Frequency and Voltage Analysis of the Hybrid Power System in Suðuroy, Faroe Islands

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***Abstract*—The power system of Suðuroy, Faroe Islands, is a hybrid power system with wind, photovoltaic (PV), hydro and thermal power. A battery system and synchronous condenser are to be installed in 2021. The study analyses the impact the currently installed inverter-based generation (IBG) has on the frequency and voltage fluctuations in the system. This is done by selecting a time period to analyse, validating dynamic simulations with measurements and then conducting simulations with and without the existing wind power and PV plant. The results show that with the current configuration the fluctuations in the IBG and the penetration of the IBG have a negative impact on the frequency fluctuations, and to some degree the voltage fluctuations. However, the wind power plant is currently not using its ability to contribute to smoothen frequency and voltage fluctuations, and this will be revised with the added battery system and synchronous condenser.**

I. Introduction

The Faroese Power Company SEV has a vision to reach a 100% renewable electricity generation by 2030. Suðuroy is the most southern island in the Faroe Islands. The island is electrically isolated from the other islands and is a hybrid power system with an installed capacity of 13.4 MW thermal power (heavy fuel oil), a 6.3 MW wind power plant (WPP), 3 MW hydro power and 0.26 MW photovoltaic (PV) power. In 2020 the total production in Suðuroy was 35 GWh, 84.9% thermal, 11.8% hydro, 2.8% wind and 0.5% solar. The WPP started operating in late 2020, but was officially inaugurated in February 2021; hence, the low production shares in 2020. In December 2020 the WPP produced 22.6% of the total production during test runs.

Suðuroy has a very varying demand profile, due to a relatively large fish factory in the island with a seasonal dependant demand. The demand typically varies between 2.5 MW and 4.5 MW when the factory is offline, and between 5 MW and 7 MW when it is online. The lowest hourly average demand in 2020 was 1.8 MW, and the highest was 8.0 MW. The average load in 2020 was 4.0 MW and the median was 3.5 MW. A duration curve of the load in 2020 can be seen in Figure 1. The slope of the duration curve changes slightly above 2000 hours, just below 5.0 MW, this could indicate that the fish factory was in operation over 2000 hours in total in 2020, noncontinuous.

The rated power of the WPP is higher than the average and median demand in 2020, thus it is clear that there will be a high wind power penetration at times. The demand in 2020 only exceeded 6.3 MW for roughly 10% of the time. A high penetration of IBG results in fewer synchronous generators being online, and thus, a 7.5 MW/7.5 MWh battery energy storage system (BESS) and an 8 MVA synchronous condenser will be installed in 2021 alongside the WPP, intended to provide inertia, frequency regulation and short circuit power to ensure grid stability and security of supply with a high penetration of inverter-based generation (IBG).

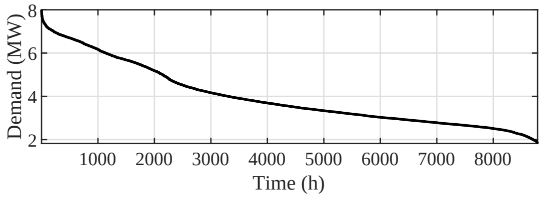

Figure 1. Demand duration curve for Suðuroy 2020

It is a well known issue that integrating IBG into a power system is challenging and this can have a negative impact on the power system operation, especially in small isolated systems [1]–[3]. The challenges are associated with both the nature of the renewable resource (intermittence, fluctuations etc.), the distribution of generators and technology itself, as it is different than traditional synchronous generators. Concerns related to reduced inertia, voltage and frequency control, power quality, protection etc. have been discussed in multiple review studies, see e.g. [4]–[6]. The previous studies on the dynamics of the Faroese Power System are limited in amount and scope, but analyses of the whole system can be found in [7], [8]. The first proposes grid reinforcements towards 2030, while the latter emphasises the importance of having a validated dynamic model. Studies focusing on Suðuroy and sizing a BESS for inertial response and primary frequency reserve [9], using heat pumps for secondary frequency control [10] and implementing a synchronverter (virtual synchronous generator) [11] have been conducted. All three options can contribute to the power system stability, but all three studies conclude that further investigations should be conducted.

