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Research Article

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System Studies to Assess Preparedness of the Zambian Electrical Grid for the Energy Transition Through Integration of Large-Scale Variable Renewable Energy Sources

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Abstract

Zambia still faces significant challenges in her quest to become a middle-income nation by 2030. Some of these issues include low access to clean energy technologies, low electrification rates and limited infrastructure to transport electricity. Moreover, for a country that is predominantly hydropower dependent with an 85% share, climate change induced droughts contributed to approximately a 30% power deficit in 2020 owing to reduction in the hydropower generation capacity. Two years down the line the situation has not changed much with load management anticipated to commence in the fourth quarter of 2022 with an average outage duration of 6 hours a day countrywide. However, with approximately 3000 sunshine hours per annum and an average solar insolation of 5.5 kWh/m2/day and great wind resource potential (~6 to 11 m/s) for utility scale wind power in some parts of the country at heights between 80 and 200 m above sea level (A.S.L), Zambia has potential to benefit from its immense renewable resources endowment to accelerate electricity access and decarbonization of the power sector. In 2019, RES4Africa alongside Enel Foundation and with technical expertise from CESI conducted an optimal technical-economic penetration of variable renewable energy sources (VRES) in Zambia. This study had limitations as it did not tackle site-specific geospatial mapping of VRES, nor did it delve into technical system studies to include steady state and dynamic stability analyses for the Zambian power grid owing to the large-scale VRES penetration.

With this motivation in research gap, a systematic methodology was developed by the author for the potential of conducting renewable energy penetration system studies for the Zambian integrated power system for the year 2025 and 2030. Thereafter, the potential sites were mapped using QGIS before applying the formulated modelling methodology on the Zambian grid to conduct steady state and dynamic stability studies for the various scenarios and study cases (i.e., 2025 base, 2025 peak demand with VRES, 2025 peak solar, 2025 peak VRES). The results obtained using Power factory Dig SILENT modelling, and simulation software are presented as system steady state, short circuit, system inertia estimation and dynamic stability analyses.

The results obtained for each scenario were compared to the base case i.e., before connecting the proposed VRES projects. Further, investigation of system adequacy and security were performed through contingency analysis. The 2025 steady state analysis for the peak VRES case revealed that the loading of the transmission lines was below 100%. With the proposed VRES projects contributing to about 68% of the total system generation under this condition, the results showed huge reduction in loadings of the transmission lines from the major power plants i.e., Kariba North and Kafue Gorge Power plants when compared to the base case results. The 2025 system inertia analysis for the peak VRES case showed a reduction in the system inertia by approximately 68.5% compared to the base case. This is because the dispatch to serve the grid load in this scenario prioritized VRES over hydropower. The 2025 short circuit analysis revealed that the largest decrease in the fault level was Kariba North Bank and Kafue gorge power stations under peak VRES condition with a reduction of 6kA owing to all the machines being switched off at Kariba North from the initial 6 while Kafue Gorge upper had 2 running machines from the initial 6 in the base case. On the other hand, an overall increase in short circuit levels was experienced across the network for the Peak demand case with VRES. In the dynamic stability analysis, fault ride through (FRT) studies were conducted to ensure that VRES plants stay connected when the AC grid voltage is temporarily reduced or increased due to a fault or large load change in the grid. Moreover, the study demonstrated that for all 2025 study cases, a general increase in rate of change of frequency (RoCoF) values was observed with increased VRES integration. However, all RoCoF values obtained were well below the 1Hz/s threshold as stipulated in the Zambian transmission grid code with both frequency nadir and zenith values being well within the 50±2.5% limits.

Seeing that a large share of grid demand will be met by VRES in 2025, 2030 and beyond, detailed future research must go towards utilization of machine learning and artificial intelligence in nowcasting and day ahead short-term forecasts. This has the potential to optimize both system operations during dispatch and energy market trading both local and regional.

Keywords: Variable Renewable Energy Source, System Studies, Hydropower, Onshore Wind, Solar Photovoltaics, Steady State, Dynamic Stability, System Inertia, Short Circuit, Peak Demand, Climate Change, Machine Learning, Fault Ride Through, Rate of Frequency Change

1. Introduction

1.1. Background

Zambia is endowed with outstanding and diversified renewable energy sources, namely hydro, wind and solar. However, for many decades, the development of the electricity sector was based on the exploitation of hydro resources that made the electric power system dependent on water and particularly exposed to the climate change. Therefore, an adoption of a diversification strategy of the energy mix to include low water consumption technologies such as floating photovoltaics (FPV), ground based photovoltaics (PV) and onshore wind would improve the resilience of the Zambian hydro-dependent power system, thereby, addressing the consequences of climate change and variability. The country had experienced four major droughts in the past fifteen years. This exacerbated the load management strategies in the recent past (2019 through to 2020). A recent study by hybridized the hydropower with a mix of FPV and onshore wind in the Zambian context. Scholarly analyses revealed the potential of PV and concentrated solar power in serving mining demand in Zimbabwe [3].

According to the 2019 study done by RES4Africa Foundation which focused on integration of variable renewable energy sources (VRES) in the Zambian grid, the operational flexibility ensured by the hydroelectric power plants allows 27% VRES penetration both in the 2025 and 2030 scenarios under consideration, even without power trading on the competitive market. The study revealed that an installed capacity up to 1,176 MW from PV and 1,200 MW from wind could be integrated by 2025; these capacities can be increased up to 1,376 MW from PV and 1,400 MW from wind by 2030 (excluding the regional export potential). These optimal VRES capacities, in addition to the existing and committed programmable generation fleet (2,413 MW hydro and 370 MW fossil fuels power), are not enough to ensure the electrical self-sufficiency of Zambia, therefore, additional non-VRES flexible capacity (e.g., hydropower) shall be integrated to achieve this target (about 600 MW with 30% capacity factor by 2030).

The study scope included both technical and economic constraints such as balancing resources, reserve requirements, generation fleet flexibility, and security of supply, grid loadability and economic competitiveness of VRES technologies in the regional power pool. However, the RES4Africa study did not delve into and analyse the static and dynamic behaviour of the electric power system in presence of the proposed VRES power plants. Further, the study did not also factor in the geospatial locational distribution of the VRES plants. Thus, this study advantages on the aspects not covered in the RES4Africa study.

1.2. Objectives, Scope and Research Contributions

The specific aims of this study are: (1) Mapping of VRES plants (2) to carry out Renewable Energy penetration studies for the Zambian integrated power system (IPS) for the year 2025 and 2030; (3) To determine Grid Code requirements for asynchronous generators connecting to the grid; (4) To determine the optimal Variable Renewable Energy Source that can be integrated on each major substation in the Zambian IPS. This will be achieved through:

• Development of a methodology for detailed system studies leveraging on the recommendations made by the RES4Africa study.
• Defining and adopting study assumptions
• Selection and Geospatial mapping of VRES sites.
• Application of the modelling methodology on the Zambian grid to conduct steady state and dynamic stability studies before and after VRES integration.
• Discussion of the findings.
• Study limitations and further research to be done.
• Further, this research will help in the implementation of renewable energy technologies such as floating/land photovoltaics, and onshore wind to help increase electricity generation and supply. The study will contribute to closing the data gaps that have existed in this field of study in Zambia. To put this into perspective, the existing national grid code does not address the technical requirements (i.e. rate of frequency change, low/high voltage fault ride through, extent of reactive power support etc.) of integrating VRES into the network. Therefore, this paper also addresses the nature and depth of technical studies that have to be done to enhance participation from independent power producers. Moreover, the research will help decision makers to make timely and informed decision in this area. This research will also form as a basis for further studies in the academic realm. Additionally, the outcome of this study should provide answers to one or several of the following questions:

1. Is it possible to connect all planned wind/PV plants to the Zambian grid (e.g. transmission grid) without having to reinforce it or with only minor grid reinforcements (e.g. reactive power compensation but no new transmission lines)?
2. What is the impact on system stability?
3. In the absence of applicable grid code requirements for the connection of wind/PV plant: have the performance requirements for wind/PV plant (for later inclusion in a grid code) been defined?
4. What is the impact of planned wind/PV plants on system flexibility requirements/active power balancing? Are the existing conventional power plants able to balance wind/PV variations?
5. What are the limiting factors for wind/PV generation in Zambia?
6. What are the required grid reinforcements/grid expansions for accommodating planned wind/PV plants?
7. What is the optimum generation expansion plan assuming

load growth and the inclusion of potential renewable generation projects?
8. What are the required dynamic performance characteristics of the power plants in the Zambian integrated power system?

Of course, this is not an exhaustive list of questions and for this study, it is very important to clearly define:

- The period of the analysis.
- The precise question(s) that the study shall answer.
- The constraints with regard to study assumptions (which aspects are fixed, and which aspects are variable?).

Against this background, the remainder of the paper is structured as follows: The subsequent section looks at the literature review in section 2, thereafter; section 3 describes the methodology employed in this study. Section 4 defines and adopts the assumptions used in the study and data collection strategy. The developed methodology was then applied to the Zambian case. Furthermore, the write-up is beyond a mere proposal but fully-fledged research with details of actual work packages and deliverables. The results of the detailed system studies and formulated models were examined and discussed in section 5. The conclusion of the research in section 6 was drawn by referencing the research outcomes and key results. Finally, further work to be done is presented in section 7.

2. Literature Review

2.1. Systems Studies & Grid Integration Overview

Grid and system integration studies on integration of renewable generation plants look at the impact of planned and existing generators on power systems. Studies can either analyse the local impact of generation plants on the surrounding network, e.g., the impact of one or several wind farms or PV plants on the surrounding distribution or sub-transmission grid. Those studies are here called "Grid Integration Studies". Alternatively, studies can be carried out at system-wide level including aspects like wide-area power flows, system stability, reserve allocation and frequency control or the impact on generation expansion planning. Studies relating to system-wide aspects are referred to as "System Studies" . A further distinction can be made between studies for longer-term planning aimed at identifying required network reinforcements, and grid expansions, and short-term impact studies mainly used to answer the question "is it possible to connect a wind/PV plant or several wind/PV plants to the existing grid without major grid reinforcements" .

2.2. Frequency Range of Operation Considering VRES

Specifications for frequency range of operation and permitted operating range should be the same for renewable generators and for conventional generators because frequency is a global variable in a synchronised power system. Frequency range requirements should always consider that a renewable power plant could not always deliver its rated power. Hence, each technical requirement, in which "rated power" or "rated capacity" is relevant, must clearly specify whether "rated capacity" is indeed meant or whether "Maximum Available Power" should be used instead. Maximum Available Power refers to the maximum power that a renewable power plant can deliver during a certain moment of time depending on the availability of primary energy (wind, sun) [10]. For variable speed wind turbines, it is significantly less challenging (compared to thermal power plants) to operate under full generation capacity, even over a wider frequency range, because rotational speed of the turbine and grid frequency are entirely decoupled. The technical and cost impact on wind turbines with Fully Rated Converters and for PV inverters is extremely low, because a static converter can basically operate at any frequency. It may be slightly more challenging to operate wind turbines with doubly-fed induction generators (IEC-Type 3) or wind turbines with variable rotor resistance induction generators (IEC-Type 2) at full capacity because these generators require operation over a wider frequency range.

