A Wind Power Plant's Impact on the Grid Frequency

Analysis of Measurements in an Electrically Isolated Island with High Penetration of Inverter-Based Wind Generation

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***Abstract*—Suðuroy, the most southern island of the Faroe Islands, is electrically isolated from other power systems. A relatively large and the first wind power plant was installed in the power system of Suðuroy in 2021. An observation of the probability density functions of the measured grid frequency on Suðuroy with and without the wind power plant, initiated further analyses of the measurements. The aim was to identify which situations lead to increased frequency variations seen in 2021 compared to 2018, 2019 and 2020. This paper presents the mentioned analysis. Curtailing the wind farm does not seem to decrease the variations, and the impact of the magnitude of the wind power generation is also limited. The impact of the shares of the wind power generation compared to the total generation, and the inertia of system at each frequency measurement, should be investigated further.**

Keywords-component; Wind power, frequency, isolated power system and probability density.

I. INTRODUCTION

In 2021 the first wind power plant was inaugurated in the isolated power system of Suðuroy, Faroe Islands. This is a 6.3 MW wind power plant (WPP) with 7 Enercon E-44 wind turbines. Prior to this inauguration the generation capacity in Suðuroy consisted of four generators driven by heavy fuel oil rated at 13 MW in total, 3 MW of hydro power (two turbines) and a 0.26 MW photovoltaic power plant. Figure 1 is a map showing the location of the Faroe Islands. Suðuroy is also marked on the map.

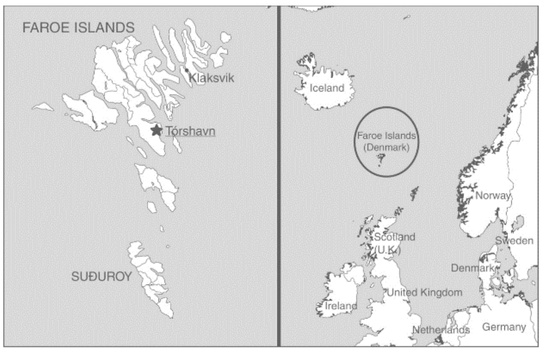

Figure 1. Map showing the location of the Faroe Islands and the island of Suðuroy [3].

The power system of Suðuroy is in continuous development. An 8 MVA synchronous condenser is being tested in the spring of 2022, and a 7.5 MW/7.5 MWh battery system is being installed as well. The synchronous condenser will provide short circuit power and inertia to the system, while the aim of the battery system is to provide frequency regulation. The goal is to be able to run the power system of Suðuroy with the synchronous condenser, the battery system and the WPP only, at times with relatively good wind conditions.

The mean load in 2020 was 4 MW, with a minimum of 1.8 MW and maximum of 8 MW. This large variation is caused by a fish factory, which does not run continuously throughout the year, and has a demand in similar magnitude to the rest of the island. In 2020 this fish factory was online over 2000 hours. The time duration curve in Suðuroy in 2020 is shown in Figure 2 [1].

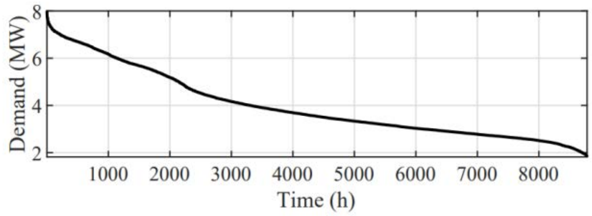

Figure 2. Time duration curve of the demand in Suðuroy in 2020 [1].

The probability density functions (PDF) based on grid frequency measurements with a resolution of 1 Hz in 2018, 2019, 2020 and 2021 have been obtained [2]. This showed that while 2018, 2019 and 2020 are almost identical, the PDF for 2021, with the WPP in operation, deviates significantly from the others. Therefore, it was decided to conduct further analyses of exactly which situations lead to the increased frequency variations. The analysis is conducted by comparisons of the grid frequency and the WPP's active power production and setpoint.

This paper is structured as follows: The approach of the analysis and the measurements used is described in section II, while the analysis itself is presented in section III. Section IV is a brief discussion of the results, and finally the study is concluded in section V.

