Republic of Malawi

Ministry of Energy

BESS GRID INTEGRATION AND OPTIMIZATION IN MALAWI

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WSP

8 First Street
Manchester
M15 4RP

Phone: +44 161 200 5000

WSP.com

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Prepared by	Filip Milankovic Jelena Piper	Filip Milankovic Jelena Piper	Filip Milankovic Jelena Piper	Filip Milankovic Jelena Piper
Signature				
Checked by	Nikola Djeric	Nikola Djeric	Nikola Djeric	Nikola Djeric
Signature				
Authorized by	Nikola Djeric	Nikola Djeric	Nikola Djeric	Nikola Djeric
Signature				
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INTRODUCTION AND OBJECTIVES

1 INTRODUCTION AND OBJECTIVES

1.1 BACKGROUND

The Global Energy Alliance for People and Planet (GEAPP) is supporting Malawi to achieve universal electrification based on renewables while ensuring inclusive economic growth and sustainable livelihoods. The GEAPP is committed to supporting a universal electrification agenda, covering both DREs and the grid-based energy transition, and has identified Malawi among high priority countries. There is a need for the country to rapidly expand its generation capacity, and an opportunity to capitalize on opportunities for early successes in this area and demonstrate a heavily renewable, least-cost pathway for providing affordable energy for underserved people and businesses throughout the country. This will displace the traditional thermal generation in the country's current integrated resource plan, and directly impact vulnerable populations in a country that has just 12% access to the electricity grid. A recent bankability analysis contracted by GEAPP laid out top priorities for attracting investment into the sector and was accepted by relevant government agencies. These priorities include updating the national integrated resource plan and supporting the utility on business planning, integration of DREs and battery systems, and grid extension. Key Electricity Sector Institutions are currently preparing for an update of the national integrated resource plan. In addition, there are decisions underway towards replacement of on-grid thermal generator systems. Grid-integrated battery storage systems may be able to play significant roles in both of these.

A range of institutions are active in the sector and aligning these groups for rapid decision-making will require technical analyses in support of the distribution utility (ESCOM), the single buyer unit (PML), and the Ministry of Energy (MoE). Supporting Malawi at this critical stage will require agile and highly specialized expertise in modelling of electricity grids and battery energy storage systems, to provide timely input and support decision making in the sector. In that respect, WSP was chosen to perform the studies and support stakeholders in this journey.

1.2 KEY OBJECTIVES

The primary objective of this assignment is to provide transmission system compatibility assessment for the proposed replacement of diesel generators and to provide the most optimal way of the BESS distribution along the Malawian network. This workstream represents a continuation of the Workstream 1 and aims to conclude an overall benefit for the system taking into consideration all the aspects of the power system. The objective of installation of grid-integrated BESS is to minimize impacts of variable solar power on the grid.

<u>The results/recommendations of the study and BESS size/s proposed are based on an isolated system, but once the interconnector is in by December 2023, the solution/proposals will be different.</u>

1.3 REPORT ORGANIZATION

This Report comprises the following sections:

- Section 1: INTRODUCTION AND OBJECTIVES– The general overview of the study is given.
- Section 2: OUTCOMES FROM THE WORKSTREAM 1– Overview of the main findings from the techno-economic optimization from the workstream 1, that will serve as inputs for the workstream 2.

- Section 3:METHODOLOGY– Overview of the methodology and assumptions used for execution of the studies.
- Section 4:DIGSILENT MODEL – Description and main settings of the DigSilent model which was adopted for the purpose of this study.
- Section 5:STATIC ANALYSES – Steady state analysis for different cases, that should address an initial voltage concerns and solutions.
- Section 6:DYNAMIC ANALYSES – Dynamic analysis for different cases, that should address answers on possible transient stability issues and how the system reacts on large disturbances.
- Section 7: BESS SERVICES - Overview of the services that Battery Energy Storages might be able to provide
- Section 8: BESS FINANCING CONTEXT - Overview of the basic conditions for defining an appropriate business case for BESS
- Section 9: ASSOCIATED REGULATIVE - Overview of the needs for the regulative amendments
- Section 10: GRID IMPACT STUDY - COMMENTS – WSP overview of the conclusions and recommendations from the previous study done by Mot McDonald (2016)
- Section 11: CONCLUSIONS AND RECOMMENDATIONS – Overview of the overall findings, conclusions and recommendations

2

OUTCOMES FROM THE WORKSTREAM 1

2 OUTCOMES FROM THE WORKSTREAM 1

The analysis from the Workstream 1 was aiming to provide a quick answer on what was an efficient way of replacing the diesel generators in the Malawian power system.

These answers are of utmost importance to alleviate a decision making for the operational planning activities. Although the focus was supposed to be on a quick cost-benefit analyses, the wider context had to be taken into consideration, which includes the current IRP findings and a longer horizon (up to 2032).

PLEXOS analysis has been carried out for period 2022–2032 to determine optimal generation portfolio for efficient replacement of the diesel generators. The goal of LT calculations was to determine expansion plan for defined period considering reliability criteria.

With regards to the expansion candidates, two different pathways were considered:

1. **Generic PLEXOS Cases** – Candidates for expansion are generic 1MW PV, wind and BESS units, and confirmed candidate units (PV, wind and gas). Hydro candidates for expansion are not included.
2. **Planned Projects Cases** – Candidates for expansion are confirmed candidate units (PV, wind, gas and hydro). Generic 1MW PV, wind and BESS units are not included.

After the discussion with stakeholders, we found the Planned Project Case (so called Pipeline case) as the most appropriate and the most likely for future analyses. The demand forecast for this case, as a fundamental driver for the expansion plan, was taken from the RMI (Rocky Mountain Institute) study.

The following figure shows installed capacity per technology for the period up to 2032

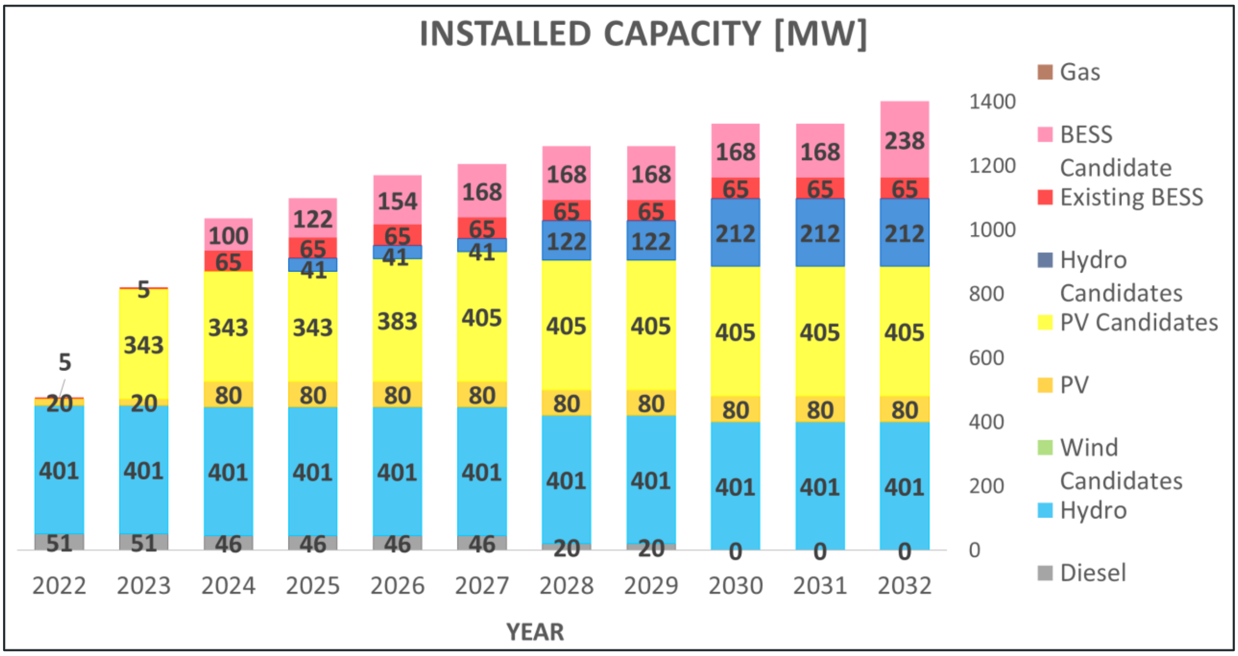


Figure 2-1 - Installed capacity for the Pipeline case up to 2032

In order to have a comprehensive look at costs and all the benefits, the case was accompanied by the CBA review table to point out all the implications that the case produces. The table is not associated with quantification factors for each issue, it is rather indicative.

Table 2-1 -Cost Benefit overview for Pipeline case

	Costs	Benefits
Annualized Build Cost	Increased, caused by expansion (PV, BESS, Hydro)	
Fuel Cost		Decreasing due to reduced diesel deployment
Levelized Cost [$/MWh]		Decreasing
PV penetration	High, but not as much as in case 2	
Wind penetration	no wind	
BESS contribution	Reasonable, much lower then in case 2, as hydro generation contributes a lot to overall system flexibility	Possibilities for other services: frequency regulation, reserve, voltage support, black start
Firm capacity of the system		hydro units provide sufficient firm capacity
Influence on operating reserve	Increase of spinning reserve requirements due to variable nature of soar	
Influence on system security		Given that BESS are high-performance facilities, security is expected to be just better
Environmental concerns		Reduced emissions
Social concerns		This pathway is more aggressive in RES penetration, that can cause benefit for society (job creation)

3

METHODOLOGY

3 METHODOLOGY

3.1 GRID PERFORMANCE ASSESSMENT

Analyses in the Workstream 1 were purely techno economic, considering just the generation portfolio and optimizing the total system cost while ensuring balance between generation and demand over the 10-years time horizon. Transmission system was considered as a “black-box”.

However, on order to get the feasible expansion plan and to deploy potential facilities for wider services, the transmission system compatibility assessment is necessary. The following Figure 3-1 shows the basic methodological steps to reach the goal.

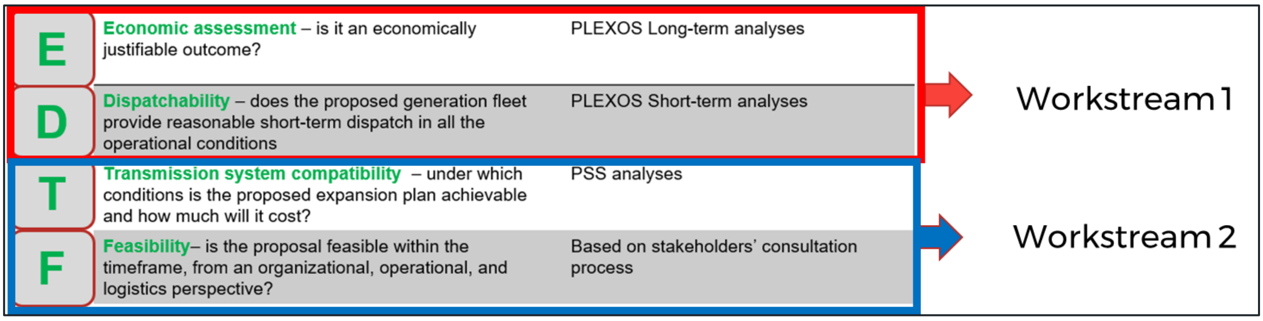


Figure 3-1 - Basic methodological steps in power system development

Optimal dispatch from the workstream 1 will be input for the network model:

- For different regimes – peak, off-peak, solar max, hydro min/max,
- For different BESS locations.

There are several questions of interest for transmission system compatibility, such as:

- Voltage problems,
- Line loadings and line contingencies,
- Reactive power support,
- System inertia level,
- Rate of change of frequency in case of critical incidents,
- Voltage recovery in case of critical faults.

To address these questions a set of different analyses need to be performed, as shown in the following Figure 3-2.

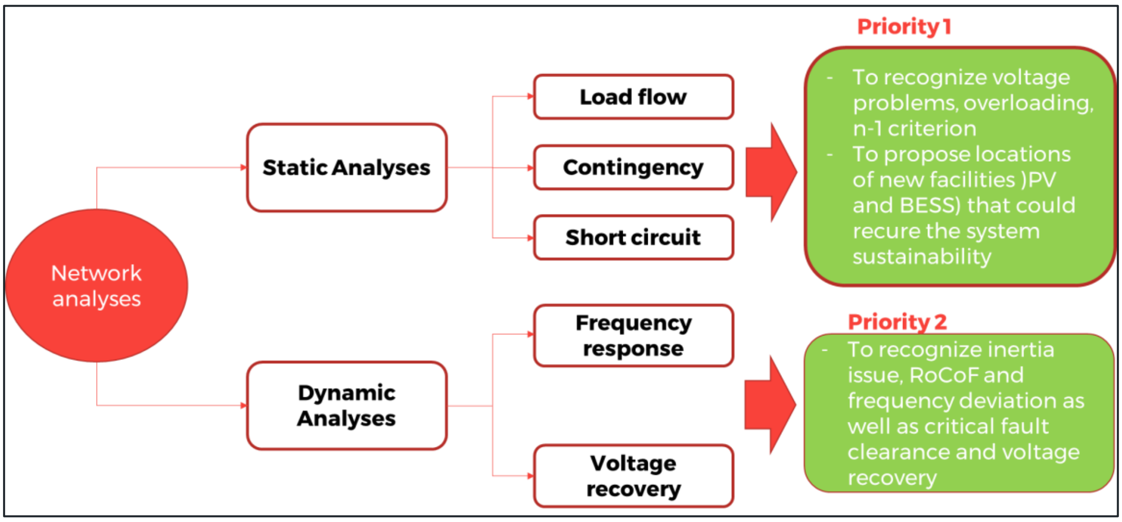


Figure 3-2 - Network Analyses Methodology

3.2 STUDY CASES

Although the time horizon for the techno-economic analyses was up to 2032, a focus for the network analyses will be on medium-term, covering the horizon up to 2025. So, the target years for analyses will be:

- 2022,
- 2025.

With regards to regimes that might be relevant for conclusions we will consider extremes:

- Solar peak – 13rd hour when the Solar generation is max,
- Evening peak – 20th hour when the demand is max.

Given the existing network state we believe that consideration the off-peak regime is not necessary, and no relevant conclusion might be drawn.

Therefore, study cases that we will consider are shown in the following figure.

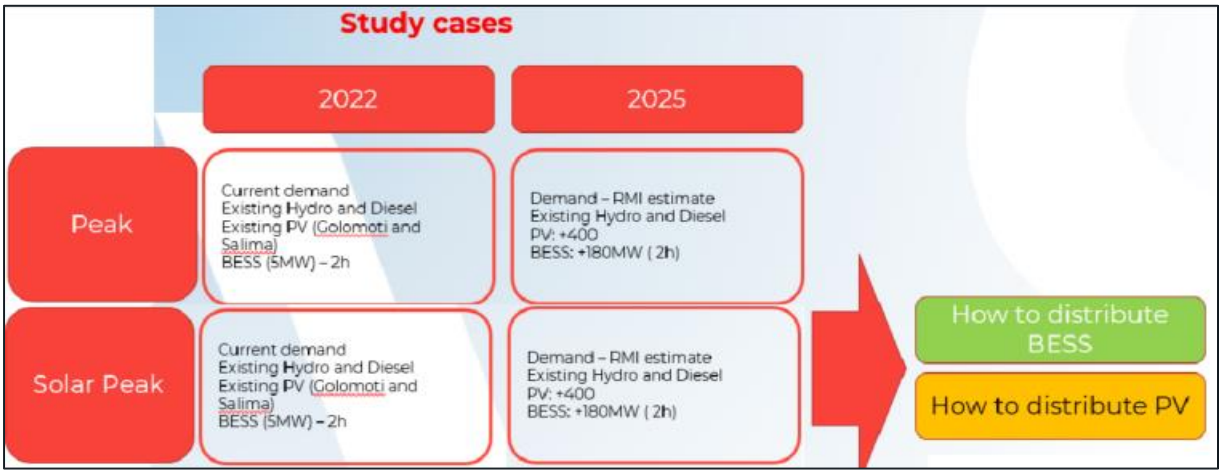


Figure 3-3 - Network study cases

As can be seen in the Figure 3-3, analyses should show that the distribution of BESS facilities and PV plants is optimal and overall impact on the network is beneficial. Finding the most efficient BESS and PV distribution over the system will not be a result of some optimization function, it will be a result of the logical approach based on the real system needs.

To do that, we start with the weak points identification of the existing Malawian system. Given the configuration of the Malawian transmission system, we recognise the essential problems, as shown in the Figure 3-4.

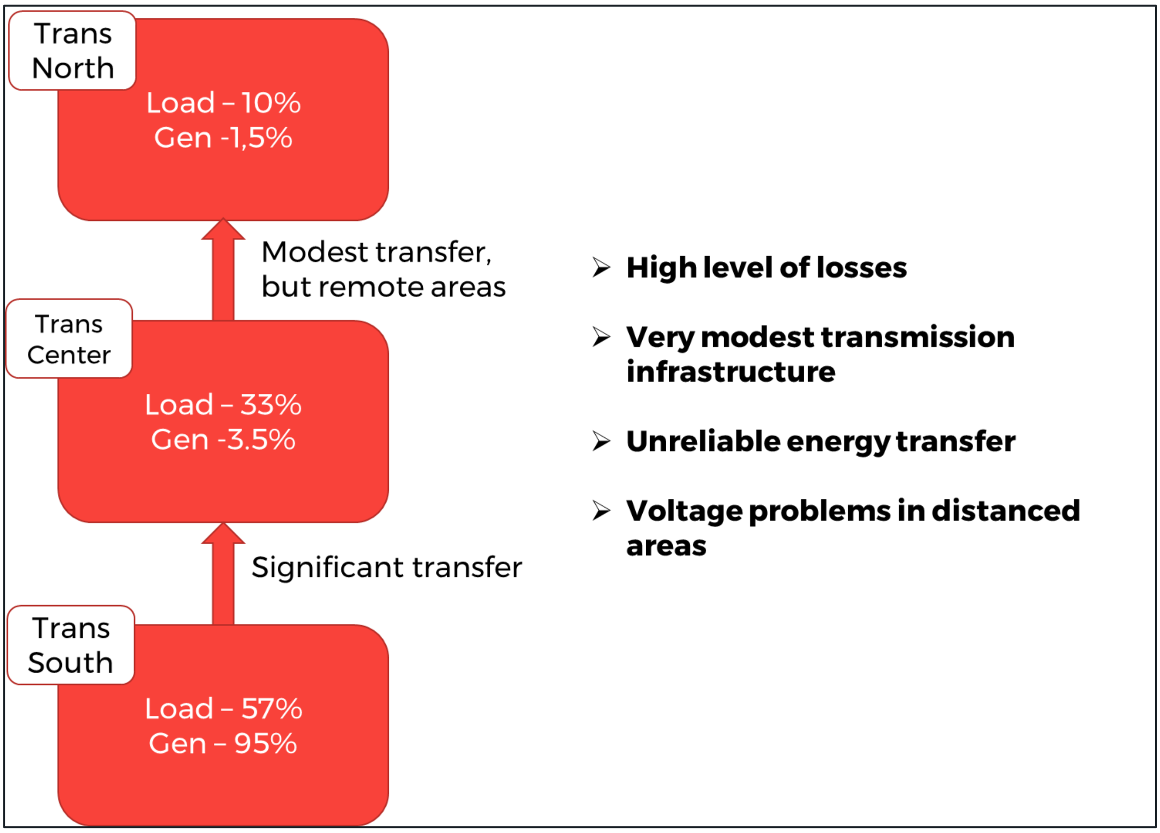


Figure 3-4 - Malawian system weak points

High level of transmission losses is a direct consequence of the significant energy transfer from south where the bulk of production facilities are placed, to central and north region.

Transmission infrastructure is very modest and mostly with no redundant paths that might cause the unreliable transfer to remote places.

Obviously, because of the concentrated generation and distributed demand, there are a lot of problems with voltages in distanced areas.

To resolve these problems, the following approach is used:

- Any new PV facility should be placed in the electrical vicinity of the weak electrical nodes,
- To avoid additional unnecessary transmission losses, any new BESS facility should be placed in the same node as the PV plant, in the electrical vicinity,

- Given the Malawian system size (300-350MW) a single BESS facility does not exceed 30MW installed capacity because greater unit would represent the reference incident more than 10% of the power system size, and that can cause unwanted frequency deviation and possible wider consequences,
- Reactive power capability of BESS is assumed with a 0.95 power factor,
- Construction and spatial feasibility were not taken into consideration.

4

DIGSILENT MODEL

4 DIGSILENT MODEL

The Malawian power system network model is built in DIGSILENT software and it was given by ESCOM to WSP to conduct the power system study. The model consists of modelled regions:

- Generation,
- Trans North,
- Trans Centre,
- Trans South.

In **Table 4-1** generation units within the Malawian power network are shown. Agrekko Kanengo DG located in the Trans Centre region is in service, hence operating with zero power output, as highlighted in **Table 4-1**.

Table 4-1 -Generation units data within the Malawian power system network

Generator name	Type	Rated power [MW]	Active power [MW]	Reactive power [MVAr]	Name of the corresponding substation	Name of the line that goes from the corresponding substation	Ending bus
Kapichira G1 (reference machine)	Hydro	32	9	6.4	Kapichira_132	Tedzani - Kapichira	Ted_132 kV Main
Kapichira G2	Hydro		28.8	6.6			
Kapichira G3	Hydro						
Kapichira G4	Hydro						
Tedzani G5	Hydro	31	26.5	4.4	Tedzani 132	Tedzani – Kapichira line, Nkula 'B' – Tedzani line	Kapichira _132 bus, Nkula 'B' 132kV Main bus
Tedzani G6	Hydro						
Tedzani IV	Hydro	20	20	-19.1	Tedzani IV 66kV	Tedzani IV-Tedzani I &II	Tedzani 66kV/1
Tedzani G1	Hydro	10	10	3.8	Tedzani 66kV/1	Nkula B – Tedzani line, Nkula A-Tedzani line	Nkula 'B' 66kV/2 bus, Nkula _A_66kV Main B/B bus
Tedzani G2	Hydro						
Tedzani G3	Hydro						
Tedzani G4	Hydro						
Nkula G5	Hydro	20	19	9.6	Nkula_66(2)	Nkula B - Tedzani	Tedzani_66kV/2
Nkula G1	Hydro	12	11.4	1.5	Double Busbar(5) (Nkula _A_66kV Main B/B bus)	Nkula A-Tedzani line, Nkula – Nkula line	Tedzani_66kV/2 bus, Nkula 'B' 66kV/1 bus
Nkula G2	Hydro						
Nkula G3	Hydro						
Nkula G4	Hydro	20	20	3.1	Nkula_66(1)	Nkula - Nkula	Nkula _A_66kV Main B/B
Nkula G6	Hydro	20	20	12.7	Nkula 'B' 132kV		

Generator name	Type	Rated power [MW]	Active power [MW]	Reactive power [MVAr]	Name of the corresponding substation	Name of the line that goes from the corresponding substation	Ending bus
Nkula G7	Hydro					Nkula 'B' - Tedzani	Ted_132 kV Main
Nkula G8	Hydro						
Wovwe G1	Hydro	1.45	1.4	0.7	Wovwe_66kV	Wovwe - Uliwa	Uliwa_66 kV bus
Wovwe G2	Hydro		1.4	0.9			
Wovwe G3	Hydro	1.45	1.4	0.7			
Luwinga_G1	Hydro	2	2	4.5	Luwinga 33kV	Luwinga-Bwengu line, Chintheche-Luwinga line	New Bwengu A 132kV bus, Chintheche_132kV Main bus
JCM Golomoti Plant	PV plant	19.2	0	5.1	JCM Golomoti 132kV B/B	JCM-Golomoti	Golomoti_132kV Main
JCM Plant 1	PV plant	20	0	26.6	JCM 132KV B/B	JCM-Nanjoka	Nanjoka_132kV Main
Agrekko_Kanengo DG	Diesel	10	0	0	Kanengo_66	Kanengo-Area48 line, Kanengo-Kauma line	Area 48_66kV bus, Kauma 66kV bus
Kanengo Diesel(1)	Diesel	10	10	0			

Table 4-2 are presented Grid summary results for Trans Centre, Trans South, and Trans North region.

