TIER 3: Transaction Advisors / SAEP Leadership / USAID COR / USAID ACOR

VRE Integration Studies in Malawi

ESCOM Malawi BESS Procurement

Technical Support

FINAL

November 14, 2023

I. ACRONYMS

Acronym	Definition
AVR	Automatic Voltage Regulator
BESS	Battery Energy Storage System
DR	Demand Response
Freq	Frequency
Hz	Hertz
kA	Kilo-Amps
kV	Kilo Volt
mHz	milli Hertz
ms	milli seconds
MVA	Mega Volt Amperes
MW	Mega Watt
Nan	Nanjoka
Nkh	Nkhotakota
PFR	Primary Frequency Response
POC	Point of Connection
pu	Per Unit
PV	Photo Voltaic
RE	Renewable Energy
RoCoF	Rate of Change of Frequency
SAPP	Southern Africa Power Pool
T1	Transformer 1
USAID	United States Agency for International Development
vRE	Variable Renewable Energy

II. TABLE OF CONTENTS

1. INTRODUCTION

Malawi's transmission and distribution utility, ESCOM, has successfully commissioned 101 MW solar photovoltaic (PV) installations. The solar PV installations are divided into three solar PV plants: the 60 MW Salima, 21 MW Phanes, and 20 MW Golomoti. The commissioning of solar PV plants – variable renewable energy (VRE) generation – has gone a long way in addressing Malawi's energy needs; however, this has given rise to new problems, such as intermittency, no dispatchability, and absence of mechanical inertia. The variability introduced by the solar PV plants has caused frequency excursions that often result in under-frequency load shedding (UFLS) and hydropower units tripping due to high frequency.

ESCOM is in the process of writing specifications for the procurement of a 20 MW Battery Energy Storage Systems (BESS) with 30 MWh storage to help with frequency stability in the power system. BESS are being increasingly used in Flexible AC Transmission Systems (FACTS) applications as a way to improve the voltage, frequency, oscillatory and/or transient stability of the system and hence enhance the reliability of power supply. These applications include different FACT controllers, where the storage devices are interfaced with the power system through either shunt or series-connected voltage-sourced converters (VSC).

The USAID Southern Africa Energy Program (SAEP), a Power Africa initiative, has conducted a study for frequency control requirements (secondary frequency) and initial settings of a 20 MW BESS with 30 MW and proposed the initial BESS settings.

This report will focus on primary frequency control to confirm the proposed BESS settings as well as a voltage control study to determine the voltage control philosophy for the integration of 20 MW BESS with 30 MWh storage capacity.

2. SCOPE OF WORK

This section outlines the project scope. The proposed 20 MW BESS with 30 MWh storage capacity will be integrated into the ESCOM power system network at Kanengo substation. The main objective of the task is to confirm the specified primary frequency settings in DigSilent for the 20 MW BESS with 30 MWh storage capacity and determine a voltage control philosophy. The scope of work is therefore outlined as follows:

- Undertake a Primary Frequency Response (PFR) study to confirm the proposed BESS settings.
- Recommend suitable PFR/Fast Frequency Response (FFR) settings for BESS deployment in the ESCOM power system network.
- Undertake a voltage control study to investigate the impact of BESS at Kanengo Substation.
- Recommend appropriate voltage control settings for BESS integration at Kanengo.

3. KEY ASSUMPTIONS AND TECHNICAL CRITERIA

The study follows the following key assumptions:

3.1. STUDY YEAR

The year of 2023 is considered as the study year. The peak and light loading for 2023 will be considered.

3.2. ESCOM CASEFILE

The 2021 updated casefile depicting the transformers at the Kanengo substation and Old Town in line with the JICA project is used.

3.3. SOFTWARE TOOL

The BESS and voltage control studies are conducted using DigSilent Power Factory software. DigSilent is suited for steady-state and dynamic studies of electric power systems.

3.4. NETWORK LOADING

The study considers the following network loading as provided by ESCOM:

- The peak loading of 368 MW
- The light loading of 220 MW.

The light loading is assumed to be 60% of the peak load.

The light-loading network conditions present worst-case conditions for the PFR study as the ESCOM system will experience lowest inertia (rotational energy) around this time. Therefore, the PFR/FFR studies done here will focus on light loading only.

3.5. GENERATION AND GOVERNING ASSUMPTION

- The renewable energy generation assumption is given as follows:
  - 101 MW of solar PV generation is assumed for the study.
    - 20 MW at Golomoti 132 kV busbar
    - 21 MW at Phanes 11 kV busbar
    - 60 MW at Salima 132kV busbar
  - Solar PV generation was left at full output under light loading and zero under peak loading.
- All other plants were left at their dispatched levels as per the system casefile.

3.6. THERMAL AND VOLTAGE LIMITS

- 100% of normal continuous ratings were observed on all lines and transformers.
- 0.95 pu and 1.05 pu were observed for the lower and higher voltage thresholds respectively.

4. METHODOLOGY

This section outlines the study's methodology.

4.1. PROJECT COMMENCEMENT AND DATA COLLECTION

The project commenced after the study objectives, the scope of work, and key assumptions were outlined. The latest data on the ESCOM transmission and distribution system was obtained from the ESCOM system operator.

4.2. DEVELOPMENT OF NETWORK MODELS

Based on the data received from ESCOM, a steady-state model for peak loading and light loading was developed for the study. The DigSilent model sourced from ESCOM already had the BESS model with a steady state and dynamic model. The SAPP integration at the 400 kV Phombeya substation was considered when studying the effects of the interconnection on the system. Figure 1 shows the proposed study area.

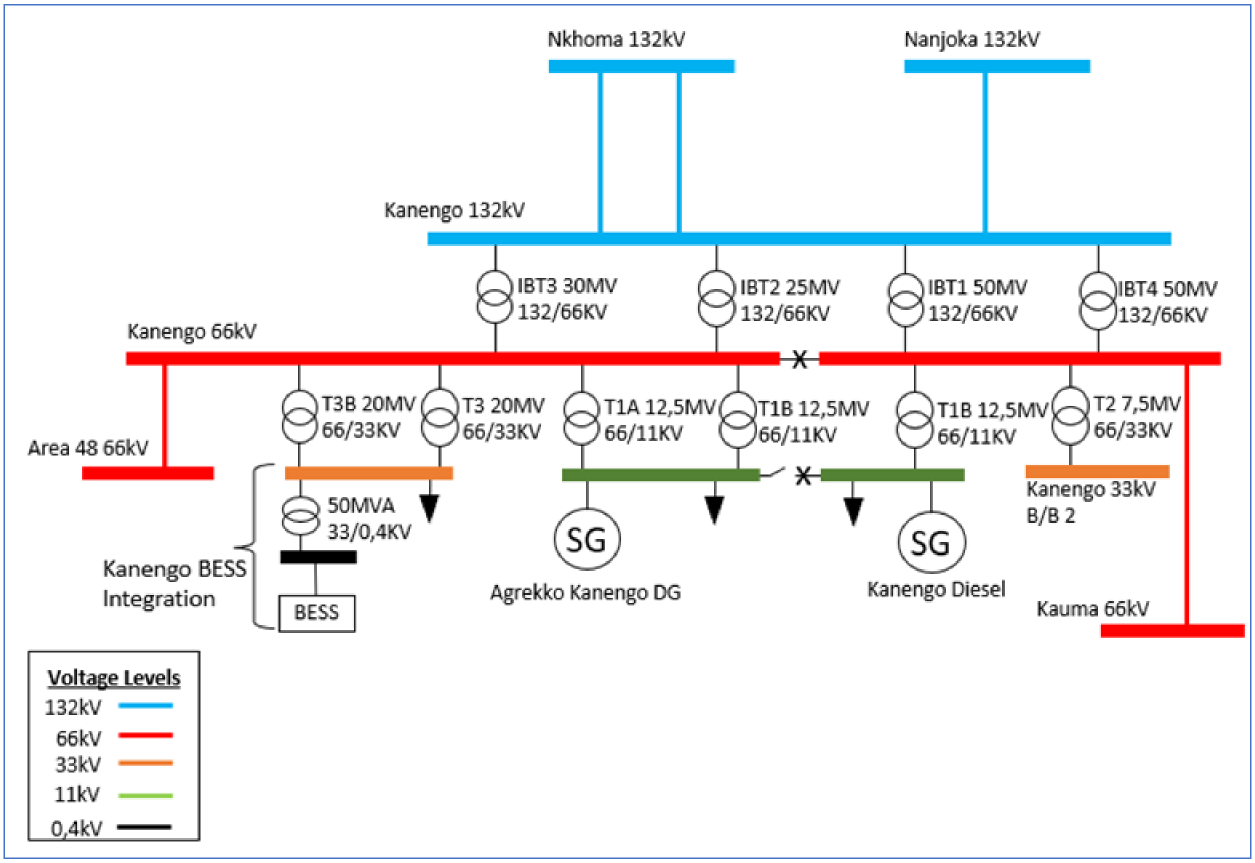

Figure 1: Study area for the project.

4.3. PRIMARY FREQUENCY RESPONSE STUDY

A PFR study investigated the impact of 20 MW BESS on PFR requirements in ESCOM's network. The study was conducted by tripping the largest units in the Malawi power system (Kapichira unit 2 at full load – 30 MW) as well as the 60 MW Salima solar PV plant, which is possible only during the day. The following scenarios were conducted:

Kapichira Unit 2 trip from 30 MW (full load)

- **Governing units only**: Quantify the amount of primary frequency reserves required by the governors of the synchronous machines to arrest the frequency at 49.5 Hz, as per the grid code requirement.
- **20 MW BESS with governors**: Quantify the amount of governing needed to supplement the 20 MW BESS for primary frequency response.
    - Use the proposed BESS settings of 0.4% droop and +/- 0.05Hz frequency dead band.
- **20 MW BESS with SAPP interconnection:** Assess the impact of SAPP interconnection and 20 MW BESS as primary frequency response.

Salima trip from 60 MW and 40 MW

- **Salima curtailment** (the prevailing curtailment regime with 40 MW max limit for Salima)
  Drop Salima to 0 MW, test PFR, and report on the amount of governing required.
- **Salima plant at 60 MW** full loading
  Drop Salima to 0 MW, and test PFR, and report on the amount of governing required.

4.4. VOLTAGE CONTROL STUDY

Voltage control philosophy and settings for voltage control at Kanengo substation

Determine the voltage settings for the 20 MW BESS by assessing different voltage setpoints. The following scenarios were assessed:

- **Peak loading**: Determine the suitable voltage setpoint and subsequent reactive power support under peak loading.
    - Scenario 1: Before BESS integration
    - Scenario 2: BESS integration with 1 pu setpoint
    - Scenario 3: BESS integration with 1.03 pu setpoint
    - Scenario 4: BESS integration with 0.98 pu setpoint
- **Light loading**: Determine the suitable voltage setpoint and subsequent reactive power support under light loading.
    - Scenario 1: Before BESS integration
    - Scenario 2: BESS integration with 1 pu setpoint
    - Scenario 3: BESS integration with 1.03 pu setpoint
    - Scenario 4: BESS integration with 0.98 pu setpoint
- **Voltage variation**: Determine the voltage fluctuation of 132 kV busbars caused by the sudden drop of Salima PV plant from 100% to 40% before and after BESS integration.
    - The aim of the study is to determine the effect of 20 MW BESS on the network when the solar PV plant experiences sudden cloud cover.

5. PRIMARY FREQUENCY RESPONSE STUDIES

This section will focus on PFR studies to determine and confirm BESS frequency settings at Kanengo in the ESCOM network. These studies will be assessed under light loading conditions only, as light loading gives worst case conditions for frequency stability studies.

5.1. PFR RESPONSE WHEN KAPICHIRA UNIT 2 TRIPS FROM FULL LOAD (30 MW)

In scenario 1, the primary frequency studies are carried out under system light loading when considering Kapichira as the largest unit trip in the ESCOM network. Kapichira will be considered the largest unit in the ESCOM system only when the Salima PV Plant is unavailable or not generating, such as at night.

5.1.1. GOVERNING UNITS ONLY

Below, the primary frequency reserves required by the ESCOM power system to turn the frequency at 49.5 Hz under light loading are quantified. Figure 2 shows the frequency response and the turbine power of the power system when the 30 MW Kapichira unit 2 is lost. The governing units have a dead band of +/- 0.15 Hz, meaning there is no response from the governors when the frequency is operating between 49.85 Hz to 50.15 Hz.

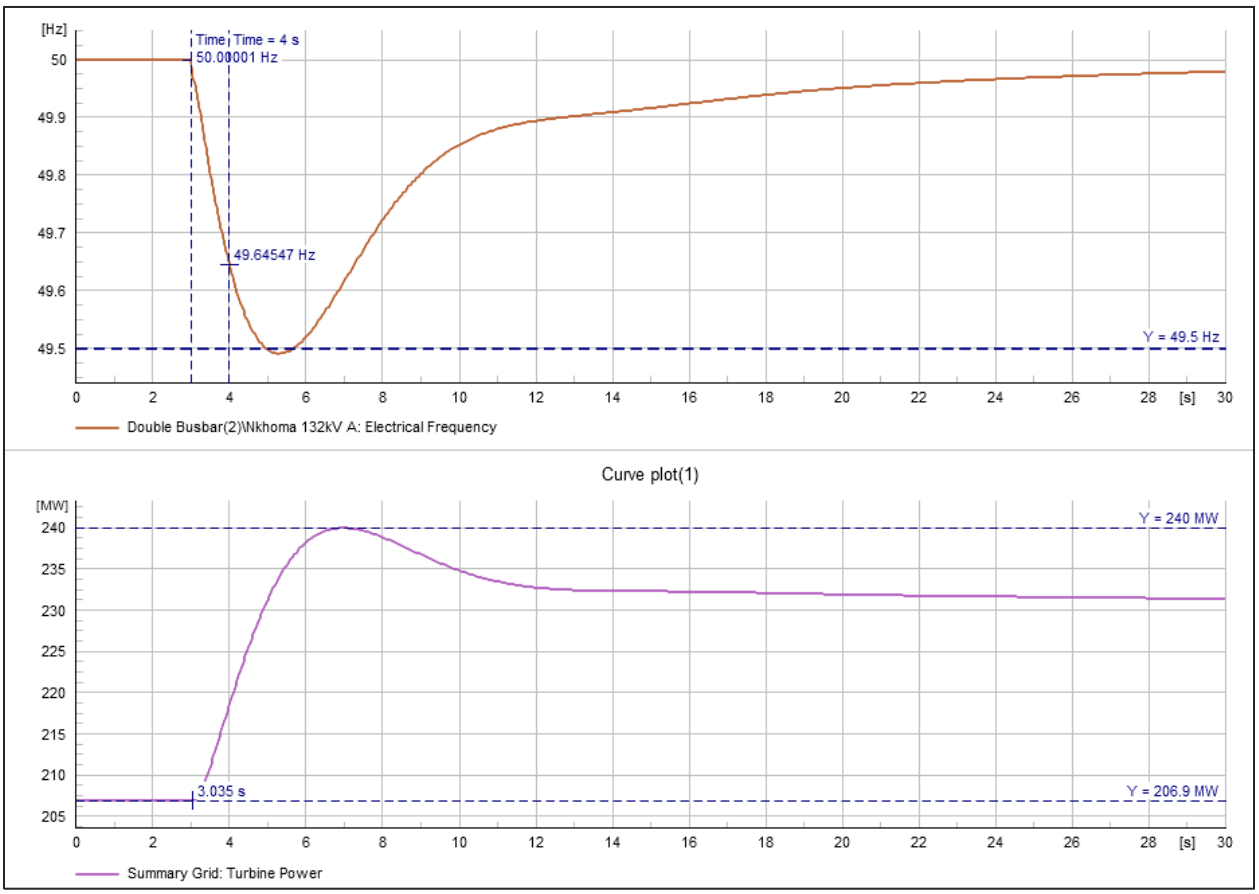

Figure 2: Frequency response and turbine power when only governing is used.

Figure 2 shows that primary frequency reserves of about 34 MW are needed to turn the frequency at 49.5 Hz during system light loading conditions. The Rate of Change of Frequency (RoCoF) is measured to be -325 mHz per second. Table 1 summarizes the simulation results for primary frequency response under light loading when Kapichira unit 2 is lost.

Table 1: Results when governors are used for primary frequency response under light loading.

Parameter	Results
Primary frequency Reserves (MW)	34
RoCof (mHz/s)	-325
Nadir (Hz)	49.50

34 MW of governing reserves are required to turn the frequency at 49.5 Hz when Kapichira unit 2 lost at full load (30 MW) during system light loading conditions.

5.1.2. GOVERNING UNITS WITH 20 MW BESS

This section looks at the impact of 20 MW BESS on PFR requirements in the ESCOM system. The 20 MW BESS settings are as follows:

- The dead band of 0.05 Hz is used. That is, there is no response from the BESS when the power system frequency deviates between 49.95 Hz and 50.05 Hz.
- Droop is set at 0.4%. This means that the BESS will increase by 20 MW if the frequency goes from 49.95 Hz to 49.75 Hz and will decrease by 20 MW if the frequency goes from 50.05 Hz to 50.5 Hz.
- It is assumed that the BESS is fully charged when the faults occur.

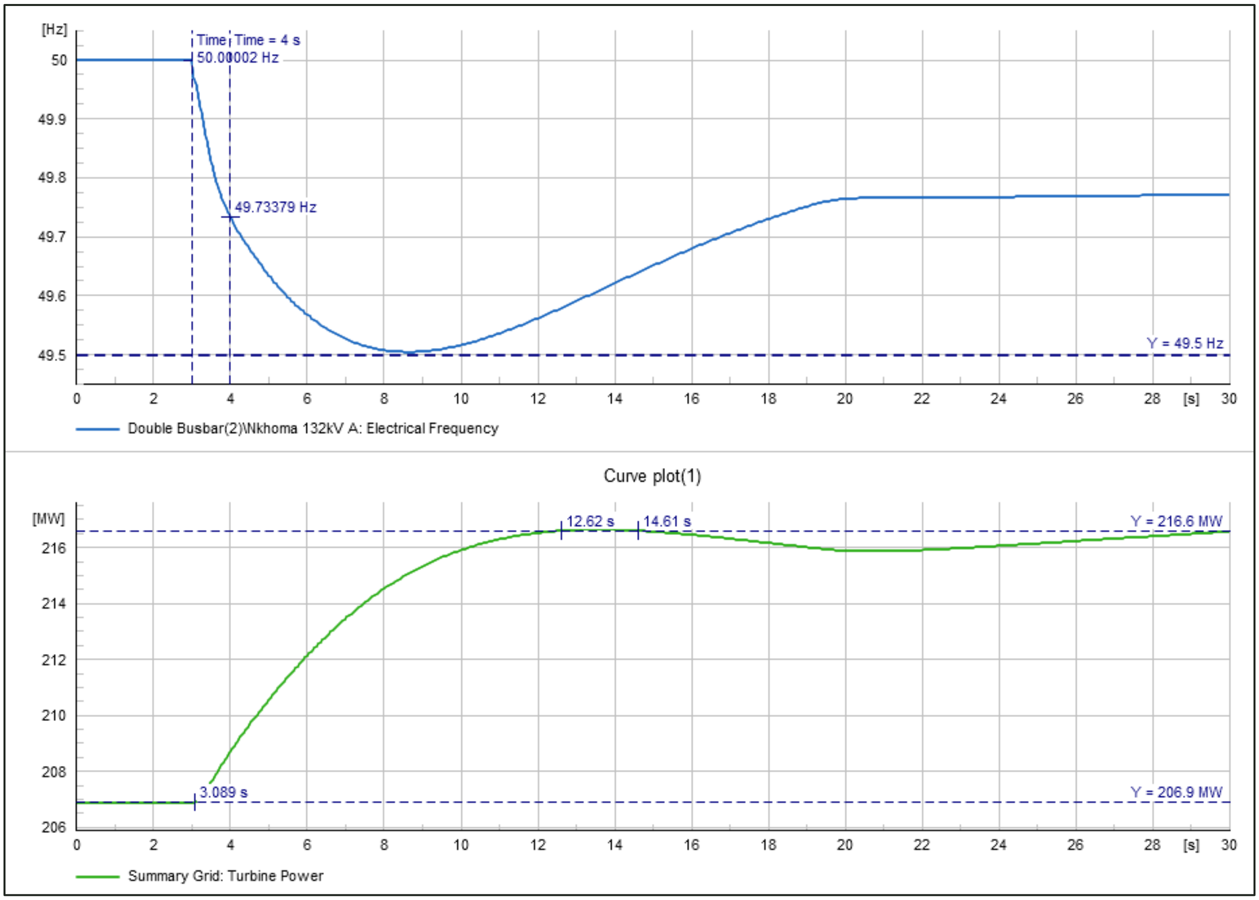

Figure 3: Frequency response and turbine power response when the governing units are supplemented by a 20 MW BESS.