This paper aims to investigate how the installed IBG, with the current components and control configuration, affect the frequency and voltage fluctuations of the hybrid power system in Suðuroy. The investigation is done by conducting dynamic simulations in DIgSILENT's PowerFactory of the current system and the previous system without wind power and PV power. Through these simulations it is possible to analyse the impact the currently installed IBG has on the frequency and voltage fluctuations.

II. Methodology and Modelling

A 4.5 hour time period under normal operation has been selected as a study case to analyse the impact of IBG on frequency and voltage fluctuations. The criteria to choose a time period was that all types of generation, i.e. wind, solar, hydro and diesel should be online, the same generators should be online throughout the the period to avoid start and stops of units, that the wind conditions should be relatively stable, PV production should be relatively high and it should be a weekday. The selected period is from 12:00 to 16:30 on a Monday. The 4.5 hour time period is RMS simulated and analysed based on the following four cases:

1) Replicating the study case and comparing simulated grid responses with measured voltages and frequencies. Thus, this case shows if the dynamic simulation model can accurately represent the power system.
2) The PV power generation in Case 1 is removed and the synchronous generation is increased accordingly. The voltages and frequencies are compared to Case 1 thus; the impact of the PV plant on the voltage and frequency fluctuations is analysed.
3) The wind power generation in Case 1 is removed and the synchronous generation is increased accordingly. The voltages and frequencies are compared to Case 1 thus; the impact of the new wind power plant on the voltage and frequency fluctuations is analysed.
4) The wind power and PV power generation in Case 1 are removed and the synchronous generation is increased accordingly. The voltages and frequencies are compared Case 1 thus; the impact of the new wind power plant and PV plant on the voltage and frequency fluctuations is analysed.

A. The Suðuroy Power System

Figure 2 shows a single line diagram of the power system on Suðuroy currently. There are 2 hydro generators, 4 diesel generators, 7 wind turbines and one PV plant. The items named on the figure are listed in Table I with additional specifications.

The synchronous generators are equipped with a governor and an automatic voltage regulator (AVR), which take care of the primary frequency and voltage control of the system. Secondary control is manual in the Faroe Islands. This means that the operator on duty is in charge of e.g. keeping the frequency between 49.5 Hz and 50.5 Hz; which he does by regulating the active power setpoints of the generators.

The wind energy converters (WEC) with their individual full-converter in the WPP can be approximated as controlled current sources. Unless they are instructed to do anything different, they inject the maximum possible active power, according to the prevailing wind conditions, and the reactive power is set to zero. However, WECs also have a certain steady-state reactive power capability. This capability can be used by a WPP controller, to make the WPP to contribute to a more stable voltage, but can not guarantee to reach a specific voltage at the controlled busbar. The contribution depends on the available reactive power from the WPP, and the impact depends on the short circuit ratio of the busbar, as well as on the other electrical generation and loads nearby. During the assessed 4.5 hour period, the WECs in the WPP were operating with setpoint regulations, which means that the active and reactive powers were only controlled by a setpoint given by the dispatch center; thus, they did not contribute to smoothen the voltage and the frequency. The variations in active power due to the varying wind speed lead to a certain change in voltage at the measured busbar. The voltage-droop control in the WPP-controller will likely be activated in the future, in order to use the steady-state reactive power capability of the WECs and make them compensate at least their own impact to the 20 kV busbar voltage due to the varying active power. In a similar way the active power of the WECs can be modified dynamically with the WPP control, by enabling the power-frequency droop. Additionally, the WECs can perform the so-called "Inertia Emulation", which was also not activated during the 4.5 hours measurement. Thus, the results shown in this analysis are without any dynamically controlled, smoothing contribution from the WPP.

There is no active or reactive power control activated for the PV plant. The PV plant produces what it is capable of based on the irradiation and with $\cos\phi = 1$. Since the PV power penetration is so low, it is not necessary to be able to curtail it.

