Frequency quality analysis

2023

FINGRID

Table of Contents

Chapter 1. Introduction

This report presents the results of the frequency quality study of the Nordic synchronous system for the year 2023. The results have been obtained by analyzing data from Fingrid's PMU (Phasor Measurement Unit) measurements. All times are given in Finnish time (CET/CEST+1).

Chapter 2 presents information about the measurement data used in this report. Chapter 3 of the report includes a frequency quality reporting framework proposed by the FQ2 (Frequency Quality, Phase 2) Project Report. This chapter also presents the frequency quality evaluation criteria defined in the System Operation Guideline (SO GL) as well as the results from Fingrid's previous years' frequency quality analysis. The fourth chapter presents in detail the frequency disturbances where the deviation exceeds 300 mHz. The last chapter is a summary of the results.

The term standard frequency range is used to refer to frequencies between 49.9 Hz and 50.1 Hz. The current Nordic target level for the number of minutes outside this range is not more than 10 000 minutes per year. 60-second oscillation, which is analyzed in Chapter 3.8, refers to a low-frequency oscillation observed in the Nordic power system with a time period of roughly 60 seconds.

Chapter 2. Measurement data

Frequency data for the analysis outlined in this report was gathered from the PMUs at different locations. For every hour, measurements from the PMU with the largest amount of available data was used. It is assumed that these measurement values represent the frequency of the whole Nordic synchronous system. The frequency data used has a sample rate of 10 Hz, meaning that the interval between two samples is 0.1 s. The data used in this study can be accessed on Fingrid's website [1].

The amount of valid measurement data in percentages per month in 2023 is presented in Table 2.1. The yearly availability of data for years 2018 to 2023 can be seen in Table 2.2 [2,3,4,5,6]. In 2023, there was valid measurement data for 99.58% of the time. Some of the data is missing due to telecommunication errors. From Table 2.1, we can see that the availability has been the worst in July. The other months than have had good availability and there are no significant differences in availability between those months.

Table 2.1. The amount of valid measurement data available per month in 2023

Month	**Available data**
January	99.98 %
February	99.98 %
March	99.99 %
April	99.94 %
May	99.96 %
June	99.98 %
July	95.99 %
August	99.61 %
September	99.96 %
October	99.83 %
November	99.91 %
December	99.97 %

Table 2.2. The amount of valid measurement data available for years 2018-2023

Year	Available data
2018	98.90 %
2019	98.47 %
2020	97.82 %
2021	99.92 %
2022	99.56 %
2023	99.58 %

Chapter 3. Frequency Quality Indices

This chapter includes the frequency quality indices defined and proposed by the Frequency Quality, phase 2 project report, for monitoring frequency quality at all times [7]. Frequency evaluation criteria for the instantaneous frequency data defined in SO GL (System Operation Guideline) Article 131(1)(a) are also presented in this chapter. Article 131 is shown on the following page.

All the input frequency data used to calculate the frequency indices has either a resolution of 0.1 seconds or the average of the 0.1 second data. For example, a resolution of 1 second means that the average of ten 0.1 second values has been used. Most of the proposed indices are presented as averages for every month of the year, day of the week, hour of the day, and minute of the hour. In some instances, yearly variation is also included.

System Operation Guideline, Article 131:

"1. The frequency quality evaluation criteria shall comprise:

(a) for the synchronous area during operation in normal state or alert state as determined by Article 18(1) and (2), on a monthly basis, for the instantaneous frequency data:

(i) the mean value;

(ii) the standard deviation;

(iii) the 1- ,5- ,10- , 90- ,95- and 99-percentile;

(iv) the total time in which the absolute value of the instantaneous frequency deviation was larger than the standard frequency deviation, distinguishing between negative and positive instantaneous frequency deviations;

(v) the total time in which the absolute value of the instantaneous frequency deviation was larger than the maximum instantaneous frequency deviation, distinguishing between negative and positive instantaneous frequency deviations;

(vi) the number of events in which the absolute value of the instantaneous frequency deviation of the synchronous area exceeded 200 % of the standard frequency deviation and the instantaneous frequency deviation was not returned to 50 % of the standard frequency deviation for the CE synchronous area and to the frequency restoration range for the GB, IE/NI and Nordic synchronous areas, within the time to restore frequency. The data shall distinguish between negative and positive frequency deviations;

(b) for each LFC block of the CE or Nordic synchronous areas during operation in normal state or alert state in accordance with Article 18(1) and (2), on a monthly basis:

(i) for a data-set containing the average values of the FRCE of the LFC block for time intervals equal to the time to restore frequency:
- the mean value;
- the standard deviation;
- the 1- ,5- ,10- , 90- ,95- and 99-percentile;
- the number of time intervals in which the average value of the FRCE was outside the Level 1 FRCE range, distinguishing between negative and positive FRCE; and
- the number of time intervals in which the average value of the FRCE was outside the Level 2 FRCE range, distinguishing between negative and positive FRCE."

3.1 Average frequency and standard deviation

This section includes the results for average frequency and standard deviation. Chapter 3.1.3 has the combined results for mean value and standard deviation according to SO GL Article 131(1)(a) (i-ii).

3.1.1 Average frequency

The following figures show the average frequency for the year 2023. The resolution of the frequency data that has been used is 1 second. The average frequency is calculated with the following formula, where f_i is the value of the frequency and n is the number of samples.

$$\bar{f} = \frac{\sum_i^n f_i}{n}$$

Figure 3.1 represents the average frequency for every month. The average frequency has been very close to 50 Hz, as even for the worst months, the averages have deviated less than 0.35 mHz from 50 Hz. The average frequency in 2023 was slightly better than the year before, since the number of over 0.25 mHz deviations was greater in 2022. In addition, the average frequency has been above 50 Hz every month, which is similar to the year 2022 but different from the previous years, where the averages were more evenly distributed around 50 Hz.

Figure 3.1*. *Average frequency for each month in 2023

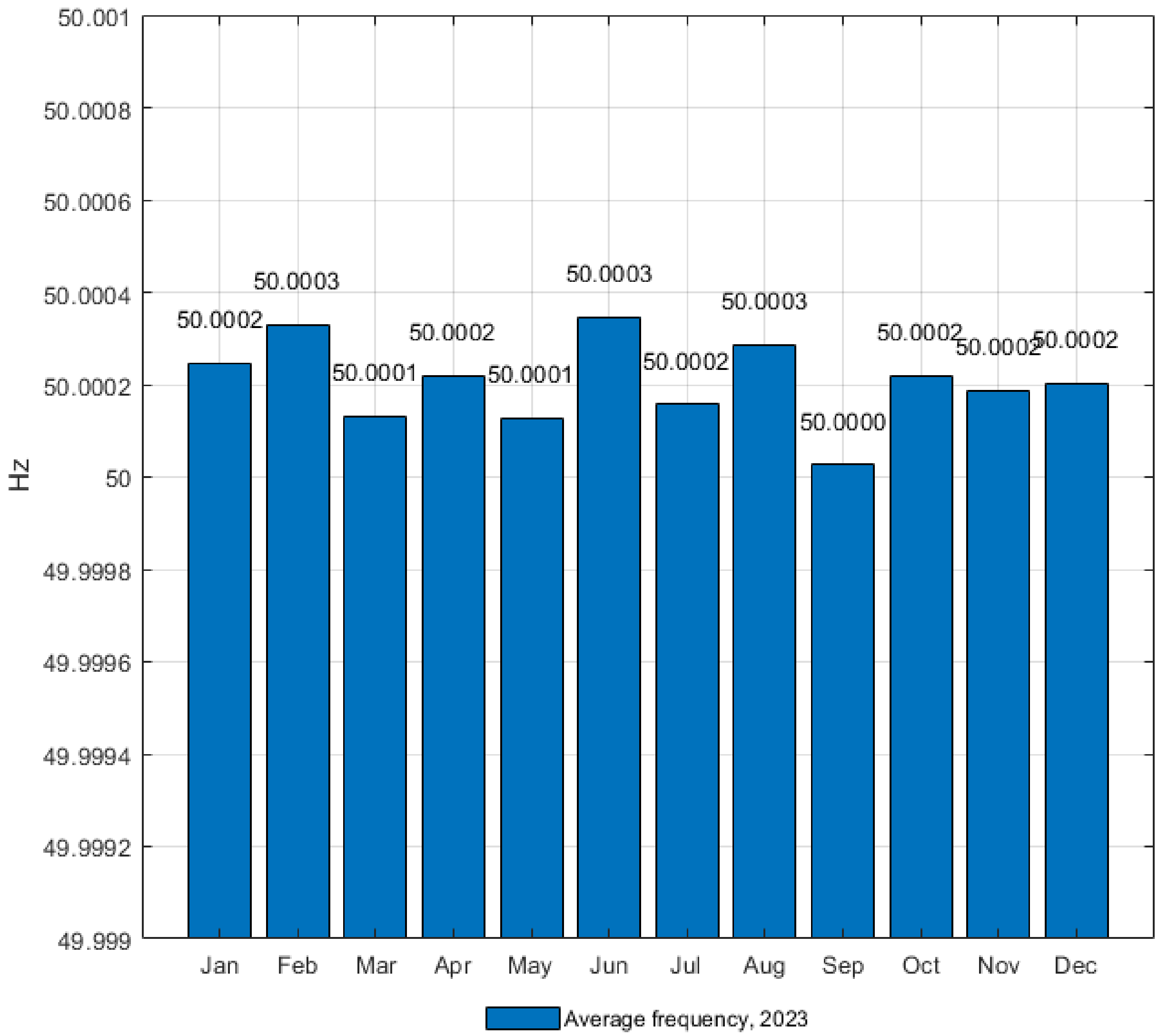


Figure 3.2 shows the average frequencies for each day of the week. The highest average frequency occurred on Monday and the lowest on Thursday. On weekends, the average frequency has been lower than on weekdays.

Figure 3.2*. *Average frequency for each day of the week in 2023

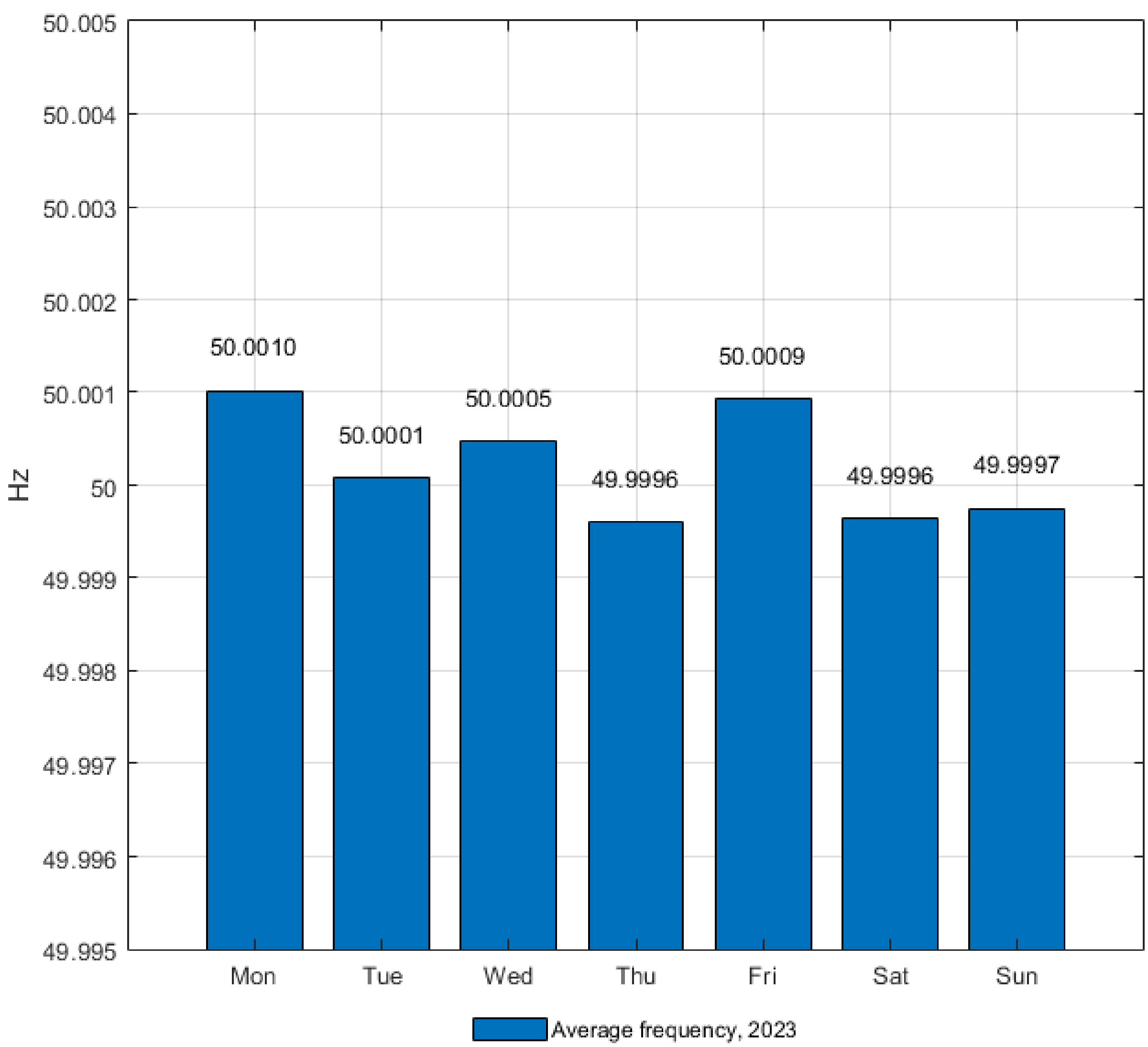


Figure 3.3 shows the average frequencies during each hour of the day. The frequency has been lowest at 7 am and 4 pm. The frequency has been higher around noon, in the evening, apart from 10 pm, and around midnight. The trend is very similar to the year 2022.

Figure 3.3*. *Average frequency for each hour of the day in 2023

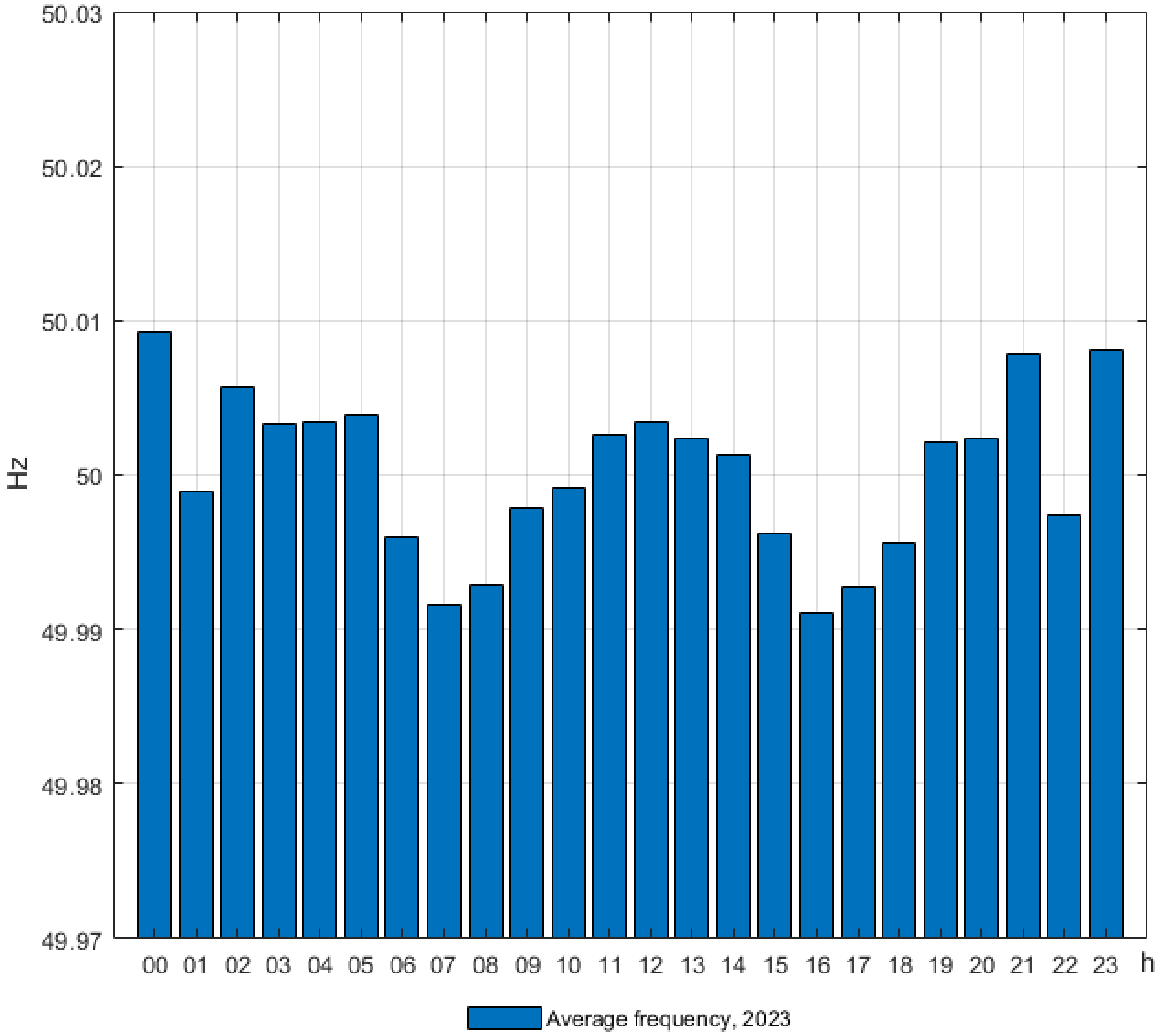
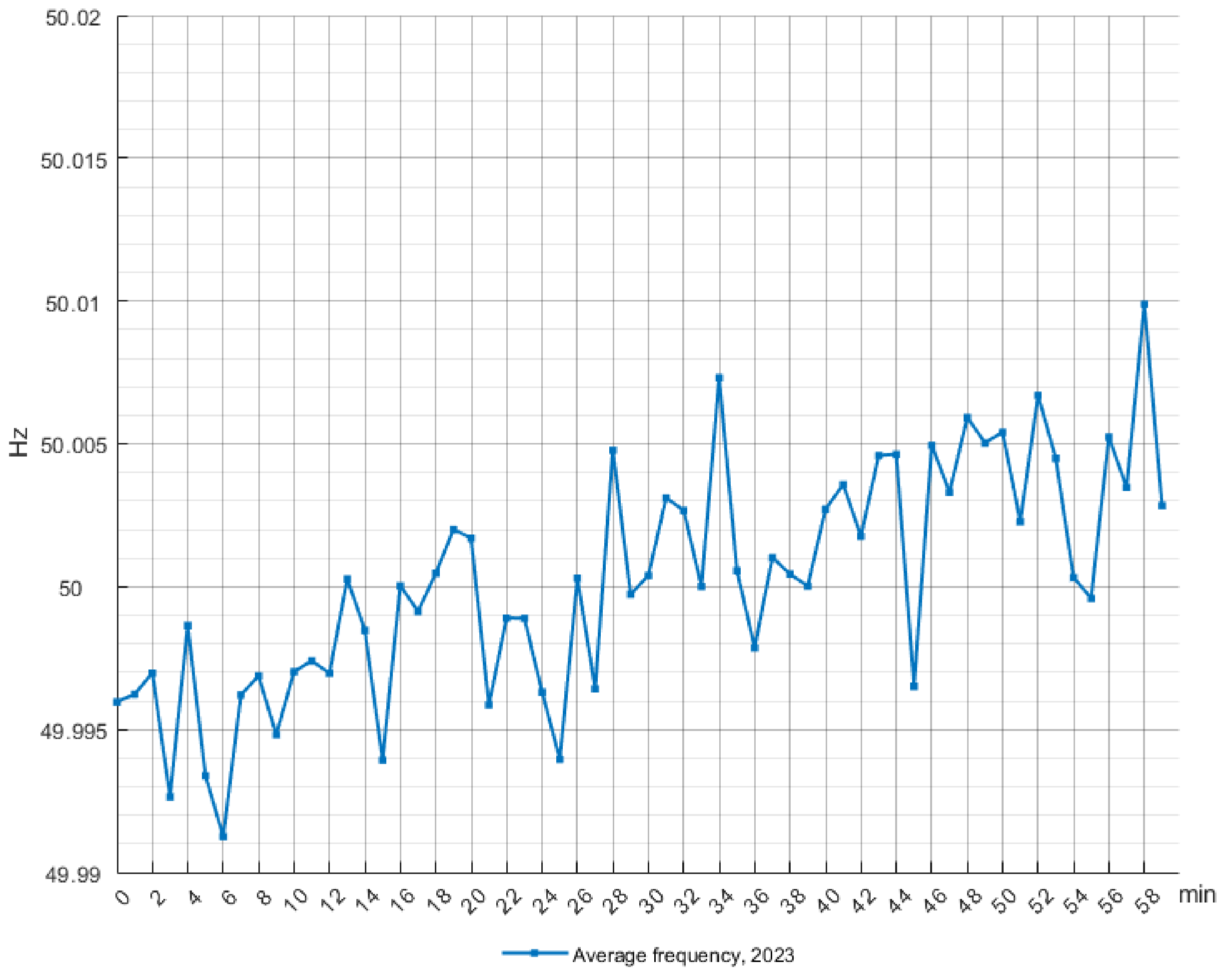


Figure 3.4 shows the average frequency within the hour. In general, the frequency has been higher in the latter part of the hour. The difference between consecutive minutes varies between 0.0 and 8.5 mHz. The largest difference has decreased slightly from the year 2022, when the largest difference was 9.6 mHz.

***Figure 3.4**. Average frequency for each minute of the hour in 2023*



3.1.2 Standard deviation

This section includes the figures representing the standard deviation of frequency during the year 2023. The resolution of the frequency data is 1 second. Below is the formula that was used to calculate the standard deviation.

$$\sigma = \sqrt{\frac{1}{n}\sum_{i}^{n}(f_i - \bar{f})^2}$$

Figure 3.5 shows the standard deviation for each month in 2023. The low values of the standard deviations in July and December indicate that the 1-second frequency values have been closer to the mean value during those months. In May, the standard deviation was the highest. Overall, the frequency has deviated approximately as much as in 2022.

Figure 3.5. Standard deviation of the frequency for every month in 2023

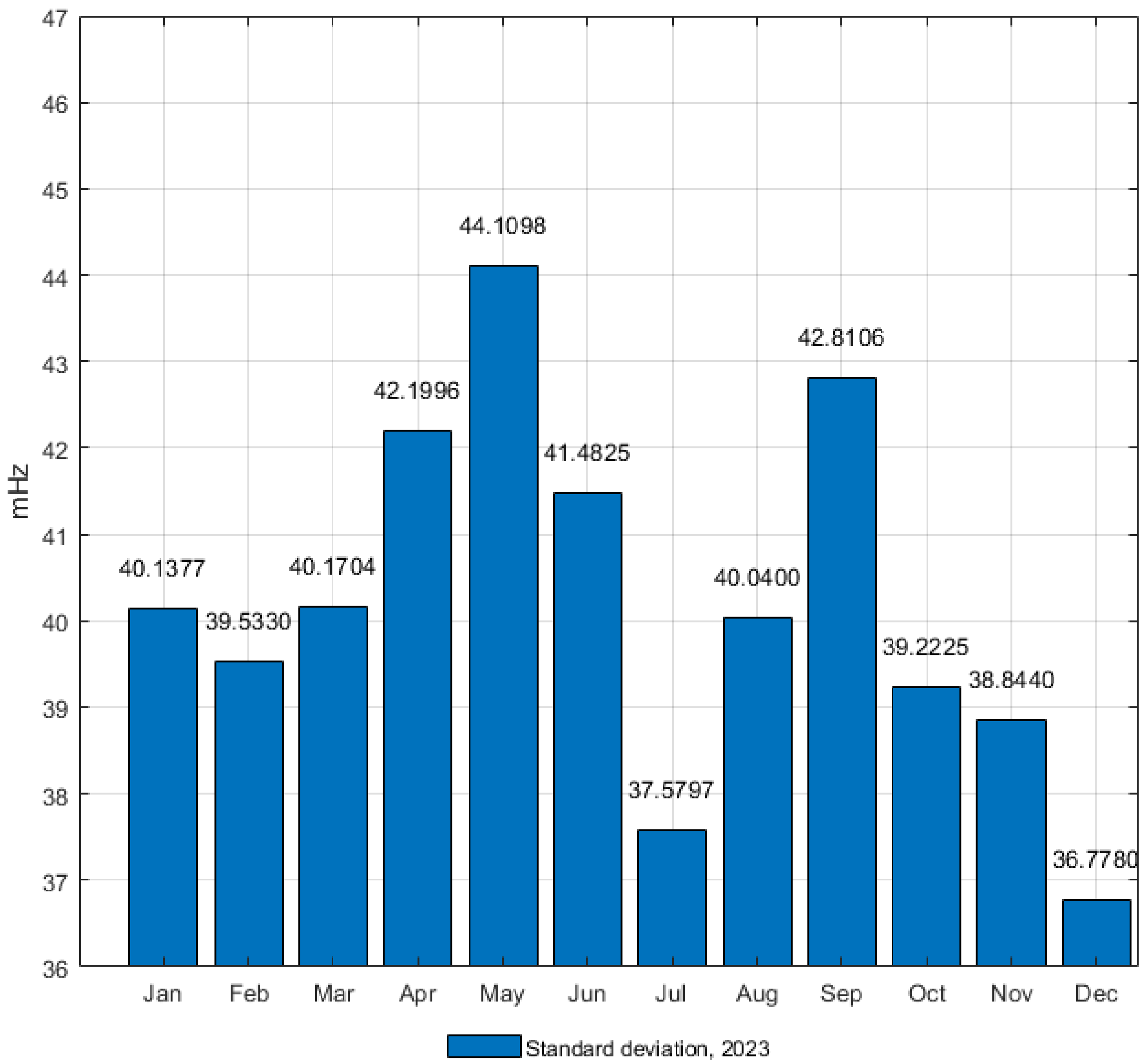


Figure 3.6 represents the standard deviation for each day of the week. Based on the standard deviation, frequency quality has been the worst at the beginning of the week and the best at the end of the week. The trend of a lower standard deviation on weekends is similar to the year 2022.

Figure 3.6. Standard deviation of the frequency for every day of the week in 2023

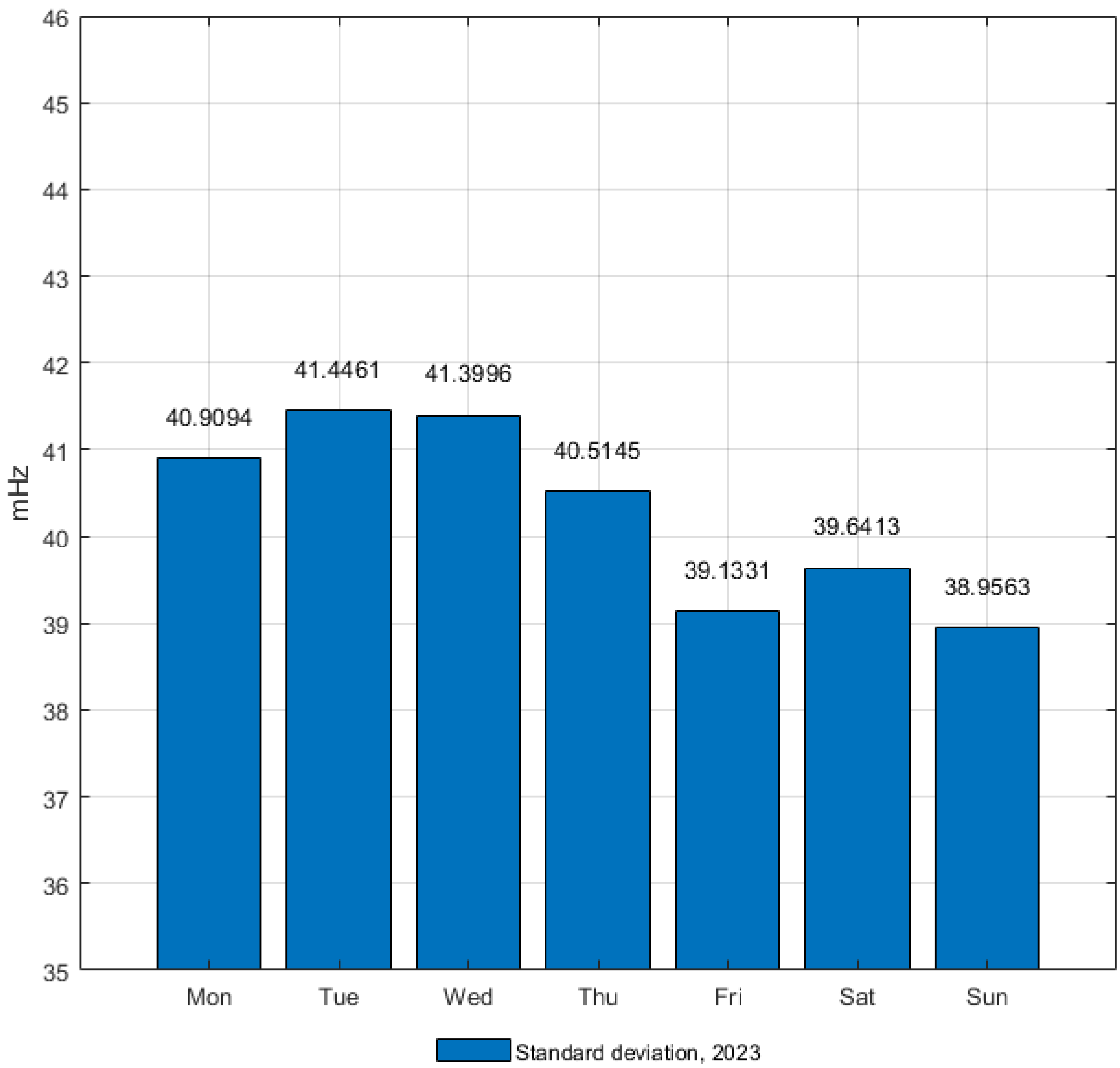


Figure 3.7 shows the standard deviation during each hour of an average day. The standard deviation values have been higher after midnight and lower around noon. The highest values were experienced in the early morning at 2 to 5 am and 7 am. The lowest values were experienced at 6 am and 22 pm. The values are very similar to those for 2022. However, compared to the years 2021 and 2020, standard deviation values are much smaller around noon.

***Figure 3.7**. Standard deviation of the frequency for every hour of the day in 2023*

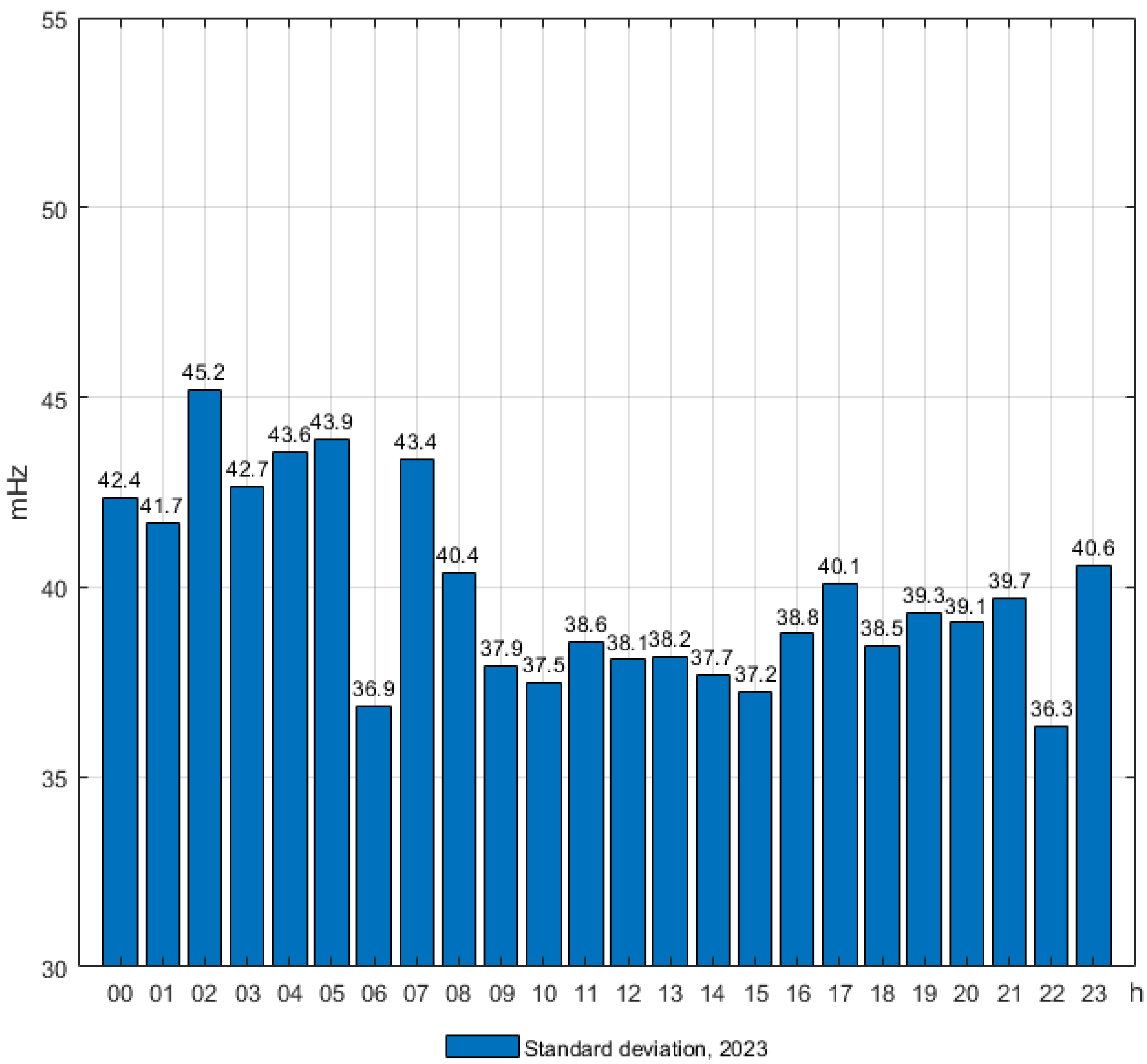
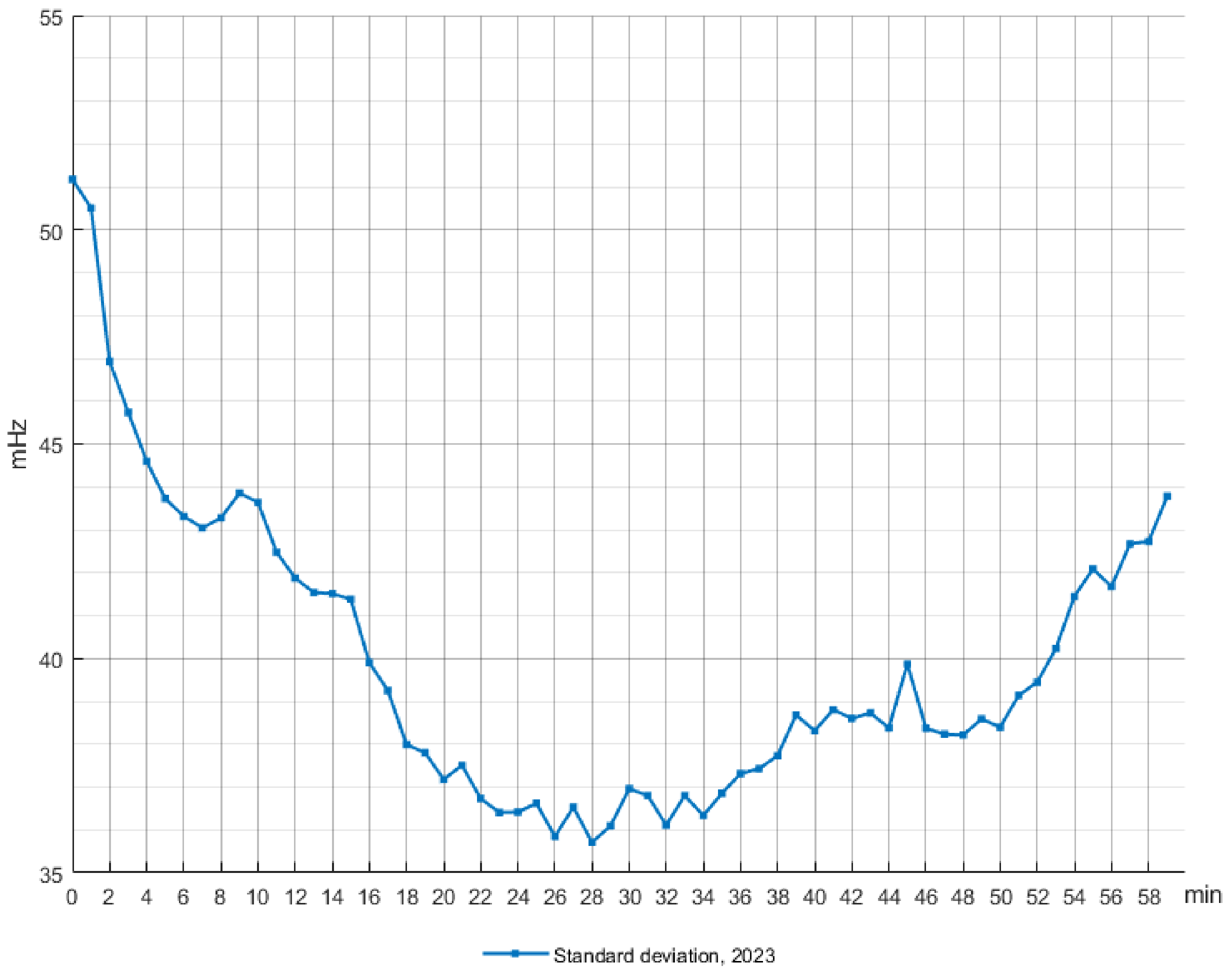


Figure 3.8 represents the standard deviation within an hour. The standard deviation has the highest values at the beginning of the hour, which indicates a weaker quality of frequency during that time. The standard deviation decreases until the half-hour mark, from where it increases again towards the end of the hour.

Figure 3.8*. *Standard deviation of the frequency for every minute of the hour in 2023



3.1.3 Mean value and standard deviation

Mean values and standard deviations of the frequency, according to SO GL Article 131(a) i and (ii), month by month for years 2018 to 2023, can be found in Tables 3.1 and 3.2. The same results are also presented in Figure 3.9. The resolution of the used data is one second.

