



# TECHNICAL ANALYSIS OF RENEWABLE ENERGY INTEGRATION WITH BATTERY ENERGY STORAGE SYSTEMS ON THE ESKOM GRID.

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**STUDENT NO: GNGJAC001**

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## **Abstract**

The Eskom fleet of coal-fired power plants is ageing and will be retired within 30 years, if not sooner. As a clean alternative towards the decarbonization of the South African electrical industry, Eskom is progressively incorporating renewable energy sources into its infrastructure. However, the intermittent nature of renewable energy sources provides a challenge for supply security and system stability.

There seems to be a need for Eskom to integrate large-scale energy storage into its grid to maintain energy security during the transition from fossil fuels to clean energy sources. Even though load shedding has been looming since 2008 and is getting worse as the fleet of power plants ages. Eskom is routinely curtailing wind energy in the early morning due to low demand, thereby wasting energy that could have been used during peak hours. In addition, Eskom's limited financial resources necessitate the delay of certain network strengthening projects.

This dissertation examines the effects of Battery Energy Storage System (BESS) on the Eskom Distribution grid. This was accomplished by selecting two Eskom BESS sites, Skaapvlei (80 MW) which will be used for ancillary services (AS) and energy support (ES) and Hex (20 MW) which will be used for AS, ES and Load shaving (LS). Both networks were modelled using DigSilent Powerfactory and hourly load data from MV90 and the Eskom data tool. Eskom contractors' BESS models were used to simulate the future network, allowing for a comparison between the current network without BESS and the future network with BESS.

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## List of abbreviations

Abbreviation	Definition
IEP	Integrated Energy Plan
PV	Photo-voltaic
CSP	Concentrated Solar Power
UNFCCC	United Nations Framework Convention on Climate Change
COP 21	Conference of Parties
GHG	Greenhouse Gases
NDP	National Development Plan
IRP	Integrated Resource Plan
DERs	Distributed Energy Resources
DG	Distributed Generation
REIPPPP	Renewable Energy Independent Power Producer Procurement Programme
BESS	Battery Energy Storage Systems
RES	Renewable Energy Sources
CO <sub>2</sub>	carbon dioxide
DoE	Department of Energy
TSO	Transmission system operator
AS	Ancillary Service
ES	Energy Support
VRE	Variable Renewable Energy
SDGs	Sustainable Development Goals
NERSA	National Energy Regulator of South Africa
BESF	Battery Energy Storage Facilities
GCAC	Grid Code Advisory Committee
WEF	Wind Energy Facilities
ESS	Energy Storage Systems
S/S	Substation/ Switching Station
PSST	Power System Simulation Tool
QDSL	Quasi-Dynamic Simulation
TEMSE	Transmission Energy Management System Evolution
POC	Point of Connection
FFP	Fabric Filter Plant Retrofits
LNB	Low NO <sub>x</sub> Burner Retrofits
P <sub>na</sub>	Nominal Active Power Absorbed
P <sub>nd</sub>	Nominal Active Power Delivered

# 1 INTRODUCTION

## 1.1 Background

The world faces the challenge of harnessing the earth's resources effectively and efficiently. Up until now, there has been a heavy reliance on fossil fuels, and both developing and developed countries have utilized this energy source. It is common knowledge that excessive use of fossil fuels has a cost, as they emit large quantities of carbon dioxide [1].

The integrated energy plan (IEP-2016) emphasizes the need for South Africa to continue pursuing a diverse energy mix that reduces reliance on a single or a few primary energy sources [2]. This plan continues to clarify why the different energy sources (i.e. coal, nuclear, natural gas, solar PV & CSP, wind, and biomass) should be included in the energy mix and what should be done to lessen the negative effects that some conventional sources, such as coal, have on the environment, as well as how renewable energy sources, such as solar PV and CSP with storage, would present excellent opportunities to diversify the energy mix and create jobs.

South Africa is amongst 196 states that reached a historic agreement to combat climate change in Paris at COP 21 on 12<sup>th</sup> December 2015 [3]. *“South Africa has begun implementing measures that will reduce the emission of greenhouse gases (GHG) into the atmosphere to meet environmental goals outlined in the Paris Agreement of the United Nations Framework Convention on Climate Change (UNFCCC)”* [3]. *“South Africa’s emissions are expected to peak, plateau and from year 2025 decline. The energy sector contributes close to 80% towards the country’s total greenhouse gas emissions of which 50% are from electricity generation and liquid fuel production alone”* [4]. There is action to reduce emissions with investment already in renewable energy, energy efficiency and public transport. Integration of renewable energy sources is a top priority for the South African electrical grid [1].

The National Development Plan (NDP) envisions that by 2030, South Africa will have an energy sector that provides reliable and efficient service at competitive rates, is socially equitable by expanding access to energy at affordable rates and is environmentally sustainable by reducing emissions and pollution with 17,8GW of electricity generation from renewable energy [2]. In formulating its vision for the energy sector, the NDP used the Integrated Resource Plan (IRP) 2010-2030 [5] as a starting point.

Government policy in South Africa encourages the incorporation of distributed energy resources (DER), such as renewable energy generation, embedded generation (EG), or distributed generation (DG), into the country's energy mix due to their advantages of being low-cost, low-carbon, and more sustainable energy sources. Since then, the government has successfully signed renewable energy contracts through the Renewable Energy Bid Window 1 (REBID1) competitive bidding process of the Renewable Energy Independent Power Producer Procurement Programme (REIPPPP), which was designed to encourage private sector investment in grid-connected renewable energy (RE) generation in South Africa [6].

The Integrated Resource Plan 2018 allocated 7 598 MW for solar and 11 442 MW for wind by 2030. The Renewable Energy Independent Power Producers Program has procured a total of 6,422 MW of wind and solar by 2019, with an operational capacity of 3,876 MW, according to the 2019 IRP. The most recent Renewable Energy Data and Information Service (REDIS) data indicates a peak operating capacity of 5044 MW (see figure 1.1).

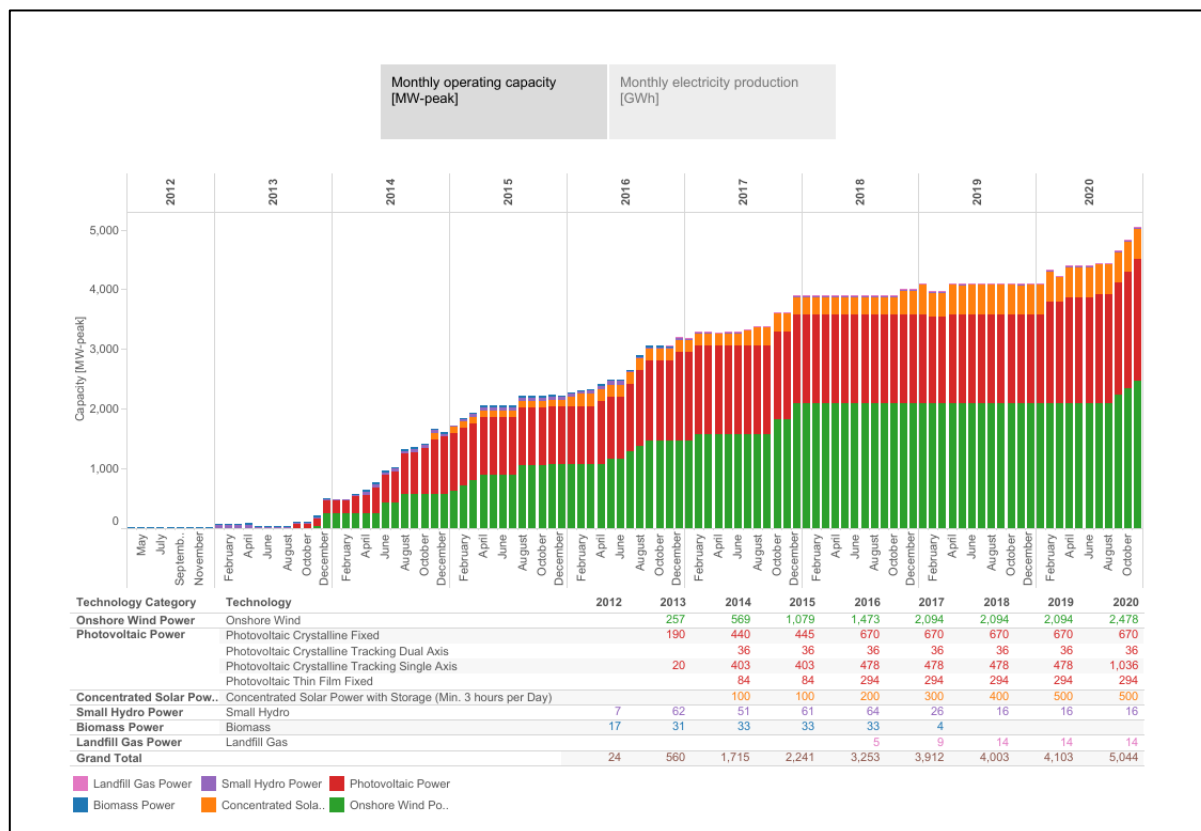


Figure 1.1: Production and Operating Capacity [MW-Peak] [7]

Figure 1.1 shows the monthly peak operating MW for each renewable technology since 2012 until 2020. As shown in the graph, the total capacity has increased by 5020 MW from 24 MW in 2012 to 5044 MW in 2020. As stated in the IRP2019, this number will exceed 20 000 MW by 2030, and renewable energy will gradually replace Eskom's coal fleet. The coal fleet serves the country as base load stations that can be dispatched to meet the constantly changing demand for electricity while also providing reserves for contingencies [8]. In contrast, wind and solar resources are not always available, so this poses a supply security risk to the power grid. Battery energy storage is required to ensure a just transition to a future energy mix that includes a high proportion of renewable energy [5].

Eskom approved the 100 MW Kiwano Concentrated Solar Power (CSP) project that was to be implemented as part of the \$3.7bn World Bank loan extended to the group in 2010, along with the 100 MW Sere wind farm, under the renewable energy component of the World Bank's Eskom Investment Support Project, which helped fund the Medupi and Kusile coal fire power stations. In 2015, the Sere wind farm began commercial operations. The

Kiwano CSP project was delayed and eventually cancelled, to be replaced by a BESS project that is expected to provide a daily rate of 1440 MWh or 525 GWh annually. [6]

Following the cancellation of the Kiwano (CSP) project, the World Bank loan criteria required an alternative green power component. Eskom proposed the Battery Energy Storage Systems project as a cost-effective alternative to the CSP project [5]. The project would be split into two phases, with Phase 1 aiming to install 800 MWh and Phase 2 aiming to install 640 MWh[9]. Eastern Cape (EC), KwaZulu-Natal (KZN), Western Cape (WC), and Northern Cape (NC) have been identified as Phase 1 sites (NC). Phase 1 is anticipated to reduce curtailment by approximately 320 MWh and 140 MWh at the Skaapvlei and Melkhout sites in Western Cape and Eastern Cape, respectively[10]. Curtailment is described as the act of limiting, reducing, or restricting something. On a power system, generation and load should constantly be balanced. Excessive system generation will result in high system frequencies, which may result in system instability. To stabilize the system, Eskom determined that wind generation should be reduced by up to 10% of available capacity or eliminated entirely. This is when the topic of energy storage is raised as a viable solution.

## **1.2 Problem Statement**

The Eskom coal power fleet is aging and will be retired gradually over the next 30 years [3]. As a clean alternative towards the decarbonisation of the South African electricity industry, Eskom is progressively integrating renewable energy sources onto its grid. However, the intermittent nature of renewable energy sources presents a challenge. To maintain energy security during the transition from fossil fuels to clean energy resources, Eskom must integrate energy storage in bulk into its grid. Eskom has routinely curtailed wind energy during the early morning hours due to low demand, thereby wasting energy that could have been utilized during peak hours [7]. Eskom also faces capital constraints, necessitating the postponement of some of the distribution network strengthening projects [8]. Moreover, load shedding has been increasing at Eskom since 2008 and is getting worse as the fleet of generation plants ages [11].

## **1.3 Hypothesis**

Battery energy storage can improve Eskom Distribution grid performance by reducing curtailment, shifting/shaving loads, and providing voltage support on constrained networks.

## **1.4 Research Questions**

Through the REIPPPP, the South African government has been successful in advancing a renewable energy path in the country's energy mix [12]. The intermittent nature of renewable energy (i.e., the Sun and wind) prevents the robust exploitation of these resources, as they cannot be dispatched during times of need because energy is only produced when the resource is available. Wind energy that is produced early in the morning, when generation exceeds demand, must be curtailed. During peak hours, certain distribution networks experience low voltages, necessitating some form of energy support to alleviate these voltages. The final

obstacle is a lack of capital for network strengthening, which results in bottlenecks on the distribution network during periods of high load demand.

Considering these challenges and the opportunity presented by Eskom's current battery energy storage system (BESS) projects, the dissertation poses the following questions.

- How will the battery energy storage systems mitigate wind power curtailment on the Eskom grid?
- How will BESS provide voltage support to the Eskom grid?

This dissertation is quantitative in nature; available data will be used to simulate the current Eskom network and the performance relationship between the current Eskom network and the future where BESS will be studied.

## **1.5 Rationale**

This research will analyse how the BESS integrated into the Eskom grid will mitigate wind generation curtailment and provide voltage support for the Eskom Distribution network.

As shown in Table 2.2, the installed coal capacity reported in the 2019 IRP was 39,126 MW (69 percent of total Eskom capacity), and by 2030, only 33,847 MW (38 percent of Eskom capacity) will remain. According to Eskom's emission reduction plan, six power stations comprising over 10,500 MW will be decommissioned prior to 2030 due to the expiration of their design life (see figures 1.2) [5]. Excluding Majuba, Medupi, and Kusile, the two additional power plants namely Duvha and Matla will be decommissioned with a total capacity of 7,000 MW by 2035 and the remaining existing plants namely Tutuka, Lethabo, Matimba and Kendal by 2044 will bring the total to 13,710 MW [13].

As can be established from the above paragraph that most of the base load stations will be decommissioned in phases while mass renewable energy will be integrated on the South African Grid. To maintain a robust grid, it is essential to install large-scale battery storage to complement variable renewable energy. Storage systems are valuable components in the majority of energy systems, particularly where renewables are employed, to ensure the stability, reliability, and resiliency of the electricity grid[2]. This study will examine the performance of Eskom's current distribution network with BESS.



were obtained from MV90, an Eskom-approved repository of data. The case file was subsequently prepared for QDSL.

QDSL was executed without BESS connected to the networks, and the results were saved in Excel format for analysis.

## **1.7 Scope and Limitations**

This dissertation is a desktop study which refers to the growing market of renewable energy industry in the country. Since the 1<sup>st</sup> REIPPPP programme bid window 1 in 2011, there has been a range of papers on renewable energy topic, but there is a limited number of papers on battery energy storage systems in South Africa, due to the infancy status of BESS.

Currently, South Africa is on its execution phase pertaining to integration of BESS on Eskom Grid. There is no secondary data available with BESS connected. A sample of the current network will be simulated in comparison with the future network when BESS is integrated, and the results will be studied.

This study will only consider the profile data of two networks connected to the Eskom Western Cape Grid during a one-year period (2021). Consequently, it will be assumed that this information is sufficient to draw conclusions that accept or not accept my hypothesis and answer my research questions. To keep the scope as small as possible, it is assumed that the meters providing this profile data are accurate.

## **1.8 Ethical Considerations**

Eskom secondary loading data will be acquired via available repositories and distribution network and simulation tool DigSilent Powerfactory will be used. This information will only be used for this dissertation and will be stored on my computer, which requires a password to access.

## **1.9 Dissertation Structure**

The remaining sections of this dissertation are as follows:

- In Chapter 2, the available literature on renewable energy, battery energy storage, their challenges, opportunities, regulatory requirements, global benchmarks, BESS for wind curtailment mitigation and voltage support will be discussed.
- Chapter 3 describes the methodology employed to address the research questions.
- Simulations, results, and discussions are presented in Chapter 4.
- Chapter 5 draws conclusions, discusses whether the results answer the research questions, meet the requirements of the problem statement, and accepts the hypothesis or not. Then recommendations and future work are discussed.

## 2 LITERATURE REVIEW

### 2.1 Introduction and Background

In this chapter, the relevant literature will be reviewed. The literature on renewable energy, battery energy storage systems, their challenges, opportunities, regulatory requirements, global benchmarks, BESS for wind curtailment mitigation, and voltage support, as well as any other literature that will help the author to answer the research questions, will be discussed.

### 2.2 Renewable Energy and South African Government Commitments

Renewable energy is defined as energy derived from non-depletable natural resources [15]. Renewable energy is a variable, non-dispatchable energy source for example solar or wind generate electricity only when the sun is shining or the wind is blowing — uncontrollable conditions [9].

To reduce the impact this has on the operation of the power system, more flexible generation capacity must be on standby for usage when the renewable resource (solar and wind) is unavailable. This could be provided by fossil-fuelled gas turbines, hydropower, and energy storage systems that store some of the energy from variable sources when it is not needed, ensuring that the ramping up is from the same renewable source, thereby replacing the fossil fuel alternative [9].

Renewable energy technologies are regarded as clean sources of energy, and their optimal use minimises environmental impacts, generates little secondary wastes, and is sustainable based on current and future economic, social, and societal requirements. Included among renewable energy sources (RES) are solar, wind, biomass, hydropower, geothermal, and marine energies. Principal renewable energy sources and their applications are listed in table 2.1 [11].

Table 2.1: Main RES and their Usage Forms

Energy Source	Energy Conversion and Usage Options
Direct Solar	Photovoltaic (PV) & Concentrated Solar Power (CSP) - thermal power generation, water heaters
Solar	PV - Solar Home System, Solar Dryers, Solar Cookers
Wind	Wind Generators - Wind Power Generators, Windmills, Water pumps
Hydro	Hydro-Power Generators, Pumped Storage
Wave	Numerous Designs
Tidal	Barrage, Tidal Stream
Modern Biomass	Heat and Power Generation, Pyrolysis, Gasification, Digestion

On the IRP 2019 [5], South African government has identified the preferred generation technology required to meet the expected demand growth up to year 2030. Table 2.2 below shows the energy mix proposed updated plan for the period of 2018 to 2030. The units of the values on the table is megawatts (MW).

Table 2.2: Energy Mix on the published IRP 2019 [5]

Year	Coal	Nuclear	Hydro	Storage	PV	Wind	CSP	Gas/Diesel	Other	Embedded Generation
2018	39 126	1 860	2 196	2 912	1 474	1 980	300	3 830	499	Unknown
2019	2 155					244	300			200
2020	1 433				114	300				200
2021	1 433				300	818				200
2022	711				400					200
2023	500									200
2024	500									200
2025					670	200				200
2026					1 000	1 500		2 250		200
2027					1 000	1 600		1 200		200
2028					1 000	1 600		1 800		200
2029					1 000	1 600		2 850		200
2030			2 500		1 000	1 600				200
<b>TOTAL INSTALLED MW</b>	<b>45 858</b>	<b>1 860</b>	<b>4 696</b>	<b>2 912</b>	<b>7 958</b>	<b>11 442</b>	<b>600</b>	<b>11 930</b>	<b>499</b>	<b>2 400</b>
<b>Installed Capacity Mix (%)</b>	<b>50.87%</b>	<b>2.06%</b>	<b>5.21%</b>	<b>3.23%</b>	<b>8.83%</b>	<b>12.69%</b>	<b>0.67%</b>	<b>13.23%</b>	<b>0.55%</b>	<b>2.66%</b>
	<b>Installed Capacity</b>									
	<b>Committed/Already Contracted Capacity</b>									
	New Additional Capacity									
<b>TOTAL MW INSTALLED 2030</b>	<b>90 155</b>									

Table 2.2 above shows the installed capacity, committed and new additional capacity required in the future up to 2030. As can be deduced from table 2.2 only 1000MW new additional capacity of coal is committed between 2023 & 2024, 5670MW of PV from 2025 up to 2030, 8100MW wind from 2025 to 2030, 8100MW gas/diesel from 2026 to 2030 and 2600MW of unknown embedded generation from 2018 to 2030.

## 2.3 Analysis of Renewable Energy Performance on Eskom Distribution Grid

As stated in the white paper [1], the South African government's vision for the role of renewable energy in its energy economy is to have an energy economy in which modern renewable energy provides affordable access to energy throughout South Africa, thereby contributing to sustainable development and environmental conservation.

The majority of South Africa's electricity is still generated by coal-fired power plants located on the coal fields of the Mpumalanga Highveld and in the vicinity of Lephalale [13]. South Africa is progressively strengthening its renewable energy sector to reduce carbon dioxide (CO<sub>2</sub>) emissions and offer reliable and sustainable electricity to its citizens [16]. The renewable energy independent power producer initiative of the Department of Energy (DoE) has led in an increase in the amount of electricity generated from renewable resources, particularly wind and solar, in the Eastern Cape, Western Cape, and Northern Cape. As depicted in Figure 2.1, as of June 2020, Eskom has a committed capacity of 6,632 MW linked to the grid. This includes onshore wind, photovoltaic, CSP, hydro, biomass, and landfill gas.

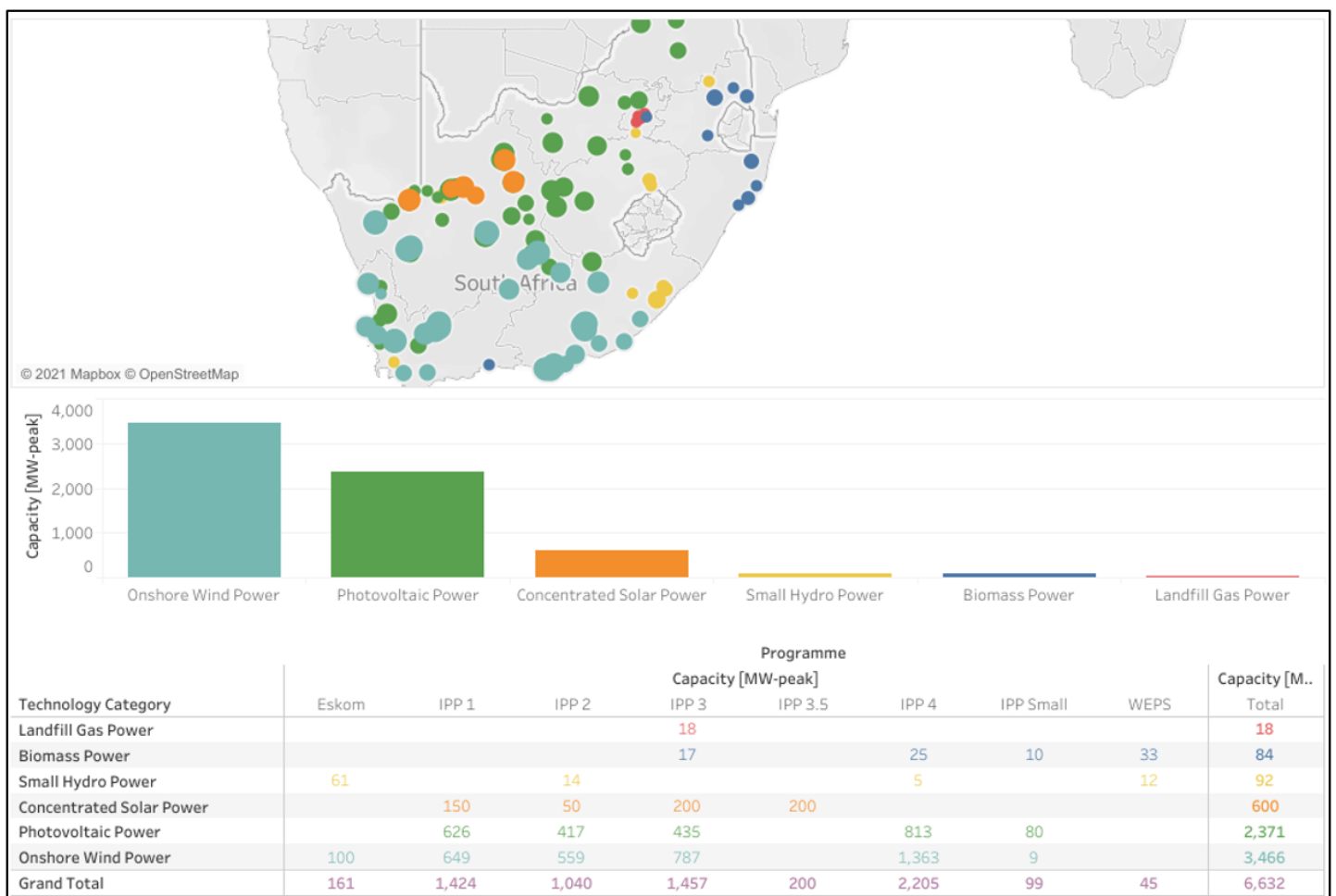


Figure 2.1: Production and Contracted Capacity [MW-Peak] [7]

Figure 2.1 shows the heatmap of how renewable energy technologies are connected across the country. As mentioned before, the target for 2030 is 17.8GW.

### 2.3.1 Renewable Energy Technologies

In the following five paragraphs, each technology will be defined and its present performance on the Eskom energy grid will be examined. Figure 2.2 illustrates the capacity factor benchmark by source. Capacity Factor, also known as Load Factor, is the ratio of the energy generated by a power generator unit over a particular period to the energy it would have produced at its reference power capacity over the same period. As shown in the diagram, nuclear energy is superior to all other energy sources in terms of capacity factor. This means that nuclear energy is more reliable because it requires less maintenance and is built to operate for longer periods before refuelling (usually every 1.5 or 2 years) [17].

The capacity factors for natural gas and coal are lower due to routine maintenance and/or refuelling at these facilities[17]. Renewable power plants are hampered by the intermittent nature of natural resources (i.e., wind, sun, or water). Consequently, these plants require a backup power source, such as large-scale storage (which is currently unavailable at grid-scale), or they can be coupled with a stable baseload, such as nuclear energy [17].

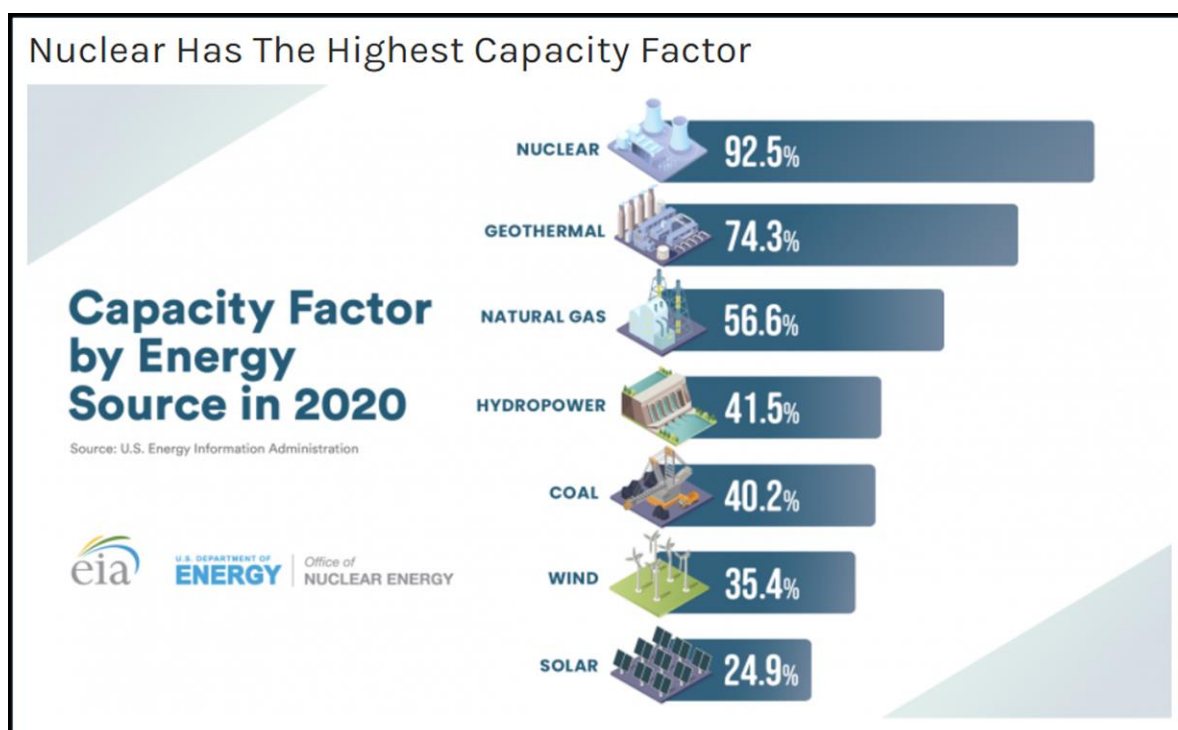


Figure 2.2: Capacity Factor Worldwide Benchmark Diagram [17]

### 2.3.2 Solar PV

Solar PV energy is electricity generated from the heat of the sun. Photo Voltaic (PV) systems capture the energy in the sunlight and convert it directly into electricity. This energy can also be used to heat water and to heat, cool and light buildings[1].