Figure 3 indicates that the RoCoF decreased when compared with the previous case where only governing units were used for primary frequency response. This is attributed to the fact that BESS gives a much faster response. It can further be noted that the governing power needed to turn the frequency at 49.5 Hz has decreased.

Figure 4 below shows the battery response when 20 MW BESS is used for primary frequency response with the governing units. The 20 MW BESS shows an almost instantaneous response to the frequency deviation, with a rise time of 608 ms.

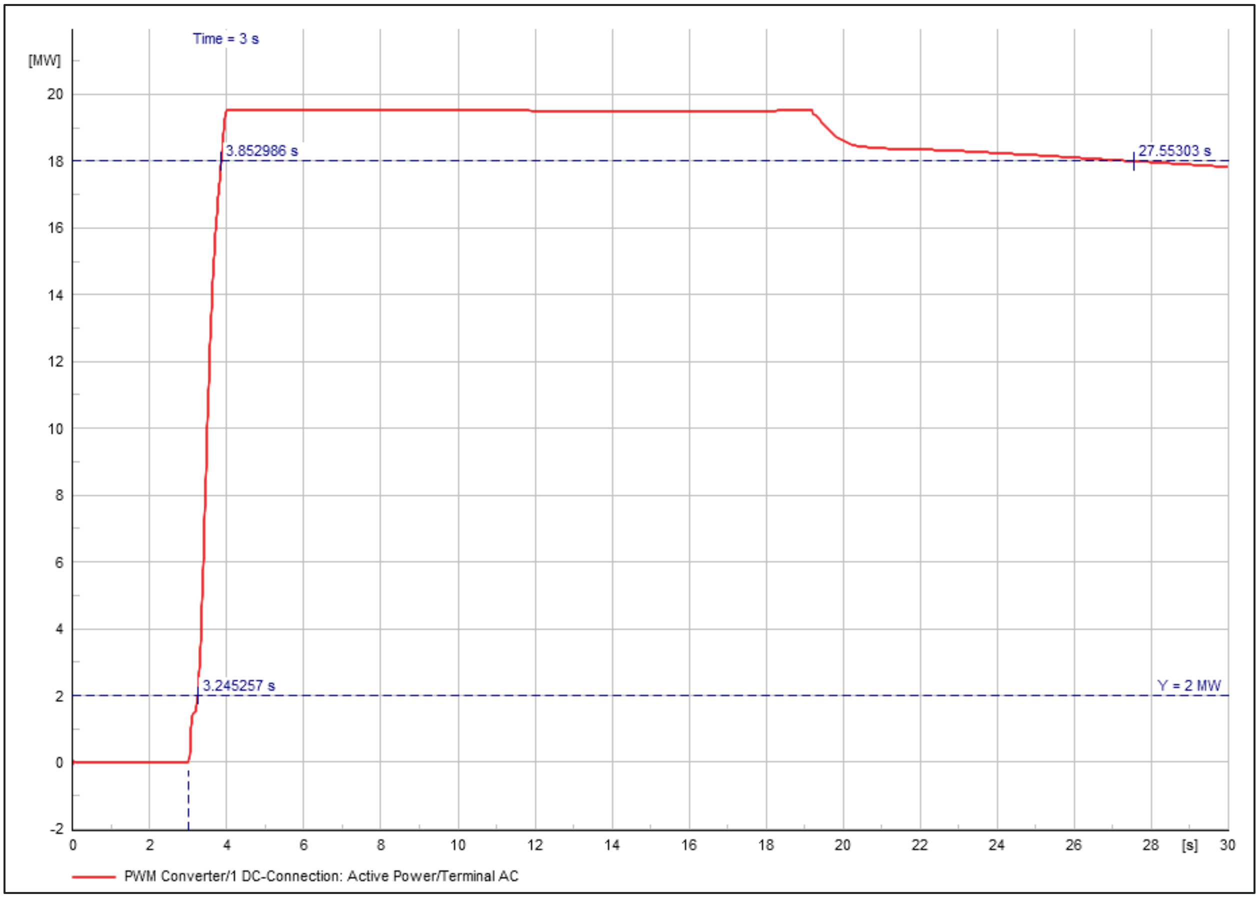

Figure 4: Response when the governing units are supplemented by a 20 MW BESS.

When deploying BESS for PFR response, the primary frequency reserves decreased from 34 MW in the previous section to almost 9.7 MW. This shows that adding a 20 MW BESS to the ESCOM power system for primary frequency response will reduce the amount of system reserves required to turn the frequency at 49.5 Hz when the largest (30 MW) unit is lost. Table 2 below shows the results of the frequency response.

Table 2: Results when the 20 MW BESS is used to supplement governors for primary frequency response under light loading.

Parameter	Results
Governing Reserves (PFR) (MW)	9.7
BESS FFR (MW)	20
RoCof (mHz/s)	-266
BESS Rise time (ms)	608
Nadir (Hz)	49.49

The battery rise time is 608 ms and the RoCoF during the fault went from -325 mHz per second when using only the governing units to -266 mHz per second when using the governing units with 20MW BESS supplementation.

5.1.3. IMPACT OF SAPP INTERCONNECTOR ON GOVERNING RESERVES/PFR

This section investigates the impact of the SAPP interconnector (at Phombeya) on PFR requirements from governing units.

The modelling of the SAPP interconnector is as provided by the ESCOM system operator and it is assumed that the static and dynamics response of the model represents the SAPP interconnector.

Figure 5 shows the frequency response when the ESCOM power system is connected to the Mozambique system via SAPP interconnector at Phombeya.

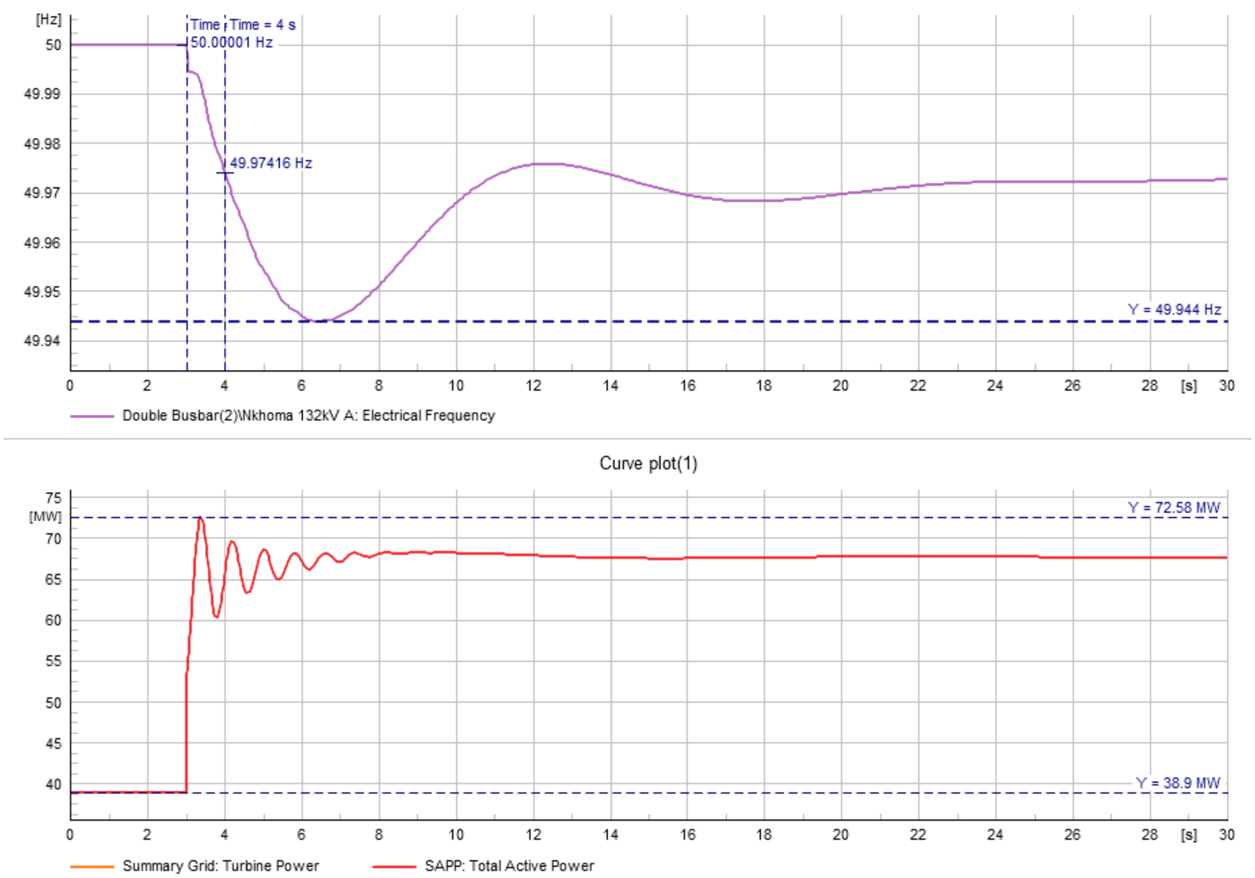

Figure 5: Frequency response and governing response when the SAPP interconnector is used to supplement the ESCOM governing units.

Figure 5 indicates that the governing response of about 34 MW is provided by the interconnected system to arrest the frequency at 49.94 Hz.

This scenario shows that the entire ESCOM network will rely on the Mozambique-Malawi interconnector for PFR requirements. Given that the ESCOM network is small compared to the SAPP network, the ESCOM network will fully depend on the SAPP interconnection for primary frequency response.

Table 3: Results when the SAPP interconnector is used for primary frequency response under peak loading.

Parameter	Results
Primary frequency Reserves (MW)	38
RoCof (mHz/s)	-25.8
Nadir (Hz)	49.94Hz

The RoCoF during the fault went to -25.8 mHz per second. This shows that the SAPP integration can provide better frequency support to the ESCOM system.

5.1.4. IMPACT OF SAPP INTERCONNECTOR ON BESS/FFR

This section investigates the impact of the SAPP interconnector on PFR when 20 MW BESS is integrated in the ESCOM network. The 20 MW BESS settings are as follows:

- The dead band of 0.05 Hz is used. That is, there is no response from the BESS when the power system frequency deviates between 49.95Hz and 50.05Hz.
- Droop is set at 0.4%. This means that the BESS will increase by 20 MW if the frequency goes from 49.95 to 49.75Hz and will decrease by 20 MW if the frequency goes from 50.05Hz to 50.5Hz.
- It is assumed that the BESS is fully charged when the faults occur.

The modelling of the SAPP interconnector is based on the model provided by the ESCOM system operator and it is assumed that the static and dynamics of the model represent the SAPP interconnector.

Error! Reference source not found. below shows the frequency response when the 20 MW BESS is used for primary frequency while the ESCOM power system is connected with the Mozambique system via the SAPP interconnector.

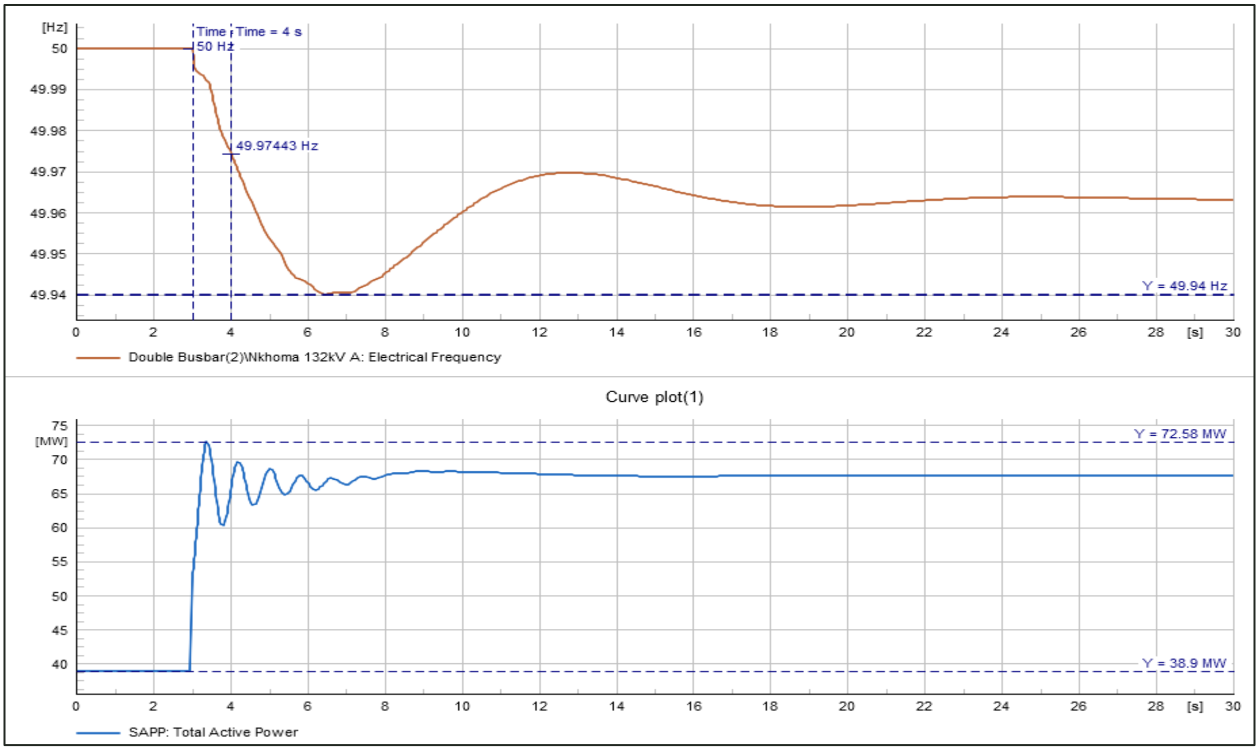

Figure 6: Frequency response and SAPP interconnector response when 20 MW BESS is used for the primary frequency when the ESCOM grid is connected to the SAPP interconnector.

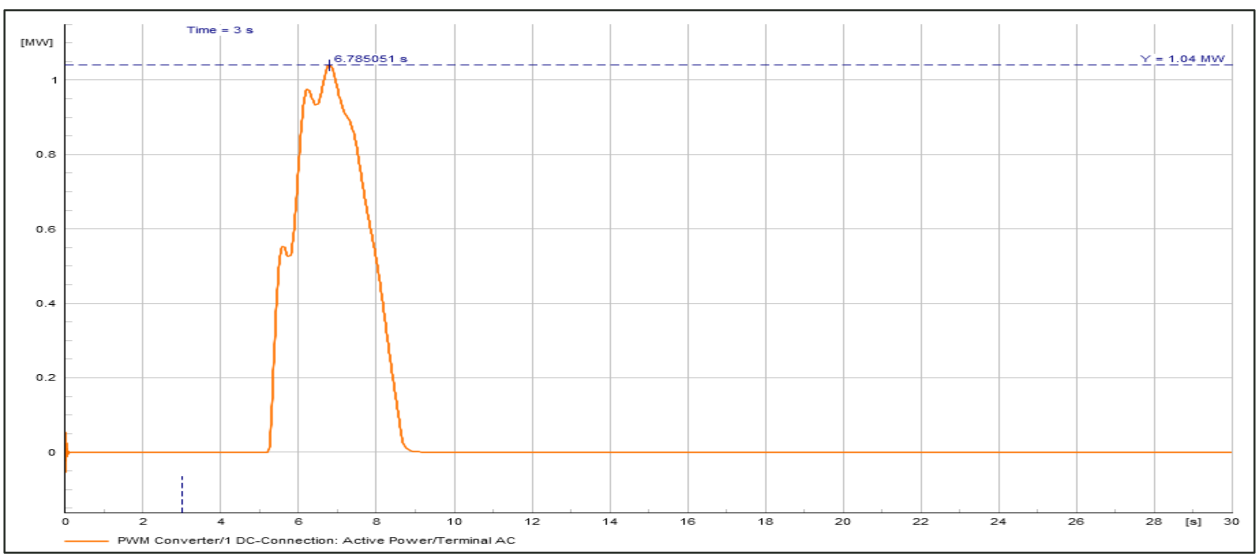

Figure 7: BESS response when 20 MW BESS is used as the primary frequency response when the ESCOM system is connected to the SAPP interconnector.

Table 4: Results when 20 MW BESS is used as PFR while the power system is connected to SAPP interconnection under peak loading.

Parameter	Results
Primary frequency Reserves (MW)	37.7
RoCof (mHz/s)	-26.3
Nadir (Hz)	49.94Hz
BESS Rise time (ms)	21.75
BESS power (MW)	6.79

From Figures 6 and 7 above and Table 4, it is evident that the interconnector will keep the frequency tightly within the dead-band even when the BESS integrated. The BESS hardly responded by about 1 MW during a trip of Kapichira. This scenario shows that the entire ESCOM network will rely on the Mozambique interconnector for PFR requirements even when 20 MW BESS is integrated.

5.2. PFR RESPONSE WHEN SALIMA PLANT TRIPS FROM FULL LOAD (60 MW)

In scenario 2, the primary frequency studies are carried out when the Salima solar PV plant is loaded at 60 MW. A trip of the plant from full load at 60 MW is simulated. This is done to depict worst case conditions during the day when the plant is generating. The scenarios under this section are done during system light loading conditions, as this presents worst case conditions for frequency stability studies.

5.2.1. GOVERNING UNITS ONLY

Figure 8 below shows the frequency response and the turbine power of the power system when the 60 MW Salima solar PV plant is lost. The governing units have a dead band of +/- 0.15 Hz and there is no response from the governors when the frequency is operating between 49.85 Hz and 50.15 Hz.

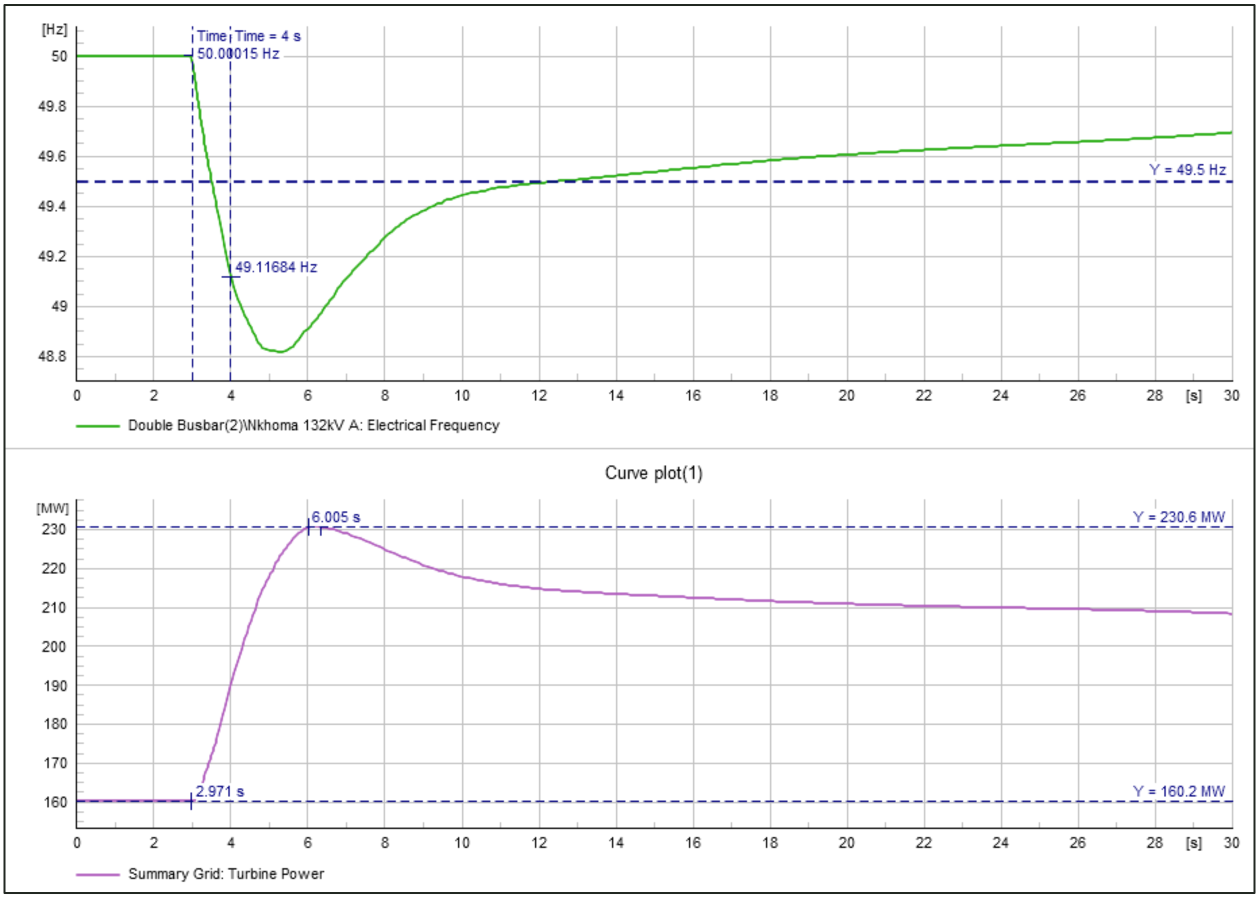

Figure 8: Frequency response and turbine power when only governing is used.