II. Analysis Aprroach and Measurements Used

This analysis has been conducted based on measurement data using statistical plots, which are described in the following subsections. The measurements used for the analyses are:

- Frequency measurements:
  - Resolution: 1 Hz
  - Duration: January to the end of September in 2018, 2019, 2020 and 2021.
  - Comment: Data has been cleaned for blackouts
- Wind power production, setpoint and potential power:
  - Resolution: 15 minute average
  - Duration: January to the end of September in 2021

A. Probability Density Function

An initial observation of the probability density function (PDF) for 2018-2021, did, as previously mentioned initiate this study. The parameters needed to obtain the PDF normally distributed measurements, e.g. the grid frequency are the standard deviation, σ, and the mean, μ, of the measurements. The formula for the PDF of a normal distribution is given by (1).

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2} \tag{1}$$

The empirical rule states that 68% of the data is within one standard deviation of the mean. Two standard deviations include 95% of the values and 99.7% of the values are within three standard deviations from the mean.

B. Boxplots

The analyses of the measurements are also illustrated using boxplots. A boxplot shows the distribution of the data. An example of a boxplot is given in Figure 3. It shows the median value with a line inside a box. The size of the box is given by the 25th (Q1) and 75th (Q3) percentiles. This means that 25% of the data are within the median and one edge of the box, i.e. 50% of the data is within the box and this is the interquartile range (IQR).

The boxplot also contains whiskers illustrating the minimum and maximum of the data, this is however excluding outliers, i.e. extremes. The definition of an outlier is found in Figure 3.

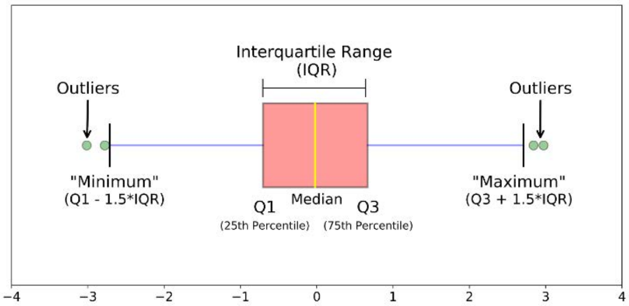

Figure 3. General illuration of a boxplot [4].

III. Measurement Analyses

This section describes the analyses conducted on the frequency measurements of Suðuroy. First the annual (2018-2021) PDF is presented. The PDF gives an overall understanding of the frequency variations in the system. This is followed by a comparison based on data from 2021 including and excluding periods with curtailment. The aim is to see if it is the periods where the wind turbines are not curtailed, i.e. the generation depends directly on the nature of the wind resource, that increase the frequency variations. Finally, the impact of the magnitude of the wind power production is analysed, to determine if this is the cause of the larger variations.

A. Annual Probability Density Function

Figure 4 shows the (a) probability density function of the grid frequency measurements from January to the end of September in 2019, 2020, 2021 and 2022. In addition to this the figure also shows the (b) probability of the frequency in a resolution of 10 mHz.

The probability density functions for 2018, 2019 and 2020 are nearly identical. The standard deviation is given in Table I. Here one can see that the standard deviation from 2018 to 2020 varies between 47 mHz and 49 mHz, i.e. a variation of 2 mHz. Following the empirical rule, this means that 99.7 % of the grid frequency measurements in 2018-2020 are within 141-147 mHz from 50 Hz (plus/minus).

The PDF for 2021 deviates significantly from the previous years with a standard deviation 84%-87% higher standard deviation of 88 mHz. The new WPP is the only significant change in the system from 2020 to 2021, and the previous years, i.e. 2018-2020, have a nearly identical PDF. This indicates that the WPP is the cause of the increased grid frequency variations.

The measurement data is fitted to the PDF, i.e. (1), but it can similarly be illustrated by plotting the number of values observed at each resolution, i.e. 50.00, 50.01, 50.02 and so on, and dividing it with the total sum of the observations. The probability of an observed measurement being equal to e.g. 50.00 Hz is then shown on the y-axis. This is shown in (a) on Figure 4. Overall, the same pattern is seen as in the PDFs, but the curves are not as smooth as this plot contains the raw data, instead of a function fitted to the observed data.

