THE BAHAMAS POWER SYSTEM STABILITY STUDY FOR THE IMPLEMENTATION OF A HIGHER RENEWABLE ENERGY PENETRATION LEVEL

QUALITATIVE STUDY OF THE SYSTEM AND ITS OPERATIONAL CHALLENGES: DATA CONSOLIDATION AND CRITICAL SCENARIOS FOR ELEUTHERA AND EXUMA

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1 INTRODUCTION

1.1 OBJECTIVES

Within the project "The Bahamas Power System Stability Study for the Implementation of a Higher Renewable Energy Penetration Level", commissioned by UNIDO and financed by GCF, Energynautics is conducting dynamic power system stability studies for the power systems on the islands of Eleuthera and Exuma on The Bahamas. The project aims to support the owner and operator of the power systems, the Bahamas Power and Light Company (BPL).

The purposes of this report are:

- (Section 1.3) To list the different sources of information used to collect data on Bahamas Power and Light (BPL) Eleuthera and Exuma systems.
- (Section 2) To provide an overview of the data needed to develop a simulation model for a dynamic stability analysis of the power systems of the Eleuthera and Exuma islands as of today in 2023 (Section 2). The model is implemented in the ETAP simulation software.
- (Section 3) To describe the critical scenarios to be investigated in the stability analyses.

For all parameters that are missing, assumptions are being made in order to allow the work to progress. It should be noted that the more assumptions have to be made, the less accurate the simulation results will be in terms of reflecting the real situations in the systems and the behavior of the power system assets. The amount of assumptions that have turned out to be necessary in this project is substantial. The data presented in this report comes with annotations indicating the sources or whether it has been assumed.

Future scenarios up to 2030 are investigated within the scope of this project. Consequently, data are not only needed for the equipment of today, but also for all equipment that is already planned to be installed until 2030.

1.2 POLICY TARGETS AND FUTURE SCENARIOS

As per The Bahamas National Energy Policy, the target is to increase the percentage of renewables in the energy mix to 30 % in 2030. Based on this target and the estimated value of current installation, three scenarios have been considered for the study:

- Base scenario: This is the present scenario, i.e. as in the year 2023. The scenario sees 10 % renewable penetration.
- Intermediate scenario: This is the intermediate scenario i.e. as in the year 2026. This scenario is considered as a transition state by the consultant. The renewable penetration is set at 20 %.
- Future scenario: This is the final scenario i.e. as in the year 2030, with the penetration of 30 % as per the national targets.

Table 1.1: % renewable penetration considered for the scenarios

Island	2023	2026	2030
Exuma	10 %	20 %	30 %
Eleuthera	10 %	20 %	30 %

1.3 SOURCES OF INFORMATION

The following sources of the information are the basis for the data collection that is depicted in this document:

[1] P. Stancevic, T. Martinovic, B. Kosanovic, K. Bryan, and M. Zeradjanin, "Renewable energy consultancy with IRP option: Five Year Renewable Energy Plan," 2018.

[2] P. Stancevic and M. Zeradjanin, "Renewable energy consultancy with IRP option: 20 Year Load Forecast," 2019.

Another fundamental source of information were the different communications maintained with representatives of BPL and which is gathered and structured in the following documents:

- The single line diagram (SLD) of the Eleuthera and Exuma system provided as 'Eleuthera System Diagram Book' and 'Exuma System Diagram Book' and the subsequent 'GTPS & EBSS Single Line Diagram' received Dec. 2022.
- The excel file 'Eleuthera and Exuma Generator Data' containing information about generator size, engine and fuel type received Dec. 2022.
- The answers to the questionnaire 'Phase2_Doubts_SLD&MD' received 3rd Feb. 2023.

2 DATA FOR THE DYNAMIC SIMULATION MODELS OF BPL'S ELEUTHERA AND EXUMA POWER SYSTEMS

This section depicts the data which is available and which is missing to develop the dynamic models on BPL's Eleuthera and Exuma power systems.

2.1 NETWORK DATA

The only source of information of network data are the SLD files for Eleuthera and Exuma provided by BPL mentioned earlier. The power system for both islands is operated at a nominal frequency equal to 60 Hz. The voltage levels used in the transmission network are 33 kV and 12.4 kV with both overhead lines and underground cables. The dynamic simulation model used in this project will represent the 33 kV and 12.4 kV networks down to the HV/MV transformers. As the line lengths in the SLD are all estimated from ArcGIS, certain sections of the network in close proximity to each other were lumped due to lack of clear data.