Table 5: Results when governors are used for primary frequency response under peak loading.

Parameter	Results
Primary frequency Reserves (MW)	70 MW
RoCof (mHz/s)	-883
Nadir (Hz)	48.8

From Figure 8 and table 5 above, it can be noted that a trip of the Salima plant from full load will result in the system frequency dropping to 48.8 Hz. Governing units provide about 70 MW of PFR reserves but this is not enough to arrest the frequency at 49.5 Hz. This can be attributed to the fact that this contingency is too big for the system to handle. The frequency response RoCoF is recorded at -883 mHz/s, an unpreceded figure as this number is close to the 1 Hz/s RoCoF, which would infringe on generator RoCoF limits.

5.2.2. GOVERNING UNITS WITH 20 MW BESS

The following scenario investigates the impact of 20 MW BESS on primary frequency requirements. The 20 MW BESS settings are given as follows:

- The dead band of 0.05 Hz is used. That is, there is no response from the BESS when the power system frequency deviates between 49.95Hz and 50.05Hz.
- Droop is set at 0.4%. This means that the BESS will increase by 20 MW if the frequency goes from 49.95 to 49.75Hz and will decrease by 20 MW if the frequency goes from 50.05Hz to 50.5Hz.
- It is assumed that the BESS is fully charged when the faults occur.

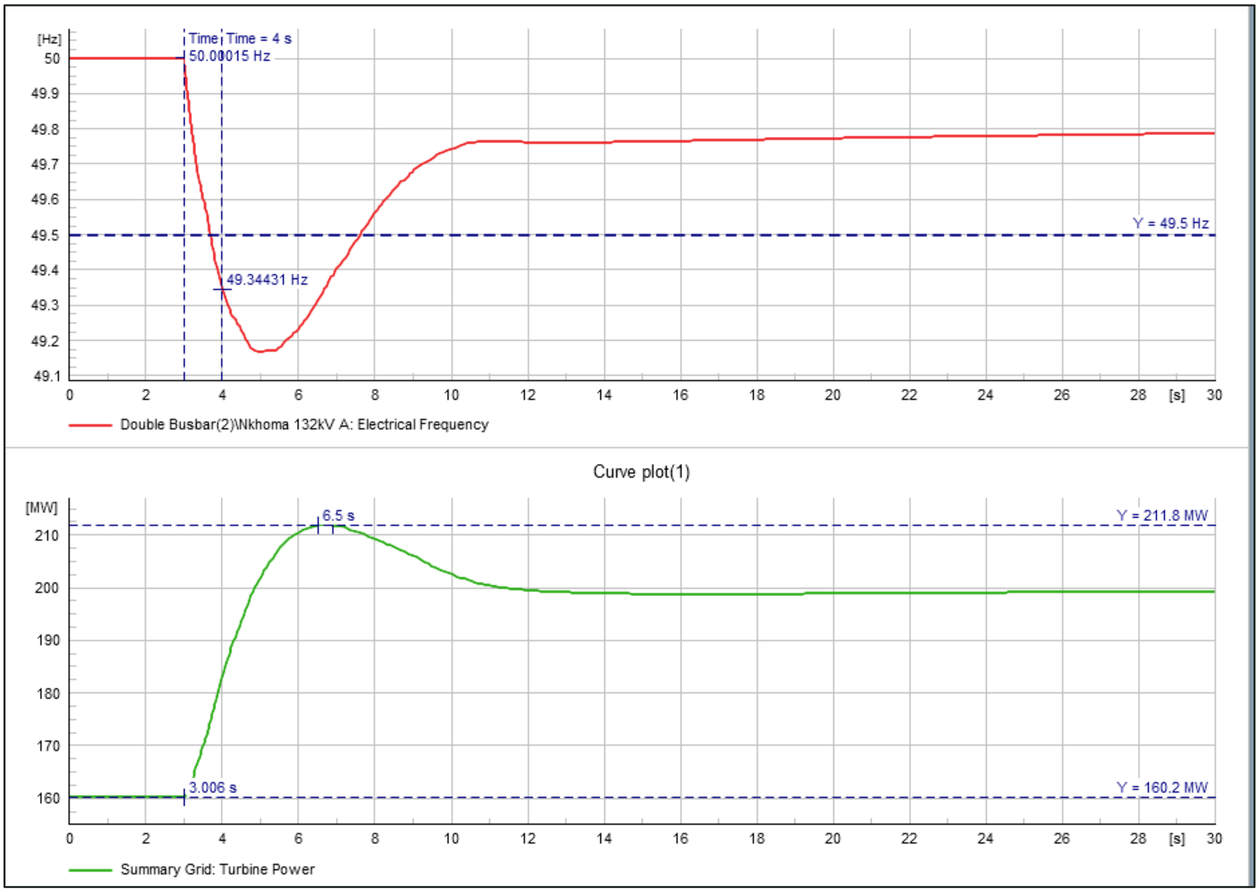

Figure 9: Frequency response and turbine power response when the governing units are supplemented by a 20 MW BESS.

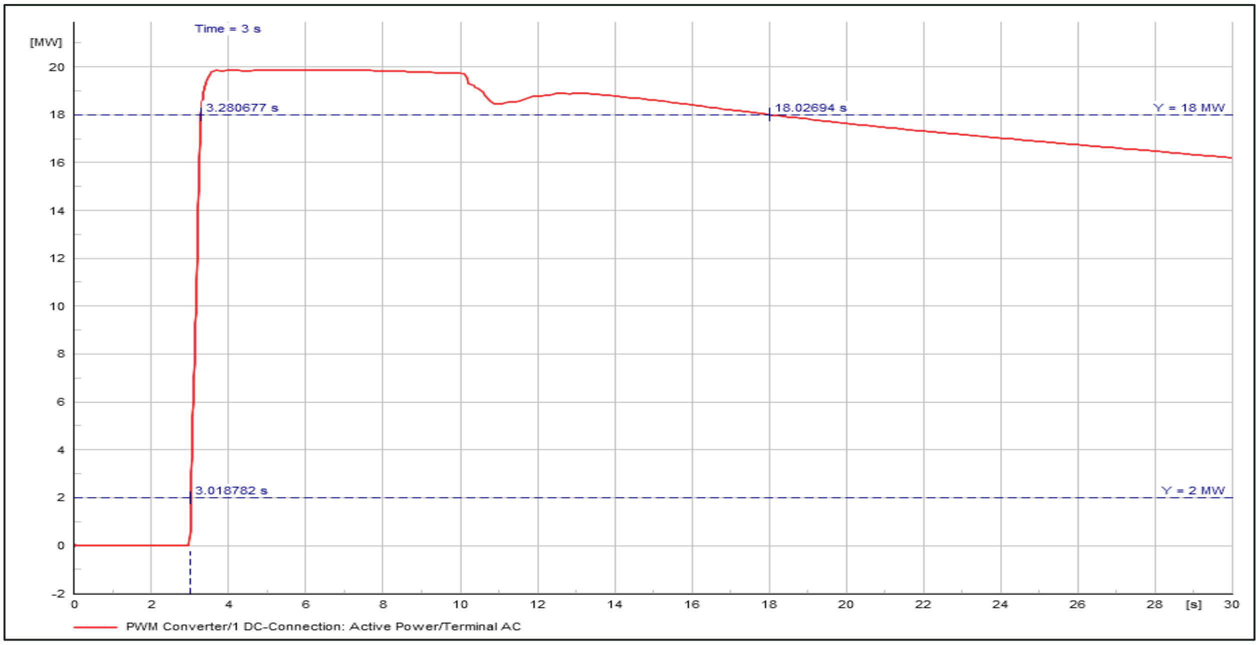

Figure 10: Response when the governing units are supplemented by a 20WM BESS.

Table6: Results when governors are used to supplement the 20 MW BESS for primary frequency response under peak loading.

Parameter	Results
Governing Reserves (PFR) (MW)	52
BESS FFR (MW)	20
RoCof (mHz/s)	-656
BESS Rise time (ms)	262
Nadir (Hz)	49.15

Figure9 and 10 and Table 6 above show that the RoCoF decreased when compared with the case where only governing units were used for primary frequency response. This is because the BESS response is much faster and instantaneous. The battery gave a full response of about 20 MW to assist with governing. However, even the presence of BESS cannot arrest the frequency at 49.5 Hz.

5.3. PFR RESPONSE WHEN SALIMA PLANT TRIPS FROM PARTIAL LOADING (40 MW) – PLANT CURTAILMENT

Scenario 3 conducts the primary frequency studies when the Salima solar PV plant is loaded at 40 MW. A trip of the plant from partial loading at 40 MW is simulated. This is done to depict worst-case conditions during the day when the plant is generating. The scenarios under this section are done during system light loading conditions as this presents worst-case conditions for frequency stability studies.

5.3.1. GOVERNING UNITS ONLY

Figure 11 below shows the frequency response and the turbine power of the power system when the 40 MW Salima solar PV plant is lost. The governing units have a dead band of +/- 0.15 Hz and there is no response from the governors when the frequency is operating between 49.85 Hz and 50.15 Hz.

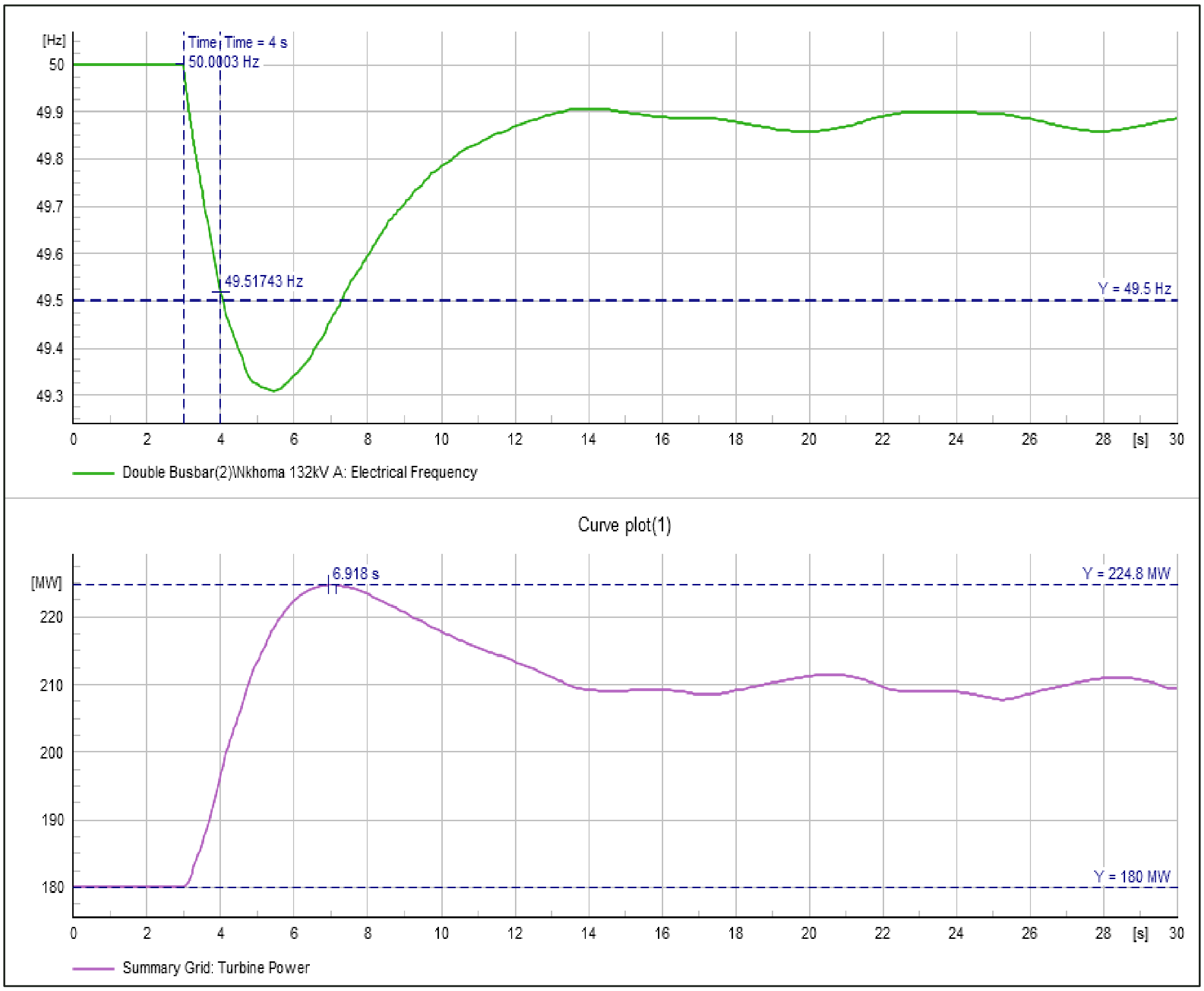

Figure 11: Frequency response and turbine power when only governing is used.

Table 7: Results when governors are used for primary frequency response when the 40 MW Salima solar PV pant is lost.

Parameter	Results
Primary frequency Reserves (MW)	44.8
RoCof (mHz/s)	-483
Nadir (Hz)	49.3

44.8 MW of governing reserves are not enough to turn the frequency at 49.5 Hz when the 40 MW Salima solar PV plant is lost. The nadir for this case is at 49.3 Hz, which is not far from activating the first stage of UFLS.

5.3.2. GOVERNING UNITS WITH 20 MW BESS

This scenario investigates the impact of 20 MW BESS on primary frequency requirements when the Salima plant is loaded at 40 MW. The 20 MW BESS settings are as follows:

- The dead band of 0.05 Hz is used. That is, there is no response from the BESS when the power system frequency deviates between 49.95 Hz and 50.05 Hz.
- Droop is set at 0.4%. This means that the BESS will increase by 20 MW if the frequency goes from 49.95 to 49.75Hz and will decrease by 20 MW if the frequency goes from 50.05 Hz to 50.5 Hz.
- It is assumed that the BESS is fully charged when the faults occur.

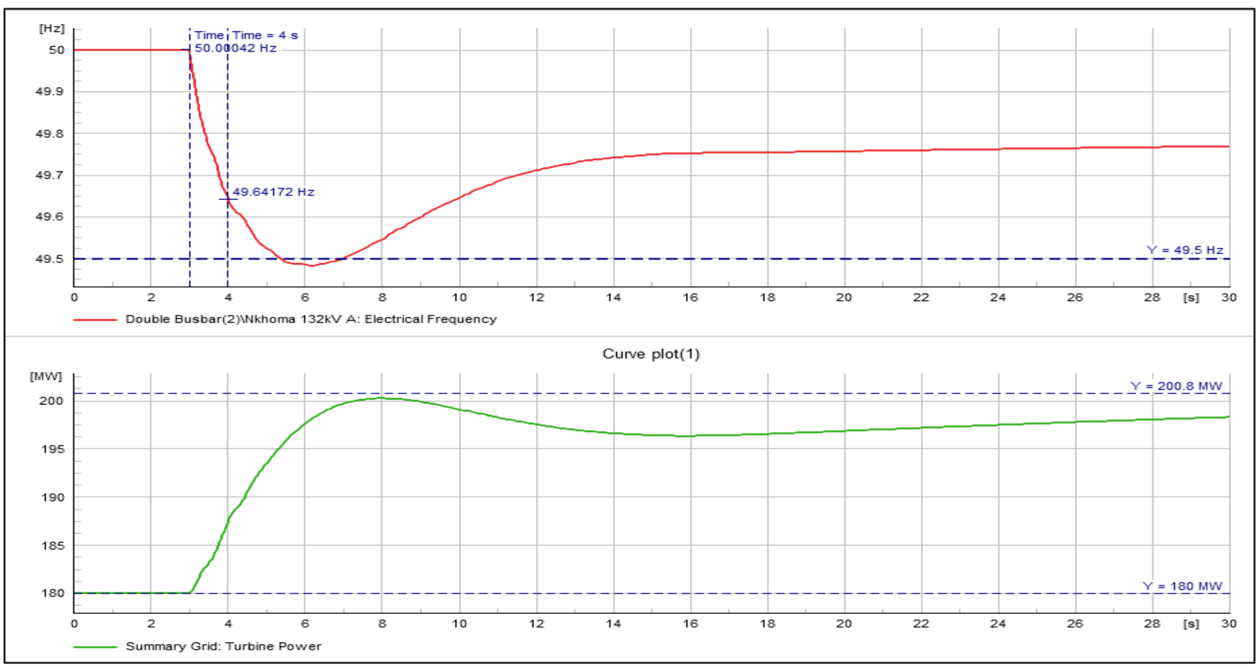

Figure12: Frequency response and turbine power response when the governing units are supplemented by a 20 MW BESS.

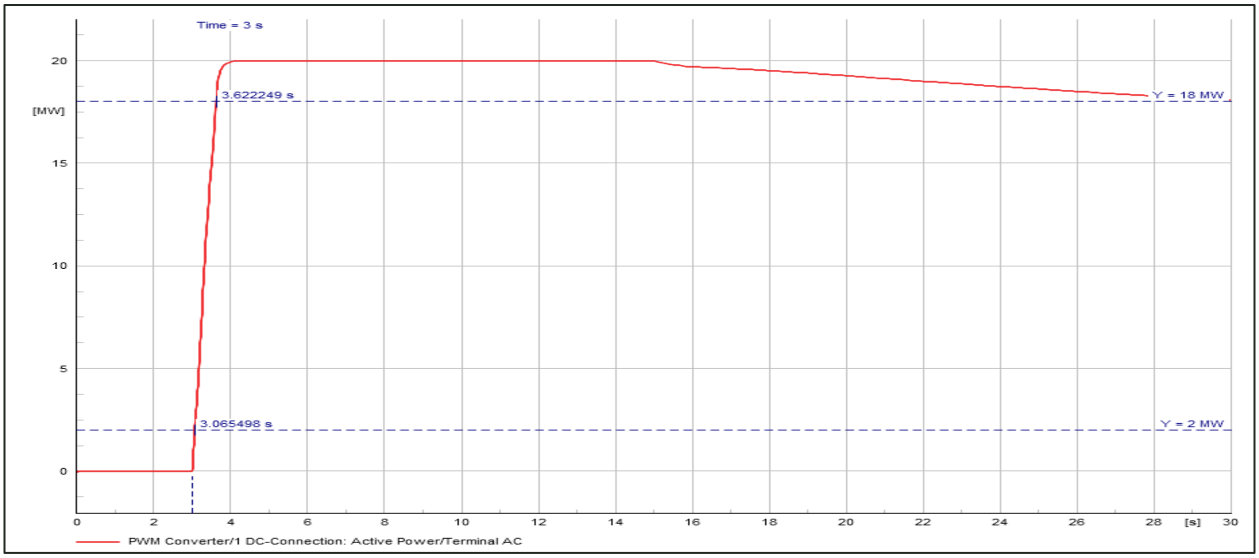

Figure13: response when the governing units are supplemented by a 20 MW BESS.

Table8: Results when governors are used to supplement the 20 MW BESS for primary frequency response under peak loading.

Parameter	Results
Governing Reserves (PFR) (MW)	20
BESS FFR (MW)	20
RoCof (mHz/s)	-358
BESS Rise time (ms)	557
Nadir (Hz)	49.48

From Figure 12 and 13 and Table 8 above, the primary frequency reserves of 44 MW are enough to turn the frequency at about 49.5HzThe RoCoF measures at -358 mHz per second. This clearly shows that BESS can assist the system with PFR reserves when the Salima plant is curtailed at 40 MW and should the plant trip from this loading.

5.3.3. SUMMARY OF 40 MW AND 60 MW SALIMA TRIP PFR STUDY ANALYSIS

This section summarizes and compares the scenarios by superimposing results plots:

- When the synchronous machines are used for governing.
- When the governing units are supplemented by a 20 WM BESS.

Figure 14 shows the superimposed frequency response for the Salama plant trips from full load (60 MW) with and without BESS.