Eskom had a capacity as reported in June 2020 of 2371 MW photo-voltaic power connected to its electricity grid. That is about 31% of the committed capacity by the IRP2018 by the year 2030. Figure 2.3 below shows PV capacity by technology.

Photovoltaic Technology performance in 2020 ranged from 23% to 28.5% in terms load factor with 3 different technologies, namely, PV thin film fixed, PV Crystalline fixed or PV Crystalline tracking Single Axis that are currently employed in South Africa, and the tracking technology outperformed the fixed technologies as shown in figure 2.4.

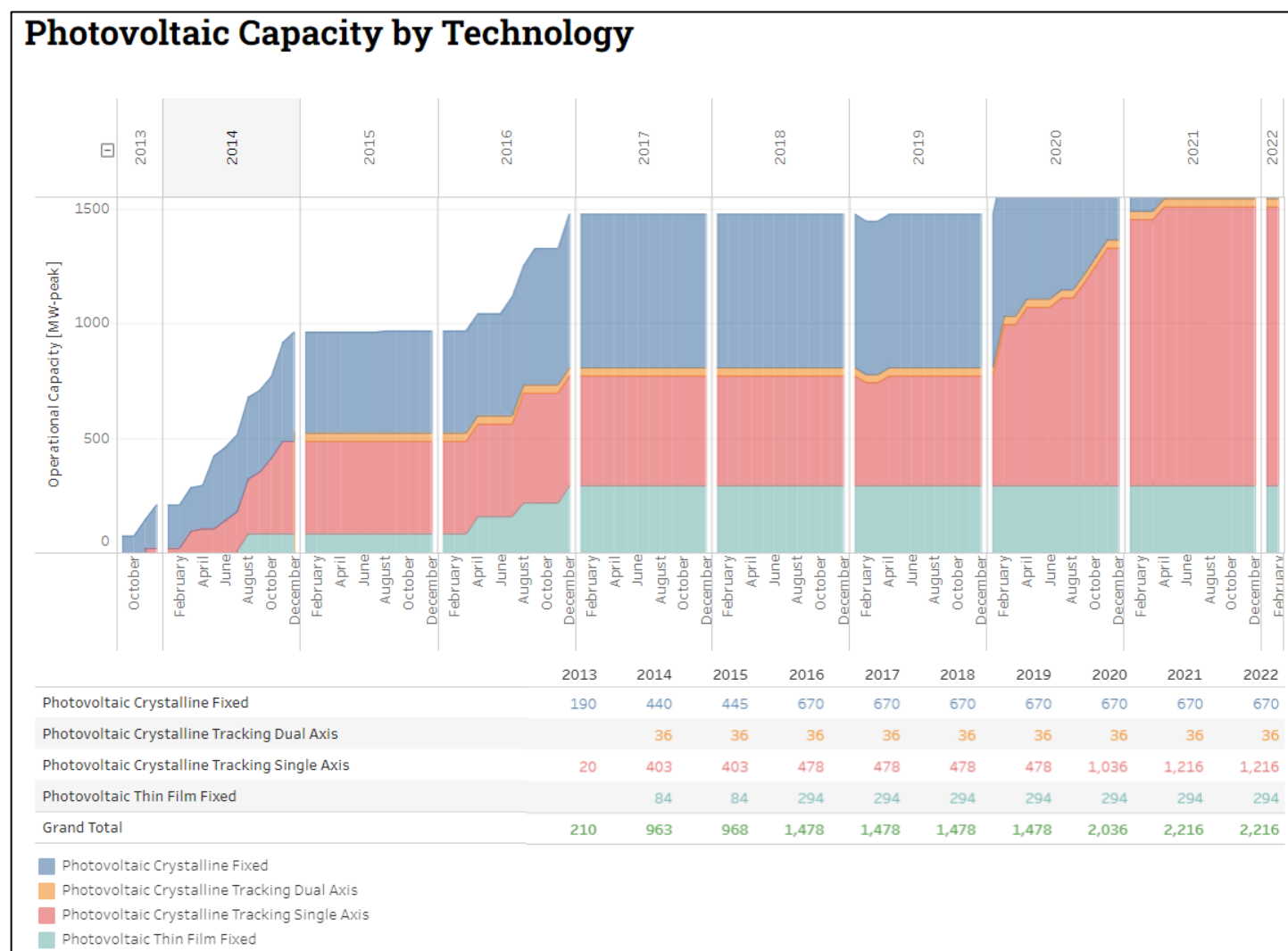


Figure 2.3: PV Operational Capacity [7]

### 2.3.3 Concentrated Solar Power (CSP)

CSP is the collection of solar energy using concentrated mirrors to generate a high-intensity heat source that can be used to generate electricity via a steam turbine or heat engine [1].

Concentrated solar power (CSP) is gaining increased global interest as the renewable energy industry enters the storage phase. Several CSP facilities are now operational or under development in South Africa. EE Publishers compiled a list of all operating and under construction CSPs in South Africa for the year 2018 in Table 3 [18]. Nonetheless, several of them have since been commissioned and are operational during the period covered by this report.

The average performance for CSP in 2020 was reported to be at 39.2% in terms of load factor as shown on figure 2.4.

Table 2.3: CSP Projects in South Africa

Project Name	Technology	Capacity MW	REIPPPP Window	Nearest Town	Status
<b>Bokpoort CSP</b>	Parabolic Trough	50	2	Groblershoop	Operational
<b>Eskom CSP</b>	Tower	100	Other	Upington	Construction
<b>Ilanga CSP 1</b>	Parabolic Trough	100	3	Kimberley	Construction
<b>Kathu Solar Park</b>	Parabolic Trough	100	3	Kuruman	Operational
<b>Kaxu Solar 1</b>	Parabolic Trough	100	1	Pofadder	Operational
<b>Khi Solar 1</b>	Tower	50	1	Upington	Operational
<b>Redstone CSP</b>	Tower	100	3	Postmasburg	Planning
<b>Xina CSP</b>	Parabolic Trough	100	3	Pofadder	Operational
<b>Totals</b>	8	700			

This was sourced from<sup>1</sup> an Energize Article Published on 29<sup>th</sup> May 2018

As reported in June 2020 by DoE, South Africa has already connected 400MW of concentrated solar power to its electricity grid. That is 67% of the committed capacity by the IRP2018 by the year 2030.

### 2.3.4 Wind

Wind power is harnessed from the naturally occurring energy of wind and is used to generate electricity, which can then be used to charge batteries or pump water. Large modern wind turbines work together in wind farms to generate electricity for utilities like Eskom. Small turbines are used to meet specific energy requirements [1].

<sup>1</sup> <https://www.ee.co.za/article/power-from-the-sun-an-overview-of-csp-in-south-africa.html>

The Wind Atlas for South Africa provides a method for calculating how much wind could be used to generate power in different areas of the country. Furthermore, the majority of wind farms have been erected in the Northern Cape, Western Cape and Eastern Cape so far [5].

Load factor for wind was reported to be 34.7% by the DoE.

### **2.3.5 Biomass**

The most common source of biomass energy is found to be fuel wood, which comes from trees. But it can't keep going if there aren't enough new trees to replace the ones that are cut down. Other types of biomasses are plants, waste from farming or forestry, and the organic parts of waste from cities and businesses. Biomass energy can be used to heat buildings, make liquid fuels and gas, and make electricity [1].

Biomass outperforms all renewable technologies with a 2015 performance sitting at 72.3% load factor and 2020 at 49.5%, which means the highest average energy output for biomass over a year is 72.3% of its total capacity and that was achieved in year 2015.

### **2.3.6 Hydro**

Hydropower is the power harnessed from movement of water under gravitational force to drive turbines to generate electricity [1]. Palmiet pumped storage power station (400MW) located at Grabouw in the Western Cape is an example of hydropower. It consists of upper and lower reservoirs. During off-peak hours, the upper reservoir is refilled with water pumped from the lower reservoir during peak hours. This pumped storage facility serves as a peaking station [19].

Small hydro technology performance sits at 37.7% as reported in 2020 by DoE (see figure 2.4).

## **2.4 The Concept of Intermittency Applied to Renewable Energy**

Intermittency, as described by the dictionary, is the occurrence of anything that ceases for a period and then resumes. In the context of renewable energy, it indicates that renewable energy power is only available when the renewable resource, such as the sun or wind, is available and ceases when the resource is not.

The recent academic and business discourse has focused on the issue of renewable energy integration into the electricity grid. Currently, penetration levels are still manageable for most grids. Due to its intermittent nature, renewable energy may pose extra challenges to the system as its penetration rate rises [20].

One of the intending solutions to this problem has been identified by [20] as the adoption of energy storage.

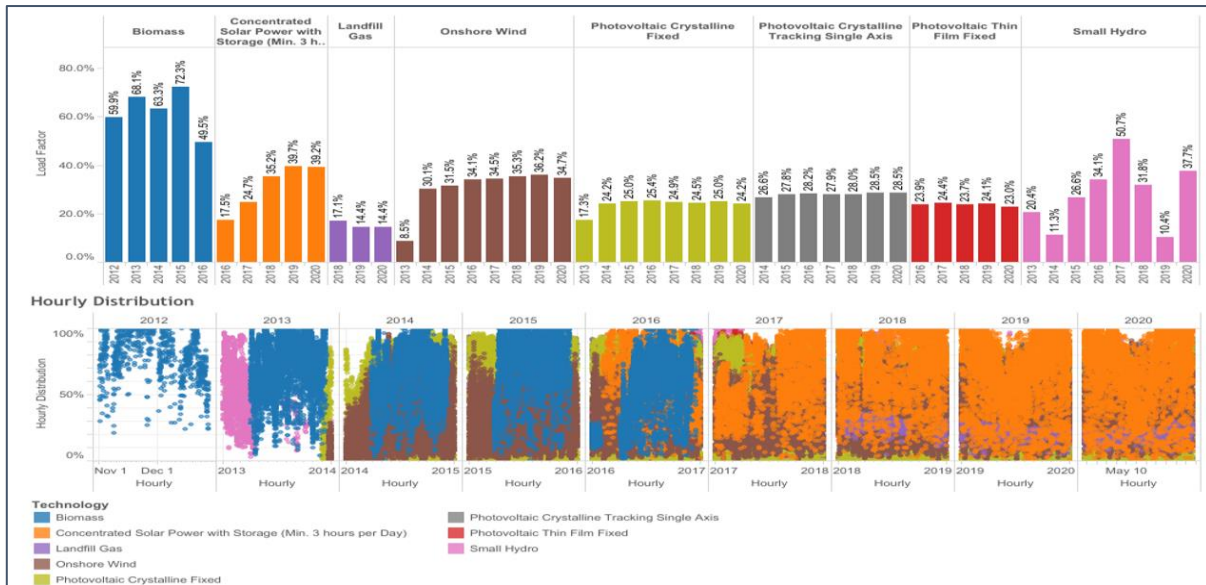


Figure 2.4: Hourly Electricity Production and Annual Load Factors [7]

Figure 2.4 shows hourly electricity production and annual load factor for all renewable technologies employed in South Africa since 2012 until 2020.

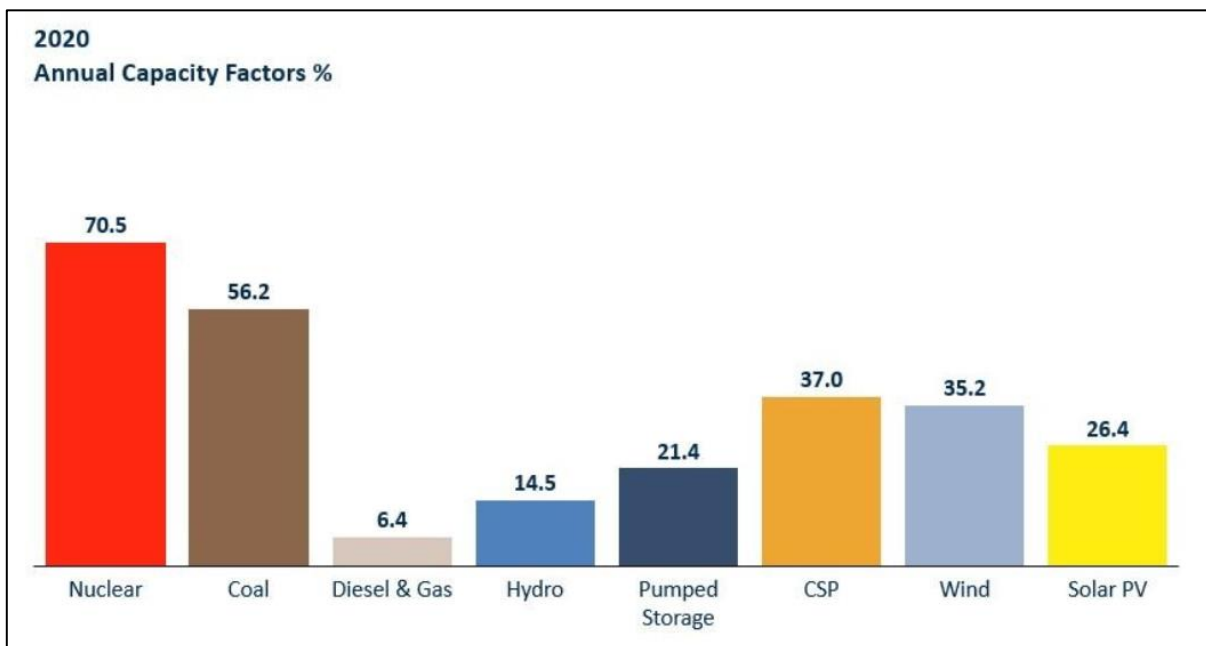


Figure 2.5: Annual Capacity Factors per Source in South Africa [7]

Figure 2.5 compares renewable capacity factors for different energy generation technologies in South Africa. As may be deduced from the graph, nuclear power ranks highest among all technologies, followed by coal; hence, both are employed as base load technologies. CSP beats other renewables due to its capacity for energy storage. Numerous experts have suggested that the addition of energy storage facilities to the grid might minimise the intermittent nature of wind and solar electricity and vastly boost their capacity factors. Furthermore, The deployment of energy storage systems (ESSs) is an important avenue for maximising the energy efficiency [7].

y of a distribution network, and their appropriate placement, sizing, and operation can improve the overall network performance.[21]

## **2.5 Challenges of Renewable Energy for Ancillary Services**

Ancillary service is defined as a service other than primary energy that generators or customers deliver to the system operator [22]. These are required to ensure a dependable, stable, and secure transmission of electricity from generation to customers in terms of frequency, voltage, supply continuity, and restoration [22].

Electric power system operation entails a complex process of forecasting electricity demand and scheduling and operating a large number of power plants to meet that varying demand [23]. Transmission system operator (TSO) dispatches reserves according to the scheduling and dispatch rules as far as possible while adhering to control of system frequency under normal and abnormal conditions procedure.

Conventionally, ancillary services are provided by large power plants and equipment with adequate capacity and capability [24]. Concerns are being raised as a result of the intermittent nature of renewable energy, which complicates the need for the power system to continuously balance generation with fluctuating load demand [25].

## **2.6 Challenges of Renewable Energy Curtailment**

Curtailment is described as the act of limiting, reducing, or restricting something. On a power system, generation and load should constantly be balanced. Excessive system generation will result in high system frequencies, which may result in system instability. The daily load demand profile is essentially same.

Figure 2.6 shows a typical South African day load profile. There is a moderate surge in the morning due to people waking up and getting ready for the day, followed by a moderate peak in the afternoon and a higher peak in the evening. Evening peak is the most demanding time for the South African energy network.

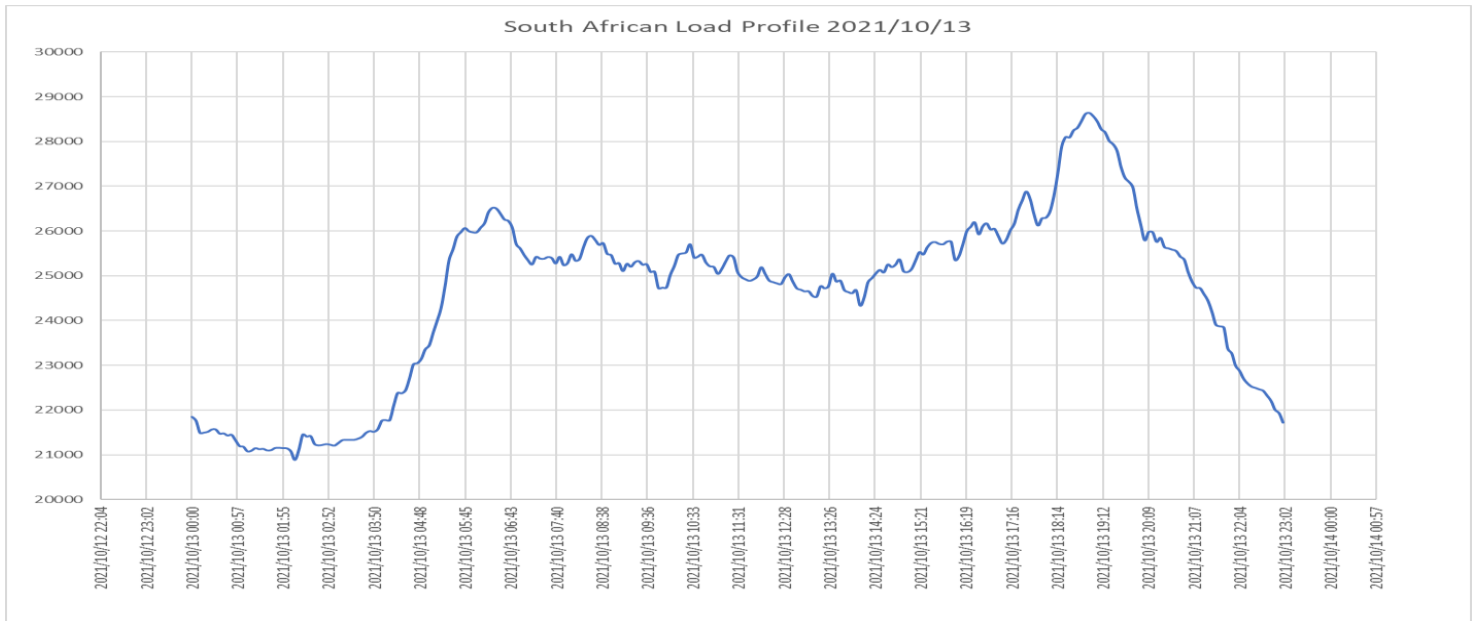


Figure 2.6: South African Typical Daily Load Profile

Data Source: Eskom Transmission Energy Management System Evolution (TEMSE)

Peak demand periods in South Africa occur in the morning from 6 AM to 9 AM and in the early evening from 5 PM to 9 PM. Early in the morning (00:00-04:00), when demand is at its lowest, Eskom is sometimes compelled to reduce generation to maintain system equilibrium. Wind generation is curtailed by National Control from a distribution standpoint [26].

This typically occurs between midnight and four in the morning, when the system load is severely low since most people are asleep and less economic activity are occurring. To stabilize the system, it is necessary to reduce wind generation by up to 10 percent of the available capacity or eliminate it entirely. This is when the issue of energy storage is brought up as a feasible solution.

## 2.7 Battery Energy Storage System

According to the grid code, battery energy storage systems (BESS) consist of batteries, chargers, power converters, and other equipment connected to a single point of connection (POC) on the NIPS for the purpose of storing electrical energy in the batteries during charging process and discharging the stored electrical energy when necessary[27].

Smart Grid systems, energy storage, and non-dispatchable renewable energy technologies based on wind and solar PV have a complementary relationship [28]. The traditional power delivery model is being disrupted by technological advances in energy storage, and more renewable energy can be harvested even though its production may occur during periods of low demand. The development of storage technologies, such as battery systems, compressed air energy storage, flywheel energy storage, hydrogen fuel cells, etc., can address this issue, particularly in the context of South Africa, where over 6 GW of renewable energy has been introduced, but the power system lacks the necessary storage capacity or flexibility [5].

It was discovered that the effectiveness of storage technology in mitigating the intermittency of renewable power depends on the ramp rate of the technology, the response delay time, the duration of storage, the maturity of the technology, the installation cost, the efficiency of the technology, its environmental impact, and the suitability of the site's topology. Consequently, no single storage technology can provide a comprehensive solution for mitigating the impact of intermittent wind power on the grid. The effectiveness of storage technology depends on the hybridization of storage technologies, which varies according to cost and technical requirements [20].

On the Eskom phase 1 & 2 BESS implementation project, ancillary service (AS), energy support (ES), load shaving, and reactive power control are expected to be the primary use cases. South Africa is still in its infancy in terms of both renewable energy implementation and complementary BESS storage [14].

Currently, there is no BESS installed on the South African power grid. Currently, mechanical storage facilities such as Palmiet, Ingula, and Gariep pumped storage facilities serve as peaking stations and perform the function of storage. The more renewables are connected to the grid, the greater the need for scalable storage, as excess power must be stored during off-peak hours for use during peak hours.

Figure 2.7 depicts a typical BESS system, including the battery, conversion system, protection, and AC transformer. Bess operates in four quadrants namely, Charge (consume), discharge (generate), Import reactive power (Inductive), Export reactive power (capacitive).

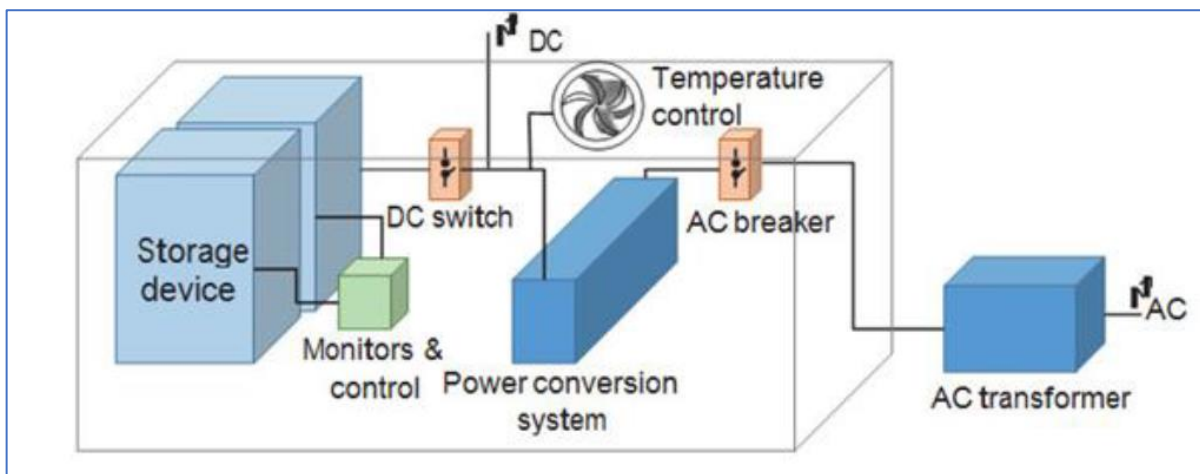


Figure 2.7 Battery Energy Storage System[9]

## 2.8 Regulatory Requirements for BESS in South Africa

*“The National Energy Regulator of South Africa (NERSA) is a regulatory authority established as a juristic entity in terms of section 3 of the National Energy Regulator Act, 2004 (Act No. 40 of 2004). NERSA's mandate includes the administrative authority for the South African Grid Code (‘the Grid Code’) in terms of sections 14(t) and 35(1) of the Electricity Regulation Act, 2006 (Act No. 4 of 2006) (‘the Act’). In accordance with the Act, NERSA shall ensure that the Grid Code is developed, implemented and complied with for the benefit of the electricity supply industry (ESI)” [29].*

*“The primary objective of the Grid Connection Code for the Battery Energy Storage Facilities (BESFs) Connected to the Transmission System (TS) or Distribution System (DS) in South Africa is to specify minimum technical and design grid connection requirements for battery energy storage facilities connected or seeking connection to the South African TS or DS. The BESF Grid Code, version 5.2 (BESF Code)[29] will be used together with other applicable requirements of the Grid Code that include Renewable Energy Power Plant (RPP) Code, Transmission Code, Distribution Code, System Operation Code and Scheduling and Dispatch Rules (SDR), as compliance criteria applicable to BESF Code. The approved BESF Code is regarded as a living document, which means the need arises after the approval of this version 5.2, it may be subjected to amendments that will be interrogated by the Grid Code Advisory Committee (GCAC) in terms of the Governance Code before they are submitted to the Energy Regulator for approval” [29].*

## 2.8.1 BESS Categories

“Compliance with grid connection code is applicable to the BESS depending on its nominal AC active power and, where indicated, the nominal power at the POC”.

There are three categories of BESS as listed in the BESF Code [29], namely Category A, B & C. These categories differ as listed in Table 2.4 below:

Table 2.4 Main Categories of BESS Facility [29]

Category	Rated power of BESS Facility		
A	>0	to	<1MW
A1	>0	to	< = 13.8kW
A2	= > 13.8 kW	to	< 100 kW
A3	= > 100 kW	to	< 1MW
B	= > 1MW	to	< 20 MW
B1	= > 1MW	to	< 5MW
B2	= > 5MW	to	< 20MW
C	= > 20 MW	-	-

Note: For a category A BESF connected to multi-phase supplies (two or three phase connection at the POC), the difference in installed capacity between phases may not exceed 4.6kW per phase

BESF Grid code also requires BESS categories to have capabilities as shown on Table 2.6:

Table 2.5 BESS Categories [29]

Function	A1	A2	A3	B1	B2	C
Power Factor Control	-	-	✓	✓	✓	✓
Reactive Power Control	-	-	-	✓	✓	✓
Voltage Control	-	-		✓	✓	✓
Remote Control Capability	-	-	✓	✓	✓	✓

This thesis will not consider much information for category A. As the BESS that is studied is of Category C. Requirements for category B and C are similar, that means that category B will be covered by default.

## 2.9 BESS Opportunities for South Africa

*“Solar PV, wind, and CSP with storage offer the possibility of diversifying the electricity mix, producing distributed generation, and providing off-grid electricity. Renewable technologies also have enormous potential for new industry development, job creation, and value chain localization”[5].*

Because it facilitates the integration of wind and solar PV plants into the grid, battery storage is critical for the key objectives of promoting low-carbon economic growth. BESS is a game-changing technology that would improve energy utilization from the Renewable Energy Independent Power Producers (REIPP) program's rapidly increasing Variable Renewable Energy (VRE) sources. Battery energy storage from VRE is a promising technology that has yet to be commercialized or demonstrated at the scale desired in South Africa and Sub-Saharan Africa [9].

The rationale for implementing BESS is twofold: first, to increase the share of VRE in the power mix, and second, to improve local and overall system reliability, allowing more customers to be connected to the grid. As the proportion of VRE2 (wind and solar PV) in the South African power system grows, so does the need to ramp up quickly.

*“The overarching goal of BESS is to save and store excess electrical output as it is generated, allowing for a timed release of electricity to the grid when capacity is needed [25]. BESS therefore provides flexibility in the efficient operation of the electricity grid through decoupling of the energy supply and demand”[30].*

### 2.9.1 Peak Shaving/Energy Arbitrage

Peak Load Shaving is like load levelling, but it is primarily used to reduce peak demand (see Figure 2.8). Peak shaving can reduce peak energy costs when peak load coincides with peak energy prices [31]. Energy arbitrage is also referred to as time shifting, in this application electricity is stored on lower power price periods and is used or sold during peak periods.