2.3. Voltage and Reactive Power Control Considering VRES

Grid and system technical feasibility impacts and cost impacts on wind and PV plants with a connection point at high voltage (HV) level are quite low if maximum required voltages are in-line with the standardised IEC limits so that standard cables and transformers can be used. Wind/PV plants connected to a HV grid usually have a transformer with an on-load tap changer that maintains the voltage in the wind/PV plant internal MV grid [11]. Hence, the required voltage range of operation at the point of connection (POC) may influence the required range of the transformer tap changer but not any wind/PV plant internal component. However, this is different for smaller wind/PV plants with their POC at MV level because they are directly connected to the surrounding distribution grid without a transformer. In this case, technical implications and cost impact mainly depend on reactive power capability requirements and the highest wind/PV plant internal voltage that must be expected [12]. It is essential for secure system operation that required voltage ranges of operation are defined correctly. Generators must operate reliably without any operational restrictions if voltage remains within the required limits. For robust system operation, it is further advisable to specify additional voltage limits for Abnormal Operating Conditions where operation with only a time constraint is required (as shown in the figure). For short disturbances (time frame of a few seconds), additional voltage vs. time requirements have to be specified which is known as Low Voltage Ride Through (LVRT) or High Voltage Ride Through (HVRT) requirements.

2.4. Role of VRES in Energy Transition

All stakeholders connected to the power system are facing huge challenges. Due to new objectives such as climate change mitigation, security of national energy supply or reduction of energy imports, renewable energy technologies are more and more supported and installed around the world. However, wind power and photovoltaic systems (PV) are fluctuating (i.e., weather-dependent) power systems. Thus, a set of additional measures is required for a smooth technical and operational integration of these power plants into the overall power system. Many power systems around the world have the target to integrate large amounts of variable renewable energy (VRE) power stations into their grid. While the political reasons for such a goal might differ from country to country, the underlying technical issues are the same. The nature of VRE power stations such as wind turbines and photovoltaics (PV) is very different to dispatchable, conventional power stations based on fossil fuels or hydropower.

3. Study Methodology

3.1. VRES Scenario Development for Grid Studies

Renewable energy generation is not only time-dependent but also strongly depends on the location of the generating capacity. For instance, at any moment in time, the wind energy generation from two identical wind turbines will be different in two different locations because the wind patterns differ. Two locations may have different availability patterns and different annual energy yield. However, the annual energy yield might also be identical for two locations, but power generation time series differs in each location. The higher the distance between two locations, the lower is the correlation of the prevailing wind speeds. The scenario development for wind and PV are illustrated in Figure 1 and Figure 2 respectively.

3.2. Onshore Wind Scenario Development

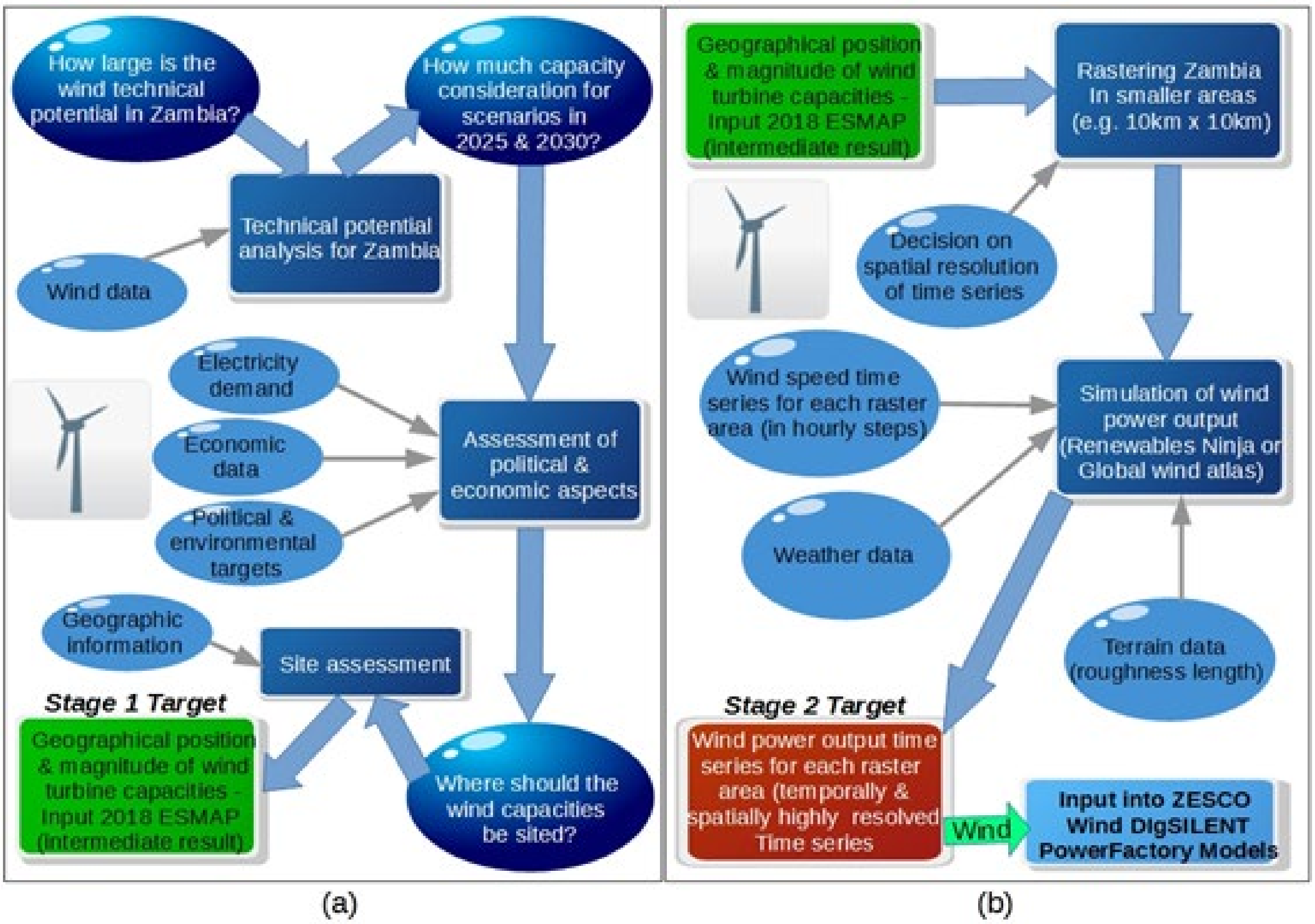


Figure 1: (a) Showing stage 1 wind scenario development for grid studies. (b) Showing stage 2 wind scenario development for grid studies

3.3. Solar PV Scenario Development

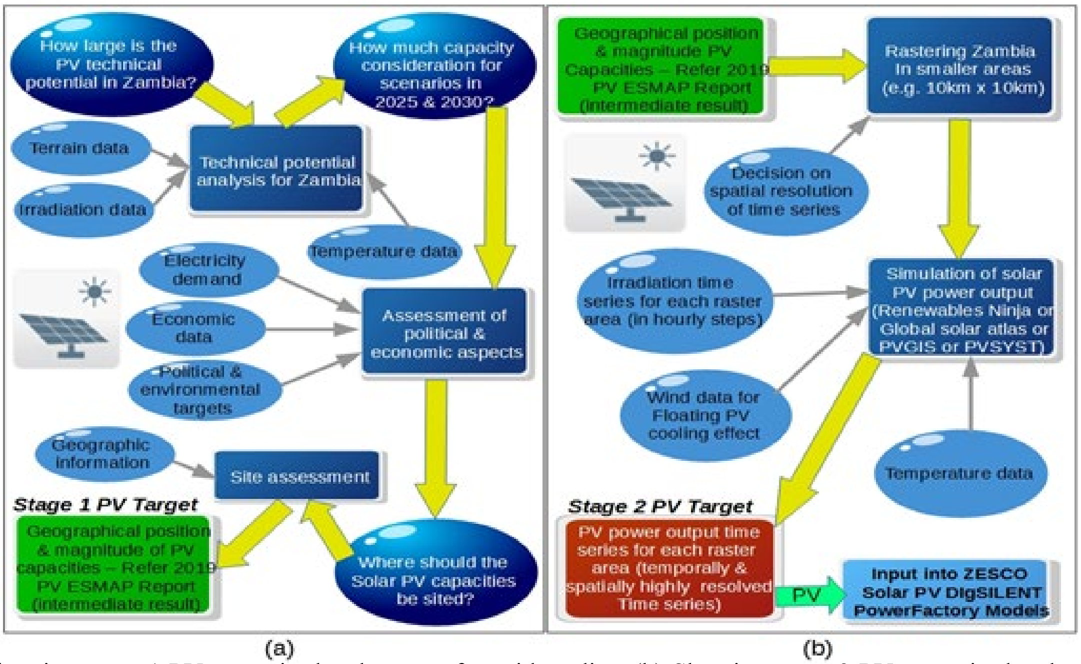


Figure 2: (a) Showing stage 1 PV scenario development for grid studies. (b) Showing stage 2 PV scenario development for grid studies

3.4. System Integration Studies Content Adoption

System Integration Studies look at global system phenomena, which are mainly defined by the interaction between generation and load. In most cases, a clear distinction between grid integration and system integration studies cannot be made and the transition between the two is rather smooth. In this study, the outcome of the system studies will feed into the grid code requirement for integration of VRES in the Zambian electrical grid for 2025 and 2030 scenarios. Figure 3 shows the adopted study methodology.