Table 4-2 - Load flow voltages in the relevant part of the Malawian network (Trans Centre)

Area: Centre			
Generation	**10 MW**	**0 MVAr**	
Inter-Area Flow	**-74.14 MW**	**-28.61 MVAr**	
Load P (U)	**77.03 MW**	**19.47 MVAr**	
Load P (UN)	**82.92 MW**	**21.25 MVAr**	
Load P (Un-U)	**5.89 MW**	**1.77 MVAr**	
Grid Losses	**7.11 MW**	**9.13 MVAr**	
Installed Capacity	**30 MW**		
Spinning Reserve	**20 MW**		
Inter-Area Flow to	**South**	**-125.2 MW**	**2.17MVAr**
	Total	**-74.14 MW**	**-28.61 MVAr**

Area: North			
Generation	4.34 MW	2.3 MVAr	
Inter-Area Flow	-20.72 MW	4.49 MVAr	
Load P (U)	24.39 MW	6.88 MVAr	
Load P (UN)	26.49 MW	7.4 MVAr	
Load P (Un-U)	2.1 MW	0.52 MVAr	
Grid Losses	0.67 MW	-.1.77 MVAr	
Installed Capacity	4.34 MW		
Spinning Reserve	0 MW		
Inter-Area Flow to	South	-14.27 MW	1.83 MVAr
	Total	-20.72 MW	4.49 MVAr
Area: South			
Generation	322.15 MW	105.47 MVAr	
Inter-Area Flow	175.3 MW	35.58 MVAr	
Load P (U)	131.6 MW	36.1 MVAr	
Load P (Un)	140.95 MW	38.79 MVAr	
Load P (Un-U)	9.35 MW	2.69 MVAr	
Grid Losses	15.25 MW	33.79 MVAr	
Installed Capacity	365.93 MW		
Spinning Reserve	43.78 MW		
Inter-Area Flow to	Centre	125.2 MW	-2.17 MVAr
	North	14.27 MW	-1.83 MVAr
	Total	175.3 MW	35.58 MVAr

5

STATIC ANALYSES

5 STATIC ANALYSES

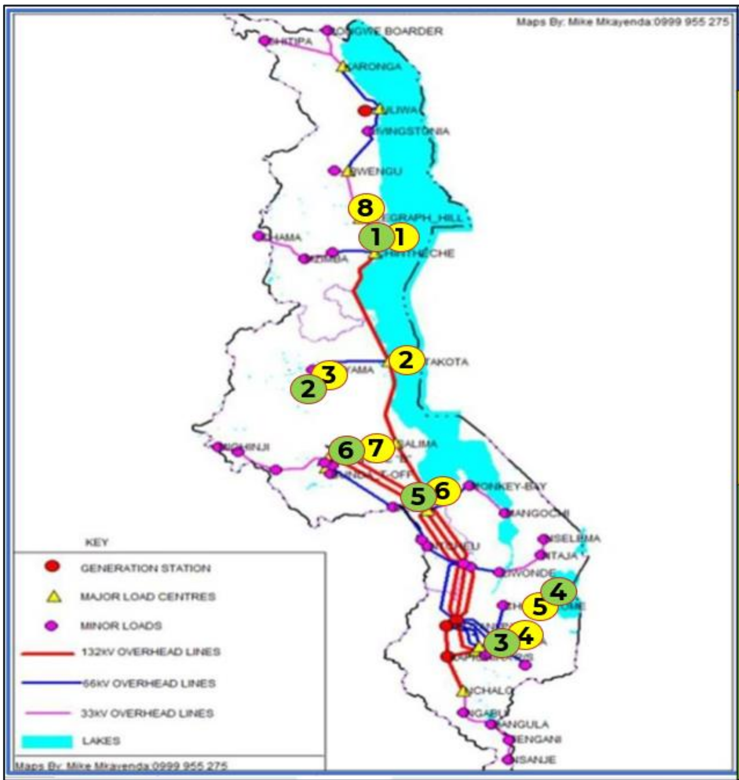
Here is an intro section to highlight the cases being studied. The two main cases are generic and pipeline. Generic was created by WSP and pipeline was provided by ESCOM. Following analyses were conducted in solar peak and peak regimes to investigate the influence of BESS and PV integration in the Malawian power system: load flow, contingency and short-circuit. Off-peak regime for the pipeline case is given in appendix chapter.

GENERIC PROJECTS CASE

This case was created by our team to get better values of voltages across the Malawian power system. Locations for PV solar plants and BESS (Battery energy storage system) was determined on the basis of low voltage busbars.

Locations of PV and BESS with their installed capacity (**Figure 5-1**):

1. Chinteche 66kV (Trans North) - 50 (PV) + 30 (BESS)
2. Nkhotakota 132kV (Trans Centre) - 50 (PV)
3. Chinayama 66kV (Trans Centre) - 50 (PV) + 30 (BESS)
4. Mapanga 66kV (Trans South) - 50 (PV) + 30 (BESS)
5. Chinegeni 66kV (Trans South) - 50 (PV) + 30 (BESS)
6. Dedza 66kV (Trans Centre) - 50 (PV) + 30 (BESS)
7. Kanengo 66kV (Trans Centre) - 50 (PV) + 30 (BESS)
8. Chinteche 132kV (Trans North) - 50 (PV)



	Installed capacity	Node	
PV	50	Chinteche 66kV (Trans North)	1
	50	Nkhotakota 132kV (Trans Centre)	2
	50	Chinayama 66kV (Trans Centre)	3
	50	Mapanga 66kV (Trans South)	4
	50	Chinegeni 66kV(Trans South)	5
	50	Dedza 66kV (Trans Centre)	6
	50	Kanengo 66kV (Trans Centre)	7
	50	Chinteche 132kV (Trans North)	8
BESS	30	Chinteche 132kV (Trans North)	1
	30	Chinayama 66kV (Trans Centre)	2
	30	Mapanga 66kV (Trans South)	3
	30	Chinegeni 66kV(Trans South)	4
	30	Dedza 66kV (Trans Centre)	5
	30	Kanengo 66kV (Trans Centre)	6

Figure 5-1 - Locations of PV and BESS in Malawian power network

PLEXOS software analysis gave the optimal dispatch for the year 2024 in which is proposed installation of 400 MW solar power and 180 MW capacity of battery energy storage system. Load from dispatch for peak regime is 419.52 MW and for solar peak is 412.29 MW. BESS generation in peak regime from dispatch is 85.9 MW. For solar peak regime BESS load is 99.77 MW and PV generation is 320.71 MW. This dispatch is presented in **Table 5-1** .

Table 5-1- Modelled regimes in DigSilent software

Regime	Load [MW]	PV generation [MW]	BESS [MW]	Hidro units generation [MW]
Solar peak	412.29	320	99.77(BESS is charging)	201
Peak	419.52	0	85.99(BESS is discharging)	333
Off-peak	291.75	46.33	0	245

In the DIGSILENT model, ESCOM 2022 PLEXOS results (16) is the peak generic regime and ESCOM 2022 PLEXOS results-Filip (15) is the solar peak generic regime.

LOAD FLOW ANALYSES

The provided ESCOM 2022 DIGSILENT model was analyzed to determine the system state before (base case scenario) and after the connection of the PVs and BESSs into the Malawian power system. The **Table 5-2** below shows results for the South, North, and Centre region. Load flow calculations are carried out to determine the voltage profiles of the adjacent grid area, as well as to confirm equipment ratings. Two different operating regimes (peak and solar peak) were analyzed.

Table 5-2 - Load flow results- Voltages at buses within the Malawian network

Network data				Voltage [p.u.]	Voltage [p.u.]	Voltage [p.u]
Voltage level [kV]	Bus name	Substation	Location	Base case	Peak regime	Solar Peak regime
Area: Centre						
400	Nkhoma 400kV A	Double Busbar (1)	Trans Centre	1	0.96	0.96
400	Phombeya 400kV A	Double Busbar	Trans Centre	1.01	0.97	0.96
	Phombeys 400kV B	Double Busbar				
132	Nkhotakota_132kV Res	Nkhotakota_132 (1)	Trans Centre	0.94	1	1.01
132	Nanjoka_132kV Main	Nanjoka_132	Trans Centre	1	0.96	0.94
132	Golomoti_132kV Main	Golomoti 132 kV	Trans Centre	1.01	0.97	0.96

Network data				Voltage [p.u.]	Voltage [p.u.]	Voltage [p.u]
Voltage level [kV]	Bus name	Substation	Location	Base case	Peak regime	Solar Peak regime
132	Kanengo_132kV Res	Kanengo_132	Trans Centre	0.98	0.93	0.94
132	Dwangwa 132kV	Dwangwa 132kV	Trans Centre	0.94	1	1.02
132	Chintheche_132kV Res	Chintheche_132	Trans Centre	0.94	1	1.04
132	Nkhoma 132kV A	Double Busbar (2)	Trans Centre	1	0.95	0.95
	Nkhoma 132kV B	Double Busbar (2)		1	0.95	0.95
132	Phombeya 132kV	Phombeya 132kV	Trans Centre	1.02	0.98	0.97
132	Nkula ‘B’ 132kV Res	Nkula ‘B’ 132kV	Trans Centre	1.03	1	0.98
132	Chintheche_132kV Main	Chintheche_132	Trans Centre	0.94	1	1.04
66	Nkhotakota_66kV/1	Nkhotakota_66	Trans Centre	0.97	1	1.02
66	Nkhotakota_66kV/2	Nkhotakota_66(1)	Trans Centre	0.97	1	1.02
66	Nkhotakota_66kV/1	Nkhotakota_66	Trans Centre	0.97	1	1.02
66	Nkhotakota_66kV/2	Nkhotakota_66(1)	Trans Centre	0.97	1	1.02
66	Mlangeni_66kV	Mlangeni_66	Trans Centre	0.95	1.02	0.98
66	Golomoti_66kV	Golomoti_66	Trans Centre	0.99	1.01	0.99
66	Chinyama_66kV	Chinyama_66	Trans Centre	0.795	0.97	1.03
66	Dedza_66kV	Dedza_66	Trans Centre	0.94	1.02	0.99
33	Nkhotakota_33kV	Nkhotakota_33	Trans Centre	1.01	1	1.01
33	Nkhotakota_33kV/2	Nkhotakota_33(2)	Trans Centre	0.94	1.01	0.99
33	Kanengo_33kV B/B 2	Kanengo_33kV B/B 2	Trans Centre	0.95	1.01	0.97
33	Nkhotakota_33kV/1	Nkhotakota_33(1)	Trans Centre	0.95	1	1.01

Network data				Voltage [p.u.]	Voltage [p.u.]	Voltage [p.u]
Voltage level [kV]	Bus name	Substation	Location	Base case	Peak regime	Solar Peak regime
33	Nkhotakota_33kV/2	Nkhotakota_33(2)	Trans Centre	0.95	1	0.99
33	Chinyama_33kV	Chinyama_33kV	Trans Centre	0.84	0.97	0.97
33	Barracks_33kV	Barracks_33kV	Trans Centre	0.93	1	1
33	Nanjoka	Single Busbar	Trans Centre	0.96	1.01	0.99
33	BB	Single Busbar (5)	Trans Centre	0.8	0.97	1
11	Area 48_11kV1	Area 48_11(1)	Trans Centre	0.95	1	0.96
11	Lilongwe OT_11kV/1	Lilongwe_11	Trans Centre	0.94	1	1.01
Area: North						
132	Chintheche_132kV Main	Chintheche_132	Trans North	0.94	1	1.04
66	Chikangawa_66kV	Chikangawa_66	Trans North	0.92	0.96	0.99
66	T/Hill_66kV	T/Hill_66	Trans North	0.92	0.94	0.95
33	Chintheche_33kV	33kV Busbar	Trans North	0.93	0.99	1
33	T/Hill_33kV	33kV Busbar	Trans North	0.95	0.98	1
11	Chintheche_11kV	11kV Busbar	Trans North	0.93	0.97	0.98
11	T/Hill_11kV	11kV Busbar	Trans North	0.93	0.98	1
Area: South						
66	Mlangeni_66kV	66kV Busbar	Trans South	0.95	1.02	0.98
66	Chichiri_66kV/4	Chichiri_66	Trans South	0.95	0.93	0.94
66	Fundis Cross_66kV Res	Double Busbar (3)	Trans South	0.87	0.84	0.88
66	Changalume_66kV	Changalume_66	Trans South	0.95	0.93	0.94
33	Liwonde_33kV	Liwonde_33(2)	Trans South	0.94	1	0.99

Network data				Voltage [p.u.]	Voltage [p.u.]	Voltage [p.u]
Voltage level [kV]	Bus name	Substation	Location	Base case	Peak regime	Solar Peak regime
33	Chichiri_33kV/3	Chichiri_33(1)	Trans South	0.94	0.93	0.94
33	Chichiri_33kV/4	Chichiri_33	Trans South	0.91	0.93	1
11	Ntcheu_11kV	Ntcheu_11	Trans South	0.94	1.01	0.97

From load flow analyses it can be concluded that after the introduction of PV and BESS systems into Malawian power system, low voltages problems across the network are resolved. Although most of the voltages are in the range of 0.95 to 1.05 per unit of nominal voltage level, there are busbars that still have under voltage problems (T/Hill 66 kV, Chichiri 66 kV/4,Fundis Cross_66 kV, Changalume_66 kV, Chichiri_33 kV/3).

CONTINGENCY ANALYSES

As an extension of the load flow analysis, an investigation of system adequacy and security was performed through contingency analysis. Contingency is an event that can occur in the system such as an outage of the main component (N-1 contingency) or multiple components (N-n contingency). Meanwhile, power system stability is determined by the ability of the system to maintain power delivery following disturbances typically referred to as contingencies. Contingency calculations were performed for the following single element outages in a wide area around the PV plant (Trans South, Trans Central, Trans South):

- Lines and cables,
- Power transformers.

Contingency analysis for the generic case has shown **that a single outage of any branch or transformer will lead to voltage violations and overloading of corresponding elements**. **Table 5-3** below represents the worst loading violations (loading above 110 %) for the generic case (peak regime). Temporary overloads in any transmission line or substation equipment should not exceed [110%] of the maximum continuous ratings.

Table 5-3 - Worst loading violations for the generic case in peak regime

Element contingence	Loaded element	Loading Base Case [%]	Loading after contingency [%]
Chintheche-Luwinga	T/Hill T1	49.2	154.6
Trf Mbongozi RoR	Kapichira GT1	81.8	160.9
Chinteche-Luwinga	T/Hill T1	49.2	154.6
Mlambe T1	Mlambe T2	83.2	151.7
Mlambe T2	Mlambe T1	71.5	147.4
Mapanga-Fundis Cross	Chichiri T4	117.3	120.7
Phombeya-Nkhoma 400kV	Nkula GT8	87.8	115.4
Shunt/Filter(2)	Chinyama T1	113.3	114

Shunt/Filter(1)	Chichiri T3	106.5	107.3
Karonga T2	Chichiri T4	117.3	117.3
Trf BESS 66/33 Chinteche	Kapichira GT1	81.8	114.7
New Bwengu IBT1	Chinyama T1	113.3	113.9
New Bwengu IBT1	Chintheche T2	103.4	107.2
New Bwengu IBT1	Chichiri T3	106.5	106.5
Karonga T2	Fundis Cross T2	100.8	100.8
New Bwengu IBT1	Chinteche IBT1	96.7	100.3
Phombeya-Nkhoma 400kV	Kapichira GT4	95	103.8

Worst voltage violations in case of branch outage are presented in

Table 5-4 and **Table 5-5**.

Table 5-4 - Worst loading violations (voltages below 0.9 p.u.) for the generic case in peak regime

Element of contingence	Bus name	Voltage Base [p.u.]	Voltage Min [p.u.]
Chinteche-Luwinga	Karonga 11kV	0.95	0.68
Chinteche-Luwinga	Uliwa 11kV	0.96	0.69
Chinteche-Luwinga	Karonga 33kV	0.96	0.69
Chinteche-Luwinga	Karonga 66kV	0.96	0.69
Chinteche-Luwinga	Wovwe 11kV/2	0.97	0.70
Chinteche-Luwinga	Wovwe 11kV/1	0.97	0.70
Chinteche-Luwinga	Uliwa 66kV	0.97	0.70
Chinteche-Luwinga	Wovwe 66 kV	0.97	0.70
Chinteche-Luwinga	Livingstonia 11kV	0.98	0.71
Chinteche-Luwinga	Livingstonia 66kV	0.98	0.71
Chinteche-Luwinga	New Bwengu A 132kV	0.99	0.71
Chinteche-Luwinga	New Bwengu B 132kV	0.99	0.71
Chinteche-Luwinga	Bwengu 11kV	0.99	0.71
Chinteche-Luwinga	Luwinga 132kV	0.99	0.72
Chinteche-Luwinga	Luwinga 33kV	0.99	0.72
Chinteche-Luwinga	Bwengu_66kV	1.00	0.72
Chinteche-Luwinga	New Bwengu_66kV	1.00	0.72
Chinteche-Luwinga	Bwengu_33kV	1.01	0.73
Chinteche-Luwinga	Luwinga_DG_0.4kV(1)	1.02	0.74
Chinteche-Luwinga	Luwinga _DG_0.4kV 2	1.02	0.74
Chinteche-Luwinga	Bwengu_T1t	1.03	0.74
BESS Chinyama 66kV	BESS_Chinyama LV	0.98	0.76
BESS Chinyama 66kV	Chinyama_66kV	0.97	0.76
BESS Chinyama 66kV	BB	0.97	0.76
BT West-Chigumula	Fundis Cross_66kV Main	0.84	0.79
BT West-Chigumula	Fundis Cross_66kV Res	0.84	0.79
BT West-Chigumula	Terminal(3)	0.84	0.79
BT West-Chigumula	Terminal(2)	0.84	0.79
BESS Chinyama 66kV	Chinyama_33kV	1.02	0.80
Phombeya-Nkhoma 400kV	Nkhoma 400kV A	0.96	0.81
Phombeya-Nkhoma 400kV	Nkhoma 400kV B	0.96	0.81

Element of contingence	Bus name	Voltage Base [p.u.]	Voltage Min [p.u.]
Chinteche-Luwinga	T/Hill_66kV	0.94	0.82
Phombeya-Nkhoma 400kV	Tsabango_132kV	0.94	0.82
Chinteche-Luwinga	T/Hill_33kV	0.97	0.82
Phombeya-Nkhoma 400kV	Kanengo_132kV Main	0.93	0.83
Phombeya-Nkhoma 400kV	Kanengo_132kV Res	0.93	0.83
Phombeya-Nkhoma 400kV	Nkhoma 132kV A	0.95	0.83
Phombeya-Nkhoma 400kV	Nkhoma 132kV B	0.95	0.83
Phombeya-Nkhoma 400kV	Lilongwe OT_66kV/2	0.95	0.83
Phombeya-Nkhoma 400kV	Kangoma_66kV	0.97	0.85
Phombeya-Nkhoma 400kV	Tsabango_66kV	0.97	0.85
Chinteche-Luwinga	T/Hill_11kV	0.98	0.85
Phombeya-Nkhoma 400kV	Kanengo_11kV/1	0.97	0.86
Phombeya-Nkhoma 400kV	Barracks_33kV	0.97	0.86
Phombeya-Nkhoma 400kV	Lilongwe OT_66kV/1	0.98	0.87
BT West-Chigumula	Chigumula_33kV	0.97	0.87
Phombeya-Nkhoma 400kV	Barracks_66kV	0.98	0.87
BT West-Chigumula	Chichiri_33kV/4	0.93	0.87
Phombeya-Nkhoma 400kV	Terminal(1)	0.98	0.87
Phombeya-Nkhoma 400kV	BESS LV	0.98	0.87
BT West-Chigumula	Changalume_66kV	0.93	0.87
BT West-Chigumula	Chichiri_66kV/4	0.93	0.87
Phombeya-Nkhoma 400kV	Kauma 11kV(1)	0.99	0.88
Phombeya-Nkhoma 400kV	Area 48_66kV	0.99	0.88
BT West-Chigumula	Chigumula_33kV	0.98	0.88
Phombeya-Nkhoma 400kV	Terminal	0.99	0.88
BT West-Chigumula	Chigumula_66kV	0.98	0.88
Phombeya-Nkhoma 400kV	Kauma 66kV	0.99	0.88
Phombeya-Nkhoma 400kV	Tsabango_11kV	1.01	0.88
Phombeya-Nkhoma 400kV	Lilongwe OT_33kV	1.01	0.88
Phombeya-Nkhoma 400kV	JCM 33KV B/B	0.96	0.88
Phombeya-Nkhoma 400kV	JCM 132KV B/B	0.96	0.88
Phombeya-Nkhoma 400kV	Nanjoka_132kV Main	0.96	0.88
Phombeya-Nkhoma 400kV	Nanjoka_132kV Res	0.96	0.88
BT West-Chigumula	FundisX_33kV	0.94	0.88
BT West-Chigumula	Ndiza 0.4kV	0.94	0.88
BT West-Chigumula	Ndiza	0.94	0.88
BT West-Chigumula	Ndiza_33kV	0.94	0.88
Phombeya-Nkhoma 400kV	Golomoti_33kV	0.96	0.88
Phombeya-Nkhoma 400kV	JCM 33KV B/B(1)	0.97	0.89
Phombeya-Nkhoma 400kV	Terminal(4)	0.97	0.89
Phombeya-Nkhoma 400kV	JCM Golomoti 132kV B/B	0.97	0.89
Phombeya-Nkhoma 400kV	Golomoti_132kV Main	0.97	0.89
Phombeya-Nkhoma 400kV	Golomoti_132kV Res	0.97	0.89
Phombeya-Nkhoma 400kV	Area 48_11kV1	1.00	0.89
BESS Chingeni 66kV	BESS _Dedza LV	0.97	0.89
Phombeya-Nkhoma 400kV	Kanengo_66kV/1	1.00	0.89
Phombeya-Nkhoma 400kV	Kanengo_66kV/1	1.00	0.89
Phombeya-Nkhoma 400kV	Monkey Bay_66kV	0.97	0.89

Element of contingence	Bus name	Voltage Base [p.u.]	Voltage Min [p.u.]
Phombeya-Nkhoma 400kV	Terminal(2)	1.00	0.89
Phombeya-Nkhoma 400kV	Monkey Bay_33kV	0.97	0.89
Phombeya-Nkhoma 400kV	Kanengo_11kV/1	1.00	0.89
BT West-Chigumula	Changalume_33kV	0.95	0.89
Phombeya-Nkhoma 400kV	Lilongwe OT_11kV/1	1.00	0.89
Phombeya-Nkhoma 400kV	Kanengo_33kV B/B 2	1.00	0.89
Phombeya-Nkhoma 400kV	Lilongwe OT_11kV/2	1.02	0.89
Phombeya-Nkhoma 400kV	Barracks_11kV	1.01	0.89
BT West-Chigumula	Fundis Cross_33kV	0.95	0.90
BT West-Chigumula	Agrekko_Chichiri_DG_0.4kV	0.95	0.90
BT West-Chigumula	Mapanga_66kV/2	0.95	0.90
BT West-Chigumula	Mapanga_66kV/1	0.95	0.90
BESS Chingeni 66kV	Dedza_33kV	0.98	0.90
Phombeya 400/132 T2	Phombeya 400kV A	0.97	0.90
Phombeya 400/132 T2	Phombeys 400kV B	0.97	0.90
BESS Chinteche 66kV	Chintheche_66kV	1.00	0.90

Table 5-5 - Worst voltage violations (voltages above 1.1 p.u.) for the generic case in peak regime

Element of contingence	Bus name	Voltage Base [p.u.]	Voltage Max [p.u.]
Chinyama L1	Chinyama_33kV	1.02	1.25
Chinyama T1	BESS_Chinyama LV	0.98	1.23
Chinyama T1	Chinyama_66kV	0.97	1.22
Chinyama L1	BB	0.97	1.19
Mapanga L1	Mapanga_DG_0.4kV	1.07	1.11
Shunt/Filter (1)	Nkula GT2t	1.05	1.10

Conclusion from contingency analyses is that outage of lines Chintheche-Luwinga, BT West-Chigumula and Phombeya- Nkhoma will lead to most contingencies.

SHORT CIRCUIT ANALYSES

All generating units contribute to the current that flows in the event of a short circuit fault in the power system. Generating plant, which is closest to the fault location, will provide the greatest contribution and those remote from the fault will provide a limited contribution to the total fault current.

The short circuit current must be interrupted by one or more circuit breakers, which must have sufficient fault current interruption capability to interrupt the total prospective fault current at the point on the system at which they are located. One of the many applications of a short-circuit calculation is to check the ratings of network equipment during the planning stage. In this case, the planner is interested in obtaining the maximum expected currents (to dimension equipment properly) and the minimum expected currents (to aid the design of the protection scheme).

As the levels of generation increase on a power system due to increased demand, so will the short-circuit currents. When the prospective short circuit currents reach the circuit breaker rating at a particular location, it will be necessary to replace it with a circuit breaker of a higher rating or reconfigure the network to reduce short-circuit levels at a particular point.

Fault level studies were carried out for the Malawian power system with considered The Max load 2025 regime to determine the system fault levels impact. Three-phase and Single-phase fault levels were calculated. According to inverter technical specifications, the maximum short circuit contribution of each inverter is 150 % of the rated current.

Calculated symmetrical breaking currents are assessed against the rated symmetrical breaking capacity of the circuit breakers. The rated capacities of the circuit breakers in the 132 kV and 66 kV substations were assumed to be 20 kA, thus assuming the worst-case scenario.

The methodology used for the calculation of short circuit currents is according to IEC 60909 standards. Three-phase and single-phase symmetrical breaking currents were calculated with a 1.1 voltage factor and saturated generator sub-transient reactances to obtain maximum possible fault currents.