In terms of MV and LV networks 7.2 kV and 0.4 kV are the existing voltage levels below 12.4 kV but these networks will not be represented in our dynamic model. Loads and distributed generation will be lumped on the HV side of those transformers.

The information available on BPL for the transmission network as well as any data gap are depicted in the following subsections.

2.1.1 Overhead lines (OHL)

The information available regarding the OHL conductors being used in BPL Eleuthera and Exuma Network is that they are typically of type 4/0 AAC. These line types have therefore been associated with the 12.4 kV lines. The 33 kV lines are specified with a value of 0.192 Al in the SLD. Based on this information, the line types shown in Table 2.1 are selected from the ETAP library.

Table 2.1: Conductors types used for the OHL

Type	Voltage Level	Current Rating	**R1** [Ohm/km]	**X1** [Ohm/km]
Rose # 4 AAC	33 kV	63.7 A	1.38	0.374
Oxlip 4/0 AAC	12.4 kV	193.7 A	0.274	0.313

ETAP automatically calculates the Pos. (positive) and Zero sequence resistances and reactances in ohms or ohms per unit length, per phase, and at base temperature T1 and T2 based on the specified configuration and grounding information of a transmission line. The following assumptions have been made for the configuration of line and the grounding wire:

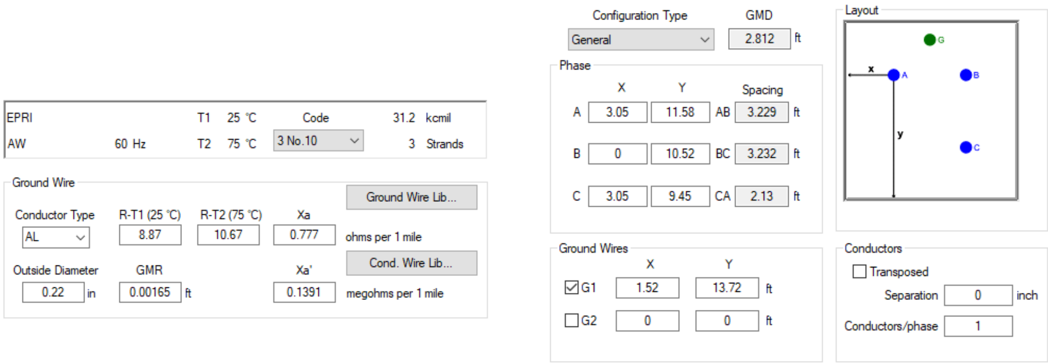

Figure 2.1: Grounding wire parameter and transmission line configuration

2.1.2 Underground cables

The information available about the underground cables is that they are 4/0 single core Cu or 2/0 single core Cu having XLPE insulation with concentric neutral. Based on this, the cable types shown in Figure 2.2 were selected, the parameters for which are listed in Table 2.2.

Table 2.2: Cable types

Cable Type	Voltage Level [kV]	Conductor Size [mm2]	Insulation Type	Conductor material	No. of cores	Current Rating (derated) [A]	R1 [Ohm/km]	Z1 [Ohm/km]
Type 4/0	33	120	XLPE	Copper	Single	258.8	0.196	0.237
Type 2/0	12.4	70	XLPE	Copper	Single	172.9	0.342	0.371