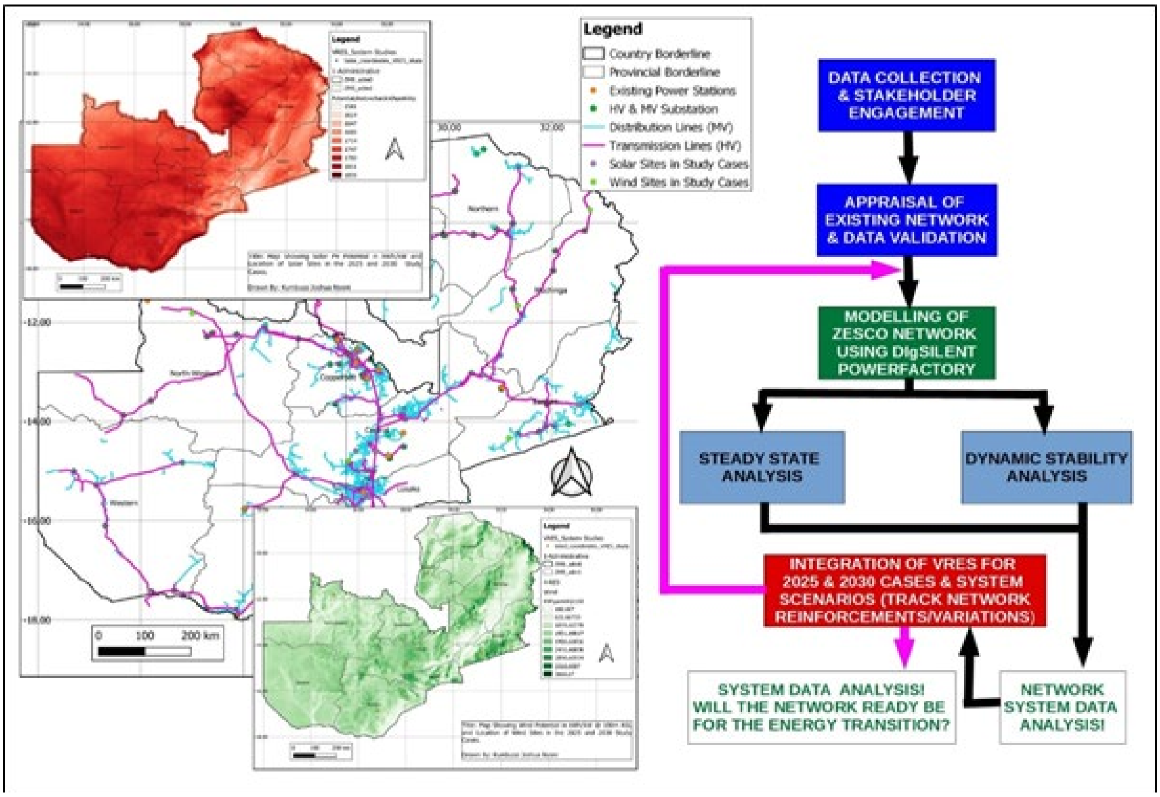


Figure 3: Showing adopted methodology for System Studies on the Zambian Electrical Grid

4. Case Definition & Selection

4.1. Case Definition

Impact studies, which are part of the network planning process, are based on worst-case assumptions: overloads that could endanger the secure operation of the power grid must not occur at any time. Classical network studies usually only look at peak load scenarios because in a classical power system (with generation at the main transmission levels and distribution downstream towards network at lower voltage levels), maximum load represents the worst-case operational situation. However, in the case of networks with generation at sub-transmission or even distribution level, worst case operational situations resulting from high generation can also occur during low load situations. This is because the local load absorbs a part of the generated power and can therefore reduce flows in adjacent lines. Cases with no RE generation represent the existing network situation, without the connection of newly planned RE generation plants. Table 1 shows the case definitions proposed in the study.

	Zambian Load Cases	
VRES Generation Cases	***High Load***	***Low Load***
High VRES generation	High load – high VRES generation	Low load – high VREs generation
No VRES generation	High load – no VRES generation	Low load – no VRES generation

Table 1: Showing Case Definitions Combining VRES Generation and Load Cases

4.2. Case Selection

In any kind of impact study, it is essential to include reference or base cases. For impact studies relating to grid integration of renewable generation, these reference cases are for systems without renewable generation (and without any grid reinforcements that have been introduced because of newly planned renewable generation projects). Otherwise, issues may be reported that are not caused by newly planned generation but that already occur in the existing grid. However, for grid impact studies investigating PV generation, the coincidence of load and PV generation must be taken into account when defining reasonable operational cases: since low load situations typically occur at night in some countries, the simultaneous occurrence of high PV generation and low load is only of theoretical interest. Hence, in studies looking at PV generation, it might be better to consider a "minimum load during daytime" instead (in Zambia peak demand is between 7 to 8pm). Therefore, the study cases looking at high wind and high PV generation in a power grid could be defined as shown in Table 2 "Selection of study cases for Zambia". In studies analysing the impact of RE generation on a transmission grid, different scenarios relating to conventional power plants must also be considered. For example, in countries with high amounts of hydro power and a subtropical climate with a dry and wet season, hydro power plants will mainly operate during the wet season. During the dry season, an increased number of thermal power stations will be in operation instead. Hence, two more operational cases relating to conventional generation must sometimes be defined: wet season and dry season. Table 2 summarizes the selection of study cases proposed in the study.

Study cases looking at high power generation from Wind and PV Systems in the Zambian Power Grid		
Load (Daytime/Night-time)	**PV Generation**	**Wind Generation**
Low at daytime	High	High
Low at night-time	no	High
Low at night-time	no	no
High / Peak	no	no
High / Peak	High	High

Table 2: Showing the Selection of Study Cases for Zambia

5. Study Assumptions & Data Collection

5.1. Study Assumptions

The study assumption considered among other things, the following:

• Undertake studies for the Zambian IPS model for the year 2025 and 2030.

• Adopt the long-term domestic load forecast data from 2019 RES4Africa study report.

• Adopt VRES generation profile from Renewables Ninja or Global Solar & Wind Atlas or PVGIS.

• Model all future transmission projects according to the ZESCO transmission expansion plans for the two years under study (2025 & 2030).

• Consider the following conventional generation projects;

• Kafue Gorge Lower hydropower plant.

• Lusiwasi Upper hydropower plant.

• Extension Chishimba Falls run-of-river hydropower plant.

• Adopt standard dynamic models for proposed future projects.

• In undertaking the studies with the interconnected SAPP network, Table 1 below shall represent the exports (+) and imports (-) to the Zambian IPS.

• In undertaking the studies, VRES projects were selected ensuring that the amount of the VRES projects for each year of study equals the results (VRES limits) obtained in the 2019 RES4Africa Foundation report. Table 3 shows the import and exports via the borders.

Year	NAMPOWER	SNEL	ESCOM	TANESCO	ZESA
2025	+100MW	+290MW	+70MW	0	Interconnection to ZESA to represent a Swing bus
2030	+100MW	+290MW	+70MW	0	

Table 3: Showing the Cross-Border Loads For Imports and Exports

5.2. Data Collection

The following data collection activities were undertaken:

• Data acquisition activity focused on the following critical data of the existing Zambian IPS.

• Parameters of the existing steady state and dynamic models of generators and controllers.

• Parameters of existing VRES plants.

• Geographical locations and size of future renewable energy plants in the country

• Time-series load and renewables data, where available:

• Load profiles

• Wind speed time-series profile for any future wind power plants

• Solar irradiance/solar power time-series profile for both existing and hypothetical future solar power plants.

• Review and update the load/generation with the aim of providing for future changes and projections.

• Review and project the generation profiles for wind and Solar PV using times series data

• Set up and validate a Base case model with the system operator.

5.3. Results and Discussions – on Actual Research Work Packages and Deliverables

Only results for 2025 study cases have been presented here for simplicity and in order to reduce the bulkiness of the capstone project write-up. However, 2030 work packages and deliverables including results and detailed analysis can be shared upon request.

5.4. 2025 Steady State Analysis

Load flow studies were undertaken to assess the steady state performance (voltage conditions and thermal ratings) of the Zambian IPS. These studies were used to compare the equipment operating values against equipment thermal limits, system voltage limits as per grid code and equipment voltage limits (Umax) and further identify stressed system dispatch scenarios associated with higer Renewable Energy penetration levels. Power system analysis was carried out for the year 2025 with the following installed VRES amounts as shown in Table 4.

VRES technology	2025 Base case	2025 case with VRES	RES4Africa amounts
Wind	0MW	1,208MW	1,200MW
Solar	76MW	1,164.5MW	1,176MW
Total	76MW	2,372.5MW	2,376MW

Table 4: Showing installed VRES capacities in the model

It should be noted that Solar and wind time series from Renewables Ninja were used in the models. This meant that the generation from the VRES was dependant on the time of study selected. Therefore, the study established the following scenarios for steady state analysis for the year 2025:

a) Peak demand with VRES condition

b) Peak Solar PV generation condition

c) Peak VRES condition

Steady state analysis was done for each of the above scenarios and the results were compared to the base case scenarios and N-1 contingency outputs. The comparison of the results directly assessed the impact of the proposed VRES. The assessment for each scenario is highlighted in the sections below.

6. Peak Demand with VRES

Peak demand scenario represents the Zambian IPS at peak system load condition, which is around 7:25PM in the model. Analysis was undertaken for normal and N-1 condition to directly assess the impact of VRES on the Zambian IPS for this scenario.

7. Base Case

The base case in this scenario represents the Zambian IPS at peak demand condition without the proposed VRES projects. Total system generation is observed to be 3,143.58MW and the only VRES in this case is the 76MW Solar PV plant. It can be observed that 0MW is reflected as generation contribution from the VRES, this is due to lack of generation from Bangweulu and Ngonye Solar power plants at the study time (7:25PM). At peak for the base case, hydro accounts for 88%, 9% coal, 3% heavy fuel oil (HFO) of the total dispatched power generation of the system.

8. Peak Demand with VRES

Peak demand with VRES case represents the Zambian IPS at peak demand condition with all the proposed Variable Renewable Energy Source projects. Total system generation is observed to be 3,155.73MW with a large contribution from VRES coming from wind power plants. It can be observed that 0MW is reflected as generation contribution from the PV, this is due to lack of generation from Solar PV plants at the study time (7:25PM). The contribution from other sources to serve peak demand includes 54% hydro, 34% wind, 9% coal and 3% heavy fuel oil (HFO).

9. Analysis in N-1 Condition

An investigation of system adequacy and security was performed through contingency analysis on the Peak demand with VRES case. Load flow calculations were performed for single element outages of the highest loaded lines under the condition of study on the Zambian IPS. The following contingencies were applied:

• Contingency No.1: Loss of Kabwe – Kitwe 330kV No.2A line.

• Contingency No.2: Loss of Kabwe – Luano 330kV No.1A line.

10. Summary Results for Peak Demand with VRES

Figure 4 and Figure 5 show the 330kV transmission line loadings and busbar voltages respectively for the Zambian IPS for base case, peak demand with VRES case and N-1 condition. Analysis of the two cases and the N-1 contingency results directly assess the impact of the proposed VRES projects on the Zambian IPS for this scenario. The load flow results in the base case showed that the loading of the transmission lines was below 100%, while voltages on all transmission busbars were within the permissible range according to the planning criteria for normal system conditions. The highest loaded lines in the base case are the three lines connecting Leopards Hill and Kabwe step down substations with each line loaded at 53.8%. The load flow results in the peak demand with VRES case showed that the loading of the transmission lines was below 100%. With the proposed VRES projects contributing to 34% of the total system generation under this condition, the results showed huge reduction in loadings of the transmission lines from the major power plants i.e., Kariba and Kafue Gorge Power plants when compared to the base case results. The reduction in transmission line loadings is due to VRES (wind generation) contribution from the Northern-Eastern circuit of the Zambian Grid in the model. In order to accommodate the VRES, the dispatch from the major hydropower plants is also reduced, this significantly contributes to the reduction of transmission line loadings. Voltages on all transmission busbars were within the permissible range according to the planning criteria for normal system conditions. The results of the single line outages of the Kabwe – Kitwe 330kV No.2A and Kabwe – Luano 330kV No.1A showed that the transmission line loadings were below 100%. The highest loaded line was Kabwe – Kitwe 330kV No.1A at 74.9% with the loss of the second line i.e., loss of Kabwe – Kitwe 330kV No.2A. Low voltages at Luano, Kitwe, Kansanshi and Chambishi East 330kV busbars were observed, which were slightly above 0.90p.u as the consequence of the contingencies. The voltage values are well within the SAPP planning criteria for N-1 contingency before any corrective measures are undertaken on the system.