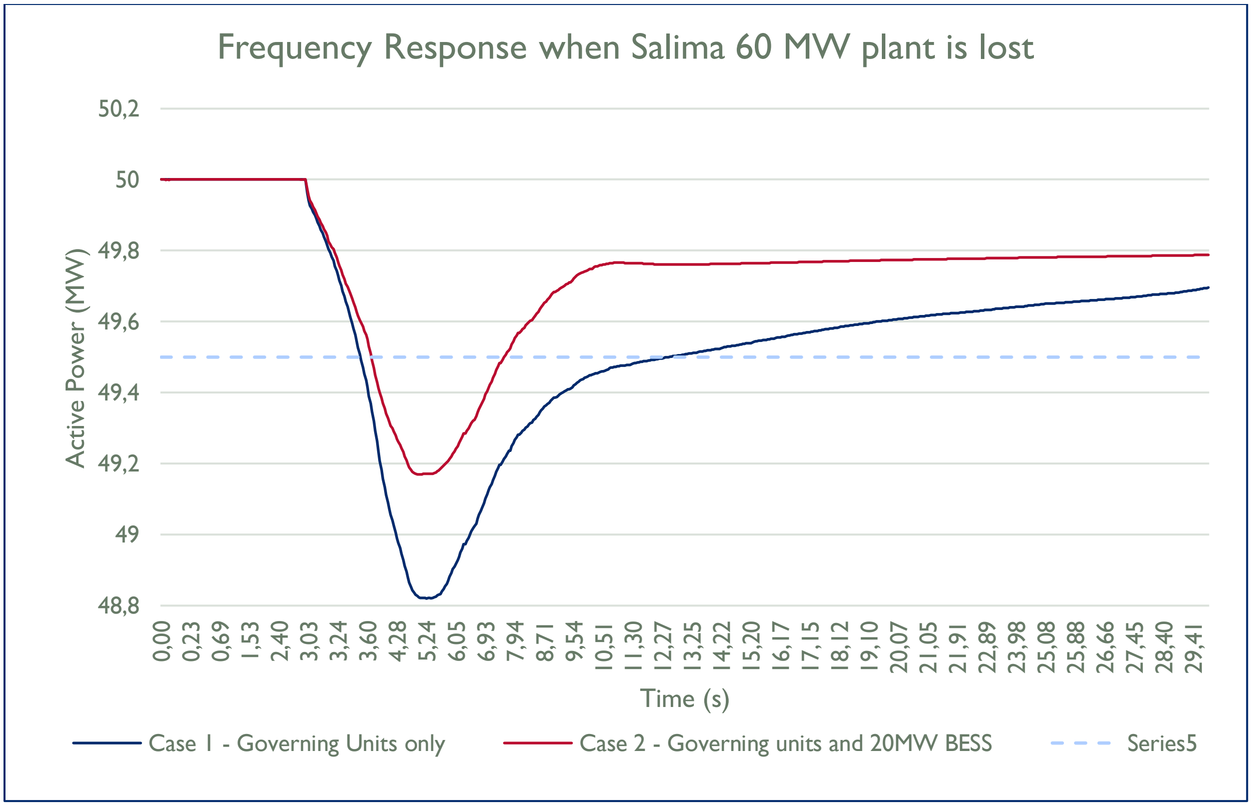

Figure 14: Superimposed frequency response representing the four scenarios studied above.

Figure 15 shows the superimposed frequency response for the Salama plant trips from partial loading (40 MW) with and without BESS.

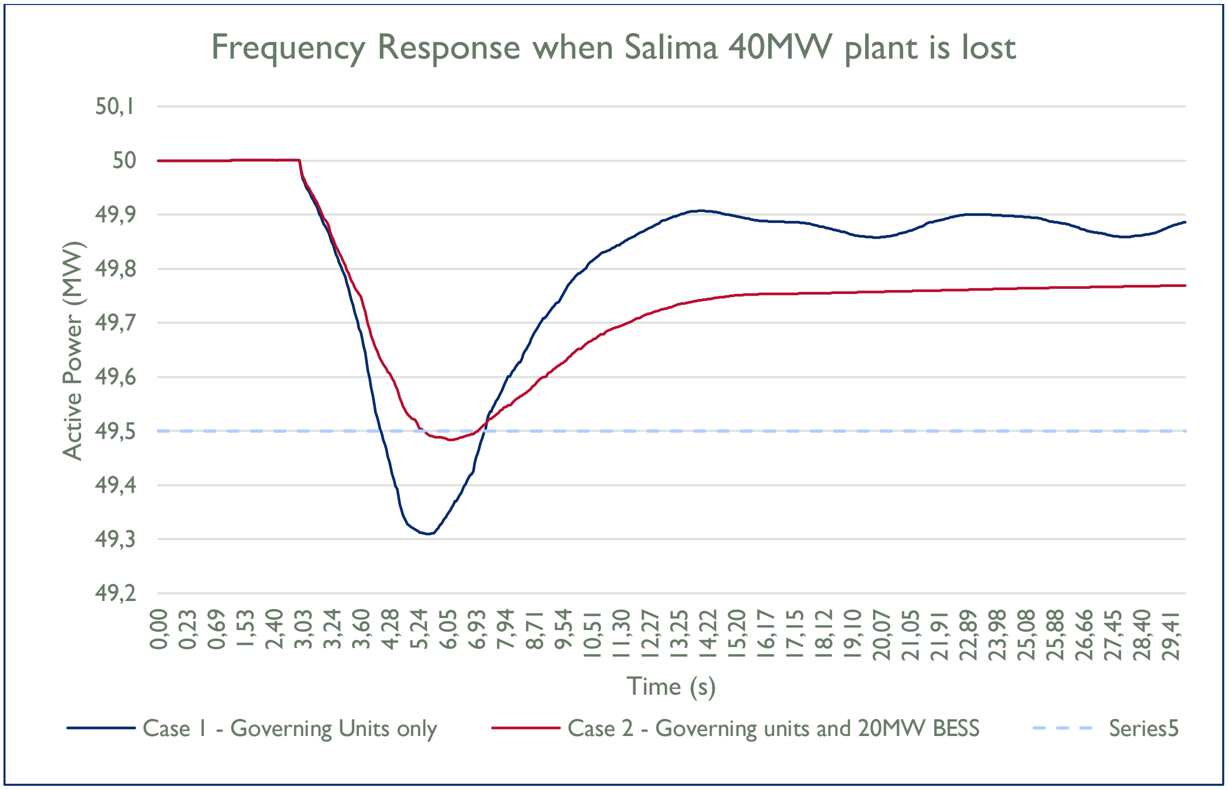

Figure 15: Superimposed frequency response representing the four scenarios studied above.

The above plots show that 20 MW BESS does improve the frequency response and when the Salima plant is loaded at 40 MW, the system seems to comply with Grid Code requirements as the frequency nadir is at 49.5 Hz.

6. VOLTAGE CONTROL STUDIES

Section 5 discussed voltage control studies to determine the effects of the 20 MW BESS on voltage control in the Kanengo area. Additionally, the study will verify voltage setpoints suitable for the BESS that will be connected to the 33 kV busbar. Figure16 below represents the study area for the voltage control studies. The 20 MW BESS is connected to the 33 kV busbar with five lines evacuating power in and out of the station. The two Kanengo diesel generators are switched off in the study.

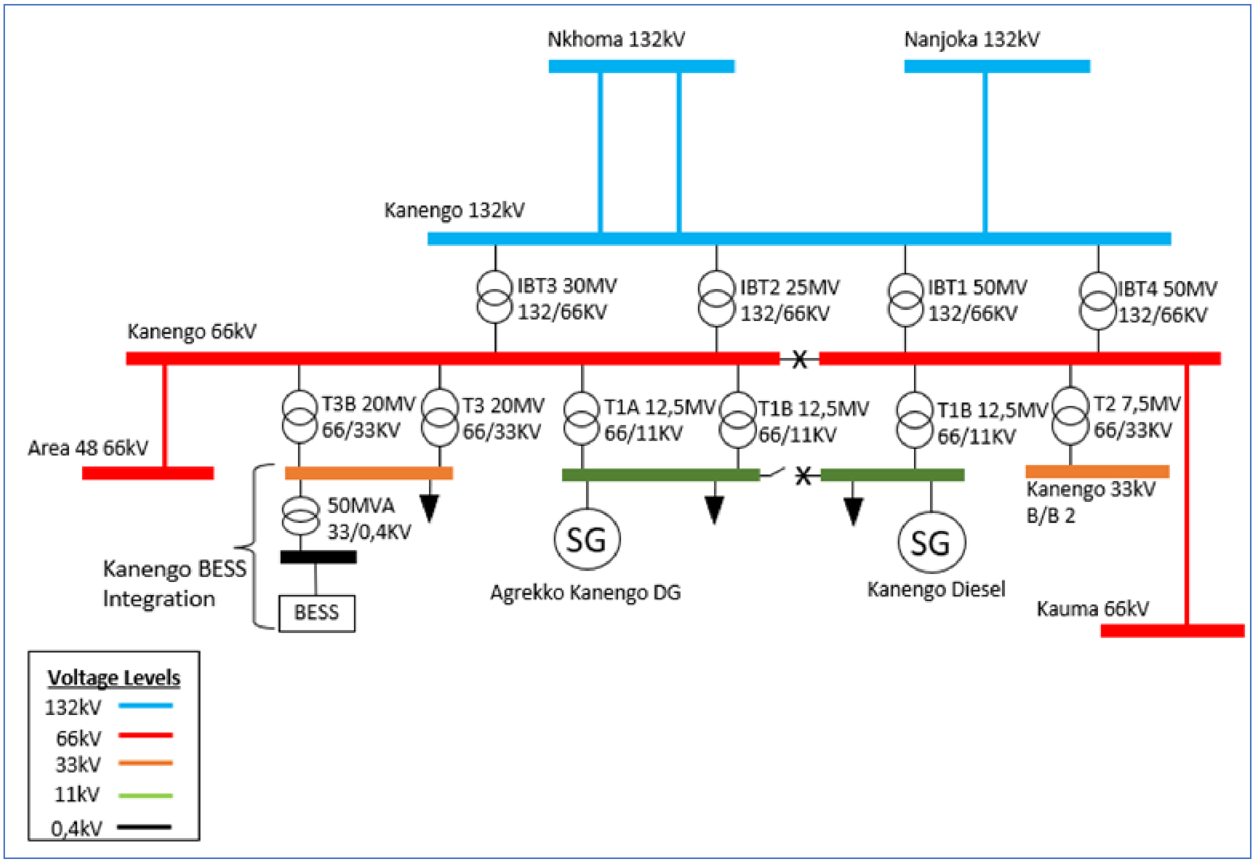

Figure 16: Study area for voltage control settings.

The voltage control study is conducted under peak and light loading to help determine the maximum and minimum reactive power support from the 20 MW BESS. The critical voltage setpoints for the study area to be tested are 1 pu, 1.03 pu and 0.98 pu and the power factor is kept at 0.95, as per the Malawi grid code.

Stations to be monitored:

- Kanengo 33 kV
- Kanengo 11 kV
- Kanengo 132 kV
- Nanjoka 132 kV
- Nkhoma 132 kV
- Golomoti 132 kV

The transformers at Kanengo substation are firm. Therefore, only the lines evacuating power in and out of the station will be considered for the following N – 1 credible contingencies:

- System healthy (normal network topology – no contingencies)
- Nkhoma – Kanengo 132 kV line A
- Nkhoma – Kanengo 132 kV line B
- Kanengo – Nanjoka 132 kV line
- Kanengo – Area 48 66 kV line
- Kanengo – Kauma 66 kV line

6.1. PEAK LOADING CASE

Conducting the voltage control study at peak loading will give the voltage limits when the ESCOM system is heavily loaded.

6.1.1. SCENARIO 1: BEFORE BESS INTEGRATION

In this scenario, the ESCOM power system is assessed before the 20 MW BESS with 30 MWh capacity is integrated. Figure17 below shows the voltage profile for the Kanengo corridor. It can be noted that there are no voltage violations under system health and N – 1 credible contingencies.

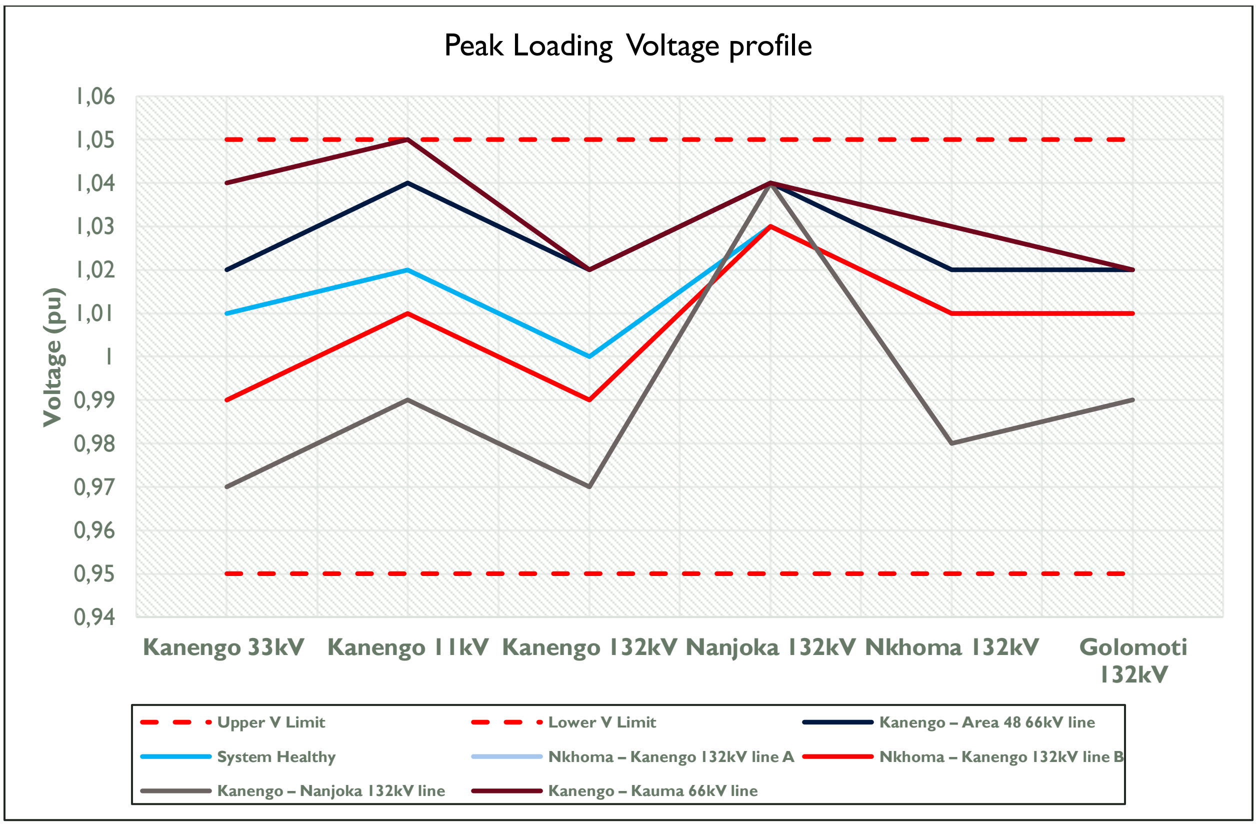

Figure 17: Kanengo station voltage profile under peak loading before BESS integration.

Table 99 shows the voltage profile results.

Table 9: Voltage level results before BESS integration at Kanengo station.

Contingencies	Busbar Voltage

	Kanengo 33 kV	Kanengo 11 kV	Kanengo 132 kV	Nanjoka 132 kV	Nkhoma 132 kV	Golomoti 132 kV
System Health	1.01	1.02	1	1.03	1.01	1.01
Nkhoma – Kanengo 132 kV line A	0.99	1.01	0.99	1.03	1.01	1.01
Nkhoma – Kanengo 132 kV line B	0.99	1.01	0.99	1.03	1.01	1.01
Kanengo – Nanjoka 132 kV line	0.97	0.99	0.97	1.04	0.98	0.99
Kanengo – Area 48 66 kV line	1.02	1.04	1.02	1.04	1.02	1.02
Kanengo – Kauma 66 kV line	1.04	1.05	1.02	1.04	1.03	1.02

\The next section assesses the effects of 20 MW BESS integration with different voltage setpoints.

6.1.2. SCENARIO 2: BESS INTEGRATION WITH 1P.U SETPOINT

In the scenario, the BESS AC voltage setpoint is at 1 pu. Figure18 shows the voltage profile for the scenario, with the highest voltage of 1.04 pu at Kanengo 11kV/1 busbar and Nanjoka 132 kV busbar. There are no voltage violations experienced in this scenario.

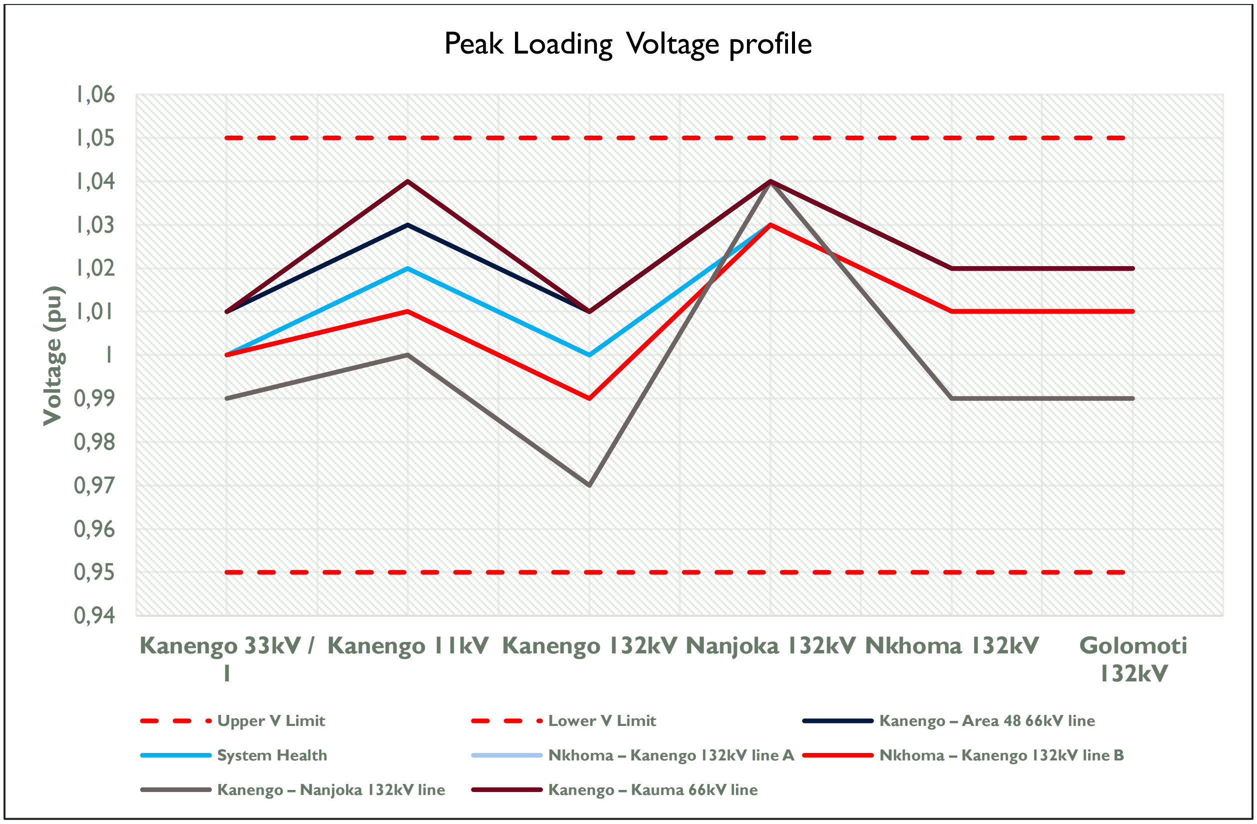

Figure18: Kanengo station voltage profile under peak loading when BESS voltage setpoint is at 1 pu.

Table9 below shows the voltage levels at different busbars under different contingencies. There are no voltage violations experienced in this scenario.

Table9: Voltage profile results when the BESS voltage setpoint is at 1pu under peak loading.

Contingencies	Busbar Voltage					
	Kanengo 33 kV	Kanengo 11 kV	Kanengo 132 kV	Nanjoka 132 kV	Nkhoma 132 kV	Golomoti 132 kV
System Health	1	1.02	1	1.03	1.01	1.01
Nkhoma – Kanengo 132 kV line A	1	1.01	0.99	1.03	1.01	1.01
Nkhoma – Kanengo 132 kV line B	1	1.01	0.99	1.03	1.01	1.01
Kanengo – Nanjoka 132 kV line	0.99	1	0.97	1.04	0.99	0.99
Kanengo – Area 48 66 kV line	1.01	1.03	1.01	1.04	1.02	1.02
Kanengo – Kauma 66 kV line	1.01	1.04	1.01	1.04	1.02	1.02

Figure19 below shows the reactive power support provided by the BESS when the setpoint is at 1 pu. Under different contingencies, the BESS is either under-excited or over-excited depending on the credible contingency and the reactive power limits not being reached.