Table 5-6 - Short circuit results within South region (Trans South)

Maximum short-circuit currents- Ik”							
BUSBAR NAME	**KV**	**THREE-PHASE FAULT [KA]**			**SINGLE PHASE FAULT [KA]**		
		BASE CASE	**PEAK REGIME**	**SOLAR PEAK REGIME**	**BASE CASE**	**PEAK REGIME**	**SOLAR PEAK REGIME**
Kapichira	132	5,112	7,595	7,038	3,623	4,145	2,527
Mlambe	132	2,109	3,385	3,783	2,124	1,837	1,534
BT West	132	4,757	7,315	6,605	3,486	4,114	2,558
Nkula B	132	6,395	9,332	6,312	4,638	5,244	2,525
Tedzani	132	5,991	8,340	6,245	4,426	4,884	2,5
Mlambe	11	15,695	25,016	29,595	12,83	16,683	15,003
BT West	66	6,763	11,175	11,057	6,016	7,478	5,036
Changalume	66	1,341	2,870	3,567	0,839	1,359	1,503
Mapanga	66	4,017	8,276	8,604	4,178	6,445	4,963
Chingeni	66	0,963	5,273	5,433	0,789	4,266	3,866
Tedzani	66	9,593	14,971	11,241	7,323	8,901	4,971

Table 5-7 - Short circuit results within Centre region (Trans centre)

Maximum short-circuit currents- Ik”			
	KV	**THREE-PHASE FAULT [KA]**	**SINGLE PHASE FAULT [KA]**

BUSBAR NAME		BASE CASE	PEAK REGIME	SOLAR PEAK REGIME	BASE CASE	PEAK REGIME	SOLAR PEAK REGIME
Phombeya	400	1,125	1,927	1,672	0,944	1,229	0,782
Nkhoma	400	1,014	1,788	1,606	0,858	1,152	0,779
Phombeya	132	4,815	7,702	5,877	3,489	4,311	2,488
Nkula B	132	6,395	9,332	6,312	4,638	5,244	2,525
Nkhoma	132	2,972	5,394	4,913	2,565	3,529	2,419
Golomoti	132	3,076	5,635	5,032	2,512	3,450	2,373
Nanjoka	132	1,885	4,519	4,5	1,708	2,816	2,221
Kanengo	132	2,596	4,828	4,591	2,597	3,677	2,531
Tsabango	132	1,946	3,673	3,691	1,490	2,166	1,778
Nkhotakota	132	0,905	4,061	4,355	1,047	2,935	2,586
Dwangwa	132	0,727	2,756	3,038	0,784	1,795	1,740
Chinteche	132	0,551	1,844	2,079	0,722	1,572	1,628
Golomoti	66	1,435	2,755	3,234	2,512	2,410	2,301
Kanengo	66	3,948	8,155	7,487	4,209	6,572	4,656
Kauma	66	2,993	6,305	6,190	2,684	4,304	3,543
Barracks	66	2,642	5,608	5,654	2,246	3,632	3,141
Nkhotakota	66	1,096	4,553	4,863	1,357	3,575	3,428
Dedza	66	0,442	3,397	3,603	0,435	2,770	2,734
Area 48	66	3,032	6,381	6,247	2,738	4,394	3,589
Lilongwe	66	2,111	4,533	4,768	1,660	2,719	2,523

Table 5-8 - Short circuit results within North region (Trans north)

Maximum short-circuit currents- Ik”							
BUSBAR NAME	KV	THREE-PHASE FAULT [KA]			SINGLE PHASE FAULT [KA]		
		BASE CASE	PEAK REGIME	SOLAR PEAK REGIME	BASE CASE	PEAK REGIME	SOLAR PEAK REGIME
Chinteche	132	0,551	1,844	2,079	0,722	1,572	1,628
Luwinga	132	0,480	1,435	1,664	0,624	1,214	1,286
New Bwengu	132	0,438	1,249	1,445	0,519	0,977	1,05
Chinteche	66	0,965	3,257	3,627	1,279	2,858	2,979

Chikangawa	66	0,422	1,349	1,457	0,371	0,784	0,815
New Bwengu	66	0,696	1,731	2,069	0,850	1,449	1,643
Bwengu	66	0,691	1,711	2,048	0,839	1,428	1,620
Livingstonia	66	0,520	1,096	1,394	0,583	0,894	1,075
T/Hill	66	0,593	1,841	2,015	0,589	1,228	1,278

Table 5-9 - Short circuit results within Generation region (Generation)

Maximum short-circuit currents- Ik”							
BUSBAR NAME	KV	THREE-PHASE FAULT [KA]			SINGLE PHASE FAULT [KA]		
		BASE CASE	PEAK REGIME	SOLAR PEAK REGIME	BASE CASE	PEAK REGIME	SOLAR PEAK REGIME
Kapichira	132	5,112	4,529	7,038	3,623	4,145	2,527
Kapichira G1	11	27,045	28,928	41,1	11,88	13,961	12,234
Tedzani IV	66	8,737	6,049	10,724	6,850	8,414	4,720
Tedzani 66KV/1	66	9,639	6,465	11,241	7,323	8,901	4,971
Tedzani G1	11	8,492	8,974	17,074	6,822	8,892	9,657
Nkula G1	11	10,988	11,279	17,713	8,562	11,419	/
Wovwe	66	0,474	0,631	1,199	0,617	0,841	1,1

Fault level studies (short-circuit) were carried out for the North, Central, South and Generation regions for three-phase and single-phase fault levels. Calculated fault currents for the network with PV and BESS installed show that the highest values are at Nkula B 132 kV (9,332 kA), Mlambe 11 kV (25,016 kA), Tedzani 66 kV (14,971 kA). However, those values are too far from the withstand capabilities of the existing equipment. The conclusion is that the introduction of the PV plant will slightly increase short-circuit currents in the Trans Centre, Trans North and Trans South region.

PIPELINE PROJECTS CASE

This project case was modelled accordingly to list of pipeline projects which was given by ESCOM in excel form.

Location of PV and BESS with their installed capacity from pipeline projects:

1. BESS 60 MW, location is Nkhoma 132 kV (trans centre), developer is Energy Storage Africa
2. PV 60 MW + BESS 5 MW location is Nanjoka 132 kV (Salima) (trans centre)
3. PV 20 MW + BESS 10 MW location is Golomoti 132 kV (trans centre)
4. PV 21 MW location is Nkhotakota 66 kV (trans centre)

5. PV 6,5 MW location is Changalume (trans south)
6. PV 18 MW location is Monkey Bay (trans south)
7. PV 50 MW location is Nkhoma (not in dispatch) (trans centre)
8. PV 40 MW location is Chingeni (not in dispatch) (trans south)
9. PV 50 MW location is Bwengu (not in dispatch) (trans north)

In addition, more locations (10, 11, 12) were included (not from pipeline projects):

10. PV 40 MW location is Kanengo (trans centre)
11. BESS 20 MW location is Chichiri /4 trans south)
12. BESS 20 MW location is Chinteche 132kV (trans north)

Input data from PLEXOS analysis are the same as from generic case above in chapter 5.1. presented. Generation units in service: Kapichira, Muloza RoR, Nkula,Tedzani I and IV.
In DiGSILENT model, ESCOM Pipeline results_Final (25) is solar peak regime and ESCOM Pipeline results_Final (24) is peak regime.

LOAD FLOW ANALYSES

Table 5-10 - Load flow results- Voltages at buses within Malawian network (pipeline case)

Network data				Voltage [p.u.]	Voltage [p.u.]	Voltage [p.u]
Voltage level [kV]	Bus name	Substation	Location	Base case	Peak regime	Solar Peak regime
Area: Centre						
400	Nkhoma 400kV A	Double Busbar (1)	Trans Centre	1	0.99	1.02
	Nkhoma 400kV B	Double Busbar (1)				1.02
400	Phombeya 400kV A	Double Busbar	Trans Centre	1.01	0.99	1.02
	Phombeys 400kV B	Double Busbar				1.02
132	Nkhotakota_132kV Res	Nkhotakota_132(1)	Trans Centre	0.94	0.98	1.01
132	Nanjoka_132kV Main	Nanjoka_132	Trans Centre	1	0.98	1.02
132	Golomoti_132kV Main	Golomoti 132 kV	Trans Centre	1.01	0.99	1.03
132	Kanengo_132kV Res	Kanengo_132	Trans Centre	0.98	0.96	1
132	Dwangwa 132kV	Dwangwa 132kV	Trans Centre	0.94	0.99	1.02
132	Chintheche_132kV Res	Chintheche_132	Trans Centre	0.94	1	1.03
132	Nkhoma 132kV A	Double Busbar (2)	Trans Centre	1	0.99	1.01
	Nkhoma 132kV B	Double Busbar (2)		1	0.99	1.01
132	Phombeya 132kV	Phombeya 132kV	Trans Centre	1.02	1	1.02
132	Nkula ‘B’ 132kV Res	Nkula ‘B’ 132kV	Trans Centre	1.03	1.01	1.02

Network data				Voltage [p.u.]	Voltage [p.u.]	Voltage [p.u]
Voltage level [kV]	Bus name	Substation	Location	Base case	Peak regime	Solar Peak regime
132	Chintheche_132kV Main	Chintheche_132	Trans Centre	0.94	1	1.03
66	Nkhotakota_66kV/1	Nkhotakota_66	Trans Centre	0.97	1	1
66	Nkhotakota_66kV/2	Nkhotakota_66(1)	Trans Centre	0.97	1	1
66	Mlangeni_66kV	Mlangeni_66	Trans Centre	0.95	0.99	1.02
66	Golomoti_66kV	Golomoti_66	Trans Centre	0.99	1.02	1.01
66	Chinyama_66kV	Chinyama_66	Trans Centre	0.795	0.89	0.87
66	Dedza_66kV	Dedza_66	Trans Centre	0.94	0.98	1.01
33	Nkhotakota_33kV	Nkhotakota_33	Trans Centre	1.01	0.98	1.01
33	Nkhotakota_33kV/2	Nkhotakota_33(2)	Trans Centre	0.94	0.99	0.98
33	Kanengo_33kV B/B 2	Kanengo_33kV B/B 2	Trans Centre	0.95	0.99	1.01
33	Chinyama_33kV	Chinyama_33kV	Trans Centre	0.84	0.89	0.89
33	Barracks_33kV	Barracks_33kV	Trans Centre	0.93	1	0.98
33	Nanjoka	Single Busbar	Trans Centre	0.96	0.98	1
33	BB	Single Busbar (5)	Trans Centre	0.8	0.91	0.88
11	Area 48_11kV1	Area 48_11(1)	Trans Centre	0.95	1.01	1.01
11	Lilongwe OT_11kV/1	Lilongwe_11	Trans Centre	0.94	0.98	1.01
Area: North						
132	Chintheche_132kV Main	Chintheche_132	Trans North	0.94	1	1.03
132	Luwinga	Luwinga_132	Trans North	0.94	1	1.03
132	New Bwengu	New Bwengu_132	Trans North	0.94	1	1.03
66	Chikangawa_66kV	Chikangawa_66	Trans North	0.92	0.99	1
66	T/Hill_66kV	T/Hill_66	Trans North	0.92	0.98	0.94

Network data				Voltage [p.u.]	Voltage [p.u.]	Voltage [p.u]
Voltage level [kV]	Bus name	Substation	Location	Base case	Peak regime	Solar Peak regime
66	Bwengu	Bwengu_66	Trans North	0.96	1.02	1.01
33	Chintheche_33kV	33kV Busbar	Trans North	0.93	0.99	1
33	T/Hill_33kV	33kV Busbar	Trans North	0.95	1.01	1.01
11	Chintheche_11kV	11kV Busbar	Trans North	0.93	0.99	1
11	T/Hill_11kV	11kV Busbar	Trans North	0.93	0.99	1
11	Uliwa	Uliwa_11	Trans North	0.98	0.99	0.99
11	Karonga	Karonga_11	Trans North	0.98	1	0.98
Area: South						
132	BT West_132KV Main	BT West_132	Trans South	1.03	1.02	1.02
66	Mlangeni_66kV	66kV Busbar	Trans South	0.95	0.99	1.02
66	Chichiri_66kV/4	Chichiri_66	Trans South	0.95	1.02	0.98
66	Chigumula_66kV	Chigumula_66	Trans South	1	1.01	1.01
66	Fundis Cross_66kV Res	Double Busbar (3)	Trans South	0.87	0.9	0.88
66	Changalume_66kV	Changalume_66	Trans South	0.95	0.98	0.97
33	Liwonde_33kV	Liwonde_33(2)	Trans South	0.94	1	1
33	Chichiri_33kV/3	Chichiri_33(1)	Trans South	0.94	0.99	0.91
33	Chichiri_33kV/4	Chichiri_33	Trans South	0.91	1.01	0.99
11	Ntcheu_11kV	Ntcheu_11	Trans South	0.94	1.01	1

From load flow analyses it can be concluded that after the introduction of PV and BESS systems into Malawian power system, low voltages problems across the network are resolved. Although most of the voltages are in the range of 0.95 to 1.05 per unit of nominal voltage level, there are busbars that still have under voltage problems (Chinyama_66 kV,Chinyama 33 kV and BB).

CONTINGENCY ANALYSES

Contingency analysis for the pipeline case has shown **that a single outage of any branch or transformer will lead to voltage violations and overloading of corresponding elements**. **Table 5-11** below represents the worst loading violations (loading above 110%) for the pipeline case (solar peak regime). Temporary overloads in any transmission line or substation equipment should not exceed [110%] of the maximum continuous ratings.

Table 5-11 - Contingency analysis-worst loading violations for the pipeline case in solar peak regime

Element contingence	Loaded element	Loading Base Case [%]	Loading after contingency [%]
Chigumula-Mapanga	2-Winding Transformer (1)	63.49	203.47
Chigumula-Mapanga	Tedzani IBT 3	74.50	178.90
PV Kanengo 66kV	Kapichira GT1	44.81	171.87
Mlambe T1	Mlambe T2	74.04	151.81
Mlambe T2	Mlambe T1	74.04	151.81
BT West IBT3	BT West IBT1	60.23	151.80
BT West IBT3	BT West IBT2	60.23	151.80
Luwinga-T1	T/Hill T1	69.35	126.70
PV Nkhotatkota 66 kV	Nkhotakota IBT1	35.78	125.98
Chigumula-Mapanga	Nkula - Mapanga #	43.51	116.13
Chigumula-Mapanga	Nkula A- Tedzani	44.01	114.05
Monkey Bay L1	Golomoti T1	60.19	113.90
Chinteche-T/Hill	T/Hill - Luwinga	57.52	112.85
Phombeya-Nkhoma 400kV	Kapichira GT2	89.76	112.28
Phombeya-Nkhoma 400kV	Kapichira GT3	89.76	112.28
Phombeya-Nkhoma 400kV	Kapichira GT4	89.76	112.28
2-Winding Transformer (1)	Fundis Cross T2	82.33	111.85
PV_Chinteche 132kV	Chintheche-T2	103.82	109.26
Phombeya-Nkhoma 400kV	Barracks_T2	91.27	108.35
Chigumula-Mapanga	Chichiri - Mapanga	91.41	106.26
Shunt/Filter (2)	Tedzani GT1	95.89	104.21
Shunt/Filter (2)	Tedzani GT2	95.89	104.21
Shunt/Filter (2)	Tedzani GT3	95.89	104.21
Shunt/Filter (2)	Tedzani GT4	95.89	104.21

Worst voltage violations in case of branch outage are presented in **Table 5-12** and **Table 5-13.**

Table 5-12 - Contingency analysis-worst voltage violations (voltages below 0.9 p.u.) for the pipeline case in solar peak regime (branch outage, bus violations)

Element of contingence	Bus name	Voltage Base [p.u.]	Voltage Min [p.u.]
Chinteche-T/Hill	T/Hill_66kV	0.94	0.74
PV Nkhotakota 66 kV	BB	0.88	0.75
Chigumula-Mapanga	Terminal (2)	0.88	0.76
Chigumula-Mapanga	Fundis Cross_66kV Main	0.88	0.76
Chigumula-Mapanga	Fundis Cross_66kV Res	0.88	0.76

Element of contingence	Bus name	Voltage Base [p.u.]	Voltage Min [p.u.]
Chigumula-Mapanga	Terminal (3)	0.88	0.77
PV Nkhotakota 66 kV	Chinyama_66kV	0.87	0.77
Chinteche-T/Hill	T/Hill_11kV	1.00	0.78
Chigumula-Mapanga	Changalume_33kV	0.95	0.80
Chigumula-Mapanga	Changalume_66kV	0.97	0.82
PV Nkhotakota 66 kV	Chinyama_33kV	0.93	0.82
Chigumula-Mapanga	PV Changalume LV	0.97	0.82
Chinteche-T/Hill	T/Hill_33kV	1.01	0.83
Chigumula-Mapanga	Chichiri_66kV/4	0.98	0.83
Chigumula-Mapanga	Chichiri_33kV/4	0.99	0.83
Phombeya-Nkhoma 400kV	Barracks_33kV	0.99	0.83
Chigumula-Mapanga	Mapanga_66kV/2	0.98	0.84
Chigumula-Mapanga	Mapanga_66kV/1	0.98	0.84
Phombeya-Nkhoma 400kV	Lilongwe OT_11kV/2	1.00	0.84
Phombeya-Nkhoma 400kV	Kangoma_11kV	0.99	0.84
PV Chingeni 66 kV	Ntcheu_11kV	1.00	0.84
PV Chingeni 66 kV	Liwonde_33kV	1.00	0.84
Phombeya-Nkhoma 400kV	Monkey Bay_33kV	0.97	0.84
PV Chingeni 66 kV	Dedza_66kV	1.01	0.84
PV Chingeni 66 kV	Dedza_33kV	1.02	0.84
Phombeya-Nkhoma 400kV	BESS_Nkhoma LV	0.98	0.85
Phombeya-Nkhoma 400kV	Nkhoma 400kV A	1.02	0.85
Phombeya-Nkhoma 400kV	Nkhoma 400kV B	1.02	0.85
Phombeya-Nkhoma 400kV	Lilongwe OT_66kV/1	1.00	0.85
Phombeya-Nkhoma 400kV	Terminal (1)	1.00	0.85
PV Chingeni 66 kV	PV Chingeni LV	1.00	0.85
Phombeya-Nkhoma 400kV	Area 48_11kV1	1.01	0.85
PV Chingeni 66 kV	Dedza_T1t	1.03	0.85
Chigumula-Mapanga	Nkula_GT1t	1.11	0.85
Phombeya-Nkhoma 400kV	Lilongwe OT_11kV/1	1.01	0.85
Phombeya-Nkhoma 400kV	Terminal (2)	1.00	0.86
Phombeya-Nkhoma 400kV	Terminal	1.00	0.86
Phombeya-Nkhoma 400kV	Lilongwe OT_33kV	1.02	0.86
Phombeya-Nkhoma 400kV	Barracks_66kV	1.00	0.86
Chigumula-Mapanga	Mapanga_33kV	1.01	0.86
PV Chingeni 66 kV	Mlangeni_66kV	1.02	0.86
Phombeya-Nkhoma 400kV	Tsabango_11kV	1.02	0.86
Phombeya-Nkhoma 400kV	Tsabango_132kV	1.00	0.86
Chigumula-Mapanga	Chichiri_66kV/3	0.91	0.86
Phombeya-Nkhoma 400kV	Barracks_11kV	1.01	0.86
Phombeya-Nkhoma 400kV	Kauma 11kV(1)	1.01	0.86
Phombeya-Nkhoma 400kV	Area 48_66kV	1.01	0.86
PV Chingeni 66 kV	Mlangeni_33kV	1.03	0.86
Phombeya-Nkhoma 400kV	Kanengo_11kV/1	1.01	0.86
Phombeya-Nkhoma 400kV	Kanengo_132kV Main	1.00	0.86
Phombeya-Nkhoma 400kV	Kanengo_132kV Res	1.00	0.86
Phombeya-Nkhoma 400kV	Kauma 66kV	1.01	0.86
Phombeya-Nkhoma 400kV	Kanengo_33kV B/B 2	1.01	0.86
Chigumula-Mapanga	Fundis Cross_33kV	1.00	0.86
Phombeya-Nkhoma 400kV	Lilongwe OT_66kV/2	1.02	0.86
Chigumula-Mapanga	BESS _Chichiri_66kV/4 LV	1.00	0.87
Phombeya-Nkhoma 400kV	Area 48_11kV2	1.02	0.87

Element of contingence	Bus name	Voltage Base [p.u.]	Voltage Min [p.u.]
PV Chingeni 66 kV	Liwonde_66kV	1.02	0.87
Chigumula-Mapanga	Nkula GT2t	1.12	0.87
PV Chingeni 66 kV	BESS_Chingeni LV	1.02	0.87
PV Chingeni 66 kV	Ntcheu_66kV	1.03	0.87
Phombeya-Nkhoma 400kV	Monkey Bay_66kV	0.99	0.87
Phombeya-Nkhoma 400kV	Nkhoma 132kV A	1.01	0.87
Phombeya-Nkhoma 400kV	Nkhoma 132kV B	1.01	0.87
PV Nkhotakota 66 kV	PV Nkhotakota LV	0.98	0.87
Phombeya-Nkhoma 400kV	Kanengo_33kV	1.02	0.87
Phombeya-Nkhoma 400kV	PV_Nkhoma LV	1.01	0.87
Phombeya-Nkhoma 400kV	PV Kanengo LV	1.02	0.88
Phombeya-Nkhoma 400kV	Kanengo_66kV/1	1.02	0.88
Phombeya-Nkhoma 400kV	Kanengo_66kV/1	1.02	0.88
Phombeya-Nkhoma 400kV	Kangoma_66kV	1.04	0.88
Phombeya-Nkhoma 400kV	Tsabango_66kV	1.04	0.88
PV Chingeni 66 kV	Atlas Balaka 66kV	1.04	0.88
Phombeya-Nkhoma 400kV	PV Monkey Bay LV	1.01	0.88
Phombeya-Nkhoma 400kV	Golomoti_66kV	1.01	0.89
PV Chingeni 66 kV	Chingeni_66kV	1.05	0.90
Chigumula-Mapanga	FundisX_33kV	0.99	0.90
Chigumula-Mapanga	Ndiza	0.99	0.90
Chigumula-Mapanga	Ndiza_33kV	0.99	0.90
Shunt/Filter	Karonga_11kV	0.98	0.90

Table 5-13 - Contingency Analysis-Worst voltage violations (voltages above 1.1 p.u.) for the pipeline case in solar peak regime (branch outage, bus violations)

Element of contingence	Bus name	Voltage Base [p.u.]	Voltage Max [p.u.]
Trf Mbongozi RoR	Terminal (3)	1.17	1.27
Shunt/Filter (2)	Nkula GT2t	1.12	1.22
Shunt/Filter (2)	Nkula_GT1t	1.11	1.21
Trf Mbongozi RoR	Chintheche_IBT2t	1.07	1.16
Trf Mbongozi RoR	BESS LV	1.04	1.12
Shunt/Filter (1)	Kangoma_66kV	1.04	1.12
Shunt/Filter (1)	Tsabango_66kV	1.04	1.12
Chinyama L1	Chinyama_33kV	0.93	1.12
Trf Mbongozi RoR	Chintheche_66kV	1.03	1.12
Trf Mbongozi RoR	Luwinga 132kV	1.03	1.12
Trf Mbongozi RoR	BESS Nanjoka LV	1.04	1.12
Trf Mbongozi RoR	New Bwengu A 132kV	1.03	1.12
Trf Mbongozi RoR	New Bwengu B 132kV	1.03	1.12
Trf Mbongozi RoR	Chintheche_132kV Main	1.03	1.11
Trf Mbongozi RoR	Chintheche_132kV Res	1.03	1.11
Trf Mbongozi RoR	Chikangawa_33kV	1.02	1.11
Shunt/Filter (1)	Lilongwe OT_66kV/2	1.02	1.11
Trf Mbongozi RoR	Chikangawa_11kV	1.02	1.11
T/Hill T1	T/Hill_11kV	1.00	1.11
Chichiri L2	Chichiri_33kV/3	0.97	1.11
Shunt/Filter (1)	Tsabango_11kV	1.02	1.10
Shunt/Filter (1)	Nkhoma 400kV A	1.02	1.10

Element of contingence	Bus name	Voltage Base [p.u.]	Voltage Max [p.u.]
Shunt/Filter (1)	Nkhoma 400kV B	1.02	1.10
Shunt/Filter (1)	Lilongwe OT_33kV	1.02	1.10
Trf Mbongozi RoR	Chintheche_IBT1t	1.02	1.10
Trf Mbongozi RoR	Gwangwa 132kV	1.02	1.10

Conclusion from contingency analyses for pipeline case is that outage of lines Chigumula-Mapanga and Phombeya-Nkhoma will lead to most contingencies.

SHORT CIRCUIT ANALYSES

The methodology used for the calculation of short circuit currents is according to IEC 60909 standards. Three-phase and single-phase symmetrical breaking currents were calculated with a 1.1 voltage factor and saturated generator sub-transient reactances to obtain maximum possible fault currents. In the appendix is additional case when BESS at Nkhoma is 60 MW.