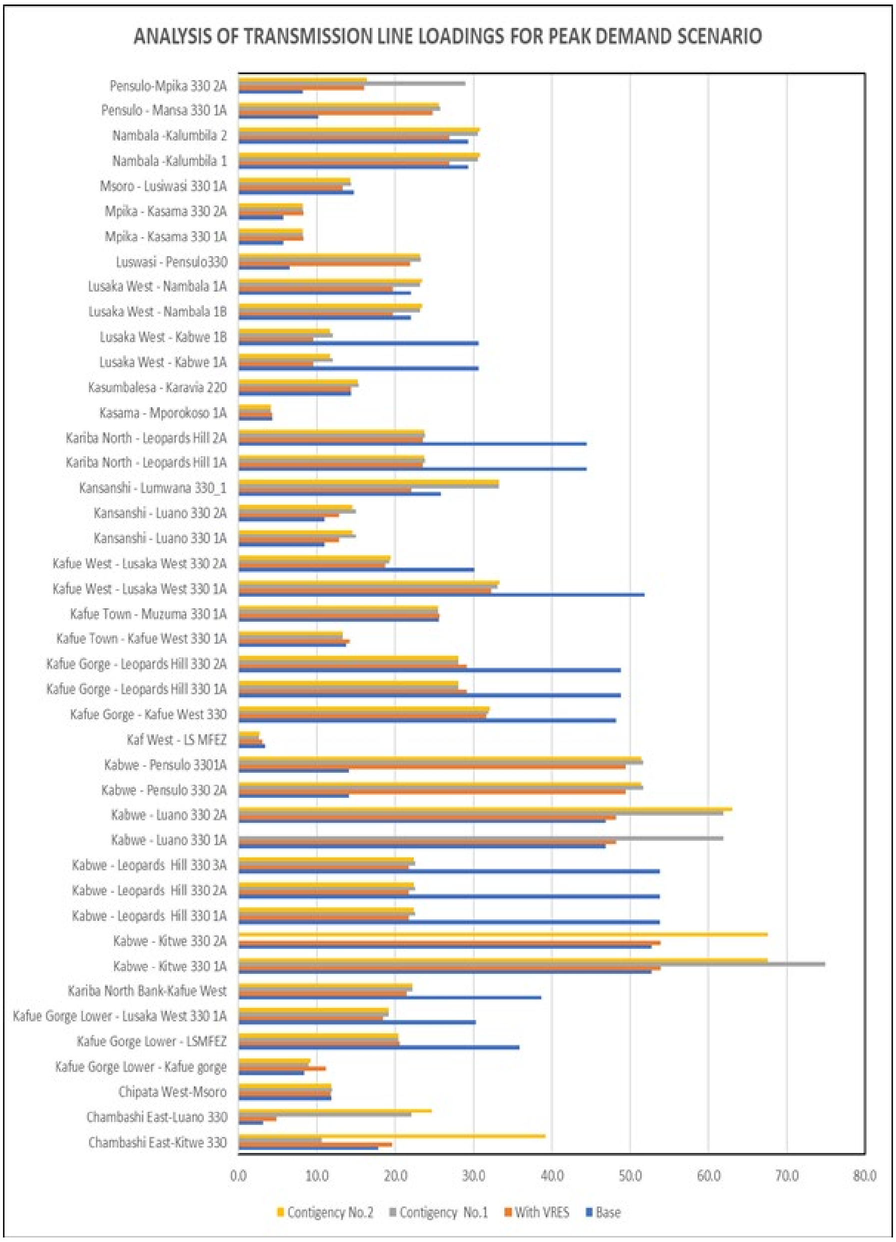


Figure 4: Showing 330kV Transmission Line Loadings for Peak Demand Scenario

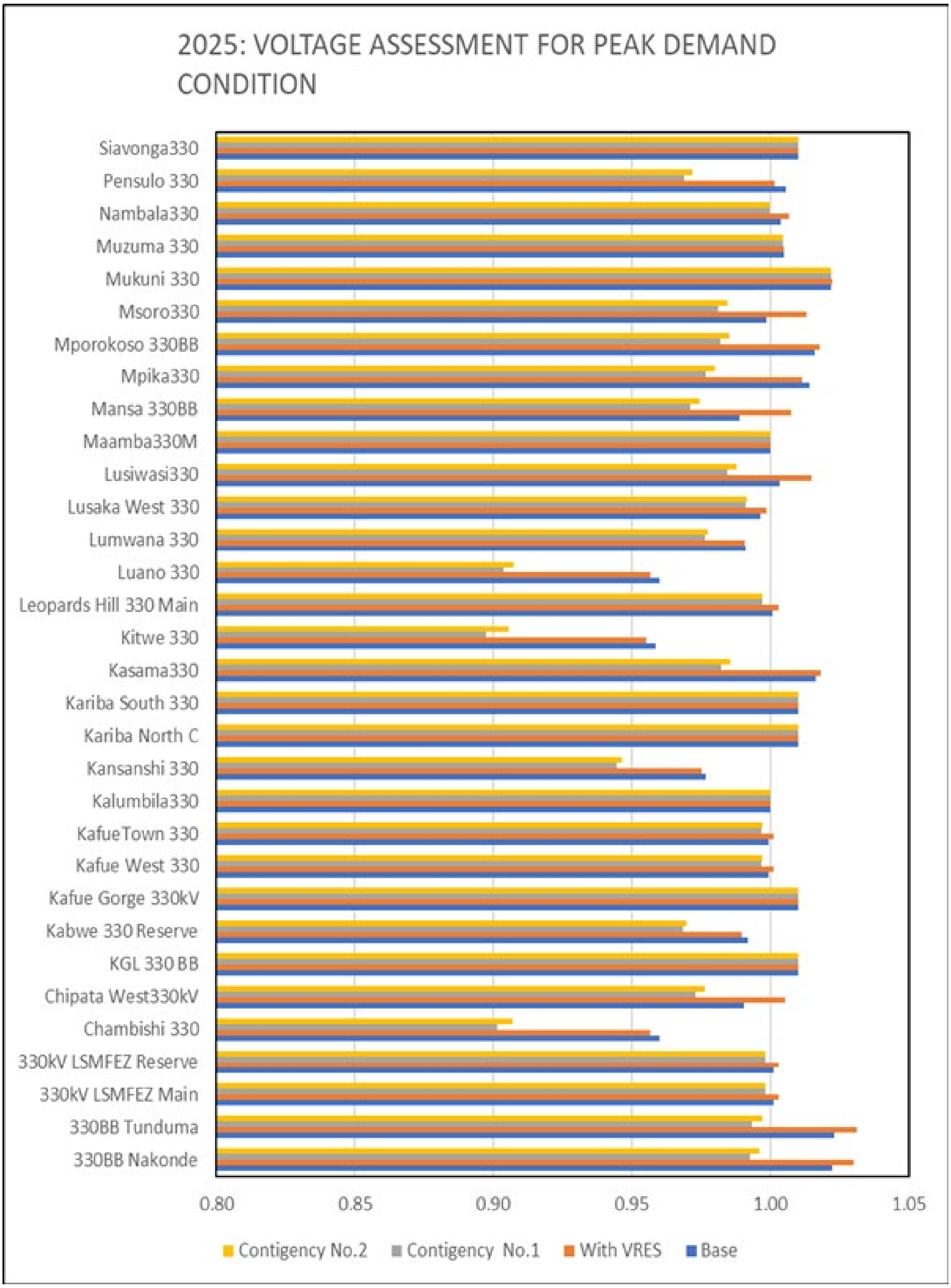


Figure 5: Showing 330kV Transmission Line Loadings for Peak Demand Scenario

11. Peak Solar PV Condition

This is undertaken when the Solar PV generation is expected to be maximum during mid-day at noon.

12. Base Case

The base case in this scenario represents the Zambian IPS at peak Solar PV generation condition without the proposed VRES projects. Total system generation is observed to be 2,883.03MW and the only VRES in this case is the 76MW Solar PV plant. This shows a generation distribution of 85% hydro, 3% solar PV, 3% HFO and 9% coal.

13.Peak Solar PV

Peak Solar PV case represents the Zambian IPS at peak Solar PV generation condition with all the proposed Variable Renewable Energy Source projects. Total system generation is observed to be 2859.61MW with a large contribution from VRES coming from Solar PV power plants. It can be observed that 40% of the total system generation is coming from Solar PV generation and 5% from wind power plants. The remaining generation mix includes 42% hydro, 9% coal and 4% HFO.

14. Analysis with N-1 Condition

An investigation of system adequacy and security has been performed through contingency analysis on the Peak Solar PV case. Load flow calculations are performed for single element outages of the highest loaded lines under the condition of study on the Zambian IPS. The following contingencies were applied:

- Contingency No.1: Loss of Kabwe – Kitwe 330kV No.2A line
- Contingency No.2: Loss of Kabwe – Luano 330kV No.2A line
- Contingency No.3: Loss of Kafue West – Lusaka West 330kV No.1A line

15. Summary for Peak Solar PV Condition

The load flow results in the base case showed that the loading of the transmission lines was below 100%, while voltages on all transmission busbars were within the permissible range according to the planning criteria for normal system conditions. The highest loaded lines in the base case are the three lines connecting Leopards Hill and Kabwe step down substations with each line loaded at 49.5%. The load flow results in the peak Solar PV case showed that the loading of the transmission lines was below 100%. With the proposed VRES projects contributing to about 45% of the total system generation under this condition, the results showed huge reduction in loadings of the transmission lines from the major power plants i.e., Kariba and Kafue Gorge Power plants when compared to the base case results. The reduction in transmission line loadings is due to the 45% contribution from VRES located near the load centres in the model. In order to accommodate the VRES, the dispatch from the major hydropower plants is also reduced; this significantly contributes to the reduction of transmission line loadings. Voltages on all transmission busbars were within the permissible range according to the planning criteria for normal system conditions. The results of the single line outages of the Kabwe – Kitwe 330kV No.2A and Kabwe – Luano 330kV No.2A showed that the transmission line loadings were below 100%. The highest loaded line was Kabwe – Kitwe 330kV No.1A at 57.9% with the loss of the second line i.e., loss of Kabwe – Kitwe 330kV No.2A. The voltages on all busbars are in the range 0.95-1.05p.u., which is well within the permissible range according to the planning criteria under N-1 system conditions. No voltage violations were observed on the Zambian IPS.