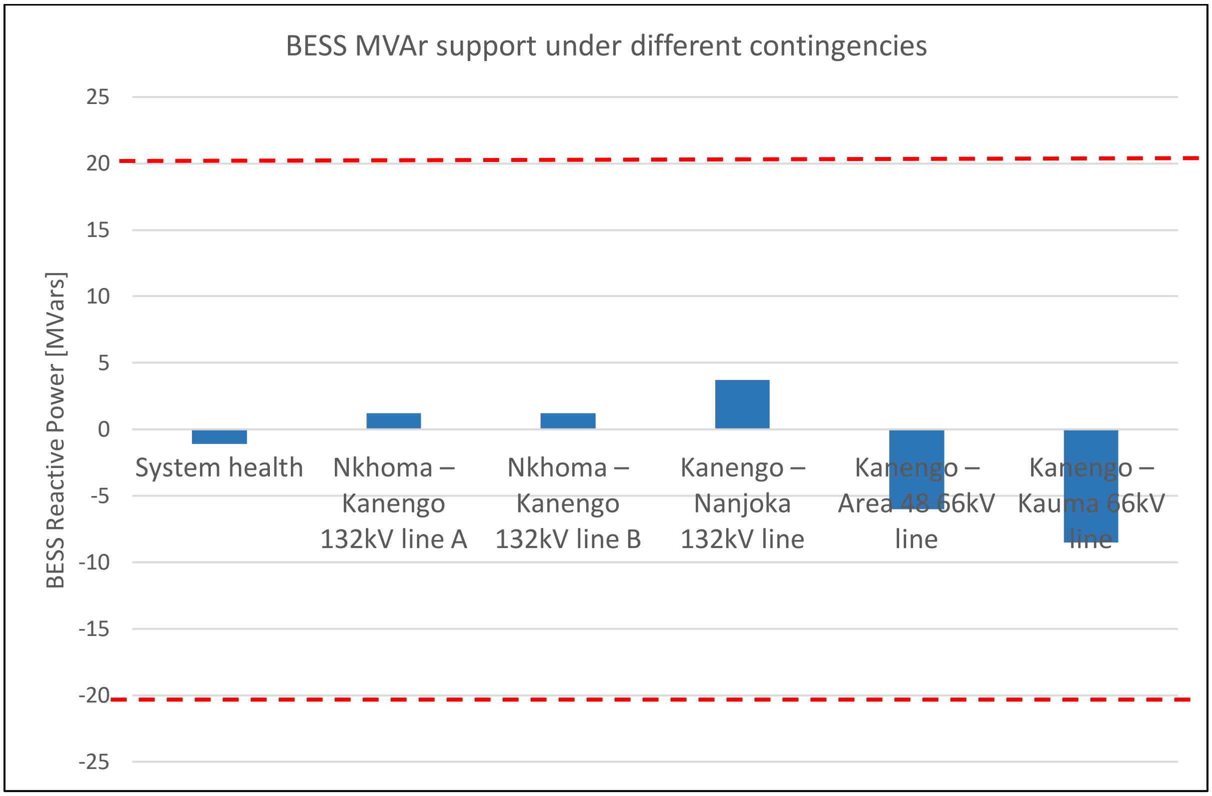

Figure19: Reactive power support by the 20MW BESS under peak loading.

Table 50 shows the reactive power support by the 20 MW BESS at different voltage levels. The reactive power limits are based on the generic models.

Table 50: 20 MW BESS reactive power support under peak loading.

Contingency	BESS Reactive power (MVAr)	Under- Excitation Limit*	Exceedance
System Health	-1.1	-20	No
Nkhoma – Kanengo 132 kV line A	1.2	-20	No
Nkhoma – Kanengo 132 kV line B	1.2	-20	No
Kanengo – Nanjoka 132 kV line	3.7	20	No
Kanengo – Area 48 66 kV line	-6	-20	No
Kanengo – Kauma 66 kV line	-8.5	-20	No

**The limit is not a practical limit; it is a limit based on the generic model.*

6.1.3. SCENARIO 3: BESS INTEGRATION WITH 1.03PU SETPOINT

In Scenario 3, the BESS AC voltage setpoint is at 1.03 pu. Figure20 below shows the voltage profile for the scenario, with the highest voltage of 1.05 pu at Kanengo 11kV/1 busbar. There is no voltage violation in this scenario.

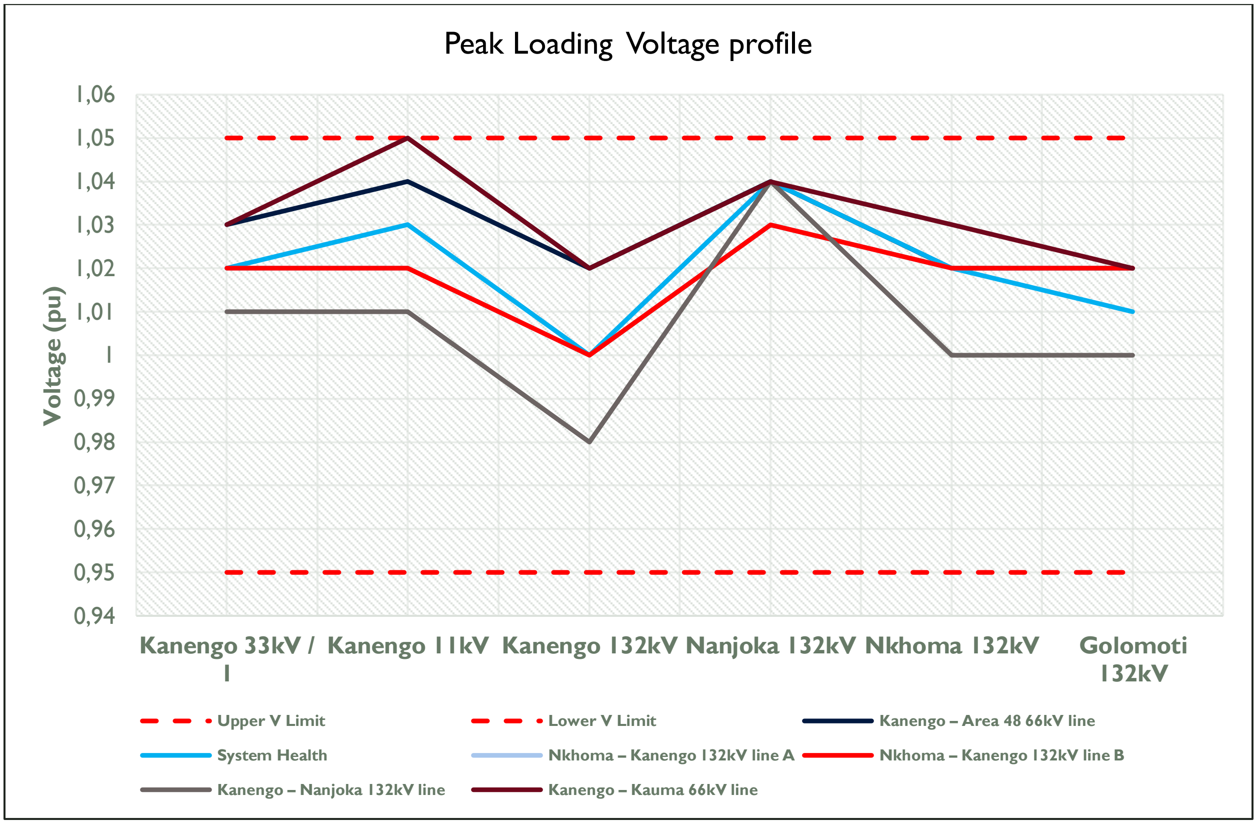

Figure20: Kanengo station voltage profile under peak loading when BESS voltage setpoint is at 1.03 pu.

Table11 shows the voltage levels at different busbars under different contingencies. The Kanengo – Kauma 66 kV line contingency causes the voltage levels at Kanengo 11 kV busbar to reach 0.5 pu.

Table11: Voltage profile results when the BESS voltage setpoint is at 1.03 pu under peak loading.

Contingency	Busbar Voltage					
	Kanengo 33kV	Kanengo 11kV	Kanengo 132kV	Nanjoka 132kV	Nkhoma 132kV	Golomoti 132kV
System Health	1.02	1.03	1	1.04	1.02	1.01
Nkhoma – Kanengo 132 kV line A	1.02	1.02	1	1.03	1.02	1.02
Nkhoma – Kanengo 132 kV line B	1.02	1.02	1	1.03	1.02	1.02

Kanengo – Nanjoka 132 kV line	1.01	1.01	0.98	1.04	1	1
Kanengo – Area 48 66 kV line	1.03	1.04	1.02	1.04	1.02	1.02
Kanengo – Kauma 66 kV line	1.03	1.05	1.02	1.04	1.03	1.02

Figure21 below shows the reactive power support provided by the BESS when the setpoint is at 1.03 pu. Under different contingencies, the BESS is overly excited in this scenario, and an under-excitation under Kanengo – Kauma 66 kV line contingency and Kanengo – Area 48 66 kV line and the reactive power limits are not violated.

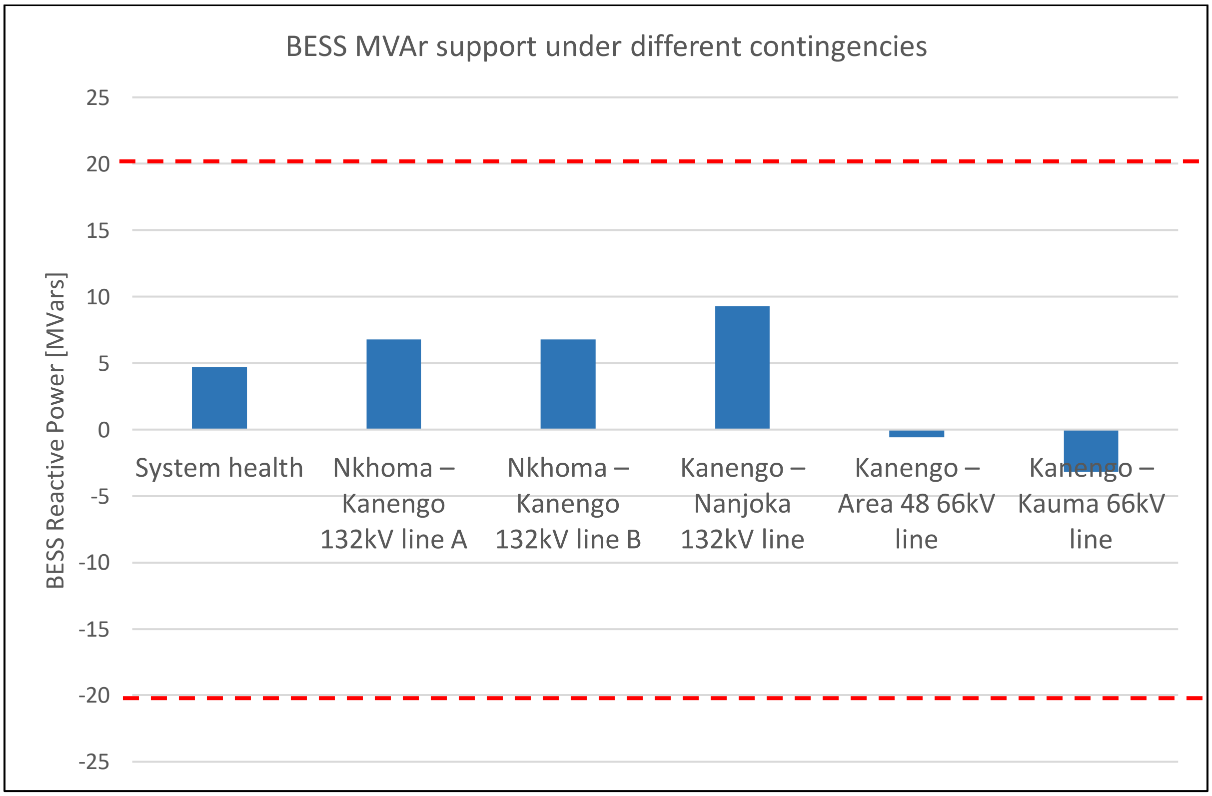

Figure21: Reactive power support by the 20MW BESS when the voltage setpoint is at 1.03pu under peak loading.

Table122 below shows the reactive power support by the 20 MW BESS at different voltage levels. The reactive power limits are based on the generic models.

Table12: Excitation limit by the 20 MW BESS for voltage setpoint of 1.03 pu under peak loading.

Contingencies	BESS Reactive power support (MVAr)	Excitation Limit (MVAr)*	Exceedance
System Health	4.7	20	No

Nkhoma – Kanengo 132 kV line A	6.8	20	No
Nkhoma – Kanengo 132 kV line B	6.8	20	No
Kanengo – Nanjoka 132 kV line	9.3	20	No
Kanengo – Area 48 66 kV line	-0.6	20	No
Kanengo – Kauma 66 kV line	-3.2	20	No

**The limit is not a practical limit; it is a limit based on the generic model.*

6.1.4. SCENARIO 4: BESS INTEGRATION WITH 0.98P.U SETPOINT

In Scenario 4, the BESS AC output voltage setpoint is at 0.98 pu. Figure22 below shows the voltage profile for the scenario at the highest voltage of 1.04 pu at Nanjoka 132 kV busbar and the lowest voltage level of 0.97 at Kanengo 132 kV. There are no voltage violations in this scenario.

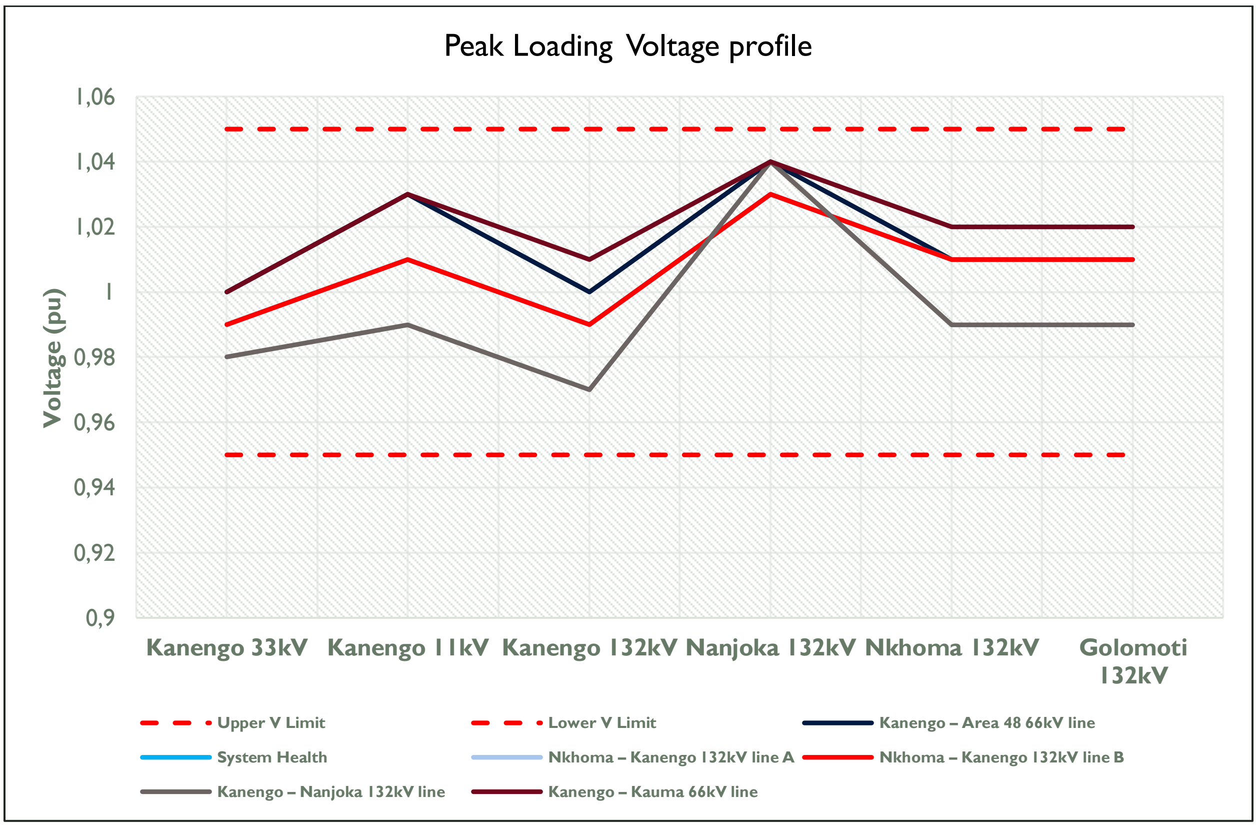

Figure22: Voltage profile results when the BESS voltage setpoint is at 0.98pu under peak loading.

Table13 below shows the voltage levels at different busbars under different contingencies. There are no voltage violations for the 0.98 pu setpoint.

Table 13: Voltage profile results when the BESS voltage setpoint is at 0.98pu under peak loading.

Contingency	Busbar Voltage

	Kanengo 33 kV	Kanengo 11 kV	Kanengo 132 kV	Nanjoka 132 kV	Nkhoma 132 kV	Golomoti 132 kV
System Health	0.99	1.01	0.99	1.03	1.01	1.01
Nkhoma – Kanengo 132 kV line A	0.99	1.01	0.99	1.03	1.01	1.01
Nkhoma – Kanengo 132 kV line B	0.99	1.01	0.99	1.03	1.01	1.01
Kanengo – Nanjoka 132 kV line	0.98	0.99	0.97	1.04	0.99	0.99
Kanengo – Area 48 66 kV line	1	1.03	1	1.04	1.01	1.01
Kanengo – Kauma 66 kV line	1	1.03	1.01	1.04	1.02	1.02

Figure23 below shows the reactive power support provided by the BESS when the setpoint is at 0.98 pu. Under different contingencies, the BESS is under excited in this scenario and the reactive power limits are not violated.

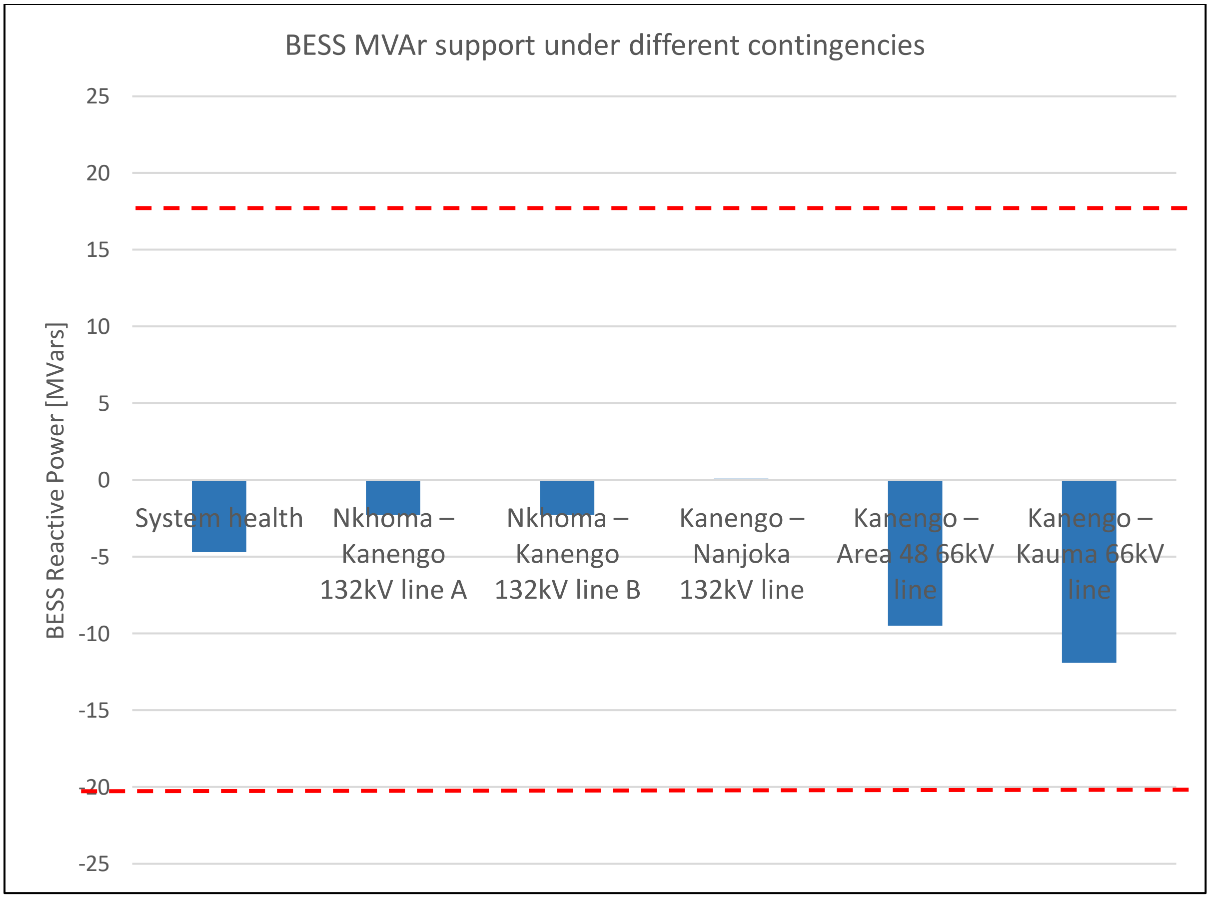

Figure23: Excitation limit by the 20 MW BESS under peak loading.

