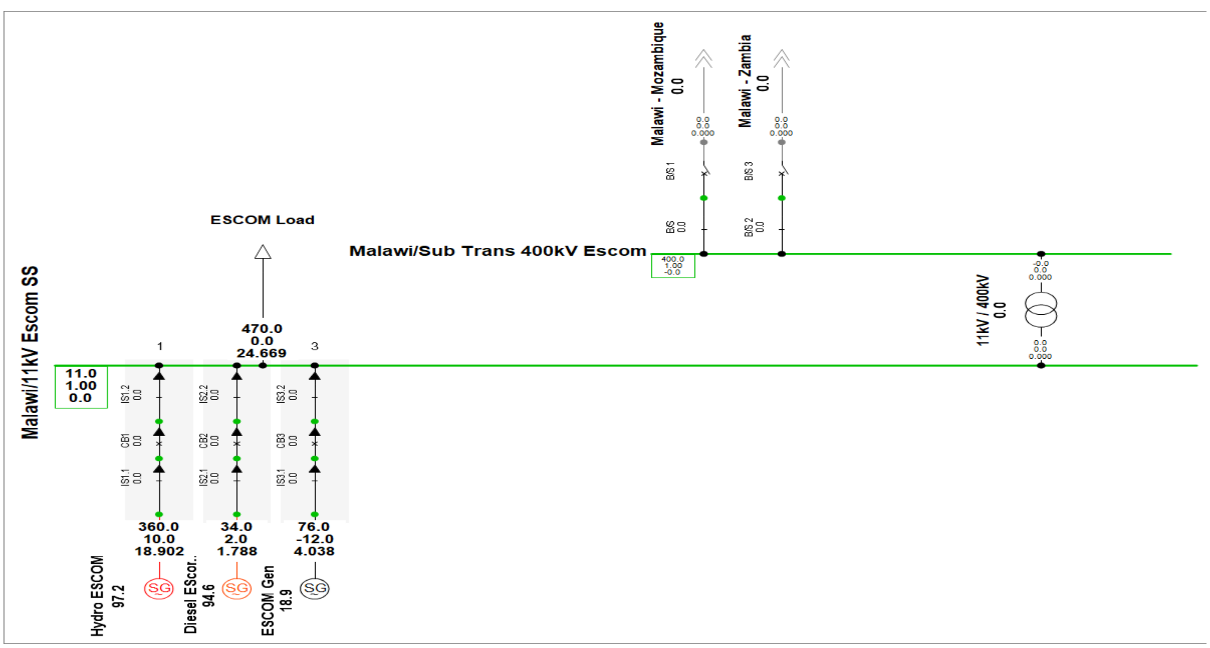


Figure 5. 20 Simulation results of Malawi (Escom) HV Grid network.

Figure 5.21 shows the Botswana SS simulation findings. Botswana has an available power of 868.2MW to a power demand of 702MW, resulting in an extra power of 166,2 MW that can be preserved for emergencies in the country or power exchange.

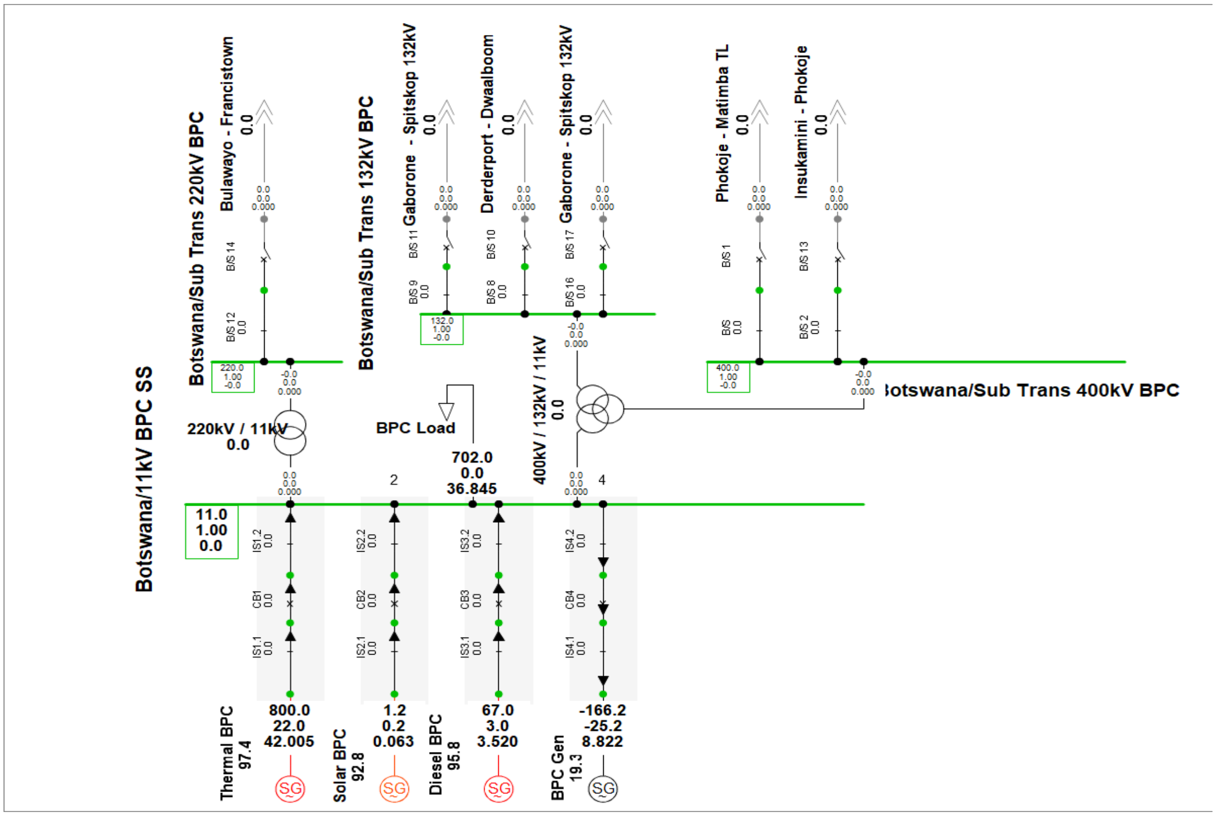


Figure 5. 21 Botswana (BPC) HV Power Grid

Figure 5.22 illustrates the simulation findings of Zimbabwe SS before power interconnections. Zimbabwe SS has 1230MW to power the demand of 2200MW, which is inadequate; Zimbabwe requires 970MW to power the Zimbabwean load demand, as presented in Figure 5.22.

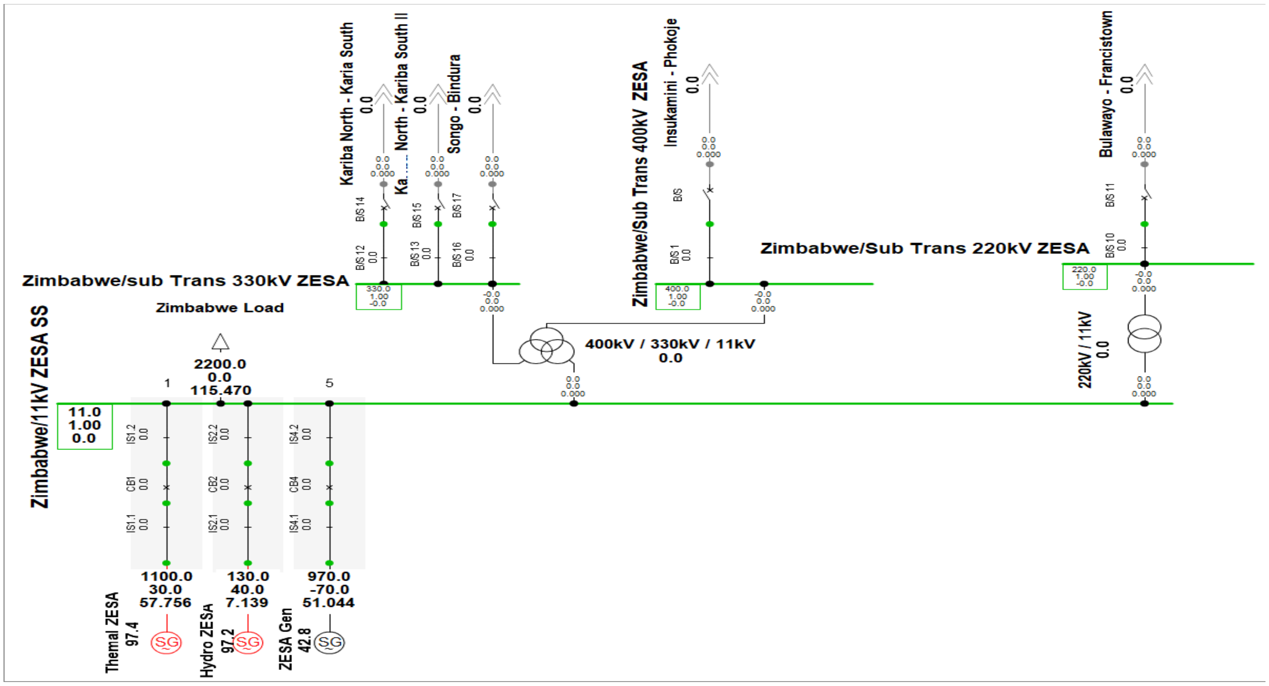


Figure 5. 22 Simulation Results of Zimbabwe (ZESA) HV Grid Network

5.3 Southern African Power exchange network model

Figure 5.23 shows the electricity exchange in Lesotho SS. Lesotho imports 2 x 42.4 MW from South Africa through two TLs named Tweespruit-Maseru.

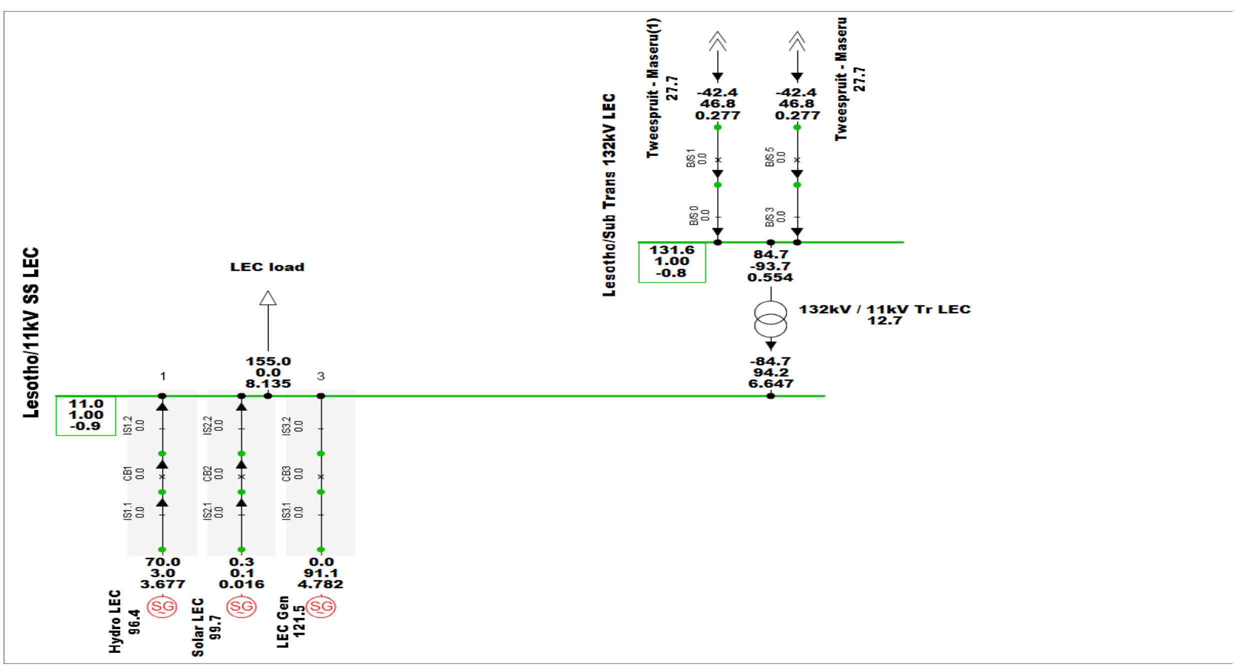


Figure 5. 23 Lesotho Power Exchange Network Model

Figure 5.24 shows the Swaziland SS, to meet their demand, Swaziland requires 153MW of electricity, with power interconnection, Mozambique transmits 277MW to Swaziland, while the remaining power from Mozambique to Swaziland is exported to South Africa through the Camden-Edwaleni and Normandie-Nhlaangano TLs.

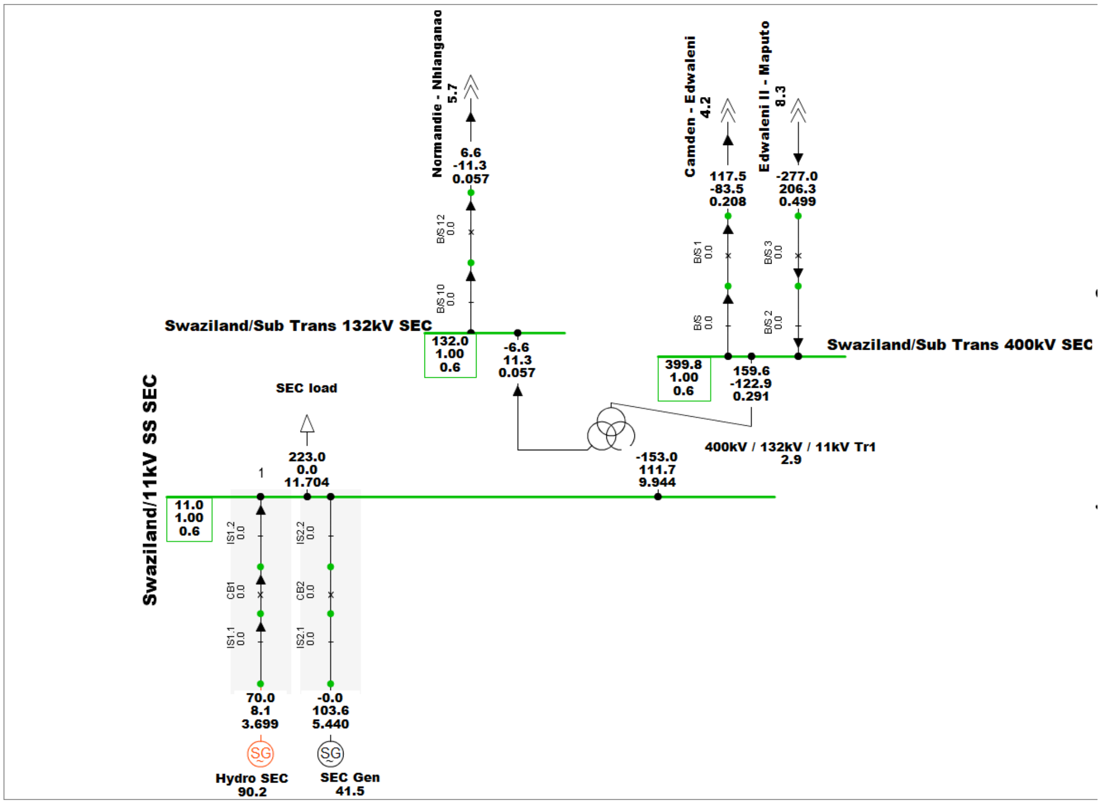


Figure 5. 24 Swaziland network model power exchange

Figure 5.25 presents the South Africa SS; South Africa is used as a reference SS because of its plentiful accessible electricity; all surplus power is from other countries is stored in South Africa, and South Africa transmits power to the five countries portrayed in Figure 5.25 through 15 TL.

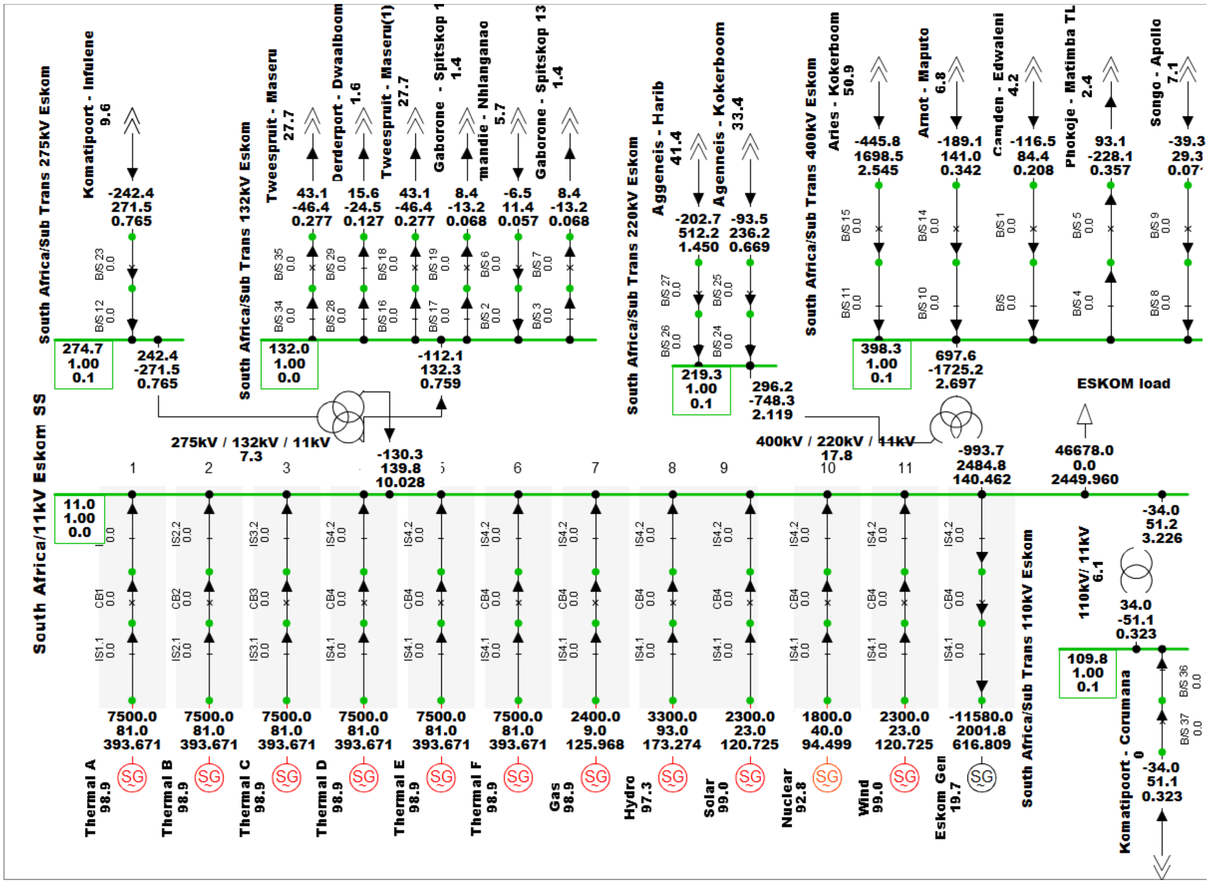


Figure 5. 25 South Africa network model power exchange

Figure 5.26 shows the Mozambique SS; Mozambique has 2937MW available electricity to meet the country's demand of 1651MW; extra power is transmitted to Malawi, Swaziland, South Africa, and Zimbabwe through transmission lines as presented in Figure 5.26.