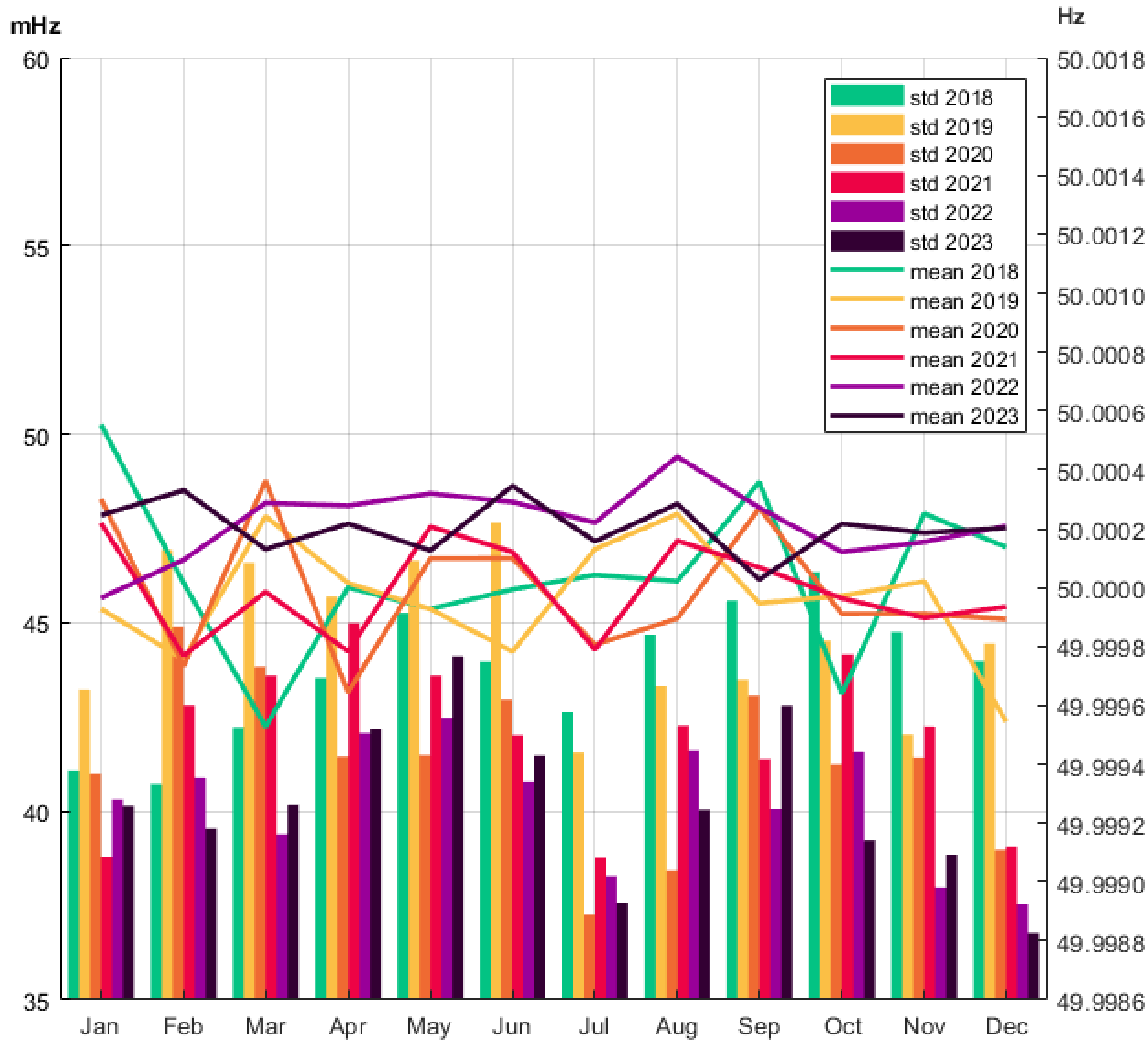
***Table 3.1**. Mean values and standard deviations for years 2018-2020*

	2018		**2019**		**2020**	
Month	**Mean value (Hz)**	**Standard deviation (mHz)**	**Mean value (Hz)**	**Standard deviation (mHz)**	**Mean value (Hz)**	**Standard deviation (mHz)**
January	50.0006	41.1	49.9999	43.2	50.0003	41.0
February	50.0000	40.7	49.9998	46.9	49.9997	44.9
March	49.9995	42.2	50.0002	46.6	50.0004	43.8
April	50.0000	43.5	50.0000	45.7	49.9996	41.5
May	49.9999	45.3	49.9999	46.7	50.0001	41.5
June	50.0000	44.0	49.9998	47.7	50.0001	43.0
July	50.0000	42.6	50.0001	41.6	49.9998	37.3
August	50.0000	44.7	50.0003	43.3	49.9999	38.4
September	50.0004	45.6	49.9999	43.5	50.0003	43.1
October	49.9996	46.3	50.0000	44.5	49.9999	41.2
November	50.0003	44.8	50.0000	42.0	49.9999	41.4
December	50.0001	44.0	49.9995	44.4	49.9999	39.0
Entire year	**50.0000**	**43.8**	**50.0000**	**44.7**	**50.0000**	**41.4**

Table 3.2. Mean values and standard deviations for years 2021-2023

	2021		**2022**		**2023**	
Month	**Mean value (Hz)**	**Standard deviation (mHz)**	**Mean value (Hz)**	**Standard deviation (mHz)**	**Mean value (Hz)**	**Standard deviation (mHz)**
January	50.0002	38.8	50.0000	40.3	50.0002	40.1
February	49.9998	42.8	50.0001	40.9	50.0003	39.5
March	50.0000	43.6	50.0003	39.4	50.0001	40.2
April	49.9998	45.0	50.0003	42.1	50.0002	42.2
May	50.0002	43.6	50.0003	42.5	50.0001	44.1
June	50.0001	42.0	50.0003	40.8	50.0003	41.5
July	49.9998	38.8	50.0002	38.3	50.0002	37.6
August	50.0002	42.3	50.0004	41.6	50.0003	40.0
September	50.0001	41.4	50.0003	40.1	50.0000	42.8
October	50.0000	44.2	50.0001	41.6	50.0002	39.2
November	49.9999	42.3	50.0002	38.0	50.0002	38.8
December	49.9999	39.1	50.0002	37.5	50.0002	36.8
Entire year	**50.0000**	**42.0**	**50.0002**	**40.3**	**50.0002**	**40.3**

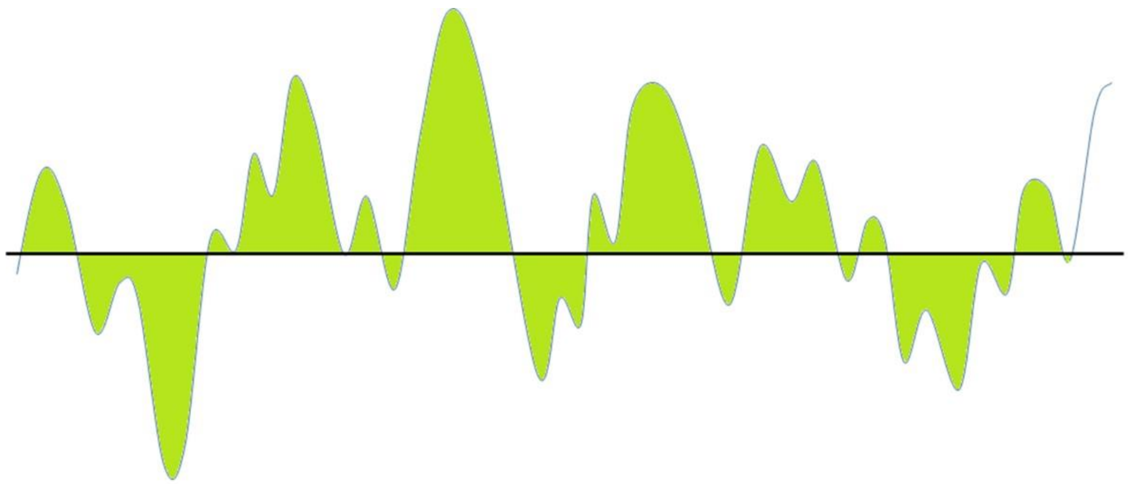
***Figure 3.9**. Mean values and standard deviations for years 2018-2023*



3.2 Frequency area

The frequency area is an indicator of how much the frequency differs from 50.0 Hz. The approach can be seen in Figure 3.10. The value is presented as a share of half of the normal frequency area (49.9-50.1 Hz). For example, when an hourly value is calculated and the frequency has been equal to 49.9 Hz for the whole hour, the value of this index is 100%. The resolution of the input frequency data is 0.1 s. The formula for determining the frequency area is presented below in Figure 3.10.

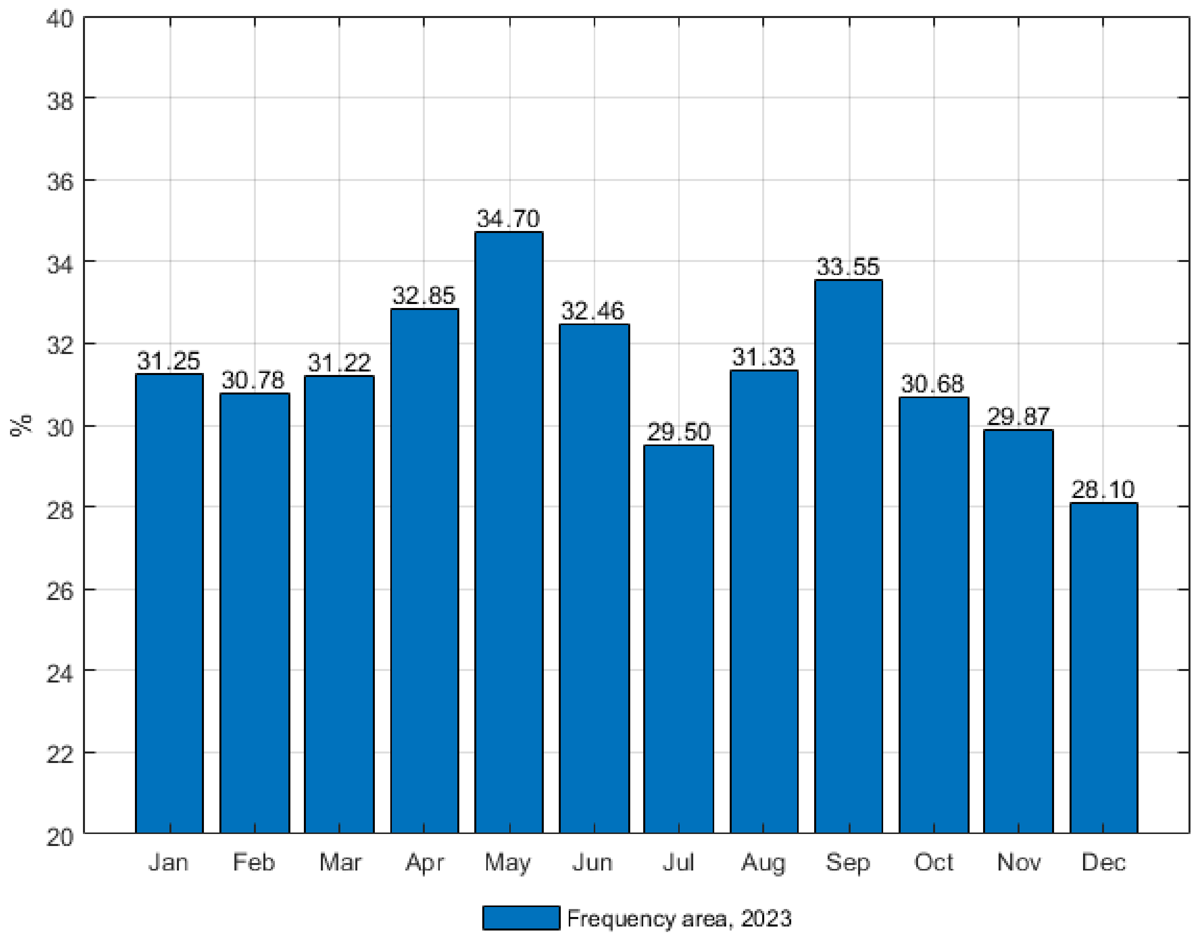
Figure 3.10*. *Frequency quality index: Frequency area [7]



$$Frequency\ area = \frac{1}{n * 0.1Hz} \sum_{i}^{n} |f(i) - 50.0Hz|$$

Figure 3.11 represents the average frequency area for every month in 2023. The frequency area has been the largest in May and September and the smallest in July and December.

***Figure 3.11**. The average frequency area for every month in 2023*



The frequency area during each day of the week can be seen in Figure 3.12. The quality of the frequency has been better at the end of the week and worse at the beginning. The values are very similar to the year 2022, as is the trend of lower values on weekends. Compared to the years 2021 and 2020, the values of the frequency area are lower.

***Figure 3.12**. The average frequency area for every day of the week in 2023*

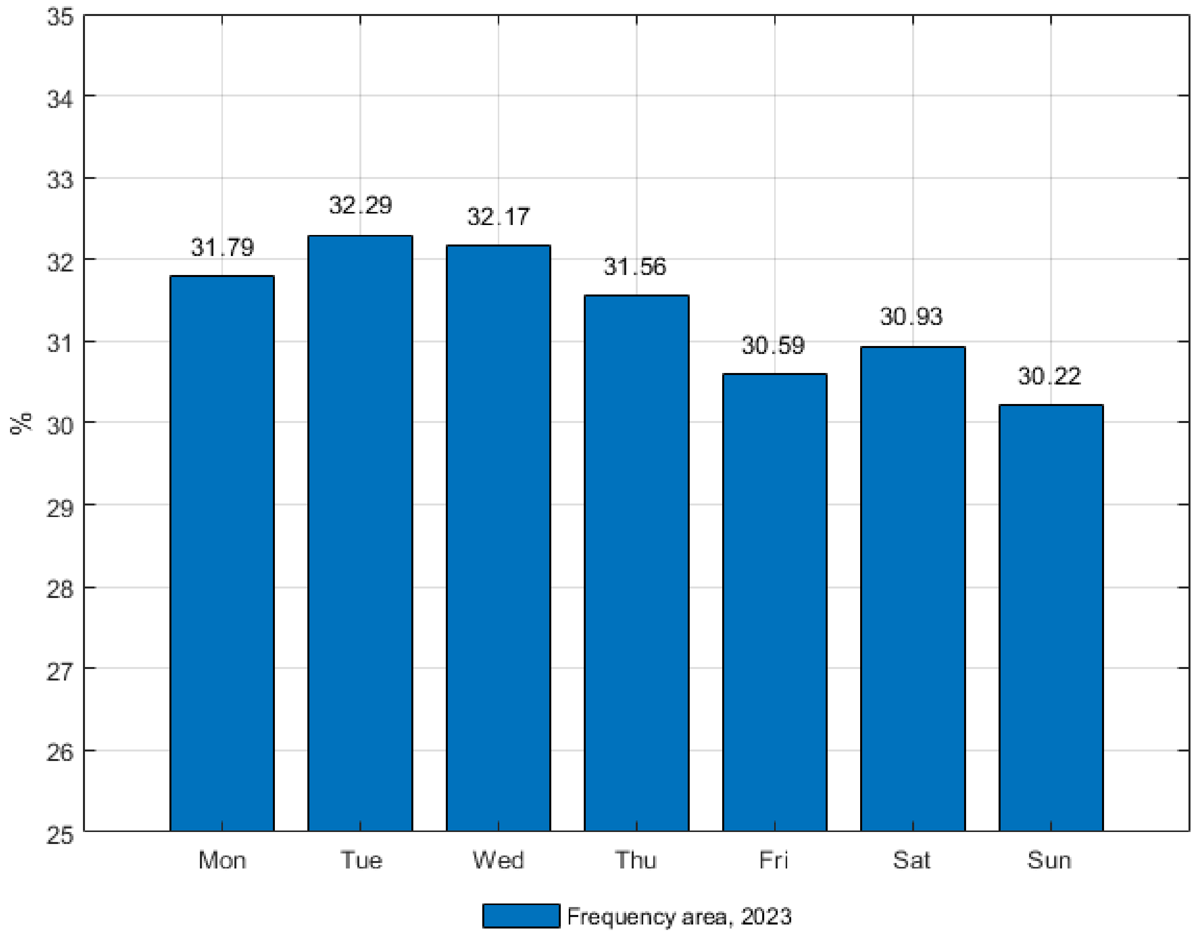


Figure 3.13 represents the frequency area for every hour of the day. The figure shows that the frequency area has been greater on average in the early morning and smaller around noon. This is similar to the year 2022 but differs greatly from the trend of the years 2021 and 2020, where the frequency area values were fairly high around noon.

Figure 3.13. The average frequency area for every hour inside the day in 2023

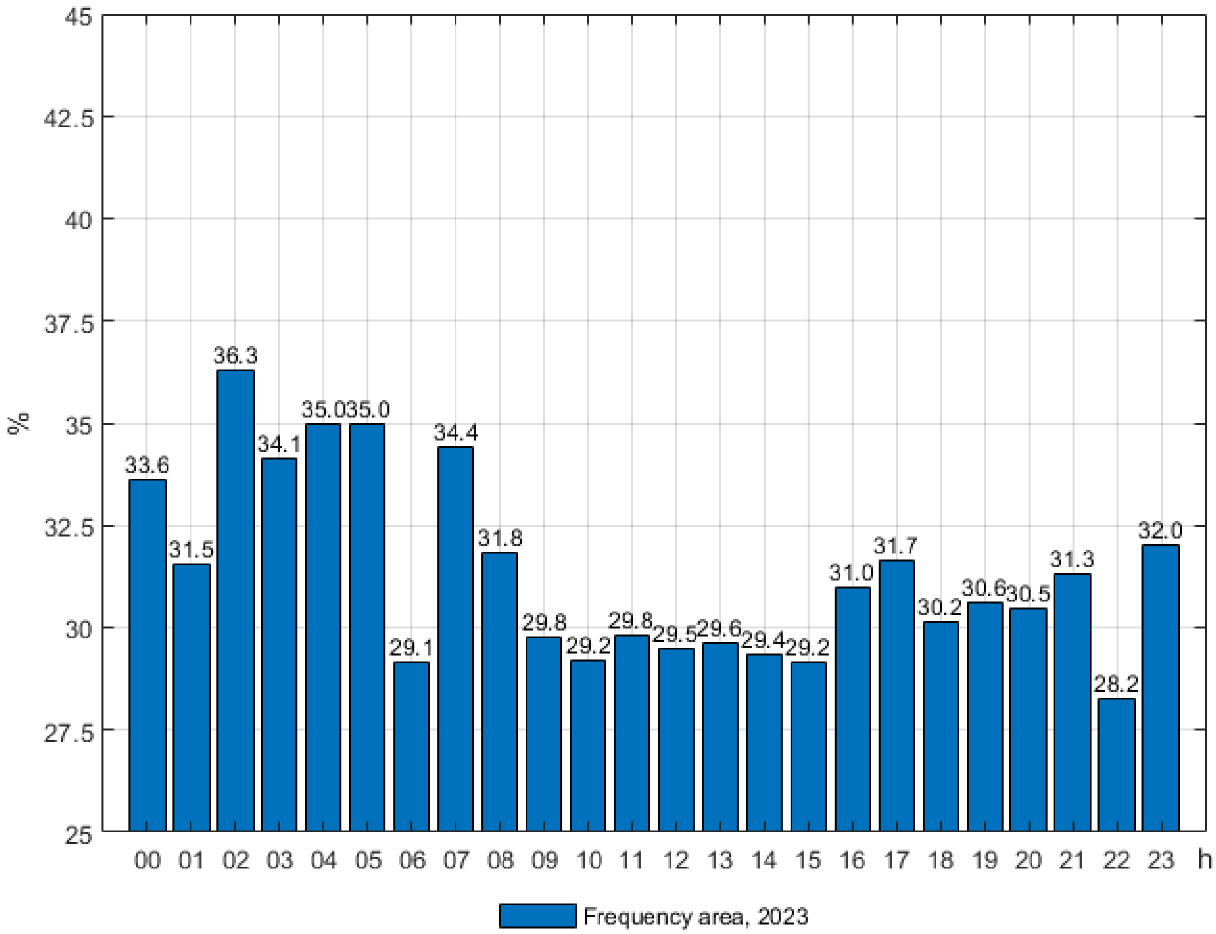
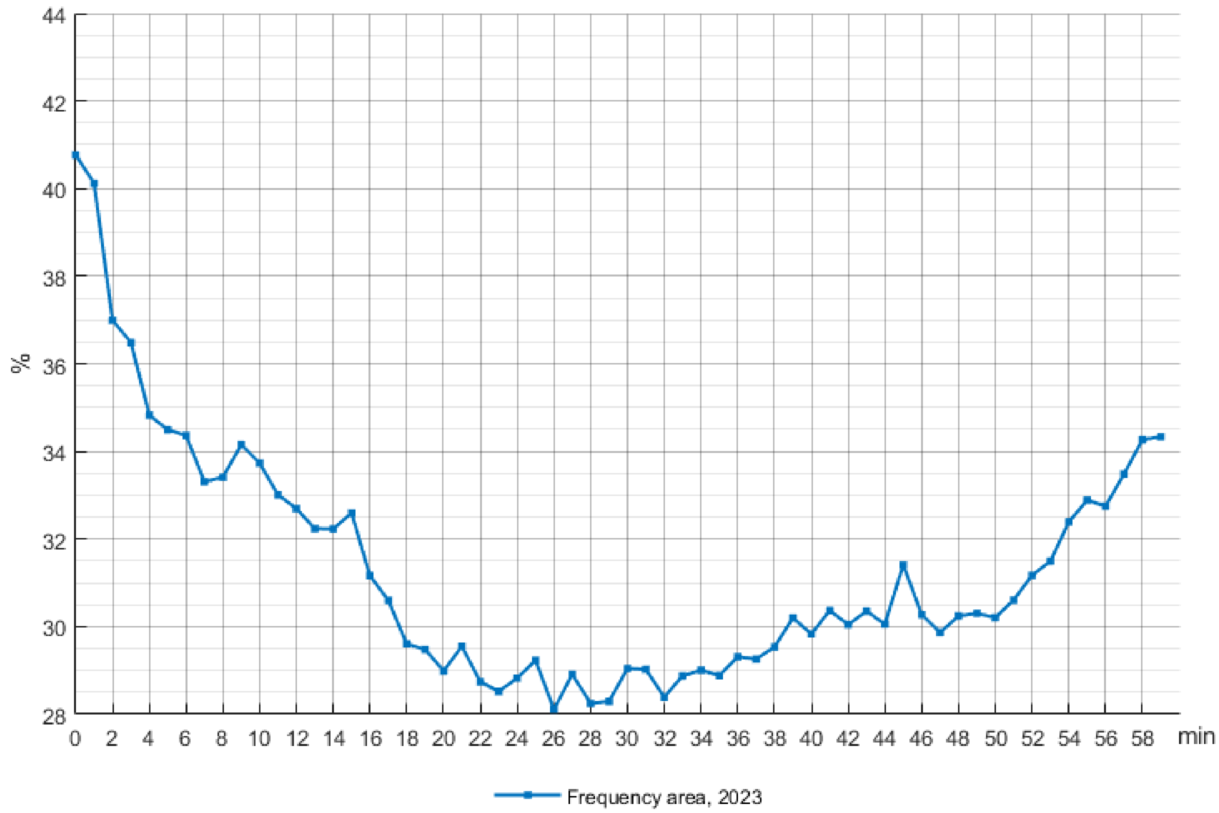


Figure 3.14 represents the frequency area within the hour. The frequency area has been smaller in the middle of the hour, while more deviation has occurred closer to the hour shift and especially in the first minutes of the hour.

***Figure 3.14**. The average frequency area for every minute within the hour in 2023*



3.3 1-, 5-, 10-, 90-, 95-, 99-percentile of frequency

A certain percentile of frequency indicates the frequency below which a given percentage of the samples in the observation period fall. For example, the 1st percentile is the frequency below which 1% of the samples are found. The same criteria are also defined in SO GL Article 131(1)(a) (iii). The resolution frequency of the data is 1 second.

The 1st, 5th, 10th, 90th, 95th, and 99th percentiles were calculated for every month and for the entire year. Tables 3.3-3.8 contain the results from 2018 to 2023. All results are summed up in Figure 3.15.

Table 3.3. The 1st, 5th, 10th, 90th, 95th, and 99th percentiles for the year 2018

	2018					
Month	**1st (Hz)**	**5th (Hz)**	**10th (Hz)**	**90th (Hz)**	**95th (Hz)**	**99th (Hz)**
Jan	49.905	49.934	49.949	50.054	50.069	50.098
Feb	49.907	49.933	49.948	50.053	50.067	50.094
Mar	49.901	49.932	49.946	50.054	50.069	50.100
Apr	49.897	49.929	49.945	50.056	50.072	50.104
May	49.894	49.926	49.943	50.057	50.074	50.108
Jun	49.900	49.929	49.944	50.056	50.073	50.106
Jul	49.901	49.931	49.946	50.053	50.069	50.102
Aug	49.896	49.927	49.943	50.057	50.073	50.106
Sep	49.894	49.926	49.942	50.058	50.074	50.106
Oct	49.891	49.924	49.940	50.059	50.076	50.108
Nov	49.899	49.928	49.943	50.058	50.074	50.106
Dec	49.898	49.930	49.945	50.057	50.073	50.102
Entire year	**49.898**	**49.929**	**49.945**	**50.056**	**50.072**	**50.104**

Table 3.4. The 1st, 5th, 10th, 90th, 95th, and 99th percentiles for the year 2019

	2019					
Month	**1st (Hz)**	**5th (Hz)**	**10th (Hz)**	**90th (Hz)**	**95th (Hz)**	**99th (Hz)**
Jan	49.901	49.930	49.945	50.056	50.071	50.101
Feb	49.895	49.925	49.940	50.061	50.077	50.109
Mar	49.893	49.925	49.941	50.060	50.076	50.107
Apr	49.897	49.927	49.943	50.059	50.076	50.111
May	49.889	49.923	49.940	50.059	50.075	50.106
Jun	49.888	49.922	49.939	50.060	50.077	50.110
Jul	49.905	49.932	49.947	50.053	50.069	50.099
Aug	49.900	49.930	49.946	50.055	50.072	50.104
Sep	49.896	49.929	49.945	50.055	50.071	50.104
Oct	49.895	49.927	49.943	50.056	50.073	50.106
Nov	49.902	49.932	49.947	50.054	50.070	50.102
Dec	49.895	49.927	49.944	50.056	50.072	50.108
Entire year	**49.896**	**49.928**	**49.943**	**50.057**	**50.073**	**50.106**

Table 3.5. The 1st, 5th, 10th, 90th, 95th, and 99th percentiles for the year 2020

	2020					
Month	**1st (Hz)**	**5th (Hz)**	**10th (Hz)**	**90th (Hz)**	**95th (Hz)**	**99th (Hz)**
Jan	49.903	49.932	49.948	50.052	50.067	50.098
Feb	49.896	49.927	49.943	50.057	50.075	50.108
Mar	49.898	49.930	49.946	50.057	50.073	50.106
Apr	49.901	49.932	49.948	50.052	50.068	50.099
May	49.902	49.932	49.948	50.053	50.068	50.099
Jun	49.900	49.930	49.946	50.054	50.071	50.105
Jul	49.913	49.939	49.953	50.047	50.061	50.090
Aug	49.912	49.938	49.952	50.049	50.064	50.094
Sep	49.901	49.932	49.947	50.055	50.072	50.108
Oct	49.904	49.933	49.948	50.052	50.069	50.099
Nov	49.903	49.933	49.948	50.053	50.069	50.099
Dec	49.905	49.936	49.951	50.049	50.063	50.094
Entire year	**49.903**	**49.933**	**49.948**	**50.052**	**50.069**	**50.100**

Table 3.6. The 1st, 5th, 10th, 90th, 95th, and 99th percentiles for year 2021

	2021					
Month	**1st (Hz)**	**5th (Hz)**	**10th (Hz)**	**90th (Hz)**	**95th (Hz)**	**99th (Hz)**
Jan	49.911	49.937	49.951	50.050	50.066	50.094
Feb	49.901	49.932	49.948	50.055	50.072	50.106
Mar	49.902	49.931	49.946	50.056	50.074	50.109
Apr	49.892	49.927	49.944	50.057	50.075	50.110
May	49.899	49.930	49.946	50.056	50.073	50.106
Jun	49.901	49.931	49.947	50.053	50.069	50.100
Jul	49.909	49.937	49.951	50.049	50.064	50.095
Aug	49.902	49.932	49.947	50.053	50.070	50.106
Sep	49.906	49.934	49.949	50.053	50.069	50.102
Oct	49.897	49.929	49.945	50.056	50.074	50.111
Nov	49.900	49.931	49.947	50.053	50.070	50.105
Dec	49.908	49.937	49.951	50.050	50.066	50.096
Entire year	**49.902**	**49.932**	**49.948**	**50.053**	**50.070**	**50.103**

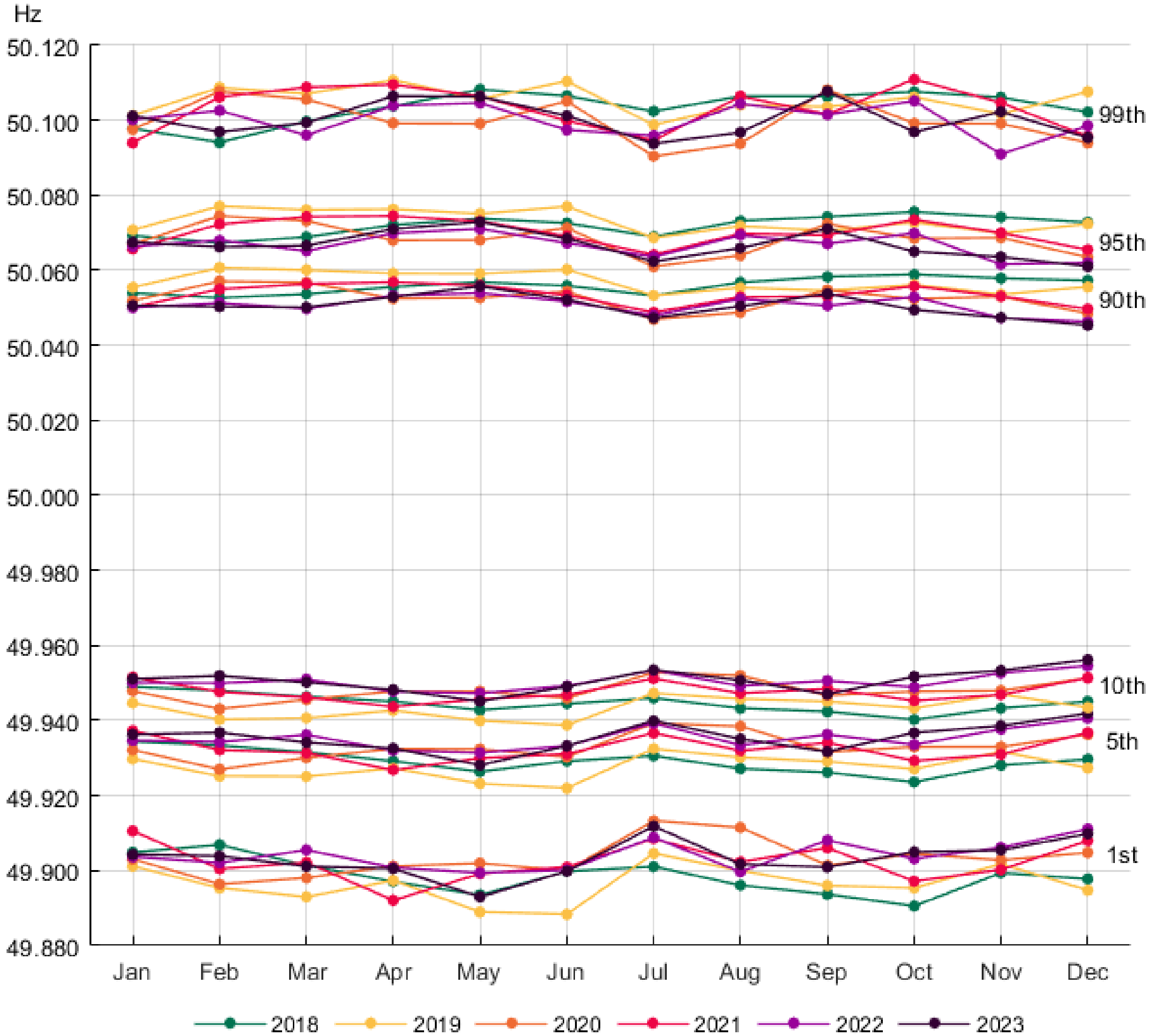
Table 3.7. The 1st, 5th, 10th, 90th, 95th, and 99th percentiles for the year 2022

	2022					
Month	**1st (Hz)**	**5th (Hz)**	**10th (Hz)**	**90th (Hz)**	**95th (Hz)**	**99th (Hz)**
Jan	49.904	49.935	49.950	50.050	50.066	50.100
Feb	49.902	49.934	49.950	50.051	50.068	50.103
Mar	49.905	49.936	49.951	50.050	50.065	50.096
Apr	49.901	49.932	49.948	50.053	50.070	50.104
May	49.899	49.931	49.947	50.054	50.071	50.105
Jun	49.900	49.933	49.949	50.052	50.067	50.097
Jul	49.909	49.939	49.953	50.048	50.064	50.096
Aug	49.900	49.933	49.949	50.052	50.069	50.104
Sep	49.908	49.936	49.951	50.051	50.067	50.102
Oct	49.903	49.934	49.949	50.053	50.070	50.105
Nov	49.906	49.938	49.953	50.047	50.062	50.091
Dec	49.911	49.941	49.955	50.046	50.062	50.099
Entire year	**49.904**	**49.935**	**49.950**	**50.051**	**50.067**	**50.100**

Table 3.8. The 1st, 5th, 10th, 90th, 95th, and 99th percentiles for the year 2023

	2023					
Month	**1st (Hz)**	**5th (Hz)**	**10th (Hz)**	**90th (Hz)**	**95th (Hz)**	**99th (Hz)**
Jan	49.904	49.936	49.951	50.051	50.068	50.101
Feb	49.904	49.937	49.952	50.050	50.066	50.097
Mar	49.901	49.934	49.950	50.050	50.067	50.099
Apr	49.901	49.933	49.948	50.053	50.071	50.106
May	49.893	49.928	49.945	50.056	50.073	50.106
Jun	49.900	49.933	49.949	50.052	50.069	50.101
Jul	49.912	49.940	49.954	50.047	50.062	50.094
Aug	49.902	49.935	49.951	50.050	50.066	50.097
Sep	49.901	49.932	49.947	50.054	50.071	50.108
Oct	49.905	49.937	49.952	50.049	50.065	50.097
Nov	49.905	49.939	49.953	50.047	50.064	50.102
Dec	49.910	49.942	49.956	50.045	50.061	50.095
Entire year	**49.903**	**49.935**	**49.951**	**50.051**	**50.067**	**50.101**

***Figure 3.15**. The 1st, 5th, 10th, 90th, 95th, and 99th percentiles for the years 2018-2023*



More detailed results for the percentiles of 2023 are shown in the next figures. Figure 3.16 is a visual representation of the given percentiles for each month in 2023. The percentiles in May and September are the furthest away from 50 Hz, which indicates that the frequency values are spread around 50 Hz with a wide distribution. In July and December, the percentiles were closest to 50 Hz, which suggests that the frequency deviations have remained within a more limited range. Apart from May and September, the 95th, 90th, 10th, and 5th percentiles have been closer to 50 Hz than on an average year of the observation period.

***Figure 3.16**. The 1st, 5th, 10th, 90th, 95th, and 99th percentile of the frequency for every month in 2023*

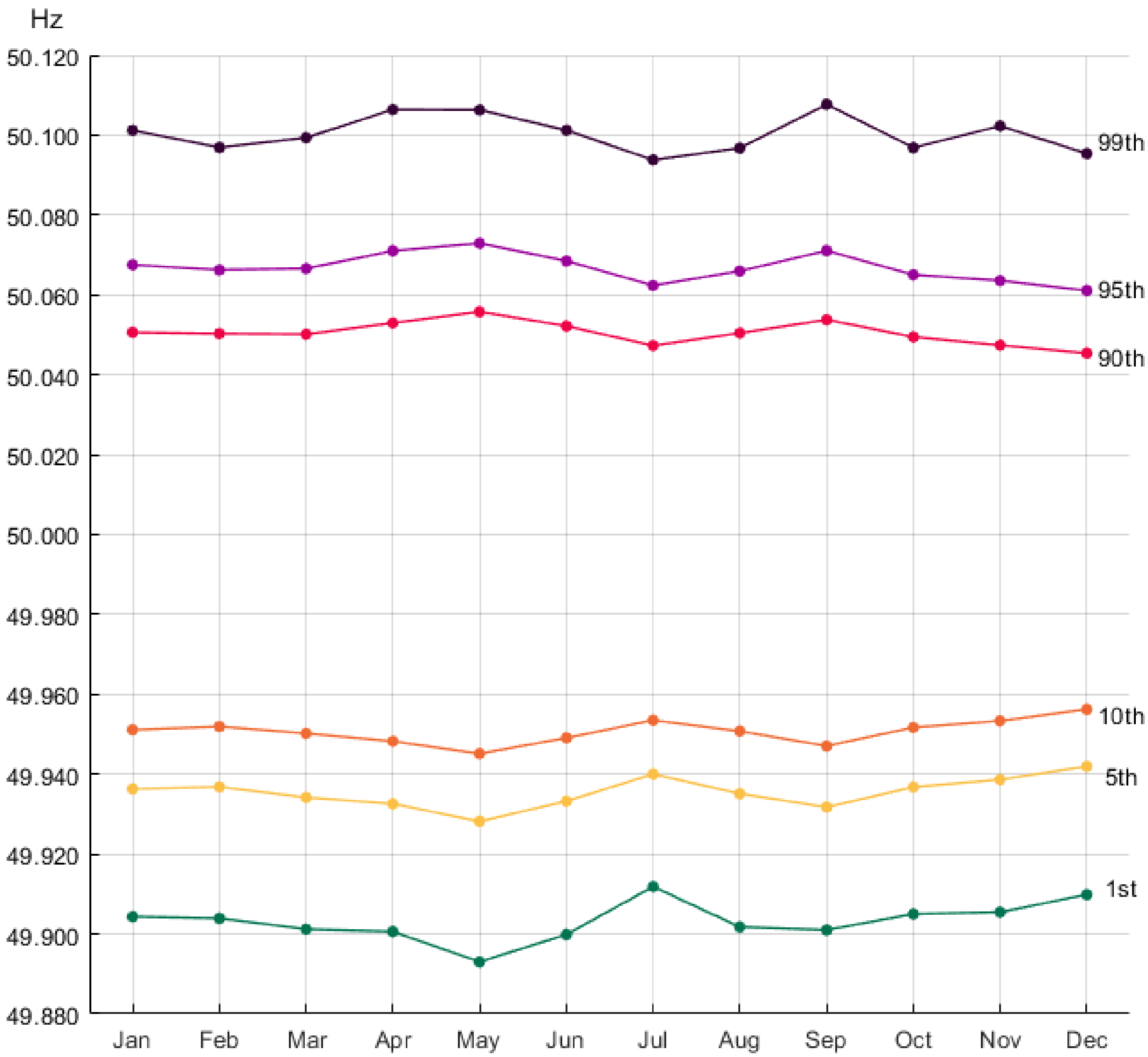


Figure 3.17 shows the percentiles for each day during the week. The percentiles at the beginning of the week are the furthest away from 50 Hz, which indicates that the frequency has deviated on a wider range during those days. In contrast, the percentiles are slightly closer to 50 Hz on Friday, Saturday, and Sunday.