Table below shows the reactive power support by the 20 MW BESS at different voltage levels. The Kanengo – Kauma 66 kV contingency have the highest under-excitation reactive power support for the scenario.

Table 13: Results for 20MW BESS reactive power support under peak loading when the voltage setpoint is at 0.98 pu.

Contingency	BESS Reactive power (MVAr)	Under Excitation Limit (MVAr)*	Exceedance
System Health	-4.7	-20	No
Nkhoma – Kanengo 132 kV line A	-2.3	-20	No
Nkhoma – Kanengo 132 kV line B	-2.3	-20	No
Kanengo – Nanjoka 132 kV line	0.1	-20	No
Kanengo – Area 48 66 kV line	-9.5	-20	No
Kanengo – Kauma 66 kV line	-11.9	-20	No

**The limit is not a practical limit; it is a limit based on the generic model.*

The next section discusses the voltage control study conducted under light loading.

6.2. LIGHT LOADING CASE.

In this section, the voltage control studies are conducted when the ESCOM power system is at light loading. The study at light loading will give the voltage limits when the system is lightly loaded.

6.2.1. SCENARIO 1: BEFORE BESS INTEGRATION

This scenario assesses the ESCOM power system before the 20 MW BESS is integrated under light loading. Figure24 below shows the voltage profile for the Kanengo corridor. The highest voltage at Kanengo is 11 kV busbar, which is caused by the Kanengo – Kauma 66 kV line and Kanengo – Area 48 66 kV line contingencies. There were no voltage violations before the integration of the 20 MW BESS.

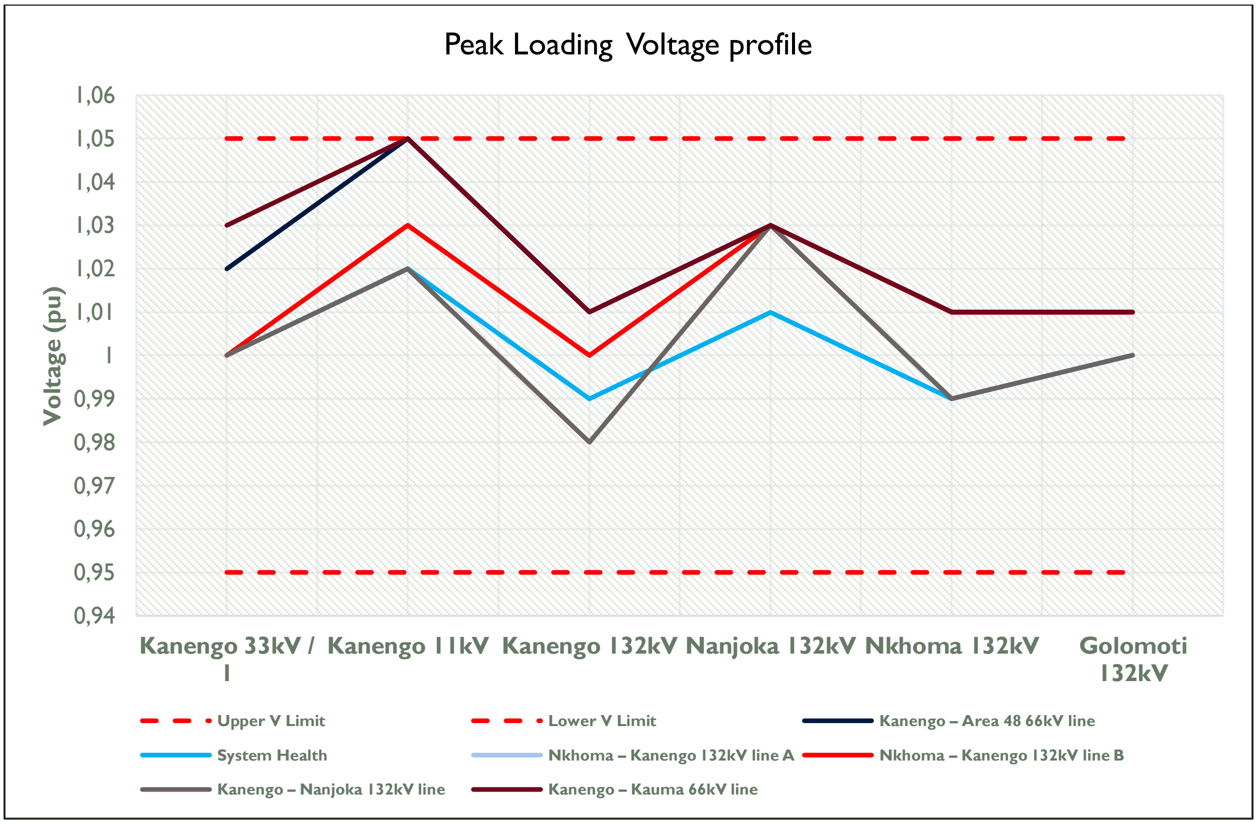

Figure23: Voltage profile before BESS integration under light loading.

Table below shows the voltage profile results before the integration of the 20 MW BESS. There are no voltage violations.

Table 14: Voltage profile results before the integration of 20 MW BESS under light loading.

Contingency	Busbar Voltage					
	Kanengo 33kV / 1	Kanengo 11kV	Kanengo 132kV	Nanjoka 132kV	Nkhoma 132kV	Golomoti 132kV
System Health	1	1.02	0.99	1.01	0.99	1

Nkhoma – Kanengo 132kV line A	1	1.03	1	1.03	1.01	1.01
Nkhoma – Kanengo 132kV line B	1	1.03	1	1.03	1.01	1.01
Kanengo – Nanjoka 132kV line	1	1.02	0.98	1.03	0.99	1
Kanengo – Area 48 66kV line	1.02	1.05	1.01	1.03	1.01	1.01
Kanengo – Kauma 66kV line	1.03	1.05	1.01	1.03	1.01	1.01

Below, we assess the effects of 20 MW BESS integration with different voltage setpoints.

6.2.2. SCENARIO 2: BESS INTEGRATION WITH 1P.U SETPOINT

In Scenario 2, the BESS AC voltage setpoint is 1 pu. Figure 24 below shows the voltage profile for the scenario as 1.04 pu at Kanengo 11 kV/1 busbar and the lowest voltage level as 0.98pu at Kanengo 132 kV. There are no voltage violations experienced in this scenario.

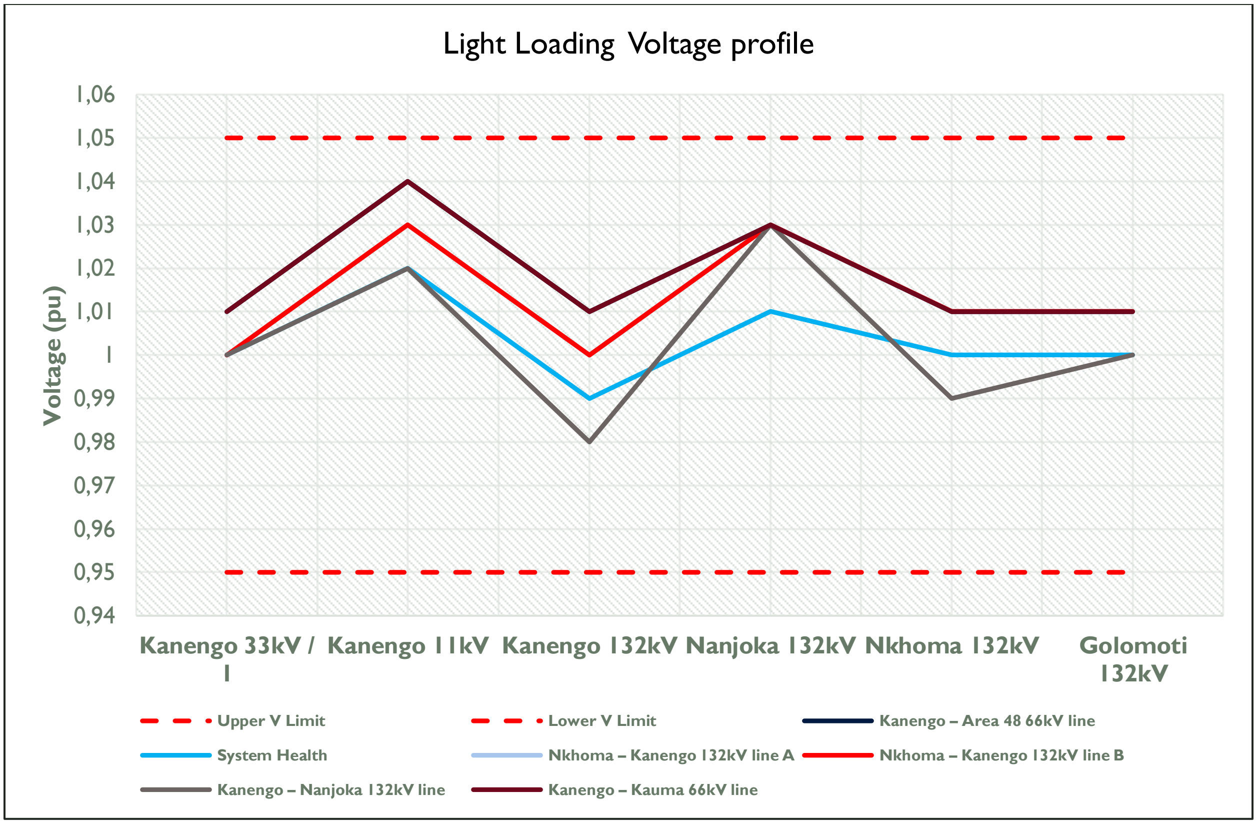

Figure 24: Kanengo station voltage profile under light loading when BESS voltage setpoint is at 1pu.

Table5 shows the voltage levels at different busbars under different contingencies. There are no voltage violations experienced in this scenario.

Table 6: Voltage profile results when the BESS voltage setpoint is at 1pu under light loading.

Contingency	Busbar Voltage					
	Kanengo 33kV / 1	Kanengo 11kV	Kanengo 132kV	Nanjoka 132kV	Nkhoma 132kV	Golomoti 132kV
System Health	1	1.02	0.99	1.01	1	1
Nkhoma – Kanengo 132kV line A	1	1.03	1	1.03	1.01	1.01
Nkhoma – Kanengo 132kV line B	1	1.03	1	1.03	1.01	1.01
Kanengo – Nanjoka 132kV line	1	1.02	0.98	1.03	0.99	1
Kanengo – Area 48 66kV line	1.01	1.04	1.01	1.03	1.01	1.01

Kanengo – Kauma 66kV line	1.01	1.04	1.01	1.03	1.01	1.01

Figure 2525 shows the reactive power support provided by the BESS when the setpoint is 1 pu. The BESS is either under-excited or over-excited, depending on the contingency being studied and the reactive power limits not being reached.

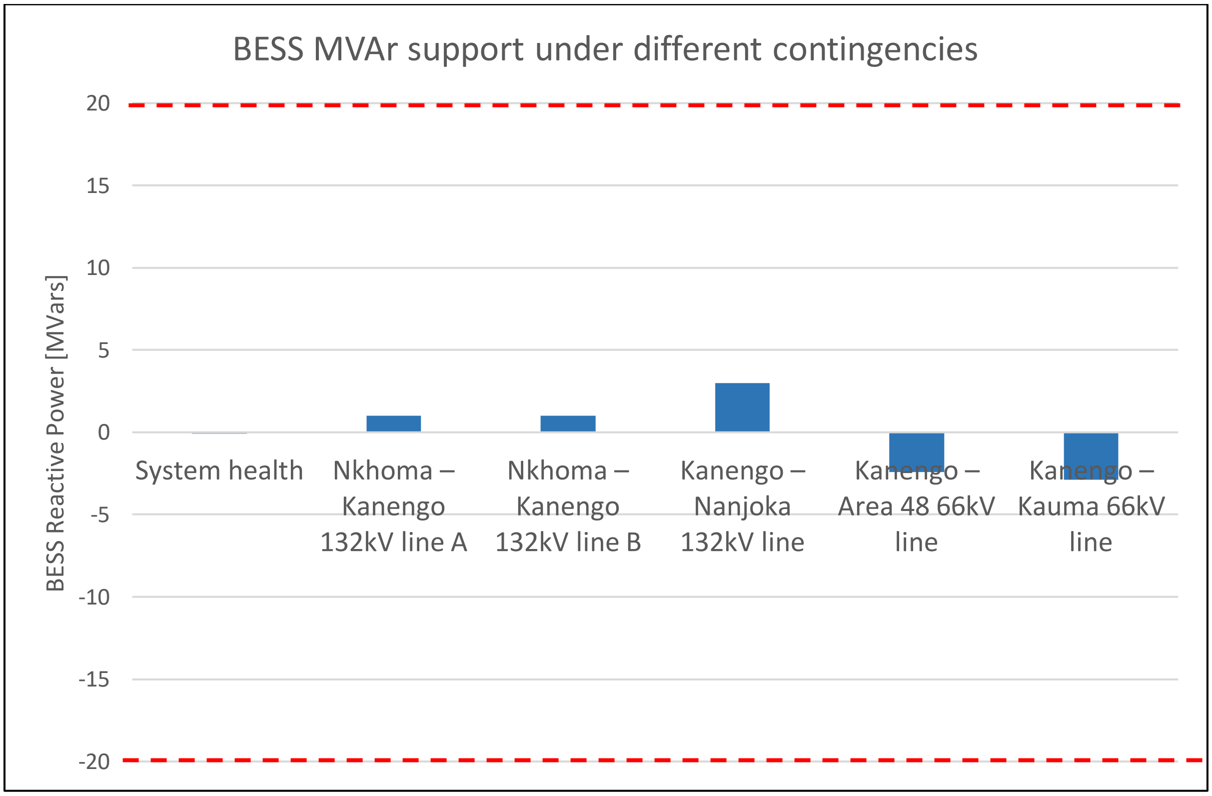

Figure 25: BESS MVAr support under different contingencies.

Table shows the reactive power support by the 20 MW BESS. Under different contingencies, the reactive power limits are not violated. The reactive power limits are based on the generic models.

Table 16: Results for 20MW BESS reactive power support under light loading when the voltage setpoint is at 1pu.

Contingency	BESS Reactive power (MVAr)	Under Excitation Limit*	Exceedance
System Health	-0.1	-20	No
Nkhoma – Kanengo 132kV line A	1	-20	No
Nkhoma – Kanengo 132kV line B	1	-20	No
Kanengo – Nanjoka 132kV line	3	-20	No
Kanengo – Area 48 66kV line	-2.4	-20	No

Kanengo – Kauma 66kV line	-2.9	-20	No

**The limit is not a practical limit; it is a limit based on the generic model*

6.2.3. SCENARIO 3: BESS INTEGRATION WITH 1.03P.U SETPOINT

In Scenario 3, the BESS AC output voltage setpoint is 1.03 pu. Figure 826 below shows the voltage profile for the scenario is at the highest voltage of 1.05 pu at Kanengo 11 kV/1 busbar under the Kanengo – Kauma 66 kV line contingency. The lowest voltage is at Kanengo 132 kV line under Kanengo – Nanjoka 132 kV line contingency. There are no voltage violations in this scenario.

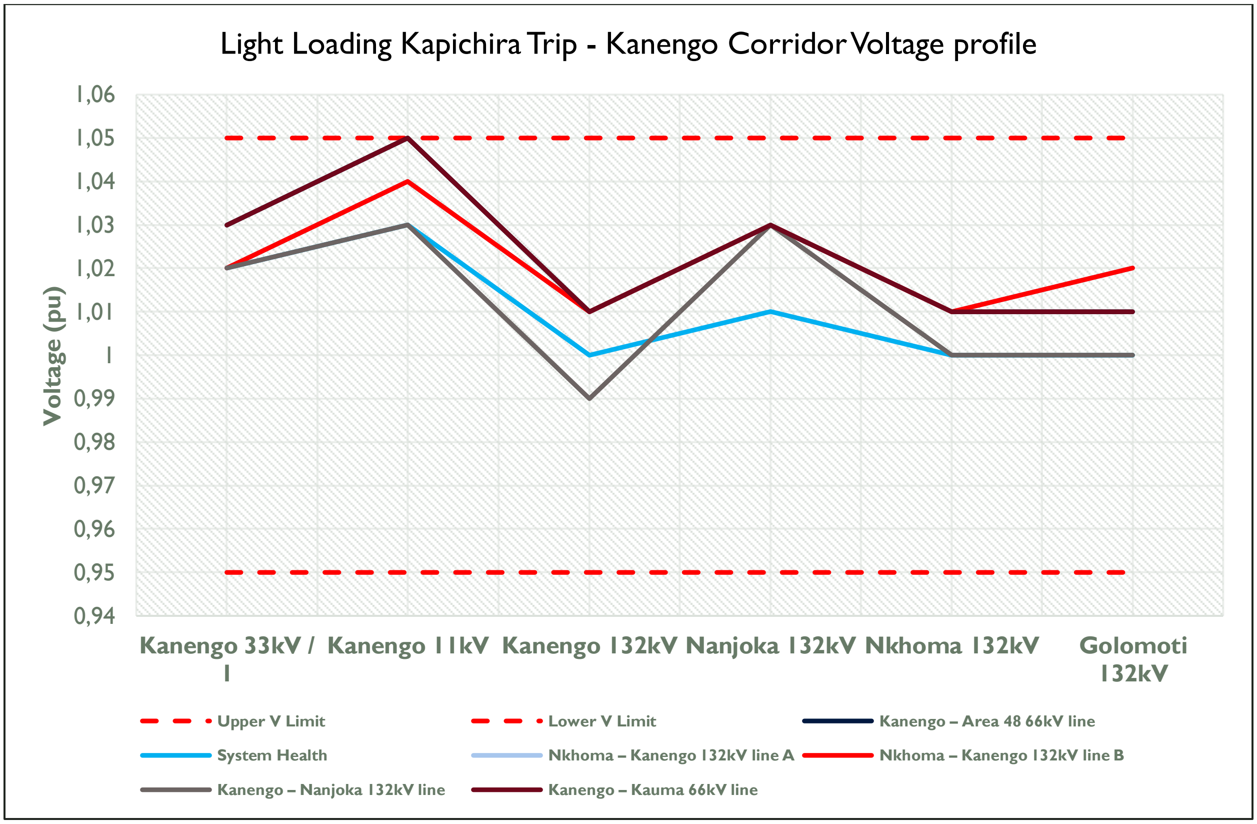

Figure 8: Kanengo station voltage profile under light loading when BESS voltage setpoint is at 1.03pu.

Table 7 below shows the voltage levels at different busbars under different contingencies.

Table 7: Voltage profile results when the BESS voltage setpoint is at 1.03pu under light loading.

Contingency	Busbar Voltage					
	Kanengo 33kV / 1	Kanengo 11kV	Kanengo 132kV	Nanjoka 132kV	Nkhoma 132kV	Golomoti 132kV
System Health	1.02	1.03	1	1.01	1	1
Nkhoma – Kanengo 132kV line A	1.02	1.04	1.01	1.03	1.01	1.02

Nkhoma – Kanengo 132kV line B	1.02	1.04	1.01	1.03	1.01	1.02
Kanengo – Nanjoka 132kV line	1.02	1.03	0.99	1.03	1	1
Kanengo – Area 48 66kV line	1.03	1.05	1.01	1.03	1.01	1.01
Kanengo – Kauma 66kV line	1.03	1.05	1.01	1.03	1.01	1.01

Figure26 below shows the reactive power support provided by the BESS when the setpoint is at 1.03 pu. Under different contingencies, the BESS is overly excited in this scenario and the reactive power limits are not violated.