Since neither the WPP nor the PV plant are currently regulating the frequency and voltage in Suðuroy, this study case is a good basis for studying the impact non-controlled (aside from setpoint regulation) IBG has on voltage and frequency fluctuations compared to traditional synchronous generators.

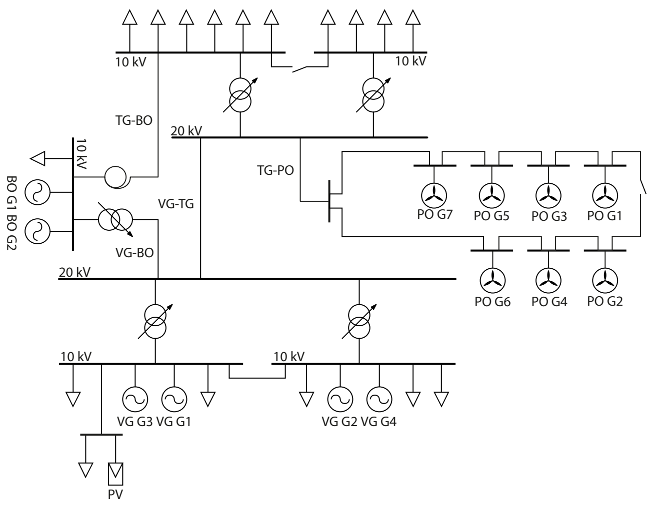

Figure 2. Single line diagram of the power system on Suðuroy. Abbreviations are found in Table I.

B. Modelling

The power system of Suðuroy has been modelled in PowerFactory, and the model has been load flow validated and dynamically validated. This has been done by conducting tests on the grid with tripping generators, and replicating the same test in the simulation model and comparing the

Table I
LIST OF NAMED ITEMS ON FIGURE 2.

Name	Description	Power (MW)	Length (km)
PV	Solar	0.26	-
VG G1 - VG G2	Heavy fuel oil	2x2.6	-
VG G3	Heavy fuel oil	4.2	-
VG G4	Heavy fuel oil	4.0	-
BO G1	Hydro	1.0	-
BO G2	Hydro	2.0	-
PO G1 - PO G7	Wind	7x0.9	-
TG-BO	Overhead line	-	10
TG-PO	Cable	-	10
VG-BO	Cable	-	6
VG-TG	Overhead line	-	12

results with measurements, i.e. active power, reactive power, voltages and frequency. Standard models from the library of PowerFactory have been used to model the governors and AVRs of the synchronous machines. The models used are tabulated in Table II. These models have been parameterised to resemble measured responses of the generators using trial and error approach and the System Parameter Identification module in PowerFactory. A signal representing the manual control during the selected period is used as an input in the governor control together with the automatic droop control. The generation and voltage of the hydro and diesel generators at the start of the simulated period is set according to the measurements at the time, and then these regulate according to their primary controllers (governor and AVR) and the manual signal throughout the simulated interval.

Table II
LIST OF STANDARD DYNAMIC MODELS FROM THE POWERFACTORY LIBRARY USED IN THIS INVESTIGATION.

Model name	Type
exc_IEEE_AC8B	Automatic voltage regulator
vtc_IEEE_1	Voltage transducer and current compensator
gov_HYGOV	Hydro governor
gov_DEGOV	Diesel governor

The power is measured at each feeder in Figure 2. These active and reactive power measurements over the selected period are used to define the loads in the simulation model. This is done by using a measurement file to control loads' external signals P_{ext} and Q_{ext} over the selected time period. The total load over the 4.5 hour time period is shown in Figure 3.

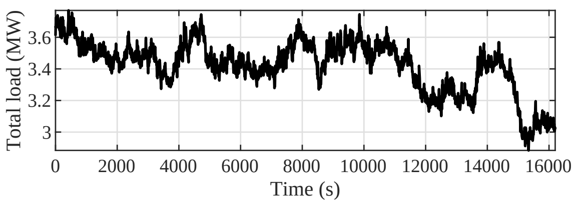

Figure 3. Total load over selected 4.5 hour period.