***Figure 3.17**. The 1st, 5th, 10th, 90th, 95th, and 99th percentile of the frequency for every day of the week in 2023*

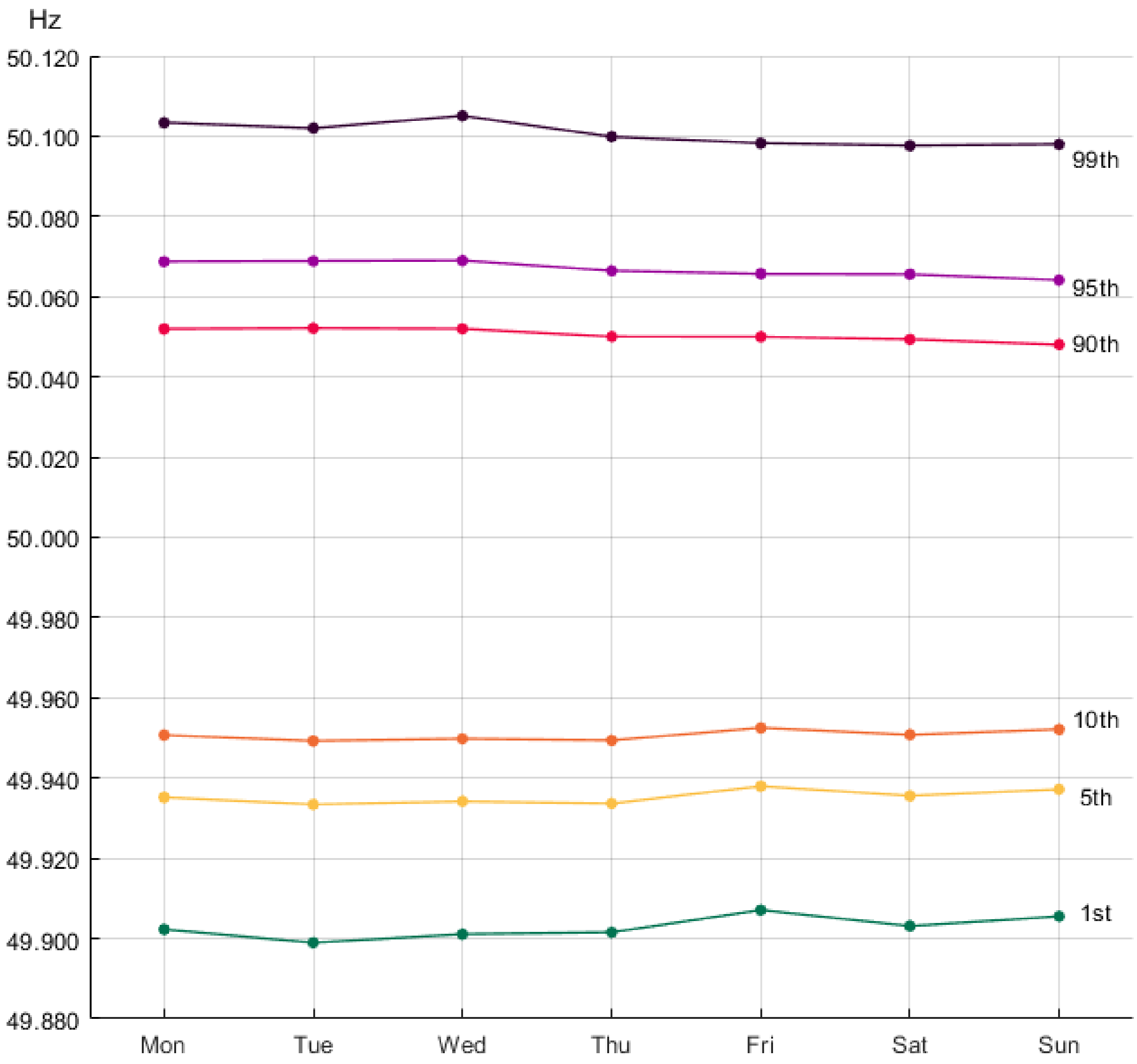


Figure 3.18 represents the percentiles within a day. All percentiles gain higher values at 9 pm, 11 pm and at midnight. This indicates that there have been more over frequencies and fewer under frequencies. Under frequencies are more typical at 1 am, 7-8 am, and in the early evening around 4-5 pm.

***Figure 3.18**. The 1st, 5th, 10th, 90th, 95th, and 99th percentile of the frequency for every hour of the day in 2023*

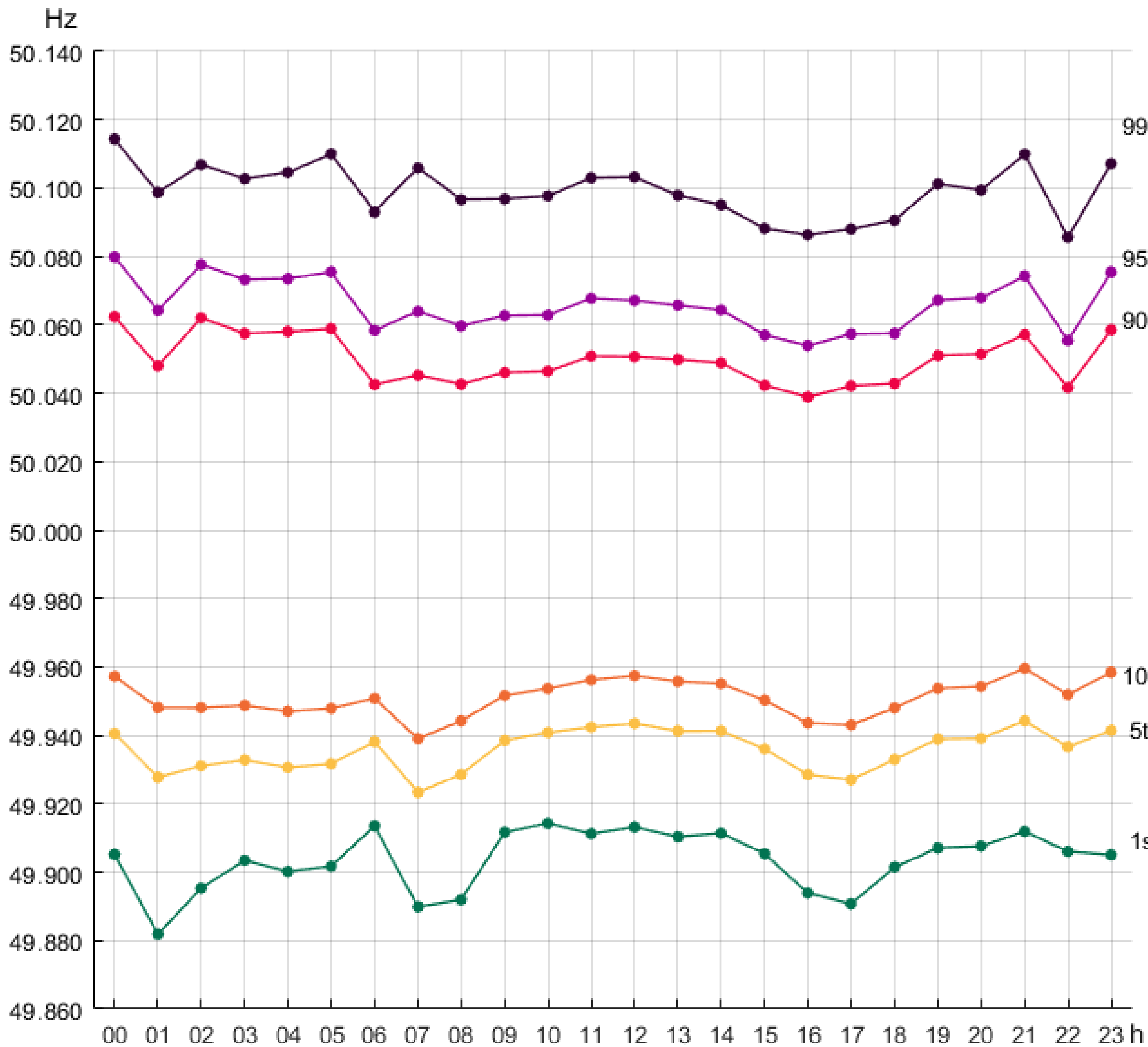
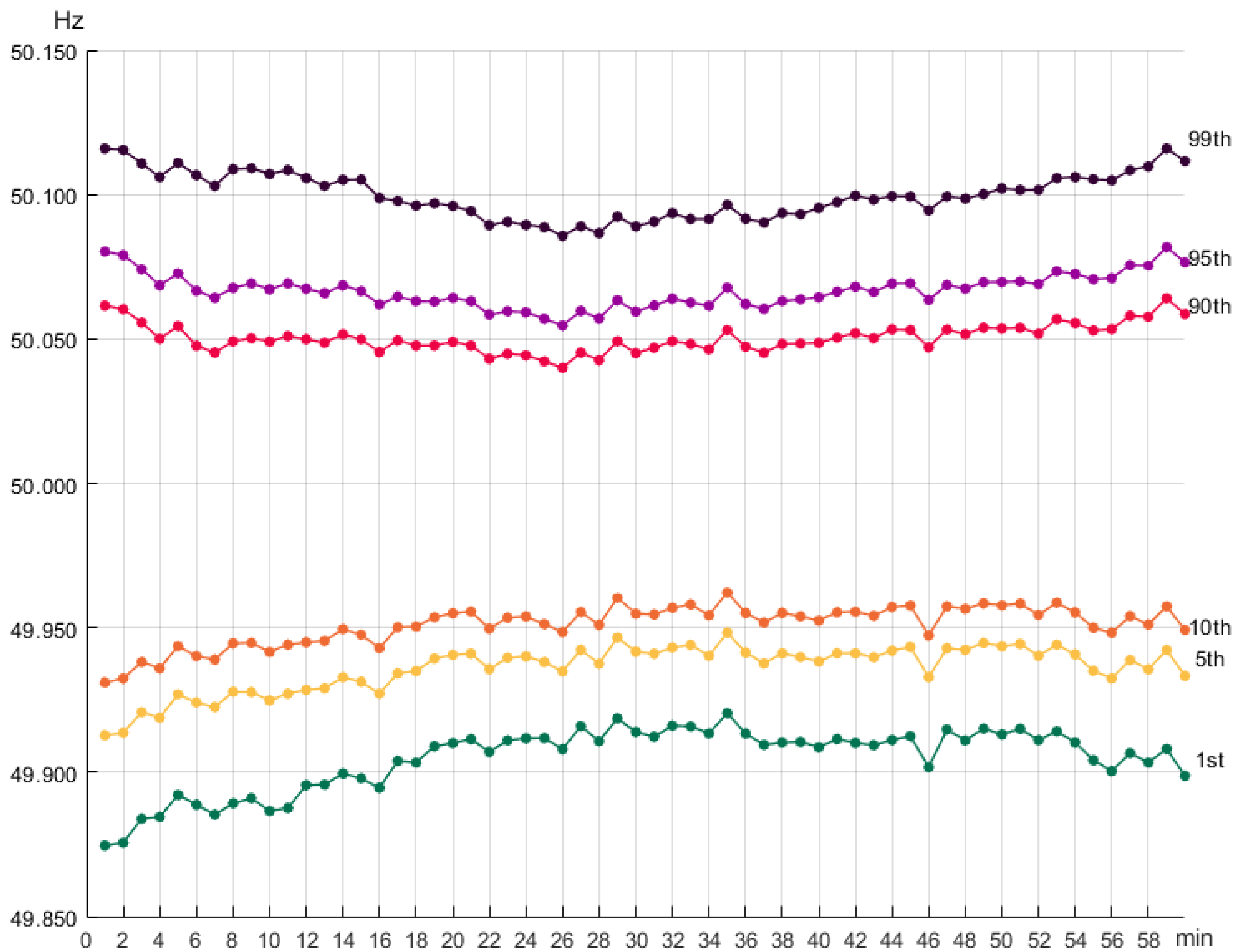


Figure 3.19 shows the percentiles within an hour. Overall, more frequency deviation has occurred close to the hour shift. The 90th, 95th, and 99th percentiles gain the highest values during a time interval of a few minutes at the hour shift. The 10th, 5th, and 1st percentiles gain the lowest values at the first minutes of the hour.

***Figure 3.19**. The 1st, 5th, 10th, 90th, 95th, and 99th percentile of the frequency for every minute inside the hour in 2023*



3.4 Time outside different ranges

Time outside a specific range is calculated by multiplying the number of samples that are outside the given frequency range by the time duration of the sample. This calculation uses data where the interval between consecutive samples is 1 second.

3.4.1 Time outside 49.9-50.1 Hz

Figure 3.20 shows cumulative minutes outside the standard frequency range in 2023. The frequency has been outside the standard range for around 10 000 minutes, which is right at the limit of the current Nordic target level. The cumulative growth of minutes outside the standard frequency range is less steady compared to 2022. From the middle of June until the end of August, the cumulative growth has been slower.

Figure 3.20. Cumulative minutes outside the standard frequency range in 2023

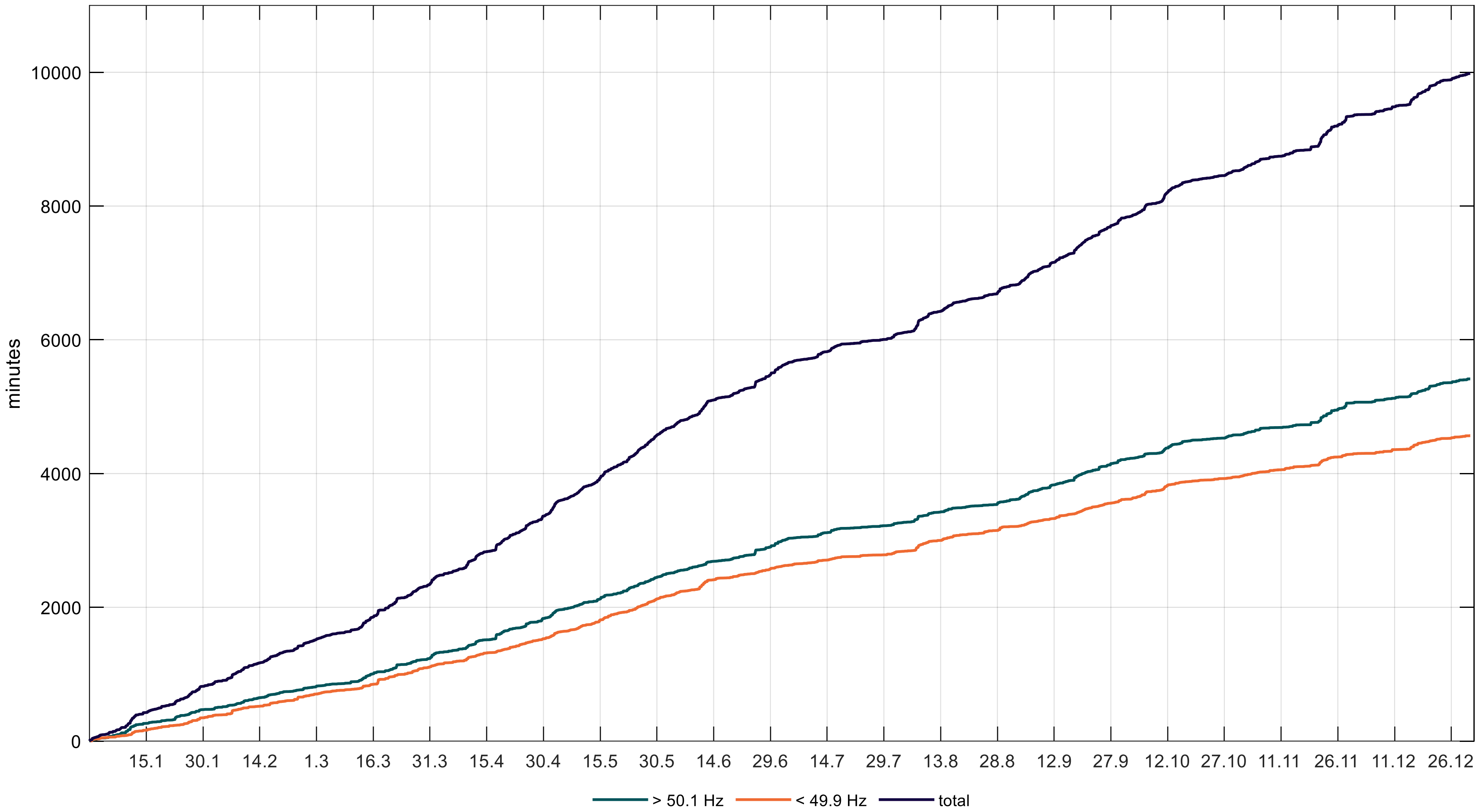
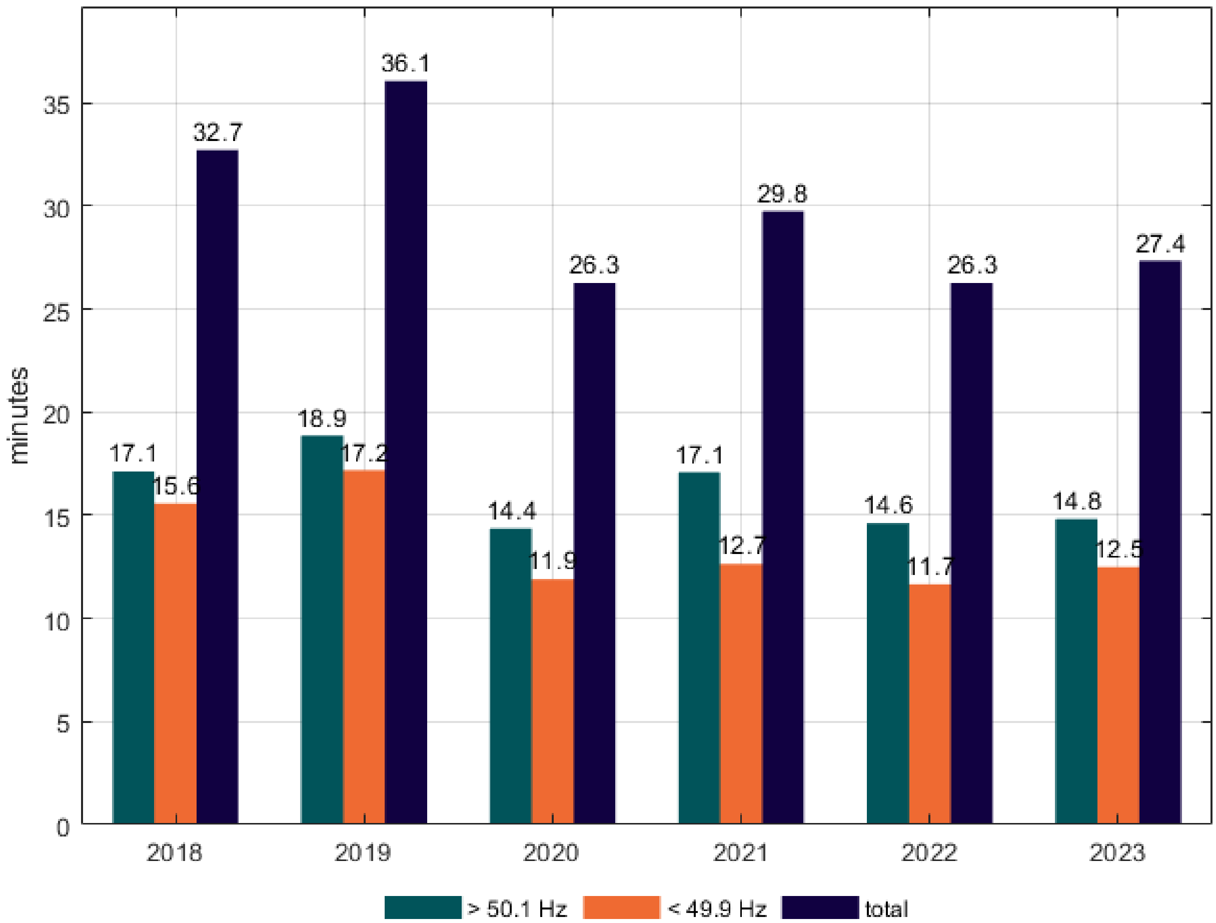


Figure 3.21 represents the daily average number of minutes for which the frequency was outside the standard frequency range in 2023. The number of minutes outside the standard frequency range has slightly increased since 2022. Every year, there have been more over frequencies than under frequencies.

***Figure 3.21**. Daily average number of minutes per year that the frequency was outside the standard frequency range in 2018-2023*



The same results can be seen in Table 3.9 as a percentage of time in and outside the standard frequency range. The availability of the data has been taken into account so that 100% corresponds to the total time for which the data was available.

Table 3.9. Percentage of time over, below, and inside the standard frequency range

Year	> 50.1 Hz	< 49.9 Hz	49.9 Hz - 50.1 Hz
2018	1.20 %	1.09 %	97.70 %
2019	1.33 %	1.21 %	97.46 %
2020	1.02 %	0.85 %	98.13 %
2021	1.19 %	0.88 %	97.93 %
2022	1.02 %	0.81 %	98.17 %
2023	1.03 %	0.87 %	98.09 %

Table 3.10 presents the total duration in minutes per year for which the frequency has been over or below the standard frequency range and the total number of minutes outside the standard frequency range. Values have been scaled with the availability of data to estimate true minutes outside the standard frequency range per year.

Table 3.10. Minutes over and below the standard frequency range

Year	> 50.1 Hz (min)	< 49.9 Hz (min)	Total (min)
2018	6328	5755	12083
2019	6997	6377	13374
2020	5375	4456	9831
2021	6247	4621	10868
2022	5357	4273	9630
2023	5438	4586	10025

Tables 3.11 and 3.12 contain the total time (in minutes) for which the frequency was outside the standard frequency range (49.9-50.1 Hz) month by month for the years 2018-2023. These results are based on the evaluation criteria defined in SO GL Article 131(1)(a) (iv). The results from the previous tables are not entirely comparable due to differences in the availability of measurement data. The same information is presented visually in Figure 3.22.

Table 3.11. Total time for which the frequency was outside the 49.9-50.1 Hz band in years 2018-2020

	2018		**2019**		**2020**	
Month	**> 50.1 Hz (min)**	**< 49.9 Hz (min)**	**> 50.1 Hz (min)**	**< 49.9 Hz (min)**	**> 50.1 Hz (min)**	**< 49.9 Hz (min)**
January	386	340	478	414	385	375
February	272	266	632	519	619	506
March	436	415	650	628	598	489
April	529	501	709	501	411	405
May	582	547	507	633	422	399
June	588	436	719	766	563	430
July	495	419	413	332	251	179
August	608	549	552	444	259	179
September	598	585	515	526	614	390
October	662	708	606	568	420	333
November	596	447	471	387	397	359
December	508	497	637	584	320	352
Entire year	**6258**	**5709**	**6890**	**6302**	**5258**	**4396**

Table 3.12. Total time for which the frequency was outside the 49.9-50.1 Hz band in years 2021-2023

	2021		**2022**		**2023**	
Month	**> 50.1 Hz (min)**	**< 49.9 Hz (min)**	**> 50.1 Hz (min)**	**< 49.9 Hz (min)**	**> 50.1 Hz (min)**	**< 49.9 Hz (min)**
January	299	199	449	363	474	356
February	547	393	454	361	332	334
March	687	390	339	315	428	420
April	682	620	524	413	600	420
May	618	466	568	460	629	621
June	428	407	373	428	459	436
July	322	262	357	285	305	211
August	589	386	555	453	365	407
September	471	295	464	267	617	408
October	717	516	574	374	370	342
November	537	425	255	306	478	334
December	346	275	420	233	359	278
Entire year	**6242**	**4631**	**5334**	**4260**	**5416**	**4568**

***Figure 3.22**. Total time for which the frequency was outside the 49.9-50.1 band in years 2018-2023*

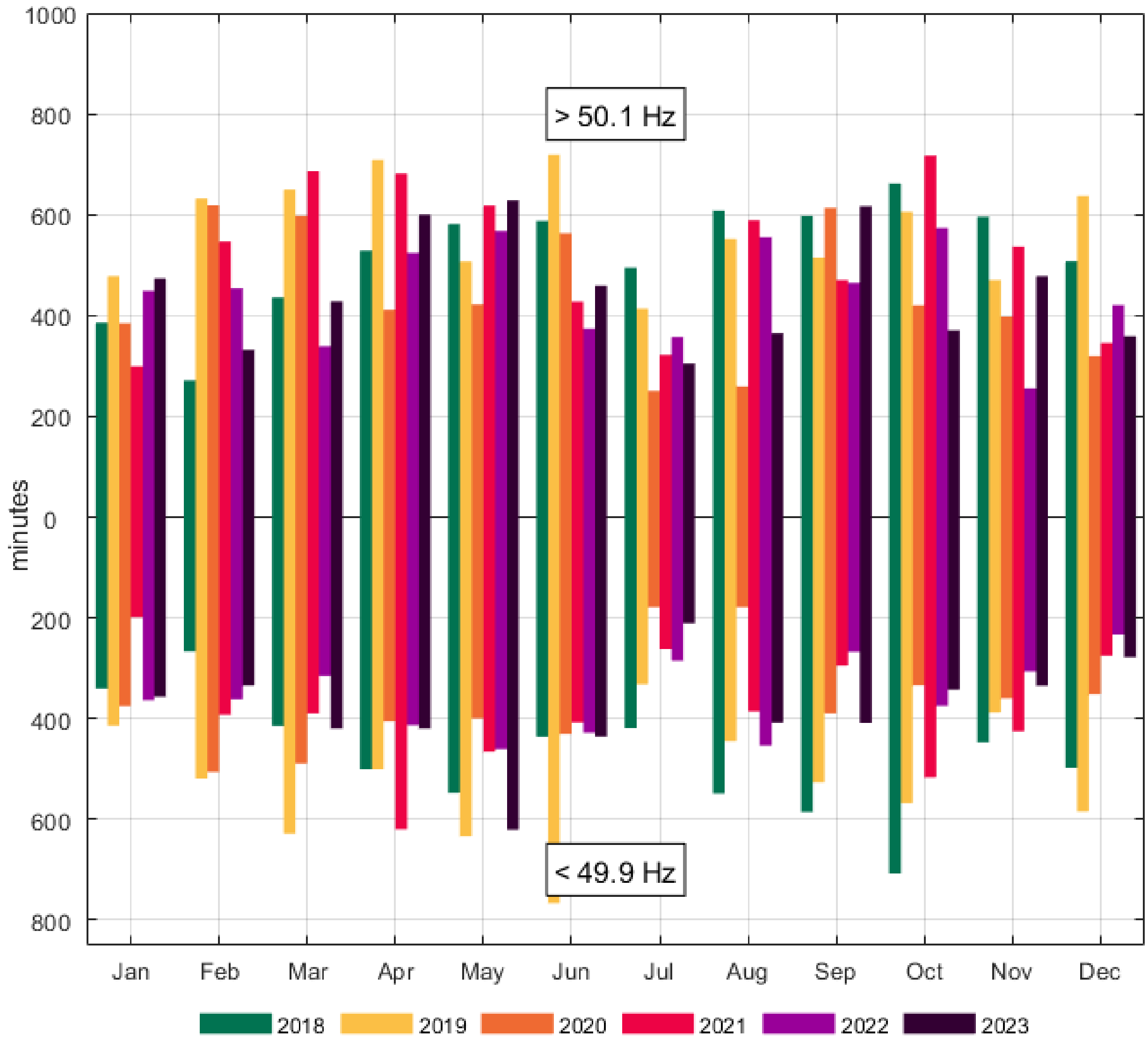


Figure 3.23 shows the daily average in minutes, month by month, for which the frequency has been outside the standard frequency range in the years 2018-2023. In 2023, May had the longest time outside the standard frequency range. July and December had the best frequency in this comparison.

***Figure 3.23**. Daily average time for which the frequency was outside the standard frequency range month by month for years 2018-2023*

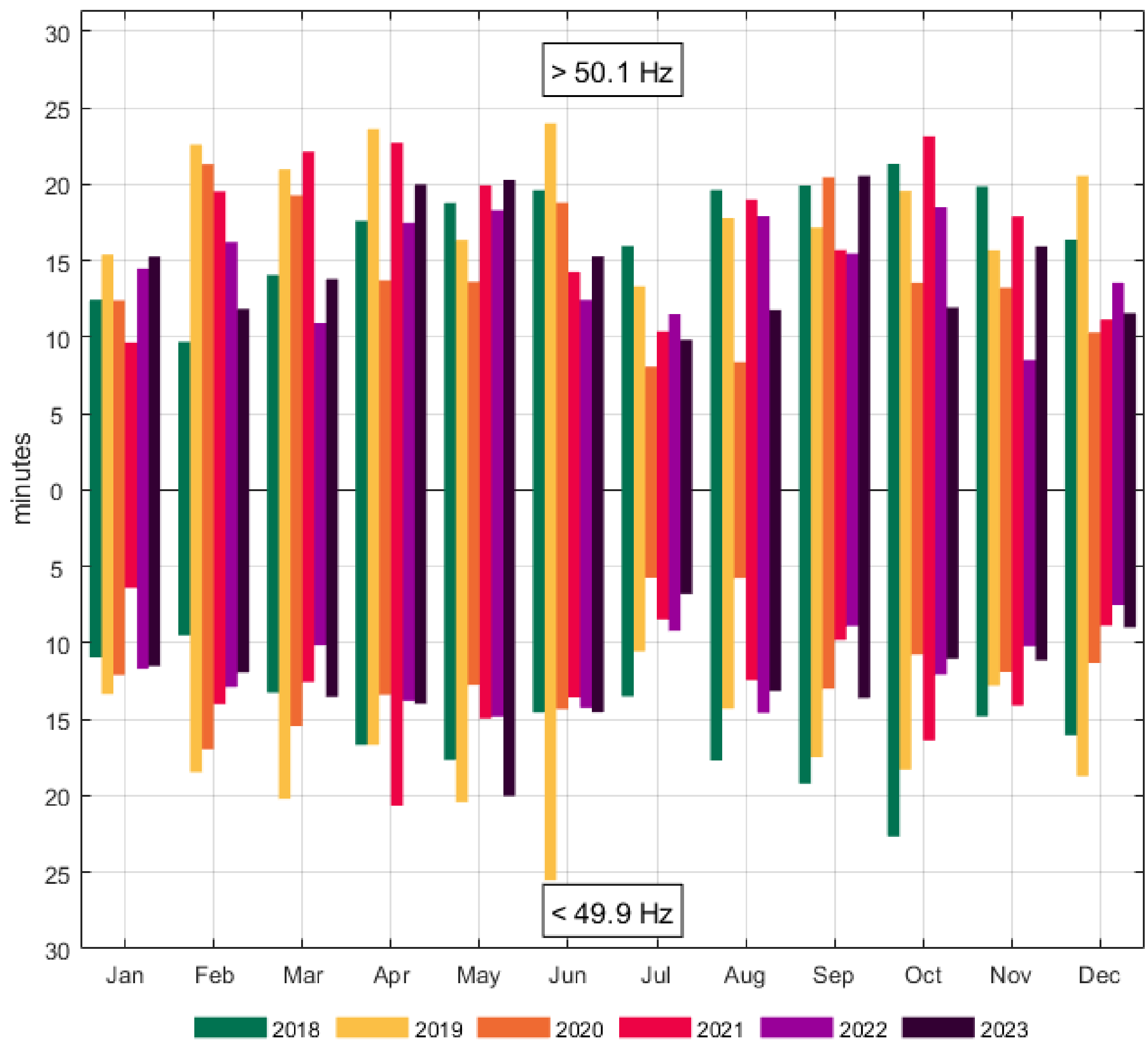


Figure 3.24 represents the daily average time for which the frequency has been outside the standard frequency range during each day of the week. In 2023, the frequency has been outside the standard frequency range the most at the beginning of the week and the least on Friday and on weekends.

***Figure 3.24**. Daily average time that the frequency was outside the standard frequency range during each day of the week for years 2018-2023*

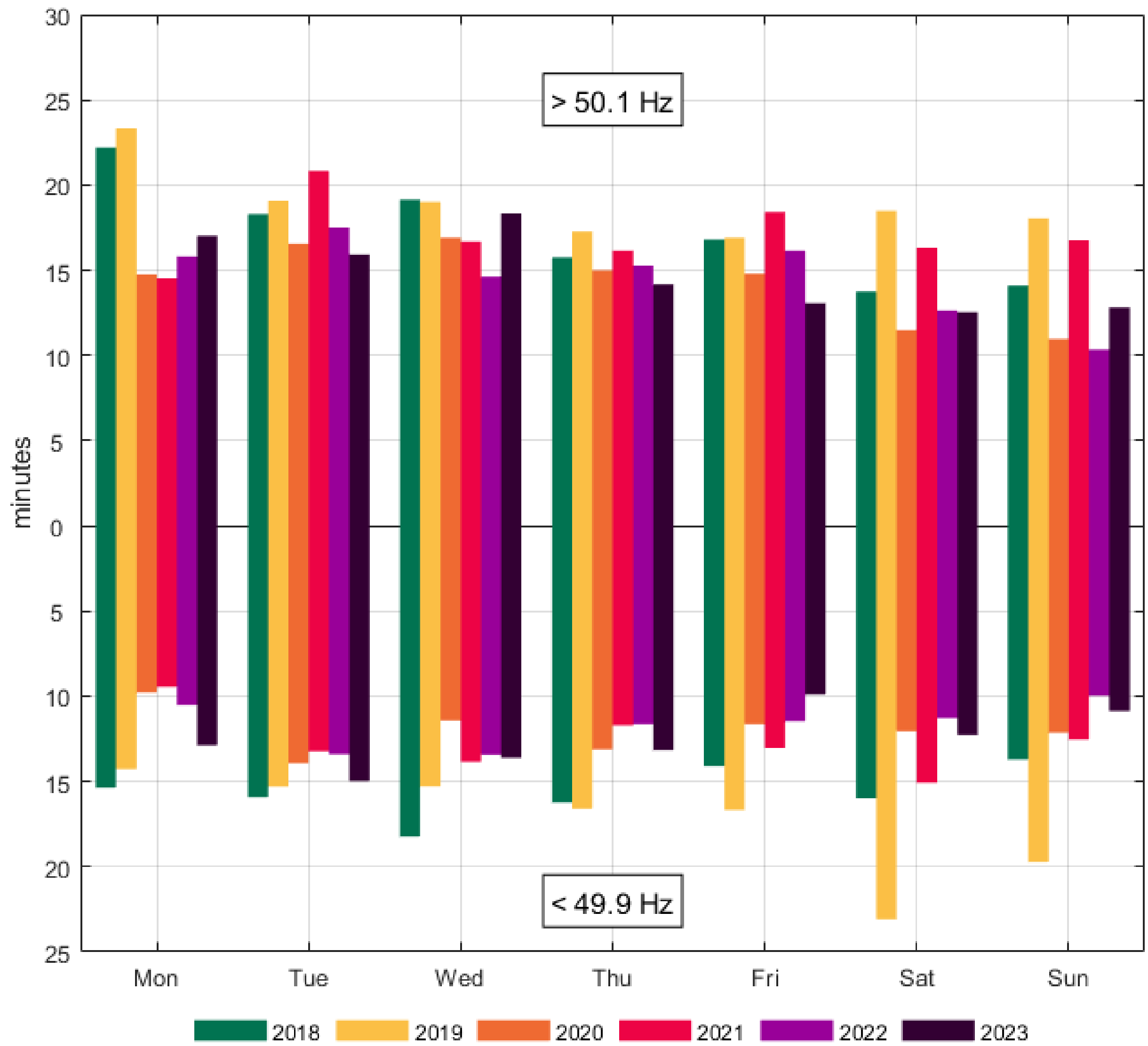


Figure 3.25 represents the daily average time for which the frequency was outside the standard frequency range for each hour within a day. In 2023, the frequency went above 50.1 Hz the most at midnight and at 9 and 11 pm. Frequencies under 49.9 Hz were the most common at 1 am, 7 am, and 5 pm. The frequency was most consistently within the standard frequency range between 9 am and 3 pm.

***Figure 3.25**. Daily average time for which the frequency was outside the standard frequency range during each hour of the day for years 2018-2023*

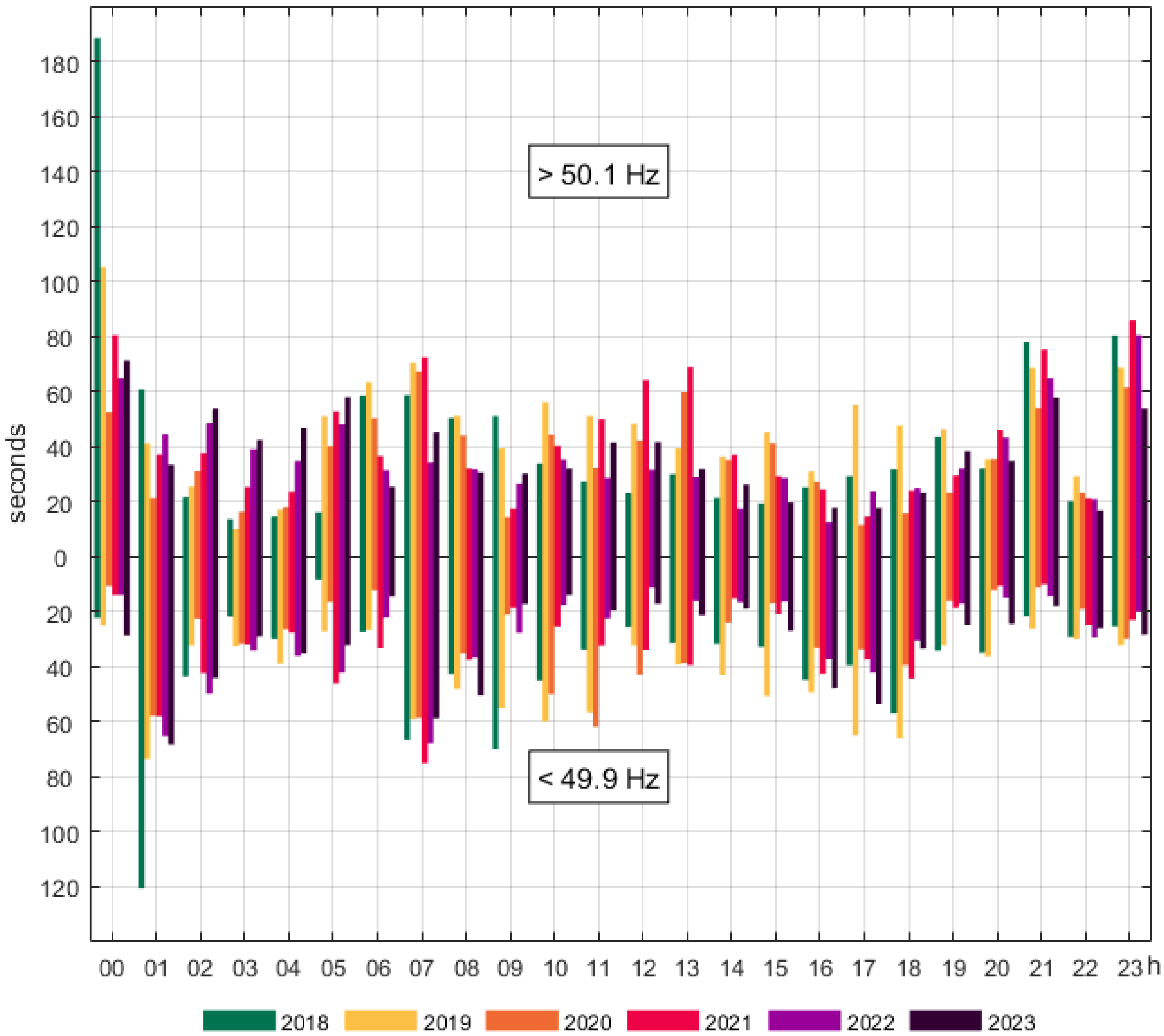


Figure 3.26 shows the daily average time outside the standard frequency range per hour and the absolute value of Nordic consumption and production differences. Also, the transmission difference of HVDC links connecting the Nordic power system to the rest of Europe is presented.