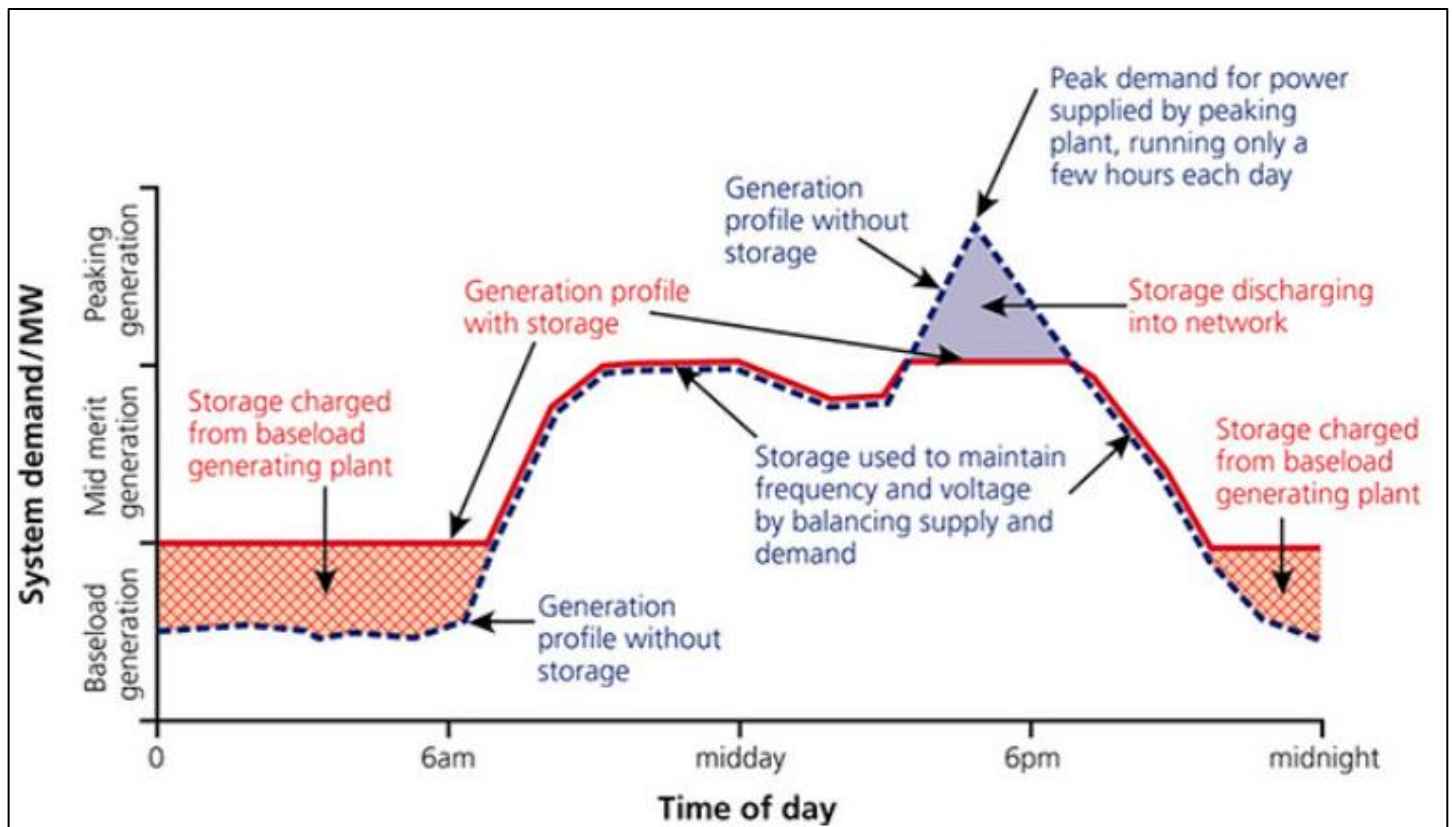


Figure 2.8 The Principle of Peak Load Shaving [31]

### 2.9.2 Voltage Support

“Voltage support is reactive power absorption or supply to bring voltages within planning limits, delaying network upgrade [32] and eliminating network bottlenecks. According to the authors in [33], the integration of distributed energy resources is a novel strategy for enhancing system capacity, stability, feeder voltage, supply quality, and reliability. In [33], the authors examine the energy requirement for distributed energy resources with battery energy storage for voltage support in three-phase distribution lines. “In addition, [33] specifies that the battery size was estimated based on the worst-case scenario (during peak load) of daily energy demand, assuming that in the worst-case scenario, the battery discharges only once per day to satisfy a lower voltage threshold.”

### 2.9.3 Wind Curtailment Mitigation

Due to an excess of generation on the system, the system frequency may rise above 50.2 Hz during low load conditions [26]. To keep the frequency under control, Eskom-owned generators will be instructed to reduce their output to a minimum generation output [26]. It is possible that wind turbines will generate during these low loading conditions, contributing to the excess generation [26]. When all other conditions for reducing generation output have been met, a curtailment instruction will be issued to assist with frequency control [26].

According to the Power Purchase Agreement, Eskom pays for each megawatt produced by the generator of the Independent Power Producer. Additionally, Eskom is charged for not utilizing the MW while the IPP is available to generate. Eskom will continue to pay for the MW that would have been generated during the curtailment period. It is essential to submit the correct curtailment instruction and cause, as there are various charges for curtailing generation due to an excess of generation on the system versus localised network constraints [26].

### 2.9.4 Bottleneck Mitigation on Constrained Networks

Grid congestion occurs when there is insufficient capacity to deliver electricity without exceeding thermal, voltage, and stability limits set to ensure reliability. Due to budget constraints, some utilities postpone strengthening projects, resulting in some constraints during peak conditions. *“For example, the town of Ashton is fast developing with several mega-projects that are visibly taking place. The Ashton network is becoming constrained due to the imminent thermal limit exceedance of the Boskloof-Klipdrif 132 kV overhead line and the 132kV minimum voltage violation at Ashton 132/66 kV Substation. The completion date for the conventional strengthening project, namely constructing a 132 kV Kingbird line from Bacchus Main Transmission Substation (MTS) to the Klipdrif Substation is unknown at this stage. As a result, the entire network is embargoed for new customer load applications”* [34].

## **2.10 Placement of Grid Scale BESS**

*“Energy utility decision-makers in South Africa require a dependable method to evaluate energy storage systems (ESSs) and their optimal geographical locations”* [35]. Therefore, literature has been developed to segment and clarify the various aspects of ESSs for the decision maker. Authors in [35] reviews the complexity of optimal energy storage location by examining the available literature. Literature indicates that the location of BESS can have a significant impact on its effectiveness. BESS is anticipated to become an integral part of the permitted Wind Energy Facilities (WEFs), allowing for energy storage and extending the generation period of WEFs [30].

### **2.10.1 Placement of BESS to mitigate intermittency by smoothing of wind energy**

Rapid and random changes in wind speed render wind power an irregular and inconsistent energy source when connected to the grid, posing a variety of protection, power quality, and generation dispatch control challenges [36]. Due to these impediments, effective intermittent smoothing strategies for wind energy outputs are required to mitigate these issues. Different literatures have been reviewed and it has been found that battery energy storage system is the most suitable and effective approach, provided that an effective control strategy is available for optimal utilization of BESS to obtain smooth output [36].

### **2.10.2 Placement of BESS to mitigate wind generation curtailment during the time of low load and excess generation**

Areas rich in renewable energy resources are frequently dispersed and located in remote regions where local energy consumption is low, particularly in the early morning [37]. That is the case with South Africa, as renewable energy is peaking up pace in the Northern Cape, Western Cape, and Eastern Cape. These regions often encounter severe wind and solar curtailment [37].

Reference [38] emphasizes how renewable energy generation is being curtailed as a "new norm." Furthermore, it reports that between 2010 and 2016, approximately 150.4 million megawatt hours (MWh), or up to 16% of total wind degeneration, was abandoned. The opportunity cost was estimated to be more than \$1.2 billion (R20.4 billion at 2018's exchange rate of R17/\$). Figure 2.9 depicts wind curtailment volume versus wind electricity generation.

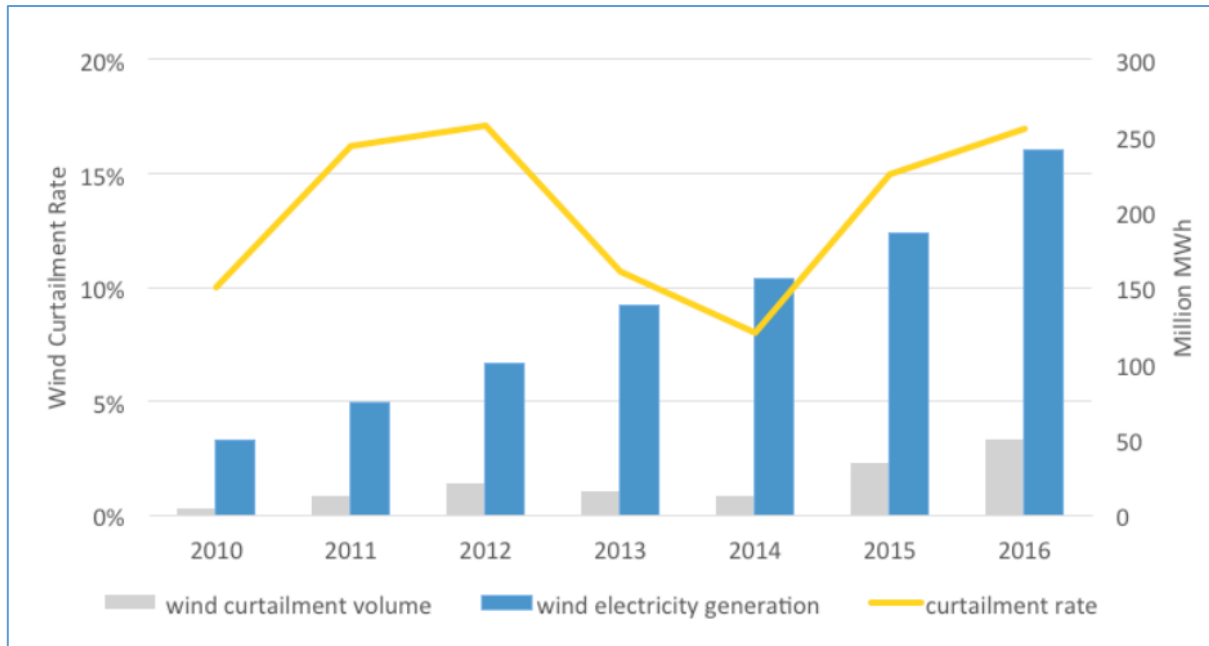


Figure 2.9 Wind Power Installation and its increase in China (2010-2016) [38]

Figure 2.9 shows that the curtailment rate has been on an upward trend since 2014. Every year, that is the power that is thrown away.

### 2.10.3 Placement of BESS for Voltage Support

Typically, distributed energy resources (DER) are located near the point of consumption, at the distribution level. DERs are able to inject various quantities of active and reactive power into the grid to satisfy feeder voltage profile[33]. The authors in [33] argue that a battery storage system can be constructed for a distribution feeder to complement DER that may not be accessible during peak hours.

### 2.10.4 Placement of BESS for Bottleneck Mitigation

There are a variety of causes for energy network bottlenecks. In the case of China during the infancy of wind development (2010-2011), this was owing to a mismatch between wind installation and transmission capacity. As was the situation in South Africa, wind farms began construction prior to constructing the essential infrastructure and strengthening the grid [38]. The mismatch between demand and supply is another factor that applies to South Africa [38]. During the early morning hours (00:00-04:00), when demand is low, wind generators produce a significant amount of electricity. The produced energy must then be transferred and routed over high voltage transmission lines. The deferral of projects owing to a lack of funds for network strengthening is a further point will be discussed further. Although it is well-known that the network must be strengthened, no funds are available for that purpose.

## 2.11 Global Lessons Learned in Promoting Renewable Energy with BESS

*“Adopted by all United Nations Member States in 2015, the 2030 Agenda for Sustainable Development presents a blueprint for peace and prosperity for people and the planet, now and in the future. In 2015, leaders from 193 nations gathered to discuss the future” [39]. “At its core are the seventeen Sustainable Development Goals (SDGs), which represent an urgent call to action by all countries, developed and developing, in a global partnership. They acknowledge that eradicating poverty and other deprivations must be accompanied by initiatives that promote health and education, decrease inequality, and stimulate economic growth, all while addressing climate change and preserving our oceans and forests” [39].*

SDG 13 is concerned with taking immediate action to prevent climate change and its consequences [39]. As a result, member states are adopting clean energy solutions towards 2050 where some of them have committed to be 100% renewable power suppliers, like Denmark.

As a result, member nations are embracing clean energy solutions in preparation for 2050, with some, such as Denmark, committing to be 100 percent renewable power suppliers.

Since 1990, Denmark has decreased its adjusted greenhouse gas emissions by more than 30 percent. With existing measures in place, the Danish Energy Agency estimated that emissions will be reduced by nearly 40% by 2020, exceeding Denmark's legally obligatory EU commitment of 34%. Denmark stands at 53% reduction (2021 data)[40]. Denmark's power system has the largest proportion of non-hydro renewables of any in the world[41].

The Danish government has established numerous goals for the expansion of the energy sector. Continuing the transition to a low-carbon energy sector in a cost-effective manner, retaining Denmark's leadership in several low-carbon technologies and systems, and ultimately achieving self-sufficiency in renewable energy by 2050. The Danish Energy Model demonstrates that the transition to energy in the twenty-first century is both feasible and affordable[41]. Danish grid lacks BESS because to the belief that it is an expensive alternative compared to the hydro, nuclear, and coal they buy from Sweden, Norway, Germany, and the Netherlands.

## **3 METHODOLOGY**

### **3.1 Introduction**

Based on the literature studied as well as our experience with distribution network analysis, for the purpose of answering the research questions in chapter 1 and to accept or not accept the hypothesis of whether BESS will improve the performance of Eskom Distribution networks, Eskom BESS sites have been chosen to be simulated and analysed using DigSilent Powerfactory.

This method was chosen because an opportunity presented itself when Eskom introduced the BESS pilot project which is composed of two phases as explained in chapter 1. Planners conducted investigations and ran simulations to determine which sites will be chosen and for which use case depending on the need of the Distribution network as well as system operator (SO) and planning reports were compiled and sent out to stakeholders. It was decided to follow a similar method to simulate the BESS for operations using a historical data of the networks in question.

The first site Skaapvlei substation (S/S) is located near a wind farm, the second one Hex, has no renewable energy located nearby. The first site is situated in the West Coast while the second one is in the Boland. The wind farm on the 1<sup>st</sup> is rated at 100 MW and connected at 132kV voltage level from Sere Wind Farm. The BESS of 80 MW (320 MWh) per day is planned to be connected by the end of 2022 at Skaapvlei and BESS of 20 MW (80 MWh) per day for Hex. Preliminary studies have been done to assess the suitability of these sites and the maximum BESS size (MW/MWh) to be connected based on the identified primary use-case [14].

These projects were constructed via Engineering, Procurement and Construction (EPC) contracts due to scale and complexity. Hex BESS EPC was awarded to Hyusong Heavy Industries (South Korea) and Skaapvlei BESS EPC to Pinggao Group (China). An example of a single line plant model is shown on annexure A.

### **3.2 Data Collection**

Hourly historical actual load data and generation profiles for the in-feeds as well as load centres were obtained from MV90, an approved and licenced data repository for Eskom Distribution network. The profiles data were then injected as profile characteristic for loads and generation on the network being studied.

### **3.3 Key Assumptions**

Currently, South Africa is on its execution phase pertaining to the integration of BESS on Eskom Grid. There is no primary data available with BESS connected. A sample of the current network will be simulated in comparison with the future network when BESS is integrated, and the results will be discussed.

### **3.4 Study Period**

A study period of 2021 was chosen as it is the period post COVID-19 pandemic. 2021 is the most accurate data compared to 2020 because 2020 was the year of the pandemic as a result lockdown was implemented, it was not business as usual, thus 2020 data would be skewed. The grid is changing every year and 2021 is the closest year to 2022. Eskom always recommends using the most recent available data because the distribution network dynamics are changing as renewable energy is integrated.

### **3.5 Network Modelling**

DigSilent Powerfactory, a power system simulation tool (PSST) used at Eskom, typically by planning and operations engineers was used to simulate the behaviour of both Skaapvlei and Hex related network under 2 scenarios:

- (1) BESS for wind curtailment mitigation.
- (2) BESS for voltage support.

This simulation tool has an existing functionality to model Quasi-Dynamic Simulation (QDSL) for BESS. DigSilent Powerfactory is also an approved modelling simulation tool in Eskom [15].

To simulate on DigSilent an existing master project casefile was used. This casefile contains a network where BESS will be integrated. This network contains characteristics, power rating, voltage levels, line lengths, fault levels and voltage settings of this network. The network was checked and verified to be the true reflection of what is on site. Network load and generation profiles (hourly resolution) for the year 2021 were obtained from MV90, an Eskom approved data repository tool. The casefile was then prepared for QDSL.

QDSL without BESS connected on the networks was run and results stored in an excel format for analysis. The same was then done with BESS connected for all three scenarios.

### **3.6 BESS Modelling**

A dynamic simulation model is available in DigSilent Powerfactory for dynamic studies, each component of a BESS, including the parametric functions for the battery management system and inverter are required to be populated. This level of modelling is only possible if precise manufacturer specifications are obtained for a particular battery type, control system and inverter system. These details are not readily available during the planning stage which makes the usage of this specific model inappropriate unless the required information is available or populated generically. The development of generic dynamic models is possible[10].

DigSilent Powerfactory is used in conjunction with an excel spreadsheet where the size, capacity and duty cycles of BESS based on various applications and characteristics are specified [10]. It allows users to input loading/generation data, operation modes of the BESS trigger points and BESS parameters and characteristics as well as allowing one to simulate the charging and discharging of the BESS system [10].

Battery energy storage systems operate over time and operate in different modes (charge/discharge); hence it is important for the simulations and the network analysis to be time based. It is therefore required that the network models be setup and that the analysis be done via the quasi-dynamic simulation functionality in DigSilent Powerfactory, which completes a series of static load-flow simulations spaced in time[10].

In analysing the integration parameters and the applicable benefits that battery energy storage systems can provide to the utility, power system models and a methodology of analysing the power system to evaluate the impact of a BESS is required. This will ensure that power systems engineers will have the capability of modelling and simulating BESS on the networks, and will be capable of analysing the integration effects accordingly, in order to make informed decisions to ensure the correct operation and sustainability of these systems on the network[10].

Unlike a typical generator, battery energy storage systems have three active states of operation, which is a charging state, a discharging state, and an idle state. In the charging state, the BESS acts as a load, whilst in the discharging state, the BESS acts as a generator. These two states of operation have differing effects on the network and are therefore required to be assessed accordingly[10]. Table 3.1 shows BESS planning limits for charging and discharging states.

Table 3.1 BESS Planning Operating States and Limits [14]

ASSESSMENT CRITERIA	BESS OPERATING STATE	LIMITS APPLIED
<b>Network Voltage Limits</b>	Charging and discharging	(0.95 -1.05) pu
<b>Network Thermal Limits</b>	Charging and discharging	Normal Rating
<b>Rapid Voltage Change</b>	Charging and discharging	5% of Nominal Voltage
<b>Load Rejection</b>	Charging and discharging	(0.9 - 1.1) pu

As can be seen from Table 3.1, BESS cannot charge while the voltage on the network is 0.95pu or below, BESS cannot charge nor discharge while the line is loaded above its normal thermal rating, BESS cannot charge nor discharge if it causes voltage change of more than 5% of the nominal value and BESS load needs to be rejected if voltage is outside the 0.9 and 1.1 per unit range.

## 3.7 Grid Code Requirements for BESS

### 3.7.1 BESS Normal Operations States and Limits

BESS operating limits as should be seen at the POC for categories B&C are listed on Table 3.2 for different voltage levels from 765kV to 11kV. BESS should be able to continuously operate within these limits at the POC.

Table 3.2 Minimum and Maximum Operating Voltages at POC [29]

Nominal Voltage, $U_n$ [kV]	$U_{min}$ [pu]	$U_{max}$ [pu]
765	0.95	1.05
400	0.95	1.05
275	0.95	1.05
220	0.95	1.05
132	0.9	1.0985
88	0.9	1.0985
66	0.9	1.0985
44	0.9	1.08
33	0.9	1.08
22	0.9	1.08
11	0.9	1.08

Table 3.2 shows that for BESS connected on a 765kV network should operate between 0.95 and 1.05 per unit of a nominal voltage. This region is called normal operating region. Same applies to voltages up to 11kV as listed on the table.

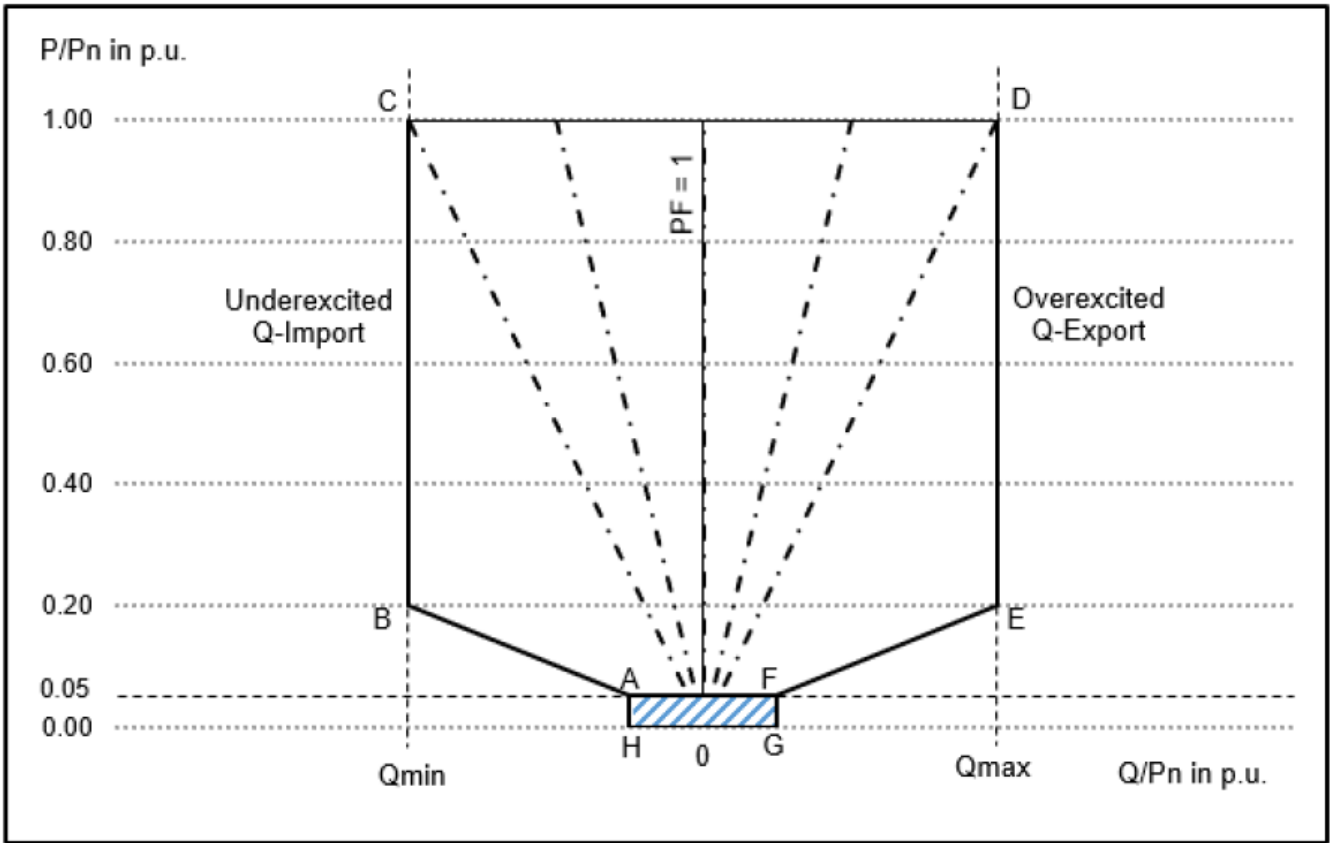


Figure 3.1 Reactive Power Capability Curve [29]

“The reactive power capability of BESS categories B and C is illustrated in Figure 3.2. According to the grid code, these facilities must be able to continuously modify their reactive power output at the Point of Connection (POC) within the operational region denoted as ABCDEF. This adjustment should occur within the voltage-dependent range specified by  $Q_{min}$  and  $Q_{max}$ , as displayed in Figure 3.2. The voltage ranges,  $U_{min}$  to  $U_{max}$ , are defined in Table 3.2.” [29].

“For BESS Category B, the reactive power range is determined as  $Q_{min} = -0.228P_{na}/P_{nd}$  and  $Q_{max} = 0.228P_{na}/P_{nd}$ . This corresponds to a power factor range of 0.975 when operating at rated active power,  $P_{nd}$  and  $P_{na}$  [MW], and it results in a lagging power factor of 0.975.” [29]

“For BESS Category C, the reactive power range is  $Q_{min} = -0.33P_{na}/P_{nd}$  and  $Q_{max} = 0.33P_{na}/P_{nd}$ . This translates to a power factor range of 0.95 when operating at rated active power,  $P_{nd}$  and  $P_{na}$  [MW], and it fluctuates between leading and lagging, with a power factor of 0.95.” [29]

“It’s important to note that the continuous operating range may also be constrained by a minimum stable active power requirement, which should exceed the line labelled AF in Figure 3.1.” [29]

“If BESS of category B&C is not producing power, or if power level is below 5% of the rated active power, the reactive power must be within a tolerance of +/- 5% of related power that is within the region AFGH” [29].

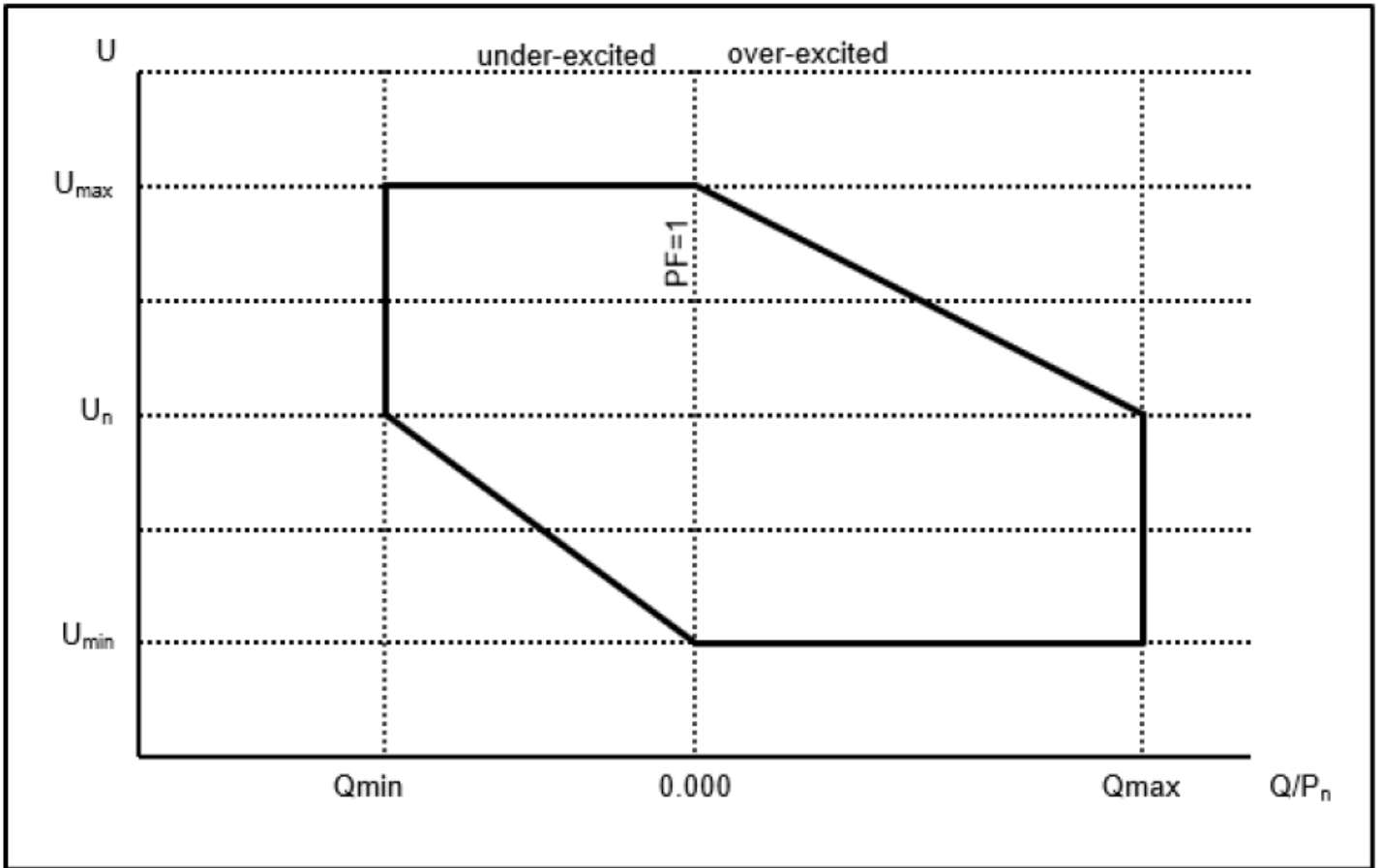


Figure 3.2 Voltage dependence of reactive power capability for BESF of category B and C [29]

Figure 3.2 shows the voltage dependence of reactive power. BESS operation should be within the bounded area. As mentioned above, this adds some limits on the operating area between  $Q_{min}$  and  $Q_{max}$ .