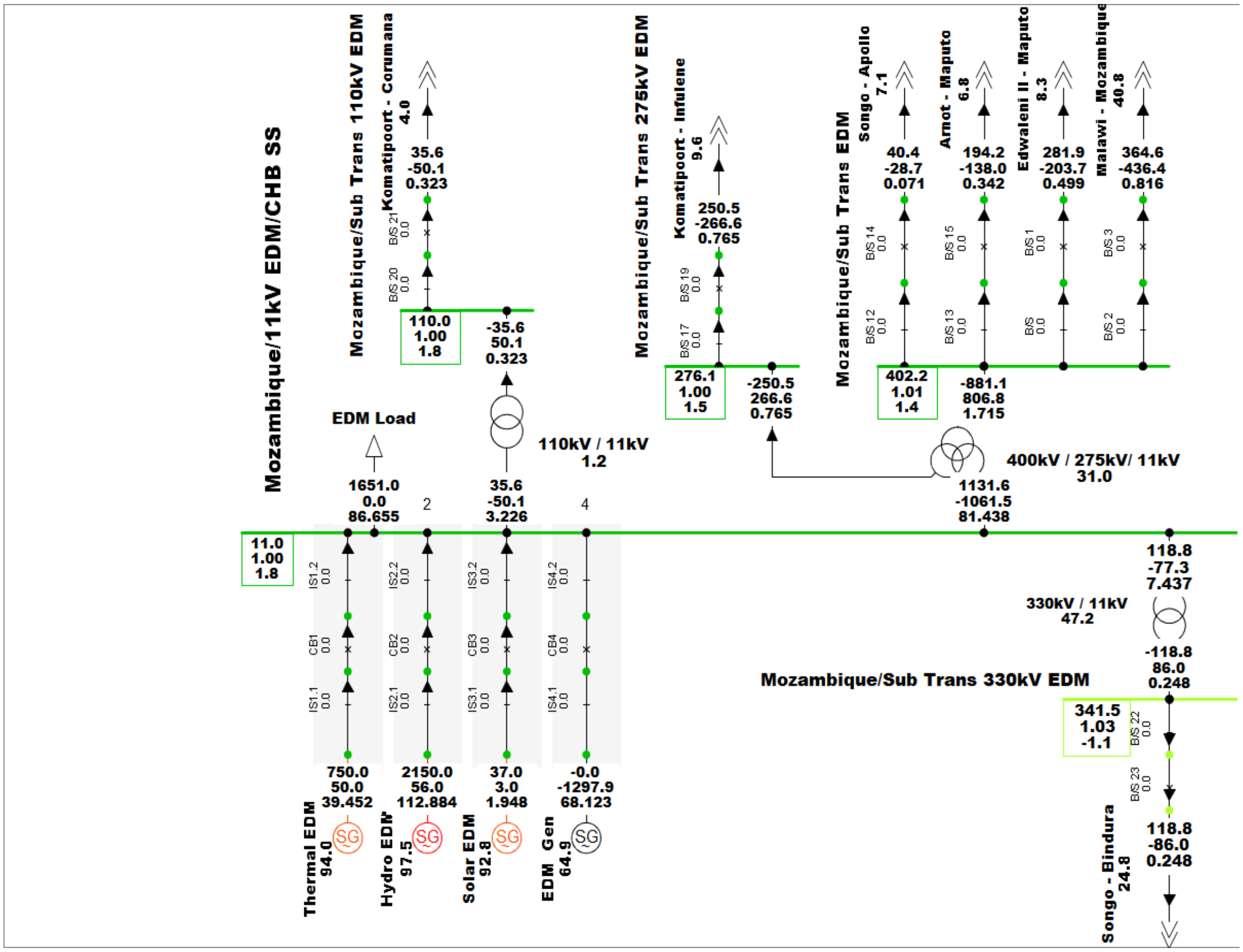


Figure 5. 26 Mozambique Network model power exchange

Figure 5,27 shows the Namibia SS, which has 620MW to meet the demands of 600MW. Namibia receives 1352,7MW from Angola, which is then transferred to South Africa through the Aries-Kokerboom, Agennesis-Kokerboom, and Agennesis-Harib TLs for power storage.

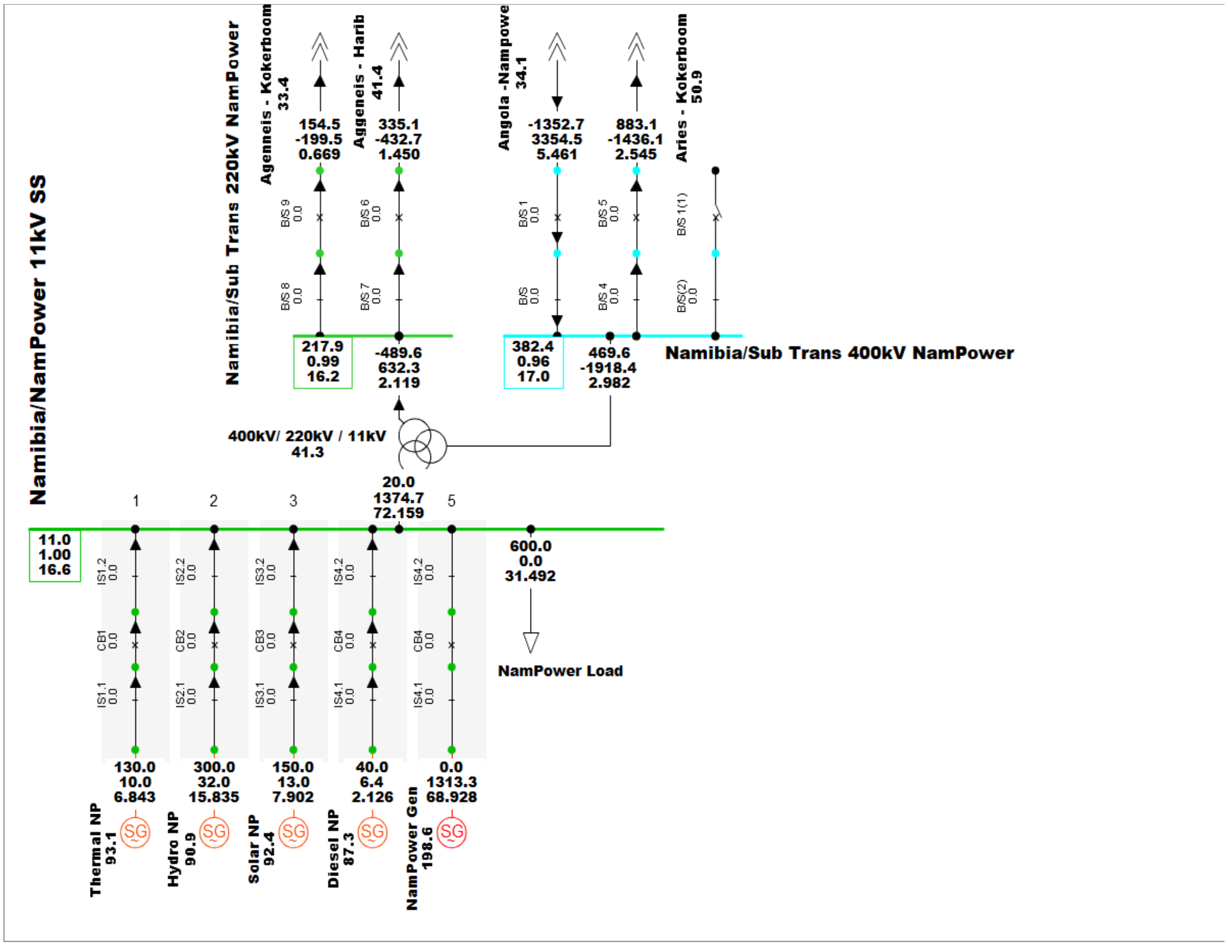


Figure 5. 27 Namibia Network Model Power exchange

Figure 5.28 shows the Angola SS; Angola has a surplus of power that is transmitted to South Africa through Namibia. Angola SS exports 2963MW of extra power to Namibia, and Namibia receives 1352.7MW owing to losses.

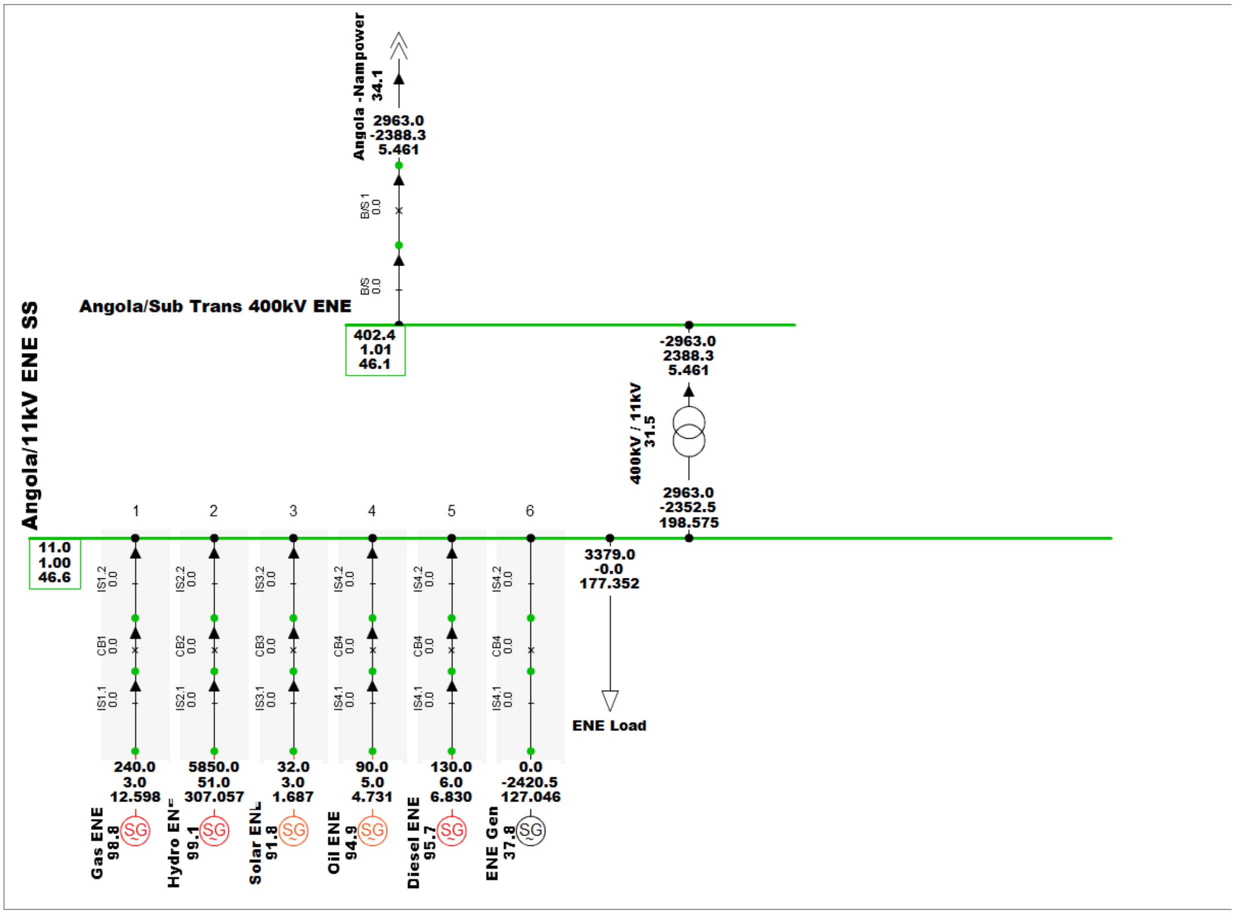


Figure 5. 28 Angola Network Model Power exchange

Figure 5.29 shows the Zambia SS, which has an available capacity of 2648MW to power the demand of 2300; the excess power is transferred to Zimbabwe, with an additional 247.1MW coming from Malawi to Zimbabwe through the Zambia SS.

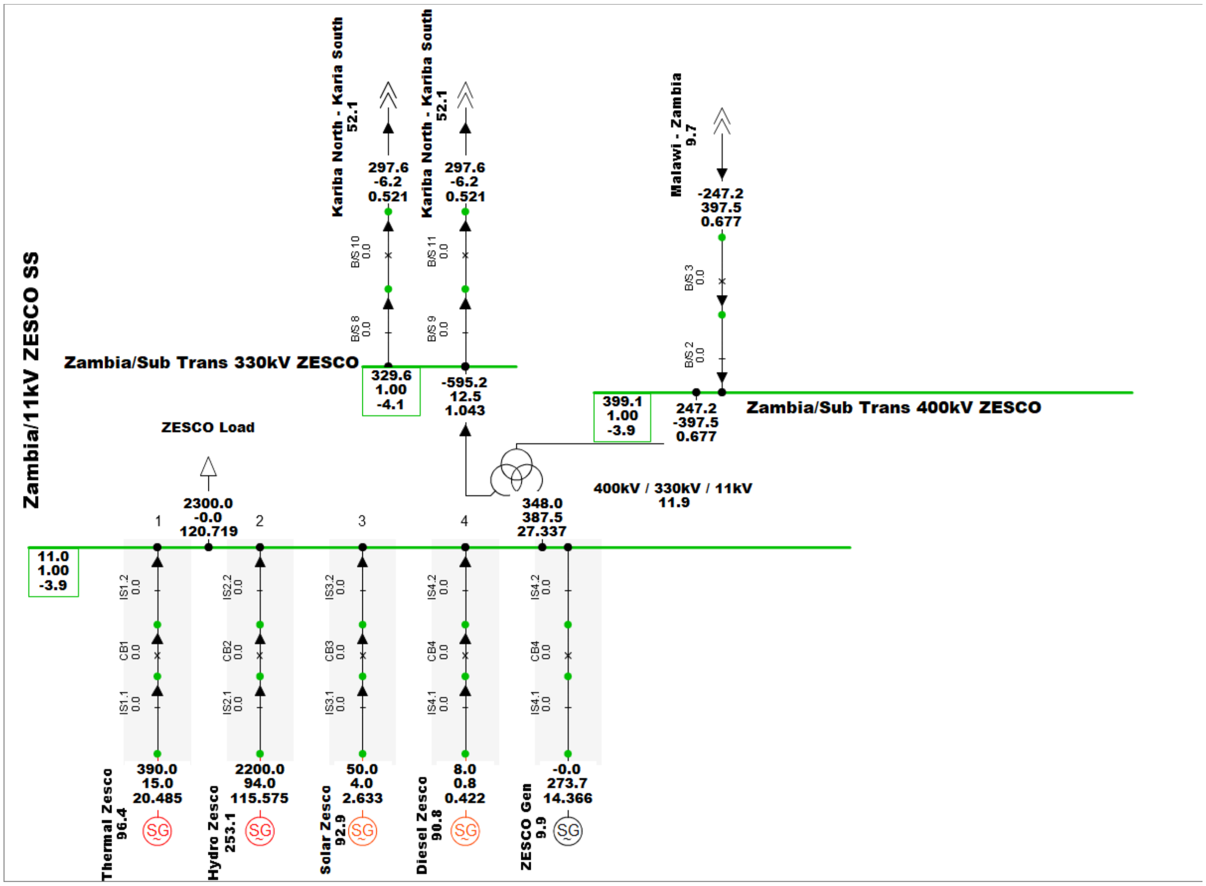


Figure 5. 29 Zambia Network Model Power Exchange

Figure 5.30 represents the Malawi SS; Malawi has 394MW available power to meet the power demand of 470MW; Malawi receives 342.8MW from Mozambique, of which 76 is being used by Malawi and the remaining 266.8 is transmitted to Zambia, although Zambia only receives 247.1MW due to losses