Δ=PIPELINE SHORT CIRCUIT-BASE CASE SHORT CIRCUIT

CASE 1 - BESS NKHOMA 30 MW AND BESS NKHOTAKOTA 30 MW (PIPELINE 1) (SOLAR PEAK)

Table 5-14 - Short circuit results within South region (Trans south) for pipeline case in solar peak regime

Maximum short-circuit currents- Ik”							
BUSBAR NAME	KV	THREE-PHASE FAULT [KA]			SINGLE PHASE FAULT [KA]		
		BASE CASE	PIPELINE1	Δ	BASE CASE	PIPELINE 1	Δ
Kapichira	132	5,112	4,529	-0,583	3,623	2,164	-1,459
Mlambe	132	2,109	2,184	0,75	2,124	1,196	-0,928
BT West	132	4,757	4,301	-0,456	3,486	2,134	-1,352
Nkula B	132	6,395	3,801	-2,594	4,638	1,978	-2,660
Tedzani	132	5,991	3,711	-2,280	4,426	1,941	-2,485
Mlambe	66	15,695	16,496	0,801	12,83	11,427	-1,407
BT West	66	6,763	7,175	0,412	6,016	4,098	-1,918
Changalume	66	1,341	1,598	0,257	0,839	0.974	0,135
Mapanga	66	4,017	5,234	1,217	4,178	3,533	-0,645
Chingeni	66	0,963	2,478	1,515	0,789	2,187	1,398
Tedzani	66	9,593	6,465	-3,128	7,323	3,635	-3,688
BESS Chingeni	33	/	4,511	/	/	0	/
PV Chingeni	33	/	4,031	/	/	0	/
BESS Chichiri	11	/	14,065	/	/	0	/

PV Monkey Bay	11	/	3,837	/	/	0	/
PV Changalume	11	/	7,089	/	/	5,037	/
Muloza RoR	0,4	/	111,479	/	/	101,823	/

Table 5-15 - Short circuit results within Centre region (Trans centre) for pipeline case in solar peak regime

Maximum short-circuit currents- Ik"							
BUSBAR NAME	KV	**THREE-PHASE FAULT [KA]**			**SINGLE PHASE FAULT [KA]**		
		BASE CASE	**PIPELINE1**	**Δ**	**BASE CASE**	**PIPELINE 1**	**Δ**
Phombeya	400	1,125	0,957	-0,168	0,944	0,604	-0.34
Nkhoma	400	1,014	0,913	-0,101	0,858	0,630	-0,228
Phombeya	132	4,815	3,499	-1,316	3,489	1,965	-1,524
Nkula B	132	6,395	3,801	-2,594	4,638	1,978	-2,66
Nkhoma	132	2,972	2,843	-0,129	2,565	1,962	-0,603
Golomoti	132	3,076	2,944	-0,132	2,512	1,944	-0,568
Nanjoka	132	1,885	2,694	0,809	1,708	1,935	0,227
Kanengo	132	2,596	2,502	-0,94	2,597	1,839	-0,758
Tsabango	132	1,946	1,955	0,09	1,490	1,301	-0,189
Nkhotakota	132	0,905	2,828	1,923	1,047	1,982	0,935
Dwangwa	132	0,727	1,785	1,058	0,784	1,202	0,418
Chinteche	132	0,551	1,199	0,648	0,722	1,134	0,412
Golomoti	66	1,435	1,525	0,9	2,512	1,580	-0,932
Kanengo	66	3,948	4,161	0,213	4,209	3,372	-0,837
Kauma	66	2,993	3,193	0,2	2,684	2,391	-0,293
Barracks	66	2,642	2,832	0,19	2,246	2,069	-0,177
Nkhotakota	66	1,096	1,931	0,835	1,357	1,952	0,595
Dedza	66	0,442	0,653	0,211	0,435	0,578	0,143
Area 48	66	3,032	3,233	0,201	2,738	2,433	-0,305
Lilongwe	66	2,111	2,280	0,169	1,660	1,605	-0,055
BESS Nkhoma	11	/	19,206	/	/	0	/
PV Nkhoma	11	/	23,251	/	/	0	/
PV Kanengo	11	/	12,860	/	/	0	/
PV Nkhotakota	11	/	7,938	/	/	0	/

BESS Nkhotakota	11	/	12,782	/	/	0	/
PV Nanjoka	11	/	14,594	/	/	0	/
Mbongozi RoR	11	/	33,031	/	/	20,397	/
BESS Nanjoka	11	/	14,371	/	/	0	/
PV Golomoti	11	/	14,410	/	/	0	/
BESS Golomoti	11	/	15,389	/	/	0	/

Table 5-16 - Short circuit results within North region (Trans north)

Maximum short-circuit currents- Ik"							
BUSBAR NAME	**KV**	**THREE-PHASE FAULT [KA]**			**SINGLE PHASE FAULT [KA]**		
		BASE CASE	**PIPELINE1**	**Δ**	**BASE CASE**	**PIPELINE 1**	**Δ**
Chinteche	132	0,551	1,199	0,648	0,722	1,134	0,412
Luwinga	132	0,480	0,861	0,381	0,624	0,792	0,168
New Bwengu	132	0,438	0,731	0,293	0,519	0,776	0,257
Chinteche	66	0,965	1,845	0,88	1,279	1,858	0,579
Chikangawa	66	0,422	0,607	0,185	0,371	0,456	0,085
New Bwengu	66	0,696	1,176	0,48	0,850	1,369	0,519
Bwengu	66	0,691	1,160	0,469	0,839	1,382	0,543
Livingstonia	66	0,520	0,731	0,211	0,583	0,739	0,156
T/Hill	66	0,593	0,899	0,306	0,589	0,738	0,149
BESS Chinteche	11	/	12,842	/	/	0	/
PV Chinteche	11	/	9,387	/	/	0	/
PV Bwengu	11	/	6,106	/	/	0	/

Table 5-17 - Short circuit results within Generation region (Generation)

Maximum short-circuit currents- Ik"							
BUSBAR NAME	**KV**	**THREE-PHASE FAULT [KA]**			**SINGLE PHASE FAULT [KA]**		
		BASE CASE	**PIPELINE1**	**Δ**	**BASE CASE**	**PIPELINE 1**	**Δ**

Kapichira	132	5,112	4,529	-0,583	3,623	2,164	-1,45
Kapichira G1	11	27,045	28,928	1,883	11,88	10,791	-1,08
Tedzani IV	66	8,737	6,049	-2,688	6,850	3,404	-3,44
Tedzani 66KV/1	66	9,639	6,465	-3,174	7,323	3,635	-3,68
Tedzani G1	11	8,492	8,974	0,482	6,822	6,806	-0,01
Nkula G1	11	10,988	11,279	0,291	8,562	8,219	-0,34
Wovwe	66	0,474	0,631	0,157	0,617	0,759	0,14 2
Wovwe	11	2,697	3,260	0,563	2,757	3,163	0,40

CASE 2 - BESS NKHOMA 30 MW AND BESS NKHOTAKOTA 30 MW (PIPELINE 1) (PEAK)

Table 5-18 - Short circuit results within South region (Trans south)

Maximum short-circuit currents- Ik”							
BUSBAR NAME	**KV**	**THREE-PHASE FAULT [KA]**			**SINGLE PHASE FAULT [KA]**		
		BASE CASE	**PIPELINE 1**	**Δ**	**BAS E CAS E**	**PIPELIN E 1**	**Δ**
Kapichira	132	5,112	5,712	0,6	3,623	3,545	-0,07
Mlambe	132	2,109	2,412	0,3	2,124	1,529	-0,59
BT West	132	4,757	5,519	0,762	3,486	3,490	0,00 4
Nkula B	132	6,395	6,524	0,129	4,638	4,144	-0,49
Tedzani	132	5,991	5,732	-0,259	4,426	3,850	-0,57
Mlambe	66	15,695	17,575	1,88	12,83	13,798	0,96 8
BT West	66	6,763	8,738	1,97	6,016	6,416	0,4
Changalume	66	1,341	1,671	0,33	0,839	0.959	0,12
Mapanga	66	4,017	6,143	2,126	4,178	5,094	0,91
Chingeni	66	0,963	2,762	1,799	0,789	2,757	1,96
Tedzani	66	9,593	9,345	-0,248	7,323	6,650	-0,67
BESS Chingeni	33	/	4,880	/	/	0	/
BESS Chichiri	11	/	14,734	/	/	0	/
Muloza RoR	0,4	/	112,294	/	/	103,919	/

Table 5-19 - Short circuit results within Centre region (Trans centre)

Maximum short-circuit currents- Ik"							
BUSBAR NAME	KV	THREE-PHASE FAULT [KA]			SINGLE PHASE FAULT [KA]		
		BASE CASE	PIPELINE1	Δ	BASE CASE	PIPELINE 1	Δ
Phombeya	400	1,125	1,276	0,15	0,944	0,966	0,02
Nkhoma	400	1,014	1,171	0,15	0,858	0,962	0,1
Phombeya	132	4,815	5,291	0,47	3,489	3,443	-0,04
Nkula B	132	6,395	6,524	0,12	4,638	4,144	-0,49
Nkhoma	132	2,972	3,553	0,58	2,565	2,956	0,39
Golomoti	132	3,076	3,774	0,69	2,512	2,909	0,39
Nanjoka	132	1,885	3,029	1,14	1,708	2,462	0,75
Kanengo	132	2,596	2,975	0,37	2,597	2,668	0,07
Tsabango	132	1,946	2,267	0,32	1,490	1,677	0,18
Nkhotakota	132	0,905	2,939	2,03	1,047	2,427	1,38
Dwangwa	132	0,727	1,779	1,05	0,784	1,312	0,52
Chinteche	132	0,551	1,140	0,58	0,722	1,142	0,42
Golomoti	66	1,435	1,617	0,18	2,512	1,809	-0,7
Kanengo	66	3,948	4,793	0,84	4,209	4,638	0,42
Kauma	66	2,993	3,553	0,56	2,684	2,970	0,28
Barracks	66	2,642	3,112	0,47	2,246	2,490	0,24
Nkhotakota	66	1,096	1,957	0,86	1,357	2,144	0,78
Dedza	66	0,442	0,670	0,22	0,435	0,614	0,17
Area 48	66	3,032	3,602	0,57	2,738	3,036	0,29
Lilongwe	66	2,111	2,458	0,34	1,660	1,848	0,18
BESS Nkhoma	11	/	21,108	/	/	0	/
BESS Nkhotakota	11	/	12,901	/	/	0	/

Mbongozi RoR	11	/	33,878	/	/	23,713	/
BESS Nanjoka	11	/	15,078	/	/	0	/
BESS Golomoti	11	/	16,851	/	/	0	/

Table 5-20 - Short circuit results within North region (Trans north)

Maximum short-circuit currents- Ik"							
BUSBAR NAME	**KV**	**THREE-PHASE FAULT [KA]**			**SINGLE PHASE FAULT [KA]**		
		BASE CASE	**PIPELINE1**	**Δ**	**BASE CASE**	**PIPELINE 1**	**Δ**
Chinteche	132	0,551	1,140	0,589	0,722	1,142	0,42
Luwinga	132	0,480	0,793	0,313	0,624	0,813	0,189
New Bwengu	132	0,438	0,660	0,22	0,519	0,639	0,12
Chinteche	66	0,965	1,772	0,807	1,279	1,874	0,595
Chikangawa	66	0,422	0,598	0,176	0,371	0,459	0,088
New Bwengu	66	0,696	1,024	0,328	0,850	1,069	0,219
Bwengu	66	0,691	1,007	0,316	0,839	1,048	0,209
Livingstonia	66	0,520	0,557	0,037	0,583	0,591	0,008
T/Hill	66	0,593	0,874	0,281	0,589	0,746	0,157
BESS Chinteche	11	/	12,367	/	/	0	/

Table 5-21 - Short circuit results within Generation region (Generation)

Maximum short-circuit currents- Ik"							
BUSBAR NAME	**KV**	**THREE-PHASE FAULT [KA]**			**SINGLE PHASE FAULT [KA]**		
		BASE CASE	**PIPELINE1**	**Δ**	**BASE CASE**	**PIPELINE 1**	**Δ**
Kapichira	132	5,112	5,712	0,6	3,62	3,545	-0,07
Kapichira G1	11	27,04	29,789	2,74	11,88	12,612	0,732
Tedzani IV	66	8,73	8,670	-0,06	6,85	6,309	-0,54
Nkula G1	11	10,98	12,069	1,08	8,56	9,195	0,63
Wovwe	66	0,474	0,441	-0,03	2,75	0,551	-2,19

Fault level studies (short-circuit) were carried out for the North, Central, South and Generation regions for three-phase and single-phase fault levels. Calculated fault currents for the network with PV and BESS installed show that the highest values are at Nkula B 132 kV (6,524 kA), Mlambe 66 kV (17,575 kA). However, those values are too far from the withstand capabilities of the existing equipment. The conclusion is that the introduction of the PV plant will slightly increase short-circuit currents in the Trans Centre, Trans North and Trans South region.

6

DYNAMIC ANALYSES

6 DYNAMIC ANALYSES

The requirements specified in the Malawi Grid Code form the basis for the dynamic analysis. Dynamic stability is determined by mutual interactions among network components. Occurred disturbances can cause oscillations in active and reactive power generations resulting in the appearance of voltage fluctuations and frequency deviations. In the DIGSILENT model of the Malawian power system network that has been provided to us all hydro generators as well as diesel generators have assigned dynamic models.

VOLTAGE STABILITY STUDIES

Transient voltage stability analysis was carried out aiming to examine the dynamic behaviour of the ESCOM power system following large disturbances and to confirm that adequate stability will be maintained following the integration of the solar PV plant and BESS. The dynamic model which was used for the transient stability study is included in the DIGSILENT model of the ESCOM system. The dynamic model included data for all hydro and diesel generators. Simulation of disturbances in the power system is the method used to check the dynamic performance and response of the power system. Fault durations for the ESCOM transmission grid were assumed to be 120 ms for the 132 kV and 66 kV voltage levels. This includes the operating times of the primary relay and circuit breaker.

For every simulation, certain quantities (system parameters) were recorded and plotted against time, for observation of the dynamic performance of the ESCOM power system. These variables are as follows:

- Voltages:
  - Chingeni_66kV,
  - Phombeya_132kV Res,
  - Chinteche_132kV Main,
- System frequency.

The purpose of these simulations is to check the ability of the power system to successfully recover voltages and maintain voltage stability.

We consider that voltage is successfully recovered if after the fault clearance the voltage remains to at least 80% after the 1 second.

For pipeline case in peak regime, two fault cases were analysed in order to investigate system response for three phase faults and outages of transmission lines. More cases for different regimes will be presented in appendix chapter.

1) ***Three phase fault at Luwinga_132kV Main bus and outage of 132kV Luwinga-Bwengu 132kV line (trans north)***:

The analysed fault is a three-phase fault at Luwinga_132kV Main bus followed by the outage of Luwinga-Bwengu 132kV line. Simulation results are shown in the figures below. The results show that the system is stable. (**Figure 6-1 and Figure 6-2**)

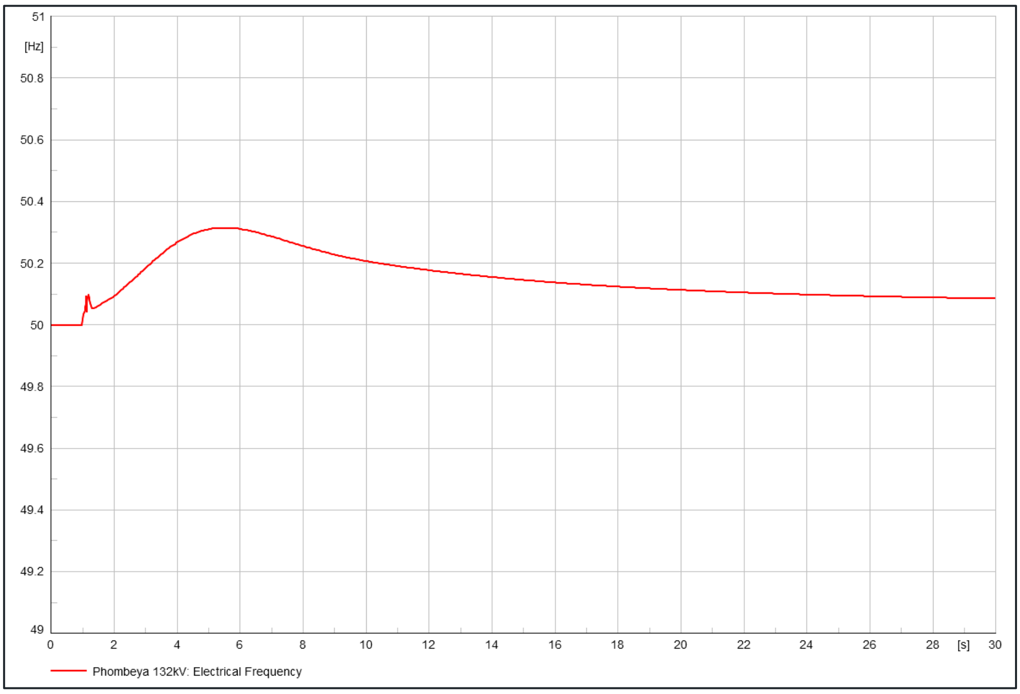


Figure 6-1 - System frequency response for three phase fault at Luwinga 132 kV followed by outage of 132 kV Luwinga-Bwengu line

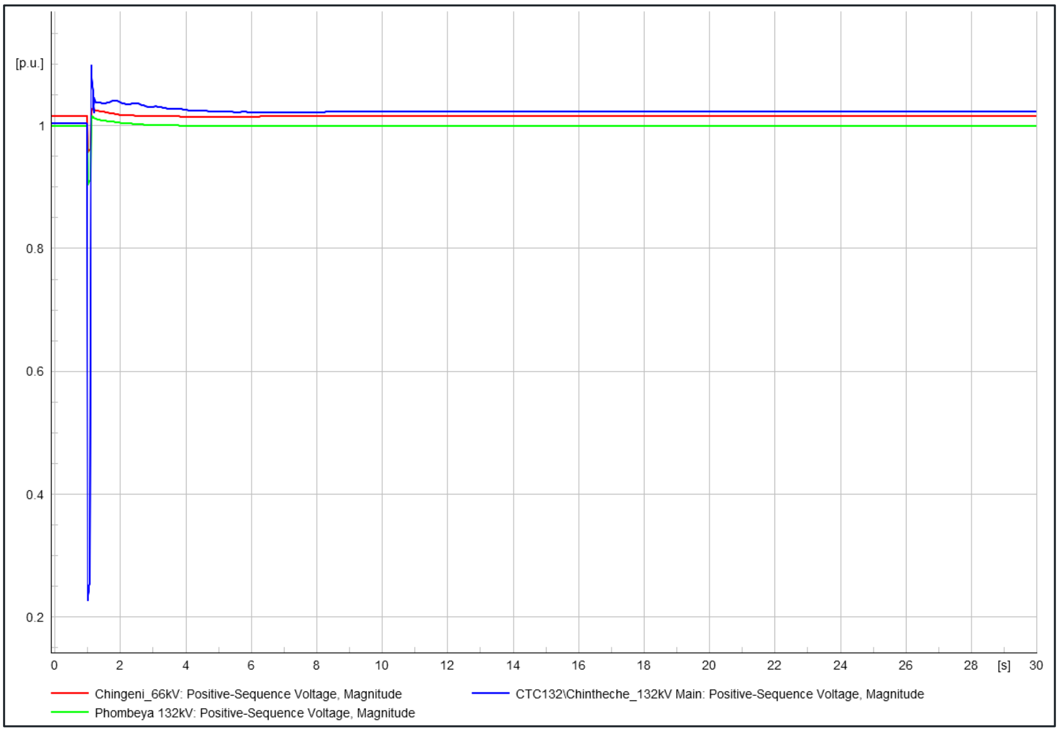


Figure 6-2 - Voltages at busbars Chingeni, Phombeya and Chinteche for three phase fault at Luwinga 132 kV followed by outage of 132kV Luwinga-Bwengu line

2) Three phase fault at Nanjoka_132kV Main bus and outage of 132kV Nanjoka – Kanengo line (trans centre)

The second analysed fault is a three-phase fault at Nanjoka_132kV Main bus followed by the outage of the Nanjoka – Kanengo 132kV line. Simulation results are shown in the figures below. The results show that the system is stable. (**Figure 6-3 and Figure 6-4**)

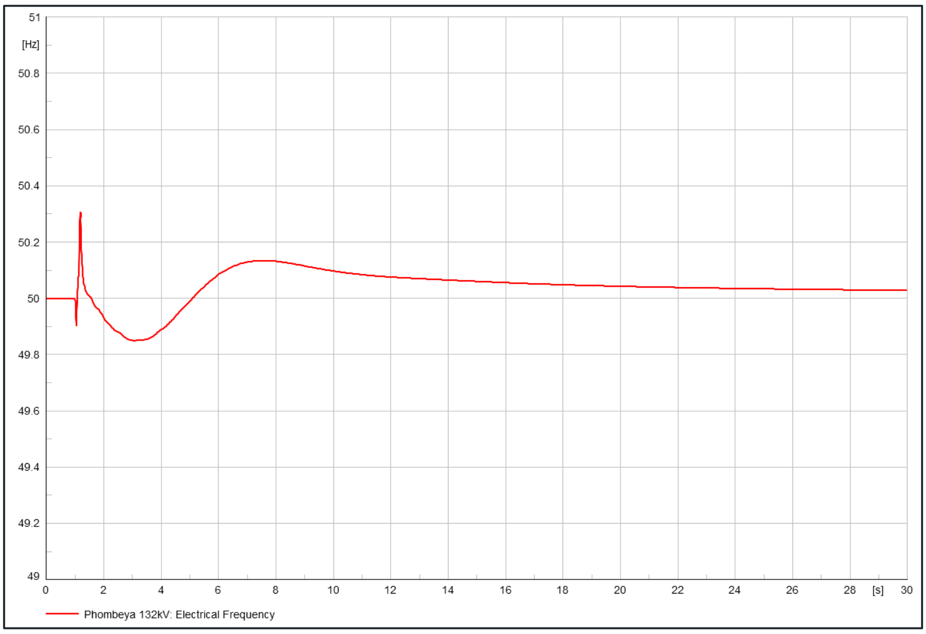


Figure 6-3 - System frequency response for three phase fault at Nanjoka 132 kV busbar followed by outage of Nanjoka-Kanengo line

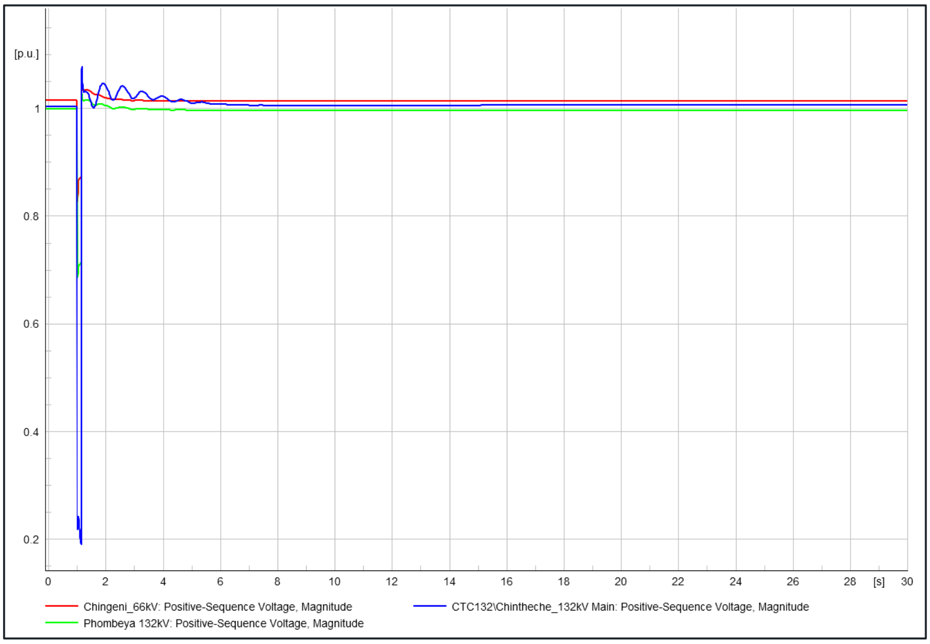


Figure 6-4 - Voltages at busbars Chingeni, Phombeya and Chinteche for three phase fault at Nanjoka 132kV followed by outage of 132 kV Nanjoka-Kanengo line

3) ***Three phase fault at Mapanga_66kV/1 busbar (trans south)***

The third analysed fault is a three-phase fault at Mapanga_66kV/1 busbar. Simulation results are shown in the figures below. The results show that the system is stable. (**Figure 6-5** and **Figure 6-6**)

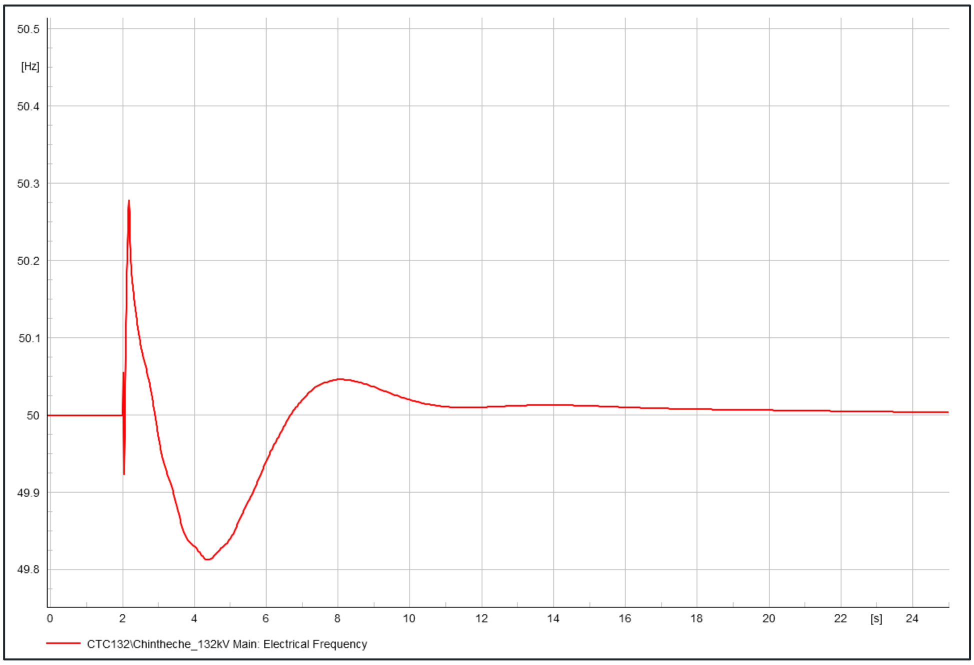


Figure 6-5 - System frequency response for three phase fault at Mapanga 66 kV/1 busbar

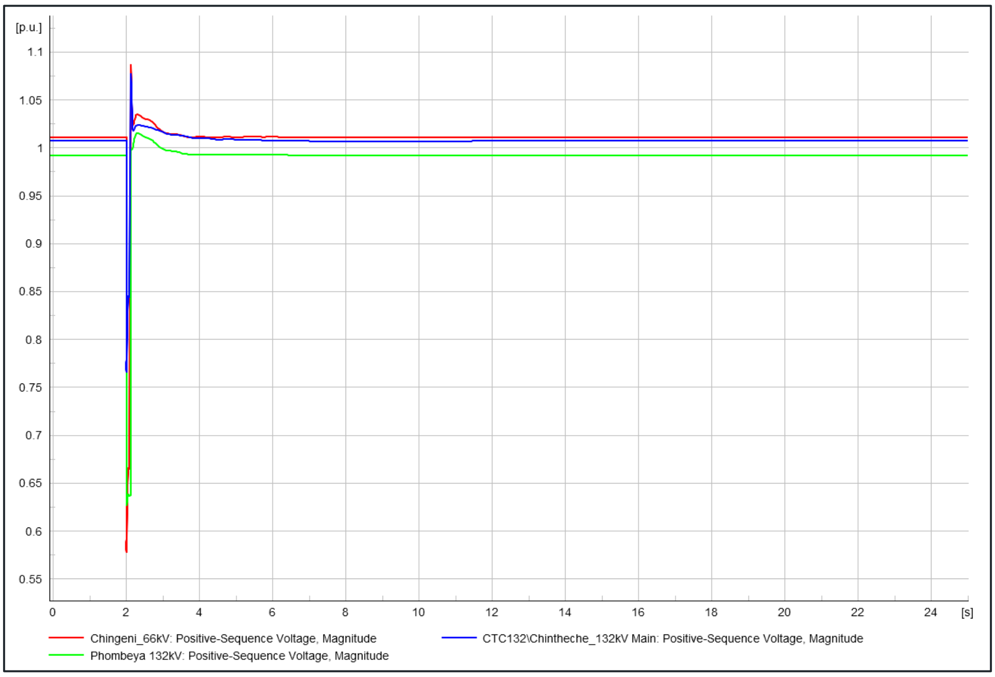


Figure 6-6 - Voltages at busbars Chingeni, Phombeya and Chinteche for three phase fault at Mapanga 66kV /1 busbar

In conclusion for this section, Malawian power system in pipeline case will successfully recover voltages and maintain voltage stability after three-phase fault and clearing of that fault in 120 ms, due to outstanding BESS performance in terms of P-Q capability.