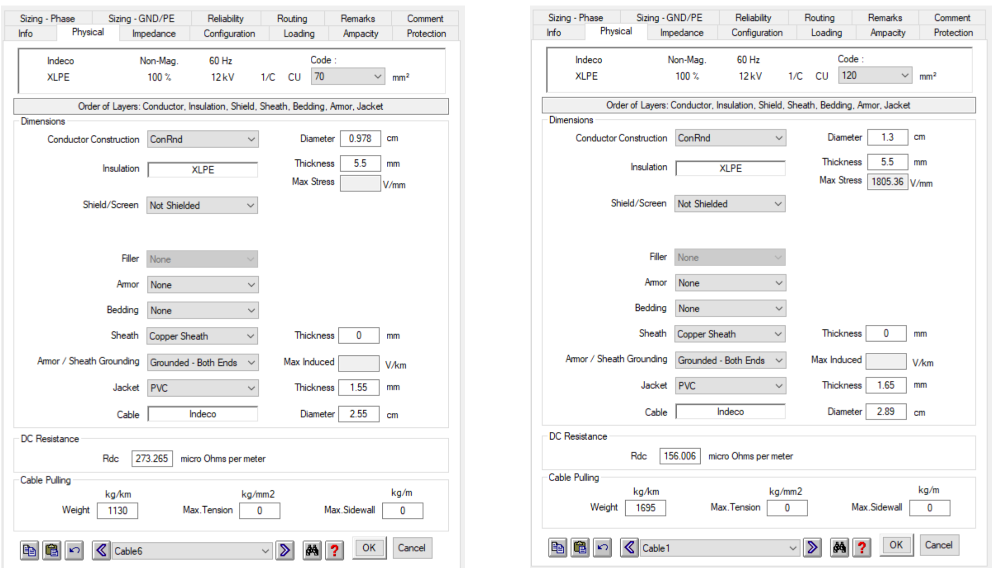

Figure 2.2: Cable physical parameters in ETAP

2.1.3 Transformers

The existing transformers of BPL Exuma Transmission Network are listed in the Table 2.3. The information has been derived from the available images of the transformer rating plates. An asterisk (‘*’) marks places where the information was not available and has therefore been assumed.

Table 2.3: Parameters for transformer in Exuma system

Transformer ID	Rating (MVA)	Primary kV	Secondary kV	Impedance %	X/R Ratio	OLTC ON/OFF	Plus Tapping	Min. Tapping	Type
Trf_GTPS-1*	8	7.2	34	7	14.23	ON	2.5%	-2.5%	YnD1
Trf_GTPS-2*	8	7.2	34	7	14.23	ON	2.5%	-2.5%	YnD1
Trf_WestFeed	8	7.2	13.065	6.68	14.23	ON	2.5%	-2.5%	YnD1
Trf_EastFeed	8	7.2	12.47	7	14.23	ON	2.5%	-2.5%	YnD1
Trf_Rental*	8	0.48	12.47	7	14.23	OFF	-	-	YnD1
Trf_EBSS-1	7.5	34.5	12.47	8.8	14.23	ON	2.5%	-2.5%	YnD1
Trf_EBSS-2	7.5	34.5	12.47	8.8	14.23	ON	2.5%	-2.5%	YnD1

No information is available regarding the BPL Eleuthera Transmission network transformers. The information has therefore been assumed for all the transformers as listed in Table 2.4.

Table 2.4: Parameters for transformer in Eleuthera system

Transformer ID	Rating (MVA)	Primary kV	Secondary kV	Impedance %	X/R Ratio	OLTC ON/OFF	Plus Tapping	Min. Tapping	Type
Trf_RSPS-GC	4.5	7.2	34	7	12.1	ON	2.5%	-2.5%	YnD1
Trf_RSPS-HB	4.5	7.2	34	7	12.1	ON	2.5%	-2.5%	YnD1
Trf_MackeyHill	0.5	34	7.2	7	3	OFF			
Trf_PinkRoad	0.5	34	7.2	7	3	OFF			
Trf_Palmetto	1	34	7.2	7	5.8	OFF			
Trf_GH	3	34	7.2	7	10.7	OFF			
Trf_JC	0.5	34	7.2	7	3	OFF			
Trf_RbowBay	3	34	7.2	7	10.7	OFF			
Trf_HB_South	6.3	13.8	33	7	13.55	ON	2.5%	-2.5%	YnD1
Trf_HB_North	6.3	13.8	12.5	6.5	13.55	OFF			
Trf_HIPS_1	4.5	7.2	12.5	5.5	12.1	ON	2.5%	-2.5%	YnD1
Trf_HIPS_2	4.5	7.2	12.5	5.5	12.1	ON	2.5%	-2.5%	YnD1

2.1.4 Network Protections

Overcurrent protection relays will not be modelled in this study. However, some of the frequency events simulated will correspond to system faults (short circuits) for which the clearing time of the existing overcurrent protections will be relevant.

2.2 POWER STATIONS AND GENERATORS

2.2.1 Existing Power Stations and Generators

The below mentioned data for the generators (except their power rating) has been assumed for the power stations in Eleuthera and Exuma.