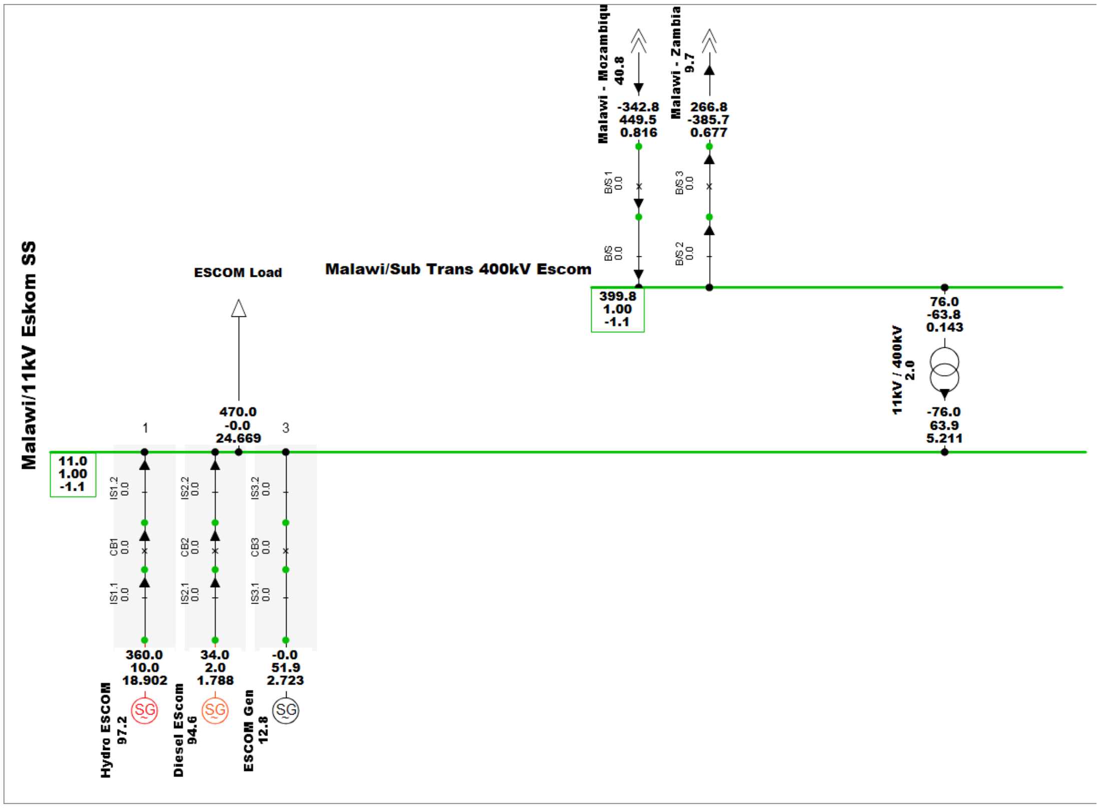


Figure 5. 30 Malawi Network Model Power Exchange

Figure 5.31 illustrates the Zimbabwe SS. Zimbabwe has 1230MW, but in order to meet the country's power demand of 2200MW, Zimbabwe requires an additional 970MW, of which 2 x 297.5MW is transmitted by Kariba North-Kariba South (I & II), 110.1MW from Songo-Bindura TL, and 127.5MW and 137.4MW from Bulawayo-Francistown and Insukamini-Phokoje TL

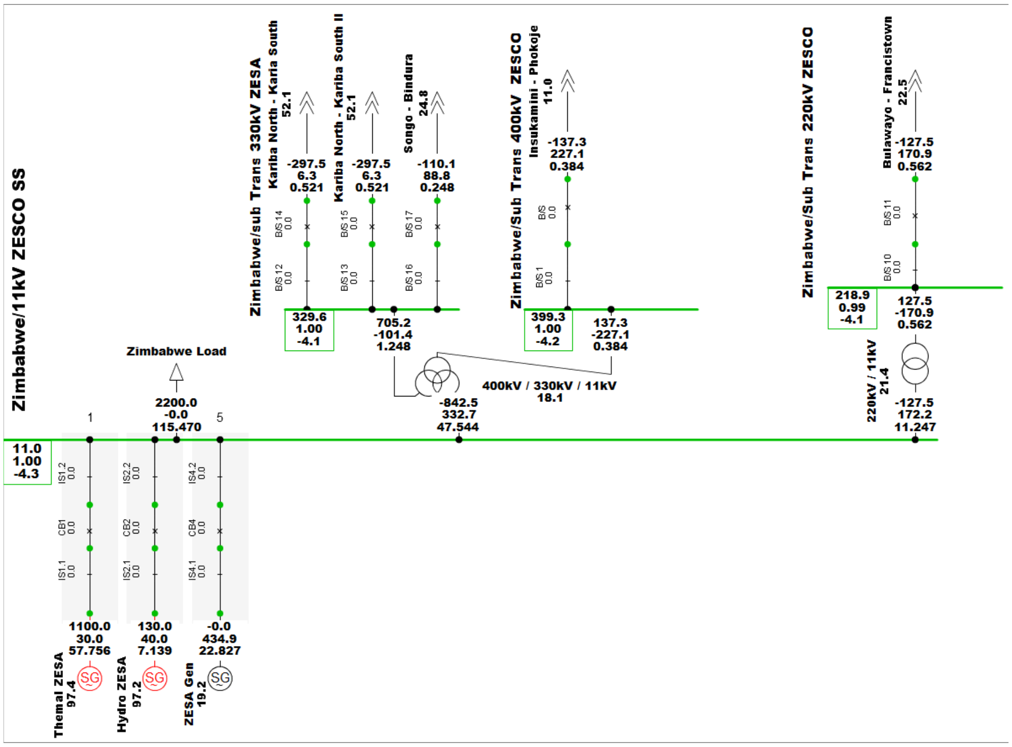


Figure 5. 31 Zimbabwe Network Model Power Exchange

Figure 5.32 shows the Botswana SS, which has 868.2 MW to power the country's demand of 702MW, leaving the country with an excess of 166.2 MW. Botswana imports 119.2MW from two x Gaborone-Spitskop, Derderport-Dwaalboom, and Phokoje-Matimba TL. Botswana then exports 136.6MW and 148.9MW through the Bulawayo-Francistown and Insukamini-Phokoje transmission lines, respectively.

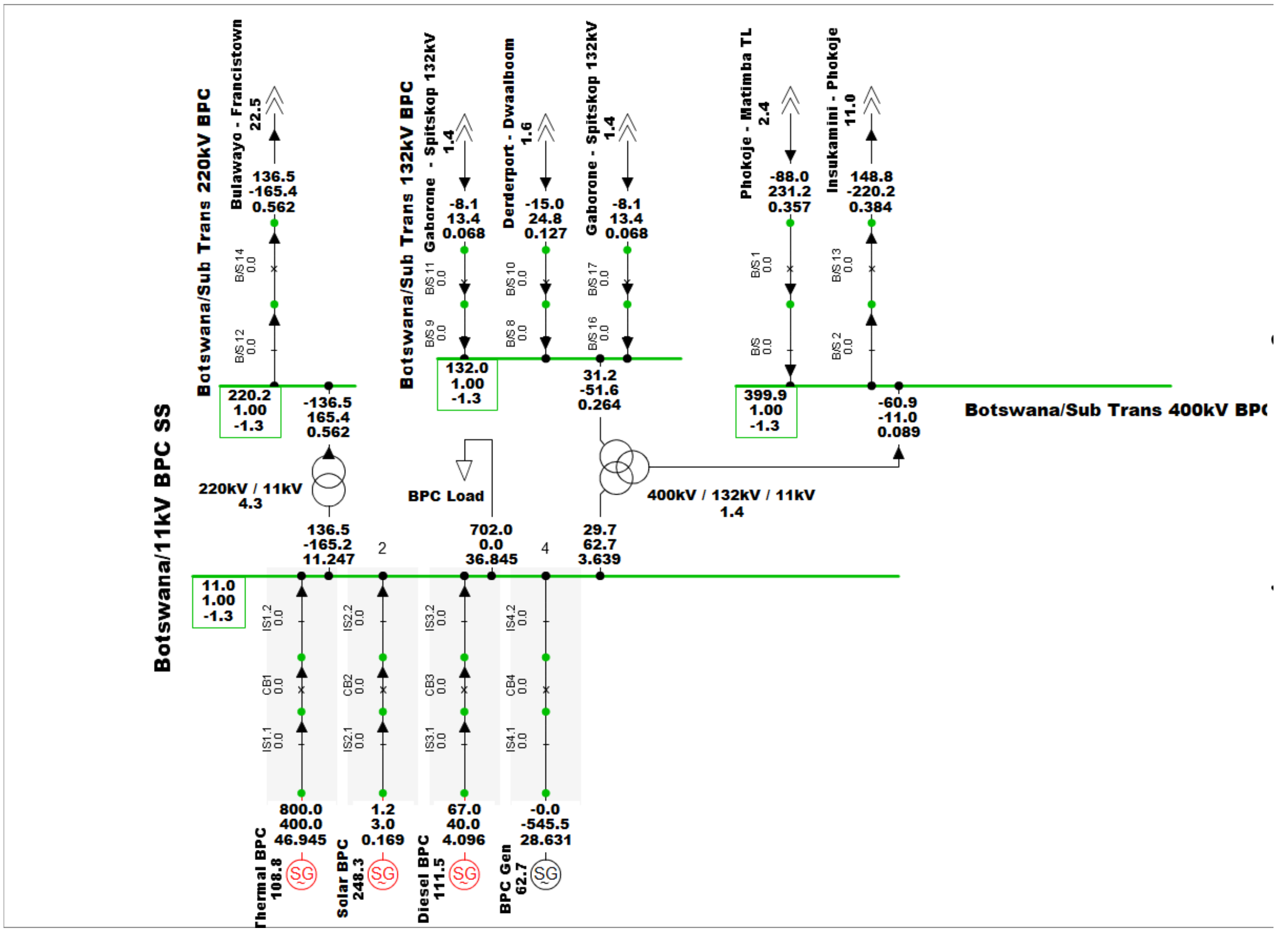


Figure 5. 32 Botswana Network Model Power Exchange

Figure 5.33 shows a complete model of the Southern African Power grid, along with country interconnectors displaying the active power of the TLs connected to the country, such as the Zimbabwe interconnector, which displays the active power of -970MW exported from Zambia, Botswana, and Mozambique. And the Swaziland interconnector displays an active power of 153MW, which is the difference between the -277MW exported from Mozambique and the 124.1MW imported into South Africa.

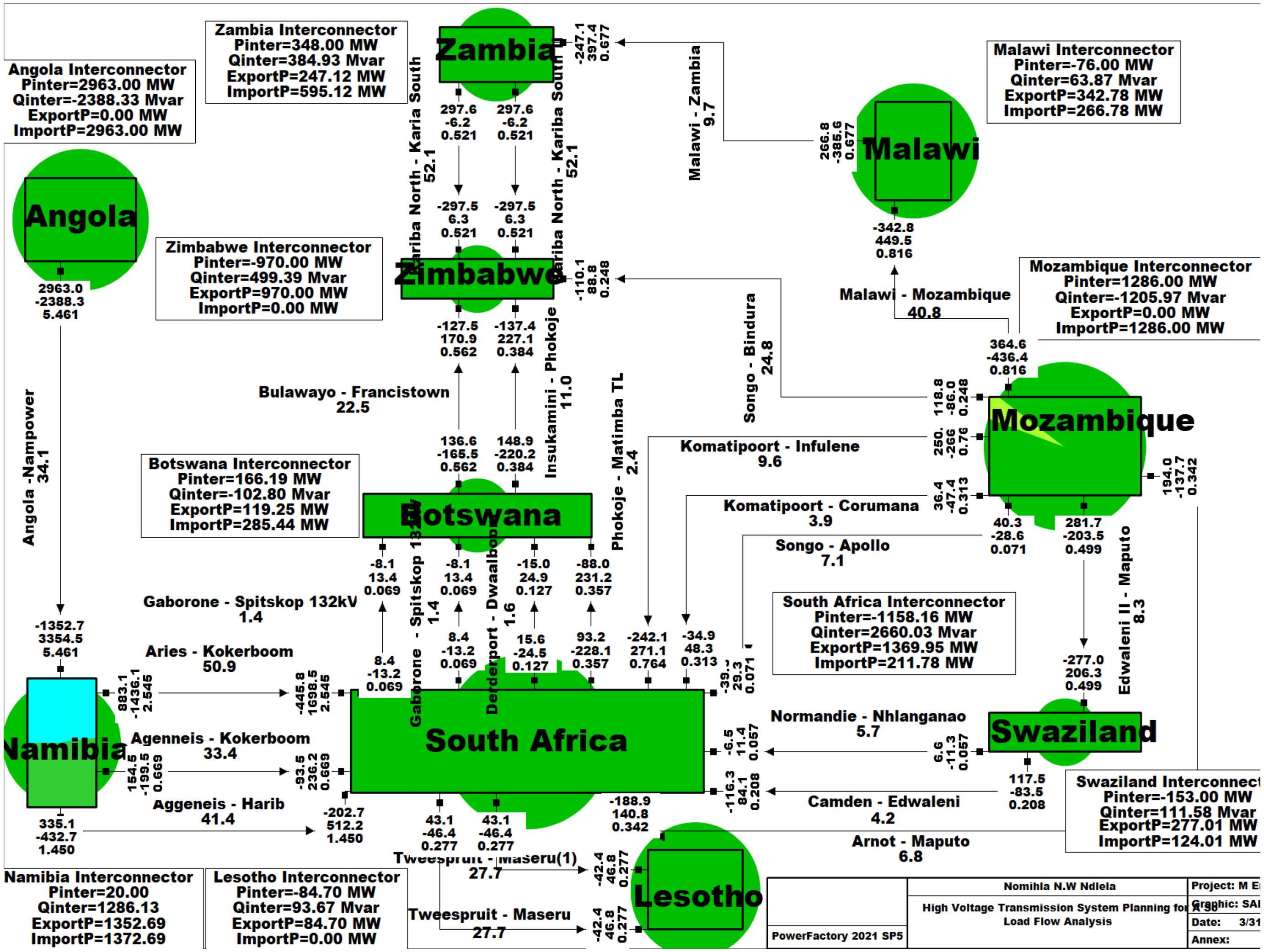


Figure 5. 33 Southern Africa Power exchange Network Model

Tables 5.1, 5.2, and 5.3 next provide the bus voltage profiles, generator output profiles, and line flow profiles for the Southern African model base case. The tables contain various indices that are critical in the calculation stage, such as voltage deviation, Power Factor, voltage magnitudes, reactive power, and line loadings, and are all derived using the Newton-Raphson solution method in DIgSILENT PowerFactory.

Table 5. 1 Base case bus voltage profile for the Southern African model

Busbar Name and utility	Country	Nom. L-L Volt. kV	u, Magnitude p.u	du, Voltage deviation %	U, Angle deg
11kV BPC SS	Botswana	11	1.00	0	-1.267
11kV EDM/CHB SS	Mozambique	11	1.00	0	1.763
11kV ENE SS	Angola	11	1.00	0	46.569
11kV Escom SS	Malawi	11	1.00	0	-1.151
11kV Eskom SS	South Africa	11	1.00	0	0.
11kV SS LEC	Lesotho	11	1.00	0	-0.929
11kV SS SEC	Swaziland	11	1.00	0	0.552
11kV ZESCO SS	Zambia	11	1.00	0	-4.346
11kV ZESA SS	Zimbabwe	11	1.000	0	-3.910
NamPower 11kV SS	Namibia	11	1.000	0	16.622
Sub Trans 110kV EDM	Mozambique	110	1.001	0.142	1.701
Sub Trans 110kV Eskom	South Africa	110	0.998	-0.145	0.060
Sub Trans 132kV BPC	Botswana	132	0.999	-0.034	-1.267
Sub Trans 132kV Eskom	South Africa	132	0.999	-0.002	0.003
Sub Trans 132kV LEC	Lesotho	132	0.997	-0.282	-0.783
Sub Trans 132kV SEC	Swaziland	132	0.999	-0.021	0.569
Sub Trans 220kV BPC	Botswana	220	1.000	0.099	-1.314
Sub Trans 220kV Eskom	South Africa	220	0.997	-0.323	0.074
Sub Trans 220kV NamPower	Namibia	220	0.990	-0.959	16.232
Sub Trans 220kV ZESA	Zimbabwe	220	0.995	-0.516	-4.126

Sub Trans 275kV EDM	Mozambique	275	1.003	0.398	1.527
Sub Trans 275kV Eskom	South Africa	275	0.999	-0.123	0.064
Sub Trans 330kV EDM	Mozambique	330	1.035	3.475	-1.087
Sub Trans 330kV ZESCO	Zambia	330	0.999	-0.112	-4.073
Sub Trans 400kV ZESA	Zimbabwe	400	0.998	-0.167	-4.177
Sub Trans 400kV BPC	Botswana	400	0.999	-0.022	-1.283
Sub Trans 400kV ENE	Angola	400	1.006	0.590	46.147
Sub Trans 400kV Escom	Malawi	400	0.999	-0.038	-1.125
Sub Trans 400kV Eskom	South Africa	400	0.996	-0.421	0.0972
Sub Trans 400kV NamPower	Namibia	400	0.956	-4.397	16.979
Sub Trans 400kV SEC	Swaziland	400	0.999	-0.050	0.590
Sub Trans 400kV ZESCO	Zambia	400	0.998	-0.235	-3.928
Sub Trans EDM	Mozambique	400	1.006	0.559	1.419
sub-Trans 330kV ZESA	Zimbabwe	330	0.998	-0.130	-4.080