FREQUENCY RESPONSE

Frequency stability analysis includes stability assessment where simulations of large active power imbalance disturbances are performed. The purpose of these studies is to check the ability of the Malawian power system to compensate for outages of large power plants and maintain acceptable frequency values.

For the sake of understanding, it should be noted that Malawian power system operates as a single synchronous zone, without interconnections with neighbouring systems. In that respect, a reference incident size should be considered against the total system size which is max 300MW.

Worldwide practice shows that the reference incident which exceeds the 10% of the total synchronous size is most likely to lead to instability. This could be a limiting factor while defining conditions for the new purchase.

Frequency response analysis was conducted in order to investigate the following:

- Frequency drop and overall frequency response of the power system,
- Active power response of generating units.

Frequency drop depends on the ratio incident size/power system size and overall system inertia during the considered incident. Given that it is not always easy to recognize the worst case, the frequency stability study usually considers different regimes.

Although the Malawian system is small and during the night regime seems to be the smallest in size and consequently quite fragile, generators in those regimes usually run on technical minimum, therefore the ratio incident size/power system size is not the worst.

For this reason we considered solar peak regime for the year 2024. It should be noted that the demand level during the solar peak regime and the evening peak regime is almost the same, but inertia level might differ. During the solar peak regime there are more Inverter based facilities (PV+BESS) than during the evening peak regime.

With regards to the reference incident size, it is usually equivalent with the biggest generating unit. This concept is relevant for the conventional units as there is always a possibility for unit to drop out. However, this concept is not necessarily relevant for the PV power plant, as the probability to drop out the whole PV power plant is very low. For the PV plant the critical incident is a sudden cloud or sandstorm, but usually followed by the loss of the part of installed capacity.

In order to consider existing generating units and units candidates from the pipeline project list, we have analysed several cases, starting from 32 MW (max existing unit size), to 60MW (BESS candidate from the pipeline project list).

First case is when BESS Nkhoma has installed capacity of 30 MW and BESS Nkhotakota has installed capacity of 30 MW for peak regime in 2024. Second case is when BESS Nkhoma has installed capacity of 60 MW and BESS Nkhotakota doesn't exist.

Case 1, when BESS Nkhoma has installed capacity of 30 MW and BESS Nkhotakota has installed capacity of 30 MW for peak regime in 2024. **Outage of Kapichira G1 32 MW** generator. (**Figure 6-7**

Figure 6-8, and Figure 6-9). On the frequency response figures, with red lines were represented minimum frequency (48,75 Hz) and maximum frequency (51,5 Hz) that are given in Malawian grid code.

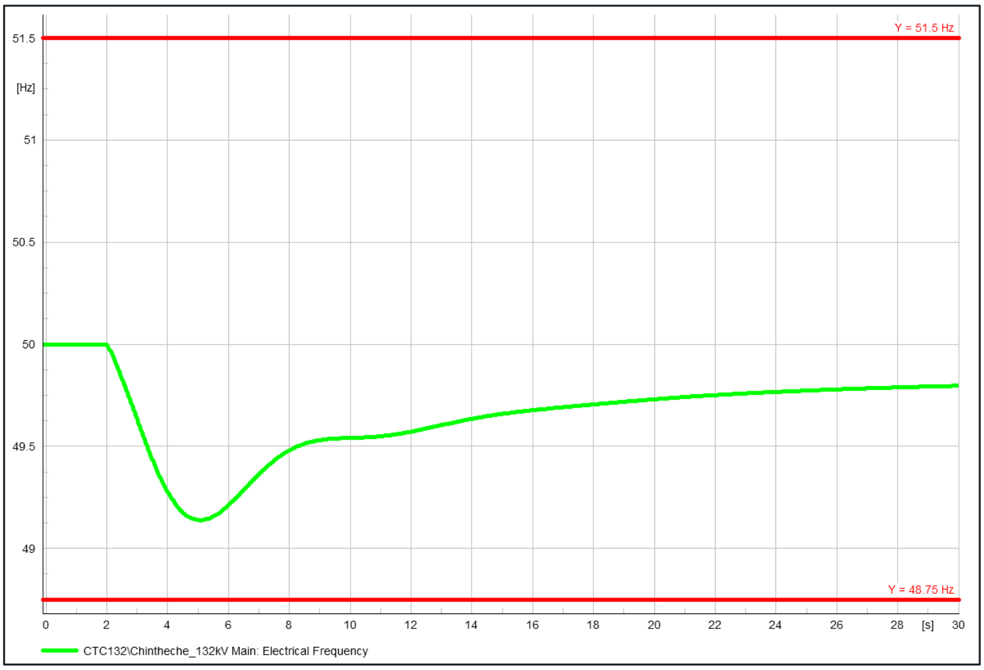


Figure 6-7 - System frequency response for outage of Kapichira G1 generator

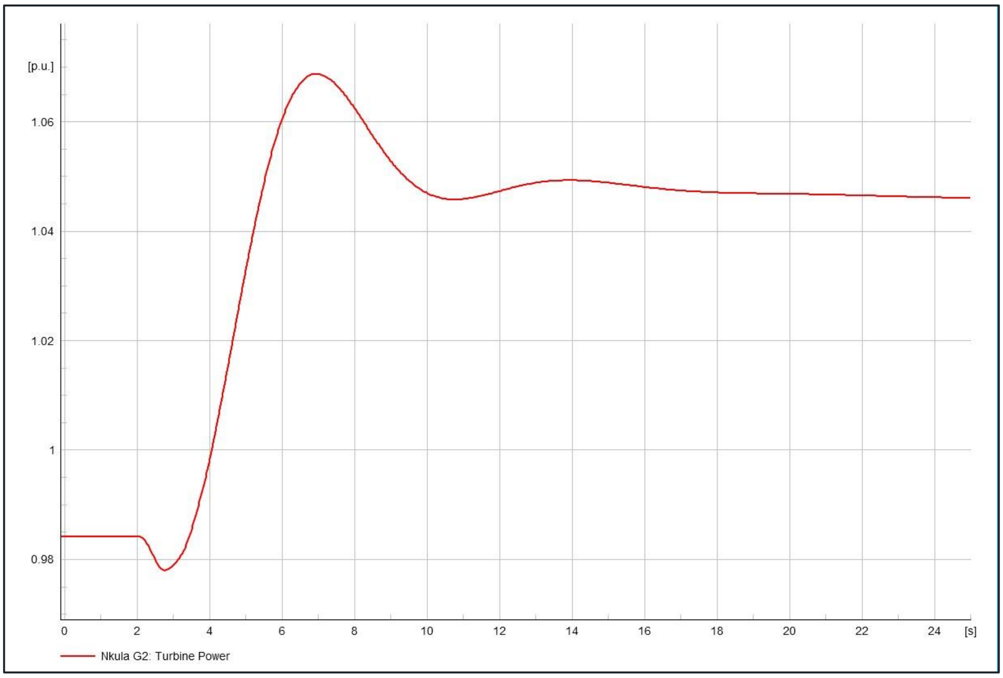


Figure 6-8 - Generator response with active power (turbine power) in pipeline case when Kapichira generator is switched off

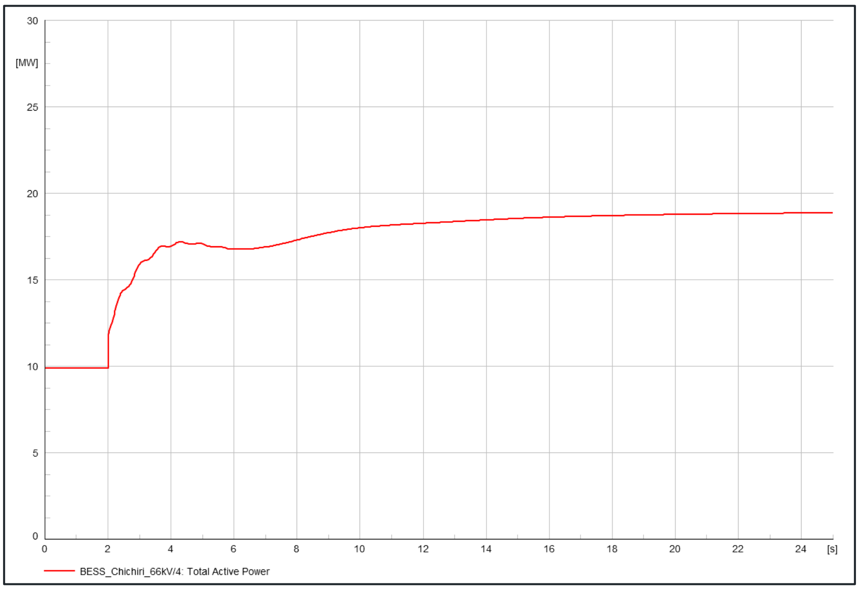


Figure 6-9 – BESS Chichiri active power response for outage of Kapichira G1 generator

Case 2, when BESS Nkhoma has installed capacity of 60 MW and BESS Nkhotakota doesn't exist, **outage of BESS 60 MW Nkhoma**, results show that system is **stable, but frequency drop is below UFLS (under frequency load shedding) threshold of 48.75 Hz which is not recommended**. (**Figure 6-10**, **Figure 6-11** and **Figure 6-12**) . Under frequency load shedding is implemented to restore power system frequency stability if system frequency drops below the operational set point during major disturbance such as loss of generation.

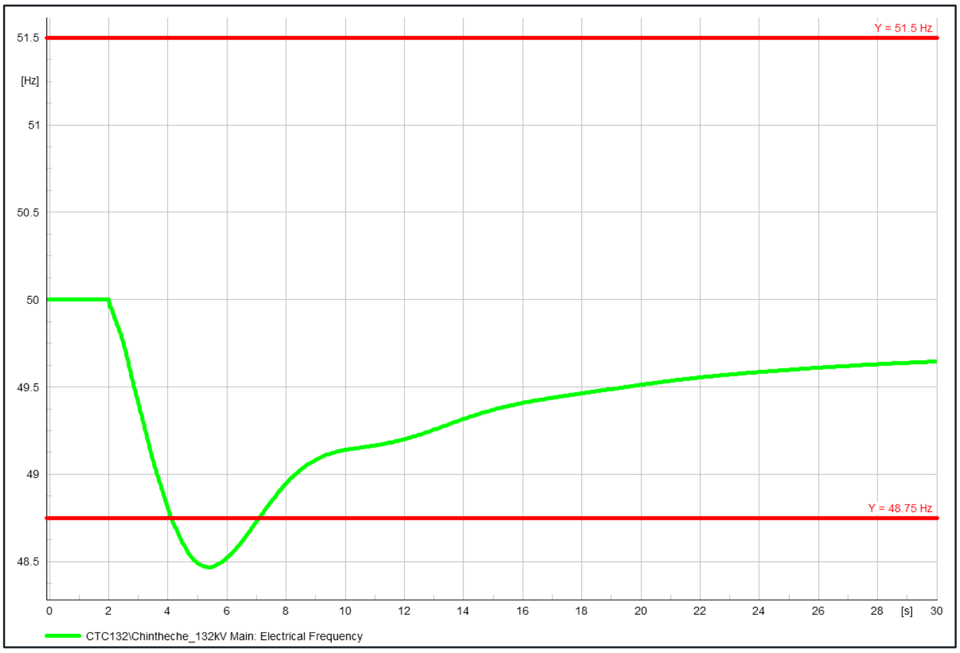


Figure 6-10 - System frequency response after outage of BESS Nkhoma 60 MW

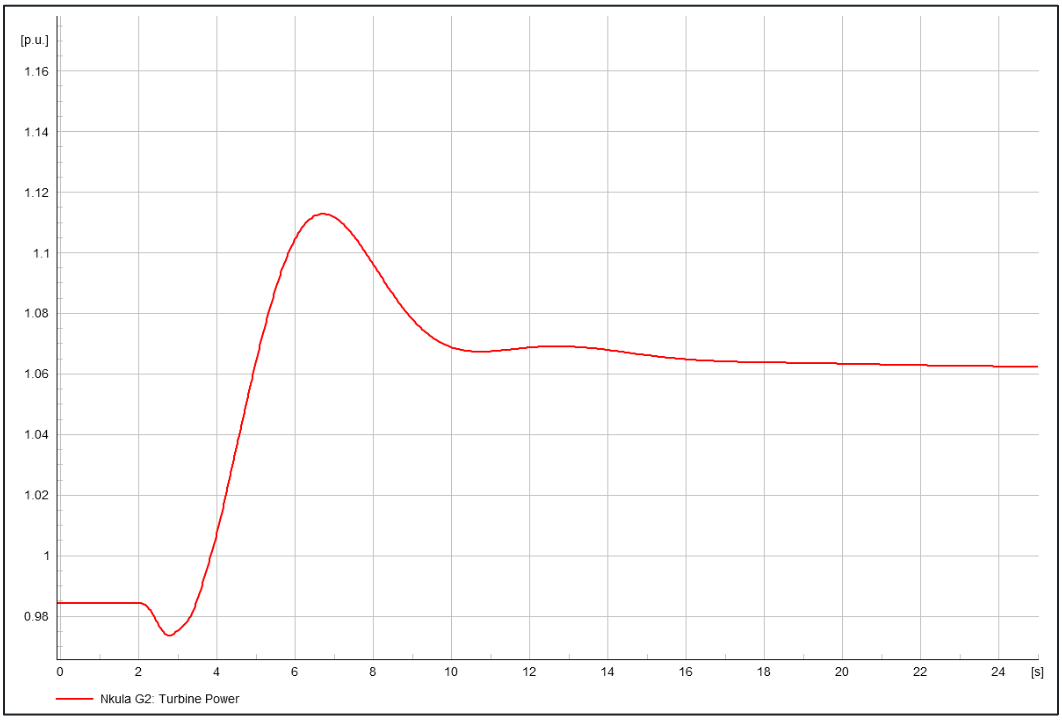


Figure 6-11 - Generator response with active power after outage of BESS Nkhoma 60 MW

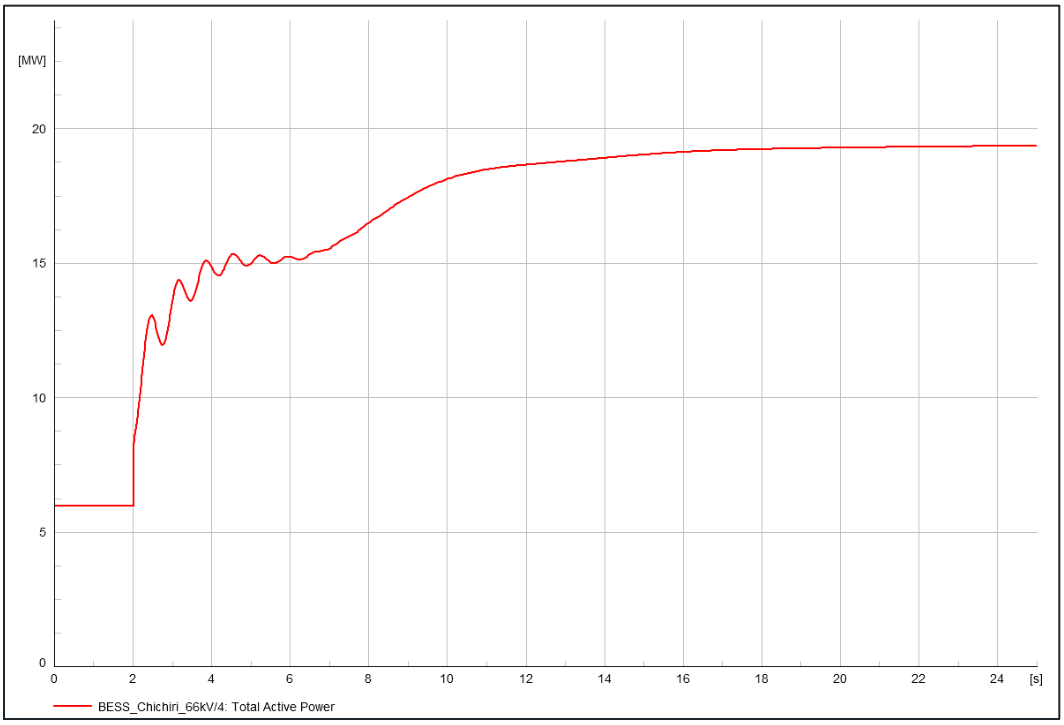


Figure 6-12 – BESS Chichiri active power response with active power after outage of BESS Nkhoma 60 MW

From the cases above**, it can be concluded that it is better to split 60 MW on two BESS rather than having one BESS of 60 MW capacity from the system stability point of view**.

ANALYSIS OF 20 MW BESS CONNECTED AT CHICHIRI S/S

Malawi commissioned the first solar power plant (60 MW) run by an IPP in October 2021. Until January 2022, the plant had been operating without any significant challenges to the grid. However, in January 2022, Malawi lost 129.6 MW of firm and flexible hydropower (Kapichira plant) due to damage to its intake dam caused by cyclone Anna. In April 2022, the Government decommissioned 78 MW of grid-based peaking diesel generators. Since the loss of 129.6 MW hydropower and the decommissioning of the 78 MW of diesel generators, the Malawi power system has been exposed to the variability of the 60 MW solar power plant.

The objective of installation of grid-integrated BESS is to minimize impacts of variable solar power on the grid. The BESS shall be sized for a minimum 20 MW capable of operating for at least 1.5 hours at nameplate rating and connected to Chichiri substation 33 kV in trans south region.

Dynamic analysis was conducted in order to investigate how the outage of the PV plant would impact the frequency deviation in Malawian system.

Two main cases were investigated:

1. Kapichira is in service
2. Kapichira is out of service

CASE 1

The following assumptions are associated to this case:

- 4 generators in Kapichira are in service
- load is 345 MW
- The following PV plants are modelled: Golomoti (20 MW), Nanjoka (60 MW) and Nkhotakota (21 MW).
- The following BESS are modelled: BESS in Golomoti of 5 MW
- Reference incident: outage of the PV Nanjoka 60 MW
- Analyzed regime: solar peak

Load flow in case 1, when generators in Kapichira are in service:

- PV Nanjoka active power=58,31 MW, reactive power=6,86 Mvar, load 97%
- PV Golomoti active power=1,469 MW, reactive power=11,3 Mvar, load 57,62%

Following figures show frequency deviation, active power response of the 20 MW BESS unit and active power response of the hydro unit, respectively: (**Figure 6-13 Figure 6-14 Figure 6-15**).

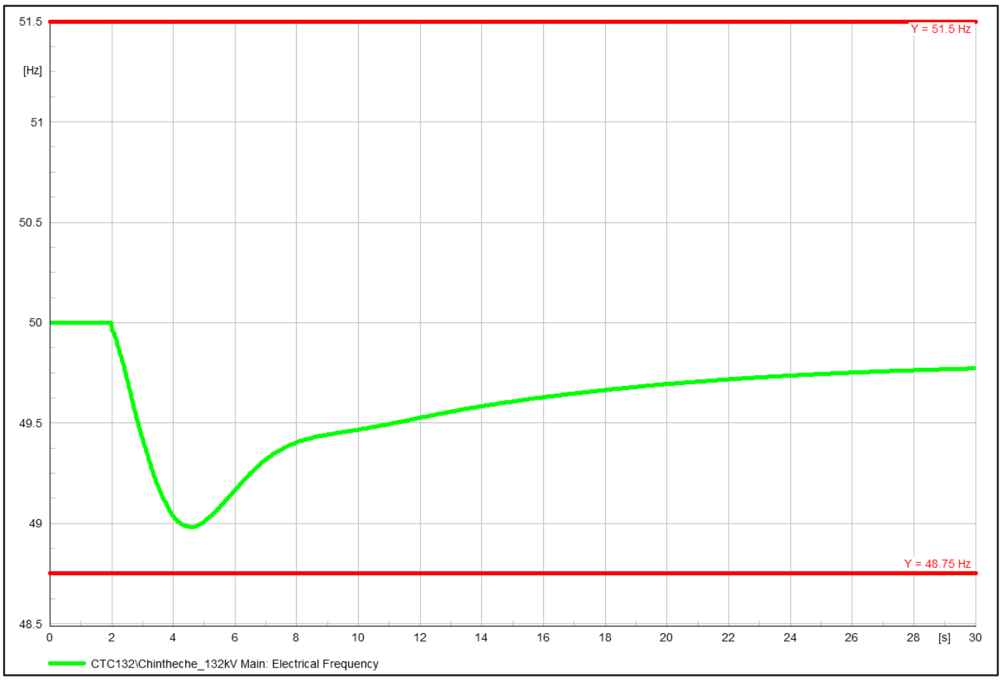


Figure 6-13 - System frequency response after outage of PV Nanjoka 60 MW

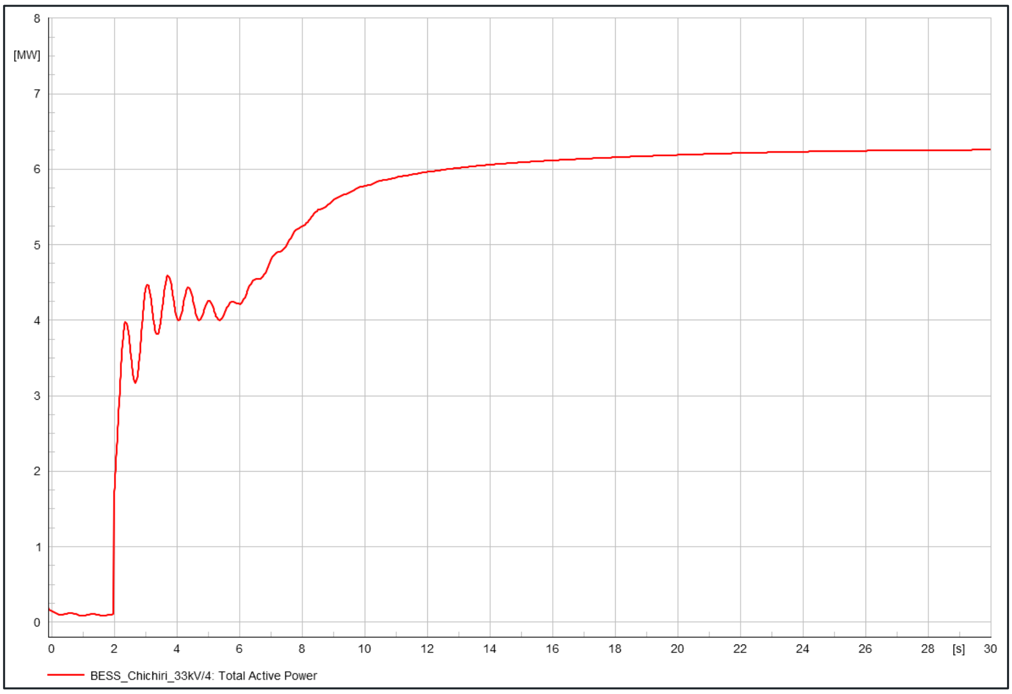


Figure 6-14 - BESS Chichiri 20 MW response with active power after outage of PV Nanjoka 60 MW

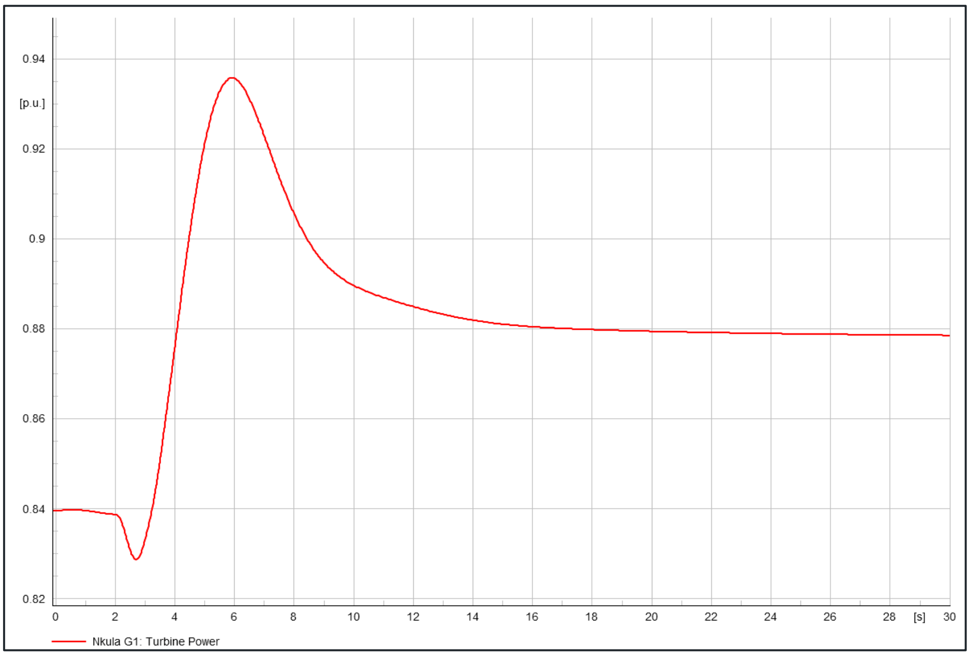


Figure 6-15 - Generator response with active power (turbine power) after outage of PV Nanjoka 60 MW

CASE 2

The following assumptions are associated to this case:

- 4 generators in Kapichira are out of service
- load is 290 MW
- The following PV plants are modelled: Golomoti (20 MW), Nanjoka (60 MW) and Nkhotakota (21 MW).
- The following BESS are modelled: BESS in Golomoti of 5 MW
- Reference incident: outage of the PV Nanjoka 60 MW
- Analyzed regime: solar peak