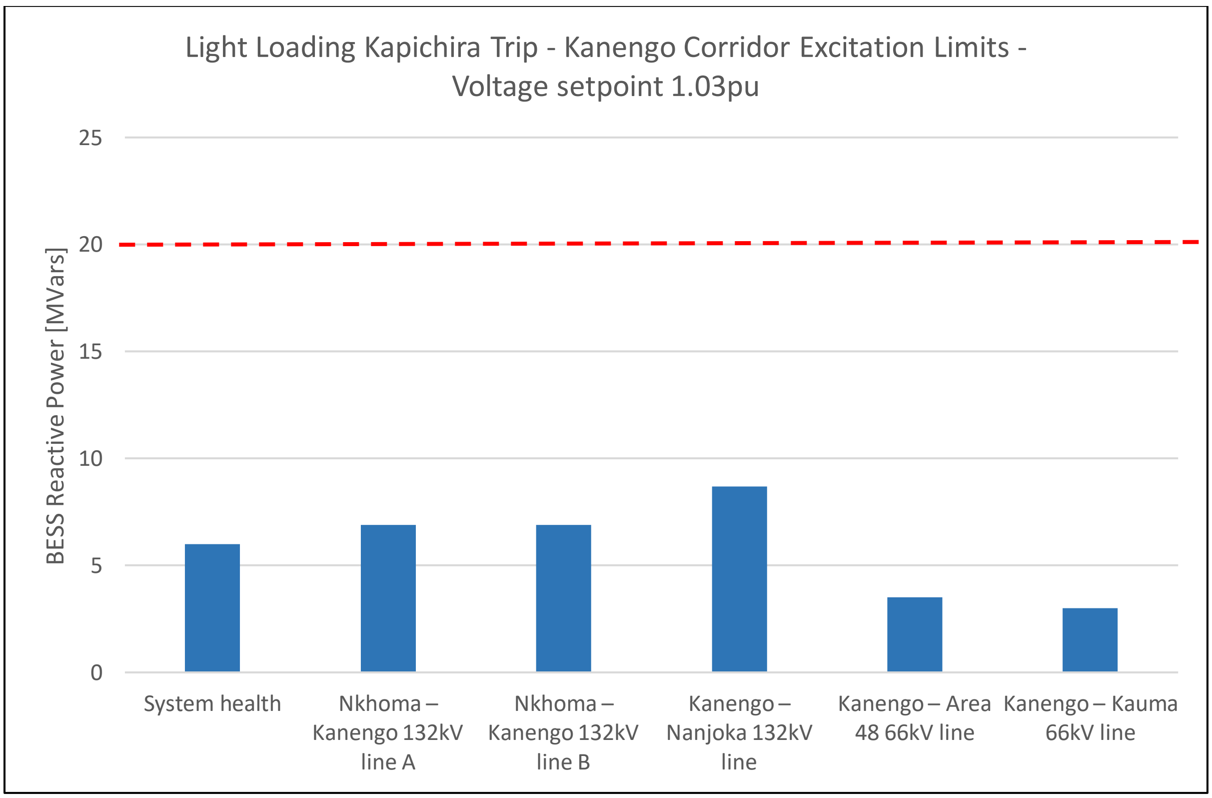

Figure26: Excitation limit by the 20 MW BESS under light loading

Table 8 below shows the reactive power support by the 20 MW BESS at different voltage levels.

Table 8: Results for 20 MW BESS reactive power support under light loading when the voltage setpoint is at 1.03 pu.

Contingency	BESS Reactive power (MVAr)	Over Excitation Limit	Exceedance
System health	6	20	No

Nkhoma – Kanengo 132kV line A	6.9	20	No
Nkhoma – Kanengo 132kV line B	6.9	20	No
Kanengo – Nanjoka 132kV line	8.7	20	No
Kanengo – Area 48 66kV line	3.5	20	No
Kanengo – Kauma 66kV line	3	20	No

**The limit is not a practical limit; it is a limit based on the generic model*

6.2.4. SCENARIO 4: BESS INTEGRATION WITH 0.98 P.U SETPOINT

In this scenario, the BESS AC output voltage setpoint is at 0.98pu. Figure below shows the voltage profile for the scenario. There are no voltage violations in this scenario.

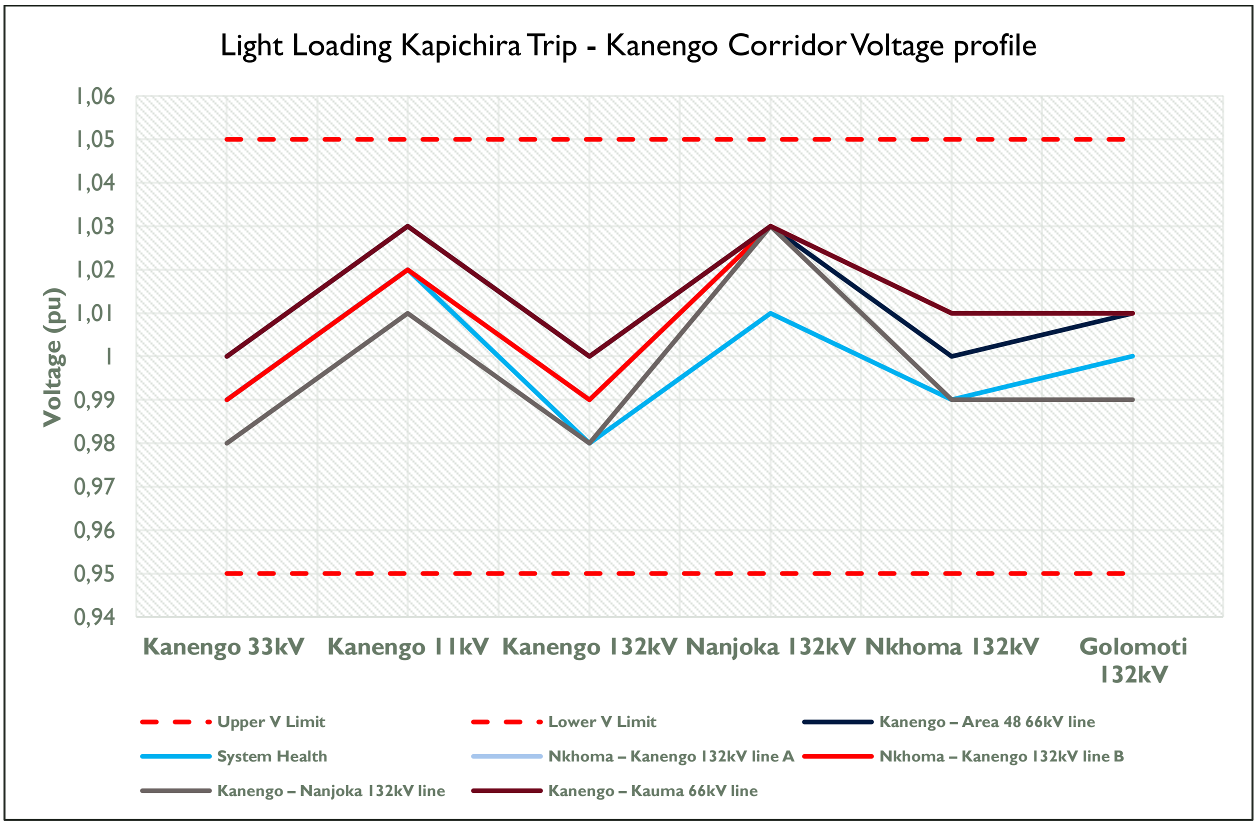

Figure27: Voltage profile results when the BESS voltage setpoint is at 0.98 pu under light loading.

Table 9 below shows the voltage levels at different busbars under different contingencies. There are no voltage violations for the 0.98 pu setpoint. The lowest voltage level is 0.98 pu.

Table 9: Voltage profile results when the BESS voltage setpoint is at 0.98 pu under light loading.

Contingency	Busbar Voltage

	Kanengo 33kV / 1	Kanengo 11kV	Kanengo 132kV	Nanjoka 132kV	Nkhoma 132kV	Golomoti 132kV
System Health	0.99	1.02	0.98	1.01	0.99	1
Nkhoma – Kanengo 132kV line A	0.99	1.02	0.99	1.03	1.01	1.01
Nkhoma – Kanengo 132kV line B	0.99	1.02	0.99	1.03	1.01	1.01
Kanengo – Nanjoka 132kV line	0.98	1.01	0.98	1.03	0.99	0.99
Kanengo – Area 48 66kV line	1	1.03	1	1.03	1	1.01
Kanengo – Kauma 66kV line	1	1.03	1	1.03	1.01	1.01

Figure28 below shows the reactive power support provided by the BESS when the setpoint is at 0.98 pu. Under different contingencies, the BESS is under excited in this scenario and the reactive power limits are not violated.

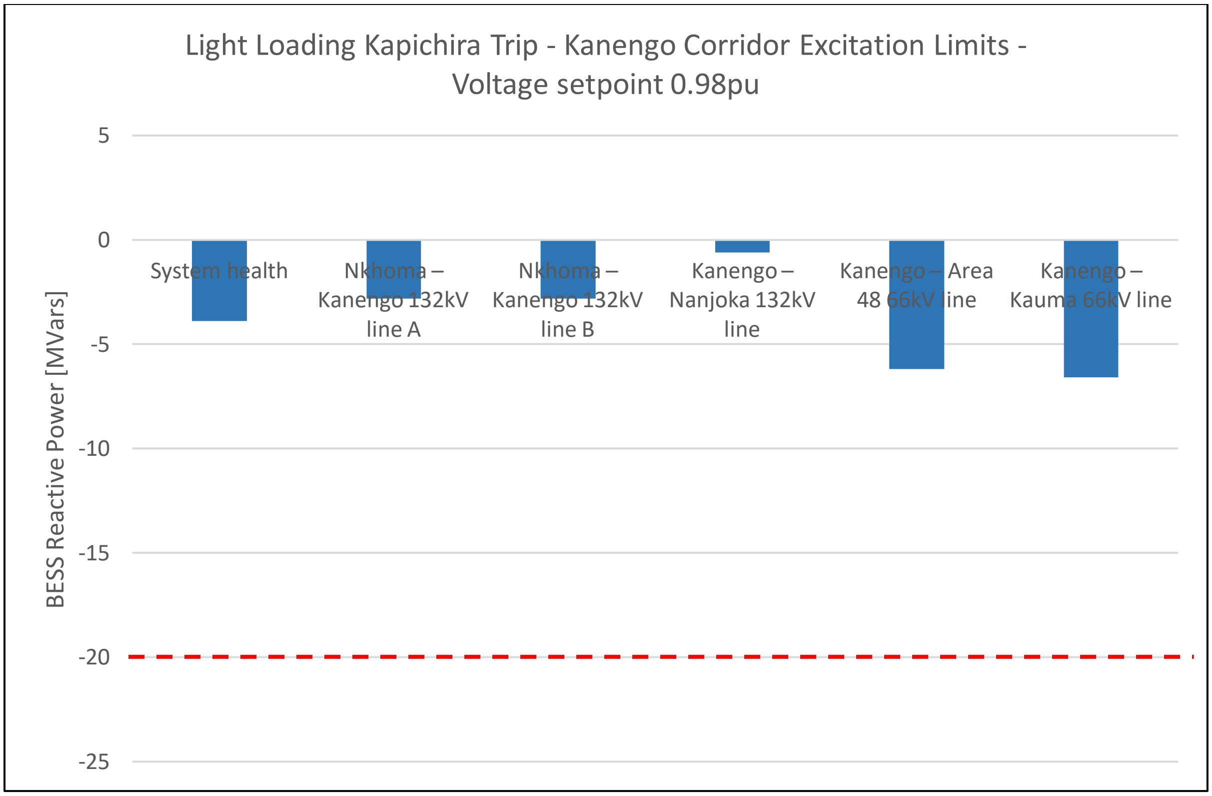

Figure28: Excitation limit by the 20 MW BESS under light loading.

Table 10 below shows the reactive power support by the 20 MW BESS at different voltage levels. The Kanengo – Kauma 66 kV line has the highest under-excitation reactive power support for the scenario.

Table 10: Results for 20MW BESS reactive power support under light loading when the voltage setpoint is at 0.98 pu.

	BESS Reactive power (MVAr)	Over Excitation Limit*	Exceedance
System Health	-3.9	-20	No
Nkhoma – Kanengo 132kV line A	-2.8	-20	No
Nkhoma – Kanengo 132kV line B	-2.8	-20	No
Kanengo – Nanjoka 132kV line	-0.6	-20	No
Kanengo – Area 48 66kV line	-6.2	-20	No
Kanengo – Kauma 66kV line	-6.6	-20	No

**The limit is not a practical limit; it is a limit based on the generic model*

6.3. VOLTAGE CONTROL ANALYSIS

<u>Peak Loading – After BESS integration:</u>

From the voltage control analysis under peak loading, before integrating the 20 MW BESS with 30 MWh capacity, the bus bar voltage ranges from 0.97pu to 1.05pu at different busbars under different contingencies. The voltages at Nkhoma 132 kV and Golomoti 132 kV busbars remained constant under different contingencies.

Peak Loading – After BESS integration:

Under peak loading conditions, after the integration of the 20 MW BESS with 30MWh capacity, there have been some improvements in terms of voltage fluctuations under different credible contingencies. When the AC output voltage of the 20 MW BESS is set at 1 pu, the busbar voltages in the study area operate closer to the 20 MW BESS setpoint. The voltage profile ranges from 0.97 pu to 1.04 pu, and the influenced bus bars are Kanengo 33 kV, Kanengo 11 kV, Kanengo 132 kV and Nanjoka 132 kV. Golomoti 132 kV and Nkhoma 132 kV busbars are not influenced by the change in voltage setpoints of the 20 MW BESS.

Light Loading – Before BESS integration:

Under light loading conditions, before the integration of the 20 MW BESS with 30MWh capacity, the voltage fluctuations range from 0.98pu to 1.05pu at the different busbars in the study area under different contingencies.

Peak Loading – After BESS integration:

Under light loading conditions when the 20 MW BESS is integrated, there was some improvement in terms of voltage fluctuations. When assessing the effects of the 20 MW BESS when the voltage setpoint is set at 1 pu, the busbar voltages range from 0.98 pu to 1.04 pu under all contingencies. When the setpoint is at 1.03 pu, the voltage fluctuation ranges from 0.99 pu to 1.05 pu. And when the voltage setpoint is at 0.98 pu, the voltage fluctuation of the busbars under all contingencies ranges from 0.98 pu to 1.03 pu. This shows that the 20 MW BESS does improve voltage control at Kanengo and Nanjoka substations.

Reactive Power Support:

Under both peak loading and light loading cases, it can be noted that the 20 MW BESS provides the ESCOM system with reactive power support. The reactive power limits were assumed to be +/-20 MVAr (this are generic reactive power limits and are not yet specific to a particular equipment). Under all contingencies, the reactive power limits were not exceeded.

6.4. DYNAMIC VOLTAGE VARIATIONS / RESPONSE – RAPID CLOUD MOVEMENT ON SALIMA PLANT

This subsection investigates the effects of the 20 MW BESS with 30 MWh capacity on voltage variations in the ESCOM network. With 101 MW of solar PV installed on the system, cloud transients can cause rapid voltage fluctuations in the solar PV system's output. The voltage fluctuation can significantly affect the voltage levels in the grid with high penetration of solar PV systems. This exercise tests the 60 MW Salima plant when loaded at 100% of its rated power. When it is loaded at 40% of its rated power, the voltage levels at different 132kV busbars are compared before and after integrating the 20 MW BESS. The voltage setpoint is set at 1 pu. The voltage fluctuations are assessed when no governing units are available.

The stations to be monitored are as follows:

- Kanengo 132 kV
- Golomoti 132 kV
- Nanjoka 132 kV
- Nkhoma 132 kV

The study is conducted under midday loading; the following generation and loading are assumed:

- Synchronous generation – 313 MW
- Solar PV generation – 101 MW
- mid-day loading – 250 MW

The system's voltage variation when there are minimal governing units is assessed. Figure 29 below shows the dynamic voltage response for the four stations monitored when 60% of the Salima solar PV plant was lost due to rapid cloud movement before integrating the 20 MW BESS.

Voltage Variation before BESS is Integrated:

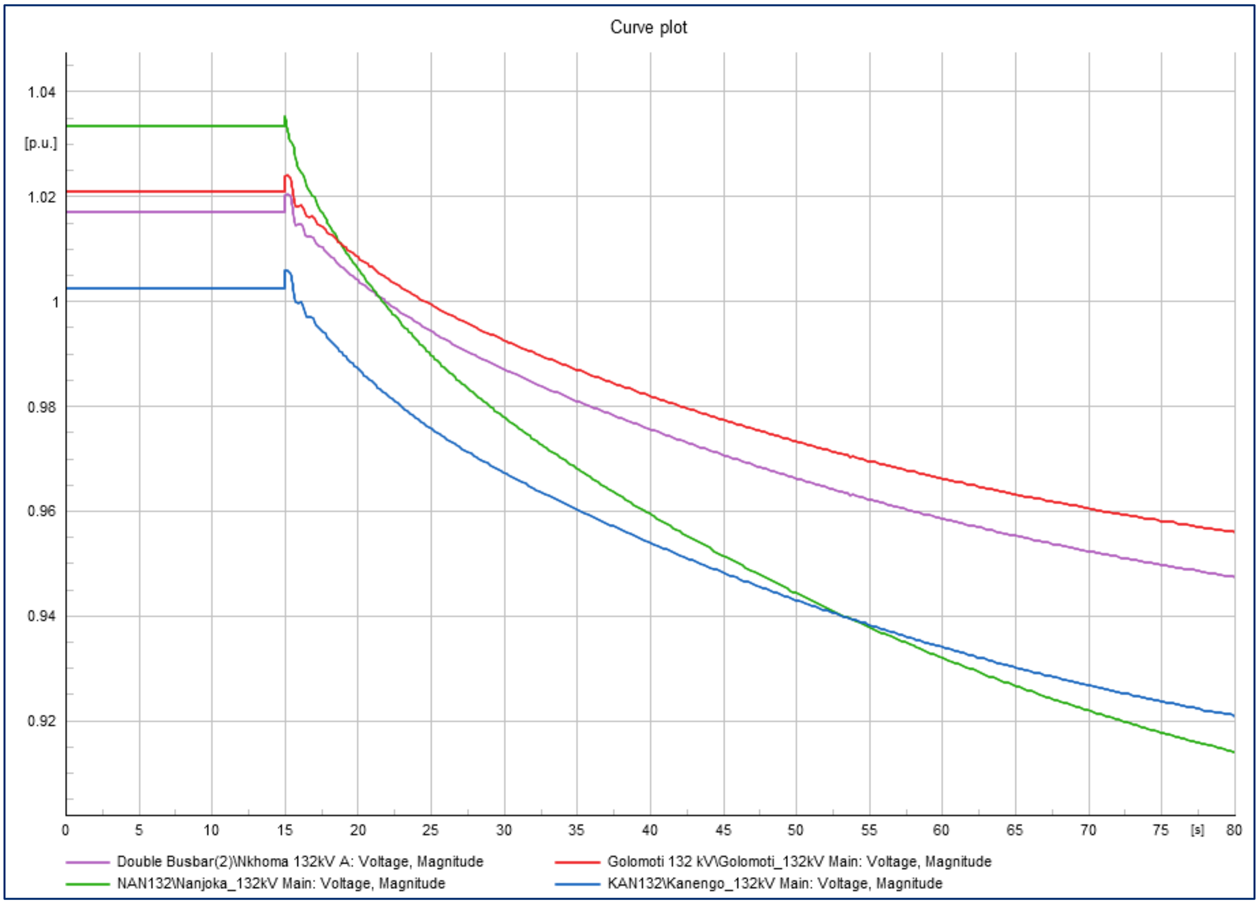

Figure29: Busbar voltage when the Salima solar PV plant power fluctuated to 40% before BESS integration.

Figure 29 shows how the voltage levels of the four stations gradually drop with Nanjoka 132 kV busbar dropping faster than the rest of the stations. The voltage levels of the station drop below 0.95 pu to about 0.92 pu. This shows that the sudden cloud cover can cause adverse voltage fluctuations in the ESCOM system, causing challenges in control in the system.

Figure3030 below shows the voltage fluctuation when the Salima solar PV plant loses 60% of its rated output power due to rapid cloud movement. The difference here is that BESS has been integrated in to the system.

Voltage Variation after BESS has been integrated.