The differences were calculated by subtracting the average power of the previous hour from the corresponding value of the current hour. The differences are presented as absolute values. Consumption and production data were retrieved from the ENTSO-E Transparency platform website, and the transmission powers of the HVDC links are direct measurement data. The hours are given in Finnish time (UTC+2 / UTC+3).

In the morning, the peak for production difference is around 2300 MWh, and for consumption difference, the peak is around 1900 MWh. At midnight, the peak for production difference is around 1600 MWh, and the peak for consumption difference is around 1400 MWh. The peaks in HVDC transmission differences have gained higher values compared to 2022. The peak at 6 pm is around 700 MWh, while in 2022 it was around 500 MWh.

***Figure 3.26*. Seconds per hour outside the standard frequency range and the absolute values of Nordic consumption, production and HVDC transmission differences in 2023**

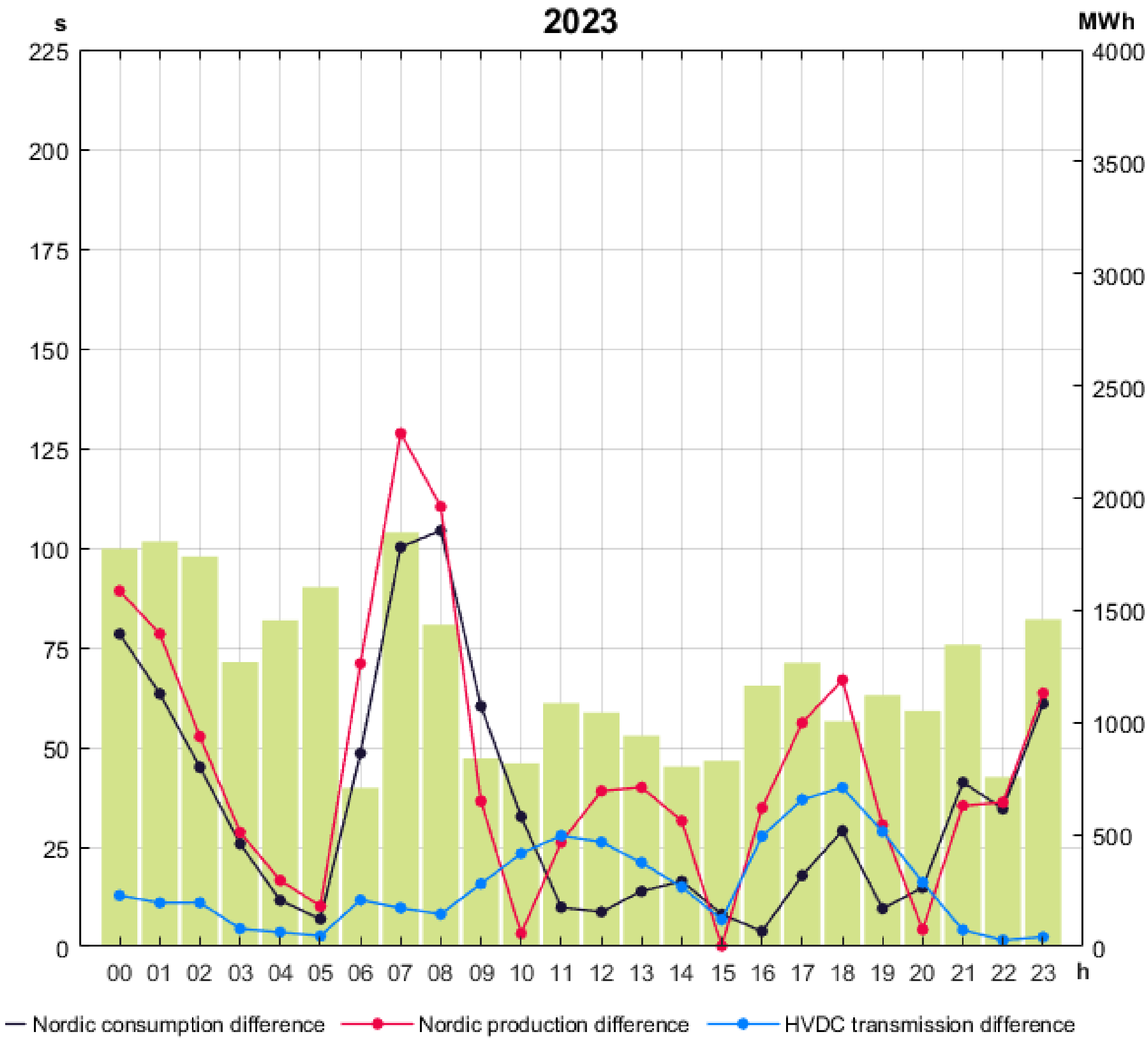


Figure 3.27 illustrates an average hour divided into 60 minutes. For each minute of the average hour, there is a value in seconds per hour indicating how long the frequency has been above or below the standard frequency range. In the years 2018-2023, the frequency has been outside the standard frequency range most often at the beginning of the hour. The frequency has stayed the best inside the standard frequency range in the middle of the hour. The time above the standard frequency range has increased again towards the end of the hour. In 2023, there is a wider distribution of values concerning under frequencies. At the start of the hour, the values for time outside the standard frequency range are higher than in the past years, while in the middle of the hour, the values are even lower than usual.

***Figure 3.27**. Number of seconds per hour outside the standard frequency range in 2018-2023 for each minute of an average hour*

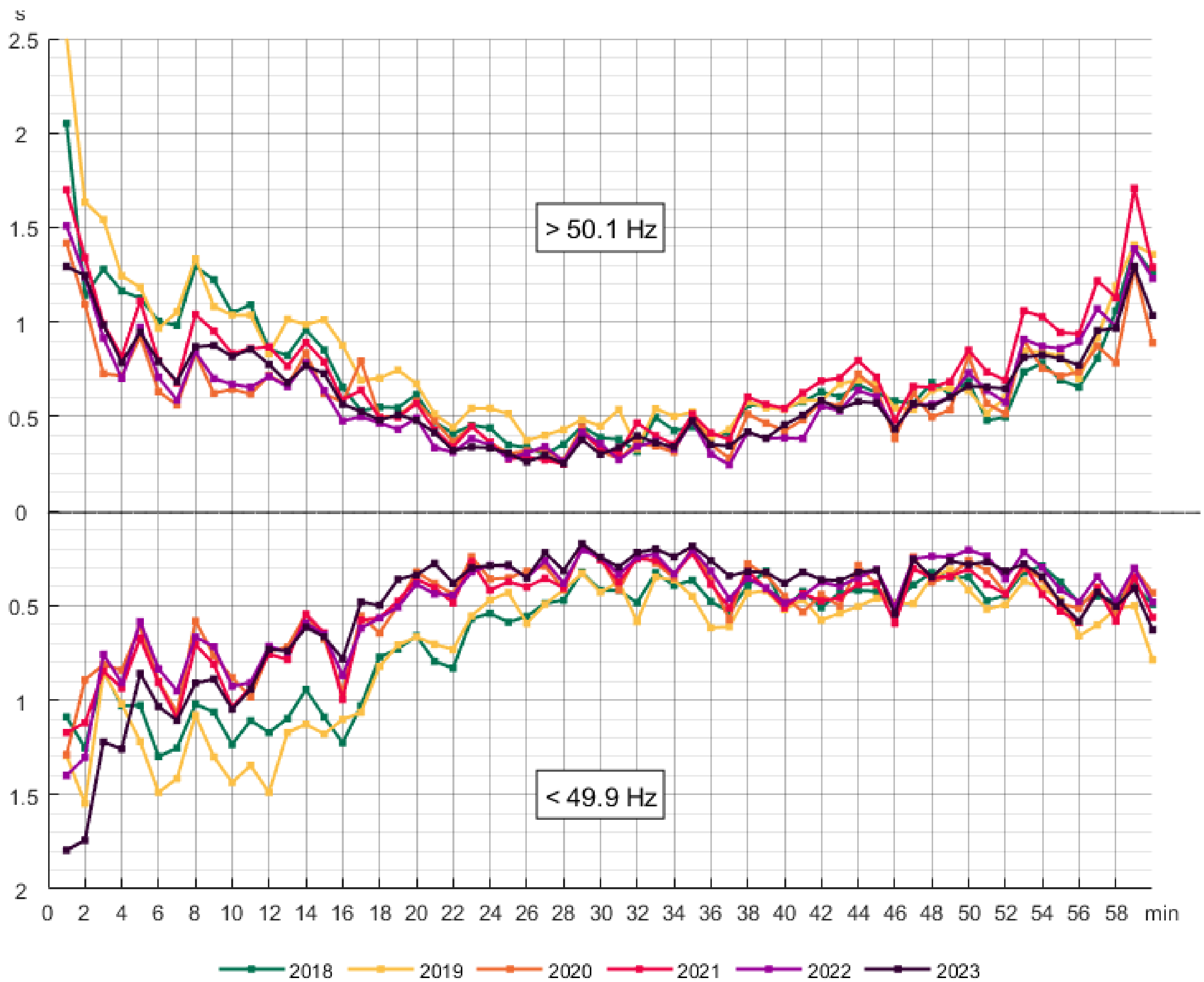
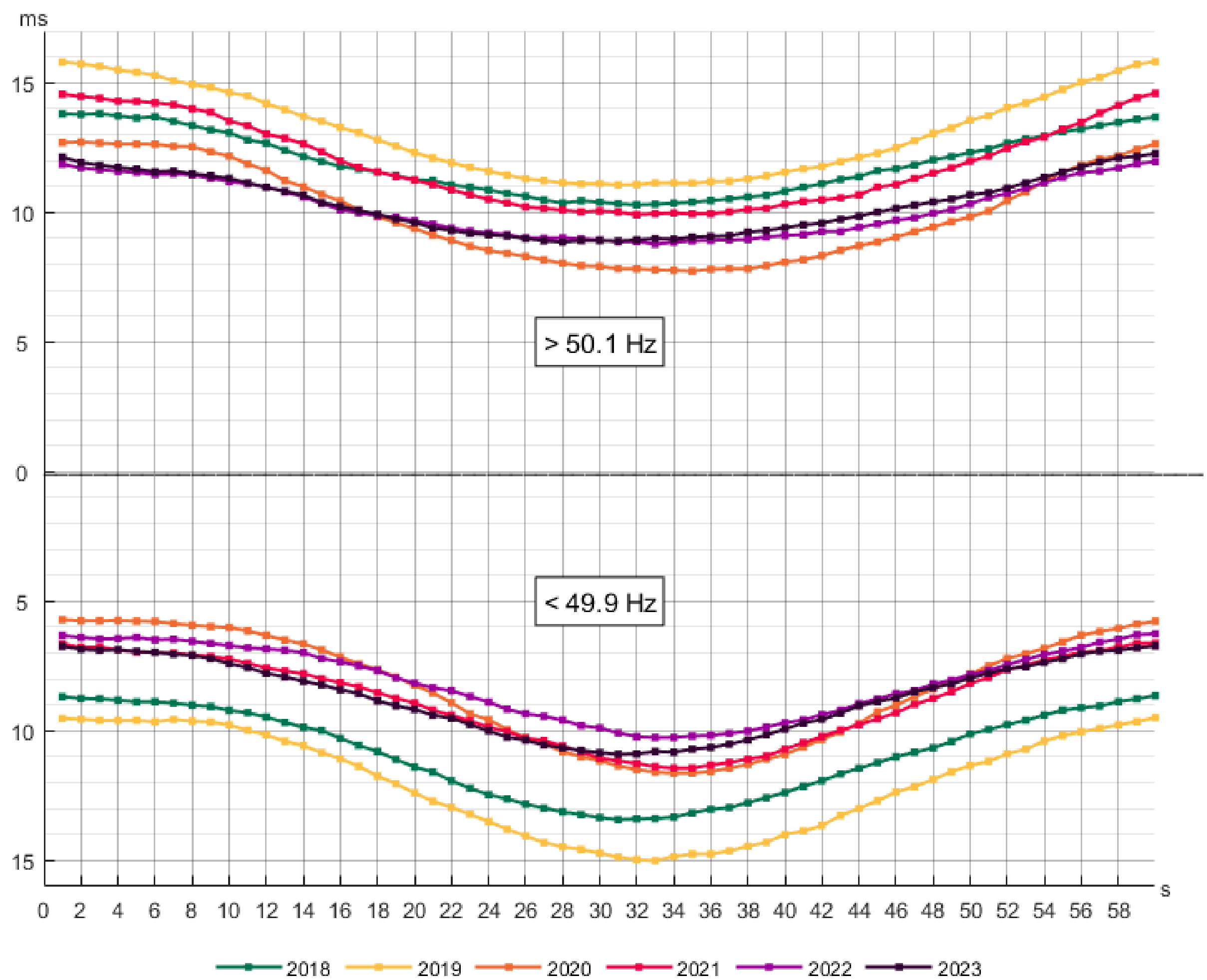


Figure 3.28 illustrates an average minute divided into 60 seconds. For each second of the average minute, there is a value in milliseconds per minute indicating the time that the frequency has been above or below the standard frequency range. There have been more over frequencies at the beginning and at the end of the average minute. Under frequencies have occurred more frequently in the middle of the minute. When comparing the year 2023 with 2022, under frequencies have been slightly more common.

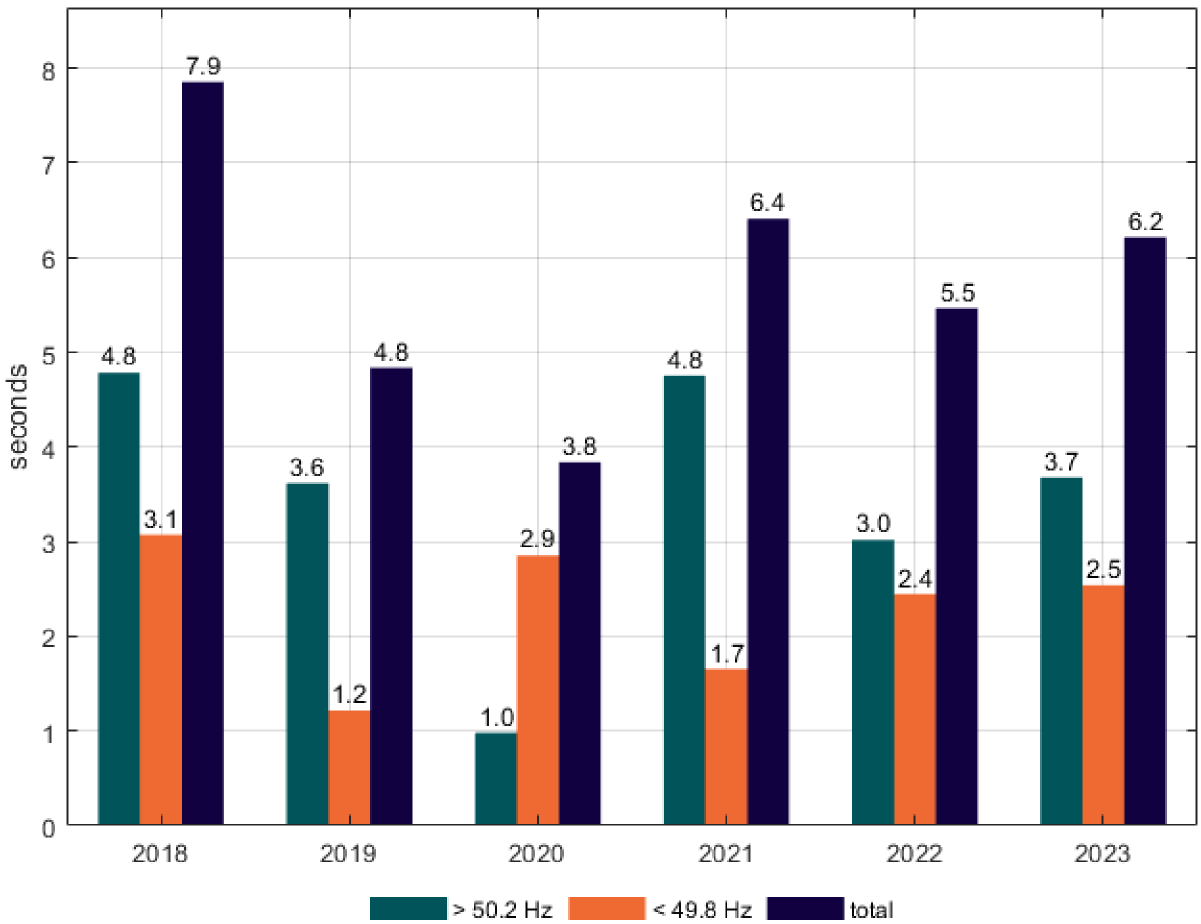
***Figure 3.28**. Number of milliseconds per minute outside the standard frequency range in 2018-2023 for each second of an average minute*



3.4.2 Time outside 49.8-50.2 Hz

Figure 3.29 shows the frequency deviations exceeding ±200 mHz as an average number of seconds per day. The total time outside 49.8-50.2 Hz was higher in 2023 compared to 2022. In 2023, over frequencies exceeding 200 mHz have been more common than under frequencies, which is in line with the trend of the previous years excluding 2020. While examining the years 2018 to 2023, the year 2023 had the third largest total time outside 49.8-50.2 Hz.

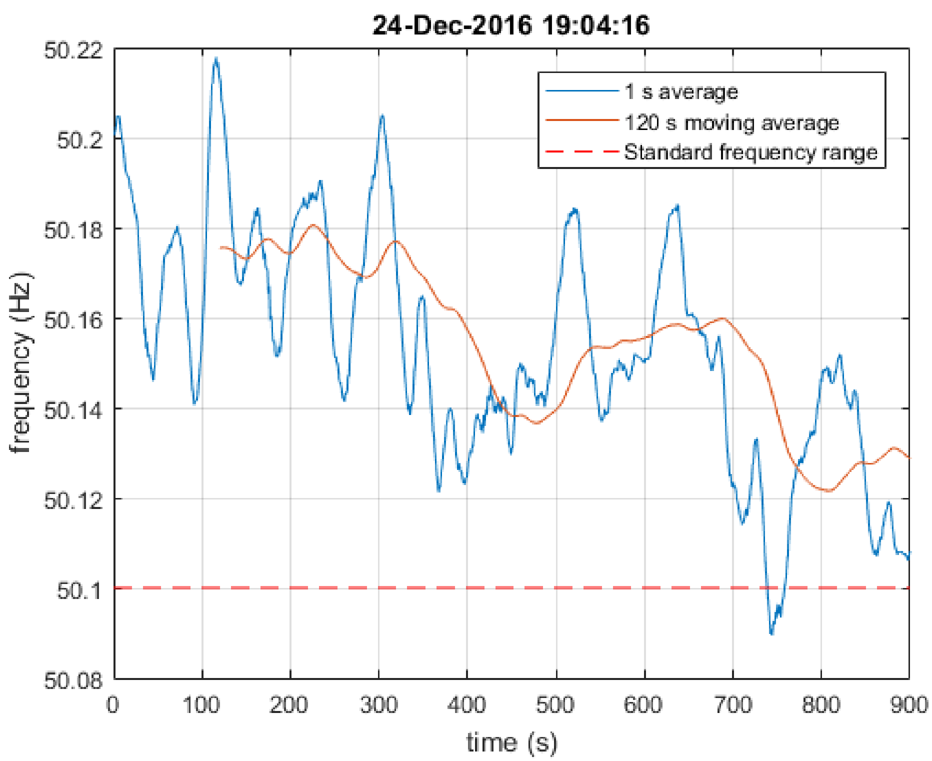
***Figure 3.29**. Average number of seconds per day that the frequency was outside the 49.8-50.2 Hz band for years 2018-2023*



The number of events for which the frequency deviation exceeded ± 200 mHz and did not return to the standard frequency range within the next 15 minutes has been calculated using two different methods. The number of events is also specified in Article 131(1)(a)(vi).
Method 1: the number of events for which the frequency deviation exceeded ± 200 mHz and none of the frequency samples were inside the standard frequency range within the next 15 min.
Method 2: the number of events for which the frequency deviation exceeded ± 200 mHz and the 120-second moving average did not return to the standard frequency range within the next 15 min. The 120-second period was chosen because it is not significantly affected by the natural 60-second oscillation of the frequency, and thus it is considered suitable for determining if the frequency restoration was permanent.

An example of the calculating method is presented in Figure 3.30, which shows a frequency deviation from December 2016. The deviation starts at 0 s as the frequency exceeds 50.2 Hz, and the figure shows the following 15 minutes. This deviation is not counted as an event when using method 1, because the frequency goes momentarily inside the standard frequency range around 750 seconds from the start. By using method 2, this deviation is counted as an event. The 120-second moving average does not go inside the standard frequency range at any point during the 15-minute period. The resolution of the frequency data used was 1 second.

***Figure 3.30**. Comparison of methods for calculating the number of events where df > 200 mHz and the frequency is not restored within 15 min*



The number of events in 2018-2023 in which the frequency exceeded 49.8-50.2 Hz and did not even momentarily return to the standard frequency range within 15 minutes is presented in Table 3.13. These results were calculated using method 1.

***Table 3.13**. Number of events for which the frequency deviation exceeded ± 200 mHz and the frequency did not return to the 49.9-50.1 Hz band within 15 minutes. Calculated with method 1.*

	2018		**2019**		**2020**		**2021**		**2022**		**2023**	
Month	**> 50.2 Hz**	**< 49.8 Hz**	**> 50.2 Hz**	**< 49.8 Hz**	**> 50.2 Hz**	**< 49.8 Hz**	**> 50.2 Hz**	**< 49.8 Hz**	**> 50.2 Hz**	**< 49.8 Hz**	**> 50.2 Hz**	**< 49.8 Hz**
January	0	0	0	0	0	0	0	0	0	0	0	0
February	0	0	0	0	0	0	1	0	0	0	0	0
March	0	0	0	0	0	0	1	0	0	0	0	0
April	0	0	0	0	0	0	0	0	0	0	0	0
May	1	0	0	0	0	0	0	0	0	0	0	0
June	0	0	0	0	0	0	0	0	0	0	0	0
July	0	0	0	0	0	0	0	0	0	0	0	0
August	0	0	0	0	0	0	0	0	0	0	0	0
September	0	1	0	0	1	0	0	0	0	0	0	0
October	0	0	0	0	0	0	0	0	0	0	0	0
November	0	0	0	0	0	0	0	0	0	0	0	0
December	0	0	0	0	0	0	0	0	0	0	0	0
Entire year	1	1	0	0	1	0	2	0	0	0	**0**	**0**

Table 3.14 shows the number of events in 2018-2023 in which the frequency exceeded the 49.8-50.2 Hz and the 120-second moving average did not return to the standard frequency range within the next 15 minutes. These results were calculated using method 2.

***Table 3.14**. Number of events for which the frequency deviation exceeded ± 200 mHz and the frequency did not return to the 49.9-50.1 Hz band within 15 minutes. Calculated with method 2.*

	2018		**2019**		**2020**		**2021**		**2022**		**2023**	
Month	**> 50.2 Hz**	**< 49.8 Hz**	**> 50.2 Hz**	**< 49.8 Hz**	**> 50.2 Hz**	**< 49.8 Hz**	**> 50.2 Hz**	**< 49.8 Hz**	**> 50.2 Hz**	**< 49.8 Hz**	**> 50.2 Hz**	**< 49.8 Hz**
January	0	0	0	0	0	0	0	0	0	0	0	0
February	0	0	1	0	0	0	2	0	0	0	0	0
March	0	0	0	0	0	0	1	0	0	0	0	0
April	0	0	1	0	0	0	0	0	0	0	0	0
May	2	0	0	0	0	0	1	0	0	0	0	0
June	2	0	0	1	0	0	0	0	0	0	0	0
July	1	0	0	0	0	0	0	0	0	0	0	0
August	0	0	0	0	0	0	0	0	0	0	0	1
September	0	1	0	0	1	0	1	0	0	0	2	0
October	0	0	1	0	0	0	0	0	0	0	0	0
November	1	0	0	0	0	0	1	0	0	0	1	0
December	0	1	1	0	0	0	0	0	1	0	0	0
Entire year	6	2	4	1	1	0	6	0	1	0	**3**	**1**
Sum	**8**		**5**		**1**		**6**		**1**		**4**	

3.4.3 Time outside 49.0-51.0 Hz

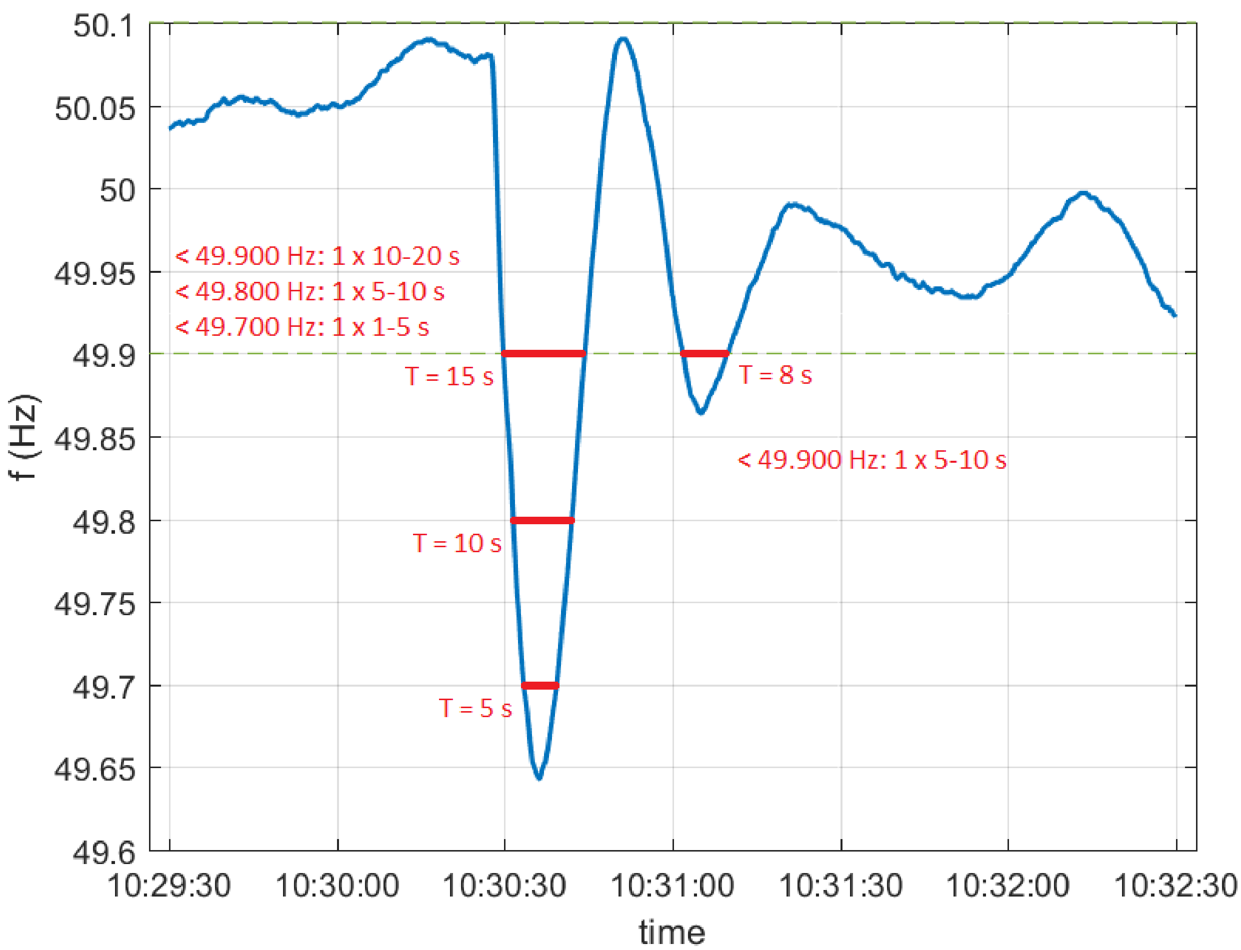
Time outside 49.0 Hz and 51.0 Hz is calculated by counting the number of samples that are below 49.0 Hz or above 51.0 Hz and multiplying the number by the time duration of the sample. The criteria are also defined in SO GL Article 131(1)(a) (v). The resolution of the data used was 1 second.

There were no instances in 2018-2023 where the frequency crossed 49.0 Hz or 51.0 Hz.

3.5 Number of frequency deviations with different durations

In this section, the deviations outside the standard frequency range have been sorted according to the amplitude and duration of the deviation, as well as whether the deviation was above or below the standard frequency range. Figure 3.31 gives an example of how the frequency deviations have been calculated. The example situation has two frequency deviations with different durations going below 49.900 Hz. This time period increases the number of frequency deviations < 49.900 Hz by two (2): one addition to the 10-20 s column and one addition to the 5-10 s column. The first frequency deviation also goes below 49.800 Hz and 49.700 Hz. These will also be counted as one frequency deviation < 49.800 Hz with a time of 5-10 s and one deviation < 49.700 Hz with a time of 1-5 s. Altogether, the example period contains four (4) frequency deviations. The time window of 5-10 s, for example, stands for frequency deviations lasting over five (5) seconds and under or exactly 10 seconds.

***Figure 3.31**. Example of how the number of frequency deviations is calculated [4]*



3.5.1 Deviations with a duration of 0-1 s, 1-5 s, 5-10 s, 10-20 s, 20-40 s, 40-60 s, and 1-3 min

The resolution of the frequency data used is 0.1 seconds.

Tables 3.15-3.20 provide more detailed information about frequency deviations from 2018 to 2023. These tables include the durations and amplitudes of the deviations, as well as the total amount, maximum duration, and average duration of the deviations.

Table 3.15. Total number of frequency deviation in 2018

f (Hz)	0-1s	1-5s	5-10s	10-20s	20-40s	40-60s	1-3 min	> 3min	Total amount	Max duration (s)	Average duration (s)
> 50.1	17272	5397	3753	5435	3687	835	640	128	37147	2043.90	9.88
> 50.2	87	45	41	44	12	3	3	0	235	155.10	7.62
> 50.3	0	0	1	0	0	0	0	0	1	5.70	5.70
< 49.9	15238	5538	3345	5244	3432	693	558	108	34156	999.30	9.73
< 49.8	79	32	29	14	10	1	1	1	167	215.70	6.89
< 49.7	1	0	4	0	0	0	0	0	5	9.60	6.72
< 49.6	0	1	1	0	0	0	0	0	2	5.10	4.05
< 49.5	0	0	0	0	0	0	0	0	0	0.00	0.00

Table 3.16. Total number of frequency deviation in 2019

f (Hz)	0-1s	1-5s	5-10s	10-20s	20-40s	40-60s	1-3 min	> 3min	Total amount	Max duration (s)	Average duration (s)
> 50.1	17123	5604	3945	6279	4075	933	682	132	38773	833.60	10.43
> 50.2	59	23	30	36	14	3	1	0	166	62.70	8.24
> 50.3	1	2	0	0	0	0	0	0	3	4.10	2.87
< 49.9	15996	5903	3903	5897	3776	858	634	110	37077	731.40	9.90
< 49.8	57	33	21	12	2	0	0	0	125	23.80	3.78
< 49.7	0	2	2	0	0	0	0	0	4	9.00	6.53
< 49.6	0	1	0	0	0	0	0	0	1	1.60	1.60
< 49.5	0	0	0	0	0	0	0	0	0	0.00	0.00

Table 3.17. Total number of frequency deviation in 2020

f (Hz)	0-1s	1-5s	5-10s	10-20s	20-40s	40-60s	1-3 min	> 3min	Total amount	Max duration (s)	Average duration (s)
> 50.1	13424	4297	3245	5139	3274	626	531	84	30620	1288.50	10.06
> 50.2	31	10	20	11	1	0	0	0	73	22.70	5.13
> 50.3	0	1	1	1	0	0	0	0	3	10.70	6.67
< 49.9	11223	4102	2917	4572	2825	515	354	60	26568	922.30	9.60
< 49.8	38	39	14	11	7	2	0	1	112	390.70	9.48
< 49.7	1	1	2	2	0	0	0	0	6	17.90	7.80
< 49.6	0	1	0	0	0	0	0	0	1	2.70	2.70
< 49.5	0	0	0	0	0	0	0	0	0	0.00	0.00

Table 3.18. Total number of frequency deviation in 2021

f (Hz)	0-1s	1-5s	5-10s	10-20s	20-40s	40-60s	1-3 min	> 3min	Total amount	Max duration (s)	Average duration (s)
> 50.1	19397	5475	3582	5807	3800	811	635	101	39608	1620.00	9.25
> 50.2	99	41	20	27	17	6	5	0	215	83.80	8.26
> 50.3	2	0	0	0	0	0	0	0	2	1.00	0.55
< 49.9	15255	5009	3409	5004	3117	522	361	42	32719	747.40	8.24
< 49.8	33	24	12	12	2	2	1	0	86	107.80	7.14
< 49.7	2	2	4	3	0	0	0	0	11	14.10	6.31
< 49.6	1	2	2	0	0	0	0	0	5	7.80	4.42
< 49.5	0	1	0	0	0	0	0	0	1	3.50	3.50

Table 3.19. Total number of frequency deviation in 2022

f (Hz)	0-1s	1-5s	5-10s	10-20s	20-40s	40-60s	1-3 min	> 3min	Total amount	Max duration (s)	Average duration (s)
> 50.1	33186	4690	3589	5274	3353	667	508	81	51348	800.80	6.21
> 50.2	113	33	24	33	6	1	1	0	211	140.10	5.28
> 50.3	1	3	2	1	0	0	0	0	7	10.10	5.34
< 49.9	29351	4385	3304	4688	2753	501	371	45	45398	756.60	5.60
< 49.8	59	24	22	13	9	3	1	0	131	83.90	6.92
< 49.7	3	2	5	2	0	0	0	0	12	11.80	5.45
< 49.6	0	1	2	0	0	0	0	0	3	8.70	6.37
< 49.5	1	1	0	0	0	0	0	0	2	4.30	2.30

Table 3.20. Total number of frequency deviation in 2023

f (Hz)	0-1s	1-5s	5-10s	10-20s	20-40s	40-60s	1-3 min	> 3min	Total amount	Max duration (s)	Average duration (s)
> 50.1	34976	5374	4141	5367	2935	607	516	121	54037	857.50	6.01
> 50.2	121	22	25	21	10	2	4	0	205	158.50	6.60
> 50.3	9	3	1	2	0	0	0	0	15	11.20	2.47
< 49.9	28930	4592	3472	4782	2641	526	478	66	45487	601.20	6.01
< 49.8	121	48	22	13	5	1	2	0	212	123.70	4.42
< 49.7	2	1	3	3	0	0	0	0	9	15.60	7.88
< 49.6	2	0	0	2	0	0	0	0	4	11.30	5.70
< 49.5	0	0	2	0	0	0	0	0	2	7.80	7.05

Figure 3.32 is a visual representation of the data in Tables 3.15-3.20. The number of deviations is now given as a daily average instead of a total number per year. The year 2020 has had the smallest number of deviations in the observation period. The number of frequency deviations of 0-1 seconds in 2023 has been a bit higher than in 2022. These two years had significantly higher values in this time category compared to the whole observation period. Long deviations that lasted for more than three minutes were more common in 2023 compared to 2022.

***Figure 3.32**. Daily average number of frequency deviations per duration*

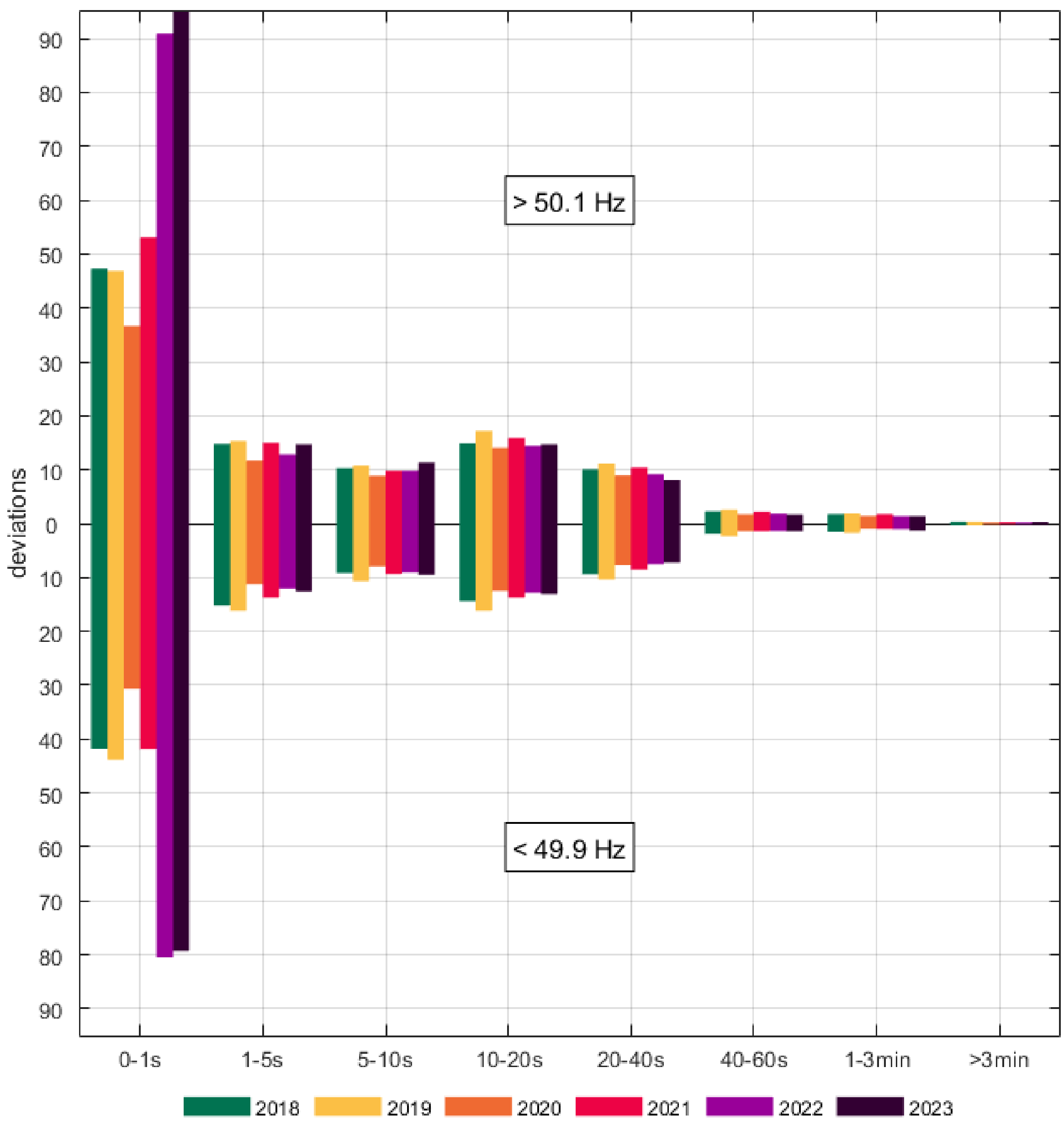
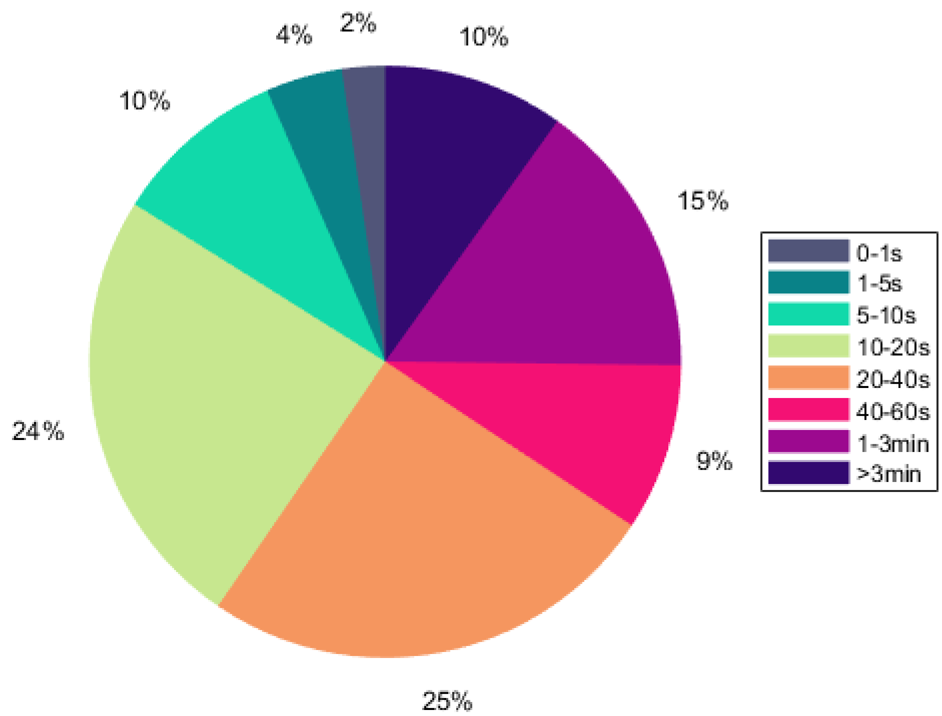


Table 3.21 shows how deviations of different durations affected the total time outside the standard frequency range in 2023. The times are given in minutes. Figure 3.33 shows in percentages how the total time outside the standard frequency range was divided between deviations of different durations. Deviations with a duration of 10-20 s and 20-40 s made up nearly half of the total time outside the standard frequency range. The share of over 3-minute deviations has increased by three percentage points.