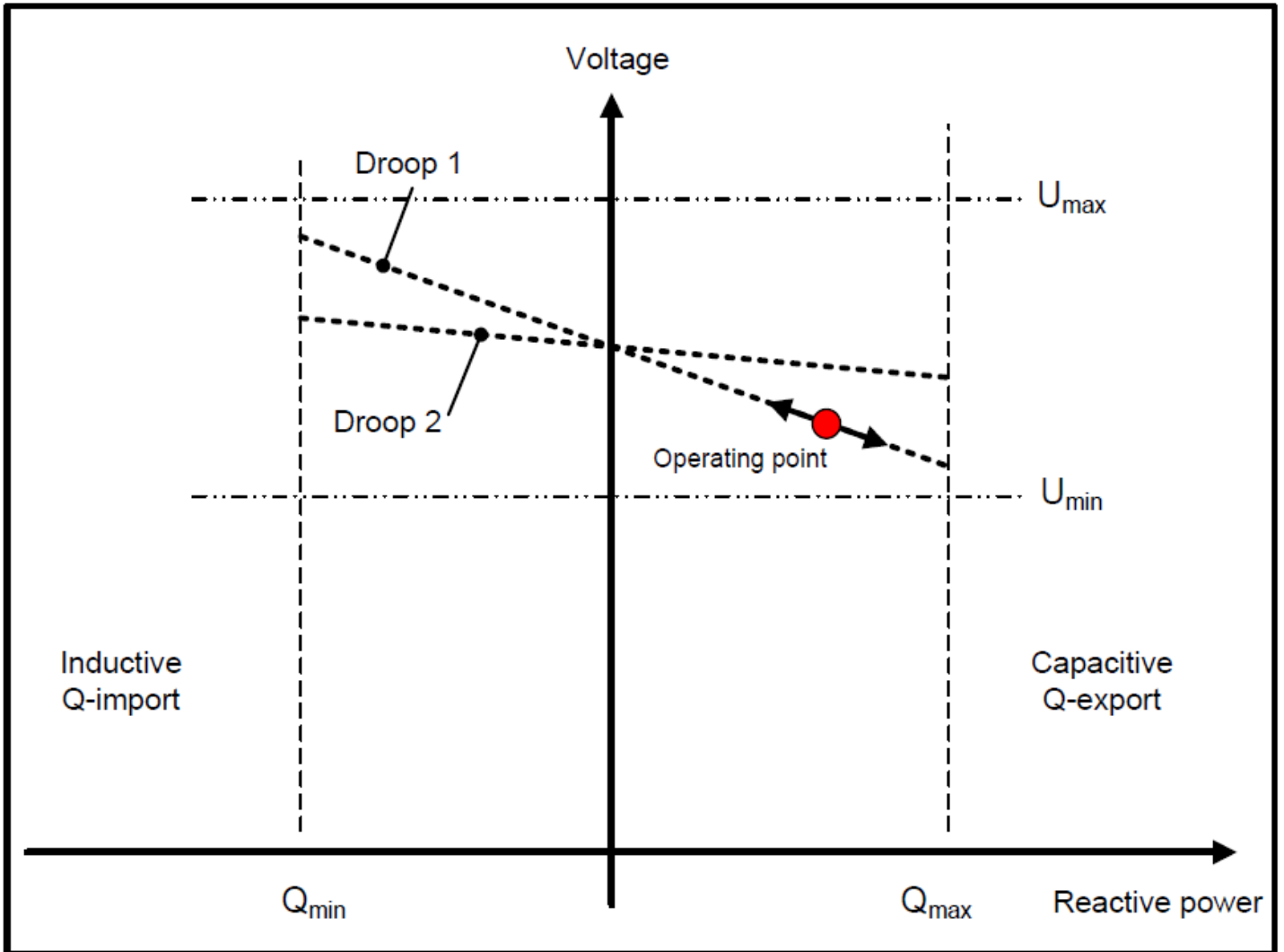


Figure 3.3 Voltage control for BESF of Category B and C at the POC [29]

Voltage control for BESS category B&C is shown on figure 3.3. "The voltage setpoint and voltage droop setpoint shall be received by the BESF of categories B and C from the SO or NSP." BESF of categories B and C must be capable of automatic voltage control based on a droop function, as indicated in Figure 3.3, within their reactive power capacity range. In this application, droop is defined as "the voltage change (p.u.) generated by a change in reactive power (p.u.)."[29]

"Following a little disturbance, the BESF must adjust its reactive power so that the voltage equals the required voltage within 0.2 percent of the voltage setpoint and droop setpoint. The accuracy shall be measured as a percentage of the rated voltage as a variation between the actual voltage and the necessary voltage. Unless otherwise negotiated with the SO or NSP, the settling time should be between 10 and 30 seconds." [29]

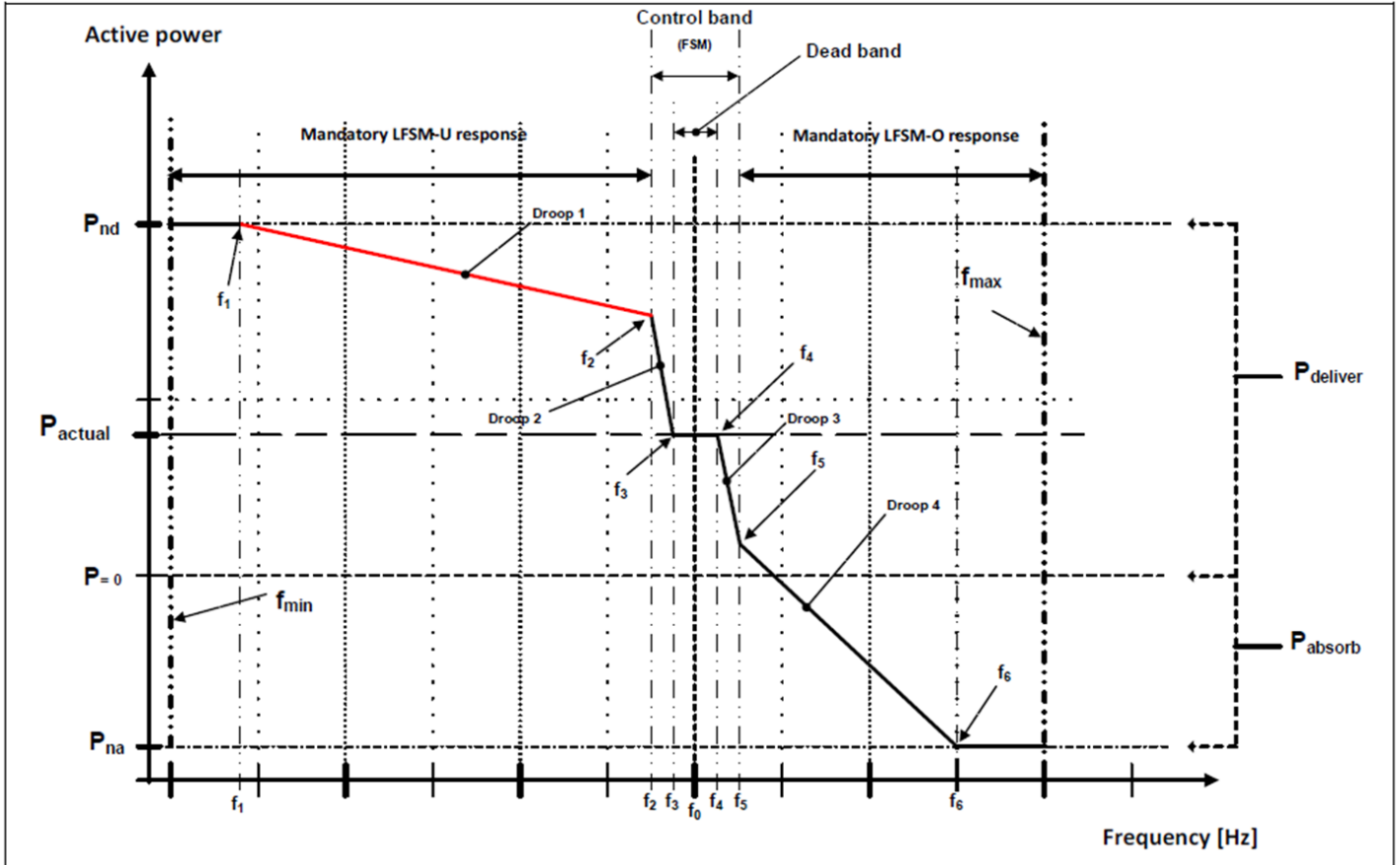


Figure 3.4 Normal/ contracted frequency range [29]

“BESFs in categories B1, B2, and C need to have the ability to offer power-frequency response, which is depicted in Figure 3.4 with droop 2 and droop 3. The frequencies  $f_2$  and  $f_5$  are crucial in establishing the control band (FSM) for contracted ancillary services. Furthermore,  $f_2$  and  $f_5$  serve as reference points to indicate the frequency limits outside of the control band, where autonomous low and high-frequency responses are necessary.”

“The frequency points  $f_3$  and  $f_4$  serve to create a dead band within the control band. The System Operator (SO) has the authority to determine and communicate to the BESF, either directly or through an agent, the necessary droop settings for controlling the system within the specified frequency points. Additionally, the frequency response control function can be enabled or disabled within the frequency range from  $f_{min}$  to  $f_{max}$ .” [29]

### 3.7.2 BESS Abnormal Operations States and Limits

“BESFs in Categories A3, B1, B2, and C must be constructed to endure voltage fluctuations, as indicated in Figure 3.5. They are required to provide or absorb reactive current during faults, as depicted in Figure 3.5, without disconnecting from the system. Specifically, they need to withstand voltage drops to zero, measured at the Point of Connection (POC), for at least 0.150 seconds without disconnecting. Additionally, Category C

BESFs must be capable of withstanding voltage peaks of up to 120% of the nominal voltage, measured at the POC, for a minimum duration of 2 seconds without disconnecting, as shown in Figure 3.5.” [29]

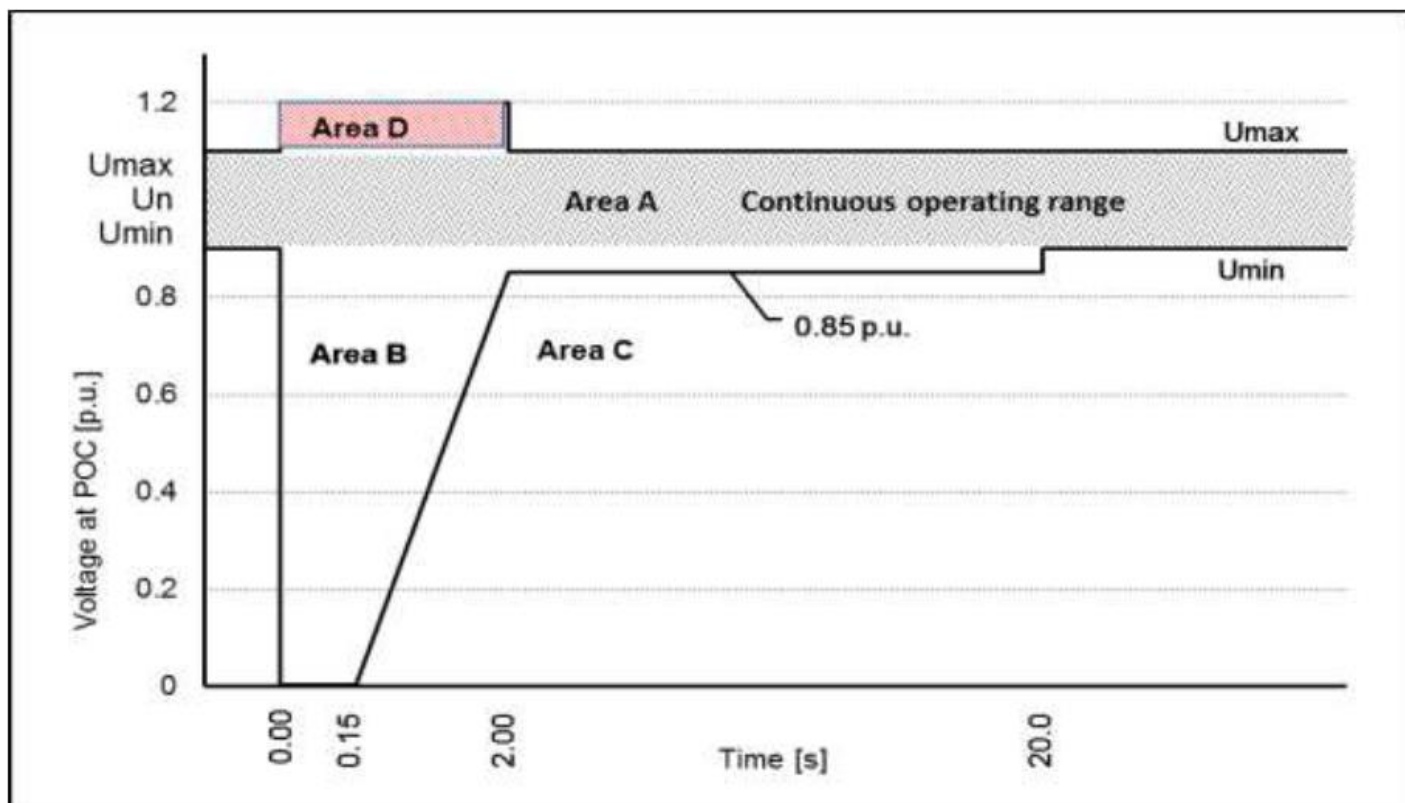


Figure 3.5 Voltage Ride through Capability for the BESF of Category A3, B1, B2 and C. [29]

All BESF categories are required to respond to frequency deviations in the National Interconnected Power System (NIPS) to help stabilize the grid's frequency. However, specific disconnection criteria apply:

1. If the NIPS frequency remains above 51.5 Hz for more than 4 seconds, a BESF is permitted to disconnect from the grid.
2. If the NIPS frequency drops below 47.0 Hz for longer than 200 milliseconds, a BESF is allowed to disconnect from the grid.

However, BESFs must remain connected to the NIPS during rate of change of frequency (RoCoF) events with values up to and including  $\pm 2.5$  Hz per second, as long as the system frequency stays within the minimum operating range depicted in Figure 3.6. [29]

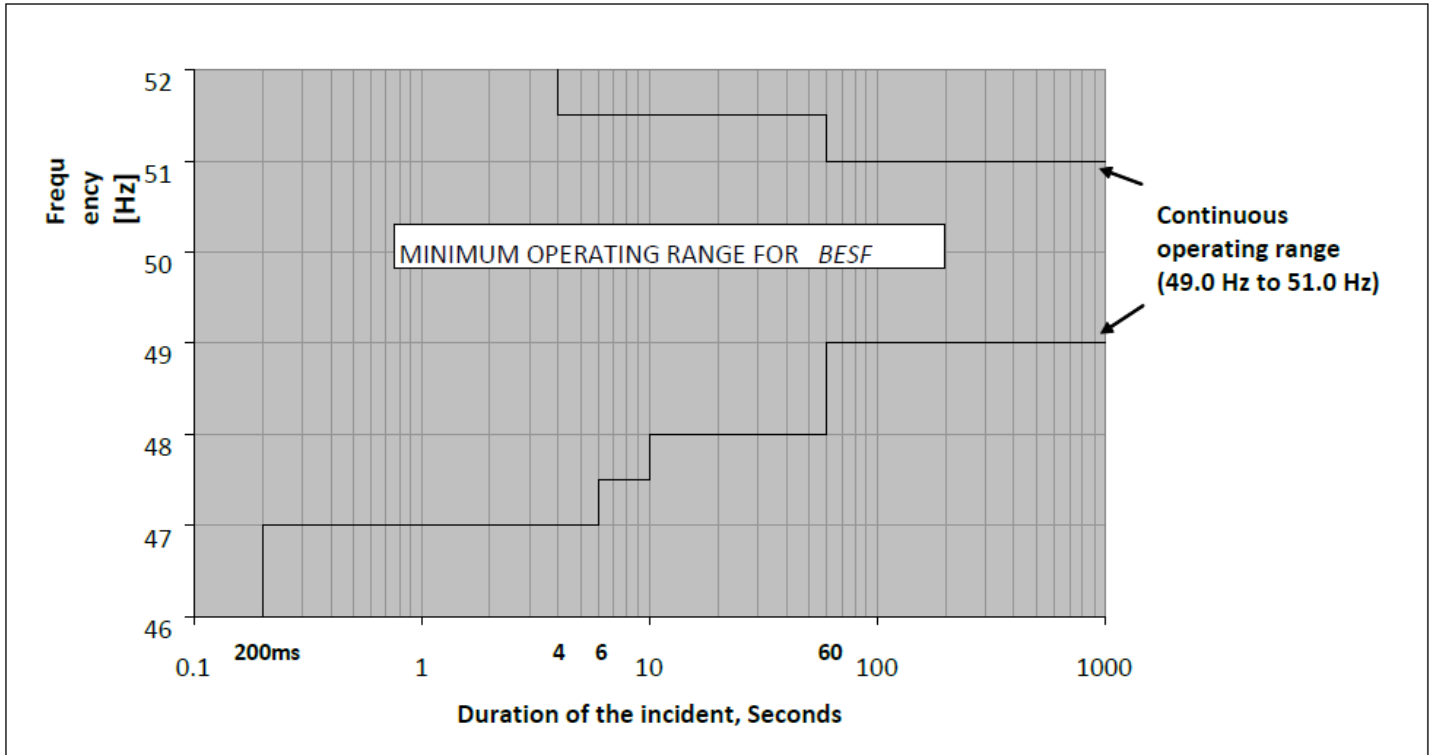


Figure 3.6 Minimum frequency operating range for a BESF (during a system frequency disturbance) [29]

## 4 BESS SITE SIMULATION AND ANALYSIS

### 4.1 Skaapvlei Network

Skaapvlei 132/33 kV distribution substation is located within the Western Cape Operating Unit (WCOU) in the vicinity of the town of Vredendal. Figure 4.1 below depicts a single line diagram (SLD) of the existing electrical network at Skaapvlei. The substation has 2 x 80 MVA transformers and connects to Juno 400/132/66 kV transmission substation via a 41 km, 132 kV Kingbird line rated at 176 MVA. The 100 MW Sere Wind Energy Facility (WEF), which was commissioned by Eskom in 2015, is connected directly to the Skaapvlei 33 kV busbar. There is currently no load or other generation sources directly connected to Skaapvlei substation. There are plans in the pipeline to construct a second Juno/Skaapvlei 132kV line to accommodate a future planned PV plant at Skaapvlei.

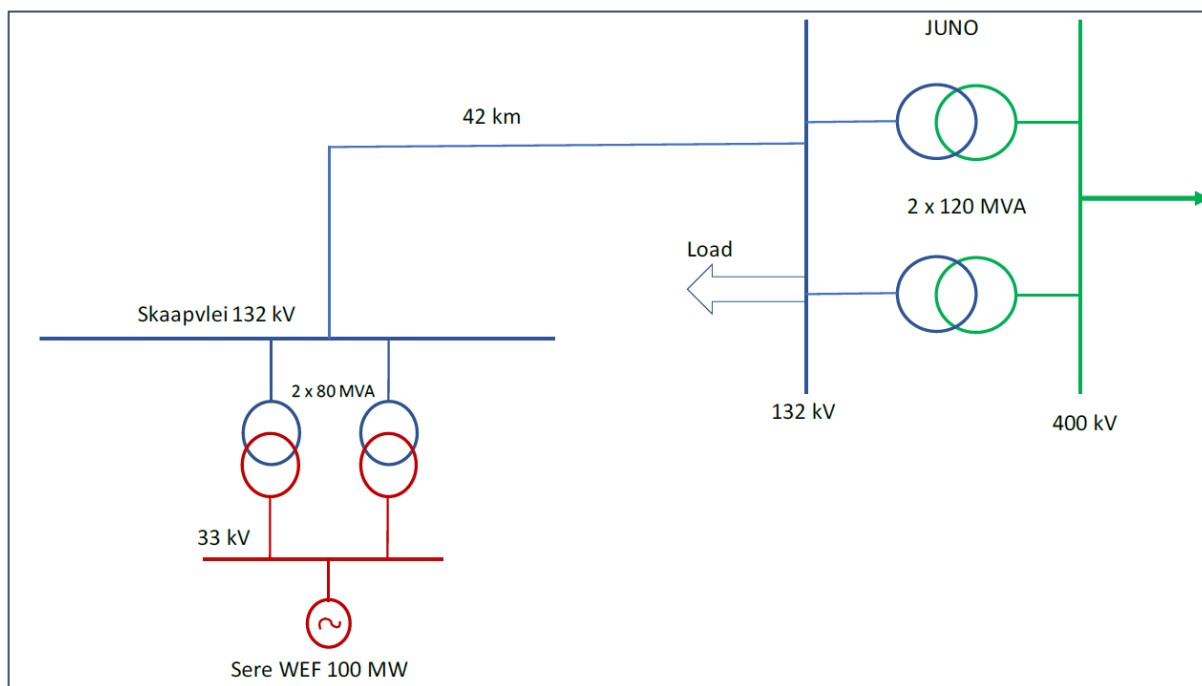


Figure 4.1 Skaapvlei Substation Single Line Diagram of the Current Network

Figure 4.1 shows Skaapvlei-Juno network as is currently configured. This was used to simulate Skaapvlei network without BESS and the results were saved to be analysed.

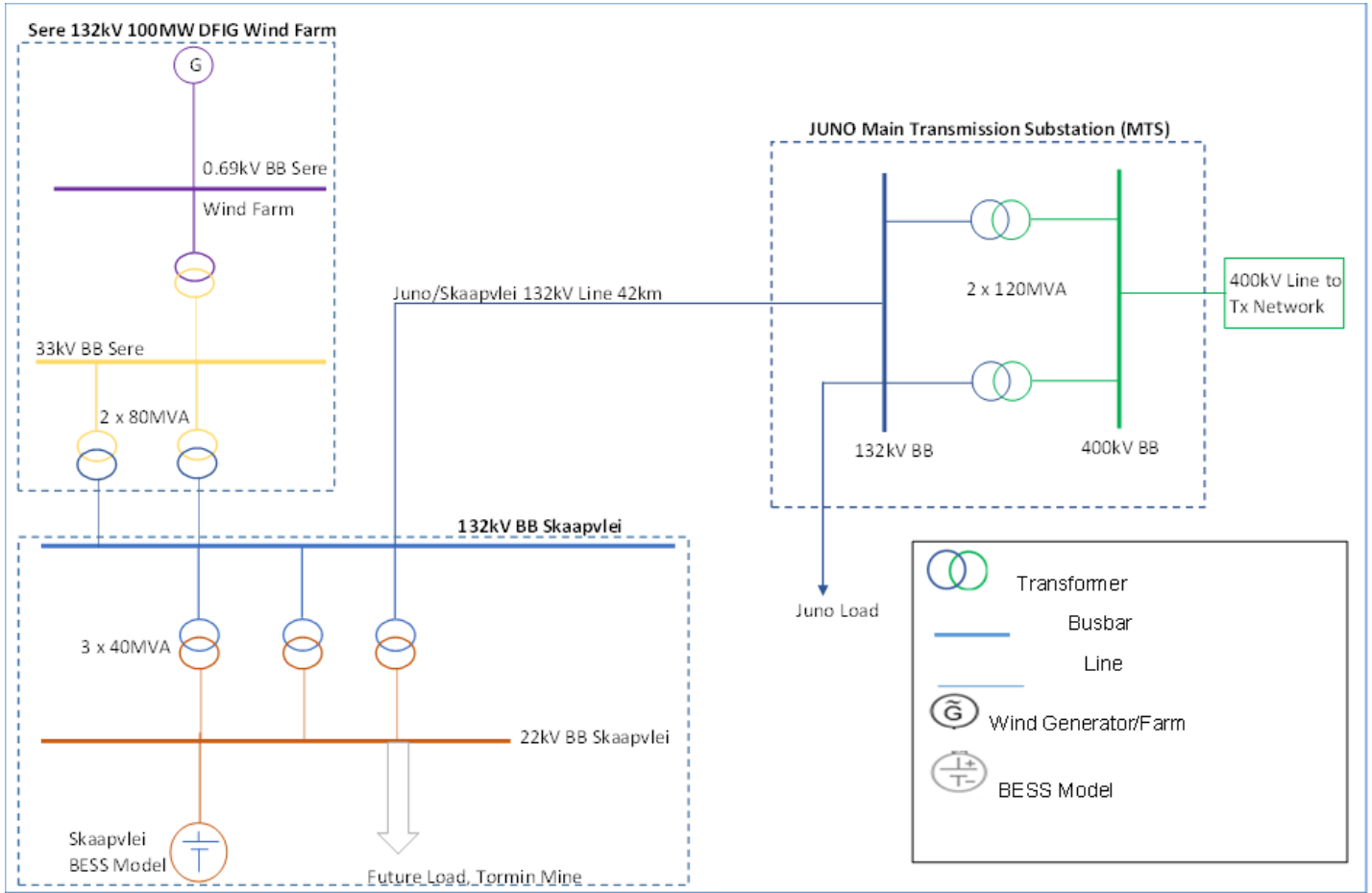


Figure 4.2 Skaapvlei Substation Single Line Diagram of the Future Network with BESS

Figure 4.2 depicts the future Skaapvlei-Juno network. This was used to simulate the Skaapvlei network using BESS, and the resulting data was recorded for analysis. The equipment is in the library at DigSilent. Below is a table with information on the equipment.