Load flow in case 2, when generators in Kapichira are out of service:

- PV Nanjoka active power=58,31 MW, reactive power=0 Mvar, load 97%
- PV Golomoti active power=11,3 MW, reactive power=-3,964 Mvar, load 60%

Following figures show frequency deviation, active power response of the 20MW BESS unit and active power response of the hydro unit, respectively:(**Figure 6-16, Figure 6-17, Figure 6-18**)

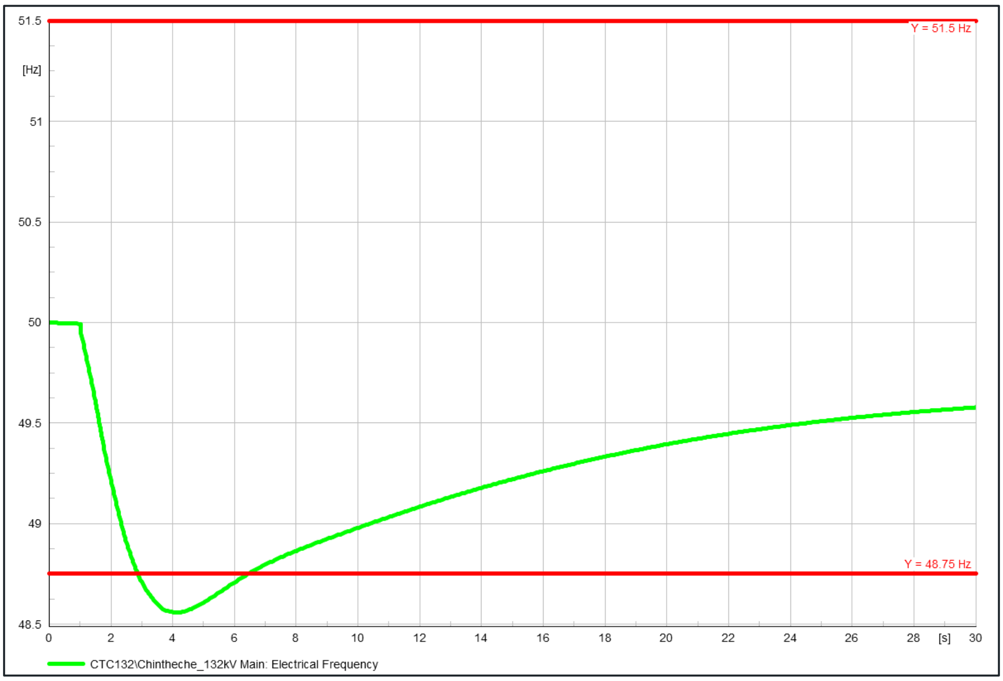


Figure 6-16 - System frequency response after outage of PV Nanjoka 60 MW

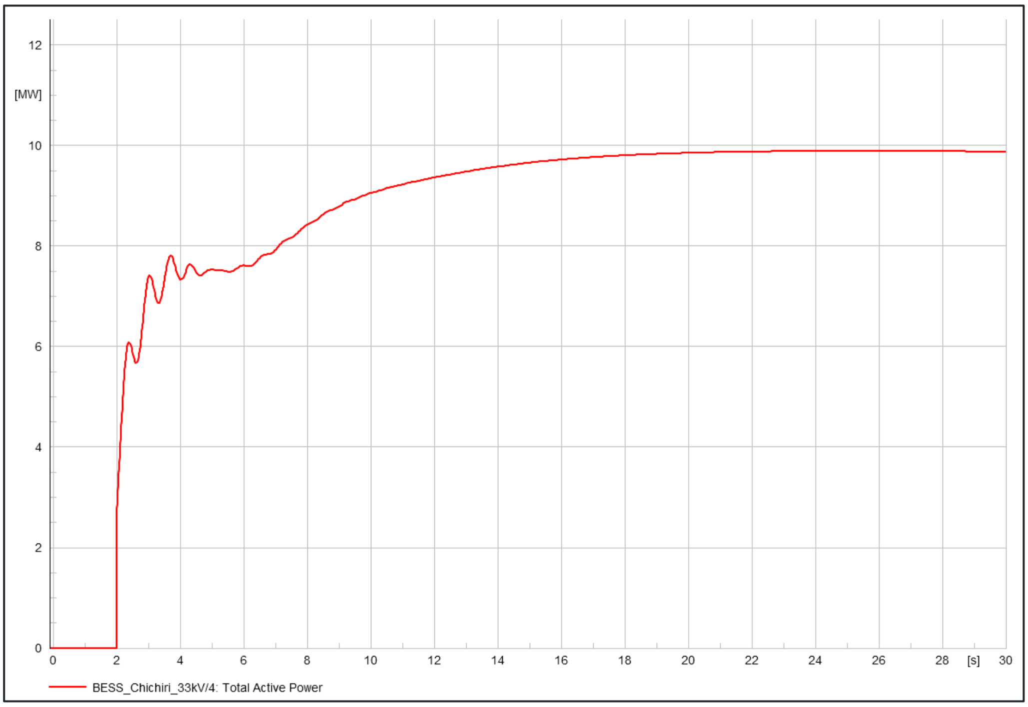


Figure 6-17 - BESS Chichiri 20 MW response with active power after outage of PV Nanjoka 60 MW

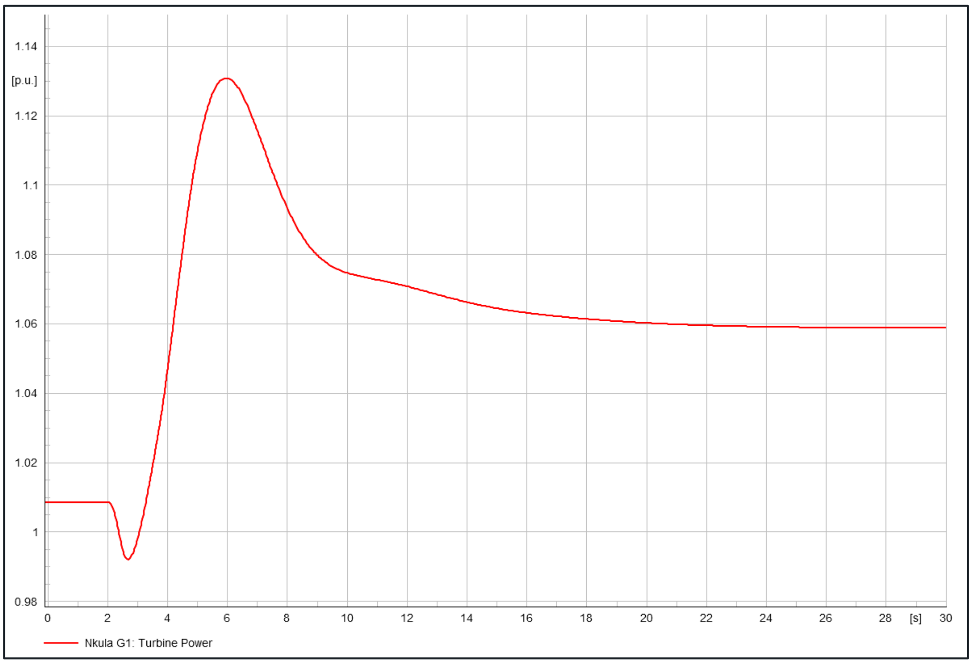


Figure 6-18 - Generator response with active power (turbine power) after outage of PV Nanjoka 60 MW

Table 6-1 - Summary table for outage of PV Nanjoka 60 MW

	Frequency [Hz]	BESS Chichiri response [MW]
CASE 1(WITH KAPICHIRA)	48.98	6.2
CASE 2 (WITHOUT KAPICHIRA)	48.6	10

In conclusion, BESS at Chichiri with installed capacity of 20 MW will have adequate response with active power support for outage of PV Nanjoka or any other generation unit.

Although system is stable, ***frequency drop is below UFLS*** (under frequency load shedding) threshold of 48.75 Hz which is ***not recommended***. Below are presented table results for outage of PV Nanjoka when it is operating with 50 MW, 40 MW and 30 MW. The results show that frequency drop in cases for outage of PV Nanjoka when its operating with 50, 40 and 30 MW will be above of ***UFLS*** threshold 48.75 Hz, which is better than the outage of PV Nanjoka when its operating with 60 MW.

Table 6-2 - Summary table for outage of PV Nanjoka 50, 40, 30 MW

Outage of PV Nanjoka (operating active power)	Frequency (with and without Kapichira) [Hz]	
50 MW	49.2 [Hz]	49.03 [Hz]
40 MW	49.4 [Hz]	49.13 [Hz]
30 MW	49.5 [Hz]	49.3 [Hz]

7

BESS SERVICES

7 BESS SERVICES

Battery energy storage systems are increasingly developing over the past years due to their operational flexibility and full four quadrant control, as shown in the following figure:

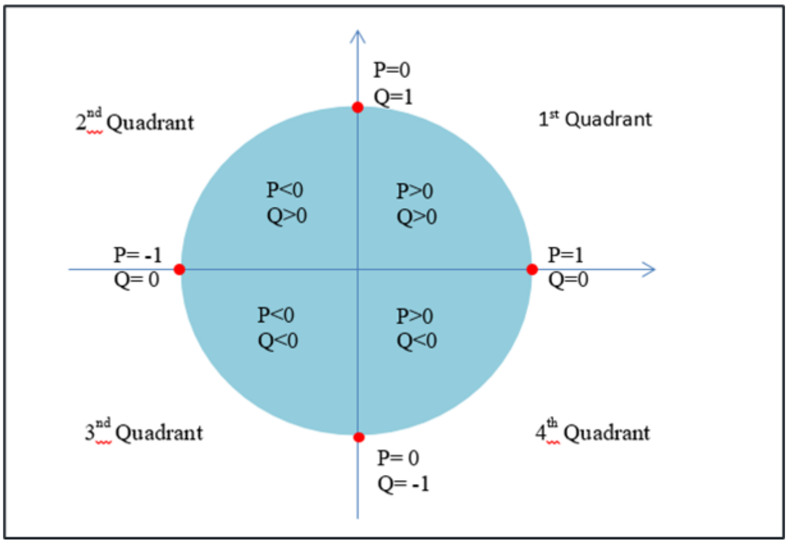


Figure 7-1 - BESS Four Quadrant Control capability

Four quadrants mean that the real current flow directions can represent either charging or discharging states, while the reactive current flows can represent either supplying or absorbing reactive power simultaneously and independently. By implementing various control logics, the services a BESS can provide include:

- Energy arbitrage if combined with variable generation facilities such as wind or photovoltaics,
- Voltage control and regulation at local, point of interconnection or plant level. The fast voltage source converter (VSC) gives storage resources with four quadrant abilities to inject or absorb VARs and correct suboptimal or excessive voltage,
- Frequency support by providing fast frequency response or being part of AGC control,
- Replacement reserve provision. Many storage technologies can be quickly synchronized to grid frequency through power electronics control, so they can provide a service equivalent to spinning reserves with minimal to zero standby losses,
- Black start capability.

Battery Storage systems may connect to the power system either independently or through some hybrid concepts along with the Power Park Modules. Anyhow, like in the case of power park module, battery storages connect the system through AC/DC converter station.

As mentioned above, most of the capabilities of non-synchronous facilities comes from the inverters, so in that manner battery storages seem to be similar as power park modules.

FREQUENCY REGULATION BY BESS SUPPORT

Frequency regulation is the process that takes place within half an hour timeframe and try to capture variations that cannot be planned and scheduled. Those variations are a result of demand variability as well as of renewable generation variability.

In that respect, frequency regulation covers:

- Primary regulation – variability within a minute timeframe
- Secondary regulation – variability within half an hour timeframe

To appropriately assess the size of BESS facility which should provide the frequency regulation, we will firstly use historical data of the demand variability within half an hour timeframe. The following figure shows the variability of consecutive values.

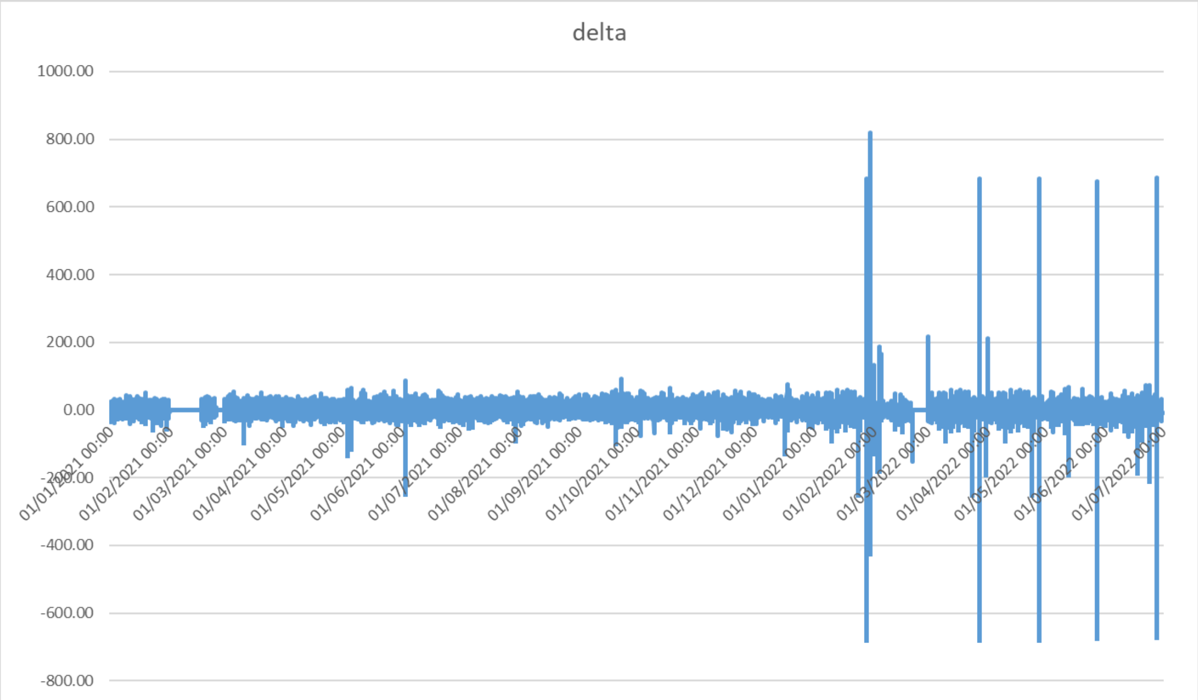


Figure 7-2 - Demand variability of consecutive values

Considering the historical values we can extract 95% distribution delta, as that could be the most probable level of demand variability over the wider horizon. Based on the recorded data, 95% distribution delta is around 25 MW.

To determine the overall variability of the system balance, we would need recorded data of the solar generation. Since there is no relevant historical record, we will assume a rough approximation based on the worldwide practice which says that 95% distribution error does not exceed 20% of the solar installed capacity, for the single site. For the multiple sites this value decreases. To be on the safe side we will assume that the max variability that comes out from the solar generation is 16 MW (20% of the 80 MW).

Total sum of the variability is a vector sum of two parts, variability that comes from the demand and variability that comes from the solar generation:

$$Pimb = \sqrt{25^2 + 16^2} = 29.7MW$$

Based on the above mentioned, 30 MW is the level of necessary reserve to deal with the imbalances within half an hour timeframe. However, this value cannot be considered as optimal value for the BESS dimensioning because of the following:

- Half-hour timeframe is wide and associated variations can be scheduled
- Given that the existing generation fleet relies on the hydro generation, there is always a level of spinning reserve on those machines

Therefore, sudden imbalances that cannot be predicted and scheduled are more likely to be caught in minute or 5-minute timeframe. These timeframes would better define imbalances that could be regulated by BESS service. Given that the demand variability within minute or 5-minute timeframes would be significantly reduced, it is expected that overall imbalance is also reduced although the variability of solar generation in those timeframes might be higher.

With regards to the BESS autonomy (MWh capacity), if preferable services do not include energy arbitraging, then BESS autonomy should be up to 1 hour.

Based on all above, WSP believes that 20 MW of BESS (1hour) would efficiently provide frequency regulation in the Malawian system.

8

BESS FINANCING CONTEXT

8 BESS FINANCING CONTEXT

In order to properly set the business case for Battery Energy Storage System, several initial issues have to be clarified:

- Overall energy sector deregulation level – defined in internal Malawian Law,
- Market structure and rules,
- Services that any future applicant will provide,
- Revenue streams based on the market rules and selected services.

Malawian Low defines the structure of the energy sector and which type of business within sector is regulated and which one is deregulated. In other words, the Low defines openness for independent power producers to invest in Malawian power system. In that respect, business case should recognize whether the investor is:

- Malawian Utility Company as direct purchaser,
- Independent Power Producer (IPP).

In accordance with the market structure and rules, IPPs may define services that they will provide. This model should further assess revenue streams based on which the overall financing concept would be set. In that respect, remuneration for IPPs might be defined as:

- Power Purchase Agreement by which all the energy (charged and discharged) will be remunerated by exact fee,
- Merchant Principle by which IPP would be set as balance responsible party and able to bid (buy and sell) freely on open market with unregulated prices,
- Leasing principle by which IPP would be remunerated by exact monthly/yearly fee.

The first option is well known for potential investors with a secure return. The second concept might be very attractive in developed market environments with extensive market activities. The last one might be attractive to cover temporary needs and where the long-term projections are nor enough reliable. With regards to leasing concept, pros and cons are different for different perspectives:

- Owner – large upfront cost, capital locked away, on-going as required maintenance costs, multiple contracts with different suppliers (civil / design / maintenance / operations / transportation etc), risks with performance, responsible for managing battery degradation, responsibility to manage spares,
- Rental – no upfront cost, contract with one supplier, continuous smaller costs, more control over performance (if it breaches agreement, you can hand it back etc), easier to end contracts if regulatory/govt incentives change, less care about battery degradation, no control of spares. Risks – vendor may pull agreement, risk of receiving old equipment - less reliability.

9

ASSOCIATED REGULATIVE

9 ASSOCIATED REGULATIVE

Given the global tendencies in development of the energy sectors, power systems are expected to migrate from the dominated by the conventional power plants to ones with high levels of intermittent solar PV and Wind plants, Due to intermittent nature of primal energy sources of those technologies, and the need to somehow increase flexibility, Battery Energy Storages are becoming a game changer but at the same time bring another perspective into the system.

Those impacts of higher penetration of large-scale solar PV plants and BESS facilities needs further study to address the following major challenges to the power system operation and dispatch:

- System stability due to low system inertia especially during low demand periods,
- System monitoring and SCADA control requirements for hybrid PV-Battery Energy Storage System Power Plants,
- Complex communications, control, data and information,
- Stability of PV power converters and mitigation of inter-converter oscillations,
- Increased system reactive power compensation requirements,
- PV power plant ancillary services and grid support functions,
- Increased requirements for reserve/storage,
- Solar PV forecasting and generation scheduling. Solar PV's variability/intermittent nature and forecast error significantly influences the required balance in the system reserve,
- Impact on system protection design and settings as non-synchronous renewable energy sources (RES) do not inherently contribute to short-circuit currents during a fault and to voltage recovery after fault clearing.

Taking the foregoing into consideration, the **Malawian Grid Code should be reviewed and amended** if necessary. The review should clearly identify the technical obligations that should be placed on renewable IPPs, on conventional IPPs and on the transmission system to enable safe and stable operation in steady state and transient conditions for a mix of plants in different operation regimes.

In addition to the Grid Code review, the Market Rules for the Malawian Electricity market should be reconsidered, given the attractive business models for the renewables technologies, such as:

- PV power plant IPPs,
- Hybrid Power Plants (PV+BESS, Wind+BESS),
- BESS stand-alone facilities,
- Demand Side Management Systems.

10

GRID IMPACT STUDY - COMMENTS

10 GRID IMPACT STUDY - COMMENTS

The main purpose of this study was looking to get a solid understanding of how many additional Megawatts (MWs) Malawi's grid could absorb on the current system, to guide and facilitate PPA development with IPPs.

As some of these IPPs are proposing Photovoltaic (PV) solar power solutions, the goal was also to get a sense of how much variable or intermittent power Malawi's grid could handle at the year 2016 and over the next 12-24 months, until MCC and the World Bank's Transmission and Distribution (T&D) improvements come online.

The following table aims to refer to conclusions and recommendations from that study and to put a new perspective resulted from this study.

Conclusions		
	Grid Impact Study	**WSP comment**
1. Steady-State Analysis	The load flow studies indicate that connections of 4MW to 300MW are possible from a steady state point of view at various busbars in the network	no comment, still applicable
	System losses decrease by up to 20% after integration at some areas of the network. However, if the distributed generation exceeds local load, losses start to increase and even exceed previous levels in some cases	We gave the similar conclusion - if the generation is distributed along the network, energy transfer from south to north will be reduced and that way losses will be reduced as well
2. Frequency Response Studies	Modified governor settings were found to provide good correlation with an actual Nkula A generator tip	no comment, still applicable
	The limiting scenario for a PV connection in the meshed network is 17MW	This is susceptible to changes. Max value will be limited probably by frequency deviation in case of outage in extreme regime. However, there can be also local constraints. On the other side, once interconnection is established this threshold will definitely go up
	The limiting scenario for a PV connection in the radial northern network is 15MW.	Again, it is not practical to deal with the strict threshold (15MW), because network evolves and steady state conditions for connection. Also, new sources such as BESS are being installed with different capabilities - all those influence the overall network ability to accommodate new source

	Although the northern system is suitable for PV connections from a system losses, geographical and network diversity point of view, it is limited in the amount of generation it can transfer due its radial nature especially for 2016 (a trip of the radial line disconnects northern PV plants from the bulk network).	This conclusion is susceptible to change as the network evolves
	Due to the meshed nature of the Southern and Central parts of the transmission system, larger increments of power can be connected on these networks.	Still applicable, no comment
	With the assumed reserve margin, multiple uncorrelated (at least 20km apart) PV units can theoretically be connected across the system however it is recommended that this is initially limited to 70MW for system inertia and governing response reasons.	This is susceptible to changes. Even without interconnection, power system is getting bigger, overall system response is changing, therefore the power system cap to accommodate RES is changing
3. PV integration Analysis	It should be noted that if PV is to be integrated, an operational project-specific study will need to be undertaken in order to determine the required amount of online units (for both inertial and governing purposes) under all possible conditions.	Still applicable, no comment
	PV plants take up approximately 2 hectares per MW of land and this needs to be considered when positioning plants.	Still applicable, no comment
	The overall study undertaken indicates that for all normal operating conditions up to 2018, a loss of a 17MW PV plant in the meshed system will not induce UFLS if only one (1) unit of Nkula A is offline. The same is true of 15MW in the radial northern system.	This is susceptible to changes - as the system is alive and new sources are coming online
	No additional load should be connected after the integration of PV plants. This is due to the fact that PV has a narrow mid-day generation band where maximum power is achievable and even then it is not guaranteed. Adding extra load will in fact decrease the existing small reserve margins (Appendix G), increasing the chance of invoking UFLS and decreasing system reliability	

4. Peaking Plant Analysis	Peaking plants should initially be limited to around 17MW in size	This is susceptible to changes
	The plants should be integrated in a meshed area of the grid to increase the availability of the peaking plant and overall system security	no comment, still applicable
	The peaking plant was found to improve the system frequency response (increased inertia and governing capability	
	The peaking plants will be transiently stable if integrated within the meshed system	This refers to diesel units, the conclusion is correct, but not applicable for our study
	Peaking plants should only be run at system peak and not at any other time (for economic reasons)	no comment, still applicable
5. Thermal Base Load Analysis	Base load plants need to provide some spinning reserve in order to allow larger units to be connected to the system (equipment prices, unit efficiency and economies of scale). An example is 4x30MW units all operating at 26MW.	Still applicable, no comment
	As with the diesel peaking plants, the thermal plants should be integrated in a meshed area of the grid to increase system security	Diesel machines are not for discussion
	Thermal plants improve the system frequency response (inertial response and governing capability.	Diesel machines are not for discussion
	The plants will be transiently stable if integrated within the meshed system.	Diesel machines are not for discussion
	Once an international interconnector is built, larger thermal units may be connected to the power system. This is because the SAPP system can then provide additional inertial response and governing capability.	This conclusion is applicable for the PV plants more than for the thermal units
Recommendations		
	Grid Impact Study	**WSP comment**
1	Multiple 17 MW PV power plants can be connected to the meshed network at system substations which meet the MEC requirements	This is susceptible to changes. Max value will be limited probably by frequency deviation in case of outage in extreme regime. However, there can be also local constraints. On the other side, once interconnection is established this threshold will definitely go up

2	Multiple 15 MW PV power plants can be connected to the radial northern network at system substations which meet the MEC requirements	This is susceptible to changes but definitely should be a part of detailed analyses
3	PV plants larger than 17 MW can be installed if they are built and connected in such a way that a single contingency only removes 17/15 MW from the system at a time. This can be achieved through multiple transmission lines and or transformers etc	Permitted single contingency depends on the system size and on the total inertia. It should be checked from time to time rather than to stick to the exact value
4	The total of installed PV should initially be limited to 70 MW	This is susceptible to changes. Even without interconnection, power system is getting bigger, overall system response is changing, therefore the power system cap to accommodate RES is changing
5	The UFLS relays should be reconfigured to operate instantaneously to improve system frequency recovery	This should be a subject to the wider security restoration procedure
6	Operational studies should be carried out for each PV plant to be connected to ensure that there will always be enough system inertia and governing reserve to ride through a plant trip under all operational conditions	Still applicable, no comment
7	PV power plants should be dispersed in the following manner: • Connected to different backbone transmission systems (e.g. northern system, Lilongwe system, Golomoti system, Salima system, various Blantyre systems) which creates electrical connection diversity • Connected in a geographically dispersed manner with electrical and weather diversity benefits	Still applicable, no comment
8	No Additional load should be connected to the ESCOM power system	This recommendation is meaningless - as the load is supposed to constantly rise, while power system should follow that rise by upgrade

9	If more load is to be serviced on the ESCOM power system, the following infrastructure should be prioritized • SAPP Interconnector (emergency reserve, regulatory reserve, system inertia from the SAPP system, energy (kWh) when available from SAPP countries, diversity from hydro, export of Malawi PV kWh when available) • Peaking HFO or Diesel plant (already in the mini-IRP and makes sense for system peak). HFO has cheaper USc/kWh, fast frequency response but likely to be too expensive as spinning reserve for non-dispatchable PV during the day • Baseload coal (emergency reserve, regulatory reserve, kWh, diversity from hydro, fast frequency response) Probably 2 x 100MW units due to the size of the Malawi system versus cost savings in terms of unit size (economies of scale) • Baseload gas (emergency reserve, regulatory reserve, kWh, diversity from hydro, fast frequency response). If gas can be obtained at ~$5/GJ to $7/GJ, gas will likely be comparable to coal but a gas source needs to be found • Solar PV (kWh, non-dispatchable, can help with frequency response if output constrained, does not increase/improve system inertia). PV can decrease coal or gas input costs when sun shining (kWhs) but cannot be relied upon for capacity • Hydro (hydro is weather dependent and if poor rainfall all hydro generators equally affected). Malawi needs to diversify away from hydro until other baseload, interconnector or peak generation sources are in place	This should be a subject of the IRP upgrade - which would consider in detail all the power subsystems: generation, transmission and distribution, taking into consideration least cost approach and overall system security

11

CONCLUSIONS AND RECOMMENDATIONS

11 CONCLUSIONS AND RECOMMENDATIONS

This report has shown studies undertaken to determine if the proposed locations of PV and BESS from pipeline and generic cases will integrate into the Malawian power system with no steady-state and transient issues. Preferable pathway was a ***pipeline project case*** that was complemented with generic BESS facilities to fit the recommendation from the Workstream 1 with respected to the installed capacity needed for the upcoming years (around 400 MW of PV solar capacity and around 180 MW of BESS capacity with 4hour autonomy).