16. Peak VRES Condition

Peak VRES scenario represents the Zambian IPS at peak VRES generation condition in the model that the combined output of the VRES plants is at its maximum. Analysis was undertaken for normal, and N-1 condition to directly assess the impact of VRES on the Zambian IPS for this scenario.

17. Base Case

The base case in this scenario represents the Zambian IPS at peak VRES generation condition without the proposed VRES projects. It can be observed that 2% is reflected as generation contribution from the VRES, this is the existing Solar PV generation from Bangweulu and Ngonye Solar PV plants. The other generation mix includes 85% hydro, 9% coal and 4% heavy fuel oil (HFO).

18. Peak VRES Case

Peak Solar PV case represents the Zambian IPS at peak Solar PV generation condition with all the proposed Variable Renewable Energy Source projects. Total system generation is observed to be 3006.17MW with a major contribution from VRES coming from wind power plants. It can be observed that 32% of the total system generation is coming from Solar PV generation and 36% from wind power plants. Other dispatched generation sources include 20% hydro, 9% coal and 3% HFO. It should be noted that in this case, Kariba North Bank power station was shut down in order to accommodate the VRES generation. This scenario depicted a stressed system dispatch on the Zambian power system.

19. Analysis with N-1 Condition

An investigation of system adequacy and security has been performed through contingency analysis on the Peak VRES case. Load flow calculations are performed for single element outages of the highest loaded lines under the condition of study on the Zambian IPS. The following contingencies were applied:

- Contingency No.1: Loss of highly loaded lines
- Contingency No.2: Loss of Chambishi East – Luano 330kV line

20. Summary Results for Peak VRES Condition

The load flow results in the base case showed that the loading of the transmission lines was below 100%, while voltages on all transmission busbars were within the permissible range according to the planning criteria for normal system conditions. The highest loaded lines in the base case are the three lines connecting Leopards Hill and Kabwe step down substations with each line loaded at 49.5%.

The load flow results in the peak VRES case showed that the loading of the transmission lines was below 100%. With the proposed VRES projects contributing to about 68% of the total system generation under this condition, the results showed huge reduction in loadings of the transmission lines from the major power plants i.e., Kariba and Kafue Gorge Power plants when compared to the base case results. The reduction in transmission line loadings is due to the 68% contribution from VRES located near the load centres in the model and in the Northern-Eastern circuit. In order to accommodate the VRES, the dispatch from the major hydropower plants is drastically reduced, with Kariba North Bank power plant shutdown, this significantly contributed to the reduction of transmission line loadings. The results showed that the highest loaded lines in the base case which are the three lines connecting Leopards Hill and Kabwe step down substations loaded at 49.5% in the base case reduced to less than 11% in the peak VRES case. Introduction of all the proposed VRES projects showed that the voltages on all transmission busbars were within the permissible range according to the planning criteria for normal system conditions.

The results of the single line outages of the Chambishi East – Luano 330kV line showed that the transmission line loadings were below 100%. The voltages on all busbars are in the range 0.95-1.05p.u., which is well within the permissible range according to the planning criteria under N-1 system conditions. No voltage violations were observed on the Zambian IPS. Further, N-1 contingency of the highly loaded lines e.g., Kabwe – Pensulo 330kV lines could not converge for single line outages. If one of the highly loaded lines were out of service, all the wind power generations from Chanka, Mansa, Mpika, Mphepo and other Solar PV plants in the Northern-Eastern circuit would be evacuated through a single transmission line causing higher power transfers on a single circuit and consequently high voltage drops for which system conditions cannot be satisfied. With a Static Var Compensator (SVC) of 250Mvar at Pensulo substation for this case, load flow converged, however leading to high transmission loading of 112.9% for the remaining circuit i.e., Kabwe – Pensulo 330kV No.2 line.

21. 2025 Short Circuit Analysis

Short circuit studies for both single-phase to ground and 3-phase faults were done on the 220 and 330kV backbone network for the 2025 study case base on IEC 60909 having a voltage factor (Cmax) of 1.1pu. The 4 study case scenarios namely 2025 base, 2025 peak solar, 2025 peak VRES and 2025 Peak demand with VRES were studied and the impact of large-scale renewable integration is summarized in the Figure below. From the results presented in Figure 6, it was found that the largest decrease in the fault level was Kariba North Bank and Kafue gorge power stations under peak VRES condition with a reduction of 6kA owing to all the machines being switched off at Kariba North from the initial 6 while Kafue Gorge upper had 2 running machines from the initial 6 in the base case. On the other hand, an overall increase in short circuit levels was experienced across the network for the Peak demand case with VRES, 2kA increments were seen at Kabwe Stepdown and Kitwe substations on the 330kV busbars. This was largely due to fewer synchronous machines being off across the network and the contributions from the various WECC type 3 wind farms. In addition to the noted increments and decrease in fault levels at various substation, the recorded fault currents were all below the 40kA breaking capacity rating threshold of 220 and 330kV breakers. Moreover, the maximum feasible breaking capacity as recommended for by IEEE std C37.011 follows a 60% (T60) envelop which guaranties the non-occurrence of transient recovery voltage across the breaker contacts which may lead to reignition of the arc. Therefore, for a T60 TRV envelop the effective breaking capacity of the circuit breakers is 24kA and the maximum recorded fault level for all study cases was 22kA at Kariba north in the base case. It was then concluded that no reinforcements were needed for the 220 and 330kV backbone switchgear, however, a system wide review of protection settings needs to be carried out in order to address the changes brought on by VRES integration and their variable nature over a 24hour hour period.

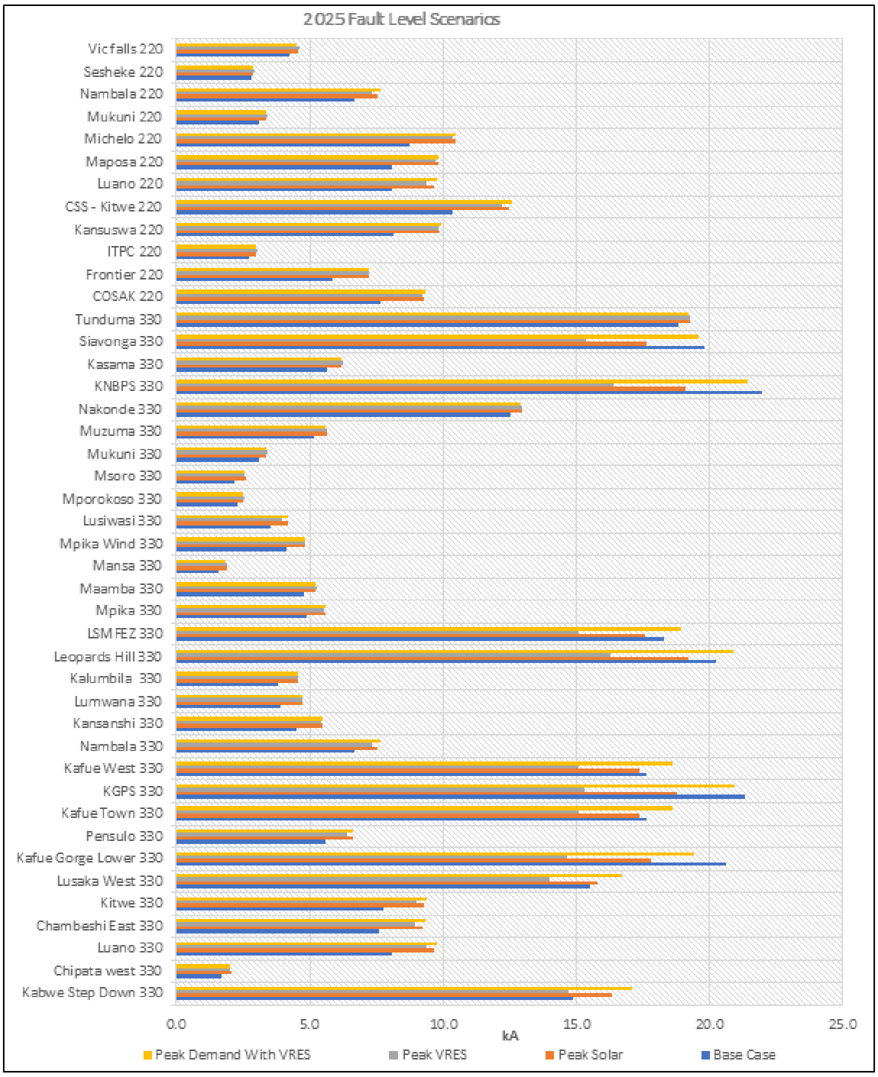


Figure 6: Showing 2025 Short Circuit Results for the Various Study Cases

22. 2025 System Inertia Estimates

System inertia estimations were done for the following study cases: 2025 base; 2025-peak demand with VRES; 2025 peak solar; 2025 peak VRES. Figure 7 summarizes the results and proportion of system inertia for each case. The system apparent power axis in figure 7 is the summation of all the machine ratings on the network. The results show that the base case had the highest system inertia of about 4.09 while the 2025 peak VRES case had reduced the system inertia by approximately 68.5% to 1.29. This is because the dispatch to serve the grid load in this scenario prioritized VRES plants (approximately 1670MW of wind and 1370MW of solar PV) and switched off a good portion of some hydropower plants (i.e., 800MW at Kafue Gorge Lower, 1200MW at Kariba North, 800MW at Kafue Gorge Lower) which offer substantial system inertia.