***Table 3.21**. Total minutes in 2023 that the frequency was outside the standard frequency range per duration of deviations*

	0-1 s	1-5 s	5-10 s	10-20 s	20-40 s	40-60 s	1-3 min	> 3 min	total
> 50.1 Hz	130	227	516	1282	1323	486	784	668	5416
< 49.9 Hz	105	191	434	1147	1195	422	742	318	4554
total	235	418	950	2430	2517	909	1526	986	9970

***Figure 3.33**. Percentage of total time outside the standard frequency range caused by deviations of different durations*



The following figures go into more detail on the deviations in 2023. Figure 3.34 represents the total number of deviations per duration for each month in 2023. Most of the deviations have lasted less than 1 second. Most deviations occurred in May and September. February, November, and December had the smallest number of deviations.

Figure 3.34**. **Total number of frequency deviations per duration for each month in 2023

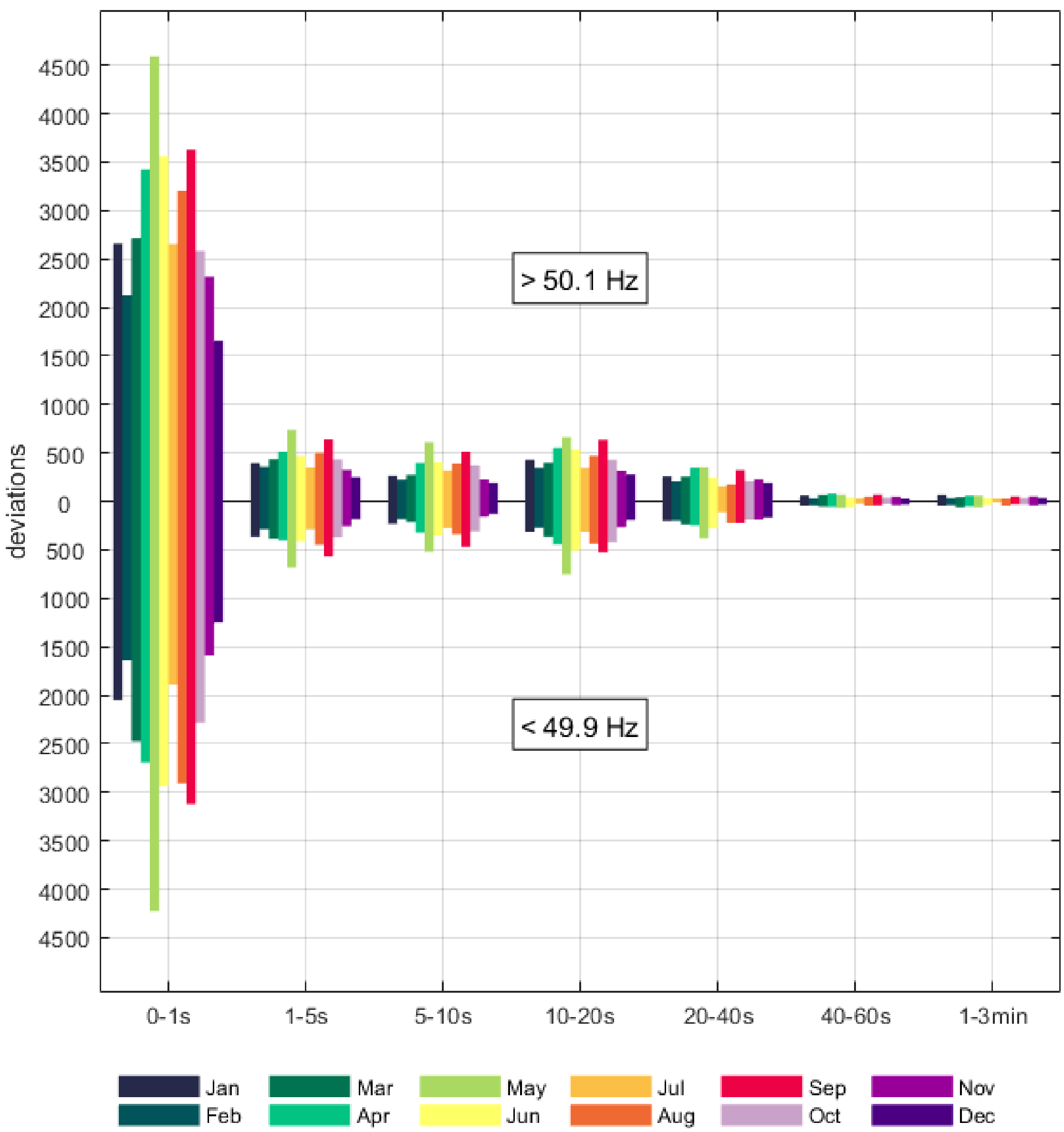
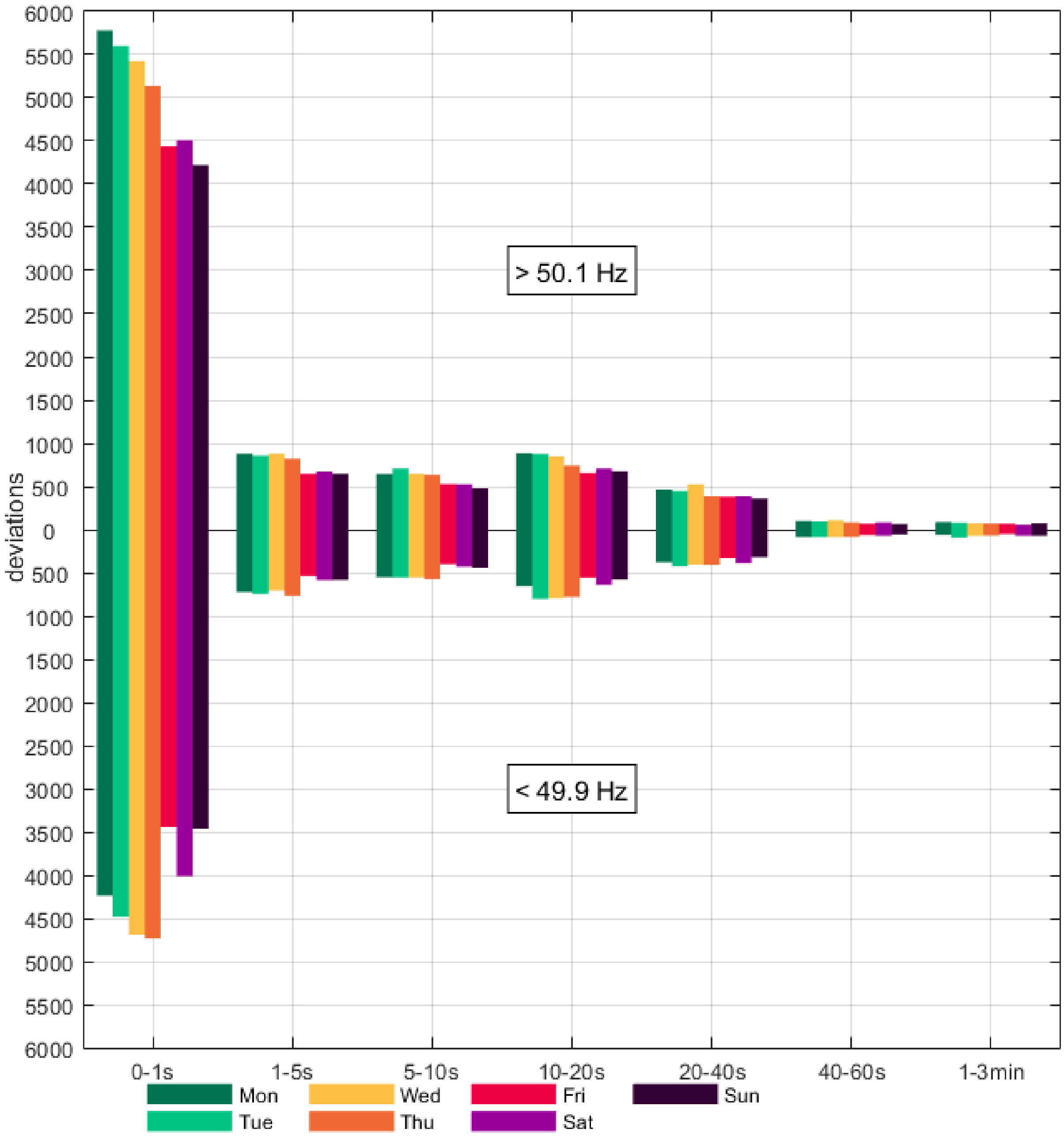


Figure 3.35 shows the number of deviations for every day of the week. Weekdays from Monday to Thursday all had a high number of deviations. Fridays, Saturdays, and Sundays had fewer deviations in every time category.

***Figure 3.35**. Total number of frequency deviations per duration for each day of the week in 2023*



Figures 3.36 and 3.37 illustrate the number of deviations per duration within the day. Figure 3.36 includes hours 0-11 and Figure 3.37 includes hours 12-23. Most deviations over the standard frequency range occurred at midnigth, 2 am, and 11 pm. With under frequencies, the most deviations happened at 2-5 am, 7 am, and 4-5 pm.

***Figure 3.36*. Total number of frequency deviations per duration for hours 0-11 in 2023**

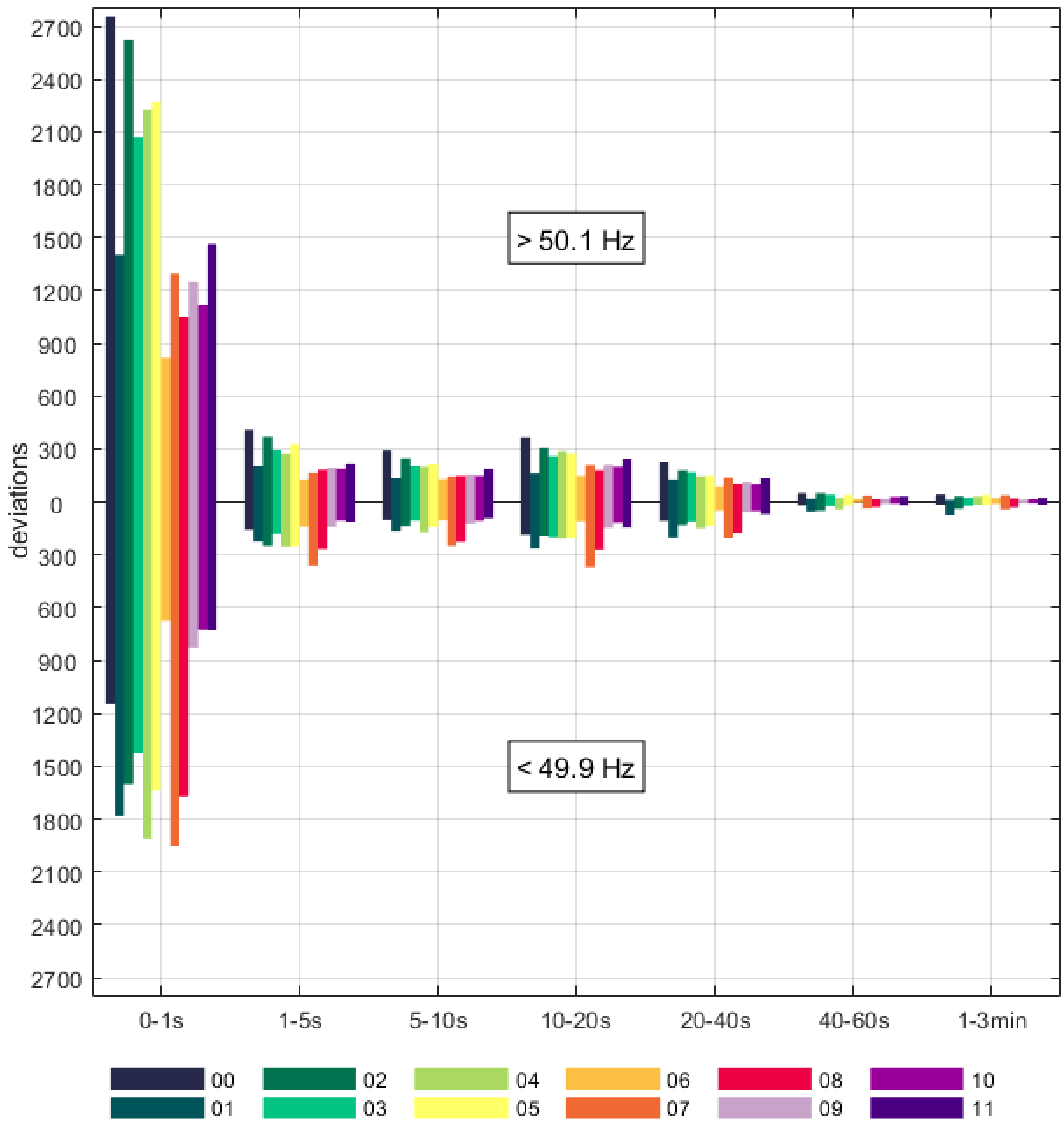


***Figure 3.37**. Total number of frequency deviations per duration for hours 12-23 in 2023*

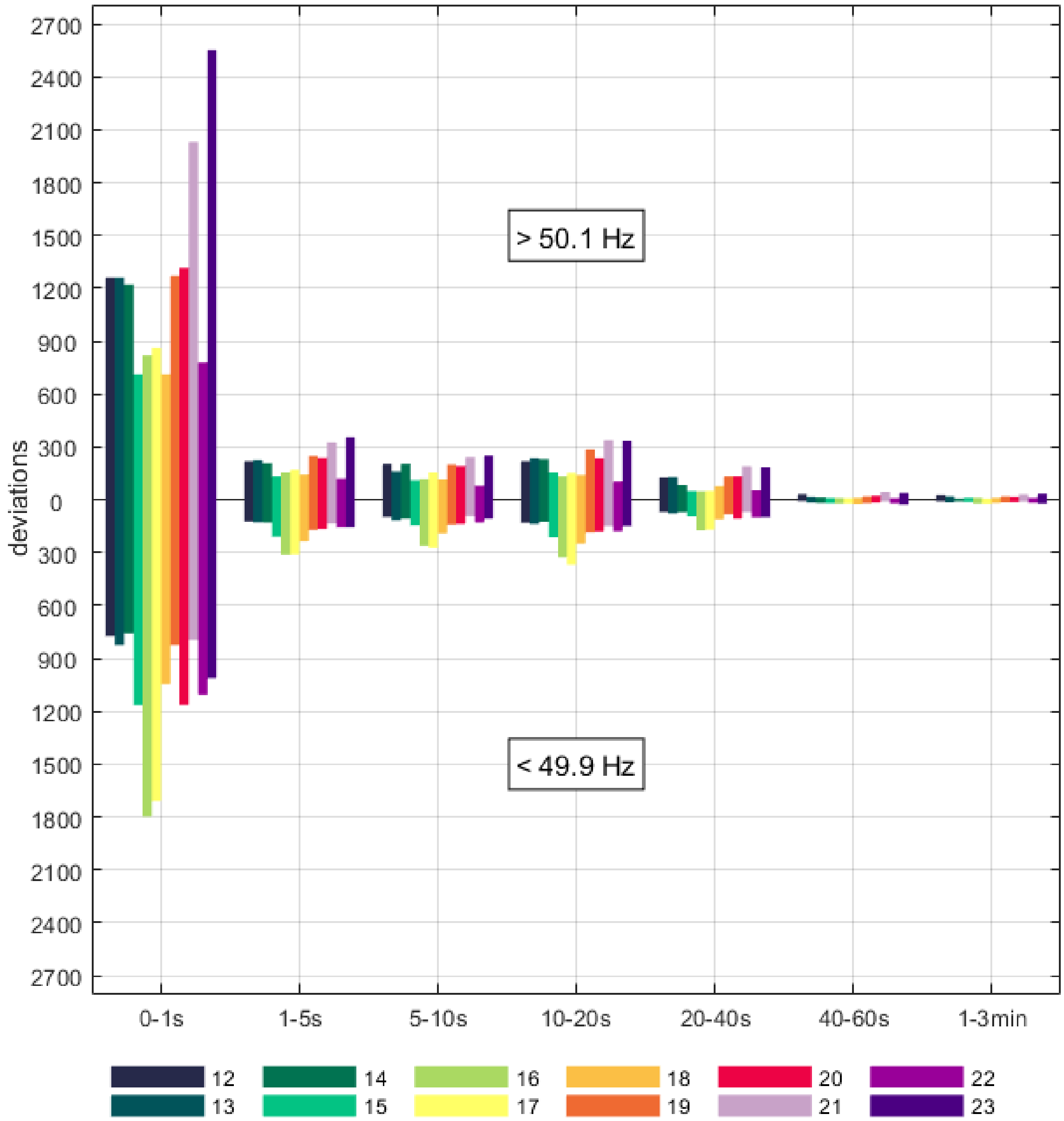
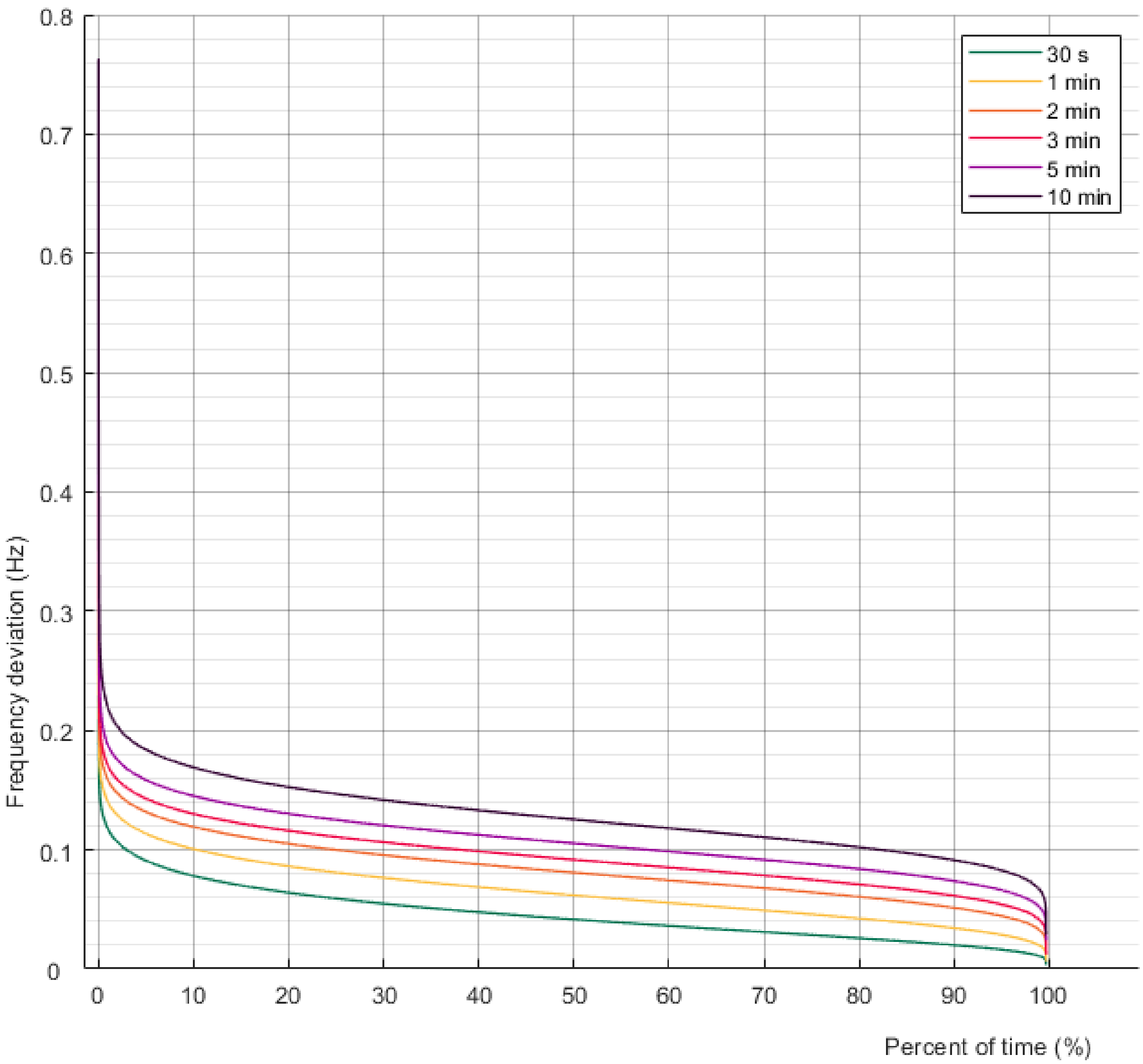


Figure 3.38 represents the duration curve of maximum frequency deviation within different time windows in 2023. The resolution of the frequency data used is 1 second. The studied time windows can be found in the legend of Figure 3.38. There have been some frequency disturbances of over 0.3 Hz, which can be seen here as a peak near 0% permanence. Chapter 4 will go through these in detail.

Figure 3.38*. *Duration curve of maximum frequency deviation within different time windows in 2023



3.5.2 Deviations with a duration of 1-3 min, 3-5 min, 5-10 min, 10-15 min, and > 15 min

The resolution of the frequency data used for these durations is one minute. Figure 3.39 shows the total number of over 1-minute deviations exceeding the standard frequency range for the years between 2018 and 2023. The number of frequency deviations increased from the previous year in all duration categories. The change was the most significant in 10-15 minute deviations.

***Figure 3.39**. Total number of longer frequency deviations per duration between 2018-2023*

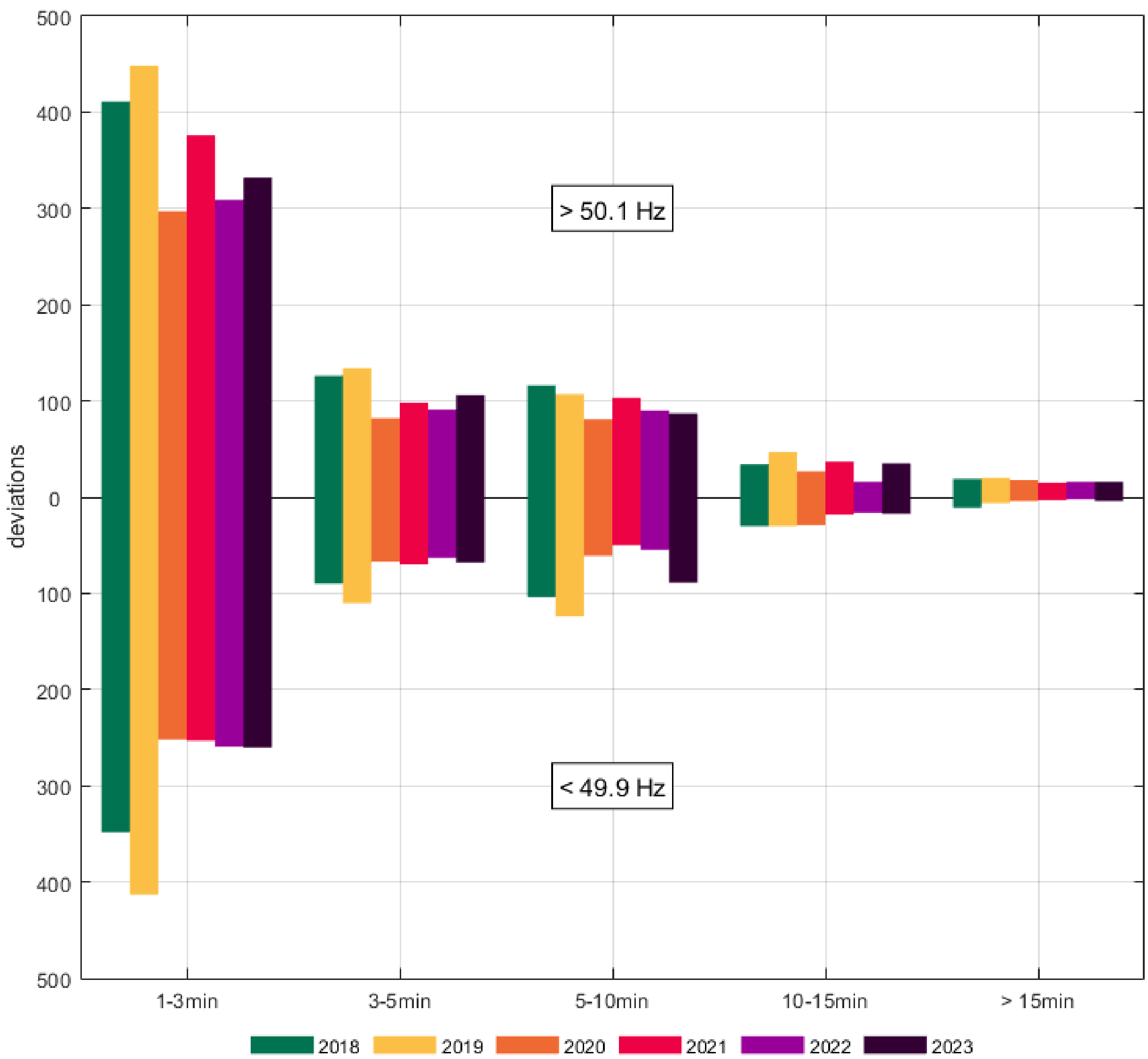


Figure 3.40 shows the total number of longer deviations exceeding the standard frequency range for each month in 2023. April, May, and September had the most over frequency deviations, while under frequency deviations were most common in March and May.

***Figure 3.40**. Total number of longer frequency deviations per duration for each month in 2023*

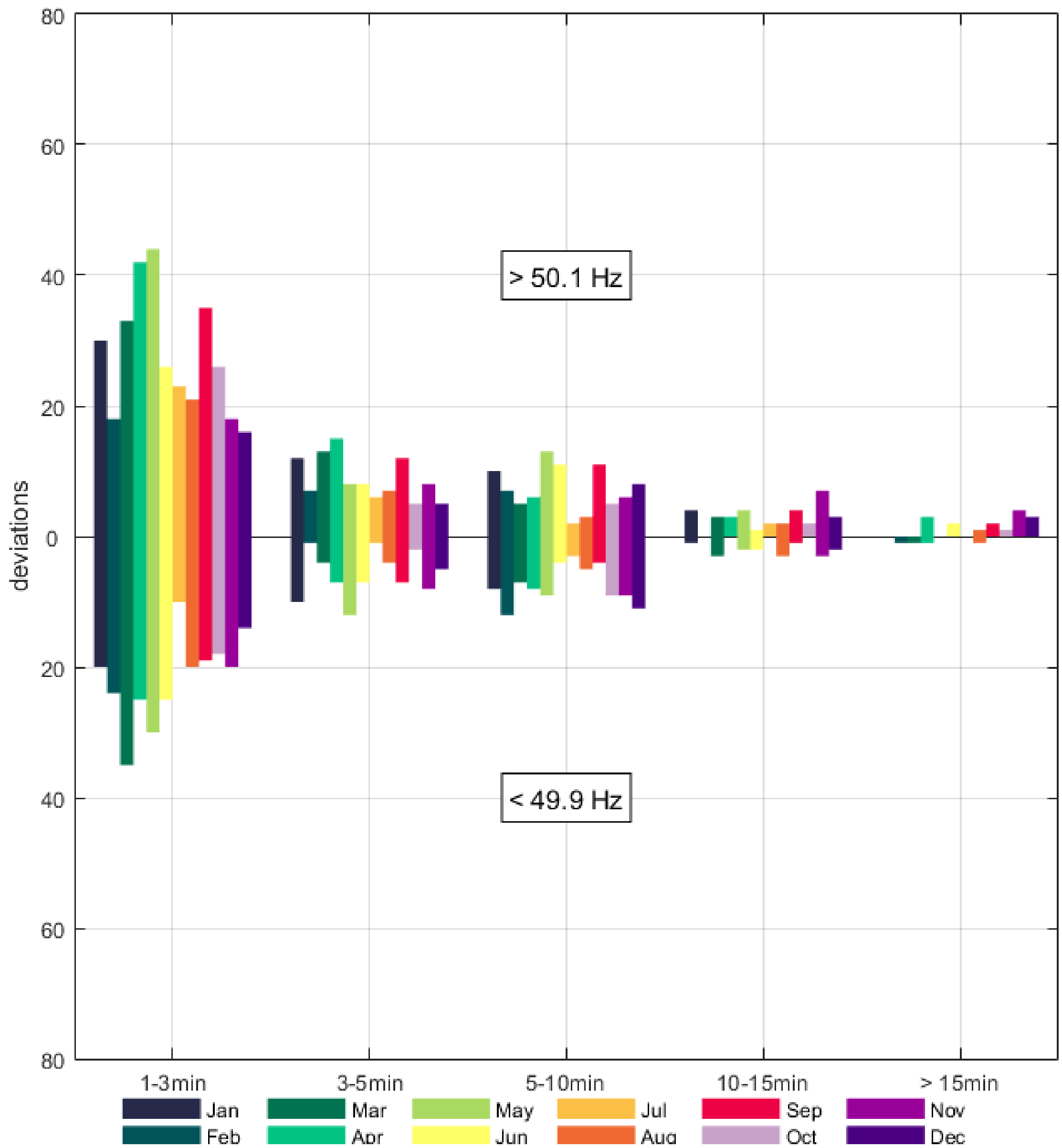
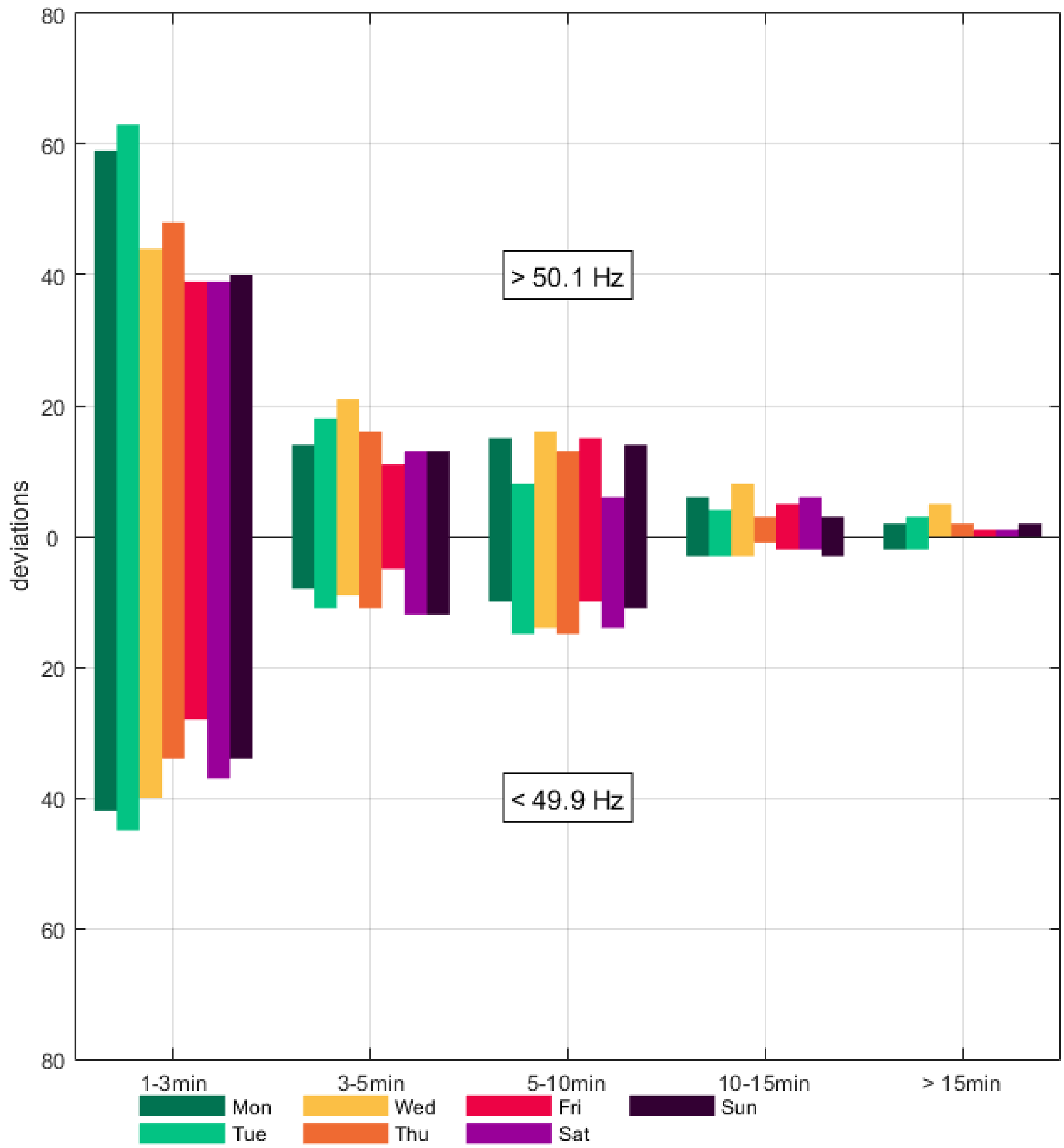


Figure 3.41 represents the number of deviations with different durations during every day of the week in 2023. Most 1-3 minute deviations happened on Mondays and Tuesdays. In the other categories, the distribution of the deviations is more evenly spread throughout the days of the week.

***Figure 3.41**. Total number of longer frequency deviations per duration for each day of the week in 2023*



Figures 3.42 and 3.43 illustrate longer frequency deviations within the day. Most deviations above the standard frequency range occurred between 2 and 3 am and 11 pm. Under frequency deviations were most common from midnight to 3 am as well as in the morning from 7 to 8 am.