Table 5. 2 Output profile of the Southern African model base case generator

Generator Name	country	Active Power MW	Reactive Power Mvar	Apparent Power MVA	Power Factor	Loading %
BPC Gen	Botswana	0	-545.49	545.49	0	62.70
Diesel BPC	Botswana	67	40	78.03	0.858	111.47
Diesel ENE	Angola	130	6	130.14	0.998	95.69
Diesel Escom	Malawi	34	2	34.05	0.998	94.61
Diesel NP	NamPower	40	6.40	40.51	0.987	87.30
Diesel ZESCO	Zambia	8	0.80	8.04	0.995	90.85
EDM Gen	Mozambique	0	-1294.33	1294.3	0	64.72
ENE Gen	Angola	0	-2420.54	2420.545	0	37.76
ESCOM Gen	Malawi	0	51.93	51.93	0	12.78
Eskom Gen	South Africa	11580.16	1998.03	11751.27	-0.985	19.68
Gas SA	South Africa	2400	9	2400.01	0.999	98.77
Gas ENE	Angola	240	3	240.02	0.999	98.93

Hydro SA	South Africa	3300	93	3301.31	0.999	97.49
Hydro EDM	Mozambique	2150	56	2150.73	0.999	99.13
Hydro ENE	Angola	5850	51	5850.22	0.999	97.24
Hydro ESCOM	Malawi	360	10	360.1	0.999	96.41
Hydro LEC	Lesotho	70	3	70.06	0.994	90.87
Hydro NP	NamPower	300	32	301.71	0.999	97.29
Hydro SEC	Swaziland	70	8.10	70.46	0.993	90.23
Hydro ZESA	Zimbabwe	130	40	136.01	0.955	97.15
Hydro ZESCO	Zambia	2200	94	2202.01	0.999	253.10
LEC Gen	Lesotho	0	91.10	91.10	0	121.47
NamPower Gen	Namibia	0	1313.25	1313.26	0	198.55
Nuclear	South Africa	1800	40	1800.44	0.999	92.80
Oil ENE	Angola	90	5	90.138	0.998	94.88
SEC Gen	Swaziland	0	103.64	103.64	0	41.46
Solar SA	South Africa	2300	23	2300.11	0.368	248.26
Solar BPC	Botswana	1.19	3	3.23	0.996	92.80
Solar EDM	Mozambique	37	3	37.12	0.995	91.83
Solar ENE	Angola	32	3	32.14	0.986	99.71
Solar LEC	Lesotho	0.30	0.05	0.30	0.996	92.36
Solar NP	NamPower	150	13	150.56	0.999	99.01
Solar ZESCO	Zambia	50	4	50.16	0.996	92.89
Thermal ZESA	Zimbabwe	1100	30	1100.40	0.999	97.38
Thermal A	South Africa	7500	81	7500.44	0.999	98.93
Thermal B	South Africa	7500	81	7500.44	0.999	98.93
Thermal BPC	Botswana	800	400	894.43	0.894	108.81
Thermal C	South Africa	7500	81	7500.43	0.999	98.93
Thermal D	South Africa	7500	81	7500.43	0.999	98.93
Thermal E	South Africa	7500	81	7500.44	0.999	98.93
Thermal EDM	Mozambique	750	50	751.66	0.998	93.96
Thermal F	South Africa	7500	81	7500.43	0.999	98.93
Thermal NP	Nampower	130	10	130.38	0.997	93.13
Thermal Zesco	Zambia	390	15	390.28	0.999	96.37
Wind SA	South Africa	2300	23	2300.11	0.999	99.01
ZESA Gen	Zimbabwe	0	434.96	434.96	0	19.16
ZESCO Gen	Zambia	0	273.66	273.66	0	9.91

Table 5. 3 Transmission line profile for the Southern African model's base case

Line Name	From Terminal i Busbar	To Terminal j Busbar	Voltage Magnitude Terminal i in p.u.	Voltage Magnitude Terminal j in p.u.	Line Loading %	Active power Terminal i in MW
Kariba North - Karia South	Sub Trans 330kV ZESCO	sub Trans 330kV ZESA	0.998	0.998	52.13	-93.46
Kariba North - Kariba South II	Sub Trans 330kV ZESCO	sub Trans 330kV ZESA	0.998	0.998	52.13	-202.71
Aries - Kokerboom	Sub Trans 400kV NamPower	Sub Trans 400kV Eskom	0.956	0.995	50.90	2962.99
Aggeneis - Harib	Sub Trans 220kV Eskom	Sub Trans 220kV NamPower	0.996	0.99	41.43	883.10
Malawi - Mozambique	Sub Trans 400kV Escom	Sub Trans EDM	0.999	1.006	40.81	194.01
Angola -Nampower	Sub Trans 400kV ENE	Sub Trans 400kV NamPower	1.006	0.956	34.13	-127.48
Agenneis - Kokerboom	Sub Trans 220kV Eskom	Sub Trans 220kV NamPower	0.997	0.990	33.43	-116.29
Tweespruit - Maseru	Sub Trans 132kV Eskom	Sub Trans 132kV LEC	0.999	0.99	27.69	-15.03
Tweespruit - Maseru(1)	Sub Trans 132kV Eskom	Sub Trans 132kV LEC	0.999	0.997	27.69	281.67
Songo - Bindura	Sub Trans 330kV EDM	sub Trans 330kV ZESA	1.035	0.998	24.78	8.39
Bulawayo - Francistown	Sub Trans 220kV ZESA	Sub Trans 220kV BPC	0.995	1.000	22.49	-8.10
Insukamini - Phokoje	Sub Trans 400kV ZESA	Sub Trans 400kV BPC	0.998	0.999	10.96	-137.38
Malawi - Zambia	Sub Trans 400kV ZESCO	Sub Trans 400kV Escom	0.998	0.999	9.67	297.56
Komatipoort - Infulene	Sub Trans 275kV EDM	Sub Trans 275kV Eskom	1.004	0.999	9.55	297.56
Edwaleni II - Maputo	Sub Trans EDM	Sub Trans 400kV SEC	1.006	0.999	8.31	36.42

Songo - Apollo	Sub Trans EDM	Sub Trans 400kV Eskom	1.006	0.9957841455	7.09	250.24
Arnot - Maputo	Sub Trans EDM	Sub Trans 400kV Eskom	1.006	0.996	6.83	-342.78
Normandie - Nhlangano	Sub Trans 132kV SEC	Sub Trans 132kV Eskom	0.999	0.999	5.72	-247.12
Camden - Edwaleni	Sub Trans 400kV Eskom	Sub Trans 400kV SEC	0.996	0.99	4.16	6.56
Komatipoort - Corumana	Sub Trans 110kV EDM	Sub Trans 110kV Eskom	1.001	0.999	3.91	-88.01
Phokoje - Matimba TL	Sub Trans 400kV BPC	Sub Trans 400kV Eskom	0.999	0.995	2.38	40.33
Derderport - Dwaalboom	Sub Trans 132kV BPC	Sub Trans 132kV Eskom	0.999	0.999	1.58	118.75
Gaborone - Spitskop 132kV	Sub Trans 132kV Eskom	Sub Trans 132kV BPC	0.999	0.999	1.37	43.11
Gaborone - Spitskop 132kV	Sub Trans 132kV BPC	Sub Trans 132kV Eskom	0.999	0.999	1.37	43.11

5.4 Transfer Capabilities in the Southern African countries

South Africa was tested for power transfer capability in Figure 5.34; South Africa is capable of importing 4051.23MW and exporting 45.49MW; South Africa's maximum power transfer capability is 4005.73MW, which is the active power in all connected transmission lines in South Africa; South Africa is used as a reference SS, and all reserved power is stored in South Africa. While conducting this analysis for South Africa, voltage instability is found in Namibia and Mozambique, which can be enhanced by FACTS devices, in this case, SVS, to improve grid reliability.

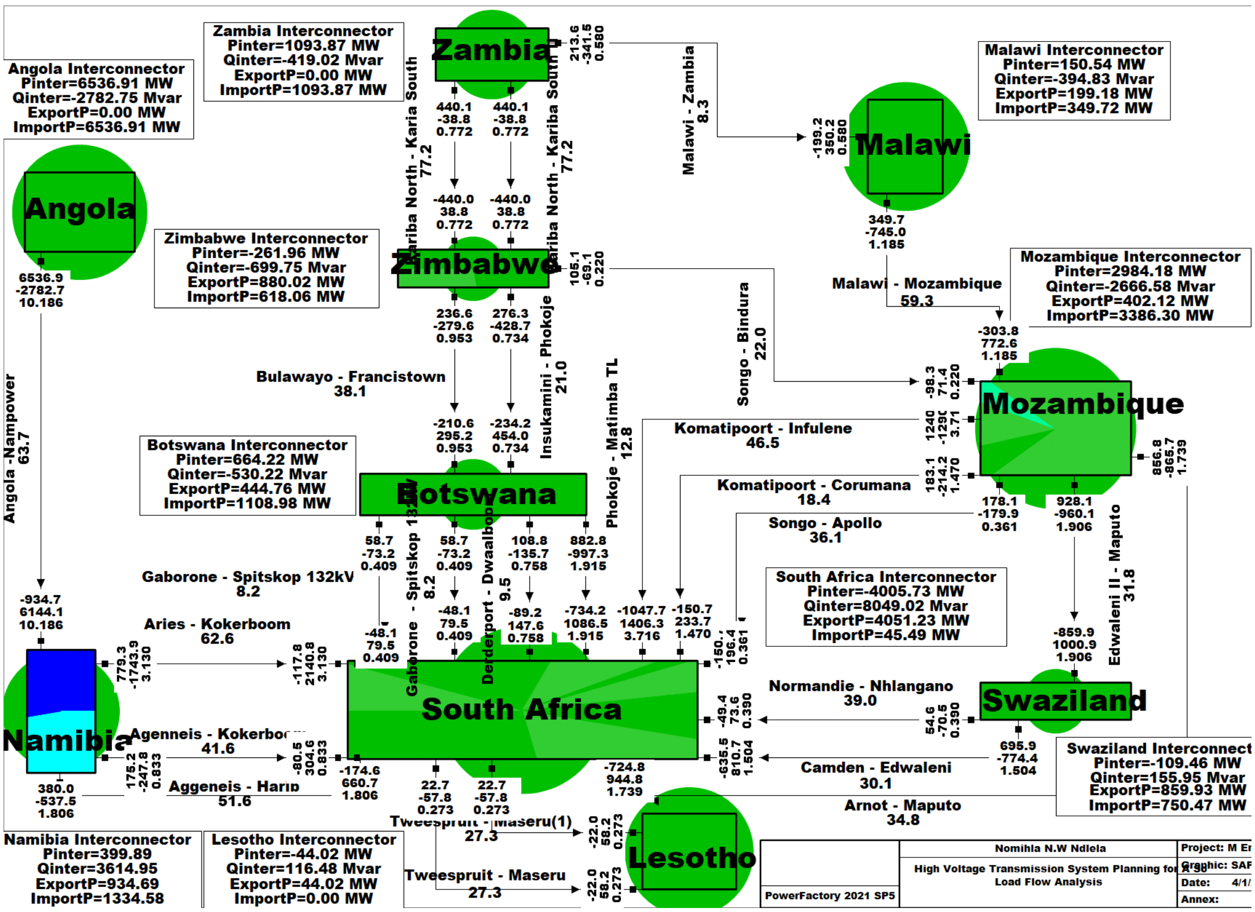


Figure 5. 34 South Africa's maximum power transfer capacity network

When Angola's overall transfer capability is simulated, Angola is capable of importing 774.4MW from Namibia. Which is the total active power in the Angola interconnector when compared with the rest of the network as observed in Figure 5.35.

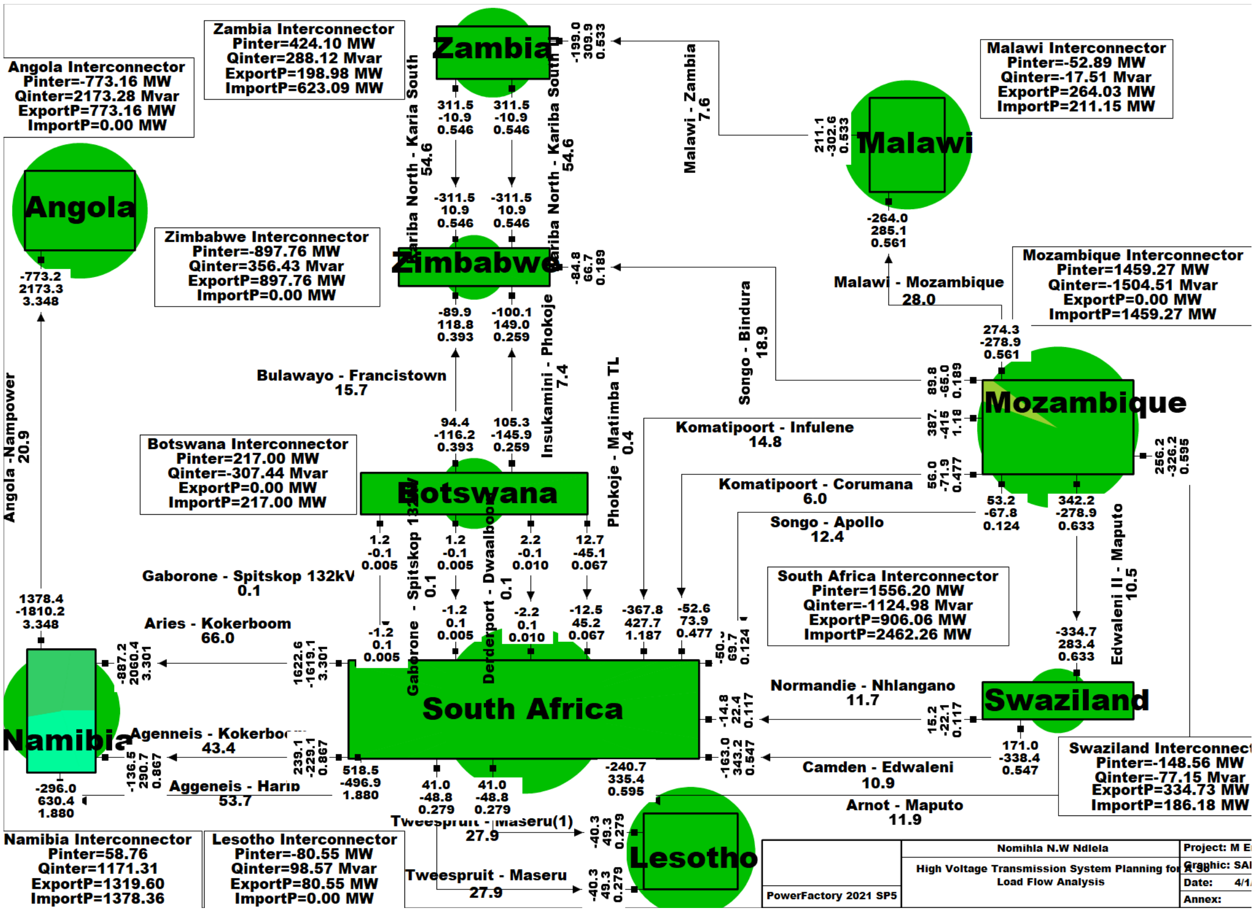


Figure 5. 35 Angola maximum power transfer capability network

When Swaziland is assessed for maximum transfer capability, it can import 308.5MW from Mozambique through the Edwaleni II-Maputo TL and export 85.5MW to South Africa through the Normandie-Nhlangano and Camden-Edwaleni TLs, as illustrated in Figure 5.36. As a result, the Swaziland interconnector has 223MW exported to Swaziland.

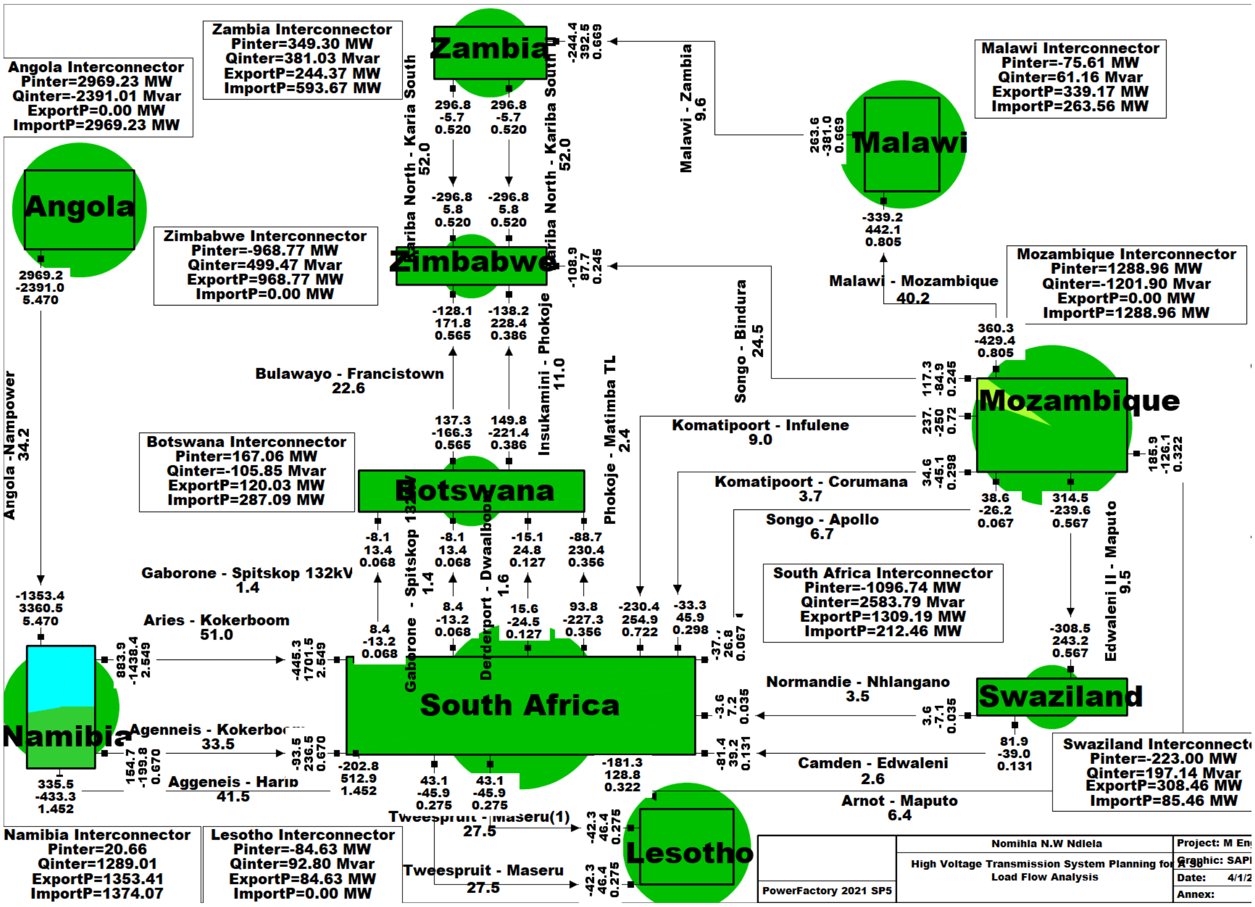


Figure 5. 36 Swaziland maximum power transfer capability

Table 5.4 was developed as a result of an analysis of the maximum feasible power flow between two parts of the network. in this case, each country in comparison to the rest of the network by scaling demand or generation in the two parts in the opposite direction. It essentially illustrates the overall transfer capability limit for each country in comparison to the remainder of the network.