The ***pipeline project case*** has already proposed locations for the future PV sites while locations for BESS facilities were proposed by WSP. The basic criteria for the optimal location choice were:

- BESS should be placed in electrical vicinity of the PV power plant to avoid transmission losses while charging and to avoid possible infrastructure upgrade while discharging,
- BESS should be placed at or near electrical nodes with poor voltage profile.

Besides BESS location, the optimal BESS size was considered. The basic criteria for the optimal size choice were:

- Not to cause any overloading and contingency issue neither while charging nor while discharging,
- Not to exceed the single incident size which could lead to dynamic instability after the sudden outage.

<u>The results/recommendations of the study and BESS size/s proposed are based on an isolated system, but once the interconnector is in by December 2023, the solution/proposals will be different.</u>

The proposal has demonstrated that ESCOM will be able to comfortably operate their system and provide reliable and secure delivery of electricity with no adverse operational disturbance or impact on either the grid or consumers of the electricity system.

The overall conclusion of the BESS optimization study for Malawi power system is that it should be continued with pipeline projects with addition of PV 40 MW Kanengo (installed capacity), BESS 20 MW at Chichiri 33kV and BESS 20 MW at Chinteche 132 kV in order to reach optimal generation of active power for year 2024 (results from PLEXOS software).

The load flow studies indicate that connections of PVs and BESS are possible from a steady state point of view at various busbars in the network and those integrations will improve voltages at busbars in all three regions of Malawian power system. Hence, the PV and BESS voltage support is not enough to improve low voltage conditions recognized on busbars: Chinyama 33 kV (Trans centre), BB 33 kV (Trans centre) and Fundis Cross 66 kV Res (Trans south).

Following additions of equipment in system is required in order to mitigate overloading of elements in power system:

- Addition of three transformer in parallel with existing three transformers between Kanengo 132 kV and Kanengo 66 kV,
- Addition of one transformer in parallel with existing between Area 48 66 kV and Area 48 11 kV,

- Addition of one transformer in parallel with existing between New Bwengu 132 kV and New Bwengu 66 kV,
- Double transmission line between Nanjoka and Nkhotakota 132 kV,
- Addition of one transformer in parallel with existing at BT West IBT3,
- Addition of one transformer in parallel with existing between Chinyama and BB.

As an extension of the load flow analysis, an investigation of system adequacy and security was performed through N-1 contingency analysis for the pipeline and generic case for three regimes: peak, off peak and solar peak. Outage of lines Chigumula-Mapanga and Phombeya-Nkhoma 400 kV will lead to most contingencies. Temporary overloads in any transmission line or substation equipment should not exceed [110%] of the maximum continuous ratings.

Fault level studies (short-circuit) were carried out for the North, Central, South and Generation regions for three-phase and single-phase fault levels. Calculated fault currents for the network with PV and BESS installed show that the highest values are at Nkula B 132 kV (6,524 kA), Mlambe 66 kV (17,575 kA), Tedzani 66 kV (9,593 kA). However, those values are too far from the withstand capabilities of the existing equipment. The conclusion is that the introduction of the PV plant will slightly increase short-circuit currents in the Trans Centre, Trans North and Trans South region.

With the respect to dynamic analysis the following conclusions are drawn:

- Due to outstanding BESS performance in terms of P-Q capability, there is no issue with voltage recovery after the most onerous faults,
- 60MW size of BESS is not recommended as the single incident of that size might lead to large frequency drop and probably activation of the low frequency demand shedding,
- It is better to split BESS of 60 MW at Nkhoma to BESS 30 MW at Nkhoma and BESS 30 MW at Nkhotakota,
- BESS at Chichiri with installed capacity of 20 MW will have adequate response with active power support for outage of PV Nkhoma or any other generation unit.

With respect to the frequency regulation service that BESS is able to provide, we recommended the following:

- If BESS is conceived to provide frequency regulation and not energy arbitrage, then its autonomy should not exceed 1 hour,
- Given that the existing hydropower fleet can be exposed to extreme inflow regimes, a contribution to AGC control in those regimes is not a good option. Those regimes require a full hydropower production, therefore the AGC control could be assigned to BESS as the most optimal solution.
- For determination the BESS size, historical record of the demand variability and solar generation variability should be given in minute or 5-minute timeframe, rather than in half-hour timeframe,
- According to the existing data, WSP believes that 20MW of BESS (1hour) would efficiently provide frequency regulation in the Malawian system.

Appendix A

APPENDIX

CONTINGENCY ANALYSIS FOR GENERIC CASE IN SOLAR PEAK REGIME

Table A-1 - Contingency analysis- Worst loading violations for generic case in solar peak regime

Element contingence	Loaded element	Loading Base Case [%]	Loading after contingency [%]
Nanjoka-Nkhotakota	Kapichira GT1	79.8	341.6
BESS Chinyama 66kV	Nanjoka-Nkhotakota	128.1	145.3
Fundis Cross L1	2-Winding transformer (1)	63.3	129.6
Mlambe T1	Mlambe T2	84.8	137.9
Mlambe T2	Mlambe T1	60.4	130
Chintheche-Luwinga	T/Hill T1	50	127.4
PV Converter (4)	Kanengo IBT1	67.7	110.8
PV Converter (4)	Kanengo IBT2	67.7	110.8
PV Converter (7)	BT West IBT3	84.6	108
Trf PV Dedza 66 kV	Trf BESS 66/33 Dedza	64.7	107.8
PV Converter (4)	Kanengo IBT3	65.8	107.8
PV Converter (7)	BT West-Chigumula	65.9	107.2
Shunt/Filter (2)	Area 48 T2	100.3	106.1
PV Converter (6)	Trf PV Dedza66kV	74.1	105.5
Phombeya-Nkhoma 400 kV	Trf PV Kanengo66kV	93.7	104.5

Worst voltage violations in case of branch outage are presented in **Table A-2** and **Table A-3.**

Table A-2 - Contingency analysis- Worst voltage violations (voltages below 0.9 p.u.) for generic case in solar peak regime (branch outage, bus violations)

Element of contingence	Bus name	Voltage Base [p.u.]	Voltage Min [p.u.]
Trf PV Dedza 66kV	BESS _Dedza LV	1.03	0.60
Trf PV Dedza 66kV	Dedza_33kV	1.02	0.60
Trf PV Dedza 66kV	Dedza_T1t	1.03	0.61
PV Converter (3)	LV (2)	1.01	0.61
Trf PV Dedza 66kV	Dedza_66kV	1.03	0.61
Trf PV Dedza 66kV	Mlangeni_33kV	1.00	0.70
Trf PV Dedza 66kV	Mlangeni_66kV	1.02	0.71

Element of contingence	Bus name	Voltage Base [p.u.]	Voltage Min [p.u.]
PV Converter (6)	Ntcheu_11kV	1.00	0.72
PV Converter (6)	Atlas Balaka 11_kV	0.99	0.73
PV Converter (6)	Atlas Balaka 11kV2	0.99	0.73
PV Converter (6)	Ntcheu_66kV	1.02	0.73
PV Converter (6)	Liwonde_66kV	1.00	0.74
PV Converter (6)	BESS_Chingeni LV	1.02	0.75
PV Converter (6)	Atlas Balaka 66kV	1.01	0.75
PV Converter (6)	LV(1)	1.03	0.76
PV Converter (6)	Chingeni_66kV	1.02	0.76
PV Converter (6)	Liwonde_33kV	1.03	0.76
Phombeya-Nkhoma 400kV	Nkhoma 400kV A	0.96	0.80
Phombeya-Nkhoma 400kV	Nkhoma 400kV B	0.96	0.80
Chintheche-T/Hill	T/Hill_66kV	0.92	0.82
Phombeya-Nkhoma 400kV	Tsabango_132kV	0.94	0.82
Phombeya-Nkhoma 400kV	Nkhoma 132kV A	0.95	0.83
Phombeya-Nkhoma 400kV	Nkhoma 132kV B	0.95	0.83
Phombeya-Nkhoma 400kV	Kanengo_132kV Main	0.94	0.83
Phombeya-Nkhoma 400kV	Kanengo_132kV Res	0.94	0.83
Phombeya-Nkhoma 400kV	Lilongwe OT_66kV/2	0.96	0.83
Phombeya-Nkhoma 400kV	Kangoma_66kV	0.97	0.85
Phombeya-Nkhoma 400kV	Tsabango_66kV	0.97	0.85
Phombeya-Nkhoma 400kV	JCM 132KV B/B	0.94	0.85
Phombeya-Nkhoma 400kV	Nanjoka_132kV Main	0.94	0.85
Phombeya-Nkhoma 400kV	Nanjoka_132kV Res	0.94	0.85
Phombeya-Nkhoma 400kV	Area 48_11kV1	0.96	0.86
Phombeya-Nkhoma 400kV	JCM Golomoti 132kV B/B	0.96	0.86
Phombeya-Nkhoma 400kV	Golomoti_132kV Main	0.96	0.86
Phombeya-Nkhoma 400kV	Golomoti_132kV Res	0.96	0.86
PV Converter (7)	Fundis Cross_66kV Main	0.90	0.86
PV Converter (7)	Fundis Cross_66kV Res	0.90	0.86
PV Converter (7)	Terminal (2)	0.91	0.86
PV Converter (7)	Terminal (3)	0.90	0.86
Chintheche-T/Hill	T/Hill_11kV	0.97	0.86
Phombeya-Nkhoma 400kV	Lilongwe OT_66kV/1	0.97	0.86
Phombeya-Nkhoma 400kV	Monkey Bay_66kV	0.96	0.86
Chintheche-Luwinga	Luwinga 33kV	0.97	0.87
Phombeya-Nkhoma 400kV	Barracks_66kV	0.98	0.87
Phombeya-Nkhoma 400kV	Phombeya 400kV A	0.96	0.87
Phombeya-Nkhoma 400kV	Phombeys 400kV B	0.96	0.87
Phombeya-Nkhoma 400kV	Kauma 11kV (1)	0.98	0.87
Phombeya-Nkhoma 400kV	Area 48_66kV	0.98	0.87
Phombeya-Nkhoma 400kV	Kauma 66kV	0.98	0.87
Chintheche-T/Hill	T/Hill_33kV	0.97	0.88
PV Converter (6)	Chichiri_66kV/3	0.91	0.88
Phombeya-Nkhoma 400kV	Kanengo_66kV/1	0.99	0.88

Element of contingence	Bus name	Voltage Base [p.u.]	Voltage Min [p.u.]
Phombeya-Nkhoma 400kV	Kanengo_66kV/1	0.99	0.88
Phombeya-Nkhoma 400kV	Tsabango_11kV	1.02	0.88
Phombeya-Nkhoma 400kV	Area 48_11kV2	0.99	0.88
PV Converter (4)	LV (3)	1.02	0.88
Phombeya-Nkhoma 400kV	Nanjoka	0.98	0.89
Chintheche-Luwinga	Luwinga_DG_0.4kV(1)	1.00	0.89
Chintheche-Luwinga	Luwinga _DG_0.4kV 2	1.00	0.89
Phombeya-Nkhoma 400kV	Phombeya 132kV	0.97	0.89
Chintheche-Luwinga	LV (1)	0.93	0.89
Phombeya-Nkhoma 400kV	Nanjoka_T1t	0.99	0.89
Chintheche-Luwinga	Bwengu_33kV	0.98	0.90
Phombeya-Nkhoma 400kV	Golomoti_66kV	1.00	0.90
Phombeya-Nkhoma 400kV	Lilongwe OT_11kV/2	1.04	0.90

Table A-3 - Contingency analysis- Worst voltage violations (voltages above 1.1 p.u.) for the generic case in solar peak regime (branch outage, bus violations)

Element of contingence	Bus name	Voltage Base [p.u.]	Voltage Max [p.u.]
Chinyama T1	Chinyama_66kV	0.99	1.19
Chinyama L1	Chinyama_33kV	1.00	1.18
Chinyama T1	LV (1)	0.98	1.17
Mapanga L1	Mapanga DG 0.4KV	1.12	1.16
Chinyama T1	BESS Chinyama LV	0.96	1.16
Chinyama L1	BB	0.96	1.13
Monkey Bay L1	Monkey Bay 33 KV	1.03	1.12
Shunt/Filter (2)	Lilongwe OT 33KV	1.05	1.1
Fundiss Cross T2	Fundis Cross 33 kV	1.02	1.1
Karonga L2	Karonga 33KV	1	1.1
Shunt/Filter (2)	Kangoma 11KV	1.03	1.1
Shunt/Filter (2)	Lilongwe OT 11kV/2	1.03	1.1
Barracks 33KV L2	Barracks 33KV	1.03	1.1
Chichiri L3	Chichiri 33KV/4	1.03	1.1

CONTINGENCY ANALYSIS FOR PIPELINE CASE IN PEAK REGIME

Table A-4 - Contingency analysis- Worst loading violations for pipeline case in peak regime

Element contingence	Loaded element	Loading Base Case [%]	Loading after contingency [%]
BESS Nkhoma 132kV	Kapichira GT1	34.8	178.5
Mlambe T1	Mlambe T2	57.7	132.5

Mlambe T2	Mlambe T1	77.2	130.5
Mbongozi RoR	Nkhotakota IBT1	98.4	116.6
Luwinga T1	T/Hill T1	35.8	110.1
BESS Chintheche 132 kV	Chintheche T2	90.5	106.9

Worst voltage violations in case of branch outage are presented in Table A-5 and **Table A-6**

Table A-5 - Contingency analysis- Worst voltage violations (voltages below 0.9 p.u.) for the pipeline case in peak regime (branch outage, bus violations)

Element of contingence	Bus name	Voltage Base [p.u.]	Voltage Min [p.u.]
Mbongozi RoR	BB	0.91	0.75
Mbongozi RoR	Chinyama_66kV	0.89	0.76
BESS_Chinteche 132 kV	Karonga_33kV	1.00	0.77
BESS_Chinteche 132 kV	Karonga_11kV	1.00	0.78
BESS_Chinteche 132 kV	Karonga_66kV	0.99	0.79
BESS_Chinteche 132 kV	Uliwa_11kV	0.98	0.79
BESS_Chinteche 132 kV	Livingstonia_11kV	0.98	0.80
Mbongozi RoR	Chinyama_33kV	0.96	0.81
BESS_Chinteche 132 kV	Wovwe_11kV/2	1.00	0.81
BESS_Chinteche 132 kV	Wovwe_11kV/1	1.00	0.81
BESS_Chinteche 132 kV	Uliwa_66kV	1.00	0.81
BESS_Chinteche 132 kV	Wovwe_66kV	1.00	0.81
Phombeya-Nkhoma 400kV	Terminal	0.95	0.82
BESS_Chinteche 132 kV	Bwengu_33kV	0.99	0.82
BESS_Chinteche 132 kV	T/Hill_66kV	0.98	0.82
BESS_Chinteche 132 kV	Livingstonia_66kV	1.01	0.83
BESS_Chinteche 132 kV	T/Hill_11kV	0.99	0.83
Phombeya-Nkhoma 400kV	Lilongwe OT_66kV/1	0.97	0.83
Phombeya-Nkhoma 400kV	Nkhoma 400kV A	0.99	0.83
Phombeya-Nkhoma 400kV	Nkhoma 400kV B	0.99	0.83
BESS_Chinteche 132 kV	Bwengu_T1t	1.00	0.83
BESS_Chinteche 132 kV	Chintheche_11kV	0.99	0.84
Phombeya-Nkhoma 400kV	Barracks_66kV	0.97	0.84
Phombeya-Nkhoma 400kV	Lilongwe OT_33kV	0.98	0.84
BESS_Chinteche 132 kV	Chikangawa_66kV	0.99	0.84
Phombeya-Nkhoma 400kV	Kanengo_132kV Main	0.96	0.84
Phombeya-Nkhoma 400kV	Kanengo_132kV Res	0.96	0.84
Phombeya-Nkhoma 400kV	Lilongwe OT_11kV/1	0.98	0.84
Phombeya-Nkhoma 400kV	Terminal (1)	0.98	0.84
BESS_Chinteche 132 kV	Chikangawa_11kV	0.99	0.84
Phombeya-Nkhoma 400kV	Kauma 11kV (1)	0.98	0.84
BESS_Chinteche 132 kV	Chikangawa_33kV	1.00	0.84

Element of contingence	Bus name	Voltage Base [p.u.]	Voltage Min [p.u.]
Phombeya-Nkhoma 400kV	Lilongwe OT_11kV/2	0.99	0.84
Phombeya-Nkhoma 400kV	Area 48_66kV	0.98	0.84
Phombeya-Nkhoma 400kV	Kauma 66kV	0.98	0.84
Phombeya-Nkhoma 400kV	Tsabango_132kV	0.98	0.84
Phombeya-Nkhoma 400kV	BESS_Nkhoma LV	0.97	0.84
BESS_Chinteche 132 kV	Chintheche_33kV	0.99	0.84
BESS_Chinteche 132 kV	New Bwengu A 132kV	1.00	0.84
BESS_Chinteche 132 kV	New Bwengu B 132kV	1.00	0.84
BESS_Chinteche 132 kV	Bwengu_11kV Busbar	1.01	0.85
BT West - Chigumula	Terminal (2)	0.91	0.85
BT West - Chigumula	Fundis Cross_66kV Main	0.90	0.85
BT West - Chigumula	Fundis Cross_66kV Res	0.90	0.85
Phombeya-Nkhoma 400kV	Tsabango_11kV	1.00	0.85
BT West - Chigumula	Terminal (3)	0.91	0.85
BESS_Chinteche 132 kV	Chintheche_IBT1t	0.99	0.85
BESS_Chinteche 132 kV	T/Hill_33kV	1.01	0.85
BESS_Chinteche 132 kV	Luwinga 132kV	1.00	0.85
Phombeya-Nkhoma 400kV	Kanengo_11kV/1	0.98	0.85
Phombeya-Nkhoma 400kV	Barracks_11kV	1.00	0.85
Phombeya-Nkhoma 400kV	Kanengo_11kV/1	0.99	0.85
Phombeya-Nkhoma 400kV	Lilongwe OT_66kV/2	1.00	0.85
Phombeya-Nkhoma 400kV	Nkhoma 132kV A	0.99	0.85
Phombeya-Nkhoma 400kV	Nkhoma 132kV B	0.99	0.85
Phombeya-Nkhoma 400kV	Kanengo_33kV B/B 2	0.99	0.85
Phombeya-Nkhoma 400kV	Kanengo_66kV/1	0.99	0.85
Phombeya-Nkhoma 400kV	Kanengo_66kV/1	0.99	0.85
Phombeya-Nkhoma 400kV	Terminal (2)	1.00	0.86
BESS_Chinteche 132 kV	Bwengu_66kV	1.02	0.86
BESS_Chinteche 132 kV	New Bwengu_66kV	1.02	0.86
Phombeya-Nkhoma 400kV	Area 48_11kV2	1.00	0.86
Phombeya-Nkhoma 400kV	Area 48_11kV1	1.01	0.86
Phombeya-Nkhoma 400kV	Kanengo_33kV	1.00	0.86
BESS_Chinteche 132 kV	BESS_Chinteche LV	1.02	0.86
BESS_Chinteche 132 kV	Chintheche_132kV Main	1.00	0.86
BESS_Chinteche 132 kV	Chintheche_132kV Res	1.00	0.86
Phombeya-Nkhoma 400kV	Kangoma_11kV	1.01	0.87
Phombeya-Nkhoma 400kV	Kangoma_66kV	1.01	0.87
Phombeya-Nkhoma 400kV	Tsabango_66kV	1.01	0.87
Phombeya-Nkhoma 400kV	Barracks_33kV	1.02	0.87
Luwinga T1	Luwinga 33kV	1.04	0.87
BESS_Chinteche 132 kV	Chintheche_66kV	1.02	0.87
Mbongozi RoR	Nkhotakota_33kV/1	0.98	0.88
Mbongozi RoR	Nkhotakota_33kV/2	0.99	0.88
Phombeya-Nkhoma 400kV	Monkey Bay_33kV	0.98	0.88
Mbongozi RoR	Nkhotakota_T1t	0.99	0.88

Element of contingence	Bus name	Voltage Base [p.u.]	Voltage Min [p.u.]
Phombeya-Nkhoma 400kV	Monkey Bay_66kV	0.98	0.88
Mbongozi RoR	PV Nkhotakota HV_66kV	0.99	0.89
Mbongozi RoR	Nkhotakota_T2t	0.99	0.89
Mbongozi RoR	Nkhotakota_132kV Res	0.98	0.89
Mbongozi RoR	Dwangwa 132kV	0.99	0.89
Luwinga T1	Luwinga_DG_0.4kV (1)	1.06	0.89
Luwinga T1	Luwinga _DG_0.4kV 2	1.06	0.89
Mbongozi RoR	Nkhotakota_66kV/2	1.00	0.89
Mbongozi RoR	Nkhotakota_66kV/1	1.00	0.89

Table A-6 - Contingency analysis- Worst voltage violations (voltages above 1.1 p.u.) for pipeline case in peak regime (branch outage,bus violations)

Element of contingence	Bus name	Voltage Base [p.u.]	Voltage Max [p.u.]
Fundis Cross T2	Fundis Cross 33kV	1.17	1.27
New Bwengu IBT1	Luwinga DG 0.4kV (1)	1.12	1.22
New Bwengu IBT1	Luwinga DG 0.4kV 2	1.11	1.21

LOAD FLOW AND CONTINGENCY ANALYSES FOR PIPELINE CASE IN OFF PEAK REGIME

Table A-7- Load flow results- Voltages at buses within Malawian network (pipeline case)

Network data				Voltage [p.u.]	Voltage [p.u.]
Voltage level [kV]	Bus name	Substation	Location	Base case	Off Peak regime
Area: Centre					
400	Nkhoma 400kV A	Double Busbar (1)	Trans Centre	1	1.02
	Nkhoma 400kV B	Double Busbar (1)			
400	Phombeya 400kV A	Double Busbar	Trans Centre	1.01	1.02
	Phombeys 400kV B	Double Busbar			
132	Nkhotakota_132kV Res	Nkhotakota_132(1)	Trans Centre	0.94	1.01

Network data				Voltage [p.u.]	Voltage [p.u.]
Voltage level [kV]	Bus name	Substation	Location	Base case	Off Peak regime
132	Nanjoka_132kV Main	Nanjoka_132	Trans Centre	1	1.02
132	Golomoti_132kV Main	Golomoti 132 kV	Trans Centre	1.01	1.03
132	Kanengo_132kV Res	Kanengo_132	Trans Centre	0.98	1
132	Dwangwa 132kV	Dwangwa 132kV	Trans Centre	0.94	1.02
132	Chintheche_132kV Res	Chintheche_132	Trans Centre	0.94	1.03
132	Nkhoma 132kV A	Double Busbar (2)	Trans Centre	1	1.01
	Nkhoma 132kV B	Double Busbar (2)		1	1.01
132	Phombeya 132kV	Phombeya 132kV	Trans Centre	1.02	1.03
132	Nkula ‘B’ 132kV Res	Nkula ‘B’ 132kV	Trans Centre	1.03	1.03
132	Chintheche_132kV Main	Chintheche_132	Trans Centre	0.94	1.03
66	Nkhotakota_66kV/1	Nkhotakota_66	Trans Centre	0.97	1
66	Nkhotakota_66kV/2	Nkhotakota_66(1)	Trans Centre	0.97	1
66	Mlangeni_66kV	Mlangeni_66	Trans Centre	0.95	1
66	Golomoti_66kV	Golomoti_66	Trans Centre	0.99	1.01

Network data				Voltage [p.u.]	Voltage [p.u.]
Voltage level [kV]	Bus name	Substation	Locatio n	Base case	Off Peak regime
66	Chinyama_66kV	Chinyama_66	Trans Centre	0.795	0.92
66	Dedza_66kV	Dedza_66	Trans Centre	0.94	1
33	Nkhotakota_33kV	Nkhotakota_33	Trans Centre	1.01	0.99
33	Nkhotakota_33kV/2	Nkhotakota_33(2)	Trans Centre	0.94	0.99
33	Kanengo_33kV B/B 2	Kanengo_33kV B/B 2	Trans Centre	0.95	0.99
33	Chinyama_33kV	Chinyama_33kV	Trans Centre	0.84	0.92
33	Barracks_33kV	Barracks_33kV	Trans Centre	0.93	1
33	Nanjoka	Single Busbar	Trans Centre	0.96	0.99
33	BB	Single Busbar (5)	Trans Centre	0.8	0.96
11	Area 48_11kV1	Area 48_11(1)	Trans Centre	0.95	1.01
11	Lilongwe OT_11kV/1	Lilongwe_11	Trans Centre	0.94	0.99
Area: North					
132	Chintheche_132kV Main	Chintheche_132	Trans North	0.94	1.03
132	Luwinga	Luwinga_132	Trans North	0.94	1.03

Network data				Voltage [p.u.]	Voltage [p.u.]
Voltage level [kV]	Bus name	Substation	Location	Base case	Off Peak regime
132	New Bwengu	New Bwengu_132	Trans North	0.94	1.04
66	Chikangawa_66kV	Chikangawa_66	Trans North	0.92	1.02
66	T/Hill_66kV	T/Hill_66	Trans North	0.92	0.99
66	Bwengu	Bwengu_66	Trans North	0.96	0.99
33	Chintheche_33kV	33kV Busbar	Trans North	0.93	1.02
33	T/Hill_33kV	33kV Busbar	Trans North	0.95	1.02
11	Chintheche_11kV	11kV Busbar	Trans North	0.93	1.02
11	T/Hill_11kV	11kV Busbar	Trans North	0.93	1.01
11	Uliwa	Uliwa_11	Trans North	0.98	0.99
11	Karonga	Karonga_11	Trans North	0.98	1.01
Area: South					
132	BT West_132KV Main	BT West_132	Trans South	1.03	1.03
66	Mlangeni_66kV	66kV Busbar	Trans South	0.95	1
66	Chichiri_66kV/4	Chichiri_66	Trans South	0.95	0.99

Network data				Voltage [p.u.]	Voltage [p.u.]
Voltage level [kV]	Bus name	Substation	Location	Base case	Off Peak regime
66	Chigumula_66kV	Chigumula_66	Trans South	1	1.02
66	Fundis Cross_66kV Res	Double Busbar (3)	Trans South	0.87	0.92
66	Changalume_66kV	Changalume_66	Trans South	0.95	0.99
33	Liwonde_33kV	Liwonde_33(2)	Trans South	0.94	0.99
33	Chichiri_33kV/3	Chichiri_33(1)	Trans South	0.94	1.02
33	Chichiri_33kV/4	Chichiri_33	Trans South	0.91	1
11	Ntcheu_11kV	Ntcheu_11	Trans South	0.94	1

CONTINGENCY ANALYSES

Contingency analysis for the pipeline case has shown **that a single outage of any branch or transformer will lead to voltage violations and overloading of corresponding elements**. **Table A-12** below represents the worst loading violations (loading above 90%) for the pipeline case (off peak regime).