Figure 3.42**. **Total number of longer frequency deviations per duration for hours 0-11 in 2023

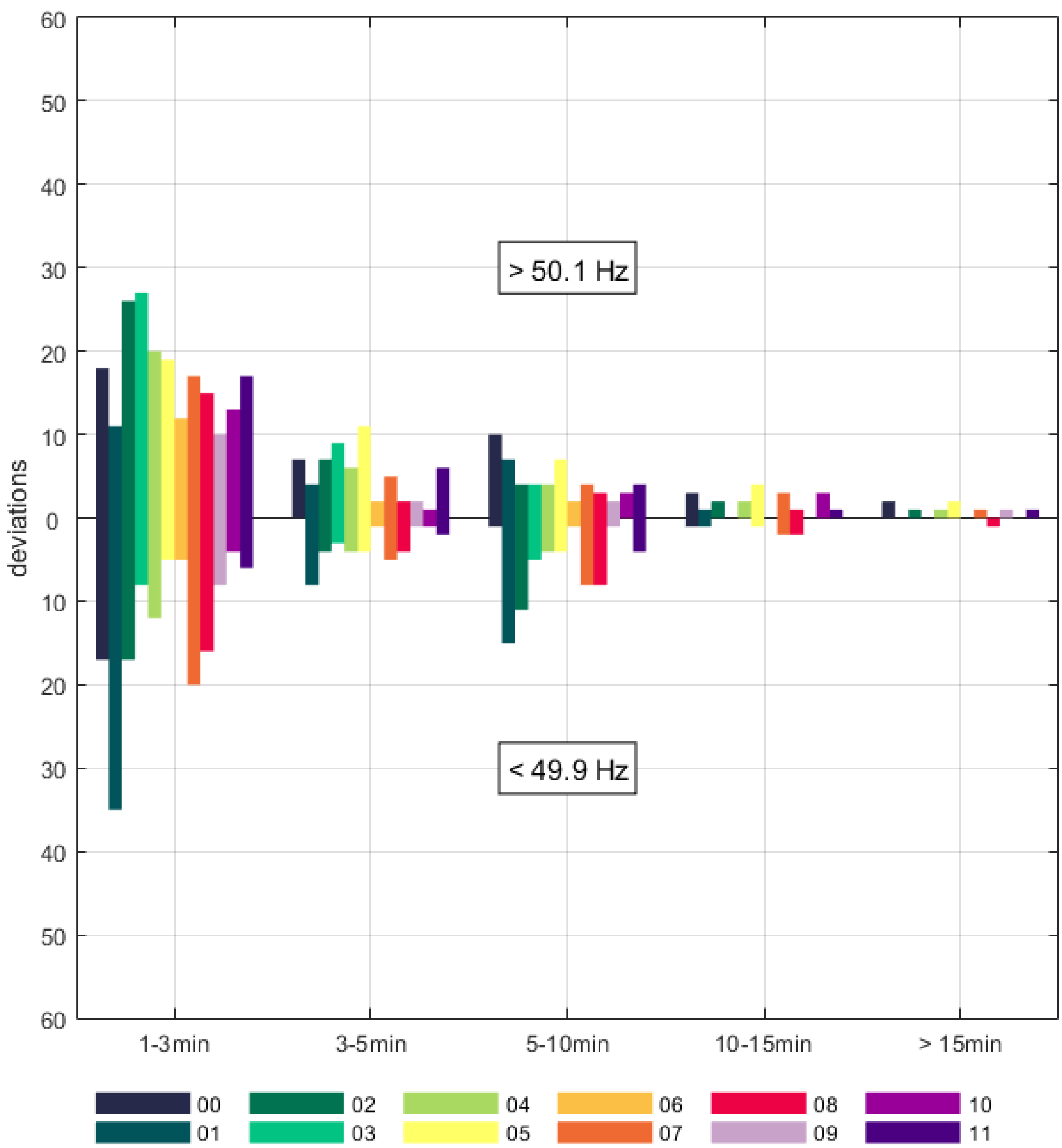
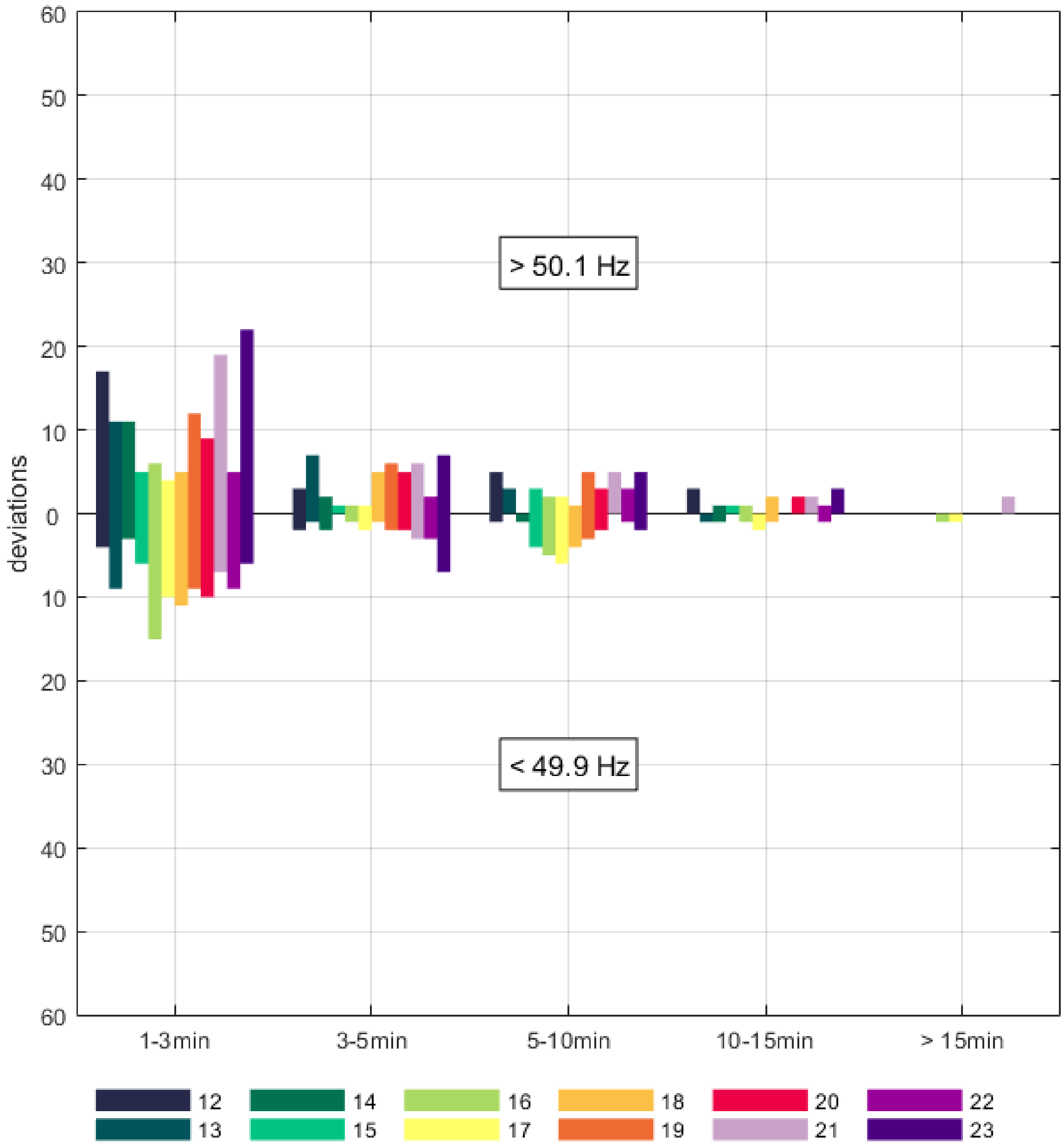


***Figure 3.43**. Total number of longer frequency deviations per duration for hours 12-23 in 2023*



3.6 Number of threshold crossings

The number of threshold crossings is calculated by counting the number of samples for which the frequency is outside the standard frequency range and the previous sample is inside the range. The number of threshold crossings is a good indicator of how many times, per given time period, the Frequency Containment Reserve for Disturbances (FCR-D) is activated. The crossings are calculated separately for the number of occasions the frequency goes above or below the standard frequency range. The resolution of the frequency data used is one second.

3.6.1 Number of 49.9-50.1 Hz crossings

Figure 3.44 shows the daily average number of threshold crossings from 2018 to 2023. There were slightly more threshold crossings in 2023 compared to 2022. Every year, there have been more threshold crossings over 50.1 Hz than under 49.9 Hz. The number of threshold crossings in 2022 is lower than the number of 0-1 second deviations in figure 3.32, since the resolution of the frequency data used in threshold crossing calculation is lower and thus cannot detect every crossing.

***Figure 3.44**. Daily average number of threshold crossings for the years 2018-2023*

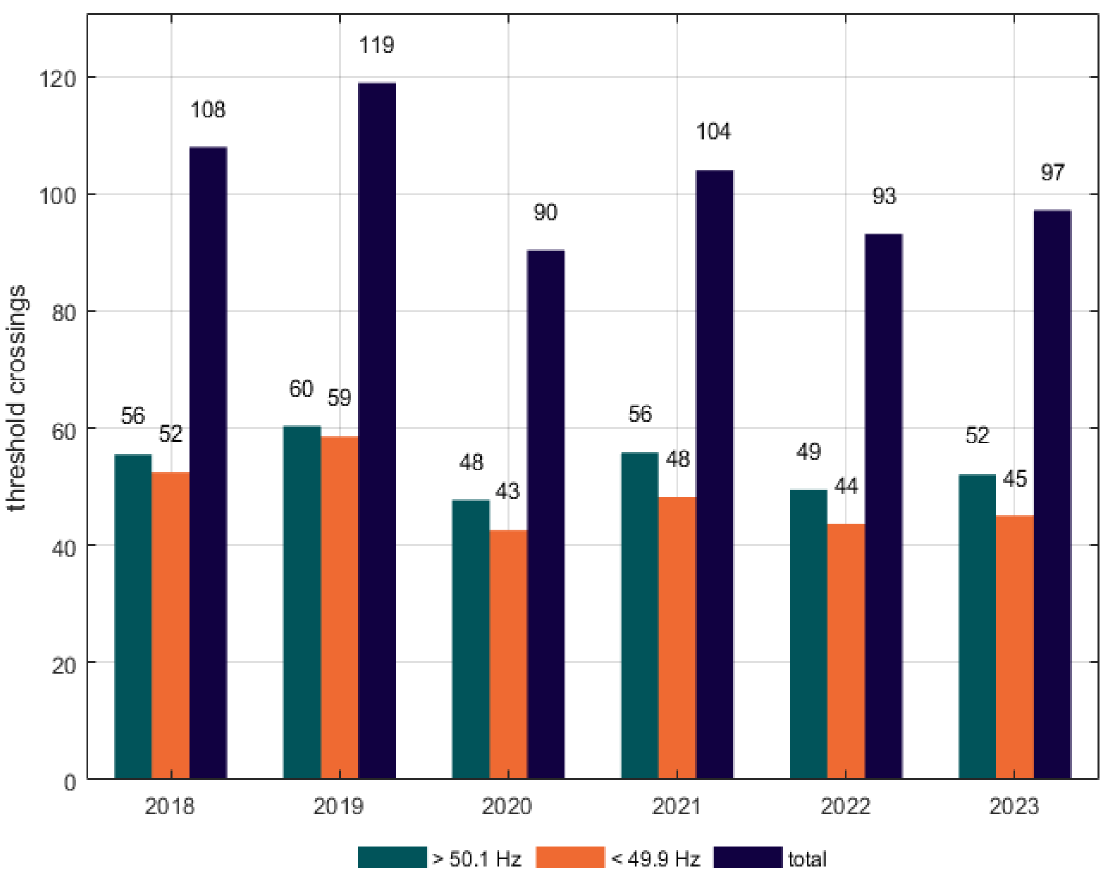


Figure 3.45 represents the daily average number of threshold crossings for each month in 2023. The frequency crossed the threshold most often in May and September. July, November, and December had the smallest number of threshold crossings.

Figure 3.45*. *Daily average number of threshold crossings for every month in 2023

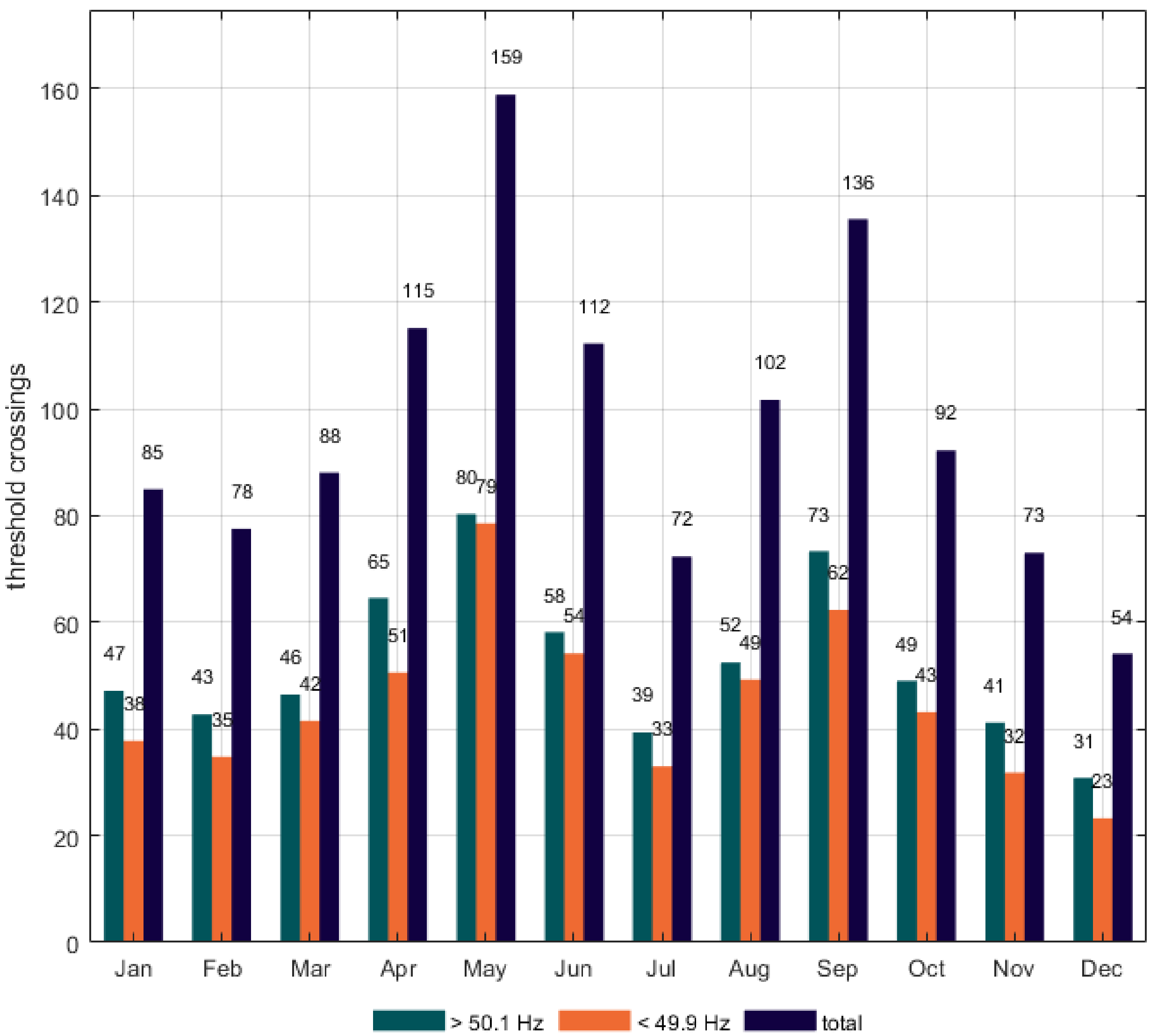
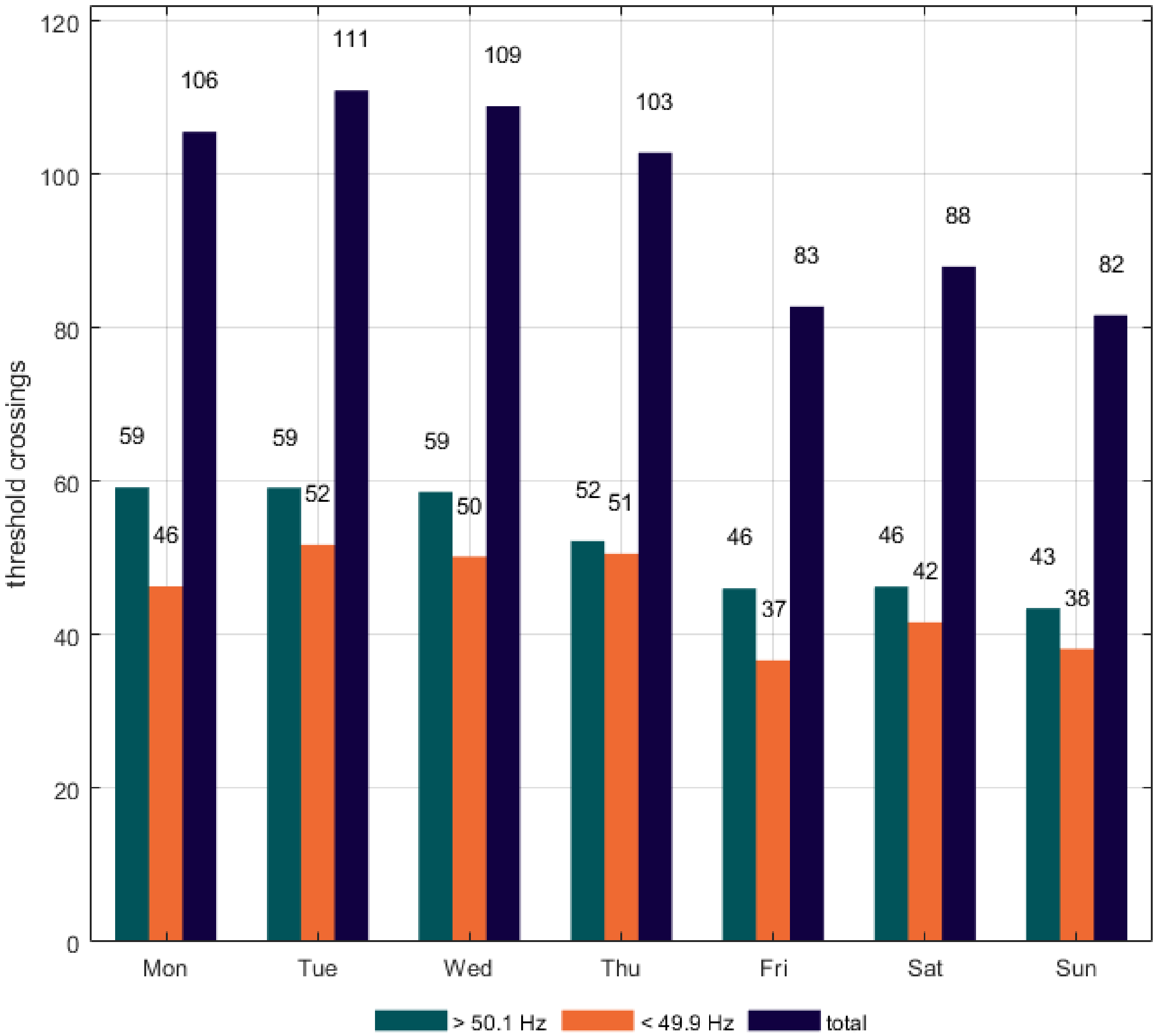


Figure 3.46 shows the number of threshold crossings for each day of the week in 2023. The number of crossings has been higher from Monday to Thursday and lower on Friday and on weekends.

***Figure 3.46**. Daily average number of threshold crossings for every day of the week in 2023*



The hourly number of threshold crossings within an average day is presented in Figure 3.47. The most crossings in 2023 happened between 11 pm and 7 am, excluding 6 am. 5 pm also had a large number of crossings. The smallest number of threshold crossings occurred at 6 am, 10 pm and around noon from 9 am to 3 pm. The trend is quite similar to 2022.

***Figure 3.47**. Average number of threshold crossings for every hour of the day in 2023*

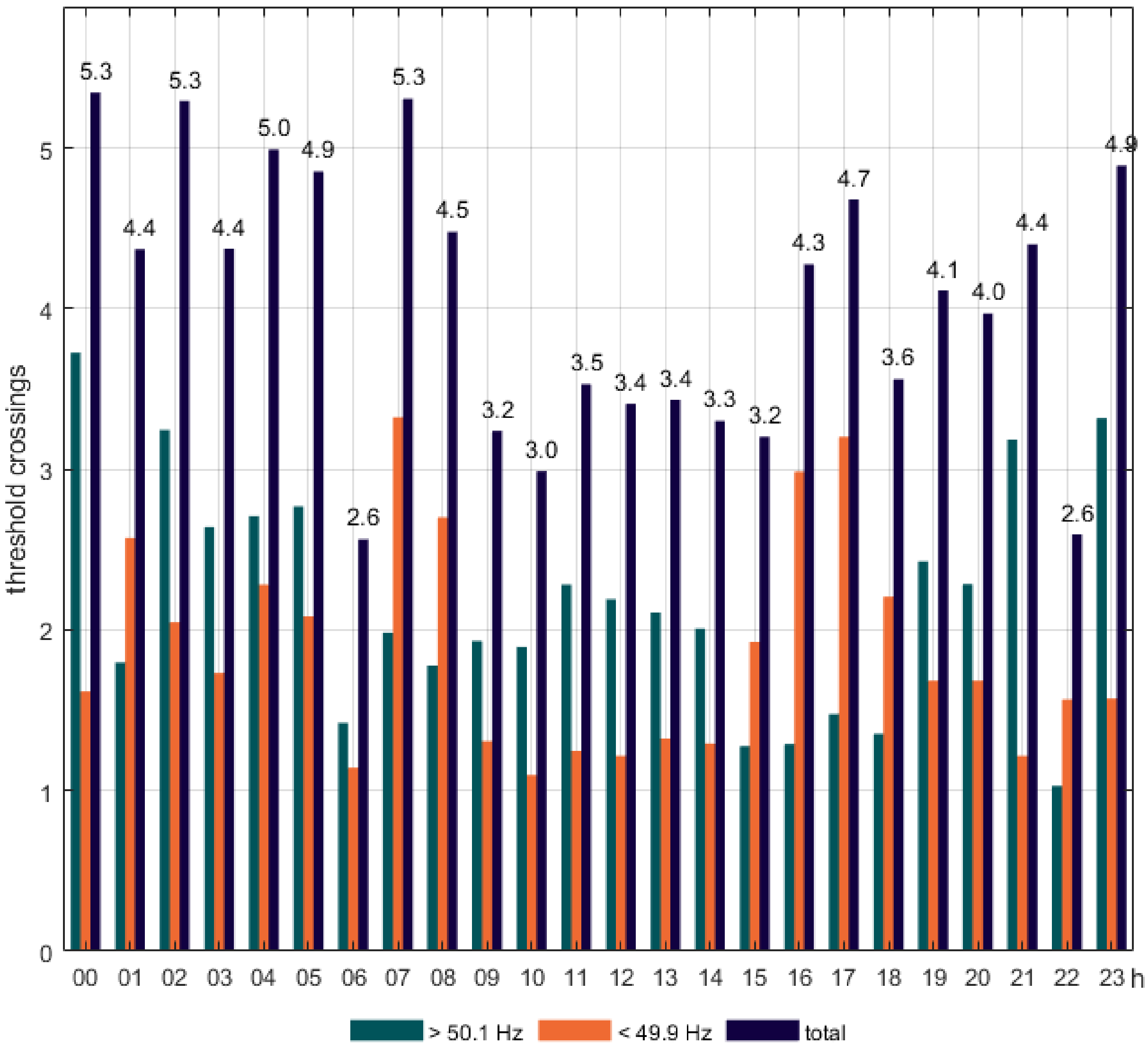
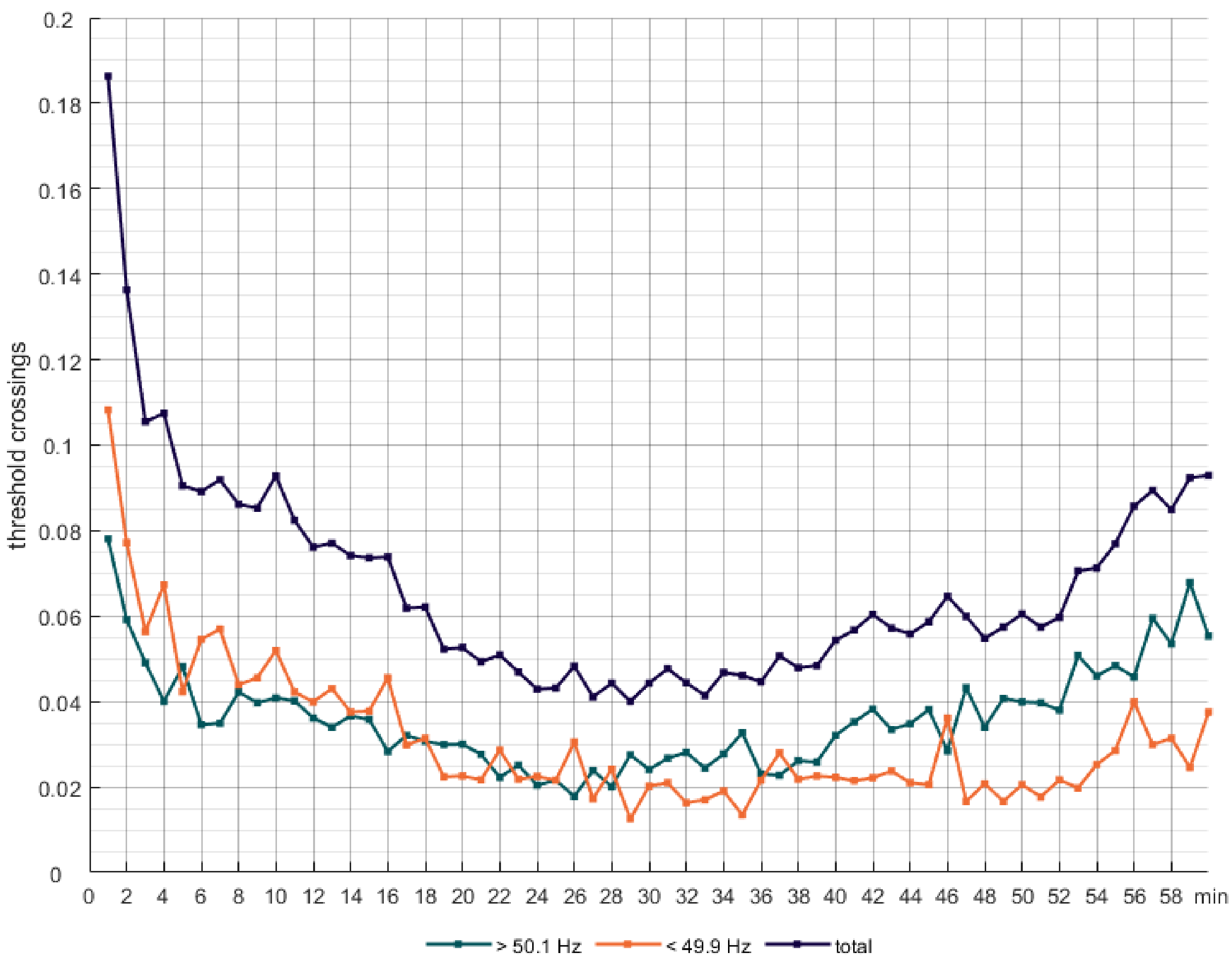


Figure 3.48 represents the average number of threshold crossings for every minute within the hour. Most crossings in 2023 occurred in the first few minutes of the hour. The crossings were least common in the middle of an hour. During the first 30 minutes of the hour, the frequency crossed 49.9 Hz more often, whereas more crossings of 50.1 Hz took place in the latter part of the hour. The trend is very similar to 2022.

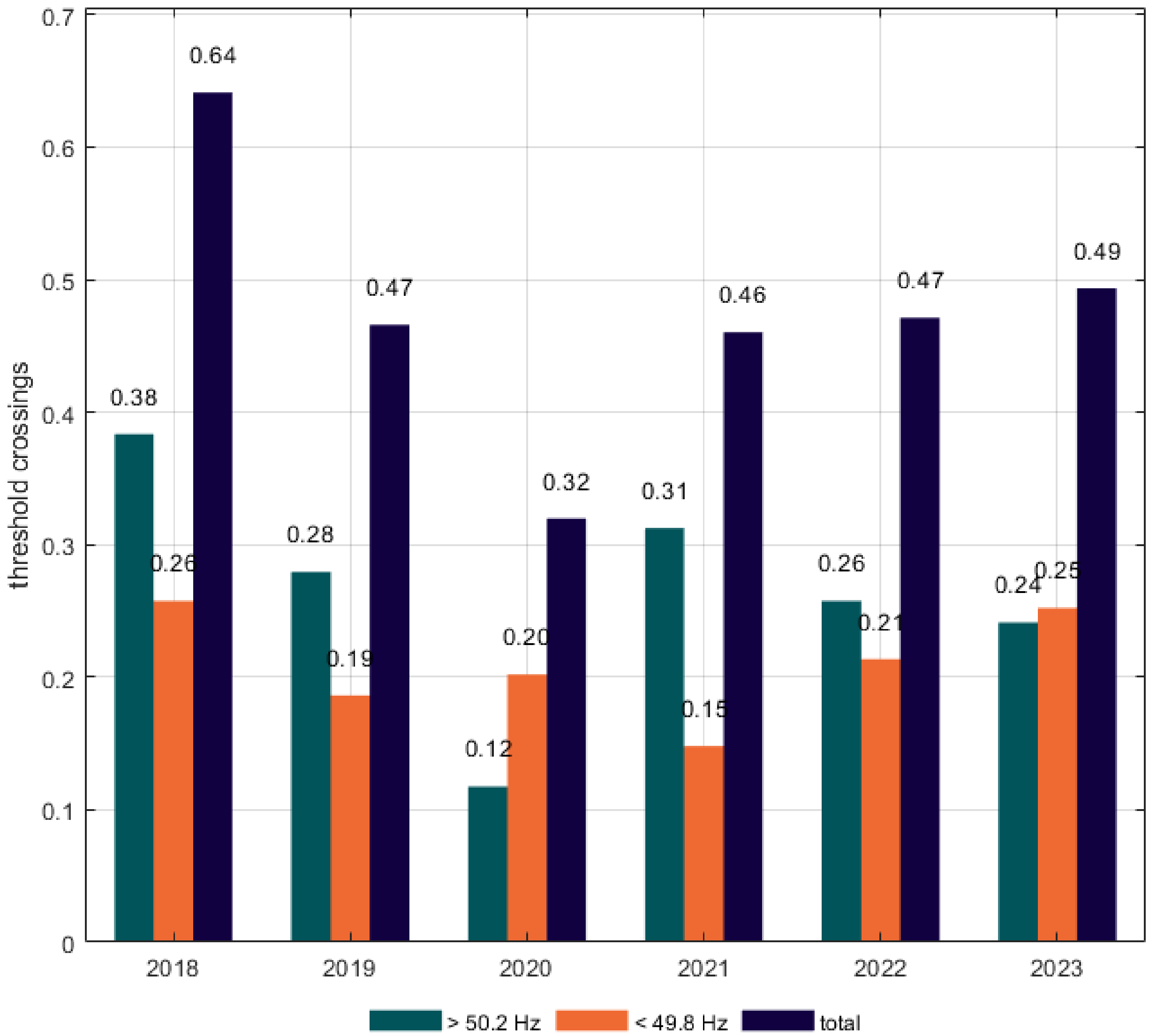
***Figure 3.48**. Average number of threshold crossings for every minute of the hour in 2023*



3.6.2 Number of 49.8-50.2 Hz crossings

Figure 3.49 represents the average number of threshold crossings per day that exceeded ±200 mHz. In 2023, the total number of crossings was slightly higher than in 2022.

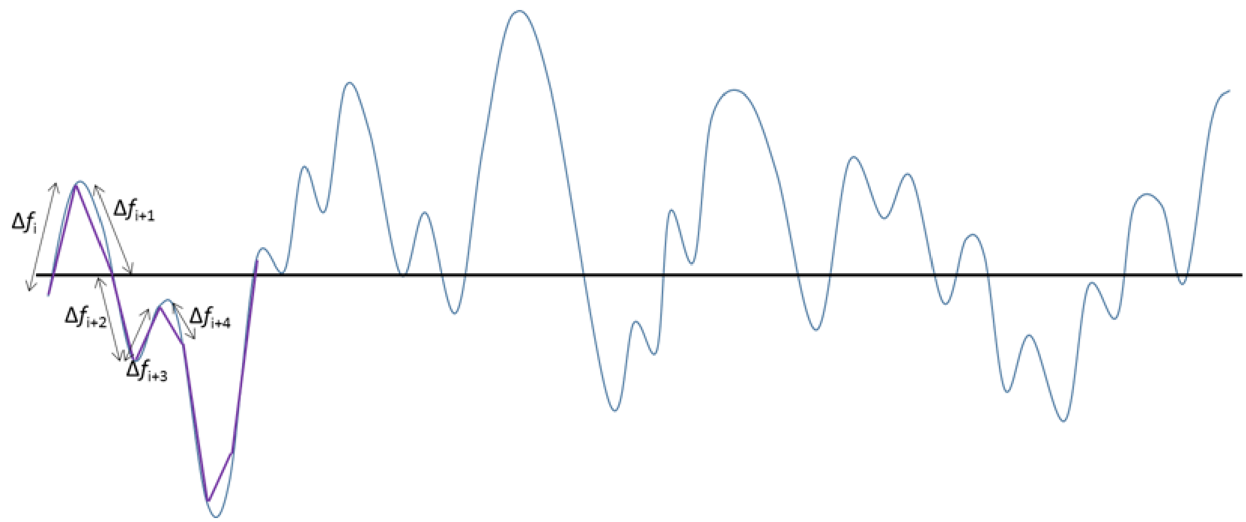
Figure 3.49. Daily average number of threshold crossings larger than ±200 mHz for years 2018-2023



3.7 Length of frequency path

The length of the path that frequency takes shows how much the frequency travels around 50.0 Hz, as can be seen in Figure 3.50. The length of the path is calculated per time period, and the length of the time step is taken into account. The resolution of the frequency data used is 0.1 seconds. Under Figure 3.50 is the formula for frequency path, where Δt is the length of the time step (in this case, 0.1 s).

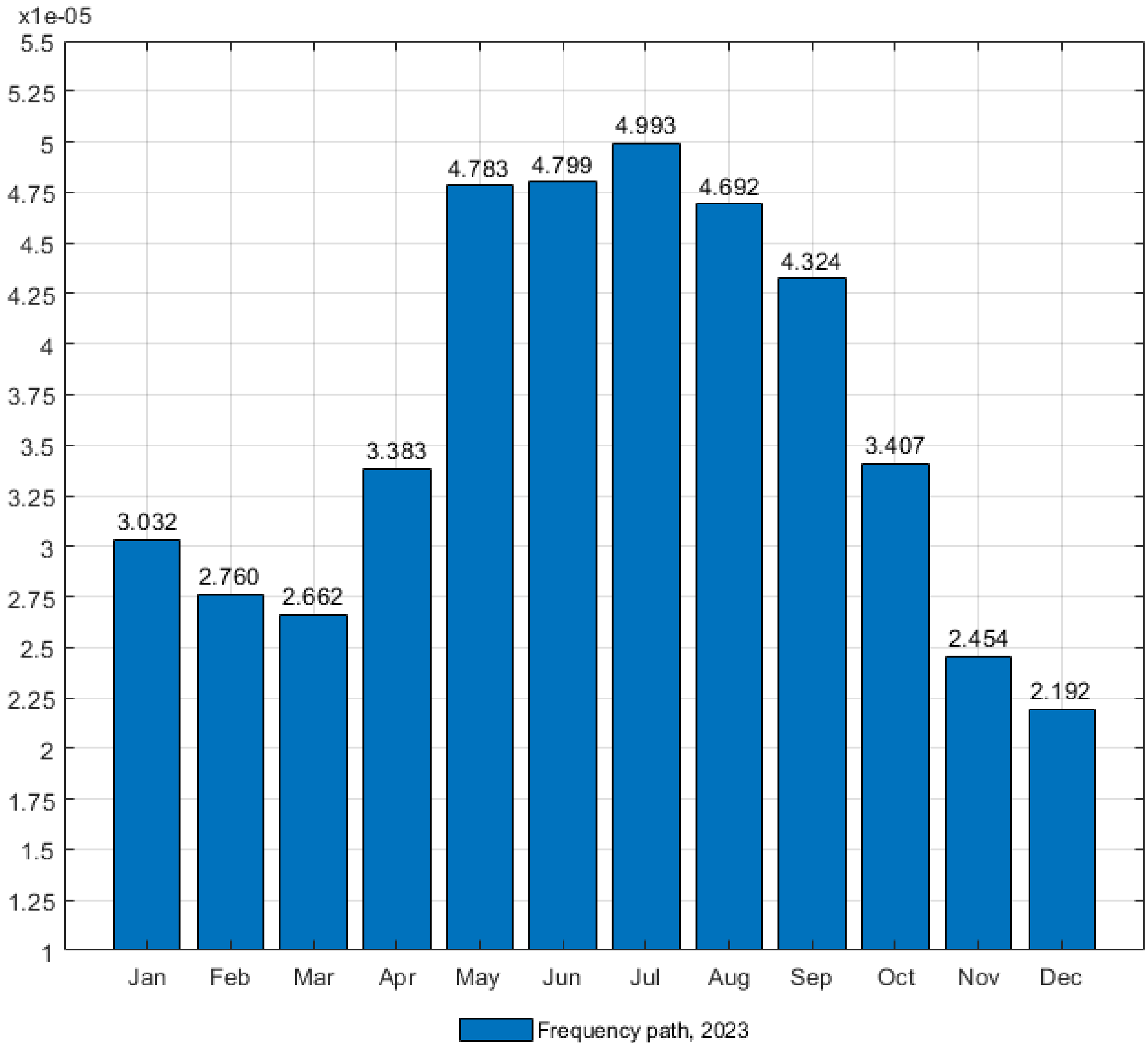
***Figure 3.50**. Frequency quality index: Length of the frequency path [7]*



$$Frequency\ path = \left(\frac{\sum_i^n \sqrt{(f(i) - f(i-1))^2 + \Delta t^2}}{(n-1) * \Delta t} \right) - 1$$

Figure 3.51 represents the frequency path for each month in 2023. The highest values of the frequency path occurred in the summer, from May until August. December, November, and March had the lowest values. Overall, both the peak value and the yearly average of the frequency path have decreased slightly since 2022. However, the average value of the frequency path is still around 60% higher compared to 2021.

***Figure 3.51**. Length of the frequency path month by month in 2023*



The frequency path for each day of the week can be seen in Figure 3.52. There has been rather little variation in the frequency path length between the days. The frequency path length has been a little shorter towards the end of the week. The path was longest on average on Wednesday.

***Figure 3.52**. Length of the frequency path for every day of the week in 2023*

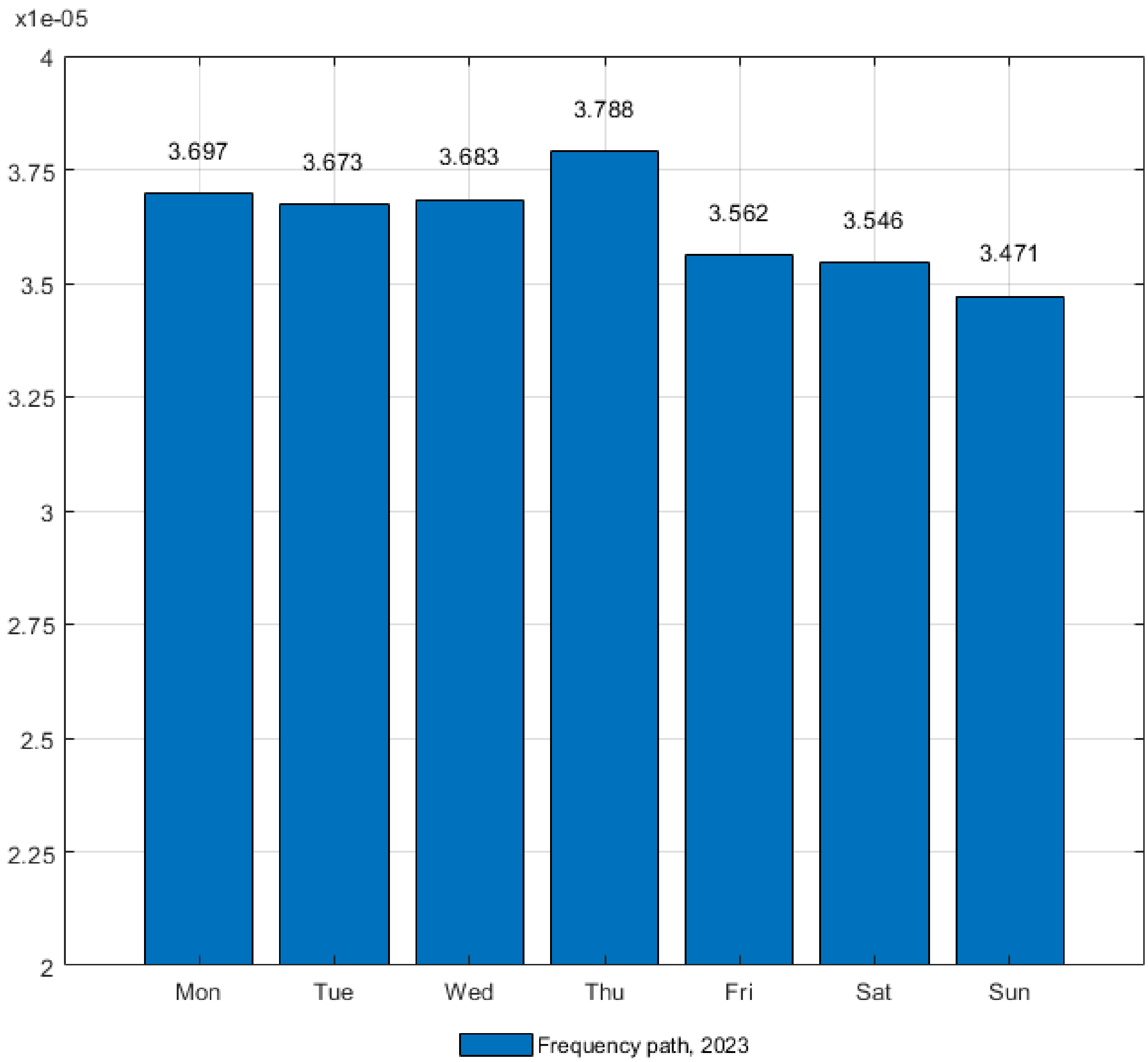


Figure 3.53 shows the frequency path for each hour within a day. The distribution of the frequency path values between different hours, compared to 2022, is more even. Morning hours from 5 to 7 am have the highest values, as well as 5 pm. The lowest values are from 8 to 12 am.