Table 4.1 Skaapvlei Network Equipment Information

Equipment	Rating	Length
1. Sere Wind Farm	100 MW	
2. Skaapvlei BESS Model	80MW	
3. Juno/Skaapvlei 132kV Line	176MVA	42km
4. Sere 1 x 33/0.69kV TRFR	160MVA	
5. Sere 2x132/33kV TRFRs	80MVA each	
6. Skaapvlei 3 x 132/22kV TRFRs	40MVA each	
7. Juno 2x 120MVA TRFRs	120MVA	

#### 4.1.1 Skaapvlei Network Performance without BESS

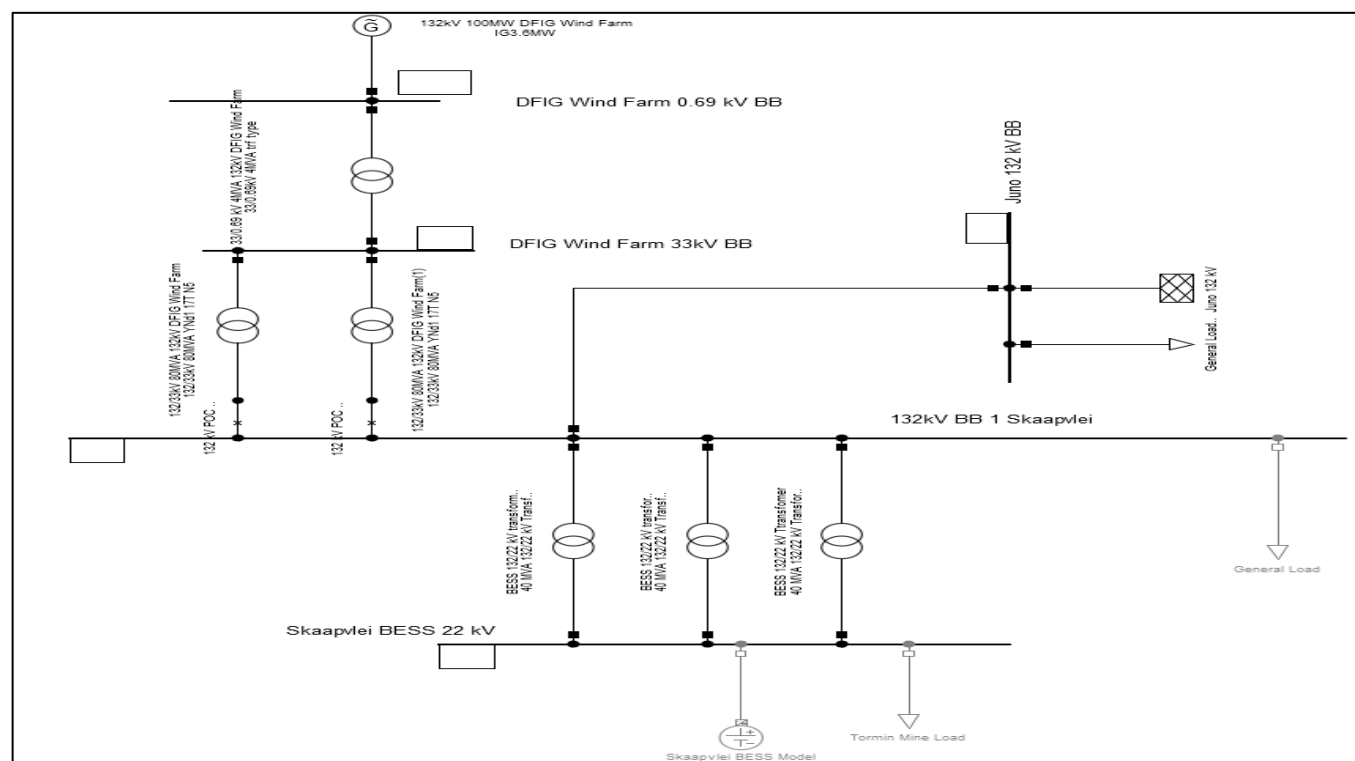


Figure 4.3 Skaapvlei-Juno Reduced Equivalent Network

As illustrated in Figure 4.3, this reduced equivalent network was modelled in DigSilent Powerfactory using equipment from the DigSilent library while BESS was deactivated. Eskom real network was modelled as a single line diagram.

The load profiles shown below were created using data from the MV90 data repository. Figure 4.4 shows Sere Wind Farm hourly loading data downloaded from MV90 and uploaded as a characteristic on the DigSilent Powerfactory. Negative denotes generation and positive denotes load. Controlled voltage setpoint at Juno was set to 1.04 p.u.

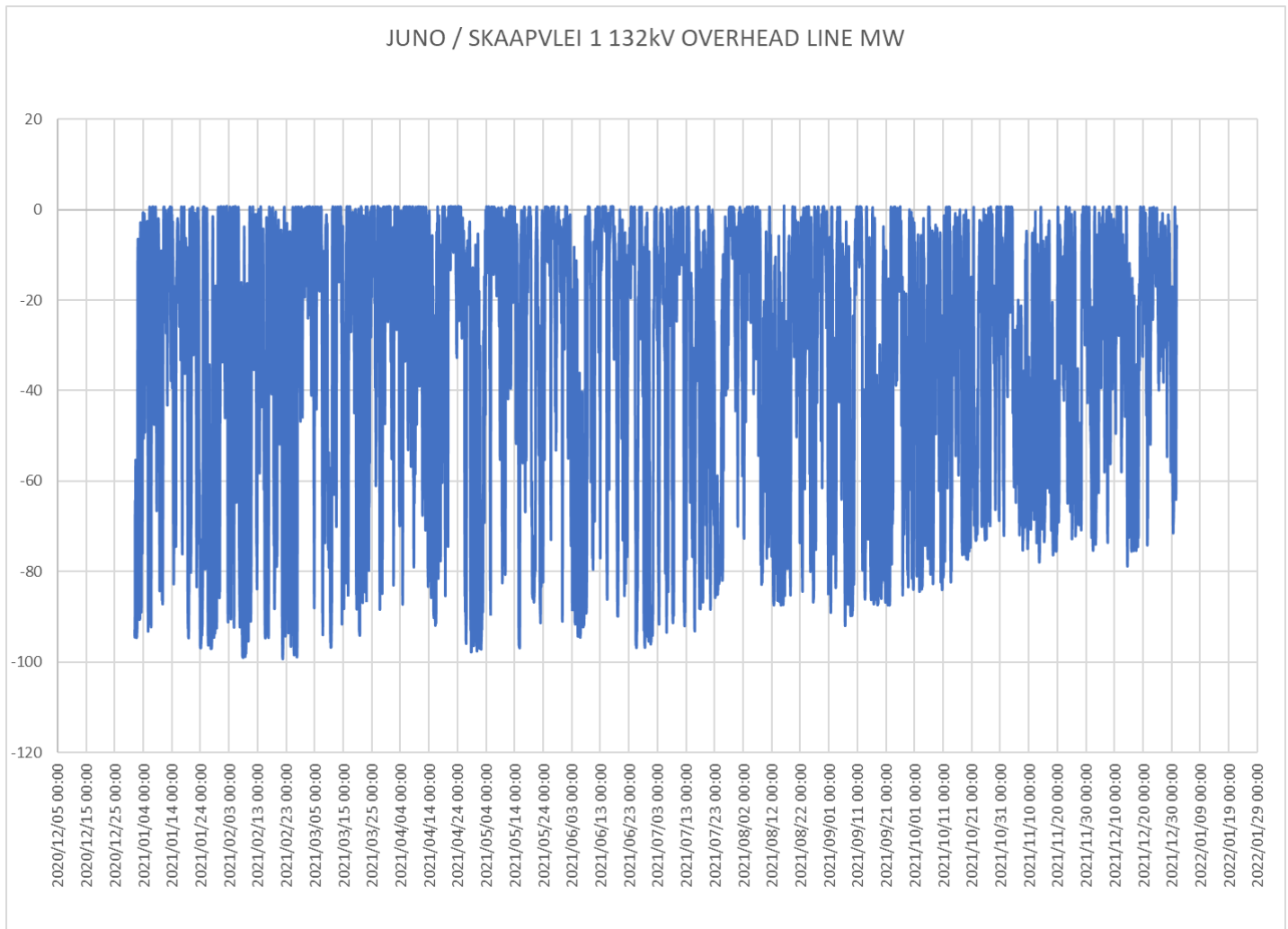


Figure 4.4 Sere Wind Farm Loading 2021

The load profile of the Juno/Skaapvlei 132kV line in 2021 is depicted in Figure 4.5. This line had a maximum loading of about 100MVA. This line is rated at 176MVA, which means the percentage loading peak for 2021 was 57%. This line's % Loading is depicted in Figure 4.6.

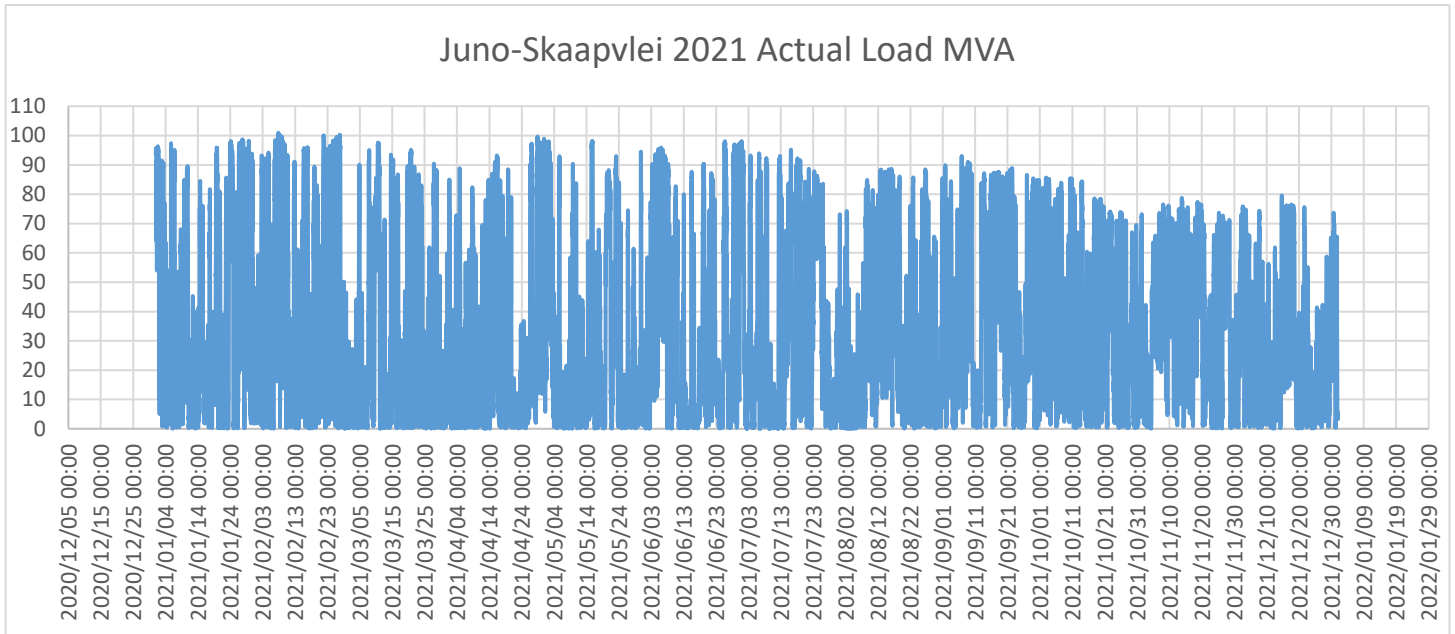


Figure 4.5 Juno/Skaapvlei 2021 Actual Loading

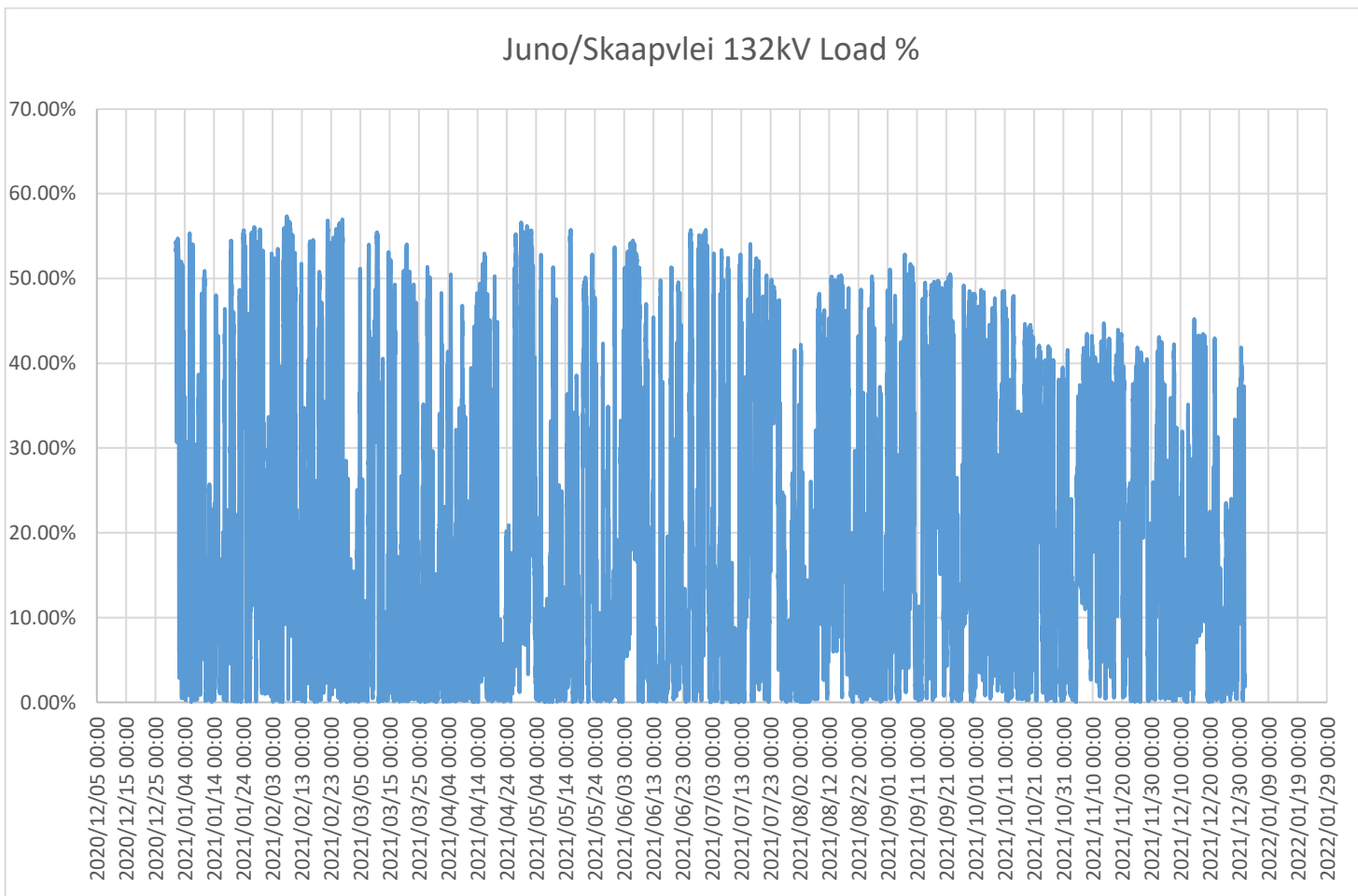


Figure 4.6 Juno/Skaapvlei Actual Loading Percentage

Figure 4.6 depicts the percentage of line loading for the Juno/Skaapvlei 132kV line in 2021. This reflects the current line load prior to BESS deployment.

### 4.1.2 Skaapvlei Network Performance with BESS

The network shown on figure 4.7 shows the Juno/Skaapvlei network during simulation, where BESS was connected on the 132kV busbar via 3x 132/22kV 40MVA transformers. BESS loading scenario is as shown on figure 4.7 below. BESS charges (+) up to 76MW per hour during off peak hours at 00:00-04:00 and discharges (-) up to 67MW per hour during peak time at 17:00 – 22:00, it then stays on idle state between 22:00-00:00 and 04:00 – 17:00.

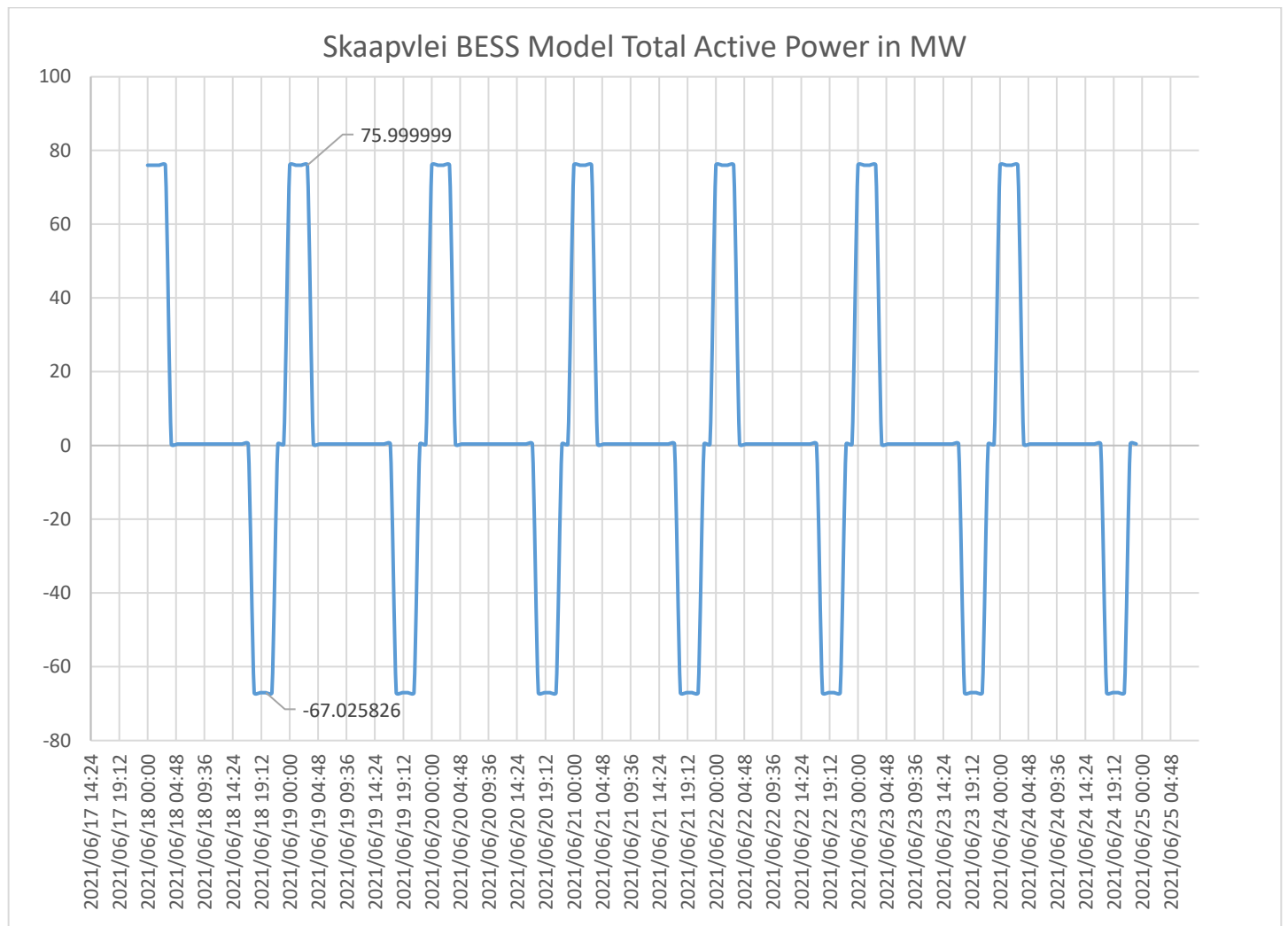


Figure 4.7 BESS Model Total Active Power MW

The active power of the battery model can be adjusted to meet the needs of the network. BESS would charge during the early morning hours, when the grid does not require Sere Wind power, and discharge during peak hours, when the grid requires all the help it can get. A more detailed diagram is shown on figure 4.8 below.

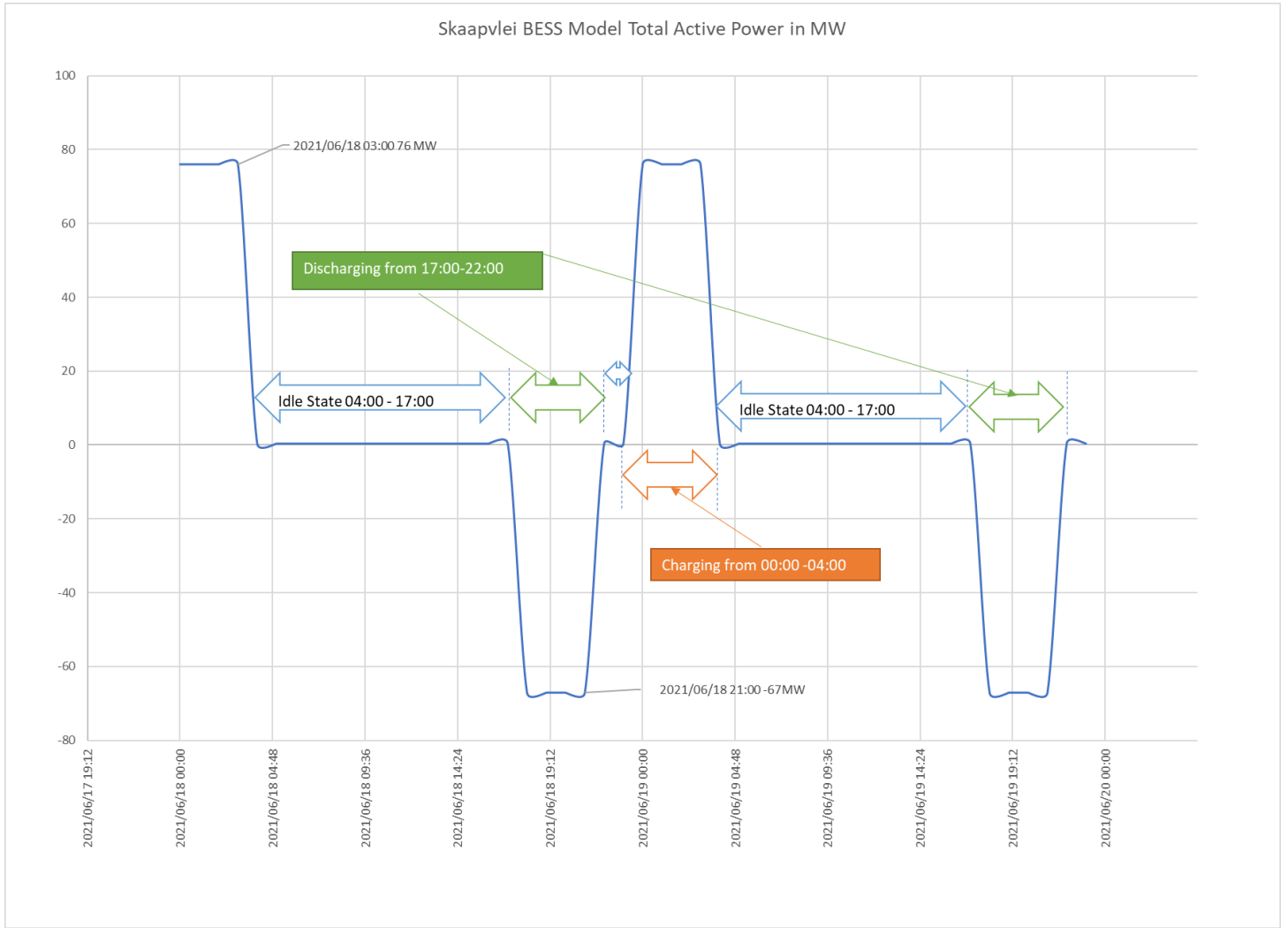


Figure 4.8 BESS Model Total Active Power MW - Detailed Diagram

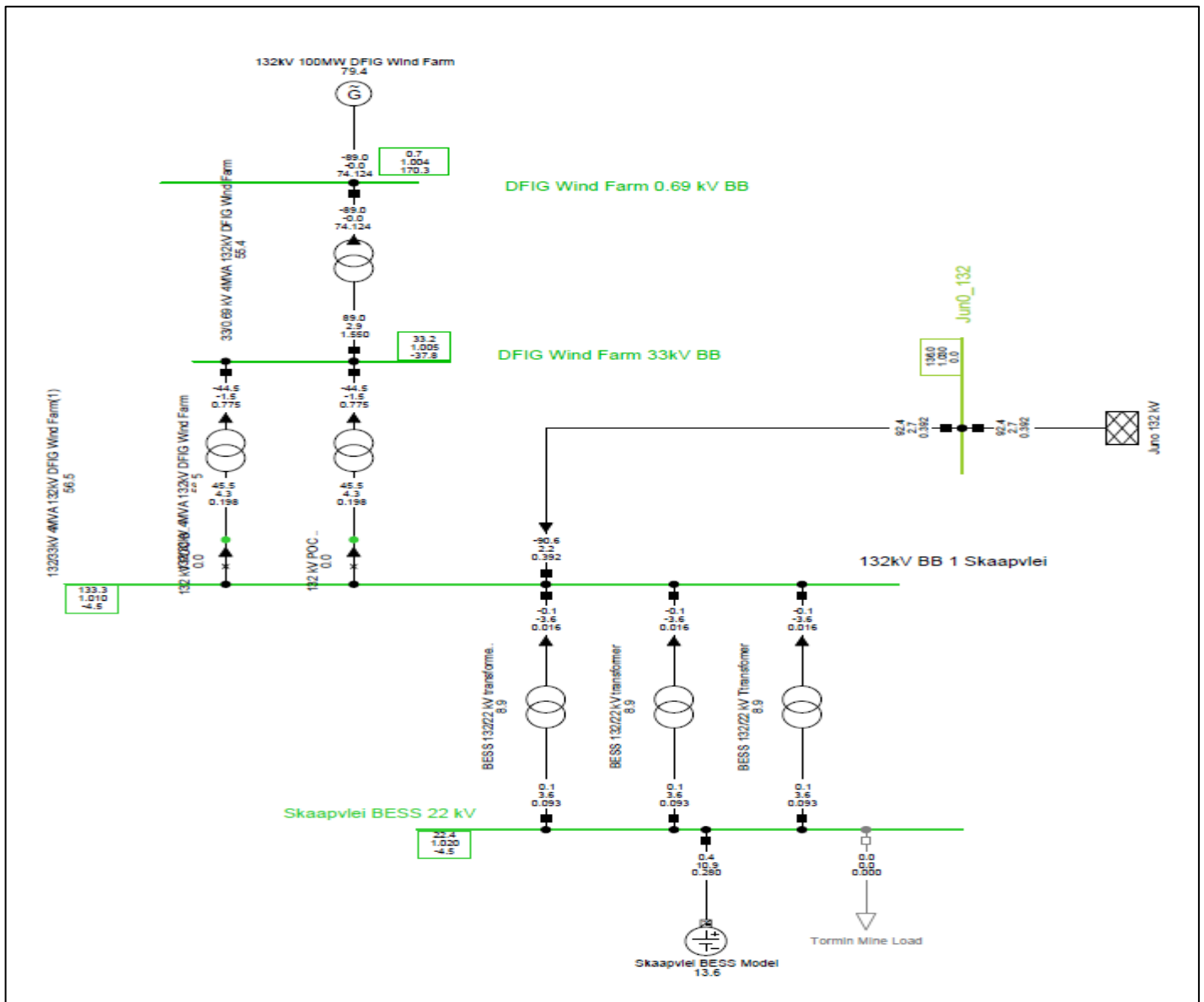


Figure 4.9 Juno/Skaapvlei Network Simulation with BESS

The voltage recorded at the Skaapvlei 132kV busbar while BESS is connected is shown in Figure 4.9. The Juno/Skaapvlei 132kV voltage profile and line loading is depicted in Figures 4.10 and 4.11. There have been instances where the line has been loaded nearly to capacity, raising concerns about network strengthening. It is also a warning to Eskom about the network's reliability, with only one 132kV line for power evacuation from Skaapvlei to Juno.

Figure 4.10 shows that Skaapvlei voltage oscillates between 1.01 and 1.04 per unit. This will later be compared on section 4.13 when BESS is connected.