Table 5. 4 Southern African countries' maximum total transfer capabilities

Southern African Countries	***Maximum Total transfer Capacity (TTC) (MW)***
South Africa	3449.61
Angola	-773.16
Mozambique	-1864.80
Botswana	-685.53
Lesotho	160.00
Malawi	-727.75
Namibia	3313.92
Swaziland	236.71

Zambia	34.26
Zimbabwe	479.84

5.5 Southern Africa model with HVDC LCC link

To minimize losses in an HVAC complete model, as indicated in Appendix 1, a southern African model was built, comprising the HVDC LCC in Angola-Namibia TL and Aries-Kokerboom TL in Figure 5.37. The power setpoint for the Angola-Namibia HVDC LCC TL was set to 1000MW coming from Angola and Namibia receiving 962.9MW with Angola-Namibia TL exporting 1963MW and Namibia receiving 1138.3MW, which implies Namibia now receives 2101.2MW whereas in Figure 5.33 Angola exports 2963MW and Namibia received 1352.7MW. Again, the HVDC LCC power setpoint in Aries-Kokerboom TL was set to be 600MW coming from Namibia to South Africa and South Africa receiving 586MW, with Aries-Kokerboom transmitting 999.5MW from Namibia to South Africa and South Africa receiving 550.3MW, which means Aries-Kokerboom TL now exports 1599.5MW from Namibia and South Africa receiving 1136MW. Appendix 2 shows the losses for this model.

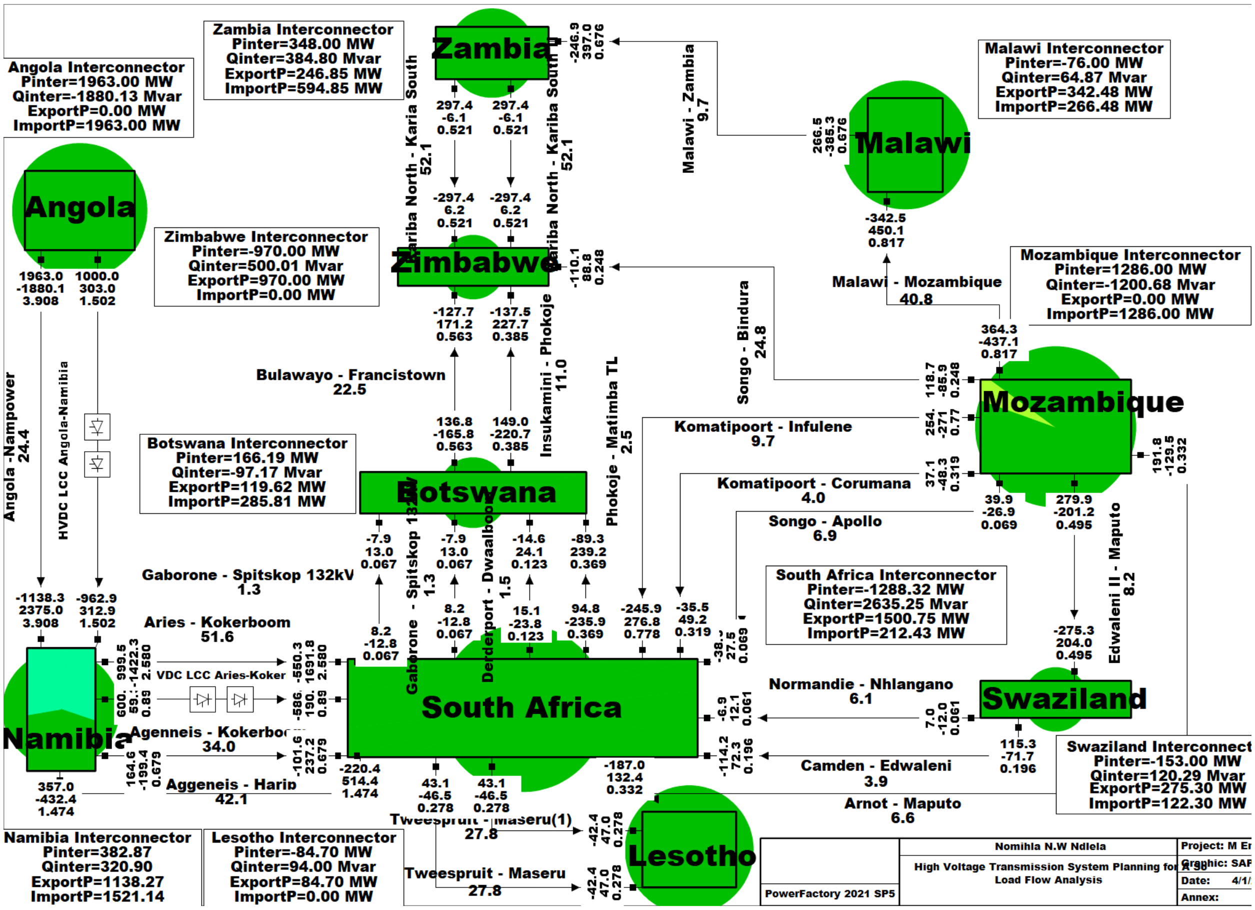


Figure 5. 37 Southern African Regional Grid with HVDC LCC link

5.6 Southern Africa network with Static Var System

In daily power system operation, preventing "loss of voltage control" necessitates the placement of additional capacitors or SVCs to maintain reactive reserves on generators, SVCs, and synchronous condensers that would otherwise deplete reactive reserves and lose voltage control. Since "loss of voltage control" instability and "clogging voltage instability" are both caused by a deficiency in reactive power supply, a Q-V curve is employed in this voltage stability security assessment methodology because it directly evaluates the deficiency in reactive supply. The optimal size of SVC (inductive/capacitive range) was chosen based on the total reactive power output needed for various buse.

Figure 5.38 shows voltage instability at Sub Tans 400kV Nampower, where the voltage drops from 400kV to 389.1kV, which may threaten network stability in the future.

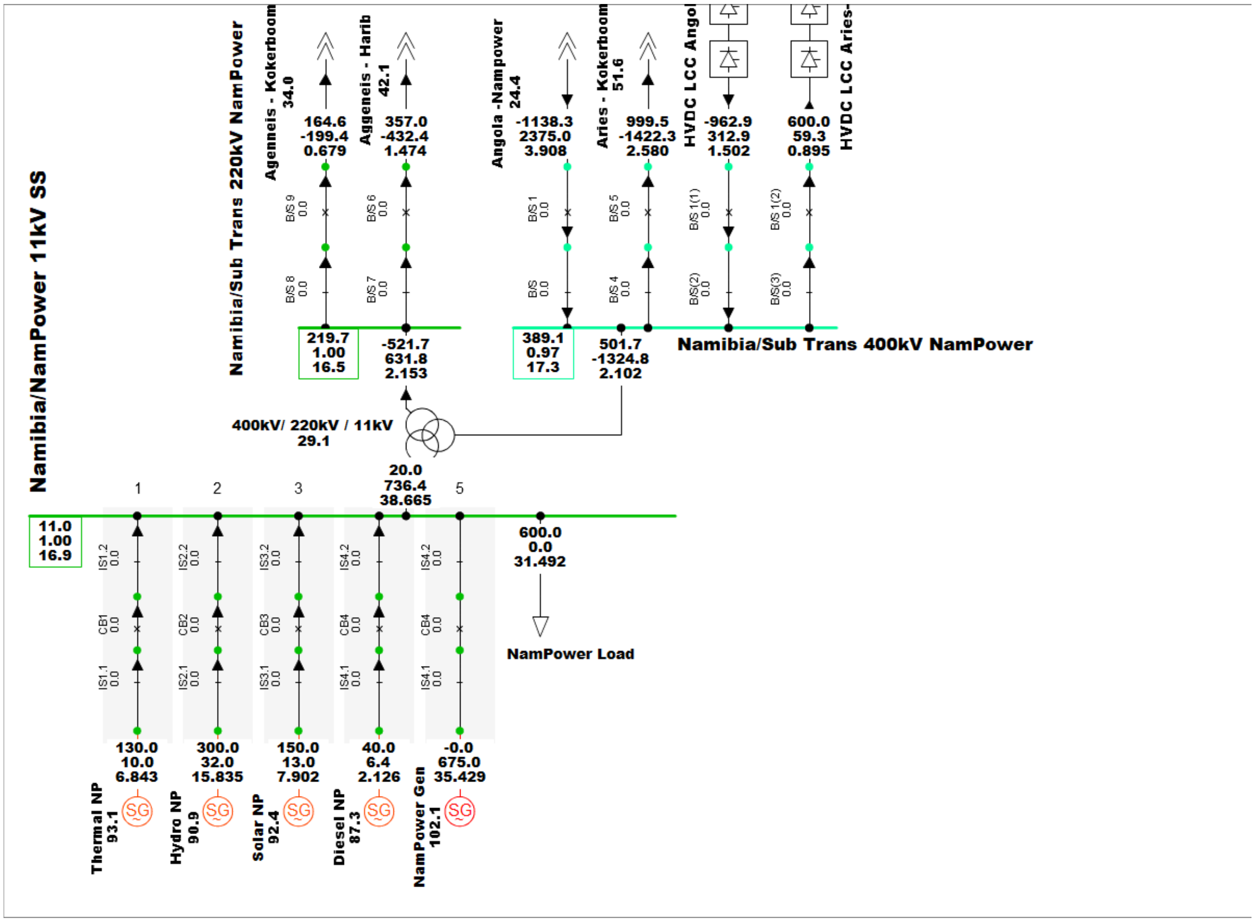


Figure 5. 38 Voltage instability in Namibia Electric Network

Figure 5.39 shows voltage instability in sub-trans 330kV EDM, with the voltage increasing from 330kV to 341.5kV.

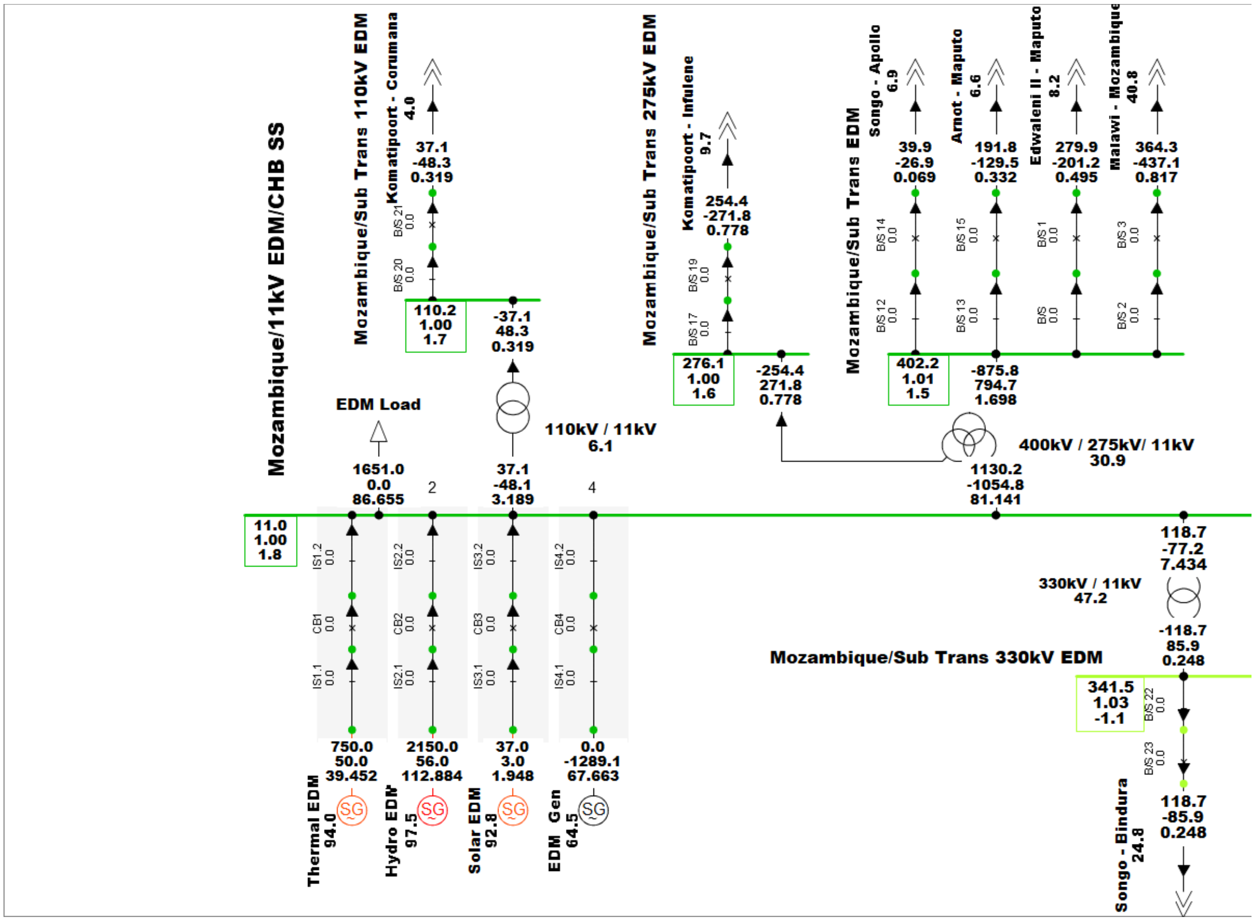


Figure 5. 39 Voltage instability in the Mozambique electric Network

The voltage instability is addressed by regulating some of the reactive power with the use of the 150MVAr Static Var System, as illustrated in Figure 5.40. As a result, the Sub Trans 330kV EDM is now at 330kV, increasing the grid's reliability.

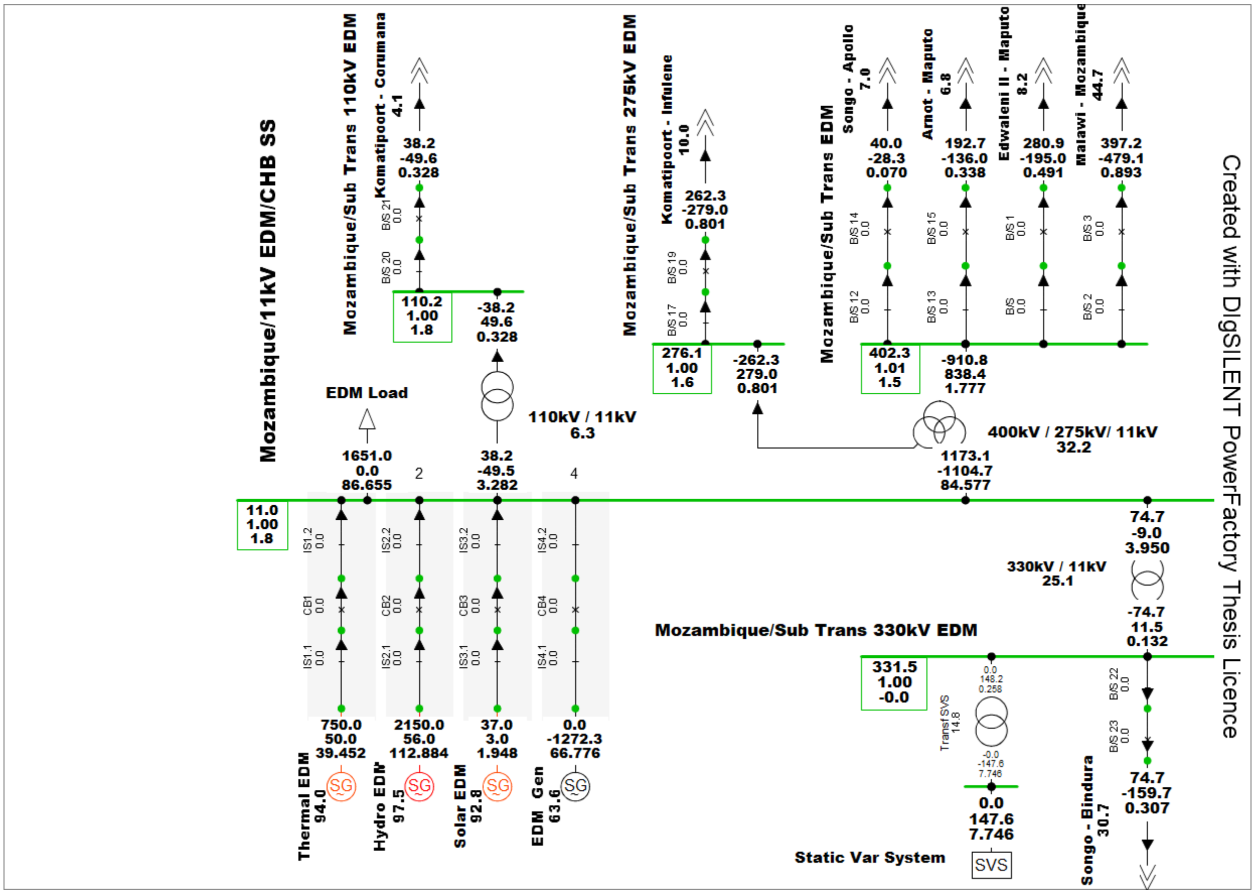


Figure 5. 40 Mozambique SS with Static Var System

Figure 5.41 shows the use of a 1300MVAr Static Var System to manage some reactive power in a 400kV Nampower substation. The voltage is now 397kV, which is good for grid stability.