In terms of modelling the WPP and PV plant, this has also been done using measurement files to control the P_{ext} and Q_{ext} signal of loads. These loads are however negative to present a production instead of a load. No dynamic models of the WPP have been used in this study, but since the production is simulated using measurements from the actual production, the dynamic behaviour during this period is included in the active and reactive power measurements. The active power measurements for the WPP and PV plant are shown in Figure 4. The PV production is varying throughout the time period and peaks just above 0.2 MW. The WPP was curtailed during the time period and the active power setpoint varied between 35% to 41% of rated power. This is due to the high WPP shares. The WPP is normally curtailed to 60% instantaneous wind power penetration, to ensure a sufficient amount of short circuit power and inertia from synchronous generation. The plan is to increase this limit when the synchronous condenser and BESS will be added. However, during the analysed period, the shares are up to 80% for a short period of time. The peak wind power production during the assessed interval is >2.5 MW.

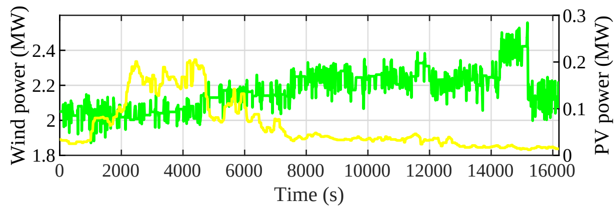

Figure 4. Wind (green) and PV (yellow) power production during the 4.5 hour period.

III. ANALYSIS OF RESULTS

A. Case 1: Replication of Measurements

The plots in Figure 5 show the frequency and voltage at the VG 20 kV busbar based on measurements and simulations of case 1. Both blue and green represent simulated values, and this is due to the two possible modelling approaches when using measurement files in PowerFactory; i.e. constant vs. linear interpolation between measured datapoints. Measurements without deadbands are accurately represented by a constant interpolation. However, the load measurements have a deadband (measurements are only logged if changes above 3% from previous value are registered), and therefore the steps in power changes using a constant interpolation are too large, which leads to overestimated frequency fluctuations. A linear interpolation would remove all sudden steps, which would lead to an underestimate of the frequency fluctuations. This is also shown on the graph, where one can see that the measured and simulated frequency and voltage have a similar behaviour, but the frequency fluctuations in the simulations are either too small or too large. The voltage fluctuations are underestimated in both approaches, but closer to the reality using a constant interpolation. This could indicate that there is some voltage/reactive behaviour that is not captured by either the load measurements or the current model. The simulated data has a frequency of 100 Hz, while the measurements have a frequency of 10 Hz, which might explain the higher frequency fluctuations in the simulation with a constant interpolation. The mean and standard deviation for the frequency and voltage are tabulated in Table III. The mean frequency using the constant method is slightly closer to the measurements, while the standard deviation is significantly higher. It was not possible to remove the deadband in the measurements for this analysis, and thus it is necessary to choose one of the interpolation methods. It was decided to use a constant interpolation for Case 2-4, mainly due to the voltage fluctuations and sampling frequency of measured vs simulated data as discussed previously. Considering the discussed aspects, the model is considered to be dynamically validated based on presented results.

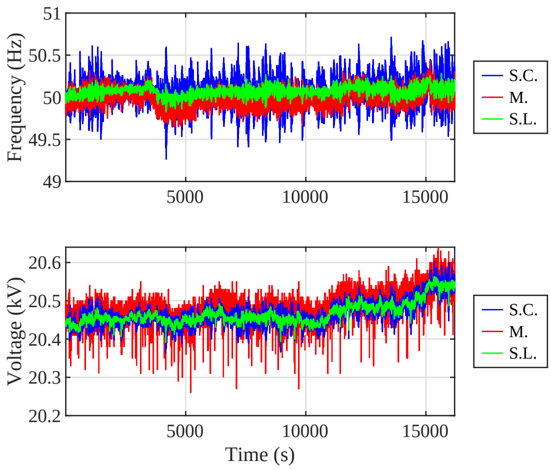

Figure 5. Frequency (upper) and voltage (lower) comparison between measurements (M.), simulations with constant interpolation (S.C.) and simulation with linear interpolation (S.L.) for Case 1.