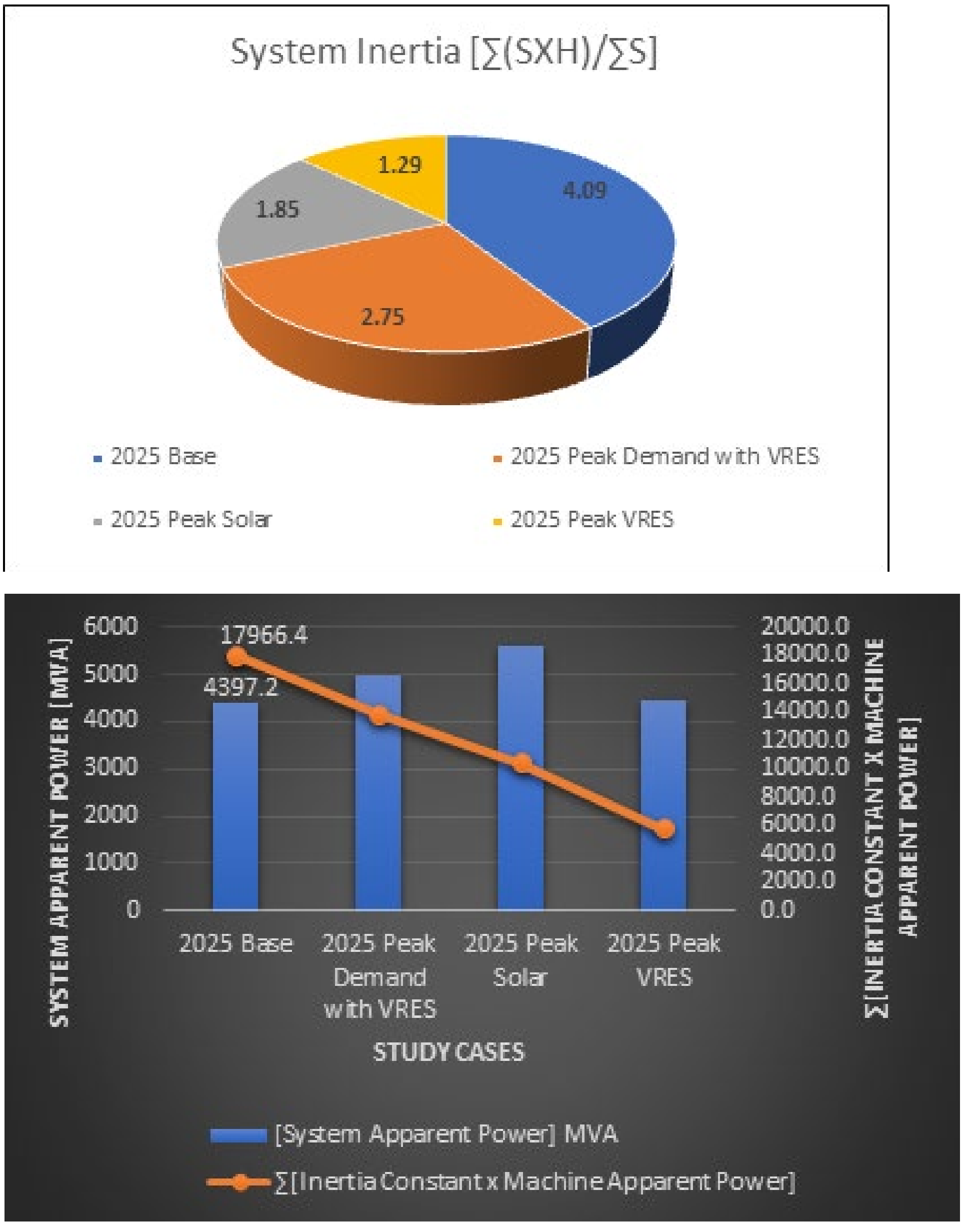


Figure 7: Showing the System Inertia for the Various Study Cases

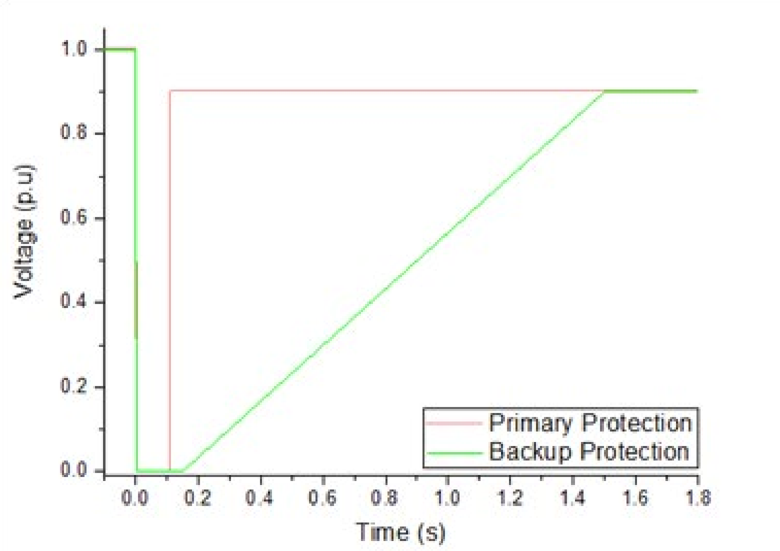
23. 2025 Dynamic Stability Analysis

23.1 Fault Ride through Capability

Fault ride through (FRT) is the ability of the system to stay connected when the AC grid voltage is temporarily reduced or increased due to a fault or large load change in the grid. The change in voltage can either be in one or two phases for asymmetrical faults and in all three phases of the AC grid for symmetrical faults. Low and high voltage ride through (LVRT & HVRT) capability curves are defined in grid codes and by system operators to maintain high availability, stability and to reduce of voltage excursions. This is achieved through synthetic inertia contribution, system short circuit level contribution and reactive power support of renewable energy plants at points of connection. The subsequent sections highlight the results of the studies that were carried out to develop the Low voltage and high voltage ride through curves for both primary and backup protection, the key IEC and IEEE standards used have also been highlighted. Powerfactory simulation software was utilised for both static and RMS transient simulation for a balanced 3-phase system, therefore, system wide capability curves are discussed below.

23.2. Low Voltage Ride through (LVRT)

Low-voltage ride-through (LVRT) capability ensures that VRES plants stay on-grid and supply the expected reactive current to support the utility during grid faults. The study was conducted in order to establish the steady state and dynamic performances of the VRES in three continuous periods after the grid fault occurred i.e., fault transient, fault continuous, and fault recovery periods. The steady state region that was used was based of the Zambian grid code and the SAPP planning criteria voltage limits under n-1 condition i.e., 1.0pu with a -20% margin. Figure 8 shows the first general curve for LVRT.



General Curve 1		
Point	Time	Voltage
	s	p.u
t0	0	1
t1	0.005	0
t2	0.109	0
t3	0.113	0.8
t4	0.113	0.8
t5	0.113	0.9

Figure 8: Showing ZESCO IPS general curve 1 for 132, 220 and 330kV busbar LVRT

24. Critical Clearing Time (CCT)

In order to develop the LVRT general curve 1 above, the system wide critical clearing (t1) was calculated. Critical clearing time is derived from the critical clearing angle under the equal area criterion for the area under the curve for maximum power transfer/generation, it is the maximum time by which a fault can be applied without the system losing its stability. This was done by applying a zero-impedance symmetrical fault at 132, 220 and 330kV buses using the IEC60909 method while simultaneously running a system scan to check for synchronous generators that were out of step. A total of 82 busbars at 132, 220, 330kV were assessed for their critical clearing time, from the results it was observed that a maximum system wide critical clearing time of 109ms was obtained Kabwe Stepdown. This served as a basis for the protection characteristic for the Low Voltage Ride Through, Table 5 shows sampled results for the 330kV buses following transient stability studies.

S/N	Substation Name	Busbar Voltage	CCT (s)
1	Kabwe Stepdown	330	0.109
2	Kafue Gorge	330	0.117
3	Leopards Hill	330	0.117
4	Kafue Gorge Lower	330	0.124
5	Kafue West	330	0.132
6	Kitwe	330	0.139
7	Lusaka West	330	0.139
8	Luano	330	0.146
9	Kariba North	330	0.184
10	Kalumbila	330	0.414

Table 5: Showing the ZESCO Sampled 330kV Substations' Critical Clearing Times for 2025

25. High Voltage Ride through (HVRT)

Just like the LVRT above, grid codes and the system operators define high voltage ride through capabilities for voltage swells in steady state. The capability curve aims to keep connected VRES plants to the grid when voltage swells arise from symmetrical situations such as the removal of large loads, reclosing of transmission line, shunt capacitor energization and so on. In order to determine the high voltage ride through capability curves, various system disturbances were tested and the disturbances with voltage excursion above 1.1pu of nominal system voltage were plotted as shown in Figure 9. It was noted that symmetrical bus faults under LVRT simulations did not result in voltages above 1.05pu in the transient recovery phase, hence, only the loss of load and loss of station bus reactors were assessed for primary protection. The backup protection limit was generated in accordance with IEC 60071-1 (2011) insulation co-ordination.

From IEC 60071-1, the insulation coordination for systems below 245kV maximum system is above 200% of nominal voltage while for 362kV systems, the insulation coordination is 150% of the nominal voltage. Consequently, the insulation coordination was based off IEEE standard C62.11 surge arrester coordination curves with prior duty having a temporary overvoltage limit of 150%, thus for 150% temporary overvoltage (TOV), it is required that surge arrestor operate within 200ms. Globally, a protection margin of 130% for a 10s temporary overvoltage is widely adopted. For the Zambian network it was noticed that the maximum continuous overvoltage was 111% on the loss of the 12Mvar Kabompo reactor, hence a 120% protection margin for a 20s duration was adopted while other protection schemes could be deployed beyond 20 seconds.

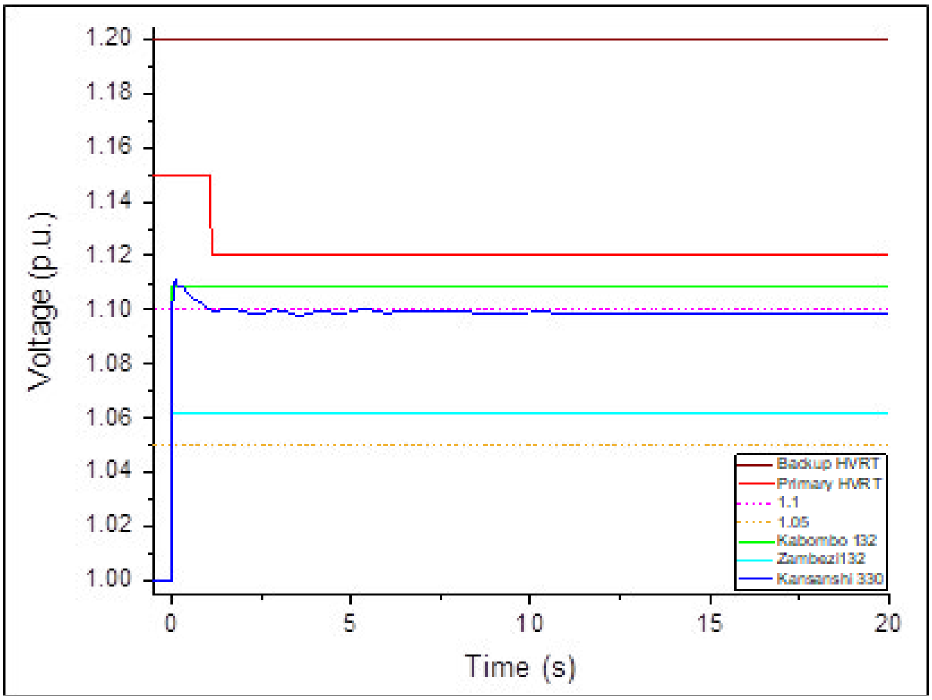


Figure 9: Showing Primary and Backup HVRT with Onerous Overvoltage Disturbances

26. Rate of Change of Frequency (RoCoOF)

The approach to understand the impact of VRES on the RoCoF was as follows, disturbances that resulted in a generation load imbalance were applied to the Peak Solar and Peak VRES case similar disturbance were applied to the Base Case at the same time the Peak Solar and Peak VRES conditions occurred. For the purpose for purpose of our analysis a limiting RoCoF value of 1Hz/s was considered.

27. Under Frequency Event – Peak Demand with VRES

A machine at KGL generating 130MW was tripped as shown in Figure 10. The following parameters were recorded from the simulation of the disturbance: RoCoF = - 0.070Hz/s; Frequency Nadir = 49.899Hz; ZESA – ZESCO Tie line Deviation of = 100MW import.