***Figure 3.53**. Length of the frequency path for every hour of the day in 2023*

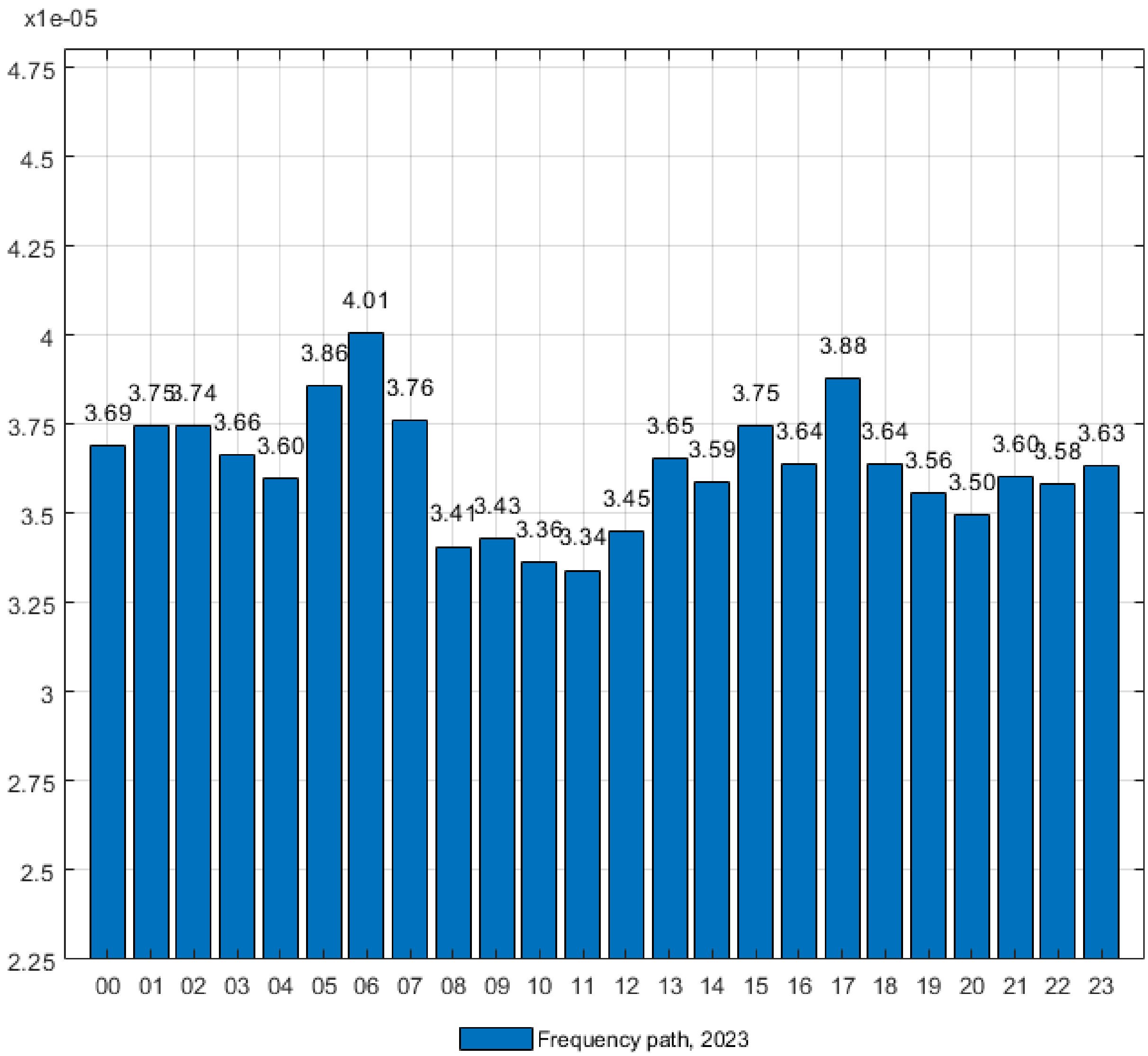
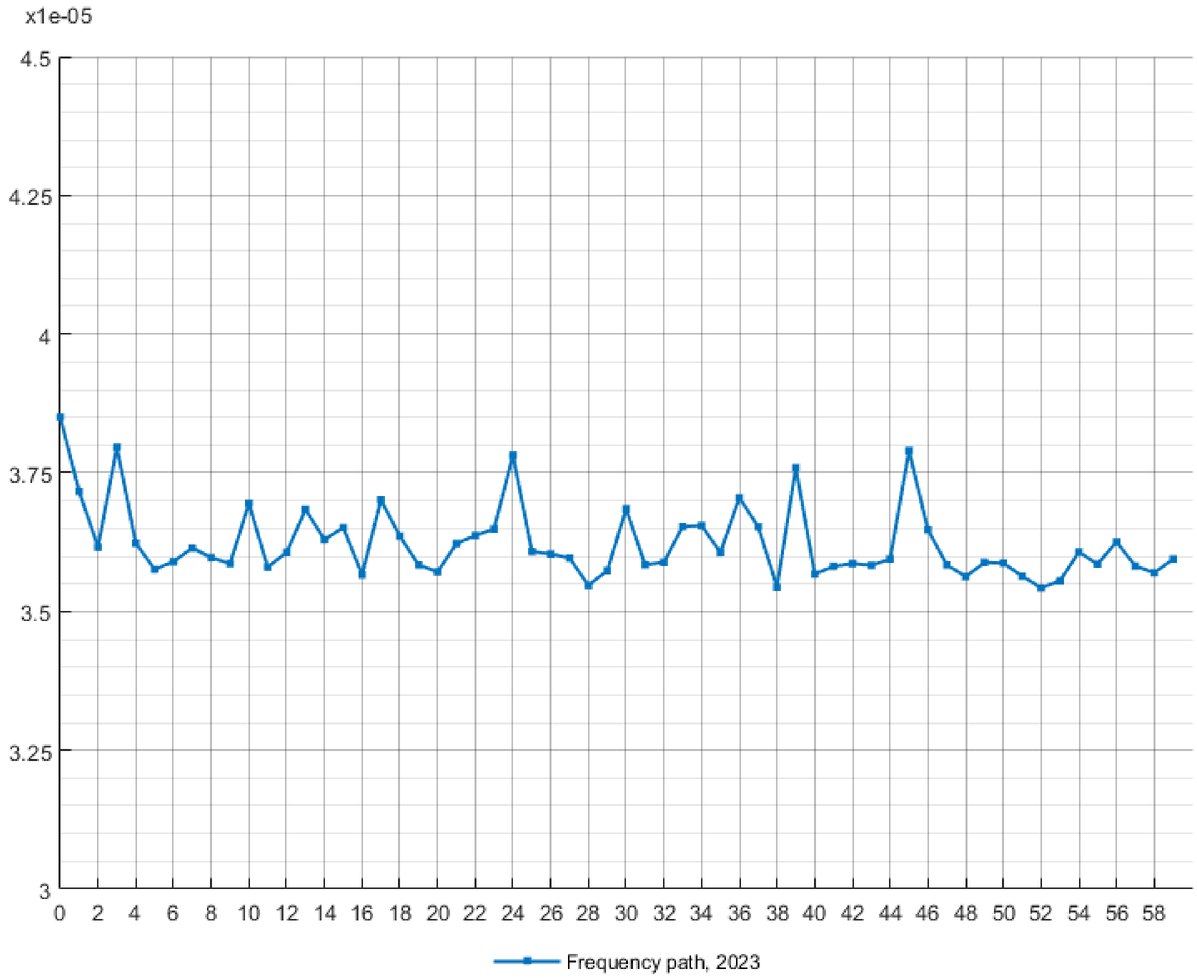


Figure 3.54 represents the average frequency path for every minute within an hour in 2023. The amount of variation in this graph has increased every year since 2020. The highest peak occurs in the first minute of the hour, but otherwise there is no clear trend.

***Figure 3.54**. Length of the frequency path for every minute of the hour in 2023*



3.8 Amount of frequency oscillation

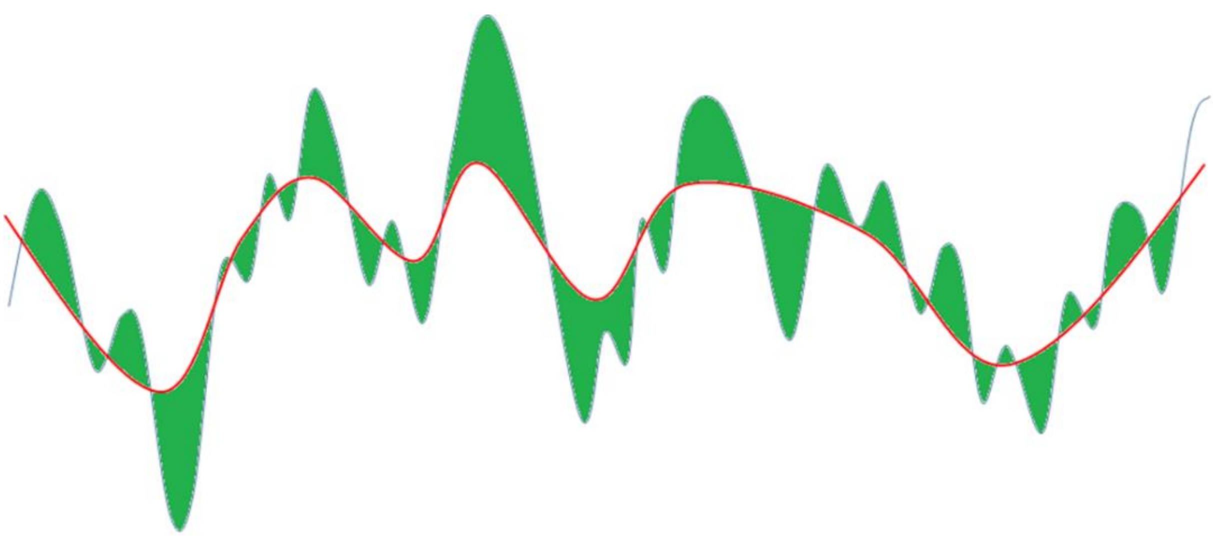
The frequency of the Nordic synchronous system oscillates constantly. The time period of the oscillation is approximately 40 to 90 seconds. This behavior is a natural characteristic of the system, but it can be influenced through adequate settings of system reserves. Oscillation has an increasing effect on time outside the standard frequency range. It also causes wear of reserve machines when controller settings are not optimal for the machine.

3.8.1 Methodology

The 60-second oscillation was studied using the Fourier transform, which can be used to decompose time series signals such as frequency measurements into sinusoidal frequency components. In other words, the sum of these sinusoidal components forms the original signal. Each of the frequency components has an amplitude and a phase. The amplitude of a certain frequency component represents the amount of sinusoidal oscillation at that frequency. It is possible to modify the signal in the frequency domain and then construct a time domain representation of the modified signal. [8]

The method used is such that the desired frequency band is filtered from the frequency data in order to estimate what the frequency would look like without the oscillation. It is possible to filter desired frequency components only partially or entirely remove them. In this study, as well as in reports from previous years [2, 3, 4, 5, 6], the frequency components were removed. The area between the filtered frequency signal and the original signal is used to represent the amount of oscillation. The approach is shown in Figure 3.57.

***Figure 3.55**. Frequency quality index: Amount of frequency oscillation [7]*



The filtering band used in all studies was 30-240 s. Choice is based on a comparison between different bands in the oscillation analysis for years 2011 and 2012 [8]. The frequency spectrum calculated from a sample containing the first 20 minutes of December 2012 is shown in Figure 3.56. Frequency bands corresponding to the 40-90 s and 30-240 s bands are marked on the figure. Figure 3.57 is an estimation of the frequency when these bands are filtered. In the studies, the Fourier transform was calculated for time intervals of one hour. The actual used band is 30-225 s, and due to the nature of FFT, it might vary slightly depending on the length of the data sample.

For the FFT-filtering calculation, there were two requirements for the data: there had to be at least 90% of eligible data for each hour, and the measurement frequency had to stay at least at 4 Hz. If these requirements were not fulfilled, the hour was skipped and removed from the calculations.

Figure 3.56. Frequency spectrum representing the first 20 minutes of December 2012 (UTC+2). The green line corresponds to the 40-90 s band, and the red line corresponds to the 30-240 s band. [8]

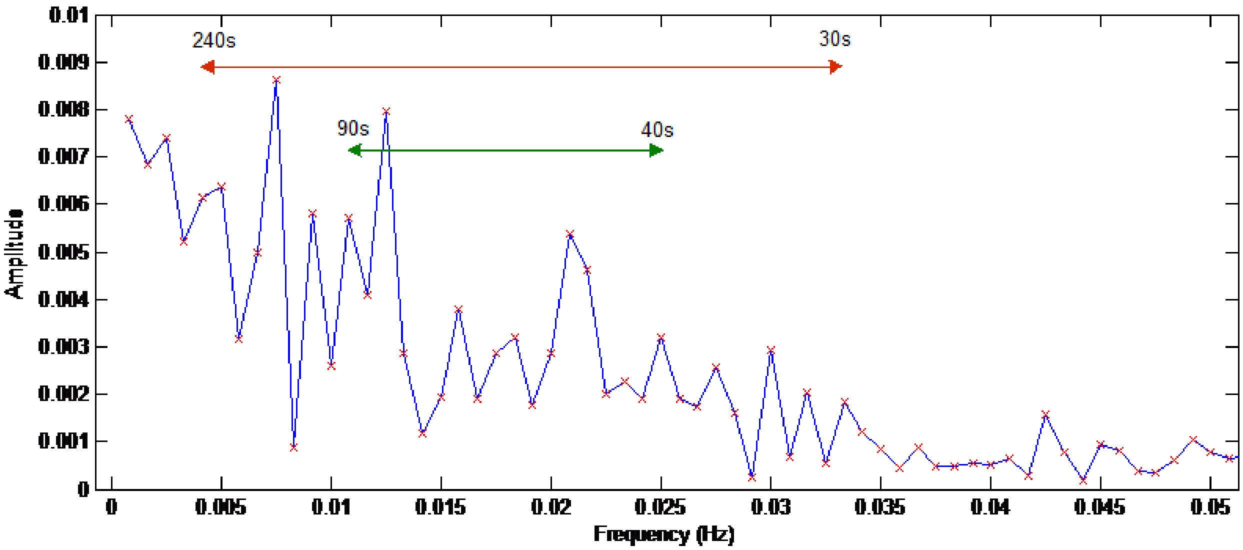
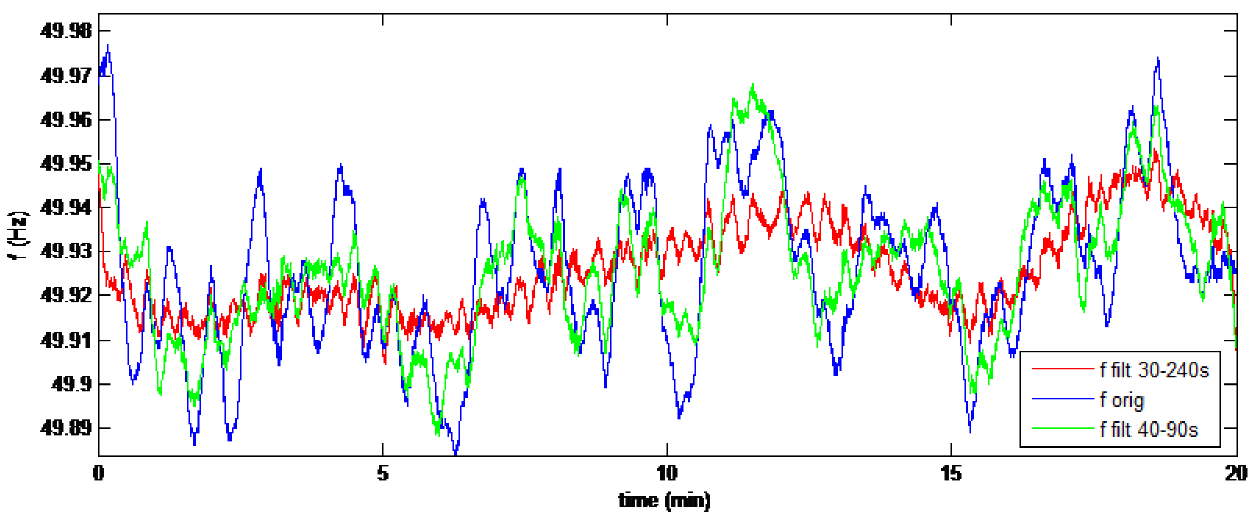


Figure 3.57. Original frequency (blue), frequency with 40-90 s band filtered (green), and frequency with 30-240 s band filtered (red). The first 20 minutes of December 2012 are shown (UTC+2). [8]



3.8.2 Amount of oscillation

Figure 3.58 shows hourly values and 24-hour moving averages for the amount of oscillation in 2023. The 24-hour moving averages were calculated if there was enough eligible data for at least 12 hours in the 24-hour frame. Gaps in the following curves indicate that there was not enough eligible data for the calculations.

The 24-hour moving average had the highest values in May and September. Compared to 2022, the peak and bottom values are further apart. Figures 3.59 and 3.60 contain the previously mentioned 24-hour moving averages for years 2018-2020 and 2021-2023, respectively.

***Figure 3.58**. Amount of oscillation in 2023*

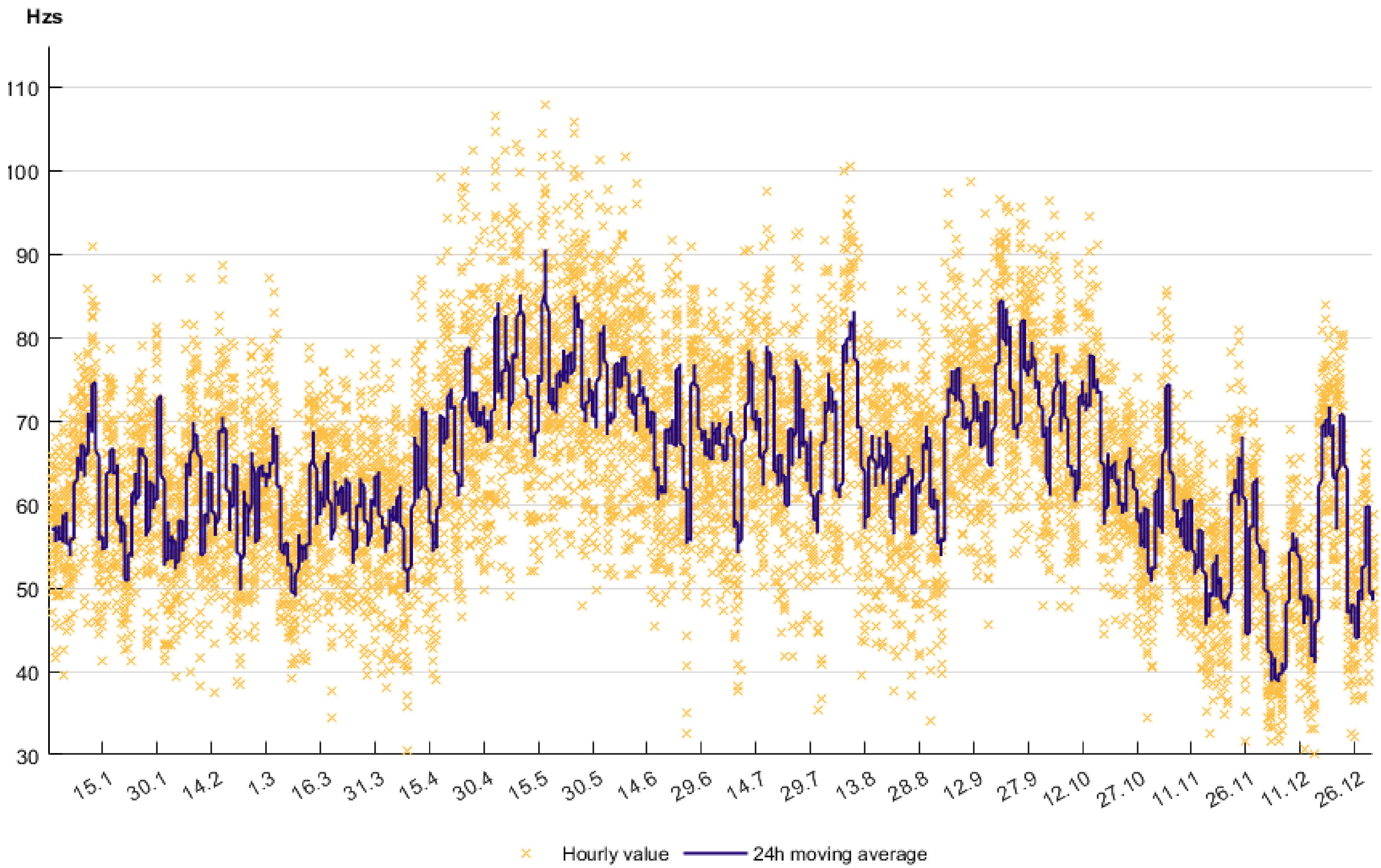


Figure 3.59. Amount of oscillation in 2018-2020

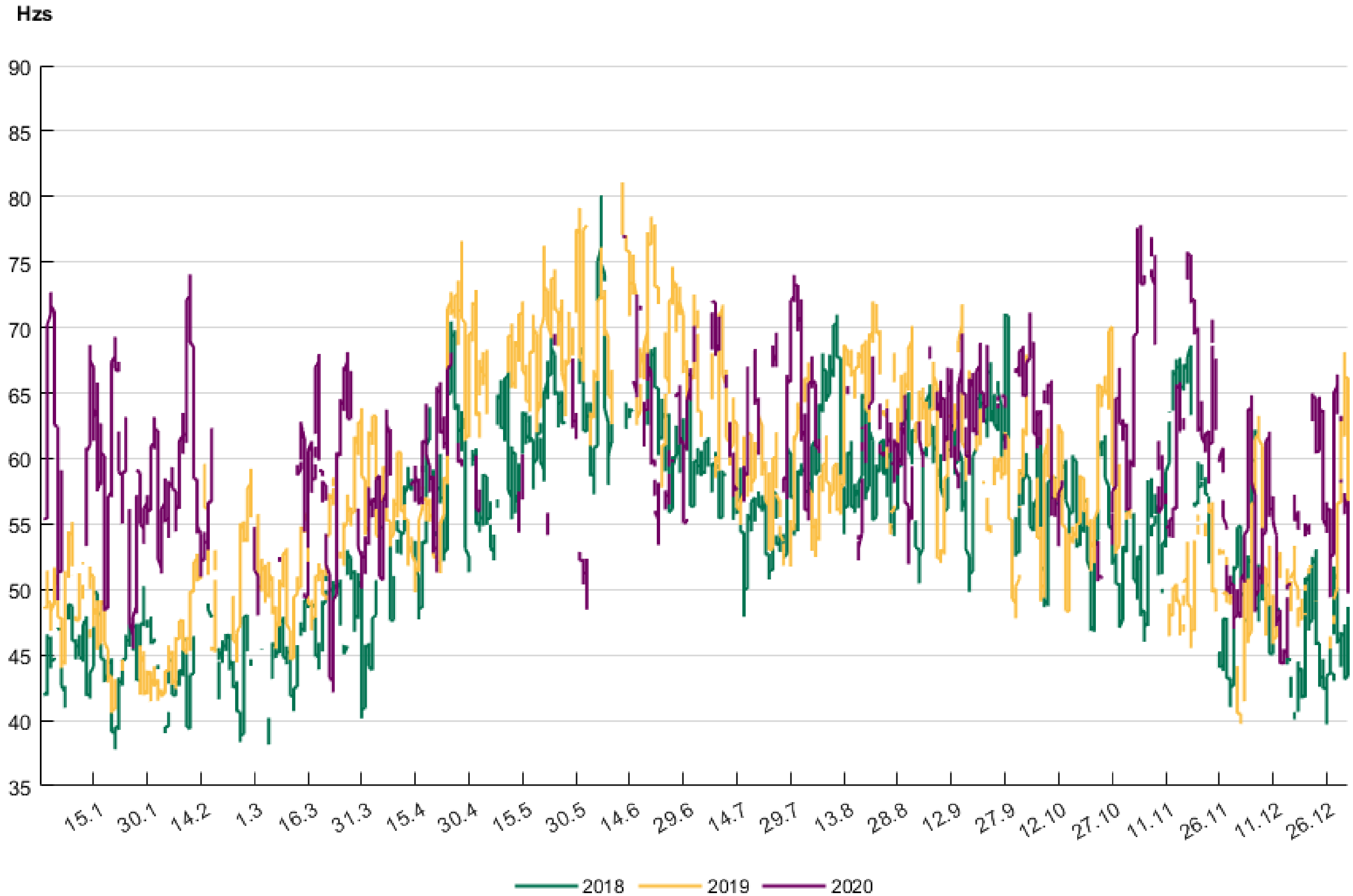
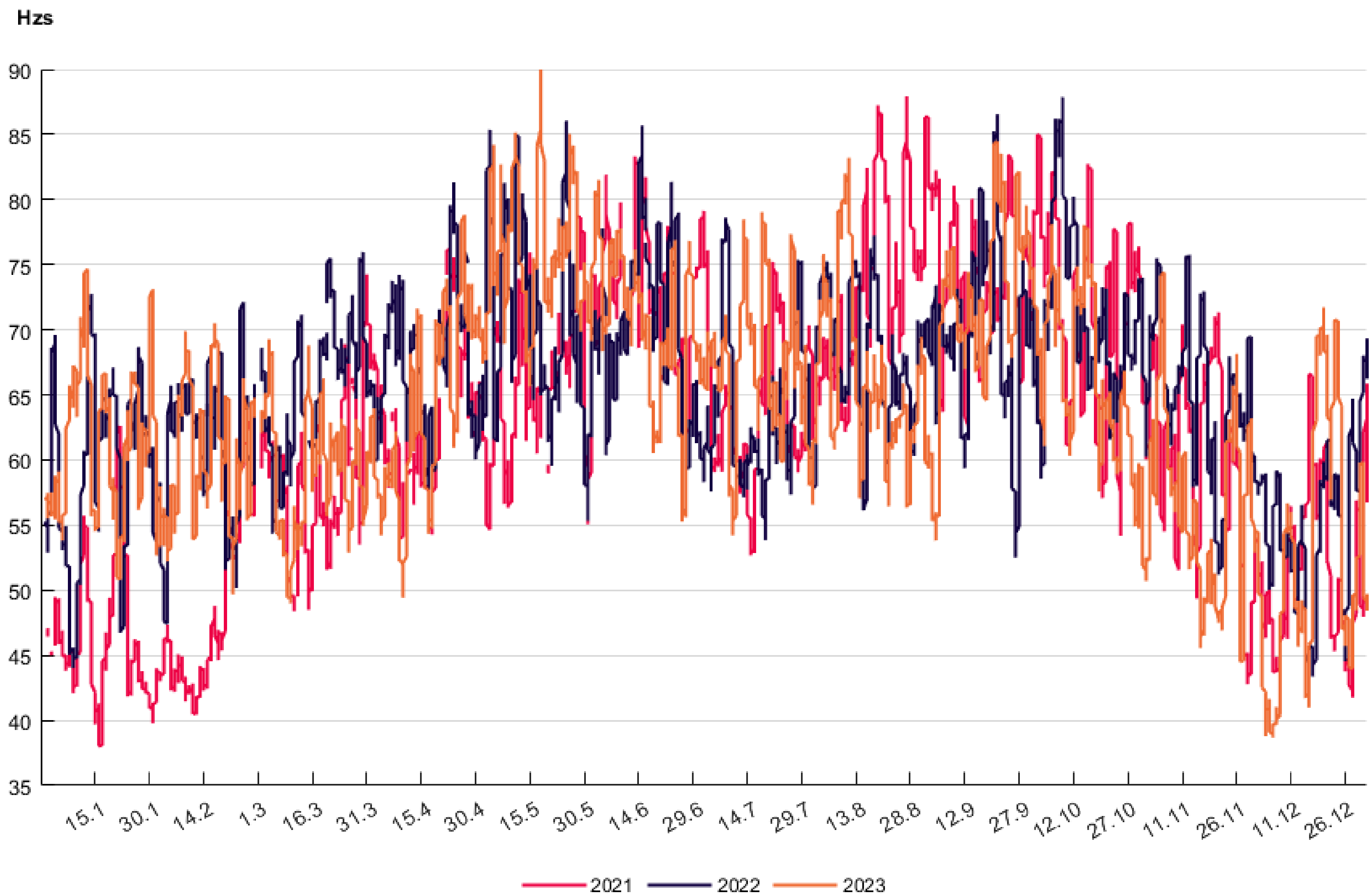


***Figure 3.60**. Amount of oscillation in 2021-2023*



The mean value and standard deviation of the oscillation for each month from 2018 to 2023 are shown in Tables 3.22 and 3.23. Figure 3.61 represents the same information in a visual form. The frequency oscillated the most in May and September. The mean amount of oscillation is slightly smaller than in 2022. However, the yearly mean is still higher than in the previous years within the observation period. The standard deviation is similar to the year 2022.

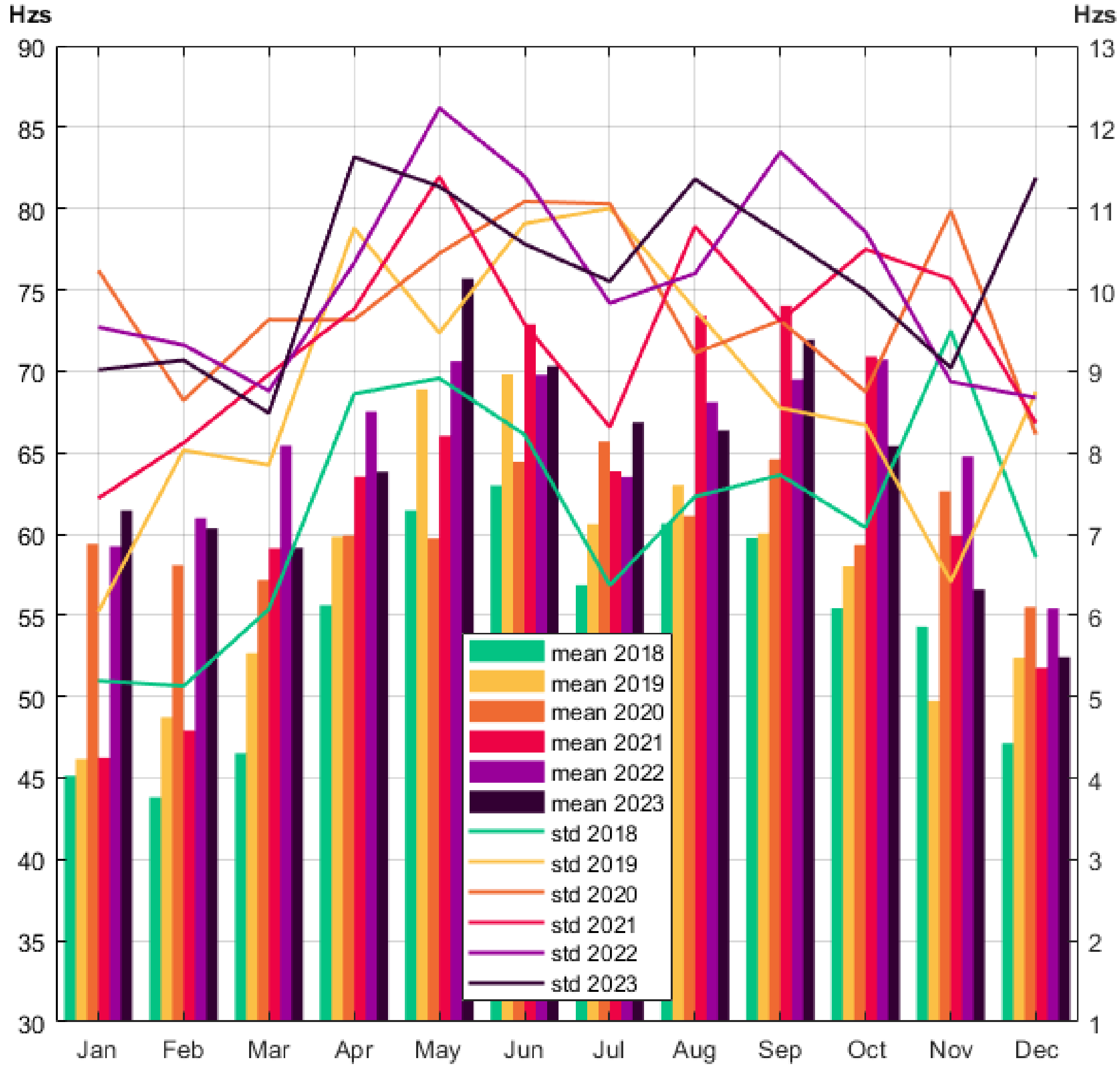
***Table 3.22**. Mean values and standard deviations for oscillation in years 2018-2020*

	Mean value (Hzs)			Standard deviation (Hzs)		
Month	**2018**	**2019**	**2020**	**2018**	**2019**	**2020**
January	45.1	46.2	59.4	5.2	6.0	10.2
February	43.8	48.7	58.1	5.1	8.0	8.6
March	46.5	52.7	57.2	6.1	7.8	9.6
April	55.6	59.8	59.9	8.7	10.8	9.6
May	61.4	68.9	59.7	8.9	9.5	10.4
June	63.0	69.8	64.4	8.2	10.8	11.1
July	56.9	60.6	65.7	6.4	11.0	11.1
August	60.6	63.0	61.1	7.5	9.8	9.2
September	59.8	60.0	64.6	7.7	8.5	9.6
October	55.4	58.0	59.3	7.1	8.3	8.7
November	54.3	49.7	62.6	9.5	6.4	11.0
December	47.1	52.4	55.5	6.7	8.7	8.2
Entire year	**54.1**	**57.5**	**60.6**	**7.3**	**8.8**	**9.8**

Table 3.23. Mean values and standard deviations for oscillation in years 2021-2023

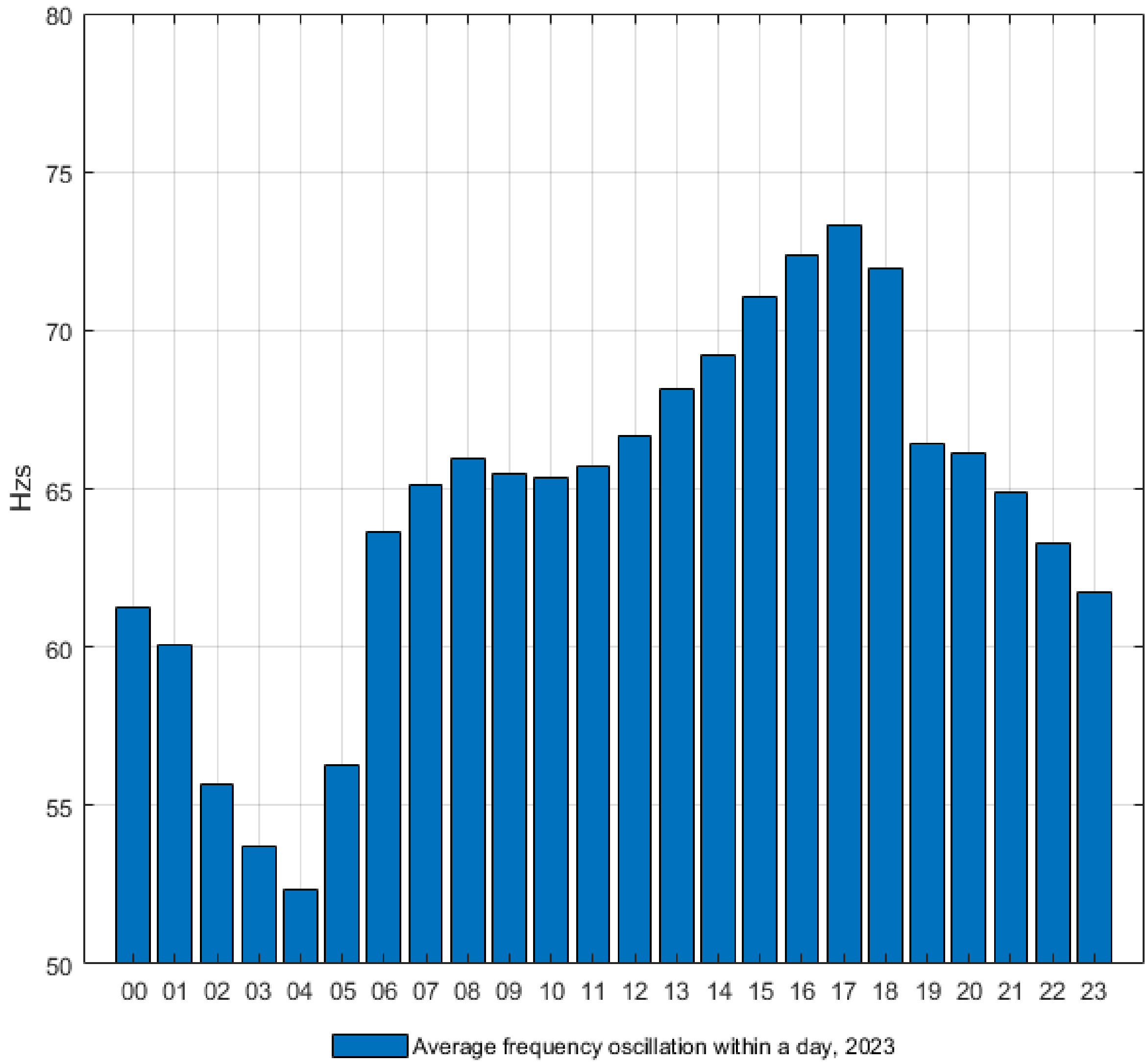
	Mean value (Hzs)			**Standard deviation (Hzs)**		
Month	**2021**	**2022**	**2023**	**2021**	**2022**	**2023**
January	46.2	59.2	61.4	7.4	9.5	9.0
February	47.9	61.0	60.3	8.1	9.3	9.1
March	59.1	65.4	59.2	9.0	8.8	8.5
April	63.5	67.5	63.8	9.8	10.3	11.6
May	66.0	70.6	75.7	11.4	12.2	11.3
June	72.9	69.8	70.3	9.6	11.4	10.6
July	63.9	63.5	66.9	8.3	9.8	10.1
August	73.4	68.1	66.4	10.8	10.2	11.4
September	74.0	69.5	71.9	9.6	11.7	10.7
October	70.9	70.7	65.4	10.5	10.7	10.0
November	59.9	64.8	56.6	10.1	8.9	9.0
December	51.8	55.4	52.4	8.4	8.7	11.4
Entire year	**62.5**	**65.5**	**64.2**	**9.4**	**10.1**	**10.2**

***Figure 3.61**. Mean values (left y-axis) and standard deviations (right y-axis) for oscillation in years 2018-2023*



The average oscillation within a day in 2023 can be seen in figure 3.62. The amount of oscillation peaked in the late afternoon. The lowest values of oscillation are at night, from 2 am to 5 am. The amount of oscillation was at its highest between 3 pm and 6 pm. The trend is very similar to previous years.