Table III
FREQUENCY AND VOLTAGE MEAN AND STANDARD DEVIATION FOR MEASUREMENTS AND SIMULATIONS.

	Mean		Standard deviation	
	f (Hz)	U (kV)	f (mHz)	U (V)
Measurement	49.99	20.48	96	38
Simulated, constant	50.05	20.47	153	31
Simulated, linear	50.07	20.47	55	28

B. *Cases 2-4: Comparison to Case 1*

In the comparison of case 2-4 to case 1, the inclusion and exclusion of IBG on the frequency fluctuations is clear, while the impact on the voltage fluctuations is more limited. The fluctuations are calculated as the difference between mean values for every second. Negative and positive fluctuations are analysed together as absolute values, as they are almost as likely to occur, with 50.1%/49.9% of the frequency fluctuations for case 1 being positive/negative.

Figure 6 shows a duration curve for each case with the frequency and voltage fluctuations. In the first case, including both wind and PV power, the frequency fluctuations are over 100 mHz from one second to another 35.5% percent of the time. If the PV power is removed, this time decreases slightly down to 30.6%. Case 3 and case 4 have very similar frequency fluctuations exceeding 100 mHz only 0.6% of the time. The similar behaviour is due to the low penetration of solar power, which is the only difference between case 3 and 4. Currently, SEV has no quality standard in terms of a specific duration curve for fluctuations, thus one can not state that case 1 and 2 violate any conditions based solely on presented figures. Table IV contains maximum, mean and standard deviation fluctuations. These values show similar behaviour for case 3 and case 4, while the difference is larger between case 1 and 2 to the others. In case 1 the maximum frequency fluctuation seen from one second to another was 568 mHz, while the mean fluctuation is 92 mHz with a standard deviation of 80 mHz. These results show that the WPP and to some degree the PV plant, have a negative impact on the frequency fluctuations seen in the grid under normal operation. Although neither the WPP nor the PV plant are modelled dynamically, their dynamic behaviour during this period is included in the active and reactive power measurements. The duration curves of the voltage fluctuations show that the four cases have very similar voltage fluctuation duration curves, and this is also shown in Table IV. The maximum fluctuation is higher in case 3 and 4 than in case 1 and 2, but the time with fluctuations above 20 kV/s are higher for case 1 and 2. Therefore there seems to be no obvious relation between the voltage fluctuations and the four cases with different amounts of IBG.

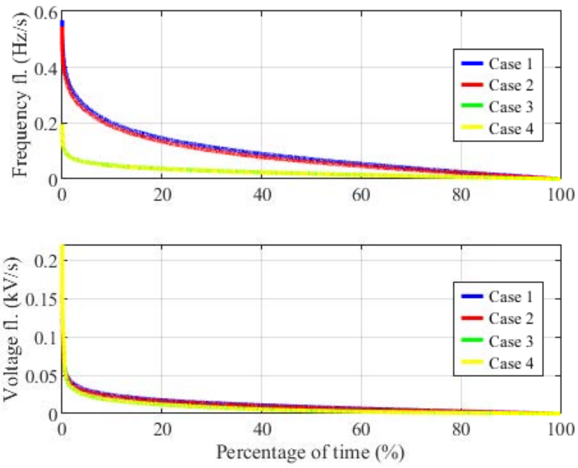

Figure 6. Frequency (upper) and voltage (lower) fluctuation duration curves for cases 1-4.

Table IV
KEY VALUES FOR FREQUENCY AND VOLTAGE FLUCTUATIONS.