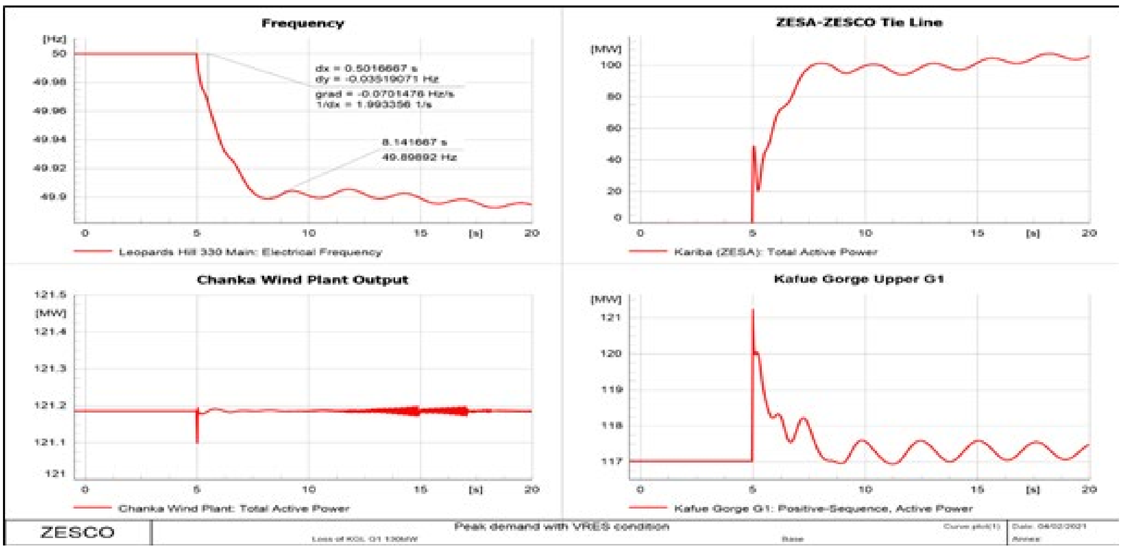


Figure 10: Showing Peak demand with VRES condition Loss of KGL G1 130MW

28. Over Frequency Event – Peak Demand with VRES

Exports of 200MW to SNEL were tripped the result can be observed in Figure 11. The following parameters were recorded from the simulation of the disturbance: RoCoF = 0.0298Hz/s; Frequency Zenith = 50.069Hz; ZESA – ZESCO Tie line Deviation of = 69.09MW Export.

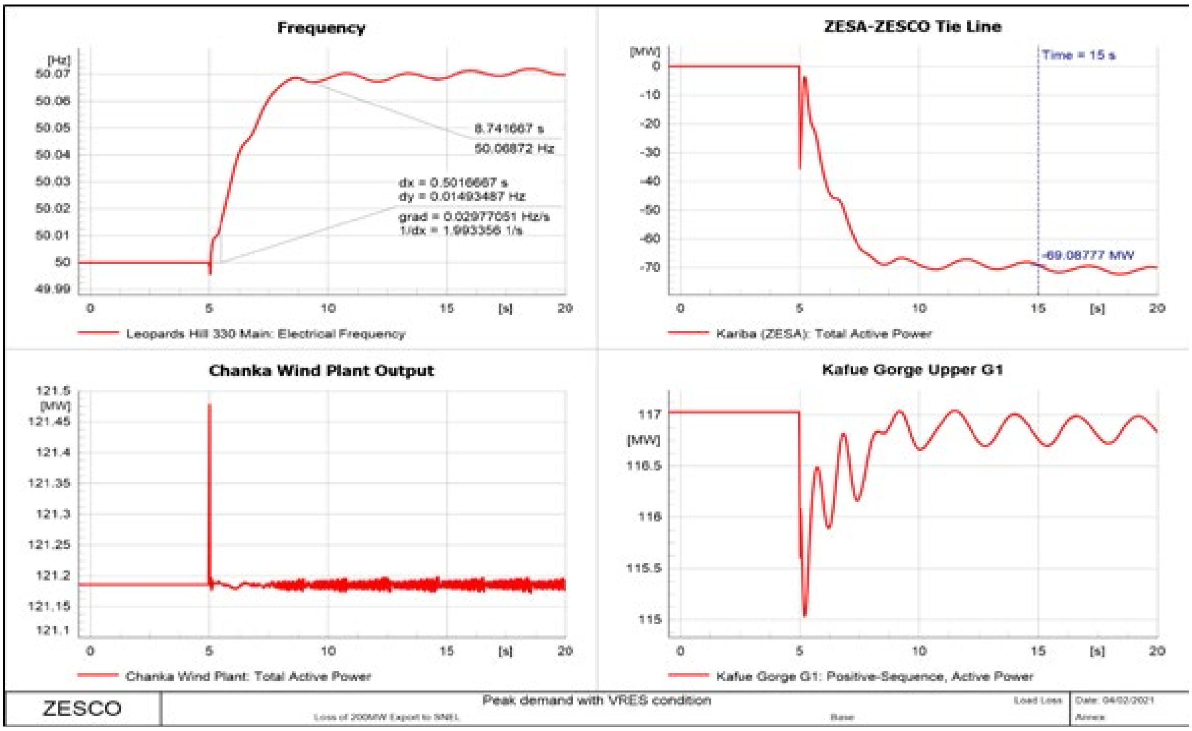


Figure 11: Showing Peak demand with VRES condition Loss of 200MW SNEL Export

29. Rotor Angle Stability

A rotor angle stability study was carried out to assess whether the conventional generating units will remain in synchronism when the ZESCO IPS is subjected to disturbances under increased VRES integration. The system was subjected to disturbance that affect the power balance of the network through variations in electrical or mechanical power and the effective reactance for power flow paths, the list of such disturbance types is given below.

• Loss of generation: For all the study scenarios, a loss of 130MW generation at Kafue gorge lower was assessed.
• Loss of Load: For all the study scenarios, a loss of 200MW export to SNEL was assessed.
• Zero impedance bus bar faults: These were done on the top 10 bus bars with the least critical clearing times following the critical clearing time study.
• Loss of transmission lines at 220kV and 330kV with 50% or more loading (will be highlighted as per study scenario).
• Single line to ground faults were done on the transmission lines listed below for all study scenarios.

- KNB - Kafue West 330kV
- Leopards Hill - Kabwe 330kV line 1
- Kabwe - Pensulo 330kV line 1
- Muzuma - Kafue Town 330kV
- Luano – Kansanshi 330kV line 1
- Nambala – Kalumbila 330 line 1

The study was carried out for various peak demand conditions of VRES integration, this was done to assess the impact of the net change in system inertia on the rotor stability of the generating units at various power stations. The inertia of the system plays a critical role in both acceleration and damping torque of the system post disturbance and thus is responsible for the overall rotor angle stability of the power system. The summary of results that exhibited system instability in the study are presented below.

30. Peak Demand with VRES Condition

For the peak demand scenario with VRES, the study events were as presented above with two (2) additional events on accounts of thermal loading beyond 50%. These two events are the loss of Kabwe-Kitwe 330 line 1 and loss of Kansuswa-Kitwe 220 line. All simulation events were stable except for the fast-single pole auto reclose (SPAR) on Muzuma – Kafue West and Kabwe – Pensulo 330kV transmission lines. The results on the Muzuma – Kafue West 330kV spar are presented in Figure 12.

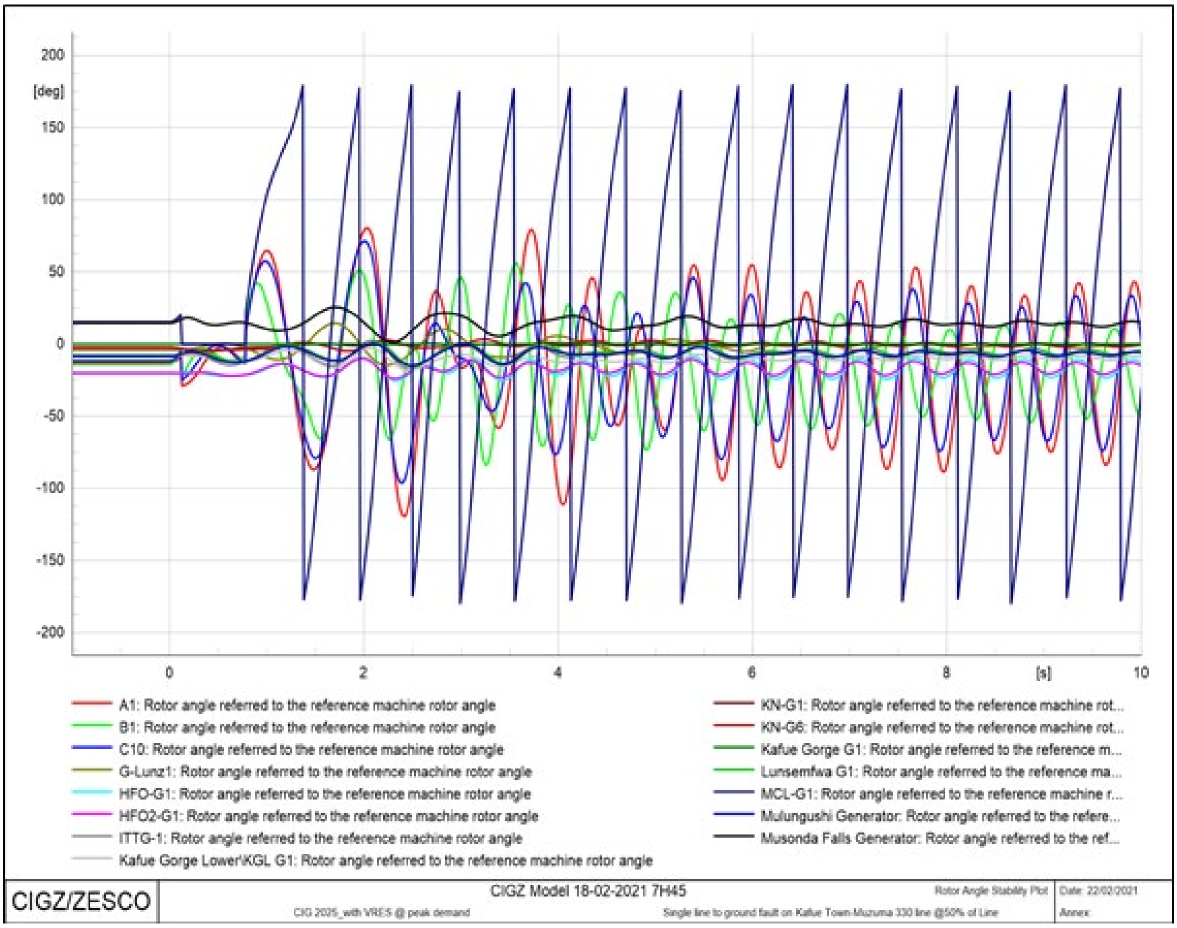


Figure 12: Showing Rotor Angle for SPAR on Muzuma – Kafue West 330kV line

From the figure above, upon clearing of the fault, the Maamba generators fail to maintain synchronism due to a large swing in reactive power causing the machines to pole slip due to a mismatch in accelerating and decelerating torque while the generators at Victoria Falls stations A, B and C exhibit undamped oscillations as they hunt for new reactive power setpoints. Consequently, the network around Victoria Falls, Muzuma and Maamba experience voltage collapse with undamped oscillations of 0.5pu for the entire simulation.