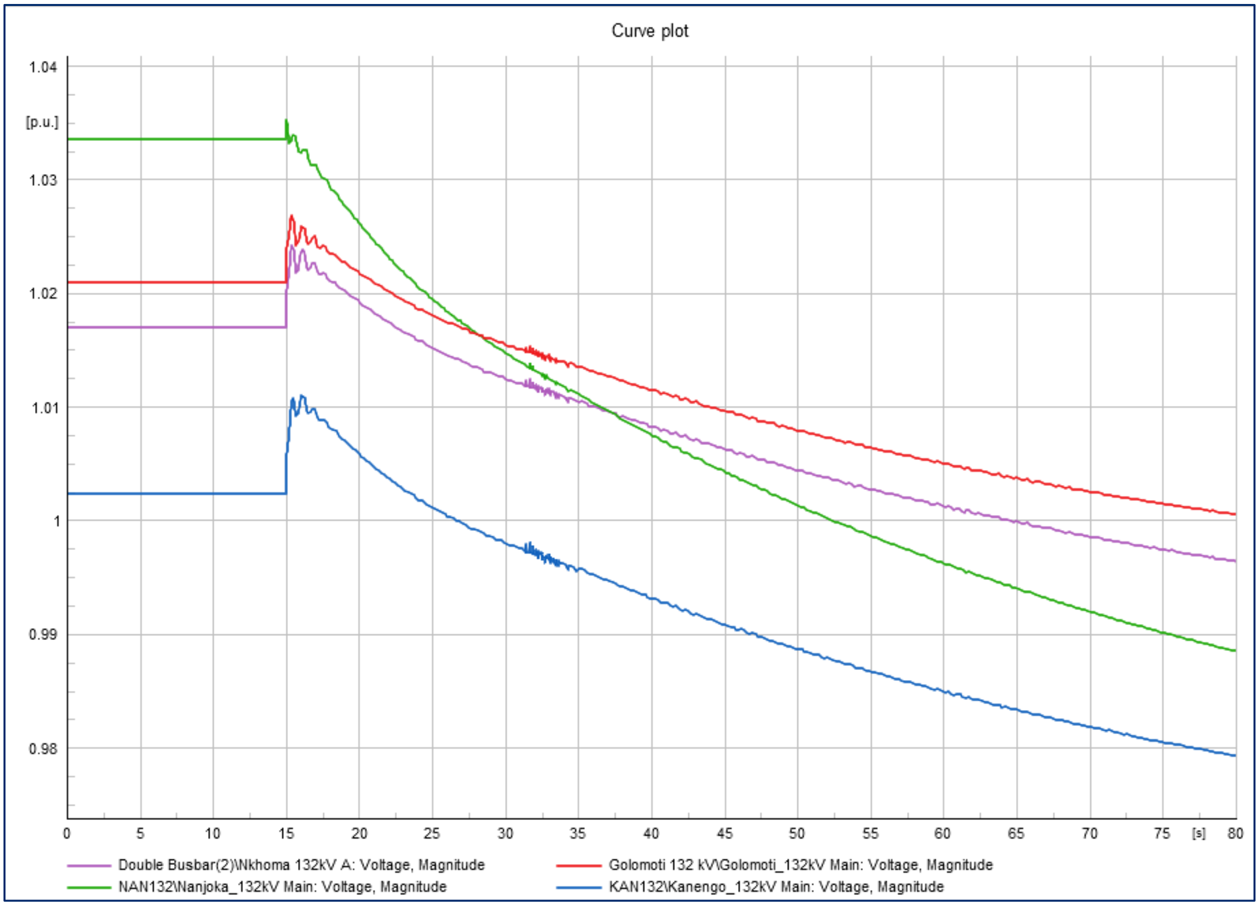

Figure30: Busbar voltage when the Salima solar PV plant power fluctuates to 40% after 20 MW BESS integration.

Figure 30 indicates that the voltage dip is smaller compared to when the 20 MW BESS is not integrated. This shows that the installation of the 20 MW BESS will help with voltage fluctuation in the system when the solar PV plant fluctuates due to cloud cover. After the Salima Solar PV plant lost 60% of its power, the voltage levels at the four stations are still within the lower voltage limit.

7. CONCLUSIONS

The completed study resulted in the following conclusions and recommendations.

7.1. PRIMARY FREQUENCY RESPONSE STUDY

The studies show that the deployment of 20 MW (30 MWh) BESS in the ESCOM power system will assist with frequency stability in the Malawian grid as the number of governing reserves required after integration of BESS reduces from 34 MW to about 9.7 MW during system light loading conditions.

The primary frequency response study was conducted using the proposed BESS settings from the secondary frequency study. The droop was set to 0.4% and the dead band was set to +/- 0.05 Hz. These settings clearly show that BESS deployment in the ESCOM system will be beneficial in assisting with frequency stability. Table 21 shows results for PFR under light loading conditions.

Table 11: Results comparison between the three scenarios under light loading.

Parameter	Governing units only	Governing Reserves with 20MW BESS
Primary frequency Reserves (MW)	34	9.7
RoCof (mHz/s)	-325	-266
Nadir (Hz)	49.50	49.49
BESS Rise time (ms)	0	608
BESS power (MW)	0	20

7.2. SALIMA PLANT CURTAILMENT CONSIDERATIONS

<u>60 MW TRIP:</u>
PFR studies were also done to depict the impact of the Salima plant trip at both full loading (60 MW) and when the plant is loaded at a partial loading of 40 MW. The results of these PFR studies showed that a trip of Salima from 60 MW loading resulted in frequency dropping down to 48.8Hz, with the ESCOM system providing 70 MW of governing. On the other hand, when BESS is incorporated, and this trip (60 MW) is simulated, the frequency drops but now turns at 49. 15Hz. This shows that BESS does improve the frequency response, although more is needed to meet the Grid Code requirements, which require the frequency to turn at 49.5 Hz.

<u>40 MW TRIP:</u>
When the plant is loaded at 40 MW and a trip is simulated from this level, the frequency drops to 49.3 Hz when only governors can provide PFR reserves. But on the other hand, when the BESS is also available to assist with PFR reserves, the frequency turns at 49.5 Hz. This proves that integration of 20 MW BESS can help with PFR when the Salima plant is run curtailed.

7.3. MOZAMBIQUE / SAPP INTERCONECTOR CONSIDERATIONS

The PFR studies were also done under light loading to quantify the amount of reserves needed to turn the frequency at 49.5 Hz and check the impact of the SAPP interconnector on PFR requirements. Two scenarios were done as follows:

- Without BESS (PFR reserves provided by governing only)
- With BESS (PFR reserves provided by BESS only)

Under both of these scenarios, it was observed that the interconnector provided all the system PFR needs for the ESCOM system. The interconnector did not seem to require any assistance from neither BESS nor governors as it was able to provide required reserves; and under both cases the frequency never dropped below 49.5 Hz – the interconnector managed to keep the frequency tightly within the dead band of +/-0.15 Hz for a trip of Kapichira unit 2 from full load (30 MW).

7.4. VOLTAGE CONTROL STUDY

Under the voltage control study, the different voltage setpoints (1 pu, 1,03 pu and 0.98 pu) for the 20 MW BESS are assessed under peak and light loading using v-control mode. All these voltage setpoints were tested with a BESS power factor setting of 0.95 as per Grid Code requirements for integration of RE generation.

It can be noted that the integration of the 20 MW BESS assists with voltage control at the Kanengo and Nanjoka substations. The busbars that were observed under contingencies showed voltage fluctuation improvements when the 20 MW BESS was integrated. The Golomoti and Nkhoma 132 kV busbars showed no voltage fluctuation improvements when the 20 MW BESS was introduced. This indicates that the voltage control will improve after BESS integration at mainly Kanengo and Nanjoka. The 20 MW BESS showed significant reactive power support to the system under different contingency conditions.

Figure 31 below shows the voltage profile for the 20 MW BESS with 30 MWh capacity under system health when the AC output voltage is set at 0.98 pu.

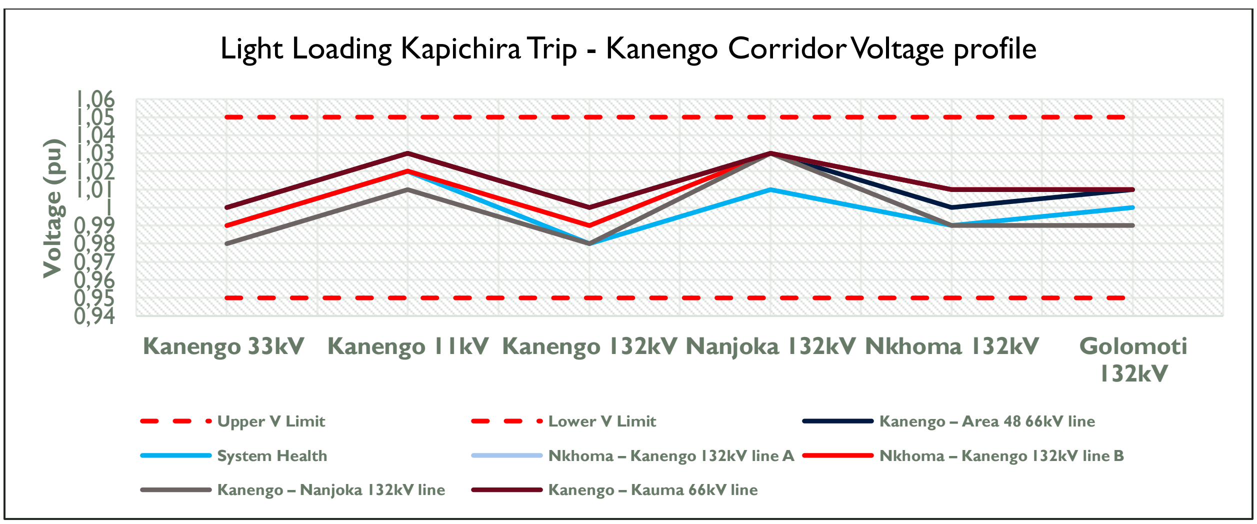

Figure31: Voltage profile results when the BESS voltage setpoint is at 0.98pu under light loading.

8. RECOMMENDATIONS

Based on the above conclusions, the following recommendations are drawn:

PFR Settings:

The following **PFR**/**FFR** settings are recommended for the 20 MW BESS with 30 MWh capacity:

- **Droop** = 0.4%
- **Dead band** = +/- 0.05 Hz

Voltage Control Settings:

Voltage control settings for BESS integration at Kanengo are recommended as follows:

- **Control mode:** voltage control
- **Voltage setpoint:** 1.0 pu
- **Power factor**: 0.95

9. APPENDIX A:

RESULTS COMPARISONS UNDER LIGHT LOADING

Below we take a look at the three scenarios:

- When the synchronous machines are used for governing.
- When the governing units are supplemented by a 20 MW BESS.
- When the governing units are supplemented by the SAPP interconnector.
- When the SAPP interconnection and 20 MW BESS are used for PFR.

Figure 532 below shows the superimposed frequency response for the three scenarios, the SAPP interconnection shows a better response compared to the other scenarios since the SAPP interconnection is larger than the ESCOM system.

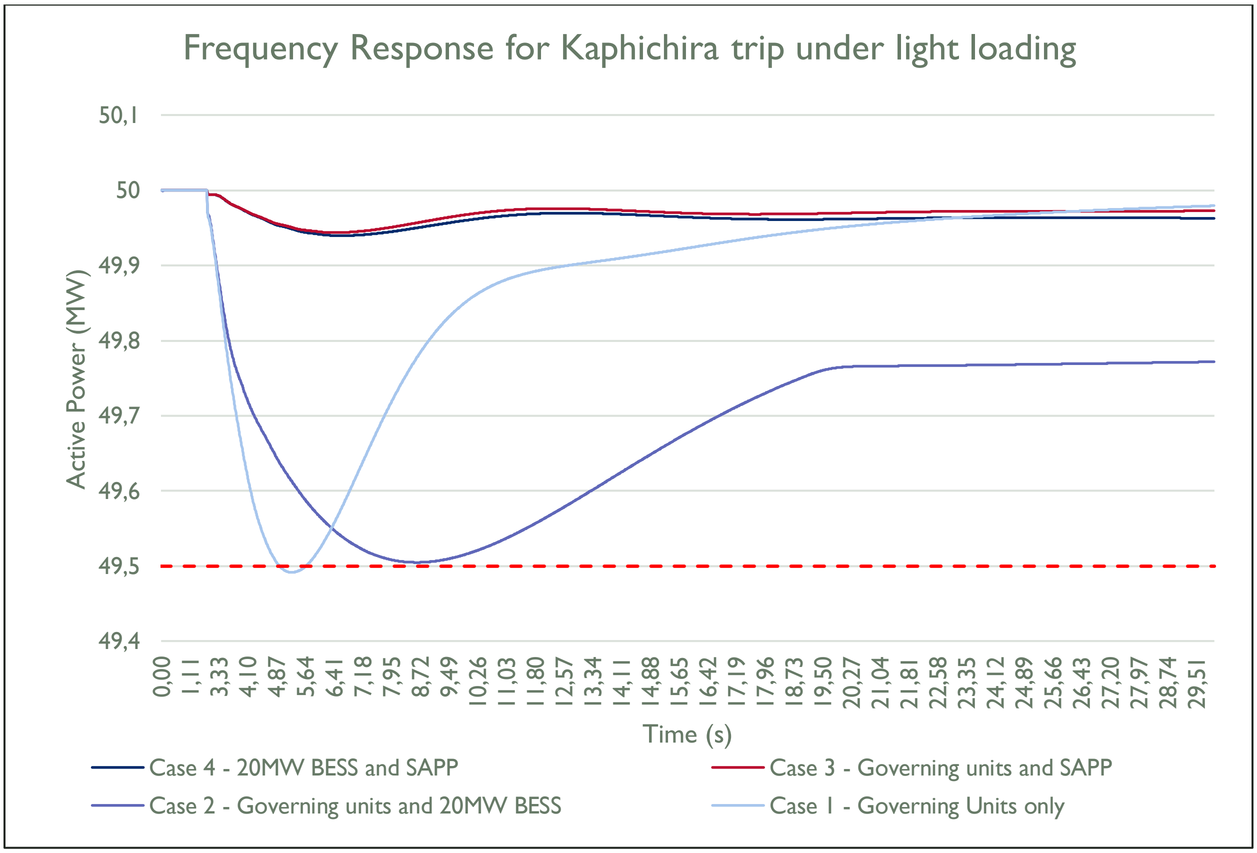

Figure 32: Superimposed frequency response representing the four scenarios studied above.

In Table 22, the four scenarios are compared.

Table 22: Results comparison between the three scenarios.

Parameter	Governing units only	Governing units supplemented by a 20MW BESS	Governing units supplemented by SAPP interconnector	20MW BESS Supplemented by SAPP interconnector

Governing Reserves (MW)	33.1	9.7	37.7	37.7
RoCof (mH/s)	-325	20	-25.8	-26.3
Nadir (Hz)	49.50	-266	49.944Hz	49.94Hz
BESS Rise time (ms)	0	608	0	21.75
BESS power (MW)	0	49.49	0	6.79

33 below represents the BESS response when the governing units are supplemented by a 20 MW BESS and when the 20 MW BESS is used for primary frequency response with the SAPP connected to the ESCOM grid.

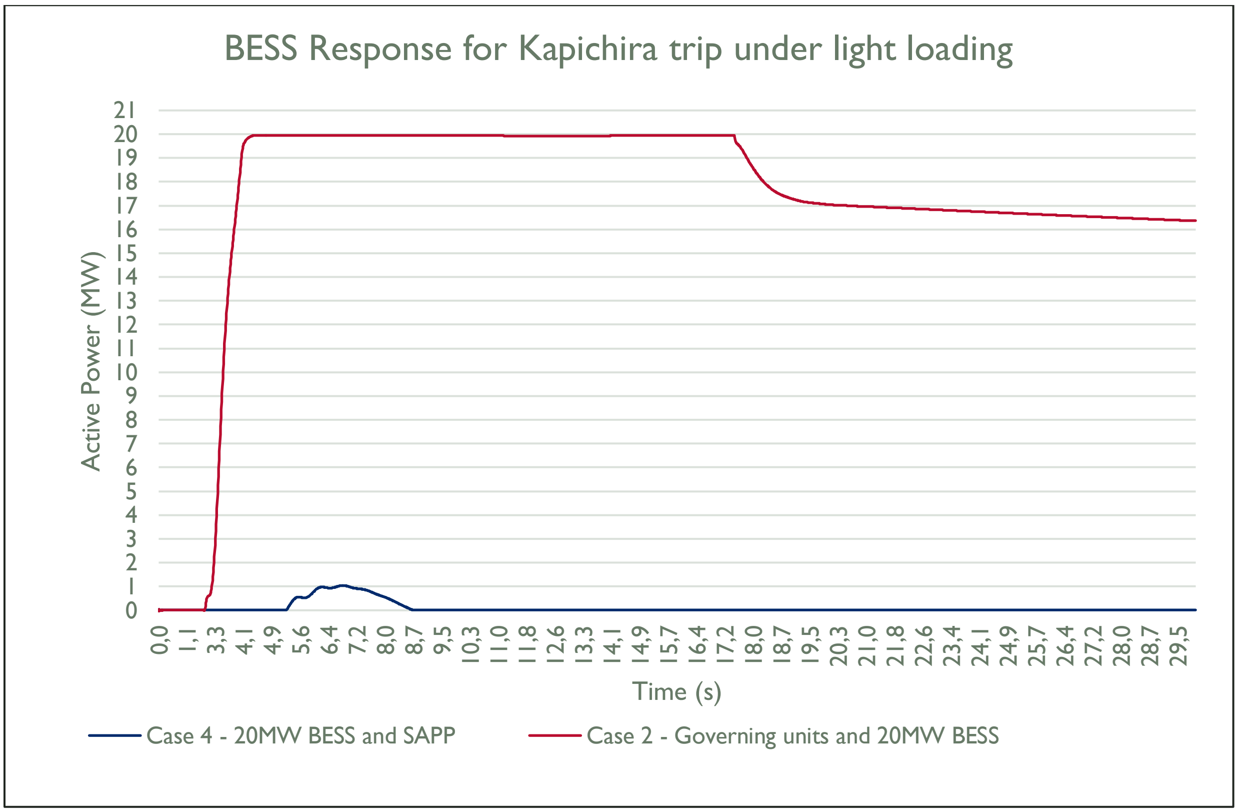

Figure 33: Superimposed BESS response representing the governing units supplemented by a 20 MW BESS and when the SAPP interconnector is supplemented by a 20 MW BESS.

Figure34 below shoes the governing response for the four cases studied above. It can be noted that less governing is required under case 2 and that the SAPP interconnector would provide more governing and the ESCOM system will not experience large frequency deviation when the Kapichira 30 MW unit is lost.

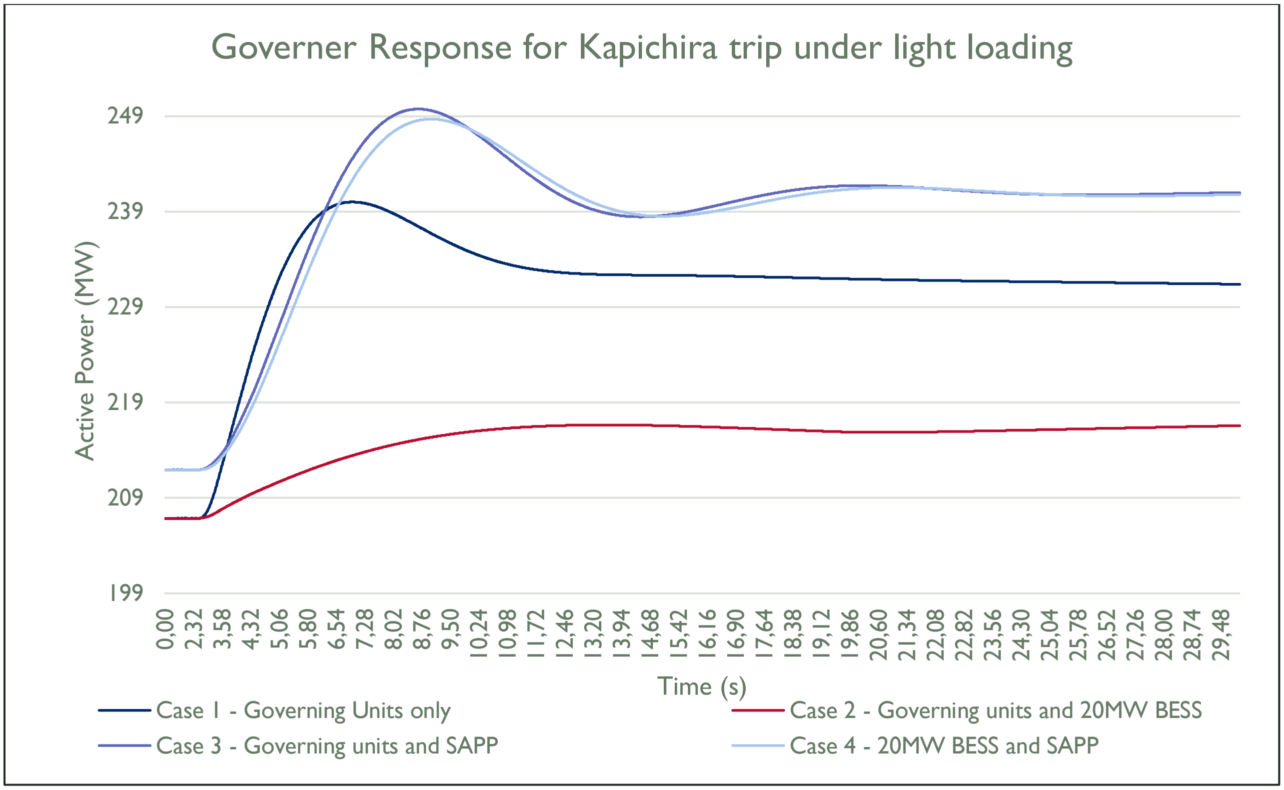

Figure34: Governing response for the four scenarios.