Frequency	Case 1	Case 2	Case 3	Case 4
Max fluct. (mHz/s)	568	546	197	195
Mean fluct. (mHz/s)	92	83	23	23
Std. fluct. (mHz/s)	80	76	19	19
Fluct. =>0.1Hz/s (% of time)	35.5	30.6	0.6	0.6
Voltage	**Case 1**	**Case 2**	**Case 3**	**Case 4**
Max fluct. (V/s)	199	199	220	220
Mean fluct. (V/s)	11	10	7	7
Std. fluct. (V/s)	11	11	11	11
Fluct. =>20V/s (% of time)	15.6	13.3	7.5	7.6

Figure 7 shows the frequency and voltage fluctuations as a function of the IBG shares. All the data points are shown as well as a mean for each IBG share and a linear trend for all cases. The IBG penetration degrees in case 1 and 2 are significantly higher than for case 3 without the WPP; thus, there is a wide gap in the data coverage. There are also few data points above 75%.

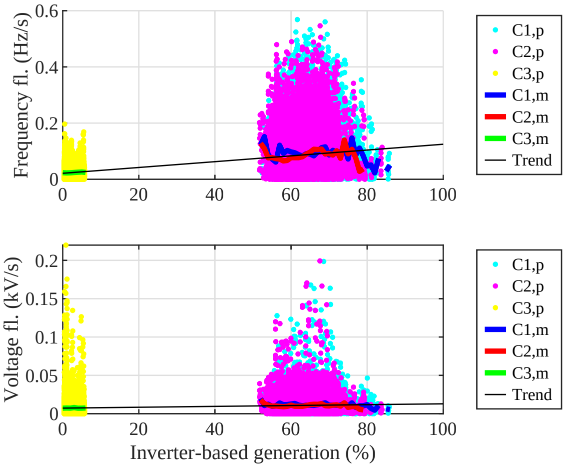

Figure 7. Frequency (upper) and voltage (lower) fluctuations as a function of IBG shares. All data points (p) and the mean (m) for every IBG share is shown for cases 1-3 (C1-C3). Additionally a linear trend is shown based on all data points.

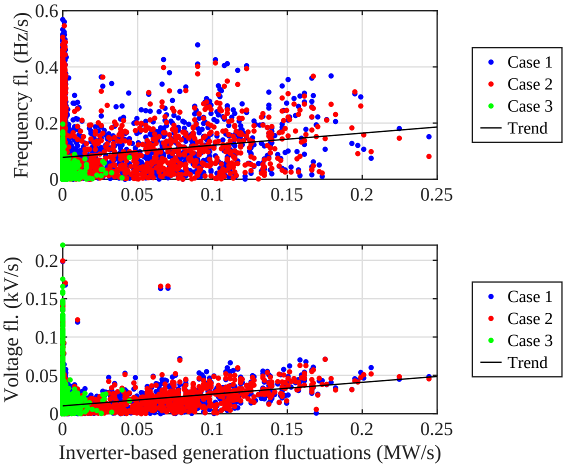

Figure 8. Frequency and voltage fluctuations as a function of IBG fluctuations with a linear trend line.

Table V
CORRELATION FACTORS BETWEEN FREQUENCY/VOLTAGE FLUCTUATIONS AND INVERTER-BASED GENERATION FLUCTUATIONS.

	Frequency		Voltage	
	All data	Fluct. above 0.02	All data	Fluct. above 0.02
Case 1	0.08	0.28	0.23	0.50
Case 2	0.08	0.29	0.25	0.54
Case 3	0.01	0.28	0.04	0.40

The frequency fluctuations increase as the IBG penetration increases, this is clear from the figure. The linear trend of the voltage fluctuations and the penetration of IBG has a lower slope than the frequency fluctuations and the IBG, but this is expected as the penetration is calculated based on the active power, which generally is associated with frequency and not voltage. The trend line has significantly lower fluctuations than the maximum fluctuations, which have the largest impact on the power system operation, so although the linear trend gives insight to how the fluctuations as a function of IBG shares increase on average, it is very important to not only consider this, but also the maximum fluctuations. The slope of the frequency and voltage trend lines are 103 mHz (0.0021 p.u.) and 6 V (0.0003 p.u.).

In order to get a better understanding of the fluctuations as a function of IBG penetration, the time period of the simulations should be expanded to include a wider spectrum of penetrations.