31. Conclusions (on actual research deliverables)

The research study presented a comprehensive assessment of the preparedness of the Zambia electrical grid for the energy transition. The framework of the study was based on the perceived gaps and recommendations made by the 2019 RES4Africa study about the integration of large-scale variable renewable energy sources in the Zambian grid. All the study objectives were successfully met which included mapping of VRES sites, carrying out of renewable energy penetration system studies for the Zambian integrated power system (IPS) for the year 2025 and 2030, determination of grid code requirements for the asynchronous generators connecting to the grid and determination of the optimal VRES that could be integrated on each major substation in the Zambian IPS. A systematic methodology was then developed factoring in the study questions and requirements. Thereafter, the author mapped the selected sites using QGIS before applying the formulated modelling methodology on the Zambian grid to conduct steady state and dynamic stability studies for the various scenarios and study cases. The results obtained using Powerfactory DIgSILENT modelling, and simulation software are presented as system steady state, short circuit, inertia estimation and dynamic stability analyses. However, only results for the 2025 study year have been presented for simplicity and keeping the capstone project paper page count within acceptable limits. The 2030 results can be shared as a separate document upon request.

32. Steady State Analysis

Load flow studies were undertaken to assess the steady state performance (voltage conditions and thermal ratings) of the Zambian IPS before and after connecting 2,372.5MW of VRES plants i.e., 1164.5MW of Solar PV and 1208MW of wind plants. Generation output from the VRES plants in the model are dependent on the time of study, as Solar and wind time series were used from renewables ninja to represent their outputs. The steady state analysis considered the following scenarios: Peak demand with VRES condition; Peak Solar PV generation condition; Peak VRES condition. The results obtained for each scenario were compared to the base case i.e., before connecting the proposed VRES projects. Further, investigation of system adequacy and security were performed through contingency analysis for each scenario highlighted above. Load flow analysis under normal conditions for peak demand with VRES condition showed that the loading of the transmission lines was below 68% and voltage levels were within acceptable limits of 0.95 – 1.05p.u. Thermal loadings of all the lines under N-1 conditions were below 100% and the voltage values were within the SAPP planning criteria i.e., the voltage limits before and after corrective actions are taken on the Zambian IPS. Load flow analysis under normal conditions for peak Solar PV condition showed that the loading of the transmission lines was below 50% and voltage levels were within acceptable limits of 0.95 – 1.05p.u. Thermal loadings of all the lines under N-1 conditions were below 100% and the voltage values were within the SAPP planning criteria i.e., the voltage limits before and after corrective actions are taken on the Zambian IPS.

33. Short Circuit Analysis

Furthermore, the short circuit study that was done for the 220 and 330kV backbone showed that the largest decrease in the fault level was at Kariba North Bank and Kafue Gorge power stations under peak VRES condition with a reduction of 6kA owing to all the machines being switched off at Kariba North from the initial 6 while Kafue Gorge upper had 2 running machines from the initial 6 in the base case. On the other hand, an overall increase in short circuit levels was experienced across the network for the Peak demand case with VRES, 2kA increments were seen at Kabwe Stepdown and Kitwe substations on the 330kV busbars. This was largely due to fewer synchronous machines being off across the network and the contributions from the various WECC type 3 wind farms. Therefore, no reinforcements were needed for the 220 and 330kV backbone switchgear as fault levels across the 220 and 330kV network remained within the 40kA breaking capacity rating of circuit break and below the 24kA 60% (T60) rating for transient recovery voltage as recommended in IEEE std C37.011 guaranteeing the non-occurrence of transient recovery voltage across the breaker contacts which may lead to reignition of the arc. Additionally, a system wide review of protection settings needs to be carried out in order to address the changes brought on by VRES integration and their variable nature over a 24hour hour period.

34. Dynamic Stability Analysis

Fault ride through (FRT) studies were conducted to ensure that VRES plants stay connected when the AC grid voltage is temporarily reduced or increased due to a fault or large load change in the grid, allowing VRES plants to offer ancillary services for the mitigation of voltage excursion on the network through inject and absorption of reactive power at respective points of connection. In order to develop low voltage ride through capability curves, a critical clearing time study was conducted. The study revealed that for the base network of 2025 with both generation and transmission projects for the pessimistic expansion plan, the system wide stability limits for clearing zero impedance 3-phase bus faults was 109ms. This time was obtained at Kabwe stepdown after a total of 82 busbars at 132, 220, 330kV were assessed, armed with this time, low voltage ride through characteristics were successfully developed. The study demonstrated that the entire ZESCO IPS could be represented by 3 LVRT curves, these being the general curve 1, general curve 2 and the Luano 220kV curve which could effectively be used as a system wide LVRT curve for primary protection.

In contrast to the LVRT curves, high voltage ride through (HVRT) curve development did not rely on the system wide critical clearing time but rather on system disturbances that resulted in voltages beyond 1.05pu of nominal voltage as stipulated for in the Zambian grid code and SAPP planning criteria of 2012. Only three (3) disturbances caused the voltage to go beyond this limit namely the loss of 265MW Kansanshi, loss of 12Mvar Kabompo 132kV bus reactor and the loss of 5Mvar Zambezi 132kV bus reactor. However, it was noticed that the maximum continuous overvoltage was 111% on the loss of the 12Mvar Kabompo reactor. Hence for the system wide HVRT curve, a 115% instantaneous protection margin was adopted as primary protection while a 120% protection margin was adopted for a 20s duration based on IEEE standard C62.11 surge arrester coordination curves with prior duty having a temporary overvoltage limit of 150%. Beyond the 20s duration, other protection schemes could be deployed in order to address the voltage excursion.

Furthermore, a rate of change of frequency (RoCoF) study was conducted in order to assess frequency regulation adequacy arising from a net change in system inertia post VRES integration. The study was carried out by subjecting the Zambian IPS to disturbances that resulted in a generation-load imbalance, which caused frequency excursions, these disturbances were applied to the Peak Solar and Peak VRES case. To form a basis of comparison, similar disturbances were applied to the Base Case at the same time the Peak Solar and Peak VRES conditions occurred. The frequency was measured over a rolling window of 500ms to avoid measurement errors and interarea oscillations while reference was made to a study conducted by the Ireland state-owned transmission company (EirGrid) which demonstrated that Hydro units have the capability to withstand up to 2Hz/s RoCoF. However, the thermal units struggled to withstand 1Hz/s RoCoF under certain power factor conditions, thus, for the purpose for purpose of our analysis a limiting RoCoF value of 1Hz/s was considered. The study demonstrated that for all 2025 study cases i.e. Peak demand with VRES condition, Peak Solar PV generation condition and Peak VRES condition, a general increase in RoCoF values was observed with increased VRES integration. However, all RoCoF values obtained were well below the 1Hz/s threshold as stipulated in the Zambian transmission grid code with both frequency nadir and zenith values being well within the 50±2.5% limits. The highest recorded RoCoF modulus value was 0.05Hz/s for the loss of 200MW export to SNEL, this resulted in an over frequency with a zenith value of 50.097Hz for the Peak VRES Generation Condition case where the combined Solar and Wind (proposed and existing) output is at its maximum. Under this disturbance, the ZESA – ZESCO Tie line helps to dampen the impact of the disturbance by exporting 96.38MW as the generating stations on the Zambian IPS reduce generation with the help of the governors via the automatic generation control (AGC). Finally, a rotor angle stability study was carried out to assess whether the conventional generating units will remain in synchronism when the ZESCO IPS is subjected to disturbances under increased VRES integration. The system was subjected to disturbances that affected the power balance of the network through variations in electrical or mechanical power and the effective reactance for power flow paths, three (3) key events were identified from the study. The first being the single pole auto-reclose for a line to ground fault on Muzuma – Kafue West 330kV line, this resulted in Maamba and Victoria falls stations A, B and C losing synchronism with wide spreadwidespread voltage collapse at substations in the Southern part of the country for all study scenarios. The second notable event was the single pole auto-reclose for a line to ground fault on Kabwe – Pensulo line 1 for the Peak Solar PV generation scenario, here the huge power flows into Kabwe Stepdown caused a reactive power imbalance for a SPAR event falsing Musonda falls and Lunzua machines to poles slip as they transitioned from maximum to minimum reactive power support. This results into voltage collapse in the Northern grid with voltages below 0.7pu at various substations. The third critical event was the loss of Kabwe – Pensulo line 1 under the Peak VRES Condition, here the simulation failed to converge beyond 2 seconds due to a large reactive power imbalance on the loss of the first line as the second line was overloaded at 109% when carrying 760MW. This overloading exacerbated the widespread voltage collapse that caused the nonconvergence of the dynamic simulation.

Further Work / Recommendation

To add value in the quest for energy transition preparedness, the following future work is recommended:

• Seeing that a large share of grid demand will be met by VRES in 2025, 2030 and beyond, detailed research must go towards utilization of machine learning and artificial intelligence in now casting and day ahead short-term forecasts. This has the potential to optimize both system operations during dispatch and energy market trading both local and regional.

• Additional research must go towards making the entire Zambian grid smart and digital with a sustainable and resilient cybersecurity framework.

• More research to go towards sector coupling (i.e., hydrogen economy and electric mobility) and how it fits into the Zambian energy transition [13].

Declarations of Competing Interests

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

Credit Author Statement

Kumbuso Joshua Nyoni: Conceptualisation; Data curation; Investigation; Methodology; Software; Formal analysis; Validation; Visualisation; Writing – Original Draft.

Able Kaonga: Conceptualisation; Data curation; Investigation; Methodology; Software; Formal analysis; Validation; Visualisation; Writing – Original Draft.

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Humphrey Phiri: Conceptualisation; Data curation; Investigation; Methodology; Software; Formal analysis; Validation; Visualisation; Writing – Original Draft.

Anthony Mumba: Conceptualisation; Data curation; Investigation; Methodology; Software; Validation; Reviewing – Original Draft.

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This paper has been written to shine light on the great works done by Zambian Electrical Engineers to assess the preparedness of the Zambian grid for large-scale integration of VRES. The results of this study were inputs to the VRES aspects of the grid code, which provided valuable information for IPPS on benchmarking the technical requirements of prospectus solar or wind power plants with a bearing 0n cost-effective investment in the energy sector. The views expressed in this paper do not necessarily reflect the Zambian government's official policies nor the final stance by ZESCO Limited. Therefore, content contained is solely to represent independent critical thinking of the researchers involved.

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