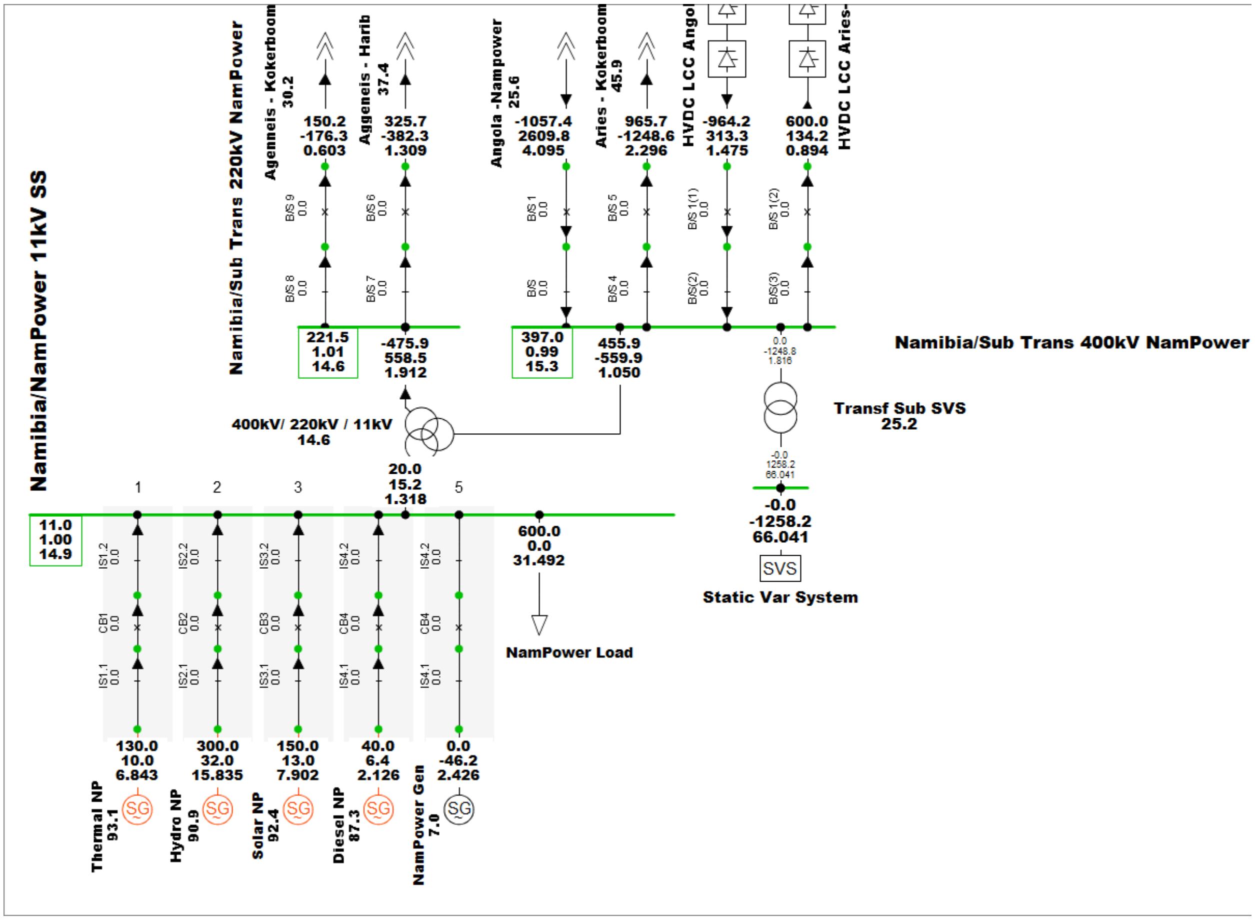


Figure 5. 41 Namibia SS with Static Var System

5.7 Complete Southern Africa Network Model with HVDC LCC link & SVS

Figure 5.42 illustrates the complete model of the Southern African region, which includes two HVDC LCCs in Angola-Namibia TL and Aries-Kokerboom TL to minimize losses, as shown in Appendix Sections 1 and 2, as well as two static Var systems in Mozambique and Namibia to increase grid reliability. The complete model also conveys the effectiveness of power exchange in developing countries such as Swaziland and Namibia.

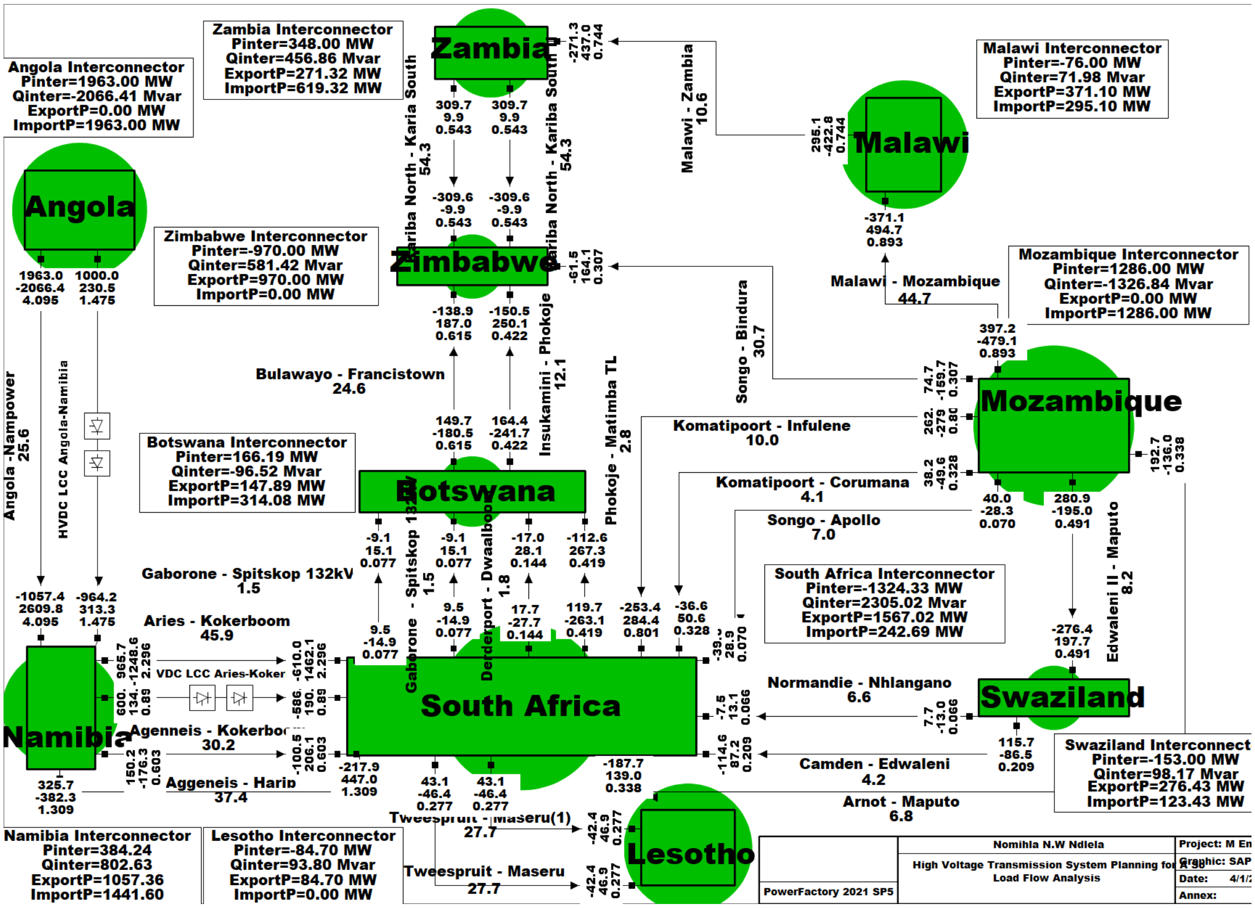


Figure 5. 42 Complete Southern Africa Model with HVDC LCC & SVS

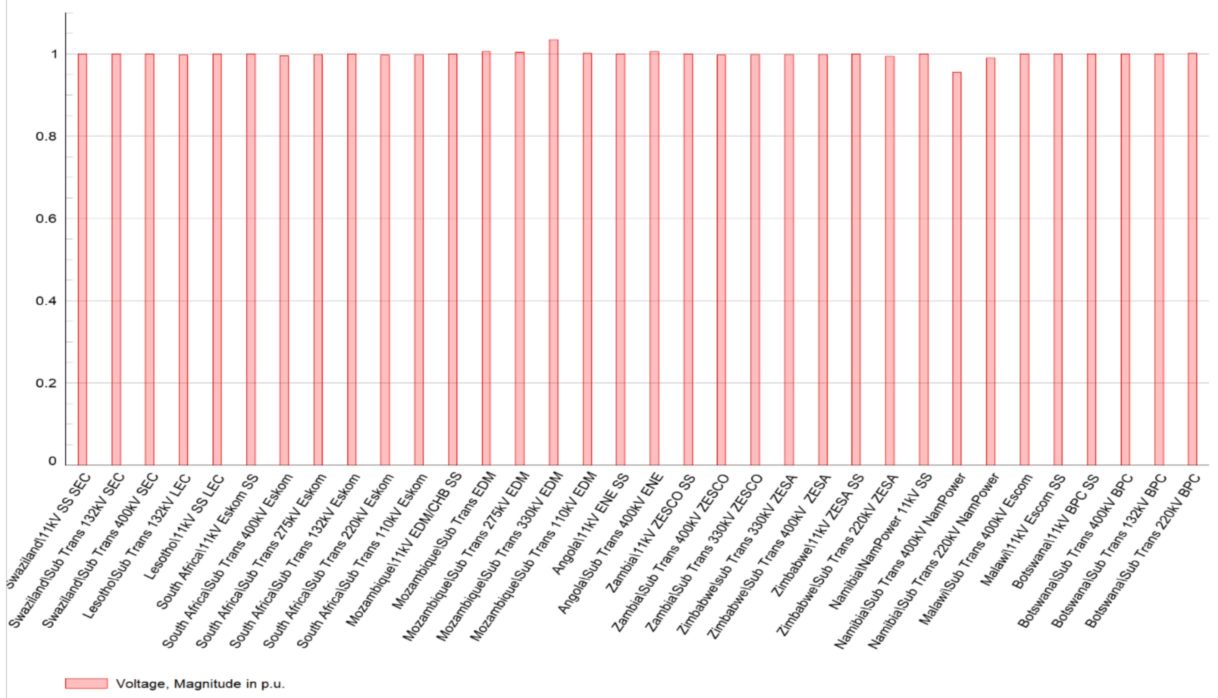
To maintain a steady frequency in power system operations, a balance between power generation and load demand is desired. The load demand of an electric power system varies during the day and also throughout the seasons; therefore, At any given time, the accessible generation should be capable of supplying this load. In this chapter, the simulation was carried out in DigSILENT PowerFactory using the previously mentioned theory and methods to obtain the desired results.

The power loss for each model is shown in Table 5.5; the SARG network has a total loss of 2341.33MW, but with the usage of SVC in Namibia and Mozambique, the loss is reduced to 2287.97MW. The SARG network was tested again with the LCC-HVDC link in Angola-Namibia and Aries-Kokerboom TL, and the losses decreased from 2341.33 to 1624.34MW. Lastly, the SARG network was evaluated using both SVC and LCC-HVDC links, resulting in 1588.31MW of losses.

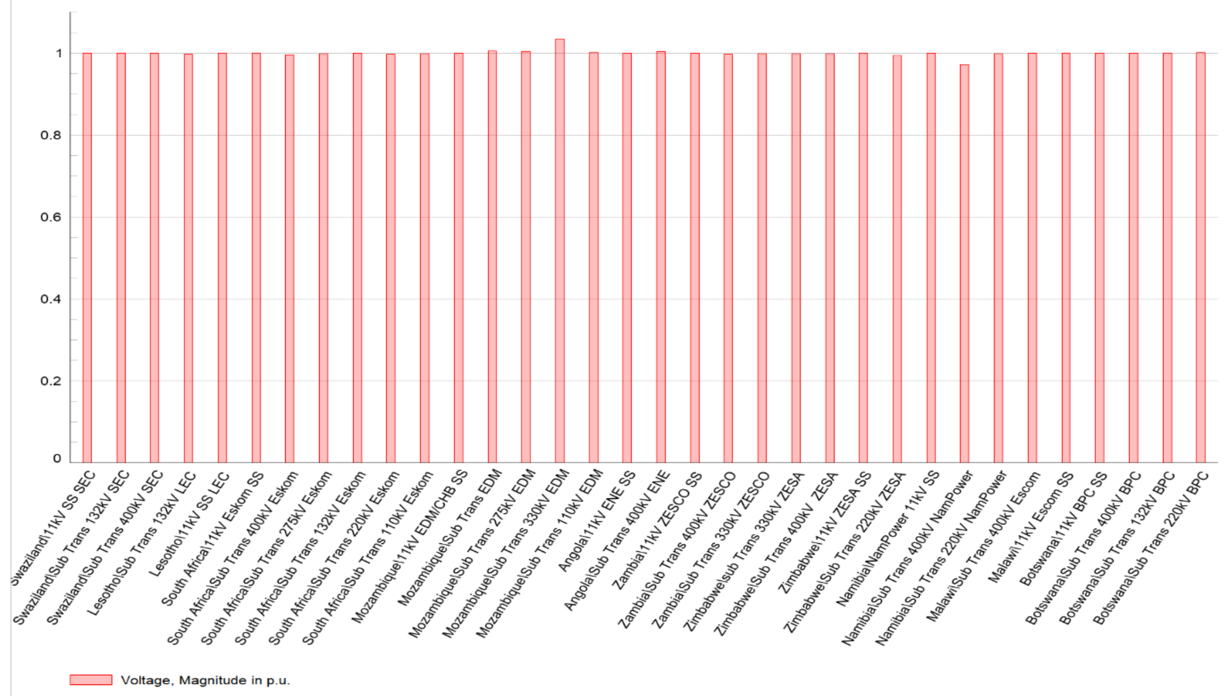
Table 5. 5 Power loss in different SARG networks.