Table 2.5: Parameters for generator in George Town Power Station

Variable	Unit	Gen 1/2/3/4
App. Pow.	[MVA]	5.2
Active Power	[MW]	4.4
Type	[-]	Diesel Salient Pole
Pow. Fact.	[-]	85%
Nom. Volt.	[kV]	7.2
Speed	[rpm]	900
H[Sgn]	[s]	0.054
xd	[p.u.]	2.1
xq	[p.u.]	1.26
xd´	[p.u.]	0.35
xd''	[p.u.]	0.25
xq'	[p.u.]	0
xq''	[p.u.]	0.21
x2	[p.u.]	0.23
x0	[p.u.]	0.10
xl	[p.u.]	0.15
Td0'	[s]	3.38
Tq0'	[s]	-
Td0''	[s]	0.05
Tq0''	[s]	0.05
SG10	[p.u.]	1.07
SG12	[p.u.]	1.18
rstr	[p.u.]	0.01
r2	[p.u.]	0.026
r0	[p.u.]	0.015

Table 2.6: Parameters for generator in Rock Sound Power Station

Variable	Unit	RS 1/2/5/6
App. Pow.	[MVA]	
Active Power	[MW]	2.5
Type	[-]	Diesel Salient Pole
Pow. Fact.	[-]	85%
Nom. Volt.	[kV]	7.2
Speed	[rpm]	900
H[Sgn]	[s]	0.064
xd	[p.u.]	0.99
xq	[p.u.]	1.05
xd´	[p.u.]	0.35
xd''	[p.u.]	0.25
xq'	[p.u.]	0.66
xq''	[p.u.]	0.33
x2	[p.u.]	0.18
x0	[p.u.]	0.07
xl	[p.u.]	0.15
Td0'	[s]	5.25
Tq0'	[s]	-
Td0''	[s]	0.03
Tq0''	[s]	0.05
SG10	[p.u.]	1.07
SG12	[p.u.]	1.18
rstr	[p.u.]	0.01
r2	[p.u.]	0.026
r0	[p.u.]	0.015

Table 2.7: Parameters for generator in Rock Sound Power Station and Harbour Island

Variable	Unit	RS 1/2/5/6 and HI1/2
App. Pow.	[MVA]	2.94
Active Power	[MW]	2.5
Type	[-]	Diesel Salient Pole
Pow. Fact.	[-]	85%
Nom. Volt.	[kV]	7.2
Speed	[rpm]	900
H[Sgn]	[s]	0.064
xd	[p.u.]	0.99
xq	[p.u.]	1.05
xd´	[p.u.]	0.35
xd''	[p.u.]	0.25
xq'	[p.u.]	0.66
xq''	[p.u.]	0.33
x2	[p.u.]	0.18
x0	[p.u.]	0.07
xl	[p.u.]	0.15
Td0'	[s]	5.25
Tq0'	[s]	-
Td0''	[s]	0.03
Tq0''	[s]	0.05
SG10	[p.u.]	1.07
SG12	[p.u.]	1.18
rstr	[p.u.]	0.01
r2	[p.u.]	0.02
r0	[p.u.]	0.01

Table 2.8: Parameters for generator in Hatchet Bay Station

Variable	Unit	HB 1/2/3/4
App. Pow.	[MVA]	4.6
Active Power	[MW]	3.2
Type	[-]	Diesel Salient Pole
Pow. Fact.	[-]	85%
Nom. Volt.	[kV]	13.8
Speed	[rpm]	900
H[Sgn]	[s]	0.061
xd	[p.u.]	0.99
xq	[p.u.]	1.05
xd´	[p.u.]	0.35
xd''	[p.u.]	0.25
xq'	[p.u.]	0.66
xq''	[p.u.]	0.33
x2	[p.u.]	0.18
x0	[p.u.]	0.07
xl	[p.u.]	0.15
Td0'	[s]	5.25
Tq0'	[s]	-
Td0''	[s]	0.03
Tq0''	[s]	0.05
SG10	[p.u.]	1.07
SG12	[p.u.]	1.18
rstr	[p.u.]	0.01
r2	[p.u.]	0.02
r0	[p.u.]	0.01

2.2.2 Data for AVR and excitation systems of existing generators

The governor model GGOV1 and excitation model AC8B have been used for the generators, the parameters for which are listed in Table 2.9 and Table 2.10.