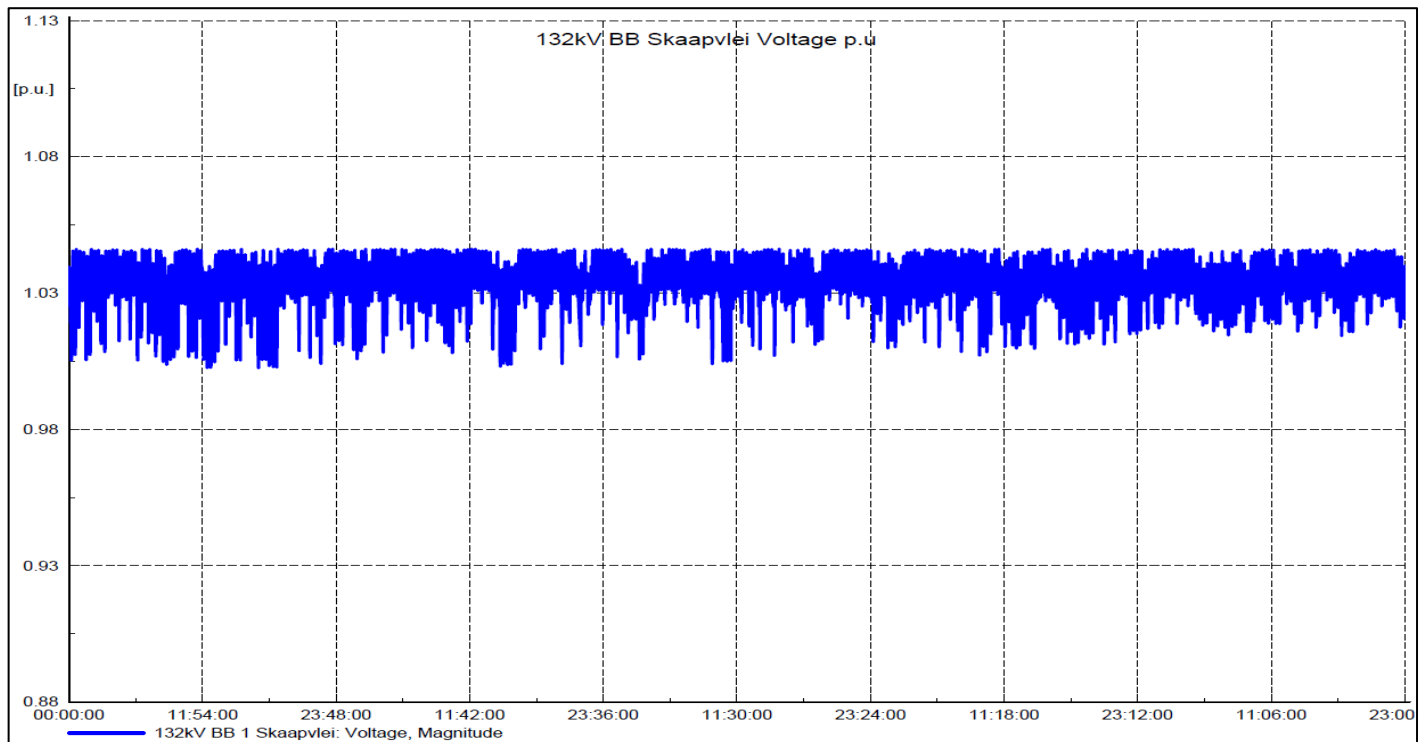


Figure 4.10 Skaapvlei 132kV Busbar Voltage p.u.

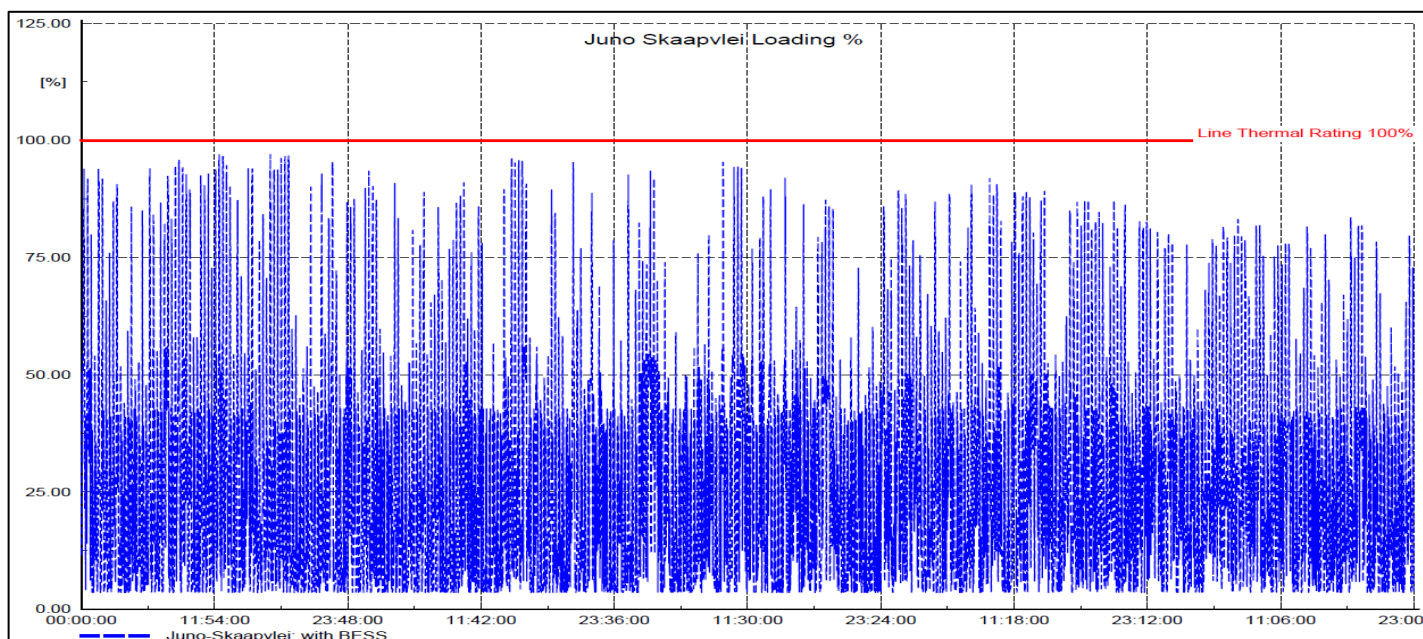


Figure 4.11 Juno/Skaapvlei Load Profile %

Figure 4.11 shows the load profile for Juno/Skaapvlei line just to highlight that its is approaching thermal loading.

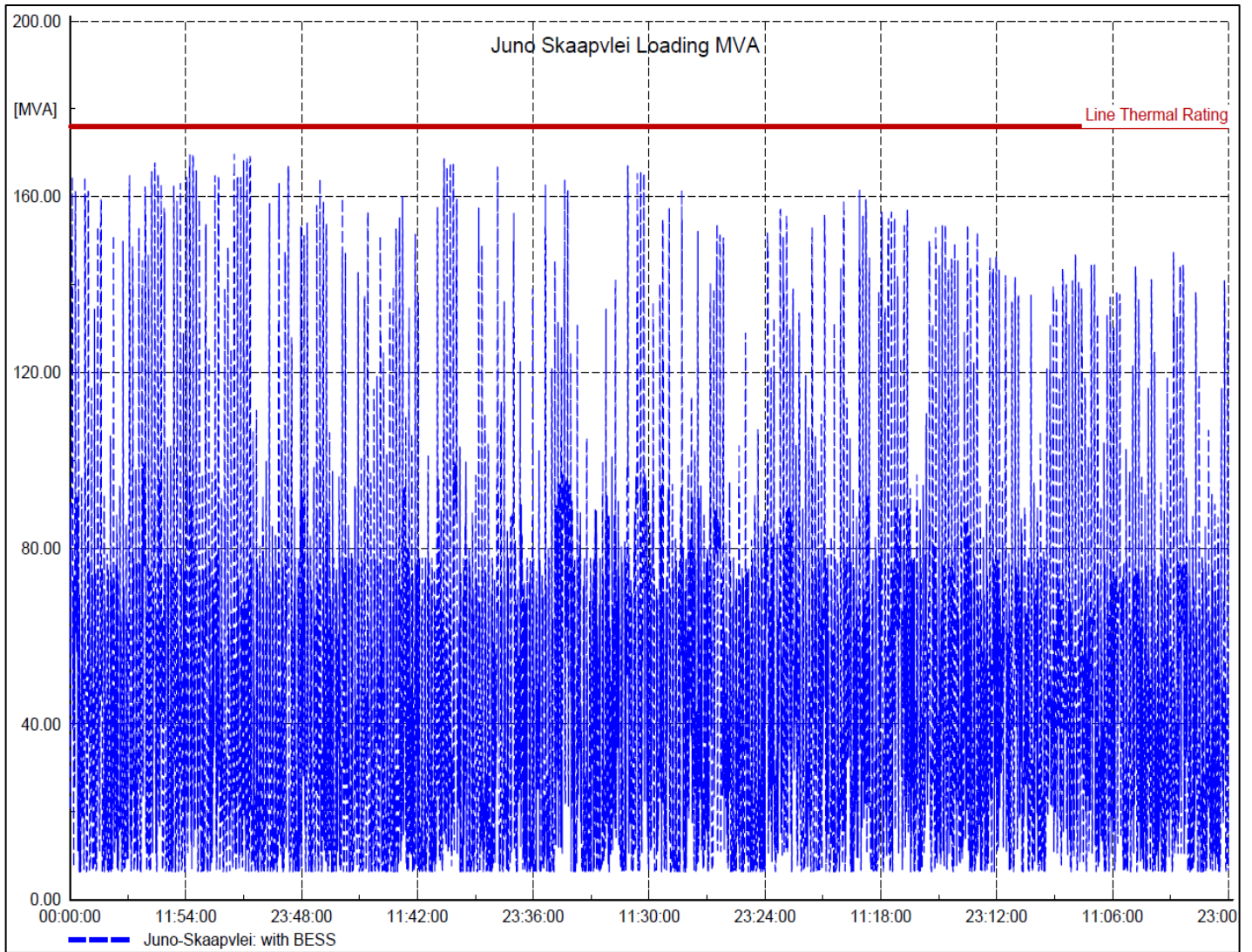


Figure 4.12 Juno/Skaapvlei Loading MVA

### 4.1.3 Skaapvlei Network Performance with BESS versus without BESS

Figure 4.12 depicts the Juno/Skaapvlei line loading before and after the use of BESS. Figure 4.13 shows that when BESS is not connected, Juno Skaapvlei load follows the pattern of Sere Wind Farm generation. When BESS is connected and charging between 00:00-04:00, the load on the line decreases; when BESS is not connected during that time, the load on the line increases. Which means that during the time of low load, the power generated at Sere is evacuated via Juno/Skaapvlei 132kV line towards Juno Main Transmission substation (MTS). However, when there is BESS at Skaapvlei substation, some of that power is consumed by the battery for charging hence the line evacuates less power.

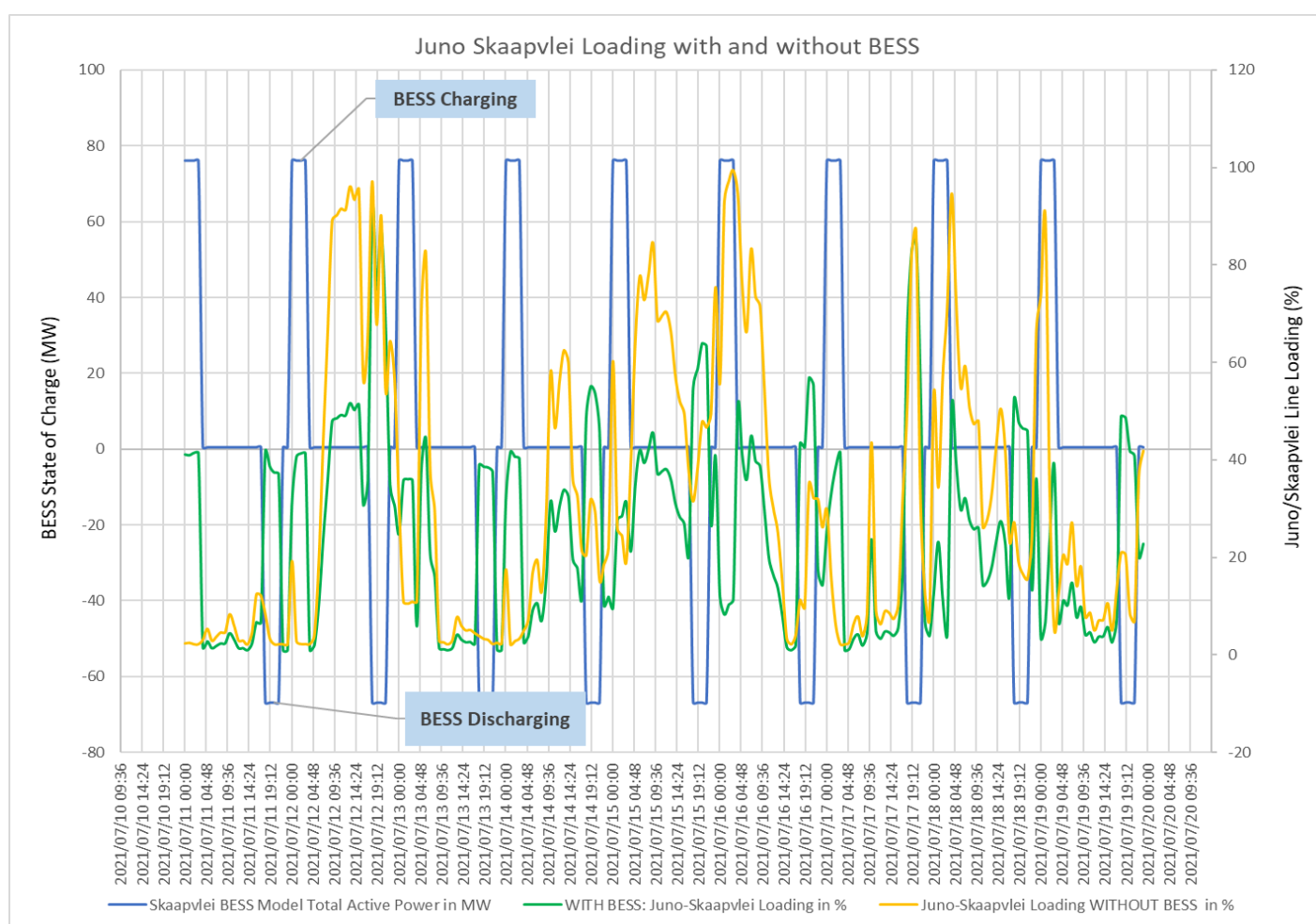


Figure 4.13 Juno/Skaapvlei with & without BESS

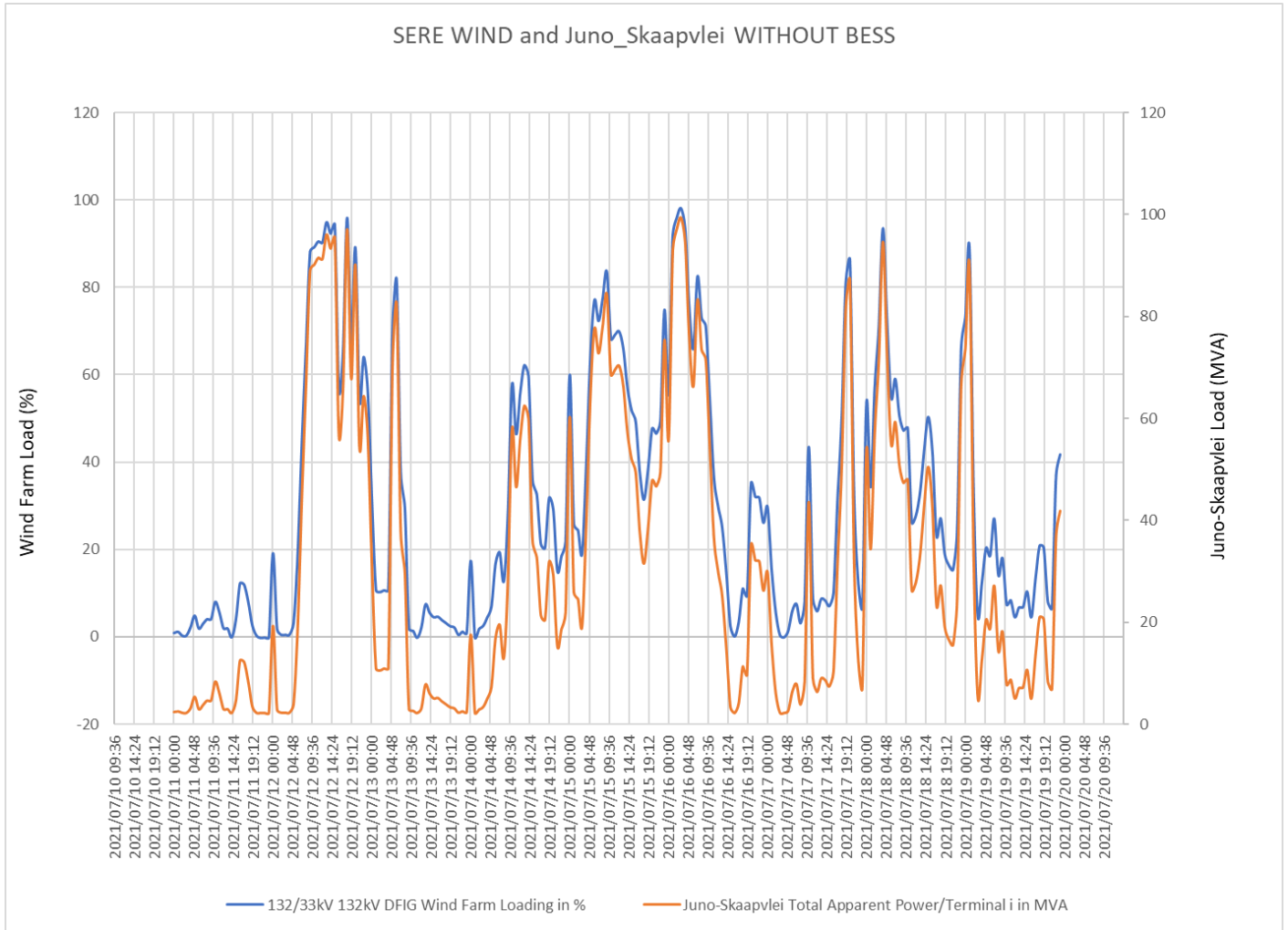


Figure 4.14 Sere Wind Output vs Juno/Skaapvlei Load

Figure 4.14 shows that Juno Skaapvlei line follows the Sere wind farm load profile. That line is indeed dedicated to evacuating wind generation from Sere Wind Farm to Juno substation.

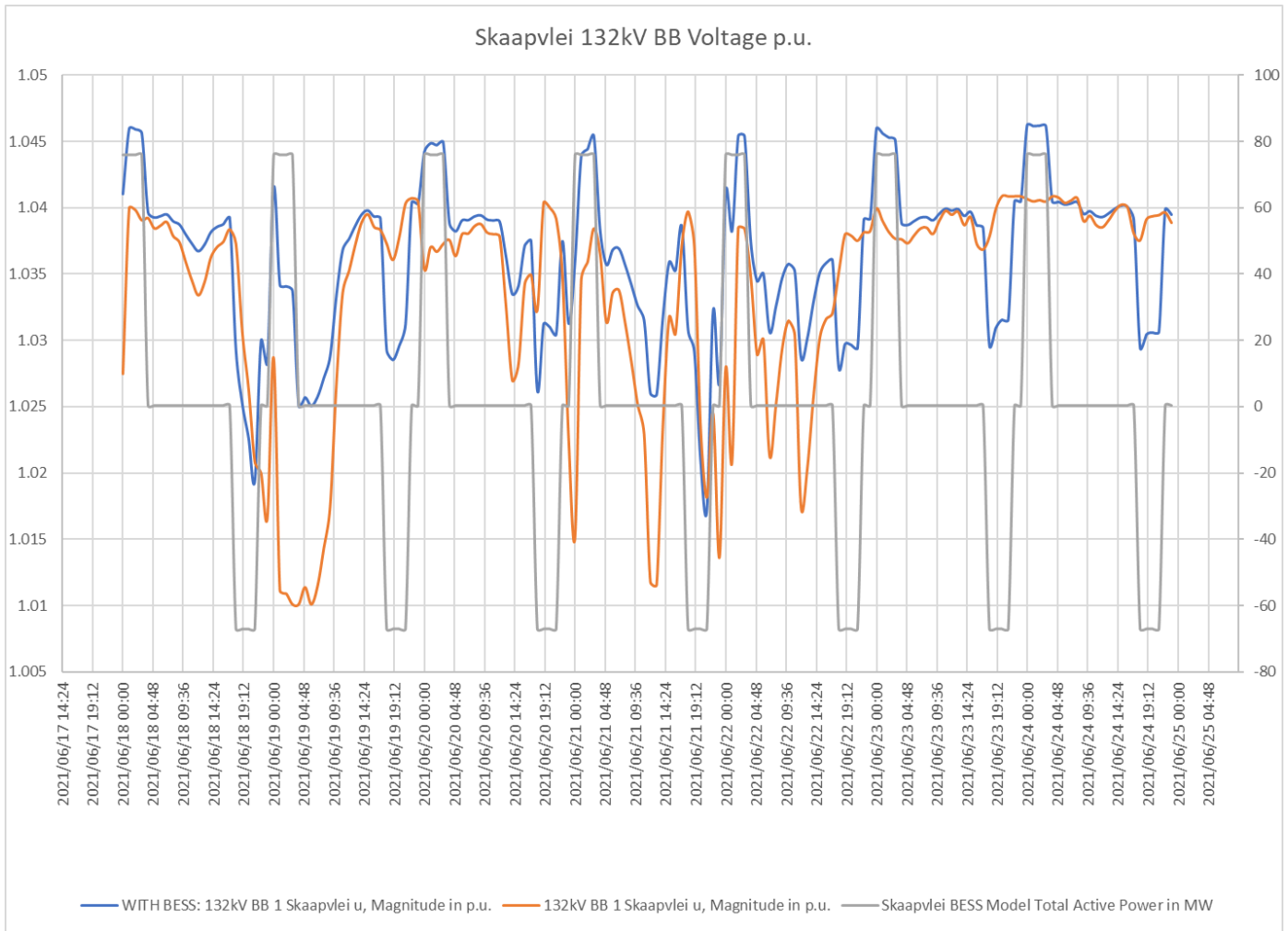


Figure 4.15 Skaapvlei 132kV BB Voltage with vs without BESS

Voltage profile of Skaapvlei 132kV busbar can be seen on diagram 4.15. The voltage is monitored at Juno 132kV BB with the setpoint of 1.04 per unit. As can be seen from the blue profile, the scenario with BESS performs better than the orange scenario without BESS. During the peak load period when BESS is charging it supports the voltage by boosting it to 1.045 per unit which is 0.005 per unit above the setpoint. When BESS is idle, the voltage is maintained above 1.025pu. When BESS is charging there are few instances where the voltage is bucked down to 1.15pu unlike on the orange profile where the voltage is mostly below the set point.

#### 4.1.4 Local Network Constraints

From Skaapvlei to Juno MTS, there is only one 132kV feeder. It has a 176MVA rating. When BESS is operating at full capacity and the Sere Wind Farm is also producing full power, the line would be loaded almost to its thermal limit. Aside from the loading issue, in the event of a fault on the Juno/Skaapvlei 132kV line, both the power from the wind farm and the BESS will not be evacuated, having defeated the core purpose. A second 132kV line from Juno to Skaapvlei is necessary.

## 4.2 Hex Network

Hex 132/66/11 kV distribution substation is within the Eskom Western Cape Operating Unit (WCOU). The single line diagram (SLD) of the existing electrical network at Hex substation can be seen in Figure 4.16 below. A 132 kV Hex/Boskloof double circuit wolf type line rated at 166 MVA integrates the substation to the Bacchus Main Transmission Substation (MTS) via the Boskloof switching station. The Hex substation, which has two 120 MVA 132/66 kV transformers and two 10 MVA 66/11 kV transformers, serves the Worcester area via the 66 kV and 11 kV network. The load in the vicinity of Hex is primarily agricultural and residential and is supplied by the 11 kV electrical network.

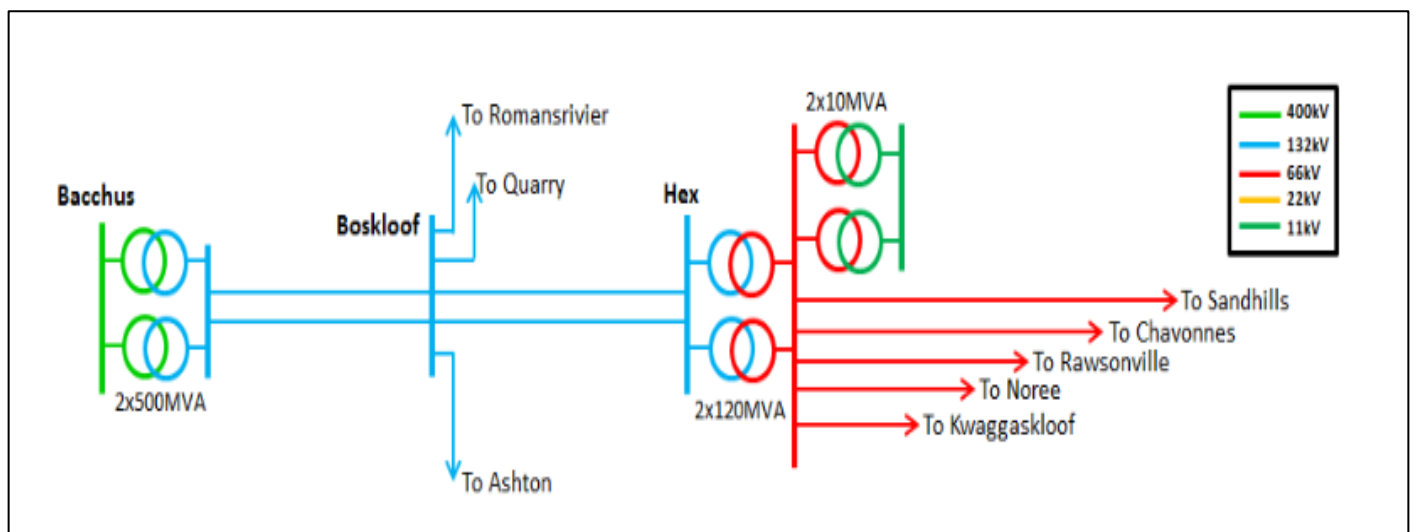


Figure 4.16 Hex Network SLD

Table 4.2 shows the information about Hex network equipment used to simulate on DigSilent.

Table 4.2 Hex Network Equipment Information

	Equipment	Rating	Length
1.	Bacchus Trfr 2 x 400/132kV TRFRs	500MVA each	
2.	Bacchus/Boskloof 132kV Lines 1&2	238 MVA	25.29 km each
3.	Boskloof/Hex 132kV Lines 1&2	82.89 MVA	7.1km each
4.	Hex 132/66kV Trfr 1&2	120 MVA each	
5.	Hex 66/11kV Trfr 11&12	10 MVA each	
6.	Hex BESS Capacity	20 MW	

The network shown on figure 4.17 shows the Hex network during simulation, where BESS was connected on the 11kV busbar via 2x 66/11kV 10MVA transformers. BESS loading scenario is as shown on figure 4.18 below. When the load profile on figure 4.18 is positive it depicts that the BESS is charging, and negative means BESS is providing power to the grid.