Name	Power loss (MW)
SARG HVAC load flow	2341.33MW
SARG load flow with SVC	2287.97MW
SARG with HVDC links	1624.34MW
SARG with HVDC links and SVC	1588.31MW

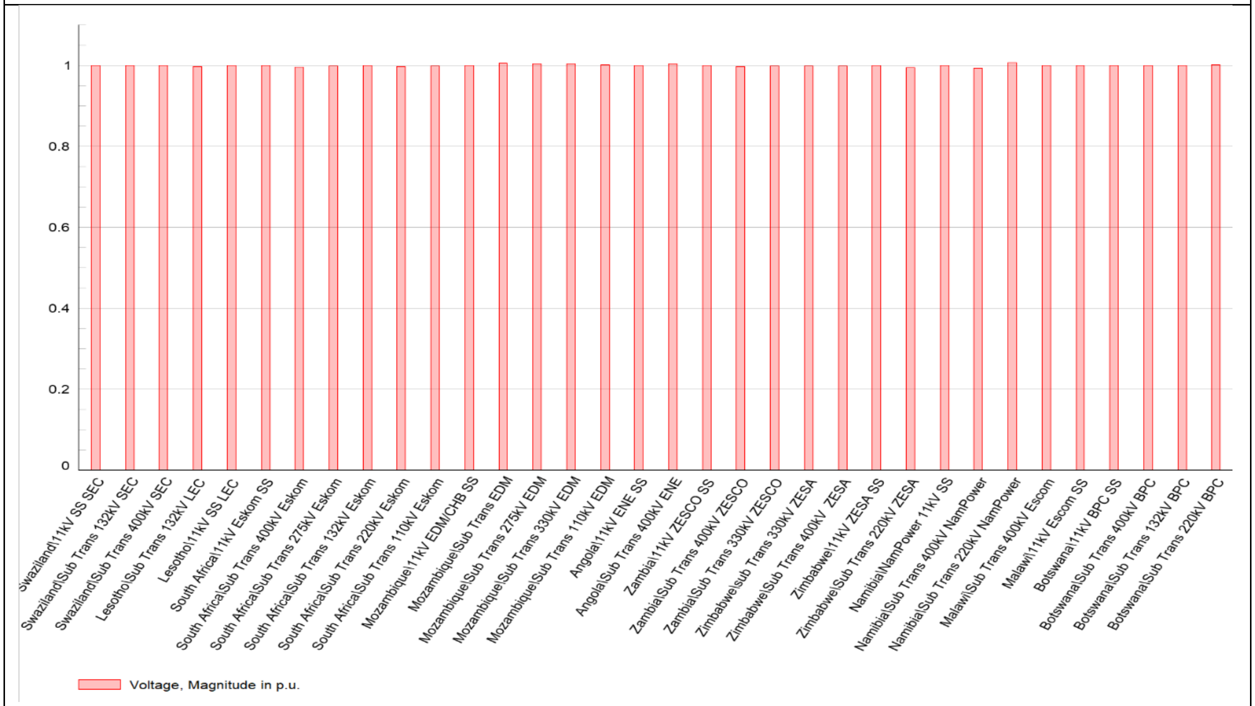
SARG busbar Figure 5.43 illustrates the voltage profile for different scenarios. 5.43 a) displays the HVAC TL busbar voltage profile, 5.43 b) illustrates the busbar voltage profile for SARG when LCC-HVDC is utilized to reduce long-distance losses, and 5.43 c) indicates the busbar Voltage for a complete model consisting of an LCC-HVDC link and SVC.



a) Busbar Voltage profile (with AC line)



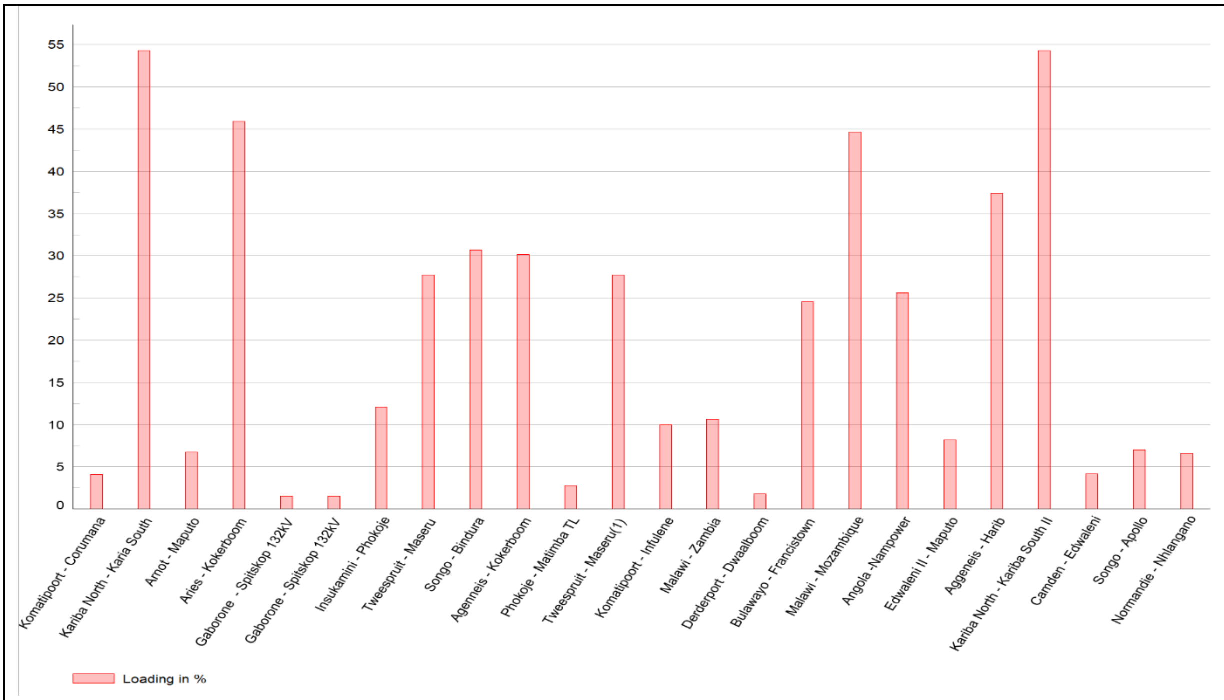
b) Busbar Voltage profile (with LCC-HVDC link)



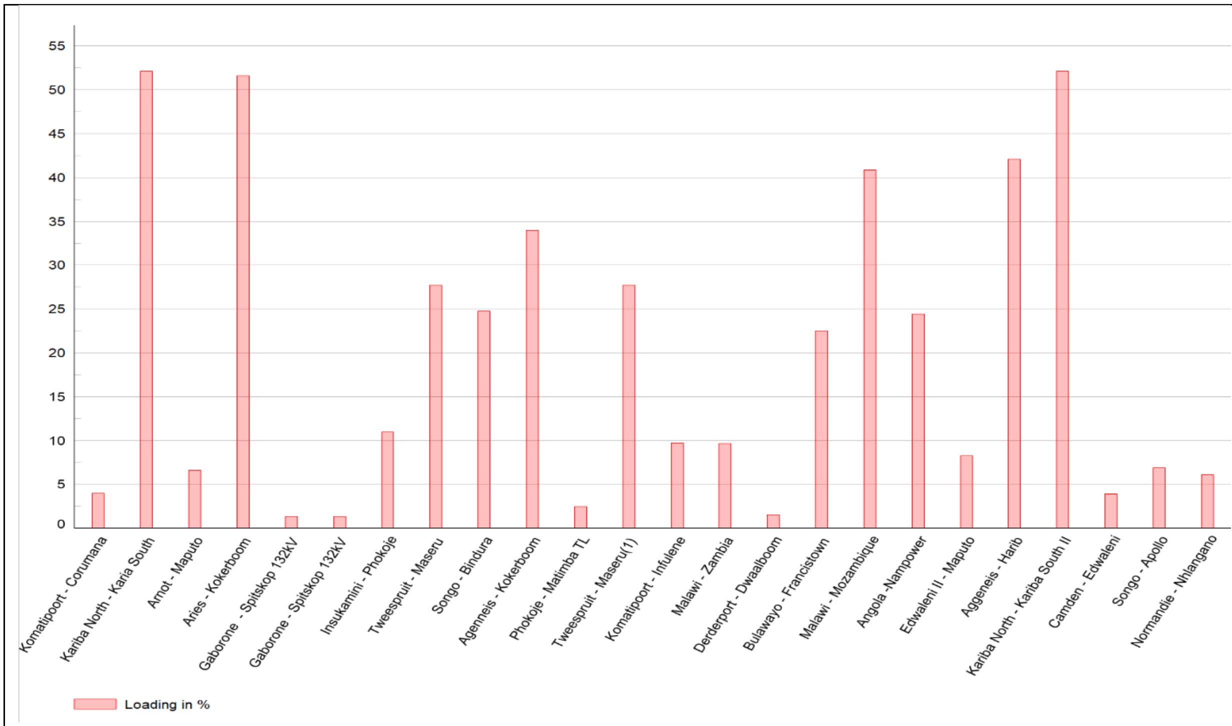
c) Busbar Voltage profile (with LCC-HVDC link and SVC)

Figure 5. 43 Different busbar Voltage profiles for SARG network.

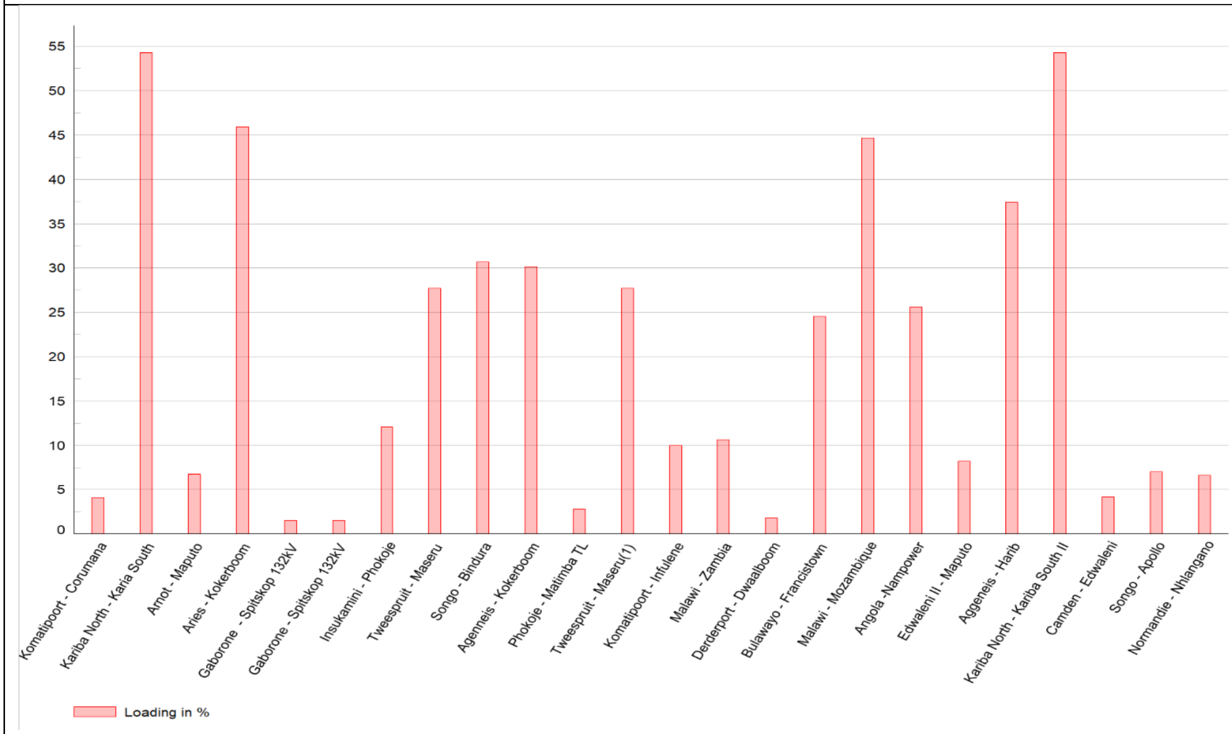
Figure 5.44 illustrates transmission line loading for various scenarios. 5.44 a) When analyzing the SARG load flow with all HVAC lines. 5.44 b) When the load flow analysis was conducted with LCC-HVDC links in Angola-Namibia TL and Aries-Kokerboom TL. 5.44 c) When a load flow analysis was conducted in a complete SARG network with LCC-HVDC connection in Angola-Namibia TL and Aries-Kokerboom TL, and the usage of SVC in Mozambique busbar and Namibia busbar to control the voltage.



a) Line loading profile (with AC line)



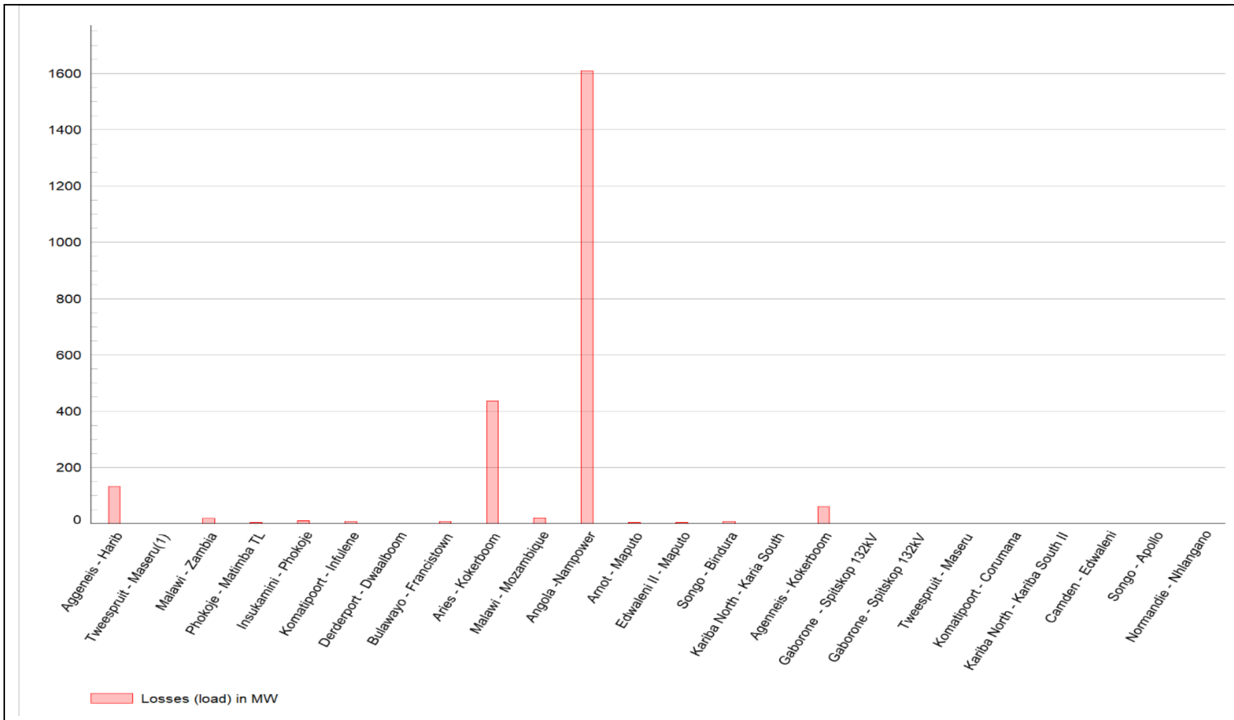
b) Line loading profile (with LCC-HVDC link)



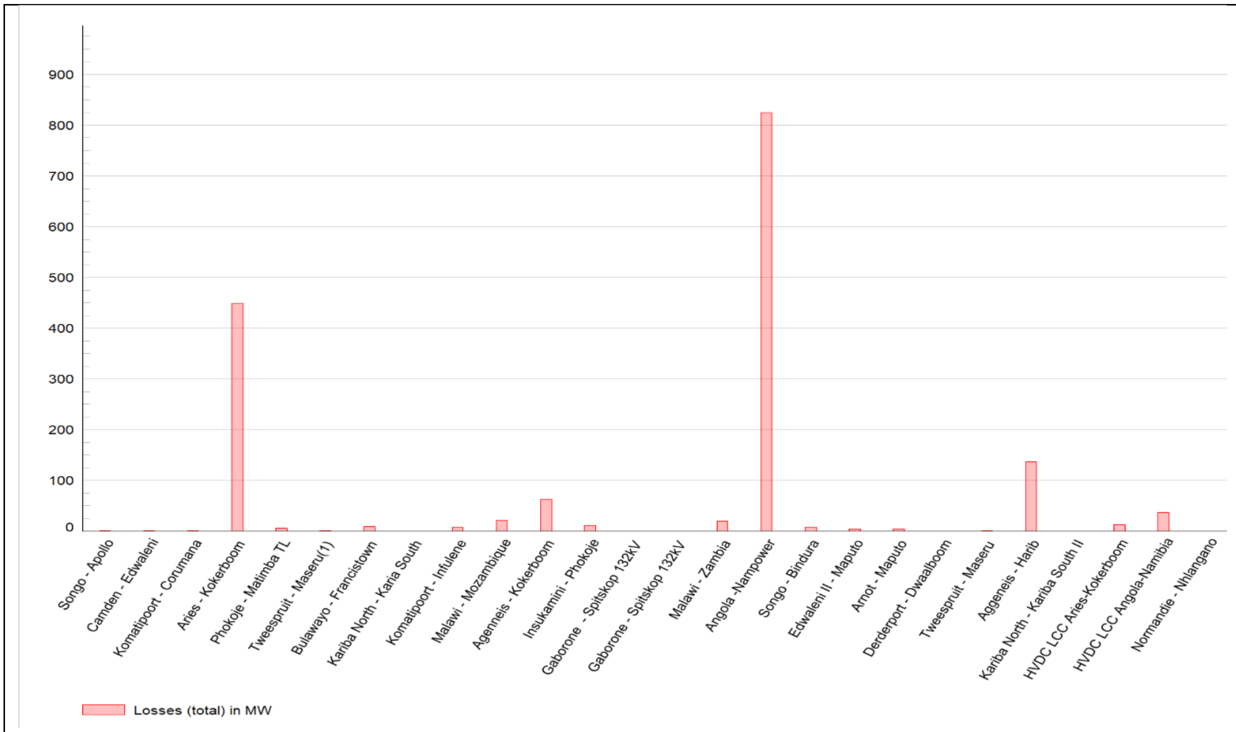
c) Line loading (with LCC-HVDC and SVC)

Figure 5. 44 Line loading for HVAC and HVDC TL.