Table A-8- Contingency analysis-worst loading violations for the pipeline case in off peak regime

Element contingence	Loaded element	Loading Base Case [%]	Loading after contingency [%]
Mbongozi RoR	Kapichira GT1	64.2	175.5
T/Hill L1	Chintheche IBT1	108.3	109.8
Mlambe T2	Mlambe T1	51.7	105.1
Mlambe T1	Mlambe T2	51.7	105.1

Worst voltage violations in case of branch outage are presented in

Table A-13 and **Table A-10.**

Table A-9- Contingency analysis-worst voltage violations (voltages below 0.9 p.u.) for the pipeline case in off peak regime (branch outage, bus violations)

Element of contingence	Bus name	Voltage Base [p.u.]	Voltage Min [p.u.]
BT West-Chigumula	Fundis Cross_66kV Main	0.92	0.79
BT West-Chigumula	Fundis Cross_66kV Res	0.92	0.79
BT West-Chigumula	Terminal(3)	0.93	0.79
BT West-Chigumula	Terminal(2)	0.93	0.79
BT West-Chigumula	Chigumula_33kV	1.00	0.85
BT West-Chigumula	Chigumula_33kV	1.01	0.87
BT West-Chigumula	Chichiri_66kV/4	0.99	0.87
BT West-Chigumula	Changalume_66kV	0.99	0.87
BT West-Chigumula	Chichiri_33kV/4	1.00	0.87
BT West-Chigumula	Chigumula_66kV	1.02	0.87
BT West-Chigumula	BESS _Chichiri_66kV/4 LV	1.00	0.87
Phombeya-Nkhoma 400 kV	Lilongwe OT_11kV/2	0.98	0.88
Phombeya-Nkhoma 400 kV	Barracks_33kV	0.97	0.88
BT West-Chigumula	Mapanga_66kV/2	1.00	0.88
BT West-Chigumula	Mapanga_66kV/1	1.00	0.88
Phombeya-Nkhoma 400 kV	Lilongwe OT_66kV/2	0.98	0.88
BT West-Chigumula	FundisX_33kV	1.04	0.89
BT West-Chigumula	Ndiza 0.4kV	1.05	0.89
BT West-Chigumula	Ndiza	1.05	0.89
BT West-Chigumula	Ndiza_33kV	1.05	0.89
BT West-Chigumula	Changalume_33kV	1.01	0.89
Phombeya-Nkhoma 400 kV	Lilongwe OT_33kV	0.99	0.89
Phombeya-Nkhoma 400 kV	Nkhoma 400kV A	1.02	0.89
Phombeya-Nkhoma 400 kV	Nkhoma 400kV B	1.02	0.89
Phombeya-Nkhoma 400 kV	Tsabango_11kV	0.99	0.89
BT West-Chigumula	Agrekko_Chichiri_DG_0.4kV	1.02	0.89
Phombeya-Nkhoma 400kV	Kangoma_11kV	0.99	0.89
BT West-Chigumula	Mapanga_33kV	1.02	0.89
BT West-Chigumula	Mapanga_33kV	1.02	0.89
Phombeya-Nkhoma 400kV	Kangoma_66kV	0.99	0.89
Phombeya-Nkhoma 400kV	Tsabango_66kV	0.99	0.89
BT West-Chigumula	Fundis Cross_33kV	1.05	0.90
Phombeya-Nkhoma 400kV	Barracks_11kV	0.99	0.90
Phombeya-Nkhoma 400kV	Lilongwe OT_11kV/1	0.99	0.90
Chintheche-T/Hill	T/Hill_66kV	0.99	0.90

Table A-10 - Contingency Analysis-Worst voltage violations (voltages above 1.1 p.u.) for the pipeline case in off peak regime (branch outage, bus violations)

Element of contingence	Bus name	Voltage Base [p.u.]	Voltage Max [p.u.]
Mapanga L1	Mapanga_DG_0.4kV	1.13	1.16
Fundis Cross L1	Ndiza 0.4kV	1.05	1.14
Fundis Cross L1	Ndiza	1.05	1.14
Fundis Cross L1	Ndiza_33kV	1.05	1.14
Fundis Cross L1	FundisX_33kV	1.04	1.14
Chikangawa L2	Chikangawa_11kV	1.11	1.14
Chikangawa L1	Chikangawa_33kV	1.11	1.14
Shunt/Filter (1)	Nkula GT2t	1.07	1.14
Shunt/Filter (1)	Nkula GT3t	1.07	1.14
Shunt/Filter (1)	Nkula_GT1t	1.07	1.14
Fundis Cross L1	Fundis Cross_33kV	1.05	1.13
Dedza L1	Dedza_33kV	1.08	1.13
Dedza L1	Dedza_T1t	1.09	1.13
Chinyama L1	Chinyama_33kv	0.99	1.11
Phombeya-Nkhoma 400 kV	Terminal	1.10	1.11
BT West-Chigumula	IBT2t	1.08	1.11
BT West-Chigumula	Terminal	1.08	1.11
Karonga L2	Karonga_33kV	1.02	1.10

SHORT CIRCUIT ANALYSIS FOR PIPELINE CASE 2-BESS NKHOMA 60 MW (SOLAR PEAK)

Table A-11 - Short circuit results within South region (Trans south)

Maximum short-circuit currents- Ik”							
BUSBAR NAME	KV	THREE-PHASE FAULT [KA]			SINGLE PHASE FAULT [KA]		
		BASE CASE	PIPELINE2	Δ	BASE CASE	PIPELINE 2	Δ
Kapichira	132	5,112	4,587	-0,52	3,623	2,168	-1,45
Mlambe	132	2,109	2,198	0,08	2,124	1,198	-0,926
BT West	132	4,757	4,359	-0,39	3,486	2,139	-1,347
Nkula B	132	6,395	3,894	-2,5	4,638	1,987	-2,65
Tedzani	132	5,991	3,789	-2,2	4,426	1,948	-2,47

Mlambe	66	15,695	16,559	0,86	12,834	11,437	-1,39
BT West	66	6,763	7,250	0,487	6,016	4,106	-1,91
Changalume	66	1,341	1,600	0,259	0,839	0.974	0,135
Mapanga	66	4,017	5,264	1,24	4,178	3,537	-0,641
Chingeni	66	0,963	2,481	1,518	0,789	2,188	1,399
Tedzani	66	9,593	6,508	-3,08	7,323	3,639	-3,684
BESS Chingeni	33	/	4,516	/	/	0	/
BESS Chichiri	11	/	14,090	/	/	0	/
Muloza RoR	0,4	/	111,510	/	/	101,832	/
PV Changalume	11	/	7,099	/	/	5,039	/
PV Monkey Bay	11	/	3,850	/	/	0	/
PV Chingeni	33	/	4,035	/	/	0	/

Table A-12 - Short circuit results within Centre region (Trans centre)

Maximum short-circuit currents- Ik"							
BUSBAR NAME	KV	THREE-PHASE FAULT [KA]			SINGLE PHASE FAULT [KA]		
		BASE CASE	PIPELINE2	Δ	BASE CASE	PIPELINE 2	Δ
Phombeya	400	1,125	0,991	-0,13	0,944	0,609	-0,335
Nkhoma	400	1,014	0,951	-0,06	0,858	0,635	-0,223
Phombeya	132	4,815	3,604	-1,21	3,489	1,976	-1,5
Nkula B	132	6,395	3,894	-2,5	4,638	1,987	-2,6
Nkhoma	132	2,972	3,005	0,03	2,565	1,987	-0,57
Golomoti	132	3,076	3,039	-0,03	2,512	1,957	-0,55

Nanjoka	132	1,885	2,676	0,79	1,708	1,932	0,22
Kanengo	132	2,596	2,595	-0,001	2,597	1,856	-0,74
Tsabango	132	1,946	2,031	0,08	1,490	1,312	-0,17
Nkhotakota	132	0,905	2,641	1,736	1,047	1,931	0,88
Dwangwa	132	0,727	1,719	0,992	0,784	1,190	0,4
Chinteche	132	0,551	1,178	0,627	0,722	1,128	0,4
Golomoti	66	1,435	1,537	0,1	2,512	1,585	-0,92
Kanengo	66	3,948	4,288	0,34	4,209	1,856	-2,53
Kauma	66	2,993	3,268	0,27	2,684	2,405	-0,27
Barracks	66	2,642	2,891	0,24	2,246	2,079	-0,16
Nkhotakota	66	1,096	1,886	0,79	1,357	1,930	0,57
Dedza	66	0,442	0,653	0,21	0,435	0,578	0,143
Area 48	66	3,032	3,309	0,27	2,738	2,447	-0,29
Lilongwe	66	2,111	2,318	0,2	1,660	1,611	-0,04
BESS Nkhoma	11	/	22,537	/	/	0	/
Mbongozi RoR	11	/	31,574	/	/	20,204	/
BESS Nanjoka	11	/	14,329	/	/	0	/
BESS Golomoti	11	/	15,578	/	/	0	/
PV Golomoti	11	/	14,593	/	/	0	/
PV Nanjoka	11	/	14,548	/	/	0	/
PV Nkhotakota	11	/	7,810	/	/	0	/
PV Nkhoma	11	/	24,134	/	/	0	/

Table A-13 - Short circuit results within Trans north region

Maximum short-circuit currents- Ik"							
BUSBAR NAME	KV	THREE-PHASE FAULT [KA]			SINGLE PHASE FAULT [KA]		
		BASE CASE	PIPELINE2	Δ	BASE CASE	PIPELINE 2	Δ
Chinteche	132	0,551	1,178	0,62	0,722	1,128	0,4
Luwinga	132	0,480	0,850	0,37	0,624	0,789	0,16
New Bwengu	132	0,438	0,724	0,28	0,519	0,773	0,254
Chinteche	66	0,965	1,820	0,86	1,279	1,850	0,571
Chikangawa	66	0,422	0,604	0,18	0,371	0,457	0,08
New Bwengu	66	0,696	1,168	0,47	0,850	1,365	0,515
Bwengu	66	0,691	1,152	0,46	0,839	1,378	0,539
Livingstonia	66	0,520	0,728	0,2	0,583	0,738	0,155
T/Hill	66	0,593	0,894	0,3	0,589	0,737	0,148
BESS Chinteche	11	/	12,670		/	0	/
PV Bwengu	11	/	6,067	/	/	0	/

Table A-14 - Short circuit results within Generation region (Generation)

Maximum short-circuit currents- Ik"							
BUSBAR NAME	KV	THREE-PHASE FAULT [KA]			SINGLE PHASE FAULT [KA]		
		BASE CASE	PIPELINE 2	Δ	BASE CASE	PIPELINE 2	Δ
Kapichira	132	5,11	4,587	-0,52	3,62	2,168	-1,45
Kapichira G1	11	27,045	28,978	1,93	11,88	10,794	-1,08

Tedzani IV	66	8,737	6,087	-2,65	6,85	3,408	-3,44
Nkula G1	11	10,988	11,289	0,3	8,56	8,220	-0,34
Wovwe	66	0,474	0,629	0,15	2,75	0,758	-1,99

CASE 2-BESS NKHOMA 60 MW (PIPELINE 2) (PEAK)

Table A-15 - Short circuit results within South region (Trans south)

Maximum short-circuit currents- Ik”							
BUSBAR NAME	KV	THREE-PHASE FAULT [KA]			SINGLE PHASE FAULT [KA]		
		BASE CASE	PIPELINE 2	Δ	BASE CASE	PIPELINE 2	Δ
Kapichira	132	5,112	5,745	0,63	3,623	3,550	-0,07
Mlambe	132	2,109	2,418	0,3	2,124	1,529	-0,59
BT West	132	4,757	5,554	0,79	3,486	3,494	0,008
Nkula B	132	6,395	6,617	0,22	4,638	4,157	-0,48
Tedzani	132	5,991	5,798	-0,19	4,426	3,860	-0,56
Mlambe	66	15,695	17,601	1,9	12,834	13,804	0,97
BT West	66	6,763	8,780	2,01	6,016	6,423	0,4
Changalume	66	1,341	1,673	0,33	0,839	0.959	0,12
Mapanga	66	4,017	6,160	2,14	4,178	5,098	0,92
Chingeni	66	0,963	2,764	1,8	0,789	2,758	1,96
Tedzani	66	9,593	9,390	-0,2	7,323	6,658	-0,66
BESS Chingeni	33	/	4,883	/	/	0	/
BESS Chichiri	11	/	14,745	/	/	0	/

Muloza RoR	**0,4**	**/**	**112,307**	**/**	**/**	**103,922**	**/**

Table A-16 - Short circuit results within Centre region (Trans centre)

Maximum short-circuit currents- Ik"							
BUSBAR NAME	KV	THREE-PHASE FAULT [KA]			SINGLE PHASE FAULT [KA]		
		BASE CASE	PIPELINE 2	Δ	BASE CASE	PIPELINE 2	Δ
Phombeya	400	1,125	1,308	0,18	0,944	0,972	0,02
Nkhoma	400	1,014	1,208	0,19	0,858	0,970	0,11
Phombeya	132	4,815	5,396	0,58	3,489	3,458	-0,03
Nkula B	132	6,395	6,617	0,22	4,638	4,157	-0,48
Nkhoma	132	2,972	3,718	0,74	2,565	2,993	0,42
Golomoti	132	3,076	3,858	0,78	2,512	2,926	0,41
Nanjoka	132	1,885	2,989	1,1	1,708	2,452	0,74
Kanengo	132	2,596	3,056	0,46	2,597	2,690	0,09
Tsabango	132	1,946	2,334	0,38	1,490	1,689	0,19
Nkhotakota	132	0,905	2,738	1,83	1,047	2,352	1,3
Dwangwa	132	0,727	1,712	0,98	0,784	1,297	0,51
Chinteche	132	0,551	1,119	0,56	0,722	1,135	0,41
Golomoti	66	1,435	1,624	0,18	2,512	1,812	-0,7
Kanengo	66	3,948	4,898	0,95	4,209	4,670	0,46
Kauma	66	2,993	3,611	0,61	2,684	2,984	0,3
Barracks	66	2,642	3,156	0,51	2,246	2,500	0,25

Nkhotakota	66	1,096	1,911	0,81	1,357	2,118	0,76
Dedza	66	0,442	0,670	0,22	0,435	0,614	0,17
Area 48	66	3,032	3,662	0,63	2,738	3,050	0,31
Lilongwe	66	2,111	2,485	0,37	1,660	1,853	0,19
BESS Nkhoma	11	/	24,483	/	/	0	/
Mbongozi RoR	11	/	32,356	/	/	23,456	/
BESS Nanjoka	11	/	14,998	/	/	0	/
BESS Golomoti	11	/	16,973	/	/	0	/

Table A-17 - Short circuit results within North region (Trans north)

Maximum short-circuit currents- Ik"							
BUSBAR NAME	KV	THREE-PHASE FAULT [KA]			SINGLE PHASE FAULT [KA]		
		BASE CASE	PIPELINE1	Δ	BASE CASE	PIPELINE 1	Δ
Chinteche	132	0,551	1,119	0,56	0,722	1,135	0,41
Luwinga	132	0,480	0,783	0,3	0,624	0,810	0,186
New Bwengu	132	0,438	0,653	0,21	0,519	0,637	0,11
Chinteche	66	0,965	1,747	0,782	1,279	1,865	0,586
Chikangawa	66	0,422	0,595	0,17	0,371	0,458	0,087
New Bwengu	66	0,696	1,015	0,32	0,850	1,066	0,21
Bwengu	66	0,691	0,998	0,3	0,839	1,045	0,2

Livingstonia	66	0,520	0,554	0,03	0,583	0,590	0,007
T/Hill	66	0,593	0,868	0,275	0,589	0,745	0,156
BESS Chinteche	11	/	12,193	/	/	0	/

Table A-18 - Short circuit results within Generation region (Generation)

Maximum short-circuit currents- Ik”							
BUSBAR NAME	KV	THREE-PHASE FAULT [KA]			SINGLE PHASE FAULT [KA]		
		BASE CASE	PIPELINE 2	Δ	BASE CASE	PIPELINE 2	Δ
Kapichira	132	5,11	5,712	0,6	3,62	3,550	-0,07
Kapichira G1	11	27,04	29,789	2,749	11,88	12,613	0,733
Tedzani IV	66	8,737	8,670	-0,067	6,85	6,315	-0,535
Nkula G1	11	10,98	12,069	1,089	8,56	9,196	0,636
Wovwe	66	0,474	0,550	0,076	2,75	0,551	-2,19

DYNAMIC ANALYSIS OF BESS 20 MW AT CHICHIRI

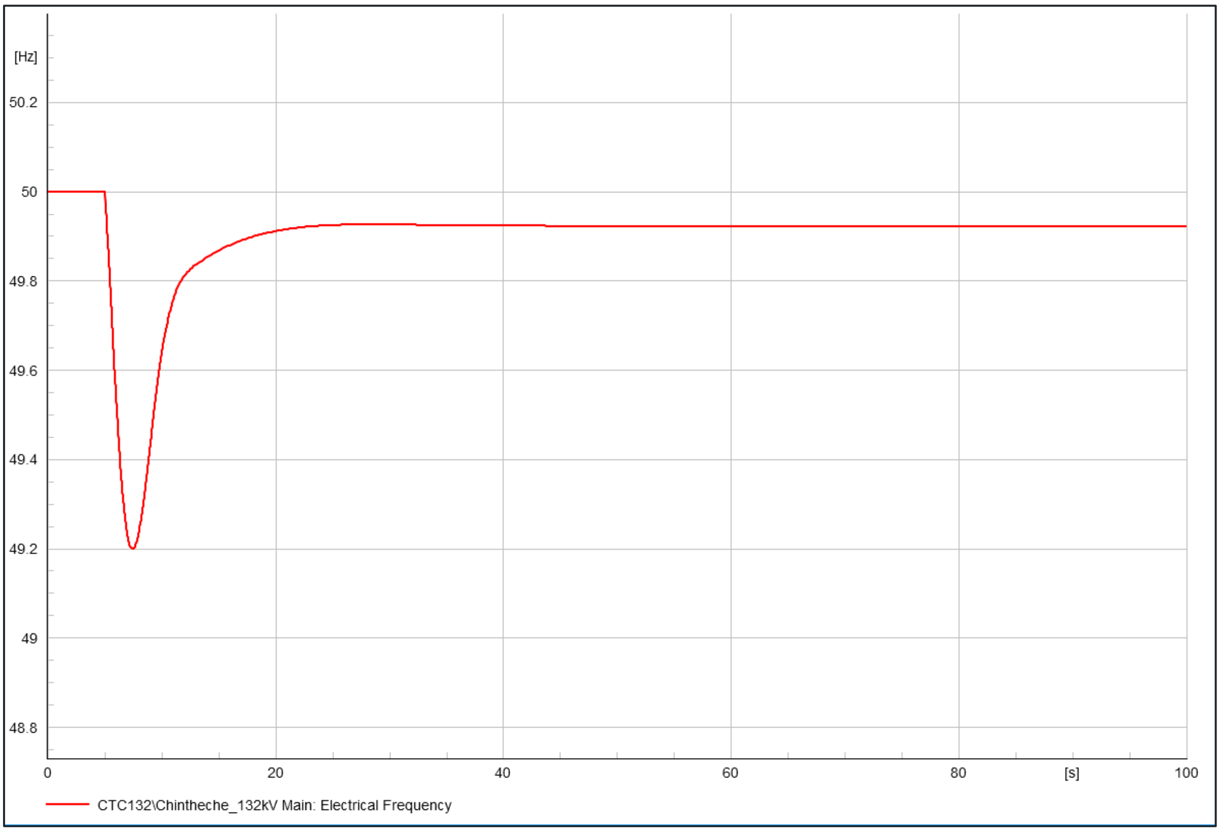


Figure A-1 – System frequency response when PV Nanjoka 50 MW is switched off and size of BESS in Chichiri is 20 MW

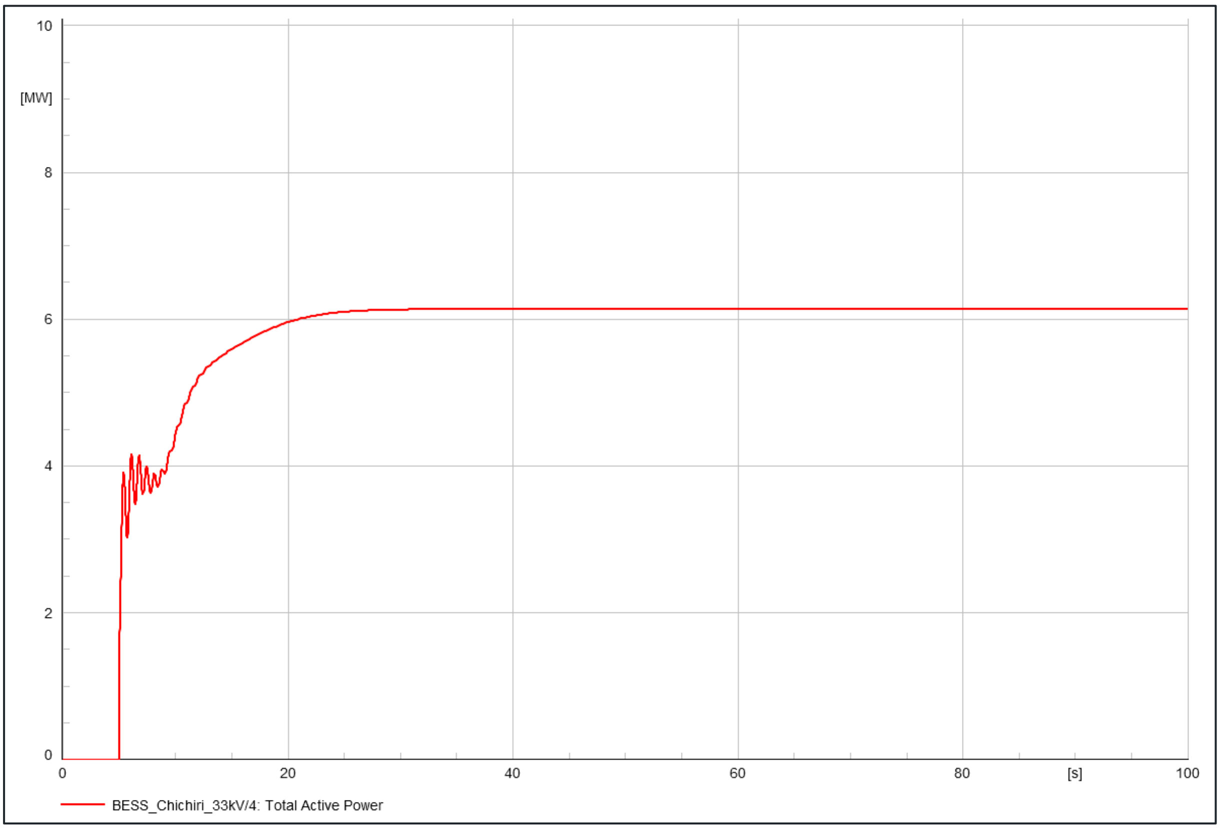


Figure A-2 - BESS Chichiri response with active power for outage of PV Nanjoka 50 MW

8 First Street
Manchester
M15 4RP

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