Frequency and voltage fluctuations as functions of the fluctuations in the production from the IBG are shown in Figure 8. In case 1 and case 2 a correlation between the IBG and frequency/voltage fluctuations is noticeable, while it is more difficult to see for case 3, as the data is more concentrated around low fluctuations. If fluctuations in the IBG increase, so do the fluctuations in the frequency. Based on the linear trend the average frequency fluctuations increase by 433 mHz for 1 MW IBG fluctuations. The correlation for voltage fluctuations is higher than for frequency fluctuations, while the impact, i.e. the slope, is lower at 153 V/MW fluctuation. However, considering the nominal values (50 Hz and 21 kV) the difference is not as significant, and the slopes are 0.0087 p.u./MW and 0.0073 p.u./MW respectively. The correlation factors are tabulated in Table V. The correlation factors have been calculated with all data as well as data were IBG fluctuations are higher than 0.02, as low IBG fluctuations disturb the correlation factors between IBG fluctuations and frequency/voltage fluctuations. These points show that the IBG is not the only reason for the fluctuations, there are other sources of disturbances e.g. loads. The interpretation of the strength of the correlation factors varies quite significantly in literature, e.g. the lower limit of a strong correlation can vary between 0.5 and 0.8 while the upper limit of a weak correlation varies between 0.3 and 0.5. One can therefore say that based on the presented data, there is a moderate to weak correlation between the frequency and the IBG fluctuations, and a moderate to strong correlation between the voltage and the IBG fluctuations. The trend line on the figure is based on all data, thus higher slopes (594 mHz/MW and 206 V/MW) would be gained by ignoring IBG fluctuations below 0.02 MW. Case 2 has higher correlation factors than case 1 and 3, which indicates that the relation between the wind power fluctuations and frequency/voltage fluctuations is stronger than the relation between PV power fluctuations and frequency/voltage fluctuations, but as mentioned previously the PV power penetration is significantly lower than the wind power during the analysed period.

IV. CONCLUSION

This study has analysed the impact of the installed IBG on the power system of Suðuroy. First the selected study case was replicated in simulations, and although there are challenges with interpolation methods, the general frequency and voltage responses are similar to the measurements, but with under- or overestimations of fluctuations. The only way to avoid this issue is to remove the deadbands of the measurements, and redo the analysis, which is practically challenging. Thus, this model has been proven to be a sufficiently accurate model to represent the current power system of Suðuroy for studies similar to this.

Four cases have been simulated and analysed. The comparison of the four cases with and without wind and/or PV power show that higher IBG shares and fluctuations lead to higher frequency fluctuations, while the voltage fluctuations are not affected to the same degree. The voltage fluctuations increase as IBG fluctuations increase, but the increase of IBG shares does not impact the voltage fluctuations significantly. As both IBG shares and fluctuations have been calculated based on active power, which generally is associated with frequency and not voltage, this outcome is expected. The correlation between IBG fluctuations and voltage fluctuations is however higher than for frequency fluctuations. In order to get a better overview of the impact, it would be interesting to analyse this with a wider range of IBG shares, as the shares between 6% and 52% are not apparent in the selected time period.

The WPP and PV in today's system are running without Q(U)- or P(f)-controls activated, and since this analysis focuses on the current and previous system, the WPP and PV are not contributing to smoothen the voltage nor the frequency in the presented results. The vision is to become 100% renewable, and a large part of this will be IBG. Therefore the challenge remains in preparing the grid for higher shares of IBG by adding alternative controllers and methods to provide needed services, tuning existing control to fit the future power composition and expanding step by step to successfully reach 100% renewables and even 100% IBG for shorter time intervals.

A. Future Work

The model used in this analysis is a cruical stepstone in the expansions and analysis of the power system of Suðuroy, but there are improvements to be done in the model, e.g. the IBG should be represented with the correct dynamic models instead of negative loads.

Since the WPP has been installed in 2020, and the BESS and synchronous condenser will become operational in late 2021, the data analysed in this paper represents an intermediate stage of the overall power system development on the island Suðuroy. Once the additional hardware components are in operation, and the actual WPP controller will be tuned to contribute to frequency and voltage stability, a similar assessment of the voltage- and frequency fluctuations shall be performed.

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