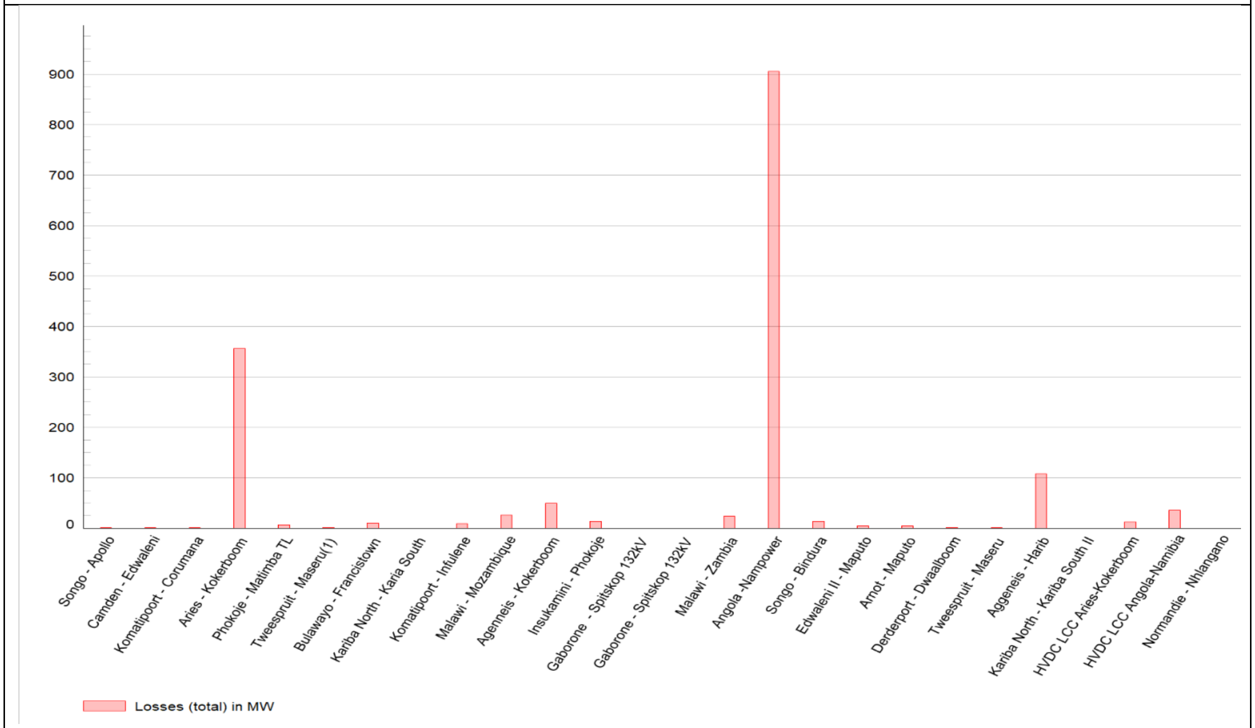
Figure 5.45 indicates transmission line losses for three different scenarios. 5.45 a) When the SARG network load flow analysis is performed on all HVAC lines, Angola-Namibia has around 1600MW TL losses. b) 5.45 b) also reveals that losses have decreased to around 800MW when the load flow study was performed with LCC-HVDC linkages as illustrated in Figure 5.37. Figure 5.45 c) illustrates the TL losses for both SVC and LCC-HVDC..



a) Transmission line losses (with HVAC)



b) Transmission line losses (with LCC-HVDC)



c) Transmission line losses (with LCC-HVDC and SVC)

Figure 5. 45 Transmission line losses for HVAC and HVDC.

5.8 Discussion of results

The main objective of this work is to exchange power within Southern African countries, particularly those lacking access to electricity, with minimum losses and ensure the reliability of the grid. Using DigSILENT PowerFactory, the SARG network was built. Each country model was developed separately and was then assembled to form the SARG network.

An HVAC load flow analysis was performed in the SARG network connecting ten countries: Angola, Namibia, South Africa, Lesotho, Swaziland, Botswana, Zimbabwe, Zambia, Malawi, and Mozambique, all the countries are referred to as SS. South Africa is used as a reference SS because it has the most installed capacity. All models were examined under the premise of a zero-generation outage. Figure 5.33 shows the entire SARG model for power exchange. South Africa exports 2 x 43.1MW through 2 x Tweespruit-Maseru TL, but Lesotho imports 2 x 42.4MW due to losses. Malawi imports 342.8MW of the 364.6MW transmitted from Mozambique through the Malawi-Mozambique TL. From Figure 5.23 to Figure 5.33, the power exchange for each country is discussed in detail. As demonstrated in Table 5.5 and Appendix 1, total SARG HVAC network losses amount to 2,341.33 MW.

All the countries were tested for power transfer capabilities as shown in Figure 5.34 to Figure 5.36 and Table 5.4. In this instance, each country is compared to the balance of the network by scaling demand or generation in the opposite way in the two segments. It illustrates the total transfer capacity limit for each country relative to the rest of the network. As shown in Figure 5.36, Swaziland was tested for maximum power transfer capability, it may import 308.5MW from Mozambique through the Edwaleni II-Maputo TL and export 85.5MW to South Africa through the Normandie-Nhlangano and Camden-Edison TL, which is the difference of 223MW active power in Swaziland TL. The total transfer capacity for the last feasible solution for Swaziland is 236.71MW. This is applied to all countries.

LCC-HVDC was recommended as an efficient solution for minimizing losses over long distances owing to its advantages in transporting bulk power over long distances.

Because of the high losses on these lines, the LCC-HVDC link is employed in the Angola-Namibia TL and the Aries-Kokerboom TL. The power setpoint for the Angola-Namibia HVDC LCC TL was set to 1000MW, and Namibia received 962.9MW out of it along with Angola-Namibia TL exporting 1963MW and Namibia receiving 1138.3MW, which means Namibia now receives 2101.2MW whereas in Figure 5.33 Angola exports 2963MW and Namibia received 1352.7MW. Again, the HVDC LCC power setpoint in Aries-Kokerboom TL was set to 600MW from Namibia and South Africa receives 586MW, along with Aries-Kokerboom HVAC TL transmitting 999.5MW from Namibia and South Africa receiving 550.3MW due to losses, which means Aries-Kokerboom TL now exports 1599.5MW from Namibia and South Africa receives 1136MW. The losses for this model are shown in Appendix 2 which appeared to be 1624.34MW. meaning that with the use of LCC-HVDC the losses were reduced from 2341.33MW to 1624.34MW.

The VSC was used in this study due to voltage instability seen in Namibia and Mozambique. The 400kV Namibia Transmission SS in Figure 5.38 has declined from 400kV to 389.1kV, which is 0.97p.u, the 13000MVAr SVC is utilized to increase voltage stability, as illustrated in Figure 5.41, where the voltage has increased to 397kV with the use of SVC. Again, as indicated in Figure 5.39, the 330kV Mozambique Transmission SS has climbed from 330kV to 341.5kV, which is 1.03p.u. The 150MVAr SVC is used to stabilize the voltage, and the voltage has decreased to 331.5kV, which is 1p.u.

The entire model is represented in Figure 5.42 showing the exported and imported power in each country's interconnector. with two LCC-HVDC in Angola-Namibia TL and Aries-Kokerboom TL to minimize losses, as stated in Appendices 1 and 2. Again, SVC is used to stabilize voltage in Mozambique and Namibia by managing some of the reactive power. The total model has a minimal loss of 1588.31MW with all busbars at 1p.u and u.99p.u, making the grid more robust.

CONCLUSION

DIgSILENT PowerFactory was used to develop the HV transmission network for a SARG. This grid will be used to exchange electricity between Southern African countries. When transmitting electricity, it is essential to use power interconnections; in this study, the existing SAPP interconnection was used to demonstrate how electricity may be carried throughout Southern African countries. As previously indicated, three prospective electricity interconnections were also included in this analysis, and those transmission lines include Angola and Malawi, which are not currently members of the SAPP. The entire network was simulated to facilitate the HV network, which includes transmission voltage levels of 11kV, 110kV, 132kV, 220kV, 275kV, 330kV, and 400kV.

Initially, the Southern African Network model was completed when all transmission lines were connected utilizing HVAC, and it is highlighted that with the usage of power interconnection, all Southern African countries are able to satisfy the growing demand by exporting power to emerging countries. The power transfer was indicated in the power interconnector as the difference between exported and imported power, once again. When compared to the rest of the network, each country's maximum power transfer capability was performed.

Other transmission lines, as seen in Appendix 1, suffer significant losses when transmitting electricity, therefore the use of LCC HVDC on those lines was adopted to mitigate losses in the Southern African grid, As illustrated in Appendix 2, losses were reduced with the deployment of LCC HVDC. However, voltage instability was also detected in Namibia and Mozambique following electricity connectivity, resulting in the implementation of the Static Var System as part of the FACTS devices to manage some of the power and control the system's stability, as well as to optimize power as shown in appendix 3. This results in a final model with LCC HVDC and Static Var System to decrease grid losses and increase grid stability while providing 100% electricity availability to all Southern African countries.

This study is very important since it establishes power connections to all Southern Africa's regions, with minimum losses while maintaining the reliability of the grid. This study might also be conducted on the Five African Power Pools, as indicated previously, in order to transfer power to the disadvantaged pools, such as WAPP and EAPP.

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APPENDIX

Appendix 1 Southern Africa base case of HVAC Load flow analysis

```
---------------------------------------------------------------------------------------------------------------------
|                |                                                        |  DIgSILENT   | Project:                  |
|                |                                                        | PowerFactory |-----------------------------
|                |                                                        |   2021 SP5   | Date:  4/1/2022           |
---------------------------------------------------------------------------------------------------------------------
---------------------------------------------------------------------------------------------------------------------
| Load Flow Calculation                                                                         Total System Summary |
---------------------------------------------------------------------------------------------------------------------
|    AC Load Flow, balanced, positive sequence             |   Automatic Model Adaptation for Convergence        No    |
|    Automatic tap adjustment of transformers      No      |   Max. Acceptable Load Flow Error                         |
|    Consider reactive power limits                No      |      Bus Equations(HV)                            1.00 kVA |
|                                                          |      Model Equations                              0.10 %   |
---------------------------------------------------------------------------------------------------------------------
---------------------------------------------------------------------------------------------------------------------
| Total System Summary                          | Study Case: Study Case              | Annex:                / 1  |
---------------------------------------------------------------------------------------------------------------------
|                                                                                                                   |
| No. of Substations    10        No. of Busbars        34       No. of Terminals      241       No. of Lines         24 |
| No. of 2-w Trfs.      8         No. of 3-w Trfs.      8        No. of syn. Machines  47        No. of asyn.Machines 0  |
| No. of Loads          10        No. of Shunts/Filters 0        No. of SVS            0                                 |
|                                                                                                                   |
| Generation           =   60699.33  MW        1568.59  Mvar   60719.59  MVA                                        |
| External Infeed      =       0.00  MW           0.00  Mvar       0.00  MVA                                        |
| Load P(U)            =   58358.00  MW           0.00  Mvar   58358.00  MVA                                        |
| Load P(Un)           =   58358.00  MW           0.00  Mvar   58358.00  MVA                                        |
| Load P(Un-U)         =       0.00  MW          -0.00  Mvar                                                        |
| Motor Load           =       0.00  MW           0.00  Mvar       0.00  MVA                                        |
| Grid Losses          =    2341.33  MW        1568.59  Mvar                                                       |
| Line Charging        =                         0.00  Mvar                                                        |
| Compensation ind.    =                         0.00  Mvar                                                        |
| Compensation cap.    =                         0.00  Mvar                                                        |
|                                                                                                                   |
| Installed Capacity   =  118015.20  MW                                                                             |
| Spinning Reserve     =   19536.47  MW                                                                             |
|                                                                                                                   |
| Total Power Factor:                                                                                               |
|   Generation         =        1.00  [-]                                                                           |
|   Load/Motor         = 1.00 / 0.00  [-]                                                                           |
|-------------------------------------------------------------------------------------------------------------------|
```

Appendix 2. Southern Africa Model base case Summary of HVAC with HVDC LCC link load flow analysis

```
------------------------------------------------------------------------------------------------------------
|               |                                                    |  DIgSILENT   | Project:              |
|               |                                                    | PowerFactory |--------------------------
|               |                                                    |   2021 SP5   | Date:  4/1/2022        |
------------------------------------------------------------------------------------------------------------
------------------------------------------------------------------------------------------------------------
| Load Flow Calculation                                                               Total System Summary |
------------------------------------------------------------------------------------------------------------
|    AC Load Flow, balanced, positive sequence            |  Automatic Model Adaptation for Convergence      No      |
|    Automatic tap adjustment of transformers       No    |  Max. Acceptable Load Flow Error                         |
|    Consider reactive power limits                 No    |     Bus Equations(HV)                        1.00 kVA   |
|                                                          |     Model Equations                          0.10 %     |
------------------------------------------------------------------------------------------------------------
------------------------------------------------------------------------------------------------------------
| Total System Summary                           | Study Case: Study Case           | Annex:              / 1  |
------------------------------------------------------------------------------------------------------------
|                                                                                                          |
| No. of Substations    10       No. of Busbars       34       No. of Terminals     245      No. of Lines          24    |
| No. of 2-w Trfs.      8        No. of 3-w Trfs.     8        No. of syn. Machines 47       No. of asyn.Machines  0     |
| No. of Loads          10       No. of Shunts/Filters 0       No. of SVS           0                                   |
|                                                                                                          |
| Generation          =   59982.34  MW      1925.77  Mvar    60013.25  MVA                                 |
| External Infeed     =       0.00  MW         0.00  Mvar        0.00  MVA                                 |
| Load P(U)           =   58358.00  MW         0.00  Mvar    58358.00  MVA                                 |
| Load P(Un)          =   58358.00  MW         0.00  Mvar    58358.00  MVA                                 |
| Load P(Un-U)        =       0.00  MW        -0.00  Mvar                                                  |
| Motor Load          =       0.00  MW         0.00  Mvar        0.00  MVA                                 |
| Grid Losses         =    1624.34  MW      1059.95  Mvar                                                  |
| Line Charging       =                         0.00  Mvar                                                  |
| Compensation ind.   =                         0.00  Mvar                                                  |
| Compensation cap.   =                         0.00  Mvar                                                  |
|                                                                                                          |
| Installed Capacity  =  118015.20  MW                                                                    |
| Spinning Reserve    =   20253.46  MW                                                                    |
|                                                                                                          |
| Total Power Factor:                                                                                      |
|   Generation        =         1.00  [-]                                                                 |
|   Load/Motor        =  1.00 / 0.00  [-]                                                                 |
|----------------------------------------------------------------------------------------------------------|
```

Appendix 3. Southern Africa model base case Summary of HVAC loaf flow analysis with HVDC LCC link and Static Var System

```
--------------------------------------------------------------------------------------------------------------------------------
|                 |                                                             |   DIgSILENT   | Project:                      |
|                 |                                                             | PowerFactory  |-------------------------------
|                 |                                                             |    2021 SP5   | Date:   4/2/2022              |
--------------------------------------------------------------------------------------------------------------------------------
--------------------------------------------------------------------------------------------------------------------------------
| Load Flow Calculation                                                                                    Total System Summary |
--------------------------------------------------------------------------------------------------------------------------------
|     AC Load Flow, balanced, positive sequence                 |    Automatic Model Adaptation for Convergence           No        |
|     Automatic tap adjustment of transformers        No        |    Max. Acceptable Load Flow Error                                |
|     Consider reactive power limits                  No        |       Bus Equations(HV)                                1.00 kVA   |
|                                                               |       Model Equations                                  0.10 %     |
--------------------------------------------------------------------------------------------------------------------------------
--------------------------------------------------------------------------------------------------------------------------------
| Total System Summary                              | Study Case: Study Case                | Annex:                       / 1  |
--------------------------------------------------------------------------------------------------------------------------------
|                                                                                                                               |
| No. of Substations      10        No. of Busbars        36        No. of Terminals      245        No. of Lines          24    |
| No. of 2-w Trfs.        10        No. of 3-w Trfs.      8         No. of syn. Machines  47         No. of asyn.Machines  0     |
| No. of Loads            10        No. of Shunts/Filters 0         No. of SVS             2                                      |
|                                                                                                                               |
| Generation          =    59946.31  MW          771.82   Mvar    59951.28  MVA                                                  |
| External Infeed     =        0.00  MW            0.00   Mvar        0.00  MVA                                                  |
| Load P(U)           =    58358.00  MW           -0.00   Mvar    58358.00  MVA                                                  |
| Load P(Un)          =    58358.00  MW            0.00   Mvar    58358.00  MVA                                                  |
| Load P(Un-U)        =        0.00  MW            0.00   Mvar                                                                   |
| Motor Load          =        0.00  MW            0.00   Mvar        0.00  MVA                                                  |
| Grid Losses         =     1588.31  MW         1013.85   Mvar                                                                   |
| Line Charging       =                            0.00   Mvar                                                                   |
| Compensation ind.   =                          147.59   Mvar                                                                   |
| Compensation cap.   =                        -1258.25   Mvar                                                                   |
|                                                                                                                               |
| Installed Capacity  =   118015.20  MW                                                                                         |
| Spinning Reserve    =    20289.48  MW                                                                                         |
|                                                                                                                               |
| Total Power Factor:                                                                                                           |
|   Generation        =        1.00  [-]                                                                                        |
|   Load/Motor        =   1.00 / 0.00  [-]                                                                                      |
|-------------------------------------------------------------------------------------------------------------------------------|
```

Appendix 4. Maximum total transfer capability of Malawi power interconnector

Iteration Number	Exporting Region Generation (MW) Malawi Interconnector	Importing Region Generation (MW) Malawi -rest of the network	Transfer (MW)	Iteration Status
0	71885.49	394.00	-589.90	OK
1	71914.99	364.50	-600.53	OK
2	71973.98	305.51	-621.63	OK
3	72091.96	187.53	-663.27	OK
4	72278.58	0.91	-727.45	OK
5	72279.49	-0.00	-727.75	OK

Generation in the Malawi -rest of the network region reached limiting value. Calculation process stopped.

The total transfer capacity (TTC) for the last feasible solution is -727.75 (MW).

Transfer capacity analysis successfully calculated.

DPL Command 'Create' started

No element with loading below 80.0%.

DPL Command 'Create' : 'exit'

Appendix 5. Maximum total transfer capability of Mozambique Interconnector

Iteration Number	Exporting Region Generation (MW) Mozambique Interconnector	Importing Region Generation (MW) rest of the network	Transfer (MW)	Iteration Status
0	69342.49	2937.00	578.65	OK
1	69371.42	2908.07	554.58	OK
2	69429.29	2850.20	506.45	OK
3	69545.02	2734.47	410.17	OK
4	69776.48	2503.01	217.61	OK
5	70239.40	2040.09	-167.56	OK
6	71165.23	1114.26	-937.96	OK
7	72256.55	22.94	-1845.73	OK
8	72279.49	0.00	-1864.80	OK

Generation in the rest of the network region reached limiting value. Calculation process stopped.

The total transfer capacity (TTC) for the last feasible solution is -1864.80 (MW).

Transfer capacity analysis successfully calculated.

DPL Command 'Create' started

No element with loading below 80.0%.