Table I also contains information about the data coverage over the time period. The coverage in 2021 is almost 100%, while in 2018 it is below 90%. Full coverage with 1 Hz measurements for the first nine months of the year results in 23.587.200 values during a common year and 23.673.600

values during a leap year. The number of measured values of the grid frequency used in this study is therefore between 21 mio and 24 mio values per year.

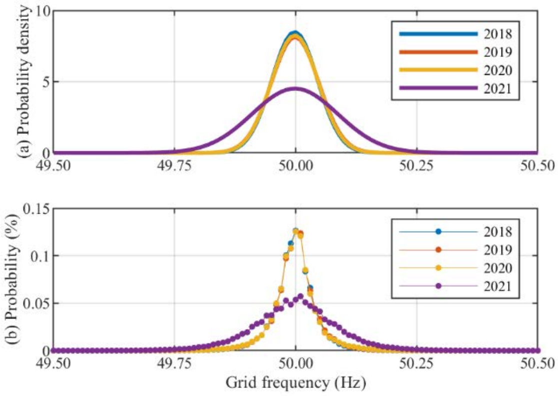

Figure 4. (a) Probability density (fitted to a normal distribution) and (b) probability of the grid frequency measurements in 2018 to 2021 from January to end of September.

TABLE I. THE DATA COVERAGE AND STANDARD DEVIATION FOR THE FREUQENCY MEASUREMENTS USED IN THIS ANALYSIS.

Year	**Data coverage**	**Standard deviation**
2018	89.4%	47 mHz
2019	91.5%	49 mHz
2020	97.5%	48 mHz
2021	99.9%	88 mHz

B. With and Without Curtailment of Wind Power Plant

The wind turbines are rated at 6.3 MW in total, while the average demand in Suðuroy was equal to 4 MW in 2020. Therefore, there are periods when the wind turbines are curtailed, i.e. producing less than the potential power.

Figure 5 shows the probability density of the grid frequency measurements in 2021 with and without curtailment. The figure also contains the full data set for 2020 and 2021 for comparison. The PDF for the data without curtailment is narrower, than the PDF for the data with curtailment. The standard deviation without curtailment is 47 mHz, while it is 49 mHz with the curtailment, see Table II. Since curtailment cuts of the top of the potential production, the fluctuations caused by the WPP due to the fluctuations in the wind speed, should be less when the wind farm is curtailed compared to when it is not, but this is not seen in the observed frequency data. The variations are actually lower without curtailment.

However, as shown in Table II, the wind turbines have been curtailed 66% of the time during the observed period. This means that the data foundation for the PDF with curtailment is better than for the PDF without the curtailment. This being said, 34% corresponds to above 8 mio measurements, thus the PDF is based on a significant amount of data, although not as much as the other data.

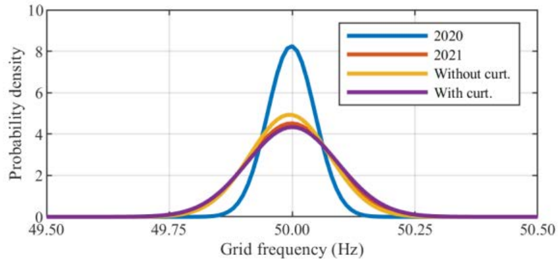

Figure 5. Comparison of probability density functions of the grid frequency in 2020 and in 2021. 2021 is shown with all data (red), without curtailment (yellow) and with curtailment (purple).

TABLE II. DURATION OF TIME WITH AND WITHOUT CURTAILMENT AND THE STANDARD DEVIATION OF THE DATA OBSERVED.

Case	**Time duration**	**Standard deviation**
2021, without curtailment	34%	47 mHz
2021, with curtailment	66%	49 mHz

C. Impact of Wind Power Magnitude

The frequency measurements have been categorised based on the magnitude of the wind power generation, and a boxplot for each range is shown in Figure 6. The boxplot located at “0.1” on the x axis contains all the values where the wind power production was above 0, but equal to or below 6.3 MW. Outliers have been excluded from the boxplots.

Frequency measurements without any wind power generation (0.0 p.u.) have the smallest IQR, and the smallest range between minimum and maximum, and there is a slight increase in the range of the IQR and the difference between the minimum and maximum values observed as the power range increases up to 0.4 p.u. This is also where the majority of the data is found, i.e. 95.8% of the data.