Table 2.9: Control parameters for governor model GGOV1

Parameter	Value
Kdgov	0.4
Aset	1000
Ta	0
Wref	1
Pref	1
Kigov	1
ropenp	0.22
rclose	-0.22
wfnl	0.2
kturb	2
r	0.0612
Kiload	0.001
Kpload	1
Ldref	1.2
Ka	1000
Tsa	1
Tsb	1
Tfload	999
Tdgov	0.01
Tpelec	0.2
Tb	0.0433
Tc	0.0433
Maxerr	0.1
Minerr	-0.1
rup	99
Rdown	-99
Vmax	1
Vmin	0.08
Kpgov	3
Kact	2

Table 2.10: Control parameters for exciter model AC8B

Parameter	Value
Xc	0
Rc	0
Kpr	30
Kir	10
Kdr	5
Tdr	0,02
ke	1
Kd	0,13
Kc	0
Ka	0.8
Vrmax	7.65
Vrmin	7.65
Ta	0.005
Vfemax	999
Vemin	0.01
MachineBaseMVA	-
Tr	0.02
Te	0.2753

2.2.3 Generation Protections

The protection settings for the generator have not been implemented as no information was available regarding the protection settings/load shedding thresholds. This is because an islanded system doesn’t have the benefit of immediate export of power and therefore the protection settings can differ from that of a connected system to prevent unnecessary tripping of generators due to minor disturbances. VRE Installation

2.2.4 Technical Characteristics

- Voltage ride-through (HV/LVRT): The dynamic models of all VRE generators, independent of their size, will include FRT capabilities to disturbance on their terminal’s voltage according to the envelope depicted in Figure 2.3.

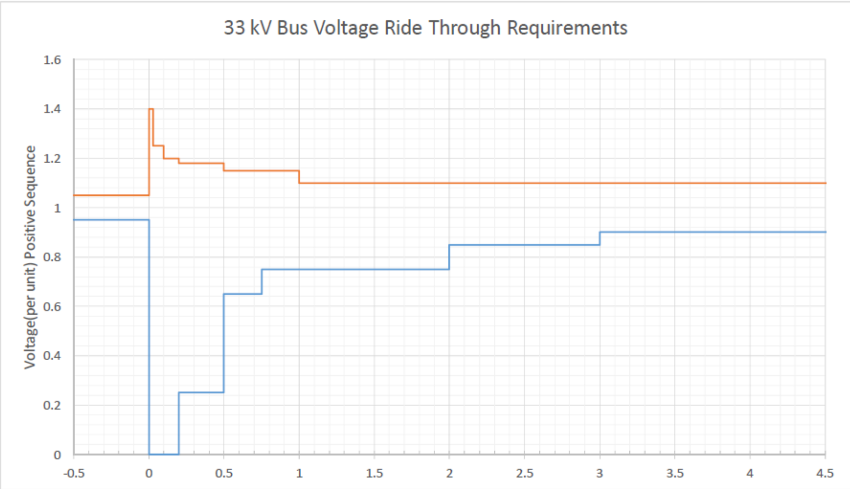

Figure 2.3: Bus voltage ride through requirements for VRE modelled in the system

- Frequency ride-through (FRT): All VRE generators will include underfrequency protections set to trip at 54 Hz. Over-frequency trips will be set at 66 Hz unless BPL decides on a lower value.
- Voltage control: VRE generators of more than 1 MW must also have their own voltage control with a reactive power capability equal to 50 % of the rated active power at any operational point.
- Dynamic voltage support: According to the information provided in the document “Simulation models for Renewable Studies1.pdf”, all VRE generators above 1 MW must dynamically support voltage at their terminal. However, the characteristics of such voltage support are not clear. Additional information in this regard is needed such as for instance the characteristics of the fast fault current injection control or the prioritization of active or reactive power depending on the terminal voltage.

2.2.5 Current installation

The information for the VRE resources installed and its penetration by the year 2023 in the islands of Exuma and Eleuthera is based as per the estimate in [1] from December 2018. The renewable penetration has been referred here as a part of the annual electricity mix.

Table 2.11: VRE installation in 2023

Island	% Demand supplied by RE	Installation (MW)	
		PV	Battery
Exuma	10	4	2
Eleuthera	10	6	3

The following VRE capacities have been considered as the best generation mix for meeting the above targets.