#### 4.2.1 Simulation without BESS

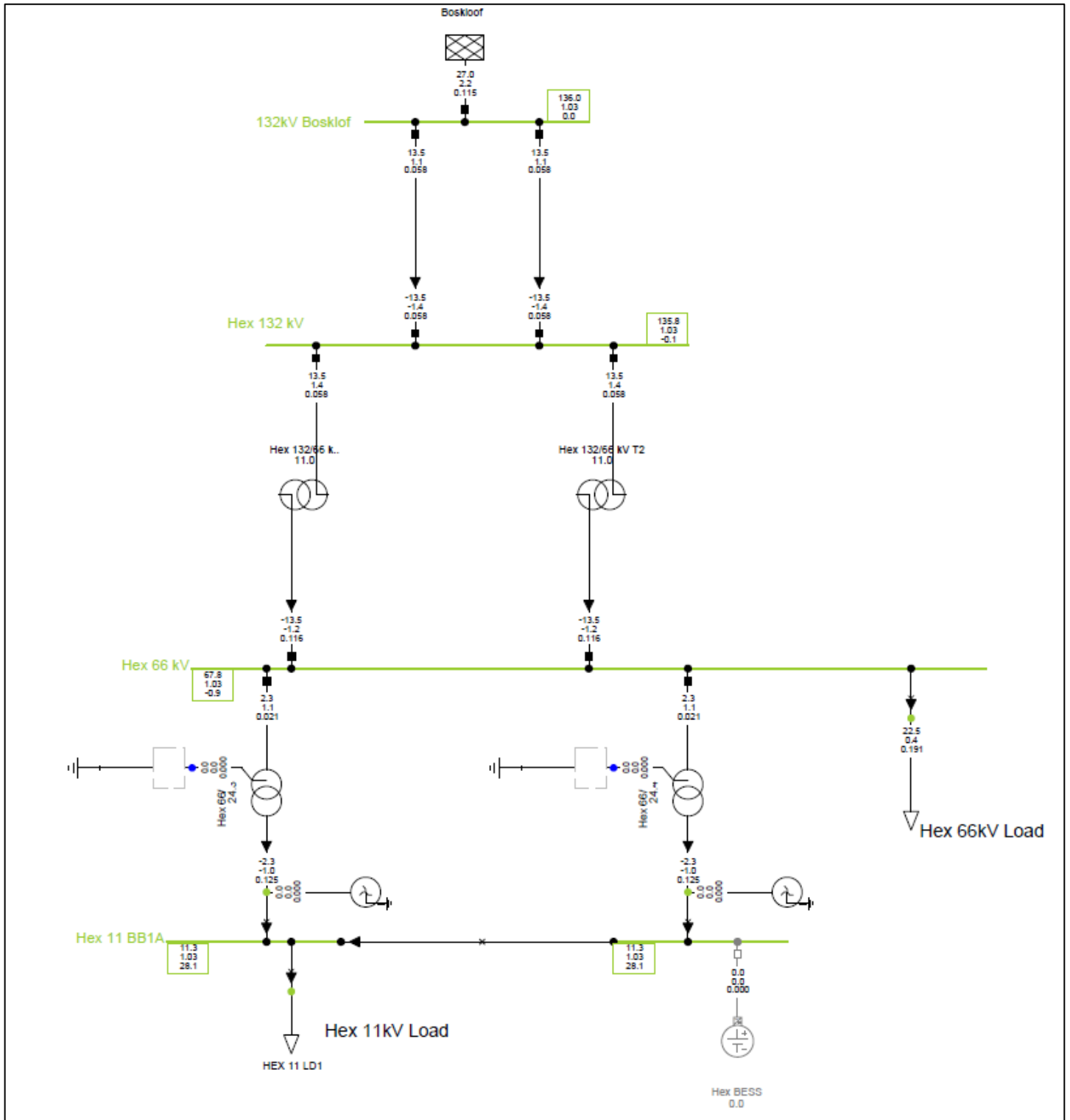


Figure 4.17 Hex Network Overview Diagram

Figure 4.18 depicts an active power output and input profile of Hex BESS. This BESS has a capacity of 20MW. The scenario tested is when the battery charges to full capacity at 16.2MW per hour for 6 hours and discharges at full capacity for 4 hours. Eskom requires 4 hours of discharge at full capacity. Where the profile is zero, it means that the BESS is idle.

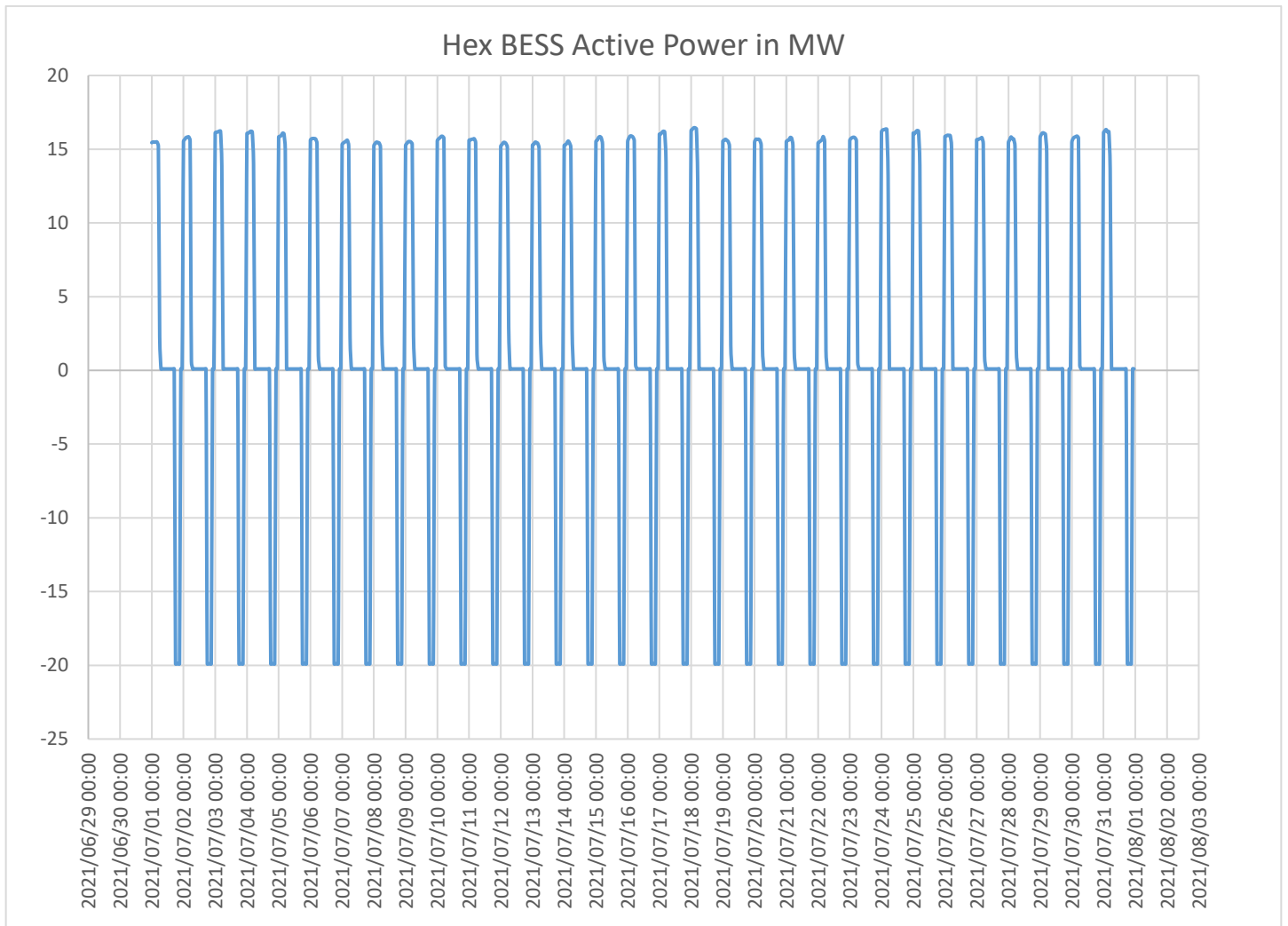


Figure 4.18 Hex BESS Model Load

The load profiles in MW and MVA for the 66kV and 11kV loads at Hex substation are shown in figures 4.19 to 4.22. This load was modelled into the casefile to simulate scenarios with and without BESS. According to the profiles, the 66kV load peaks at approximately 128 MW as seen on figure 4.19, and the 11kV load peaks at approximately 8 MW as can be seen on figure 4.21.

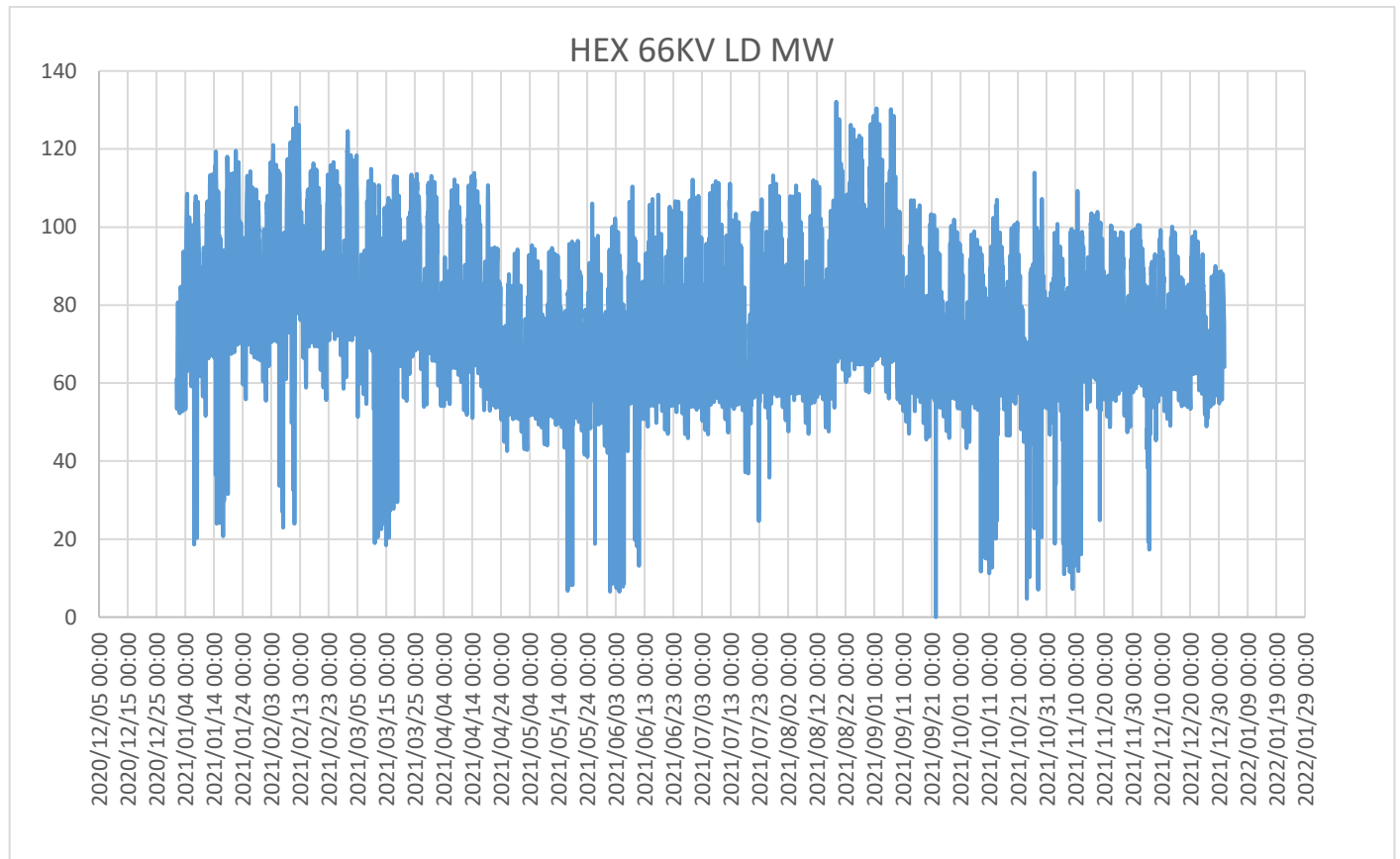


Figure 4.19 Hex 66kV Load MW

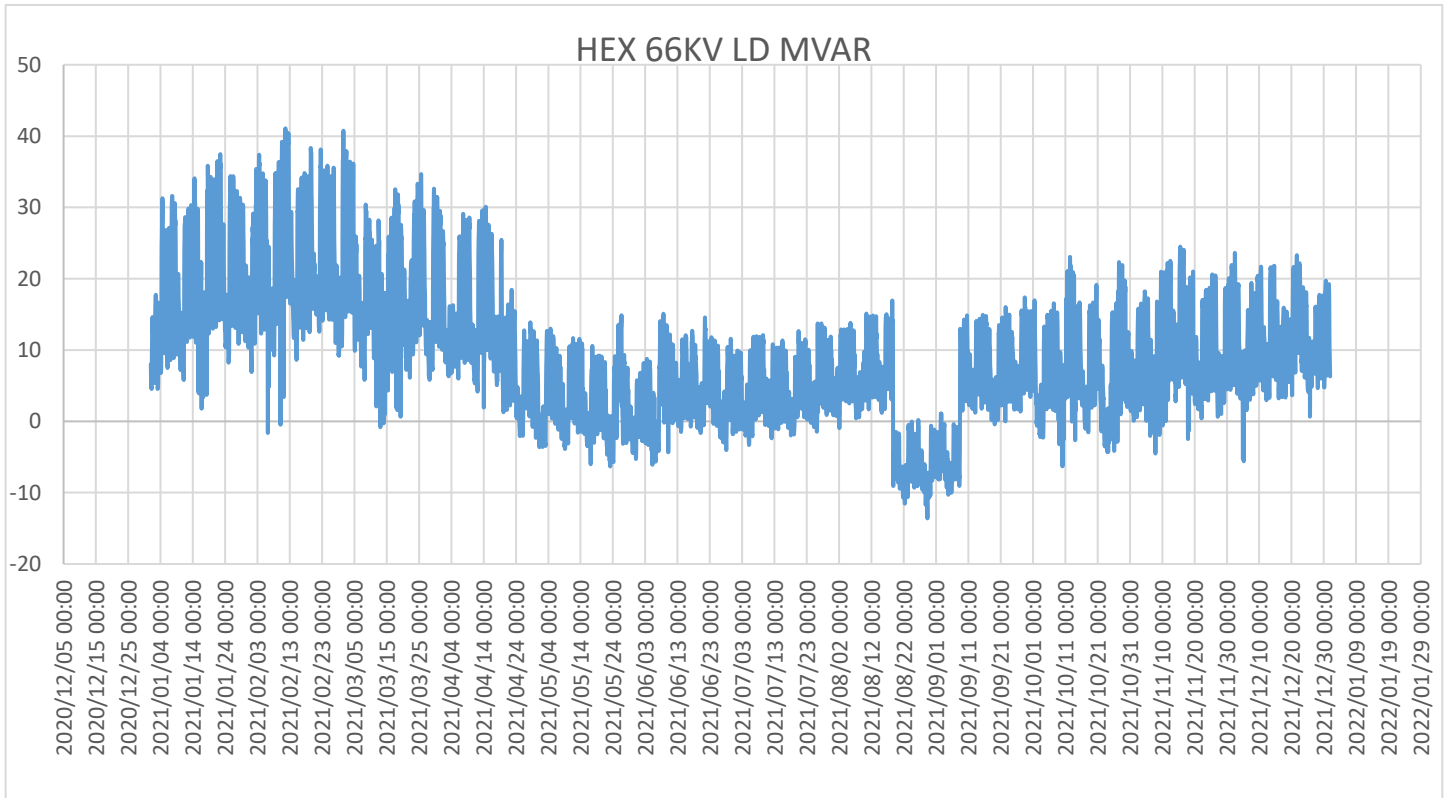


Figure 4.20 Hex 66kV Load MVAR

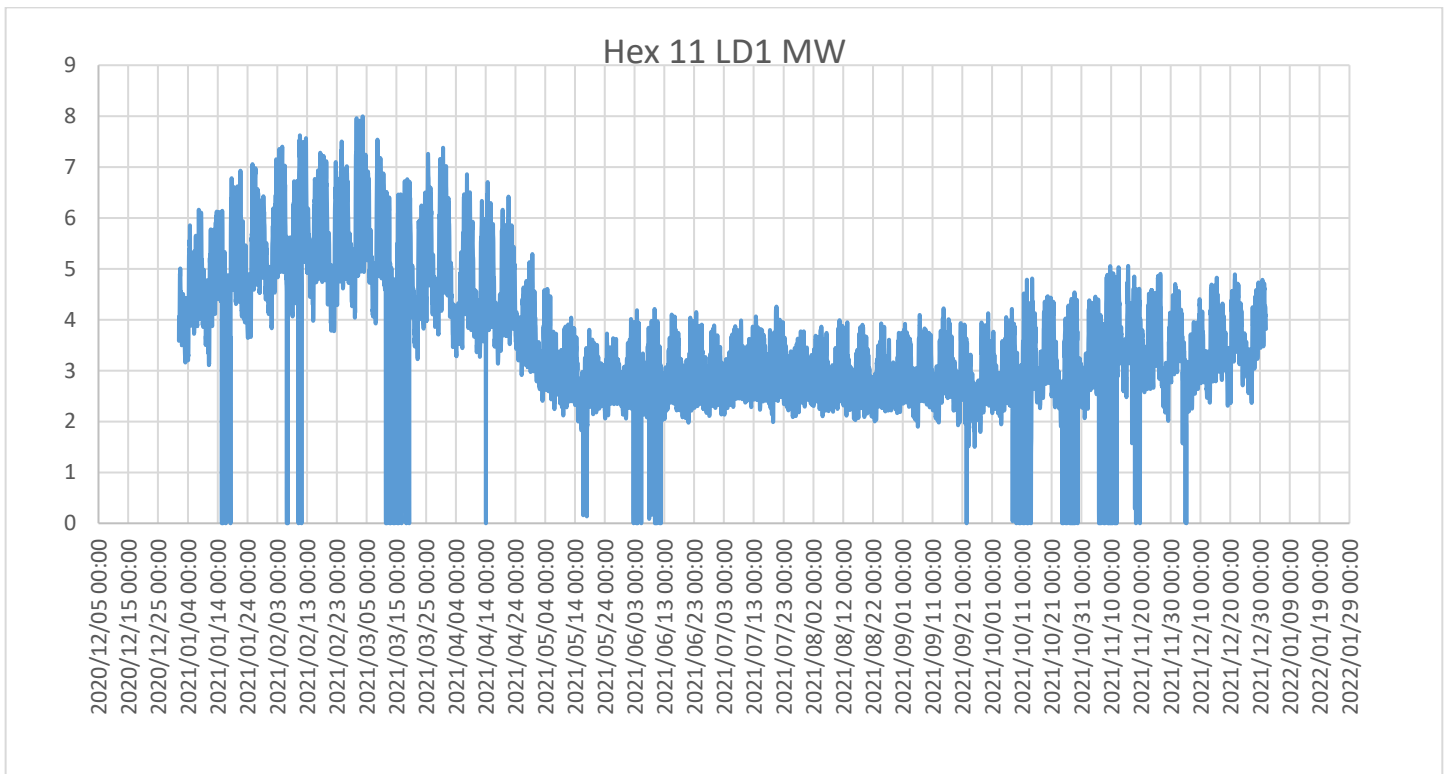


Figure 4.21 Hex 11kV Load MW

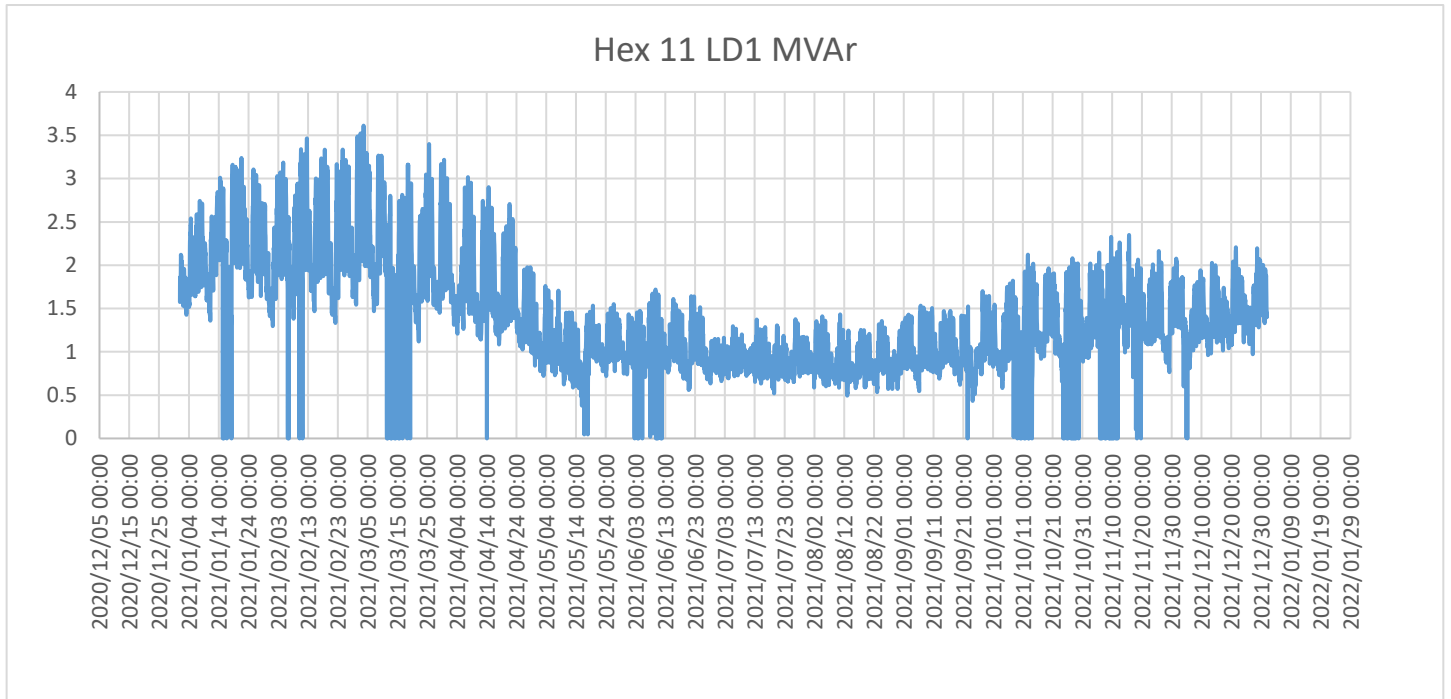


Figure 4.22 Hex 11kV Load MVAr

The profiles on figures 4.23 to 4.25 show the status of the network as modelled on DigSilent.

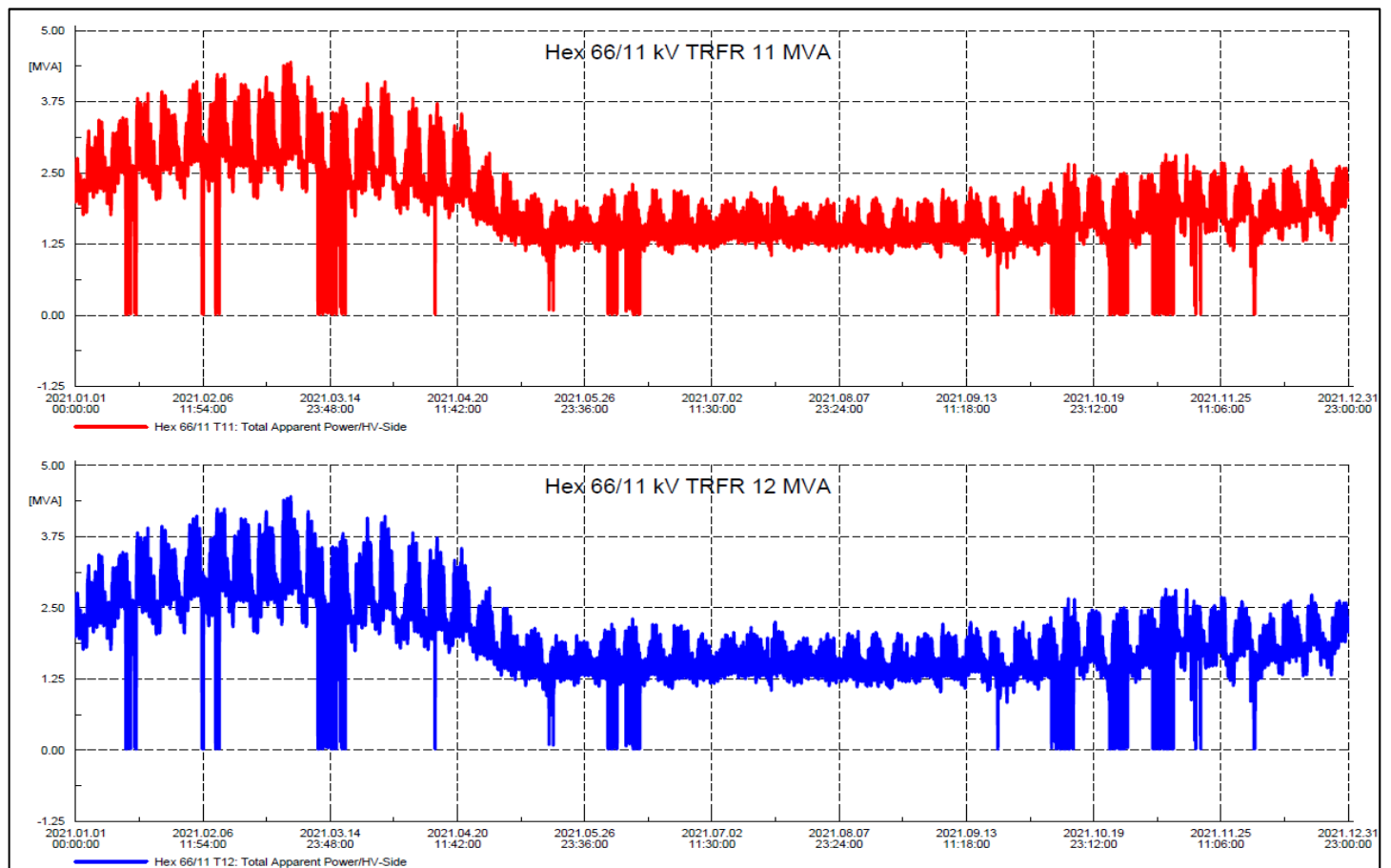


Figure 4.23 Hex 11kV Load as seen from TRFR 11&12 on DigSilent

The load profiles on figures 4.23 show that Hex load is summer peaking. The peak of the profile is seen in the February period. It declines after March and is flat from May to December.

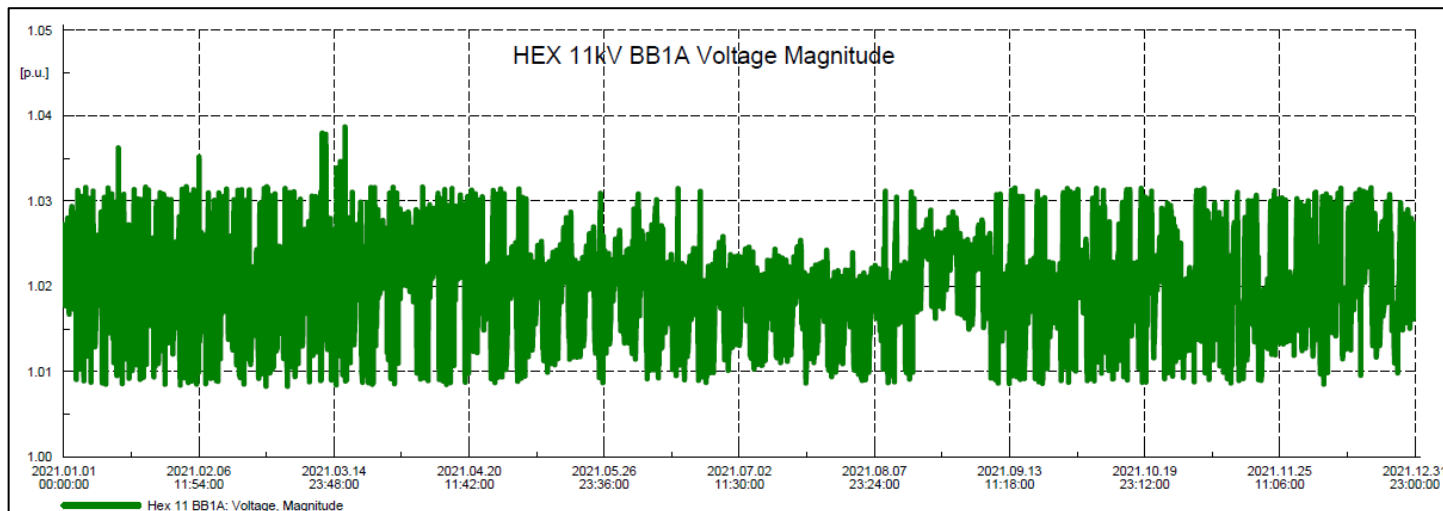


Figure 4.24 Hex 11kV BB Voltage Profile

Figure 4.24 shows the voltage profile on the 11kV busbar at Hex substation. The voltage fluctuates between 1.01-1.03 per unit.