For wind power generation in the ranges defined as 0.5 p.u. to 0.8 p.u., the data foundation is low, i.e. <3% in each range, and this is also where the pattern seen from 0.0 p.u. to 0.4 p.u. changes.

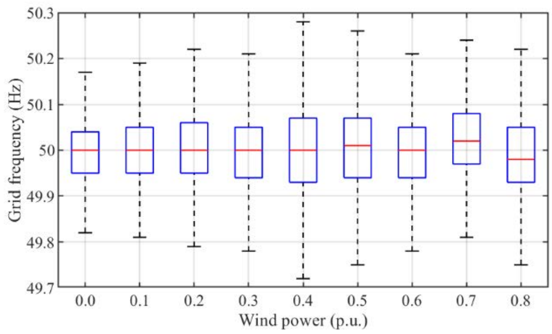

Figure 6. Boxplots of the frequency measurements categorised into the magnitude of the wind power generation.

TABLE III. PARAMETERS FOR THE BOXPLOTS SHOWN IN FIGURE 5 AND THE TIME DURATION OF THE DATA OBSERVED IN EACH POWER RANGE.

Power (p.u.)	Min (Hz)	25^{th} (Hz)	Median (Hz)	75^{th} (Hz)	Max (Hz)	Duration (%)
0.0	49.82	49.95	50.00	50.04	50.17	13.9
0.1	49.81	49.95	50.00	50.05	50.19	44.0
0.2	49.79	49.95	50.00	50.06	50.22	16.5
0.3	49.78	49.94	50.00	50.05	50.21	12.3
0.4	49.72	49.93	50.00	50.07	50.28	9.1
0.5	49.75	49.94	50.01	50.07	50.26	2.8
0.6	49.78	49.94	50.00	50.05	50.21	1.0
0.7	49.81	49.97	50.02	50.08	50.24	0.3
0.8	49.75	49.93	49.98	50.05	50.22	0.1

IV. DISCUSSIONS

The new wind power plant in Suðuroy has led to larger frequency variations. This can be said based on the fact that no other significant changes have been made in the system, that could lead to these variations, and the fact that previous years have an almost identical distribution of the frequency measurements.

When wind turbines are curtailed, the wind power production is less impacted by the nature of the resource, i.e. the wind speed, but this does surprisingly not seem to have an impact on the frequency variations. It was expected that the frequency data during periods where the wind power plant is being curtailed, would have a smaller variation than without curtailment. The data observed here showed the opposite. However, the difference is only 2 mHz, and the data coverage was not the same.

The magnitude of the wind power generation seems to have a larger impact on the frequency variations, but the difference observed is not very significant. The data coverage for the high magnitudes (0.5 p.u. and higher) is limited, and therefore it is difficult to conclude anything from this.

V. CONCLUSIONS

The frequency variations from 50 Hz have almost doubled since the wind power plant has been put into operation. Curtailment does not seem to improve the frequency fluctuations, but there are indications that the magnitude of the wind power has an impact on the variations. The exact reason on why the frequency variations have increased is yet to be identified.

Future analyses with the aim of identifying the actual cause of the variations, could focus on the shares of the wind power generation and the inertia of the system.

REFERENCES

[1] H. M. Tróndheim *et al.*, ‘Frequency and Voltage Analysis of the Hybrid Power System in Suðuroy, Faroe Islands’, in *Proceedings of Virtual 5th International Hybrid Power Systems Workshop*, 2021.

[2] H. M. Tróndheim, B. A. Niclasen, T. Nielsen, C. L. Bak, and F. F. da Silva, ‘Støðug elveiting við óstøðugum orkukeldum’. Tórshavn, Faroe Islands, 2021.

[3] M. G. Schug, A. Gottlieb, and J. DeLoache, ‘“Equal Children Play Best”: Raising Independent Children in a Nordic Welfare State’, in *A World of Babies*, Cambridge: Cambridge University Press, 2016, pp. 261–292.

[4] M. Galarnyk, ‘Understanding Boxplots’, 2018. [Online]. Available: https://towardsdatascience.com/understanding-boxplots-5e2df7bcbd51.