Table 2.12: Renewable resource installation in MW

Island	2023		2026		2030	
	PV (MW)	Battery (MW)	PV (MW)	Battery (MW)	PV (MW)	Battery (MW)
Exuma	4	2	9	2	15	4
Eleuthera	6	3	12	3	23	6

2.2.6 PV installations and their locations

At the moment, there is no clear route for installed capacities of VRE in 2030 scenario. The target is a 30% share of renewable energies in annual electricity production in order to be aligned with national targets. The following PV resources have been considered and are classified based on the land use type as follows:

- Commercial PV: The installations are located in commercial places. The size of the PVs is taken as 1 MW for each of the installed locations for the present scenario as no information was available about the system. Since these installations are larger installations, the connection requirements for these PVs is considered to be more demanding in terms of fault ride-through and frequency reserve participation. These requirements have been listed in .
- Residential PV: These installations are for residential places. The size of the PV here is lumped for different houses in a given area. As these installations are smaller in size, they are not expected to provide fault-ride through support or participate in frequency reserve. The protection settings

The locations for the PV for both Eleuthera and Exuma islands is listed in Table 2.13 and Table 2.14. Such a classification is done because commercial PVs are usually larger in size and have stricter requirements for interconnection. The battery installation is located close to a renewable plant. The size of the battery is treated as 1 MW as in the base scenario, before being expanded further in the future scenarios.

Table 2.13: Exuma installed capacities and locations for present and future scenarios

Renewable Resource	Installation Location	Rating 2023	Rating 2026	Rating 2030
Commercial PV	Bahama Sound Forest	1 MW	1.5 MW	3 MW
	Island Club	1.5 MW	1.5 MW	3 MW
	Hartswell	1.5 MW	1.5 MW	1.5 MW
	February Point	0 MW	1.5 MW	1.5 MW
Residential PV	Moss Town	0 MW	1 MW	2 MW
	Bahama Sound No. 8	0 MW	1 MW	2 MW
	Harbour View Estate	0 MW	1 MW	2 MW
Battery System	Bahama Sound Forest	2 MW	2 MW	4 MW

Table 2.14: Eleuthera installed capacities and locations for present and future scenarios

Renewable Resource	Installation Location	Rating 2023	Rating 2026	Rating 2030
Commercial PV	Weymss Bight (WB)	1.5 MW	3 MW	4 MW
	Governor Harbour (GH)	1.5 MW	3 MW	4 MW
	Rainbow Bay (RB)	1.5 MW	1.5 MW	4 MW
	Geogory Town (GT)	1.5 MW	1.5 MW	4 MW
Residential PV	Green Castle (GC)	0 MW	1 MW	2 MW
	Palmetto Point (PP)	0 MW	1 MW	2 MW
	FreeTown (FT)	0 MW	0 MW	1 MW
	Lower Booge (LB)	0 MW	1 MW	2 MW
Battery System	Hatchet Bay (HB)	1.5 MW	1.5 MW	2.5 MW
	Rock Sound (RS)	1.5 MW	1.5 MW	2.5 MW

2.3 LOADS

As the measurement data for the system was not available, the consultant has relied on the information in the load forecasting report from 2019 [2]. The current peak load estimate and the estimate for the future years for both islands is provided in Table 2.15. The estimates have been taken for the base scenario as mentioned in the cited report.

Table 2.15: Demand estimates for the considered scenarios

Island	Demand in 2017 (MW)	Estimated demand for 2023 (MW)	Estimated demand for 2026 (MW)	Estimated demand for 2030 (MW)
Exuma	9.3	13.1	14.5	17
Eleuthera	14	23.7	26.5	32

All loads modelled were considered three phase. The size of the individual loads was not known therefore the size of the load was estimated based on the size of the pole-mount transformer times a factor. The factor will be worked out based on the above estimated demand and available generation. The load was assumed as constant impedance with power factor 0.95 lagging.

2.4 OPERATIONAL DATA

2.4.1 Merit Order

No information is available for generators in Eleuthera power system. The consultants have therefore assumed the merit order in the following priority:

- Residential PV
- Commercial PV
- Battery
- Hatchet Bay Power Station
- Rock Sound Power Station
- Harbour Island Power Station

2.4.2 Reserve Margin

The reserves will be calculated on the same basis as listed in Deliverable D.4.2.ai. The reserves are carried on all conventional generators in frequency-droop control on a pro-rata basis. The secondary frequency control is performed via Automatic Generation Control (AGC), however this has not been modelled in this study..