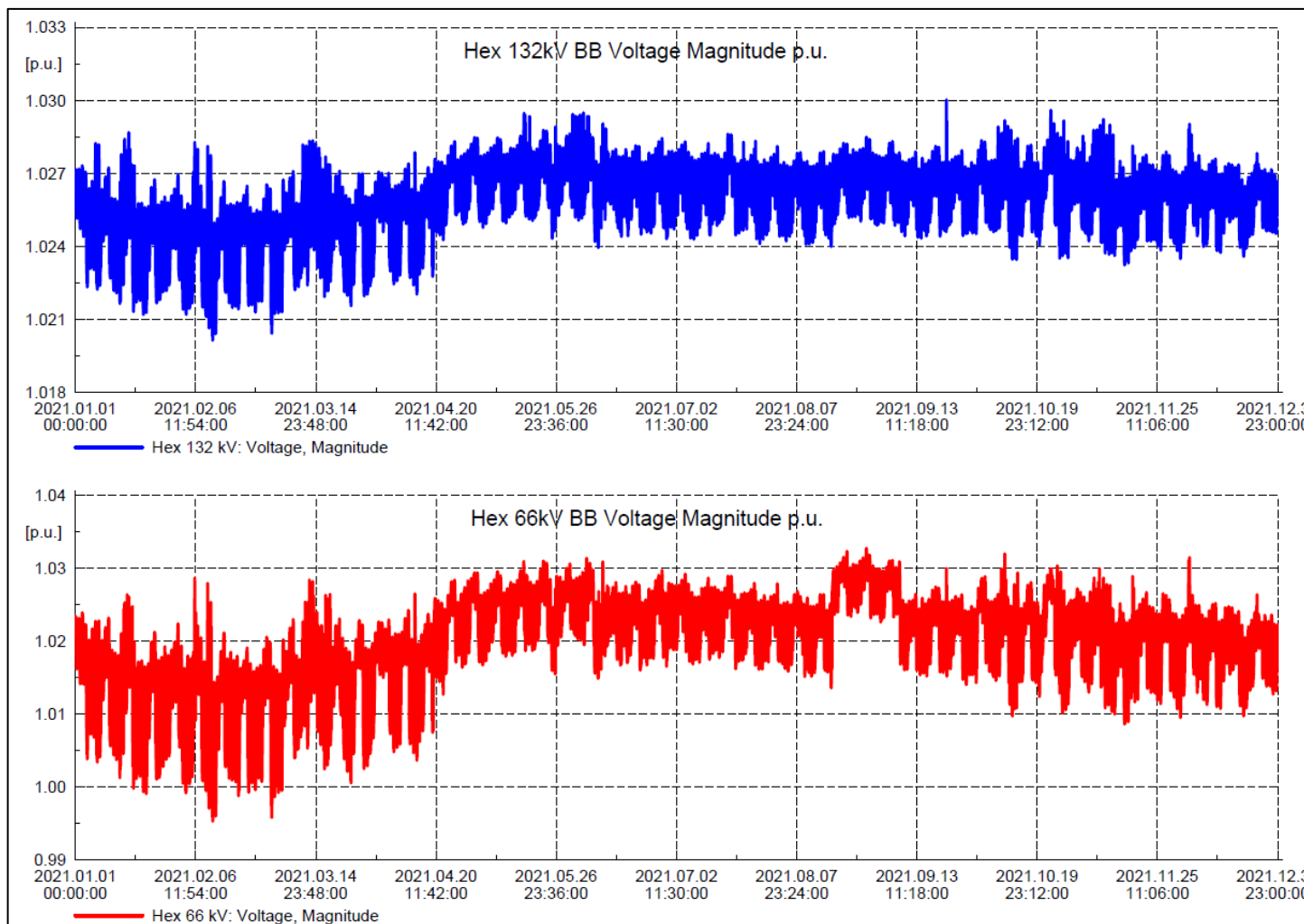


Figure 4.25 Hex 132kV & 66kV Voltage Profile

Figure 4.25 shows the voltage profile on the 132 and 66 kV busbars at Hex substation. The voltage fluctuates between 1.021-1.028 per unit on the 132kV busbar and between 1 – 1.03 pu on the 66kV busbar.

### 4.2.2 Simulation with BESS

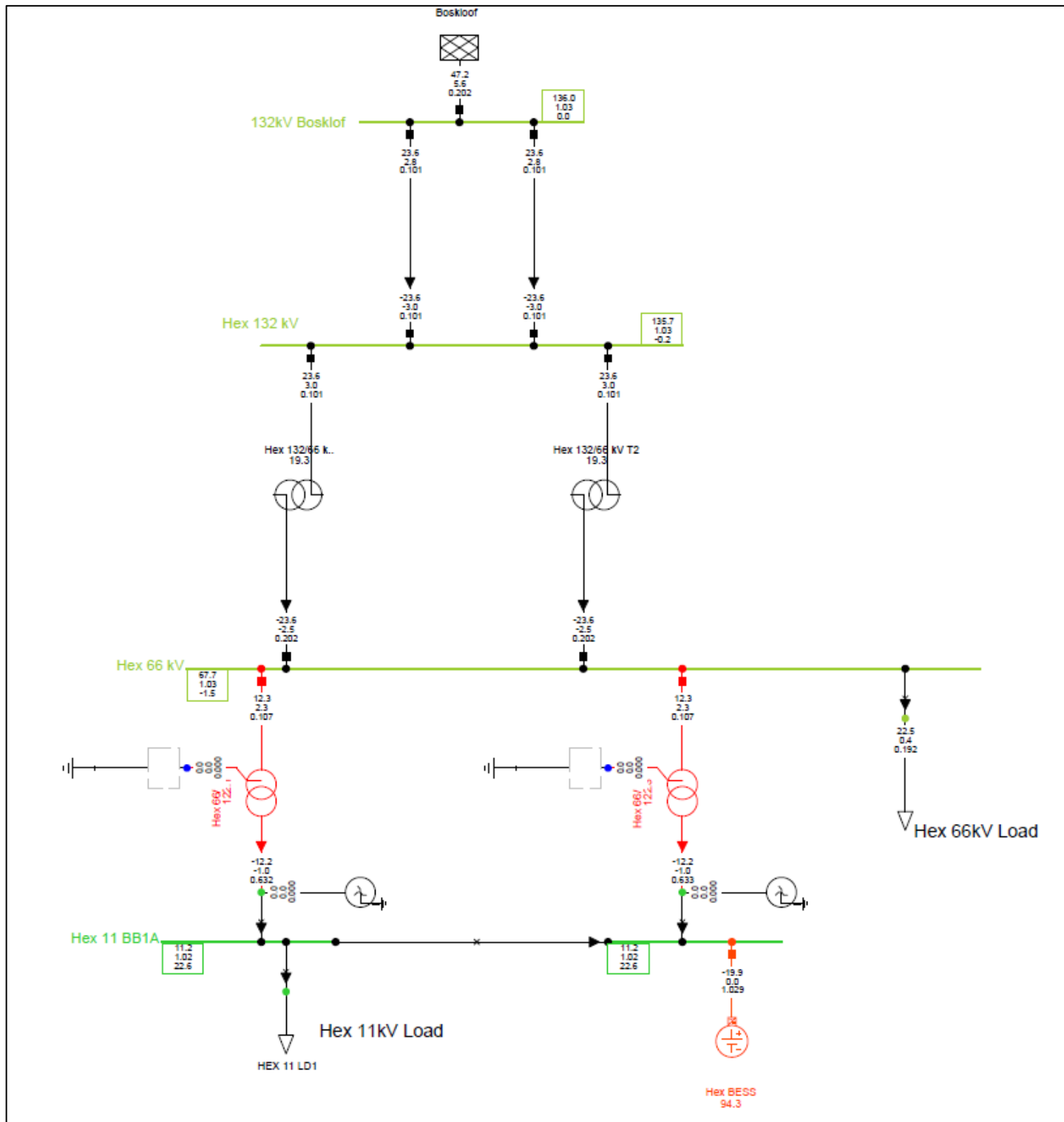


Figure 4.26 Hex Network Overview with BESS Running

Figure 4.26 shows the single line diagram as drawn and simulated on DigSilent. BESS is also shown connected on the 11kV busbar.

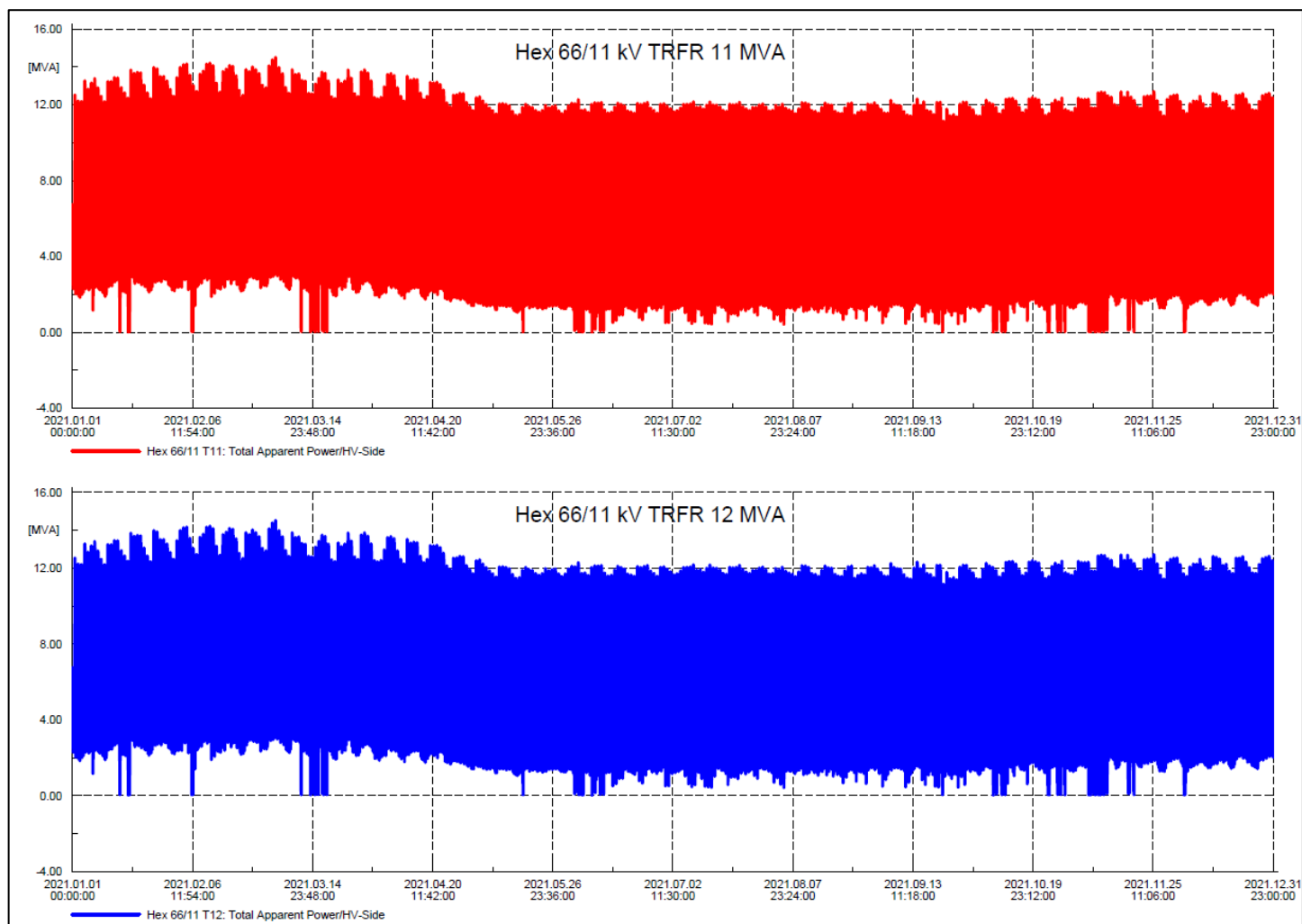


Figure 4.27 Hex 11kV Load as seen from TRFR 11&12

The TRFR 11 and 12 load was monitored, as shown in figure 4.27 above. This diagram depicts the load on the transformers while BESS is in operation. Figures 4.28 to 4.30 depict the voltage profiles as well. Boskloof has a controlled voltage with a setpoint of 1.03 per unit.

### 4.2.3 Hex Network Performance with BESS and without BESS

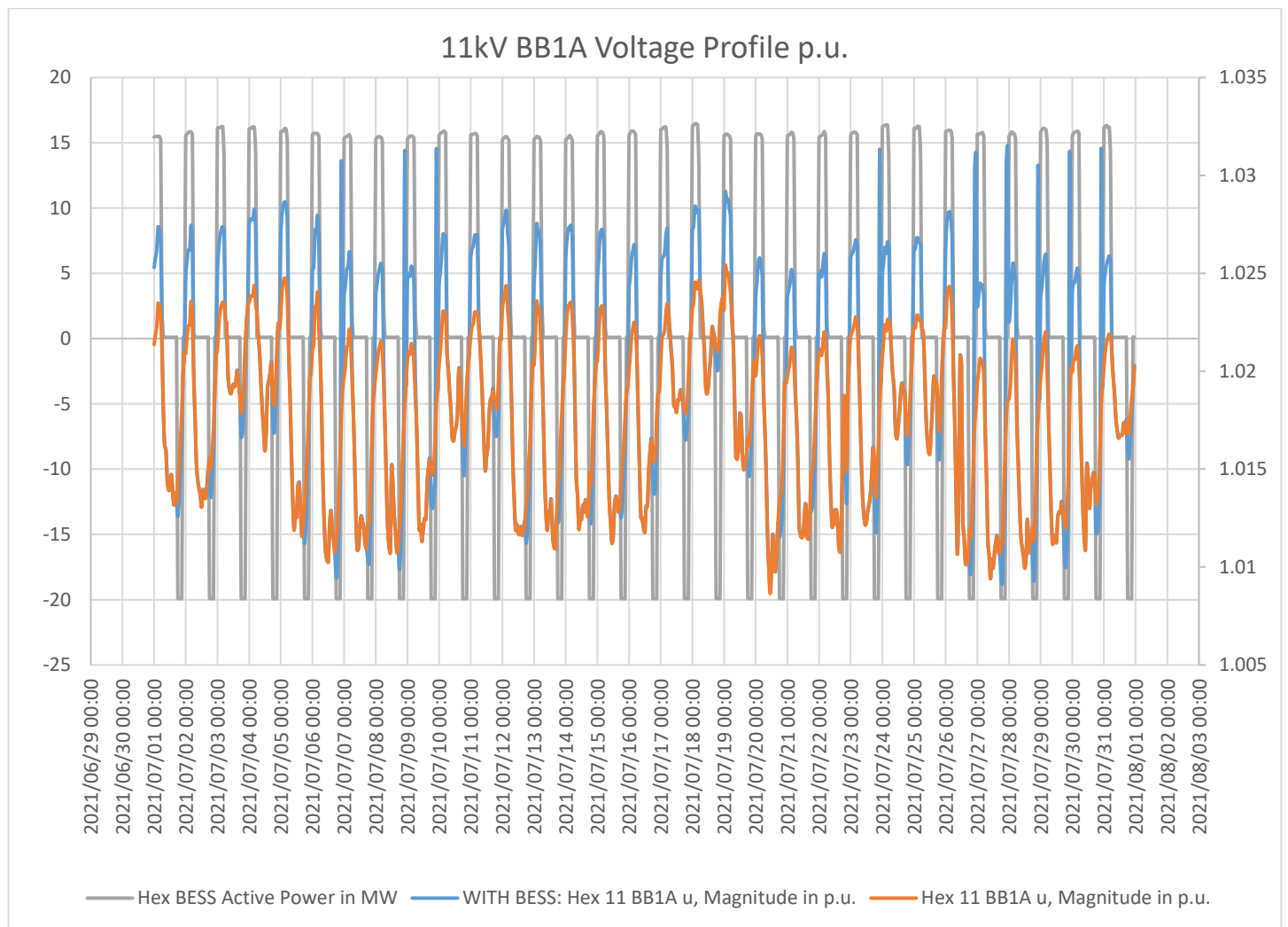


Figure 4.28 Hex 11kV BB Voltage with vs without BESS

Figure 4.28 shows Hex 11kV voltage profile when BESS is connected and without BESS. When BESS is connected, during the charging period, a voltage increase is experienced. This might be since the battery has now become load and power direction is towards the BESS, which results on voltage increase. On the 66kV busbar (see fig. 4.29), the discrepancy in voltage is experienced during the charging period, while on the 132kV busbar (see fig 4.30) is experienced during both charging and discharging.

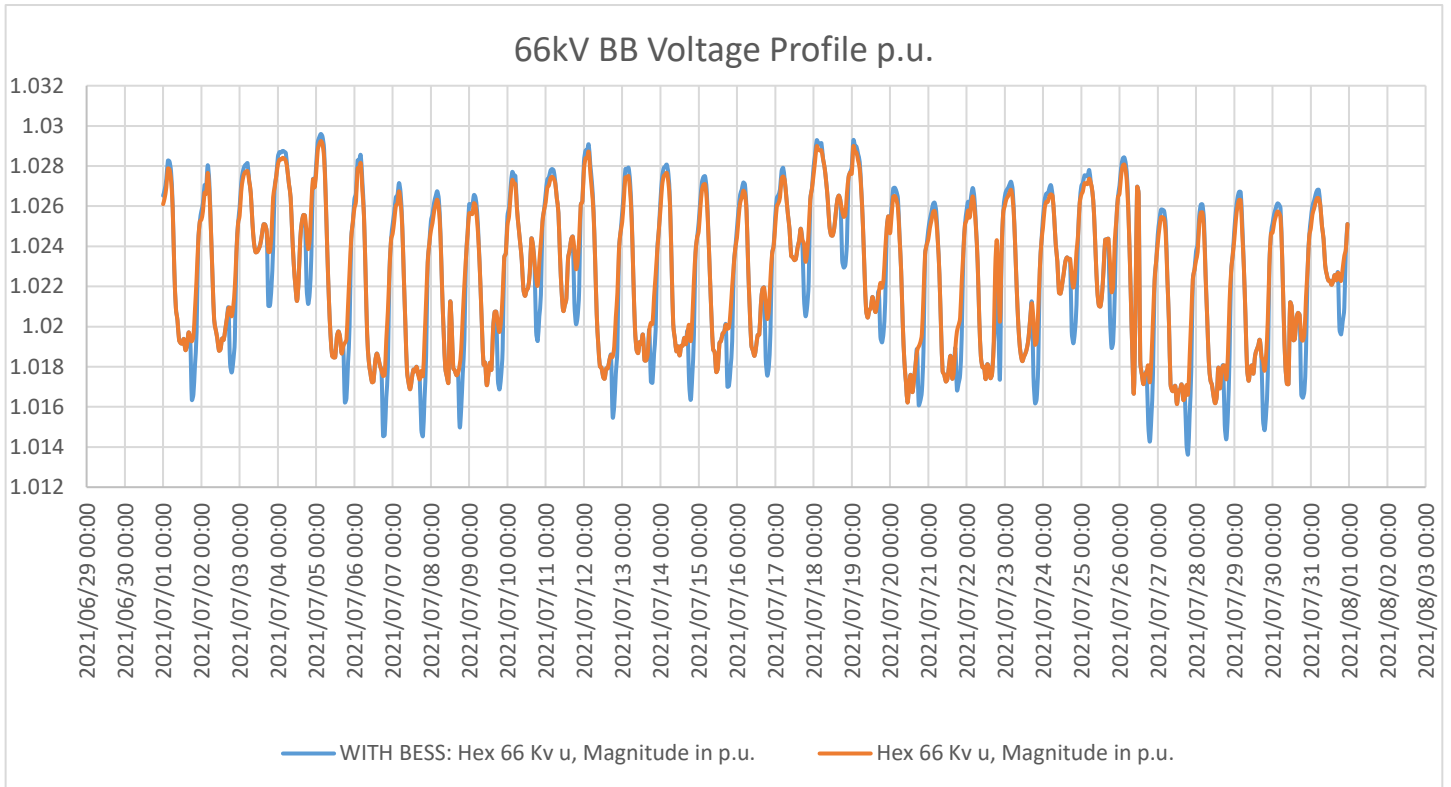


Figure 4.29 Hex 66kV BB Voltage with vs without BESS

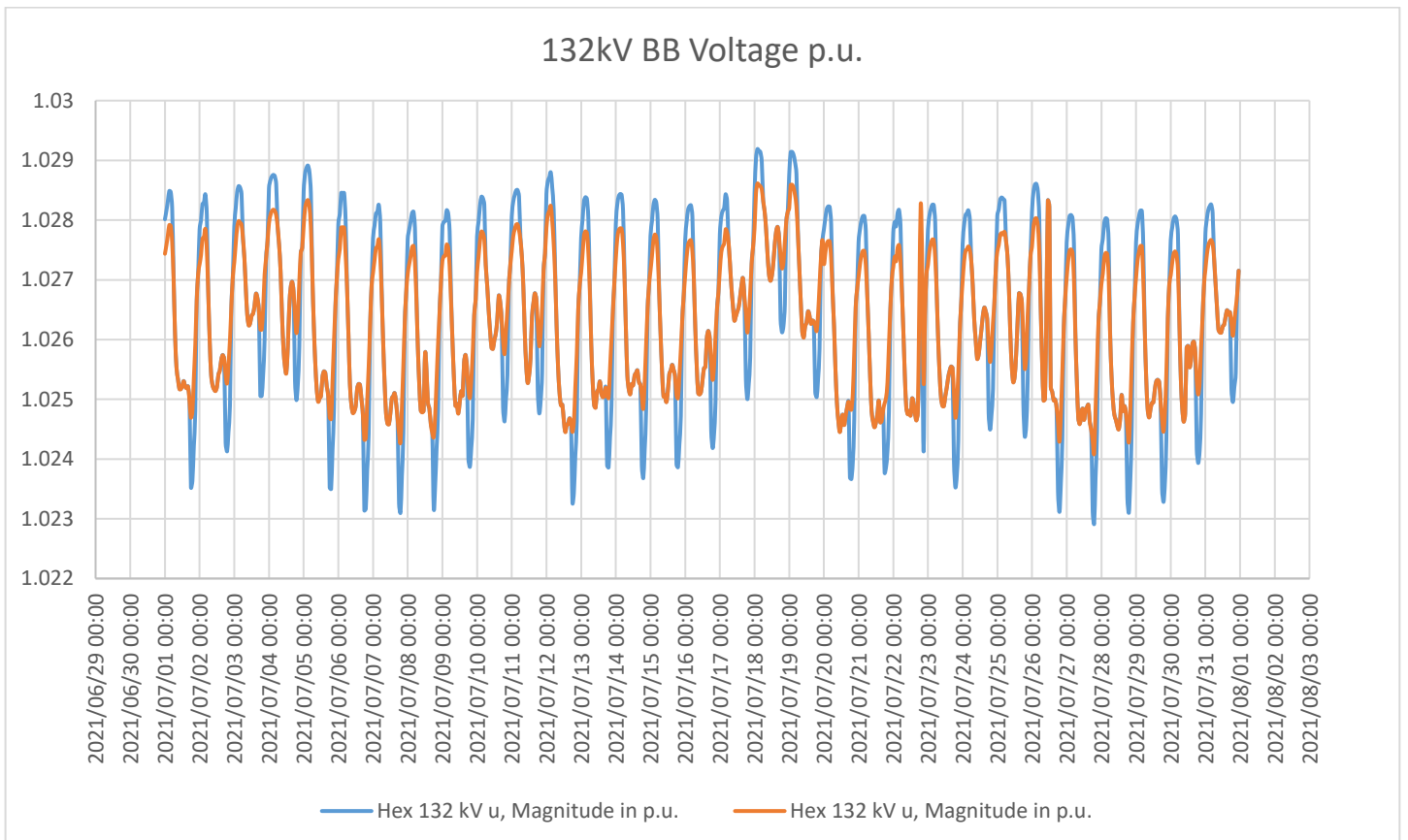


Figure 4.30 Hex 132kV BB Voltage with vs without BESS

#### 4.2.4 Local Network Constraints

The simulation results show that when BESS is charging, the 66/11 kV TRFRs are loaded above their normal rating (122%). The TRFRs are highlighted in red on diagram 4.26, indicating overloaded equipment. Furthermore, if one TRFR fails, the remaining transformer cannot handle the entire load. A transformer upgrade or a third transformer is required. This risk was acknowledged and Hex 66/11kV transformers are currently being upgraded to 20MVA each.

## **4.3 Results Analysis**

Skaapvlei and Hex BESS sites were investigated, simulated on DigSilent, and results were recorded and saved for analysis. The findings will be discussed under the following headings:

### **4.3.1 BESS for Curtailment Alleviation**

Wind generation is being curtailed during the early hours of the morning at Eskom. The problem is that the wind does not have the ability to decide to blow only during peak times, so it is frequently discovered that there is a lot of wind blowing between midnight and 4AM, which happens to be a time of low load when less power is required, so curtailment is gets implemented. During this investigation, it was discovered that BESS could play a significant role by storing power in the early hours of the morning and releasing it during peak load between 17:00 and 21:00.

### **4.3.2 BESS for Voltage Support**

During results analysis, it was noted that the voltage rises during charging period for both BESS plants and decreases during discharge period. On both Skaapvlei and Hex cases, there are no voltage violations seen. The main aim of having a BESS plant is to ensure that it supports the network during time of need, which is peak time of the grid. In the case of South African Grid, peak time is noted to be between 17:00 – 21:00. That is when BESS is expected to discharge into the network. The matter of voltage drop during discharging period is bit concerning as the network operator would like to see the voltage boosted during peak periods.

## 5 CONCLUSION, RECOMMENDATIONS AND FUTURE WORK

### 5.1.1 Conclusion

The deployment of battery energy storage systems was investigated in this dissertation using two Eskom sites. On DigSilent Powerfactory, a series of simulations were run to accept or not accept the hypothesis and answer the research questions.

Eskom is curtailing wind generation in the early hours of the morning. The challenge is that the wind cannot choose to blow only during peak hours; hence, it is frequently observed that there is a great deal of wind between midnight and 4 a.m., which is a time of low load when less power is required; therefore, curtailment is adopted. During this analysis, it was determined that BESS might play a significant role by storing energy in the early morning and releasing it between 17:00 and 21:00 during peak demand. However, this is dependent on where on the network the BESS is placed. It might be more beneficial to place it closer to the wind plant and closer to where it will be used by load to avoid transmission losses. The other factor to consider is means of evacuating the power during peak time. The equipment needs to have enough capacity to accommodate the power discharge from the battery as well as charging load when the battery is charging up.

As a result of the investigation, we would like to accept the hypothesis and conclude that BESS can mitigate renewable power curtailment by storing power during an off-peak period to use during a time of need.

On both the Skaapvlei and Hex examples, the voltage profile increases during the charging time and drops during the discharge period nevertheless, no voltage violations were observed. The primary objective of having a BESS plant is to ensure that it supports the network during peak grid demand. The highest peak period for the South African Grid is between 17:00 and 21:00. It is anticipated that BESS will discharge into the network at this time. Voltage decrease during discharge periods is concerning because the network operator would want to see the voltage increased during peak hours. One of the reasons is that voltage control at the busbar (a point in an electrical substation or distribution system where multiple circuits are connected) is typically managed by other devices such as transformers, voltage regulators, and capacitor banks. These devices are designed to regulate voltage levels and ensure that they remain within acceptable limits. BESS is primarily focused on energy storage and management and may not have the primary function of voltage regulation.

Consequently, we cannot accept my hypothesis which says that BESS can also provide voltage support on constrained networks by boosting voltage at a point of connection. This requires more research to be done on how the BESS should be operated to boost voltage at the point of connection.

## 5.1.2 Recommendations

Based on conclusions made, the author therefore recommends the following:

- The transformers and lines capacities should be considered, especially during charging and discharging times.
- During the charging period, the battery becomes a load, adding to the substation's load. It may overload the network if it is charging at full capacity.
- A workaround could be to charge it at 85% capacity or less, which will take longer to avoid overloading lines or transformers.
- A backup plan in case one of the transformers or lines fails should also be considered. The network should be designed for N-1 contingency, which means it should be stable when one piece of equipment fails.

## 5.1.3 Future Work

The author recommends that future research should address the following questions:

- How can BESS be optimized to bolster voltage during discharge periods, especially in situations where fragile networks necessitate voltage support?
- What is the impact of BESS on technical losses within the power system?
- In what ways can BESS be effectively employed to alleviate congestion and resolve bottlenecks in constrained networks?
- How can we quantify the return on investment for BESS in the context of wind power curtailment scenarios?
- Should priority be given to providing ancillary services to the System Operator when deploying BESS on the Eskom Grid?
- How can BESS contribute to black start capabilities and assist in power system restoration in the event of a blackout?

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# Annexure A: Hex Plant Model