3 CRITICAL SCENARIOS FOR STABILITY ANALYSIS ON BPL'S ELEUTHERA AND EXUMA POWER SYSTEMS

3.1 OPERATIONAL SNAPSHOTS

For each of the above mentioned scenarios, three system snapshots have been investigated. The system snapshots have been chosen to bring out the worst case system operational conditions. The snapshots are mentioned below:

- Peak Load: Occurs in the evening around 7 pm, summer loading conditions have been considered
- Light Load: Occurs in midnight around 2 am, winter loading conditions have been considered
- High PV: Occurs during mid-day around noon, summer weather and loading conditions have been considered.

As the measurement data for the islands wasn't available, it has been assumed that these conditions occur during the same time frame as for the New Providence island.

In the event that malfunctions in the system are observed as a result of the integration of renewables in any of the aforementioned scenarios, additional simulations will be carried out whose main purpose will be to determine corrective measures that guarantee a correct operation of the system. The Figure 3.1 provides a graphic overview of the simulation cases.

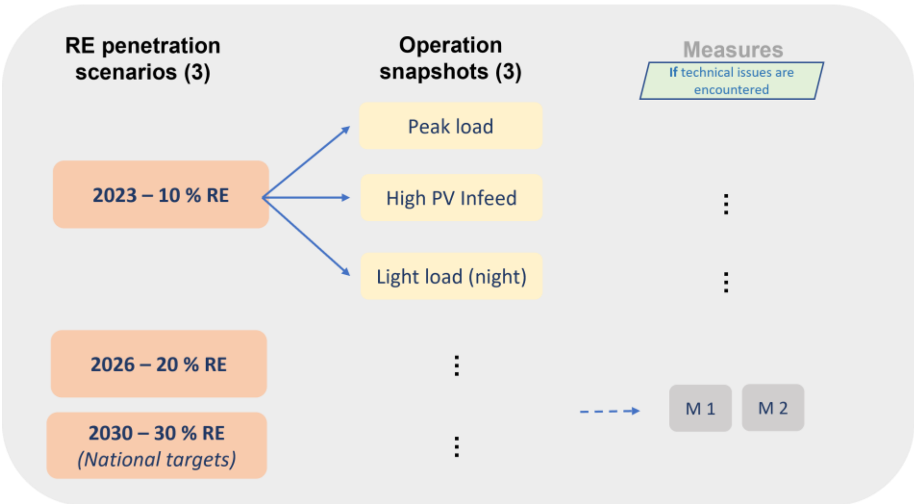

Figure 3.1: Structure of scenarios, operation snapshots, PV distribution cases and measures of the power systems stability analysis of Eleuthera and Exuma

3.2 DYNAMIC SIMULATIONS EVENTS

Table 3.1 depicts the 7 events that will be simulated to investigated the dynamic response of Eleuthera's and Exuma's power system.

Table 3.1: Dynamic Simulation events.

	Focus	Event	Description
1	**Frequency stability**	**Synchronous Generator outage**	The outage of the largest diesel/gas generator dispatched in the scenario will be simulated to assess the dynamic response of the system in the event of the loss of the largest synchronous generation in the systems
2	**Frequency stability**	**Outage of BESS unit**	The outage of a BESS unit will be simulated to assess the dynamic response of the system in such event.
3	**Voltage stability /Rotor angle stability**	**3-phase faults on a critical line and automatic clearnce**	In this study 3-fault on a critical line will be simulated to assess the dynamic response of the system
4	**Voltage stability /Rotor angle stability**	**3-phase faults on a critical line and clearance by line disconnection**	In this study 3-fault on a critical line and its clearance by disconnection of line will be simulated to assess the dynamic response of the system

3.3 MEASURES

Stability problems encountered during any of the events will be investigated individually. The consultants will investigate measures to find remedies based on the problem. Among the potential solutions are:

- Frequency stability related issues:
- Reserve estimation and participation of converter-based generation in reserves
- Droop settings of the generation
- Rotor angle stability related issues:
- FRT capabilities of the generation
- Voltage stability related issues:
- Reactive power capabilities of generators
- Installation of assets to provide additional voltage support

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