Figure 3.62*. *Average frequency oscillation within a day in 2023

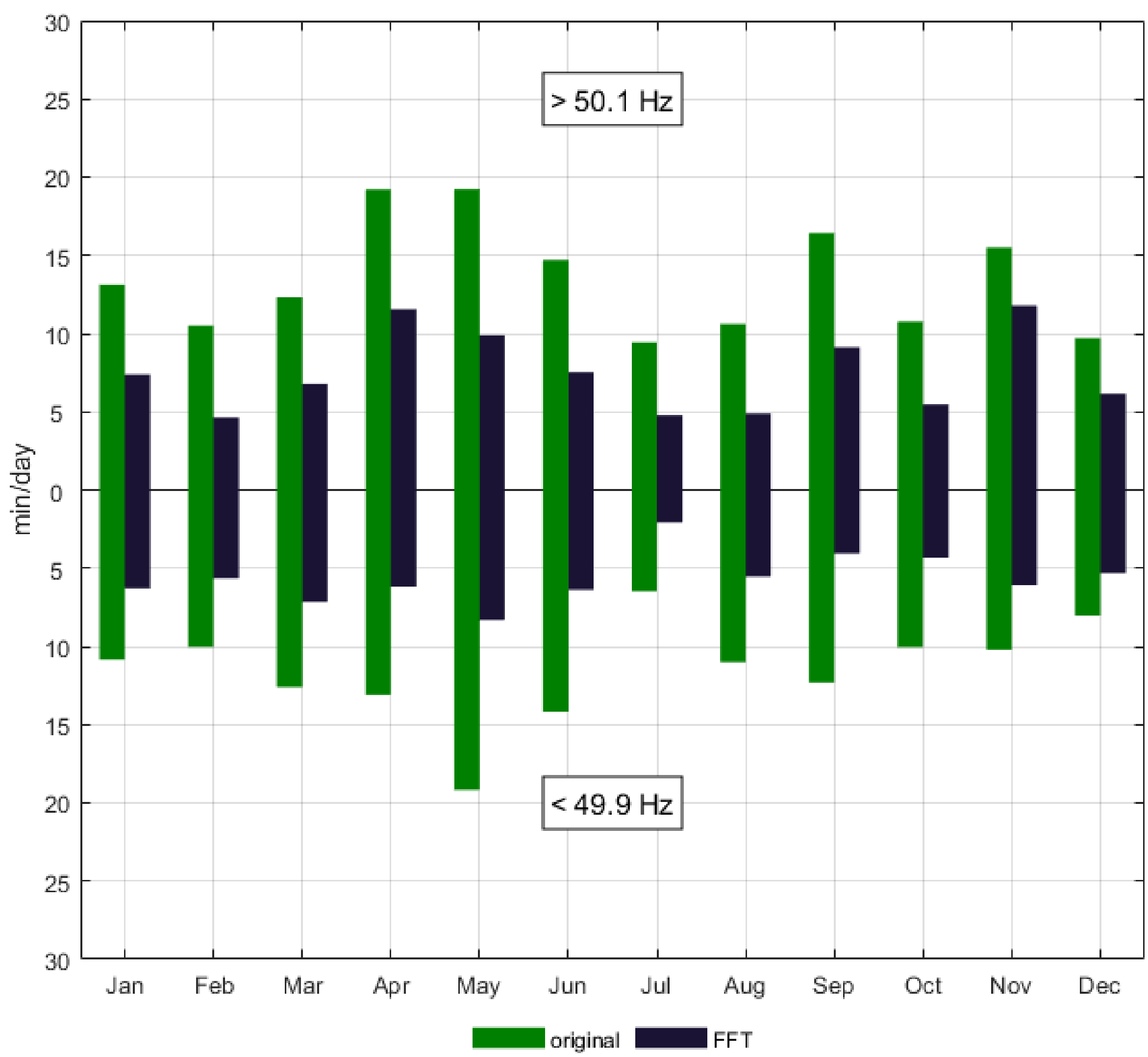


3.8.3 Influence of oscillation on frequency variations

The aim of this section is to analyze to what extent the deviations from the standard frequency range have been caused by the 60 second oscillation of the frequency.

Figure 3.63 shows the average minutes per day outside the standard frequency range in 2023 without filtering and after applying FFT-filtering. Only the parts that had enough consecutive samples for the FFT-algorithm within one hour, are taken into account.

Figure 3.63*. *Average time per day outside the standard frequency range in 2023



In Figure 3.64, the reduction of time outside the standard frequency range in 2023 through filtering is presented as percentages of the original values. The results show that filtering leads to a significant reduction in time outside the standard frequency range. The reduction is largest in July and smallest in November. The values are similar compared to 2022.

Figure 3.64**. **Reduction in time per month outside the standard frequency range after filtering in 2023

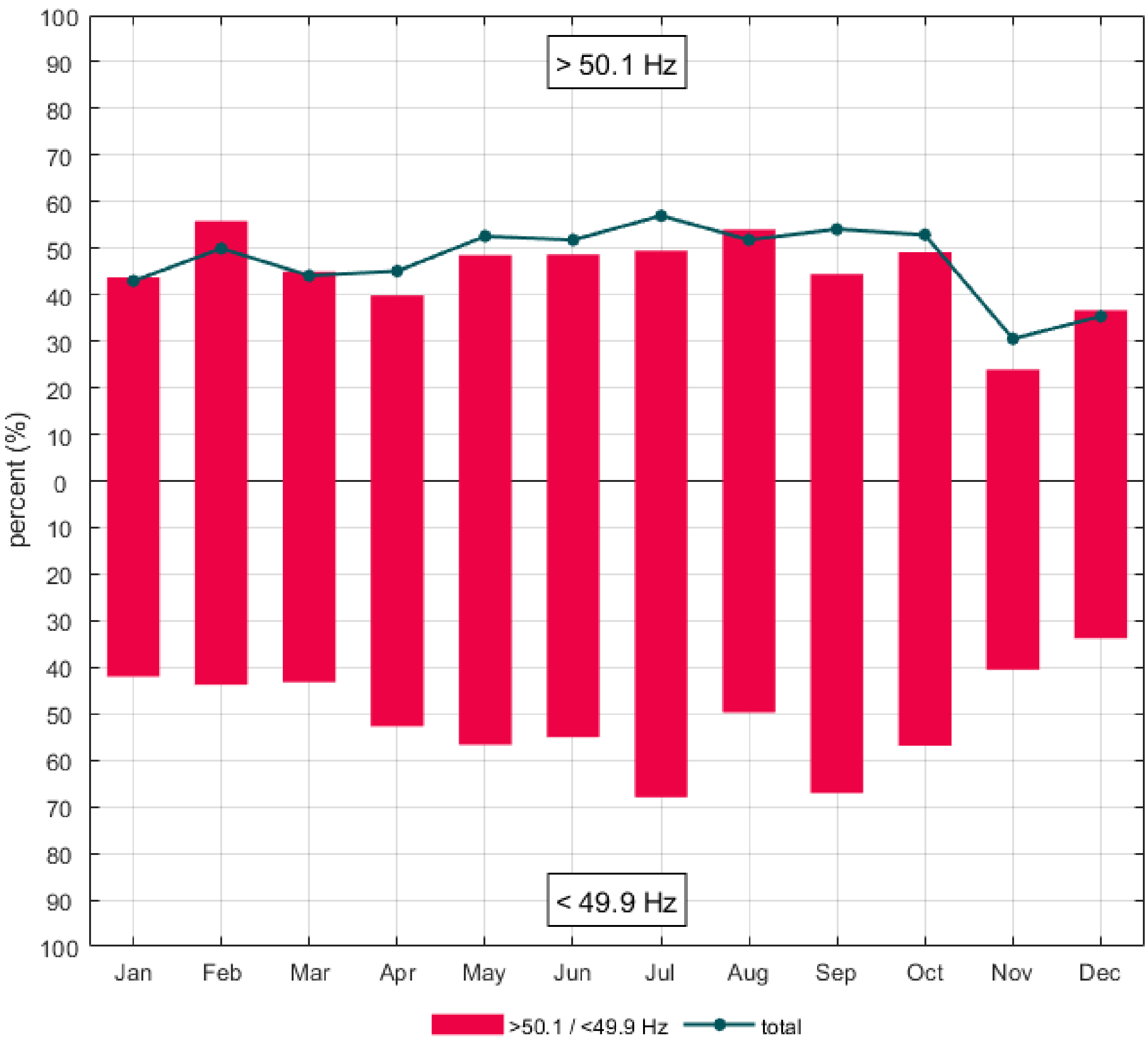
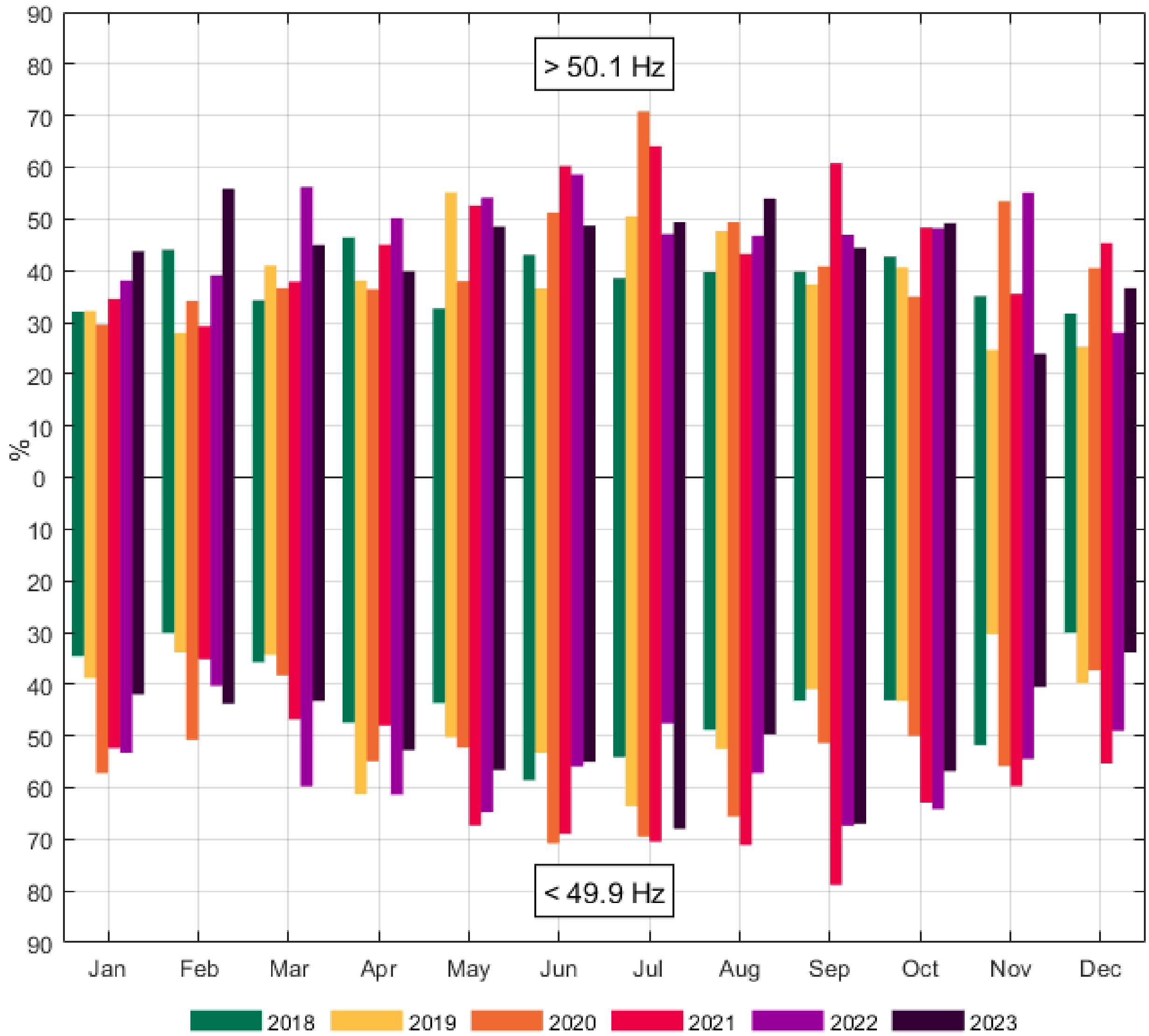


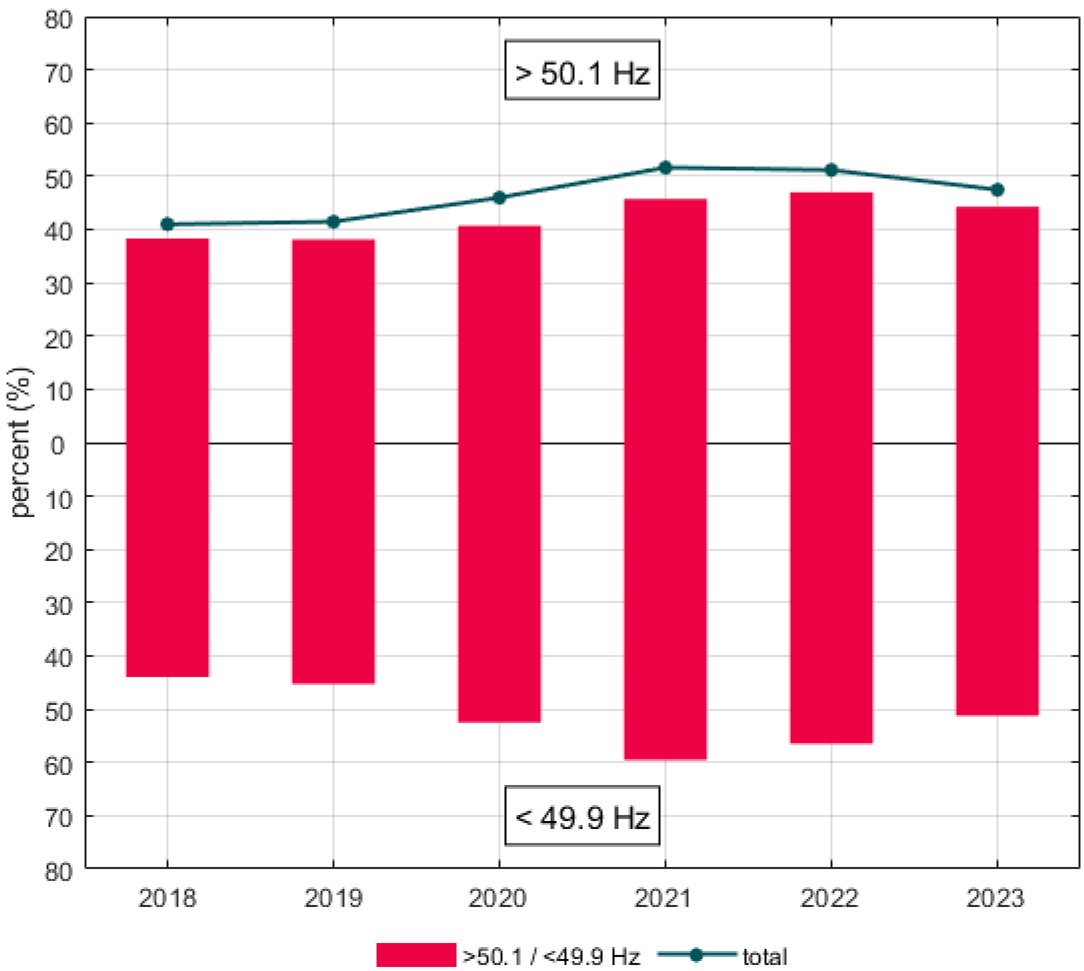
Figure 3.65 represents the reduction in time outside the standard frequency range in percentages month by month for years 2018 to 2023.

***Figure 3.65**. Reduction in time per month outside the standard frequency range after filtering in years 2018-2023*



In addition to the monthly values presented in the previous figure, results for the entire year in 2018-2023 are shown below in Figure 3.66. Filtering the oscillation reduces the duration of frequency deviations by a bit less than 50% in 2023. Slight yearly growth in reduction can be seen from 2018 up to 2021, after which the values have slightly decreased in 2023. Time below 49.9 Hz is affected more by the oscillation since the reduction values are higher with under frequencies.

***Figure 3.66**. Reduction in time outside the standard frequency range after filtering for years 2018-2023*



3.9 Frequency step around the hour shift

The frequency step around the hour shift is defined by the difference between the highest and lowest frequency during the period from 5 minutes before to 5 minutes after the hour shift. A negative sign is added if the highest frequency takes place before the lowest frequency. The frequency step is calculated for every hour shift in 2023. Of the total samples in a period, the 1st, 5th, 10th, 50th, 90th, 95th, and 99th percentiles are determined. Figure 3.67 shows the definition of deterministic frequency deviation. The resolution of the frequency data was 1 second.

Figure 3.67**. **Definition of deterministic frequency deviation [7]

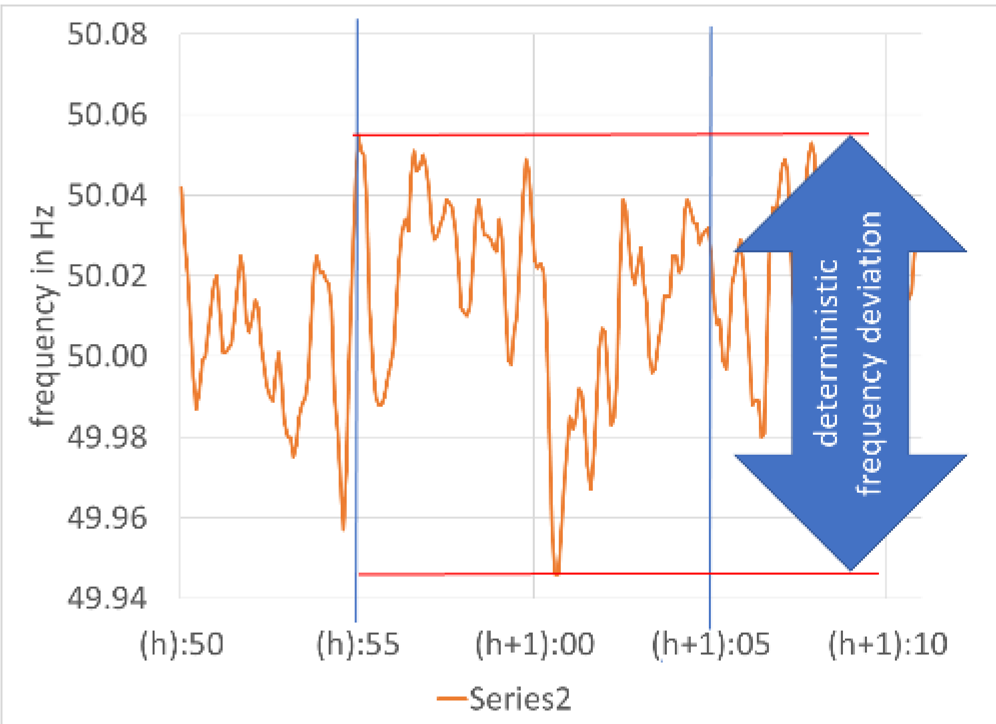


Figure 3.68 represents the deterministic frequency deviation per month in 2023. The 50th percentile stays below zero for the entire year, which indicates that the highest frequency took place before the lowest in more than half of the hour shifts. The percentiles are the furthest away from zero in May. The values are similar to 2022 but a little further away from zero than they were in 2021.

***Figure 3.68**. The 1st, 5th, 10th, 50th, 90th, 95th, and 99th percentiles of deterministic frequency deviation for every month in 2023*

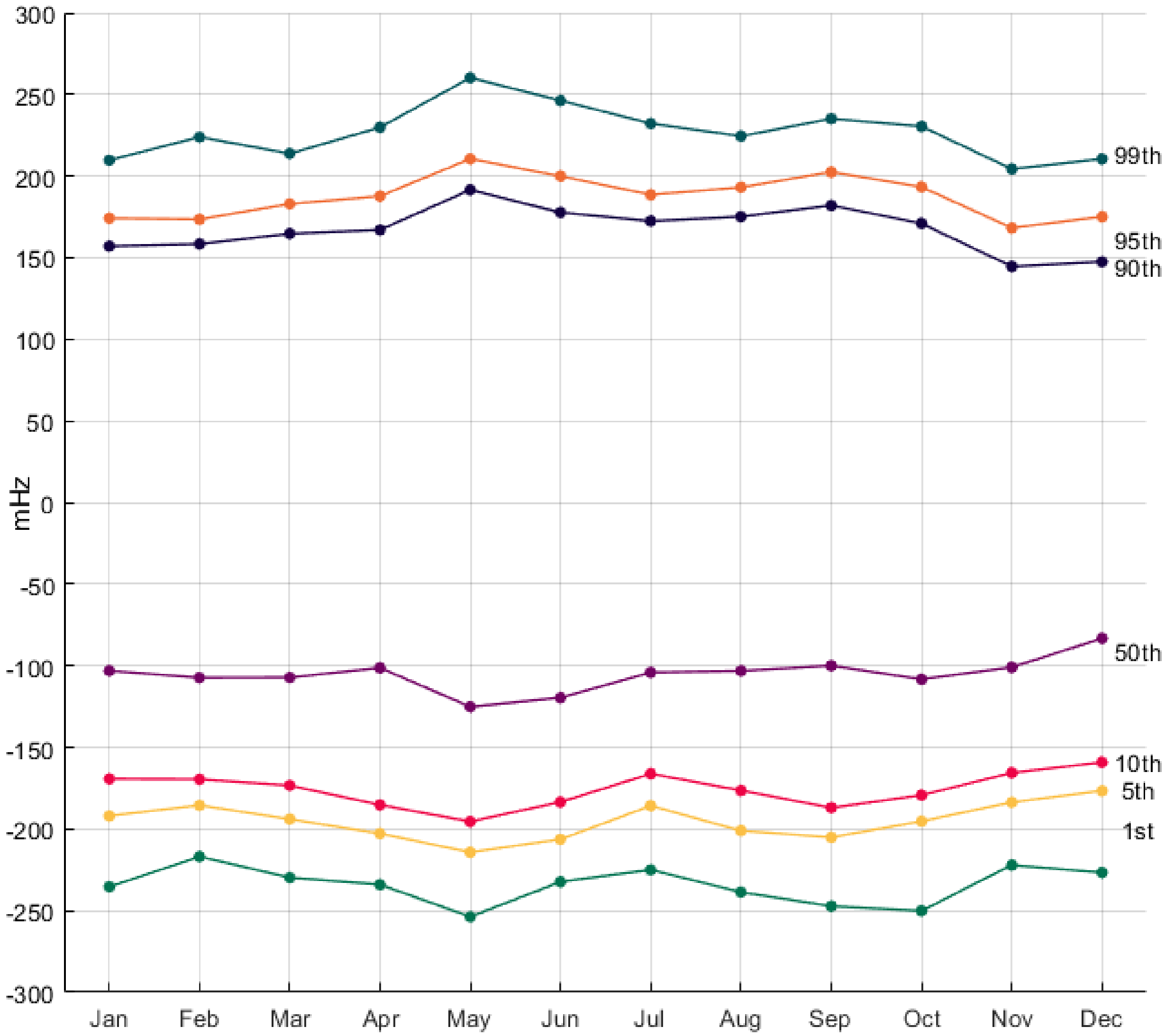
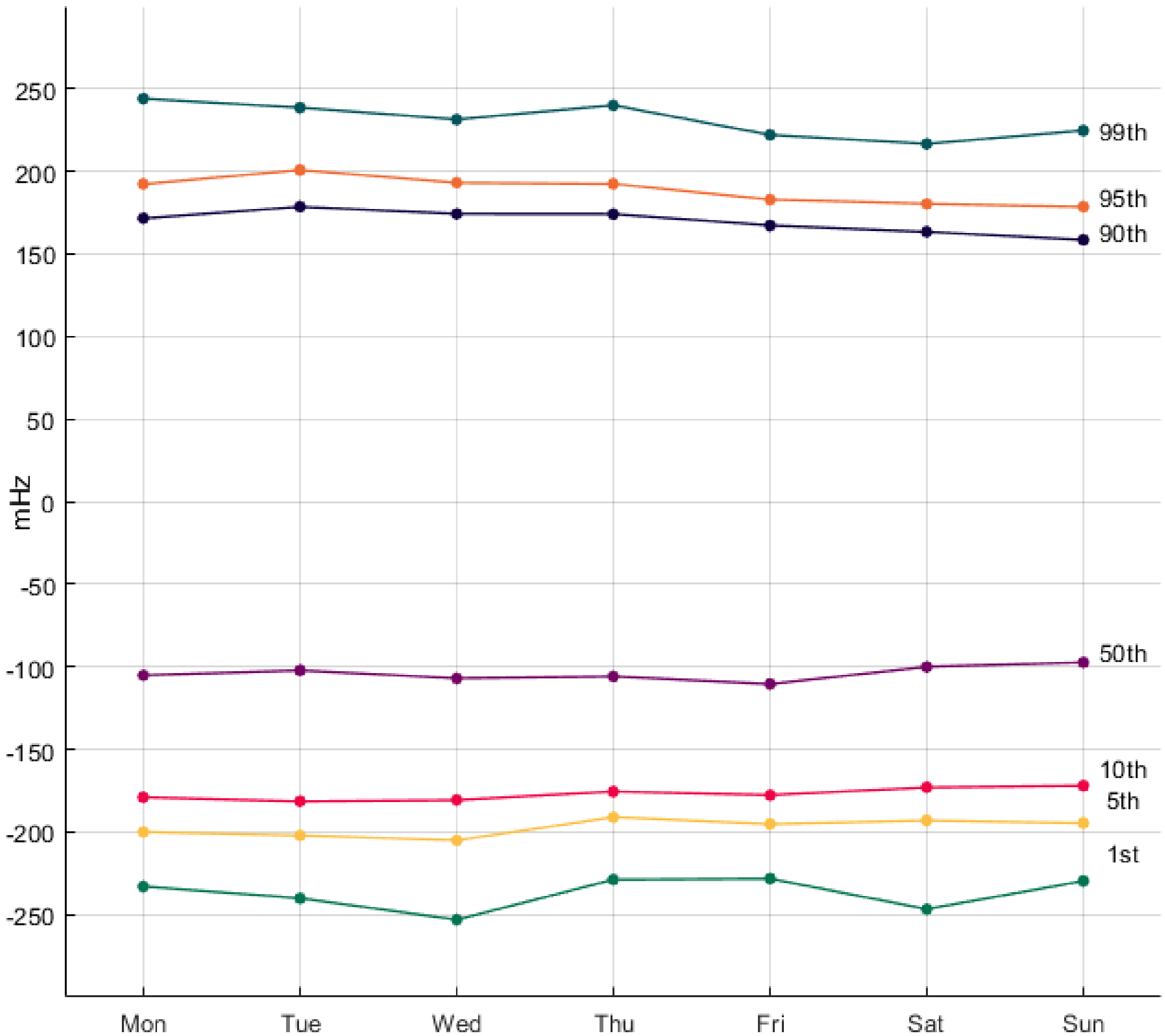


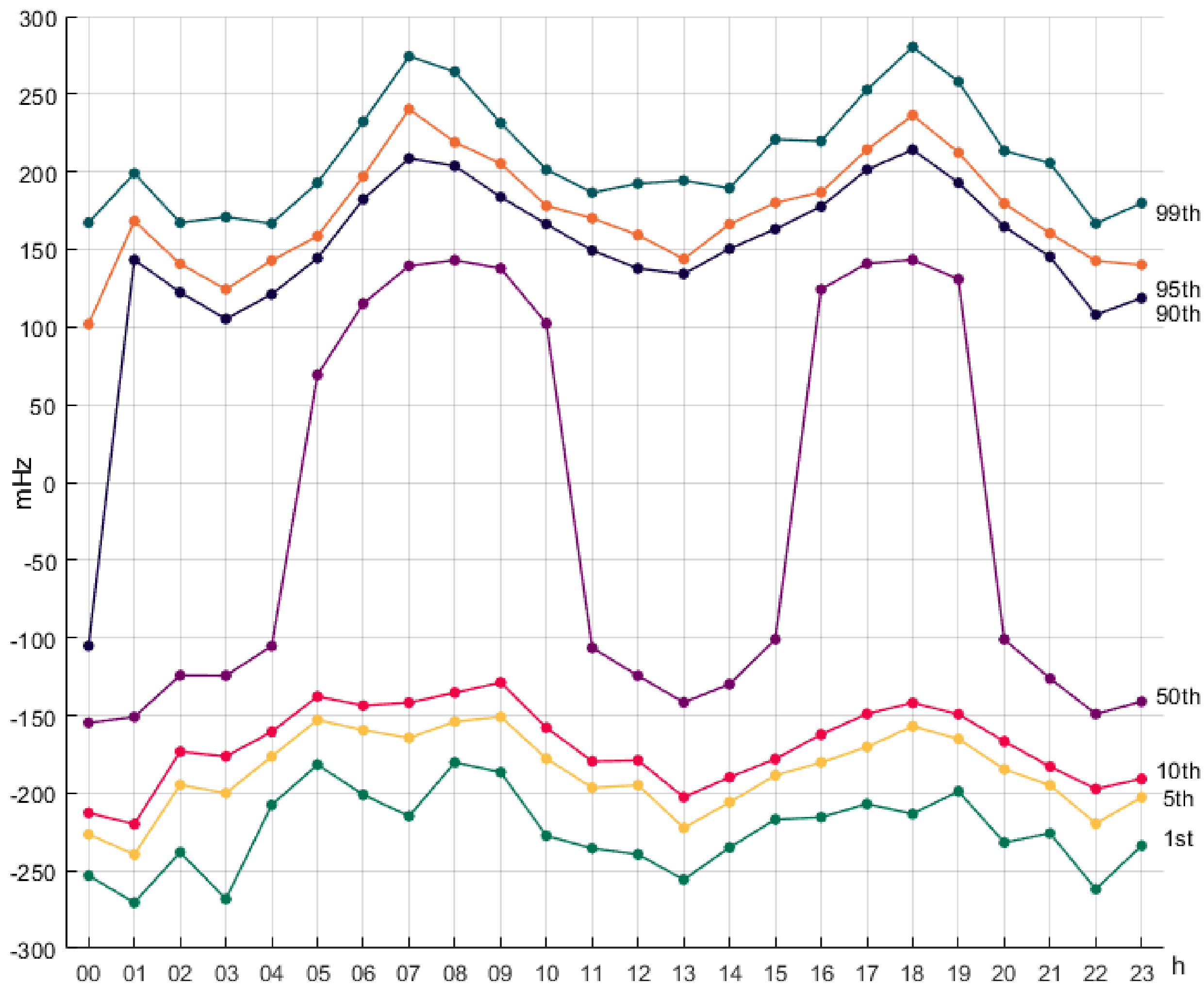
Figure 3.69 shows the percentiles around the hour shift for every day of the week in 2023. The 99th, 95th, and 90th percentiles have been slightly lower on Fridays and on weekends compared to the rest of the week.

***Figure 3.69**. The 1st, 5th, 10th, 50th, 90th, 95th, and 99th percentiles of deterministic frequency deviation for every day of the week in 2023*



The percentiles of the frequency step around the hour shift for each hour of the day have more variety than the previous figures, as can be seen from Figure 3.70. During the morning hours from 5 to 10 and in the evening from 16 to 19, the values for the 50th percentile are positive, which means the lowest frequency has taken place before the highest in more than half of the hour shifts during these hours. All the other percentiles follow the same pattern, where the values are higher during these hours.

***Figure 3.70**. The 1st, 5th, 10th, 50th, 90th, 95th, and 99th percentiles of deterministic frequency deviation for every hour of the day in 2023*

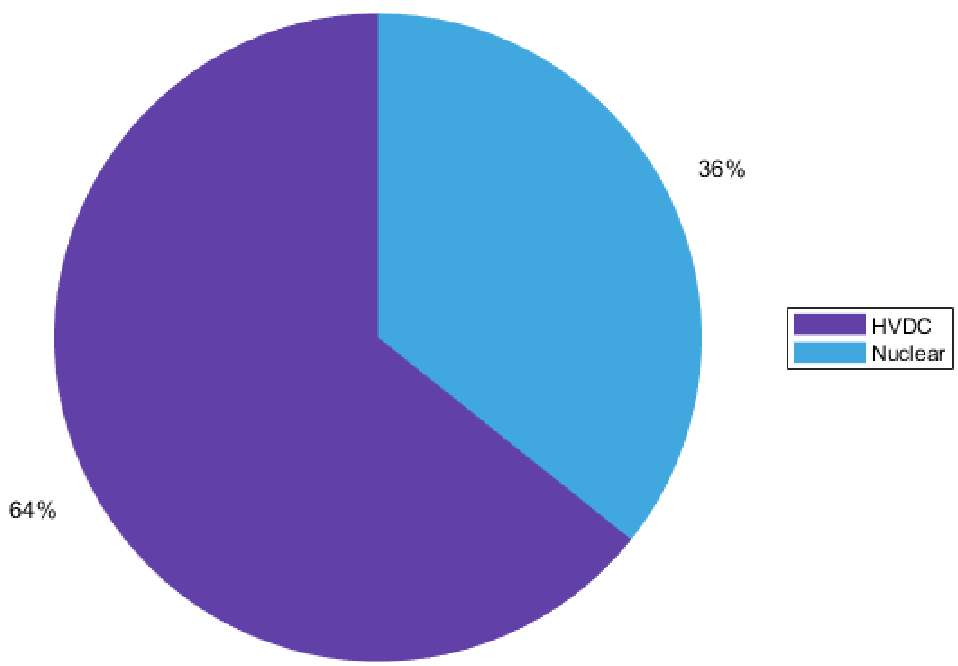


Chapter 4. Frequency disturbances exceeding 300 mHz frequency deviation

This chapter offers information on the major frequency disturbances in the Nordic synchronous system in 2023. Over 300 mHz frequency deviations, according to Fingrid's PMU located in Kangasala, are included. The measurement frequency for the PMU was 10 Hz. This data describes, at a fair level of accuracy, the frequency of the whole Nordic system.

There were 14 frequency disturbances in 2023, where the deviation exceeded 300 mHz. Five of those disturbances were caused by nuclear power plants and nine by failures in HVDC links. Figure 4.1 represents the shares of the factors causing over 300 mHz deviations. The number of 300 mHz deviations decreased by 12.5% from the previous year. However, the number of these deviations has increased compared to years 2017-2020 where there have been around 6 deviations per year. Also, nuclear power plant failures have previously been the most common reason for large deviations.

***Figure 4.1*. Shares of the factors causing over 300 mHz disturbances in the Nordic synchronous system in 2023**



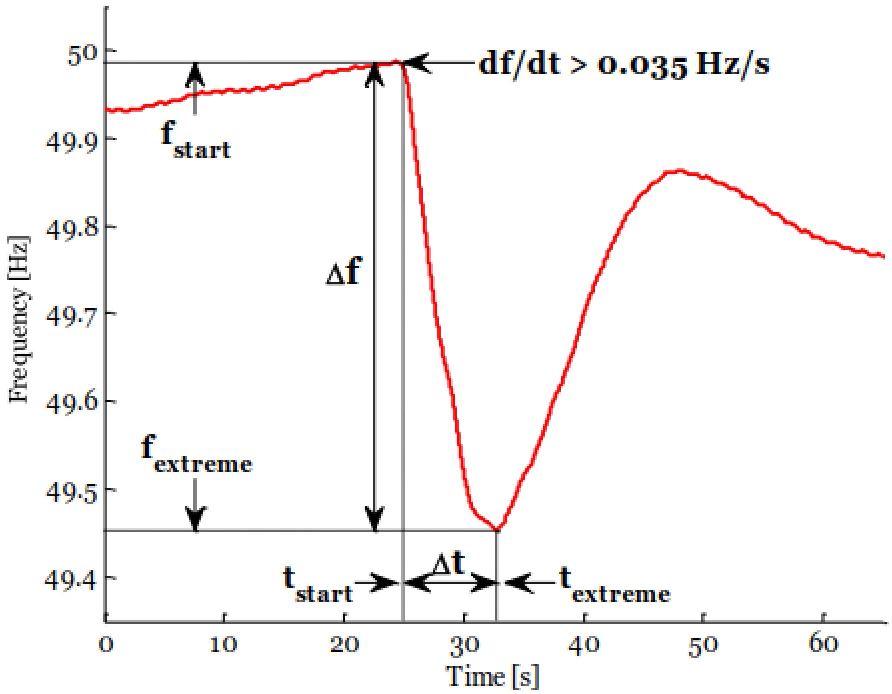
The largest under frequency deviation was caused by a fault in a nuclear power plant. The amplitude of this deviation was -0.679 Hz, and it was reported on the 26th of April. The largest over frequency deviation occurred on the 25th of June, and its amplitude was 0.483 Hz. This deviation was caused by a fault in an HVDC link.

The following part of the chapter will go into more detail on every disturbance that took place in 2023. This will include figures of the frequency at the major disturbances and information about the disturbance in table form. Table 4.1 contains a short summary of the studied disturbances. The times presented are in Finnish time (UTC+2 / UTC+3 in the summer). The information given is based on proposed indices from the FQ2 Project Report and will include:

- date
- f_{start} = frequency at the start of the disturbance
- $f_{extreme}$ = the minimum or maximum instantaneous frequency
- Δf = maximum frequency deviation
- Δt = time to reach the maximum frequency deviation
- ΔP = maximum power deviation
- E_k = synchronously connected kinetic energy before disturbance
- cause of the disturbance
- $f_{steady\ state}$ = average of the frequency between 90 and 150 s after the disturbance
- $\Delta f_{steady\ state}$ = absolute difference between $f_{steady\ state}$ and f_{start}
- $f_{extreme2}$ = second extreme in the other direction as $f_{extreme}$
- $f_{extreme3}$ = third extreme in the same direction as $f_{extreme}$
- damping of the frequency after disturbance = $| (f_{extreme3} - f_{extreme2}) / (f_{extreme2} - f_{extreme}) |$
- Frequency Bias Factor (FBF) = $\Delta P / \Delta f_{steady\ state}$

The frequency response indicators mentioned above are visually illustrated in Figure 4.2.

Figure 4.2*. *Graphical representation of frequency response indicators [9]



For a frequency disturbance to be reported as an over 300 mHz disturbance, the frequency gradient (a momentary change in frequency divided by the change in time) must be over 0.035 Hz/s at the beginning of the disturbance, as seen in Figure 4.2.

Kinetic energy (E_k) is an estimation of the rotation energy of synchronously connected generators in the Nordic synchronous system. The value for kinetic energy is given because it affects the system's inertia, which describes the system's ability to resist changes in frequency. Higher kinetic energy provides higher inertia and, therefore, a better ability to oppose frequency deviations. [9] More detailed descriptions of the events listed in Table 4.1 are presented afterwards in Figures 4.3-16 and Tables 4.2-15.

Table 4.1. List of disturbance events in 2023

Event date	Δf (Hz)	ΔP (MW)	Δt (s)	E_k (GWs)	Cause	Page
12-Jan-2023 02:13:45	-0.337	1183	8.4	138	HVDC	114
17-Feb-2023 17:09:53	-0.553	1714	6.6	181	HVDC	115
01-Mar-2023 02:07:04	0.316	689	8.6	180	HVDC	116
26-Apr-2023 07:39:59	-0.679	1118	9.3	192	Nuclear	117
08-Jun-2023 13:38:54	0.396	1299	4.0	170	HVDC	118
25-Jun-2023 21:08:32	0.483	1399	4.4	196	HVDC	119
25-Jul-2023 08:56:18	-0.356	809	9.3	195	Nuclear	120
06-Aug-2023 06:46:56	0.310	1002	4.1	175	HVDC	121
07-Aug-2023 11:13:29	0.314	539	8.8	164	HVDC	122
06-Sep-2023 05:39:51	0.390	757	4.5	159	HVDC	123
06-Sep-2023 14:21:09	-0.311	1038	10.4	189	Nuclear	124
19-Sep-2023 12:30:32	0.349	570	6.9	166	HVDC	125
19-Nov-2023 19:10:56	-0.435	1313	10.0	246	Nuclear	126
25-Nov-2023 02:39:21	-0.382	1242	7.4	205	Nuclear	127

***Figure 4.3**. Disturbance 12-Jan-2023 02:13:45*

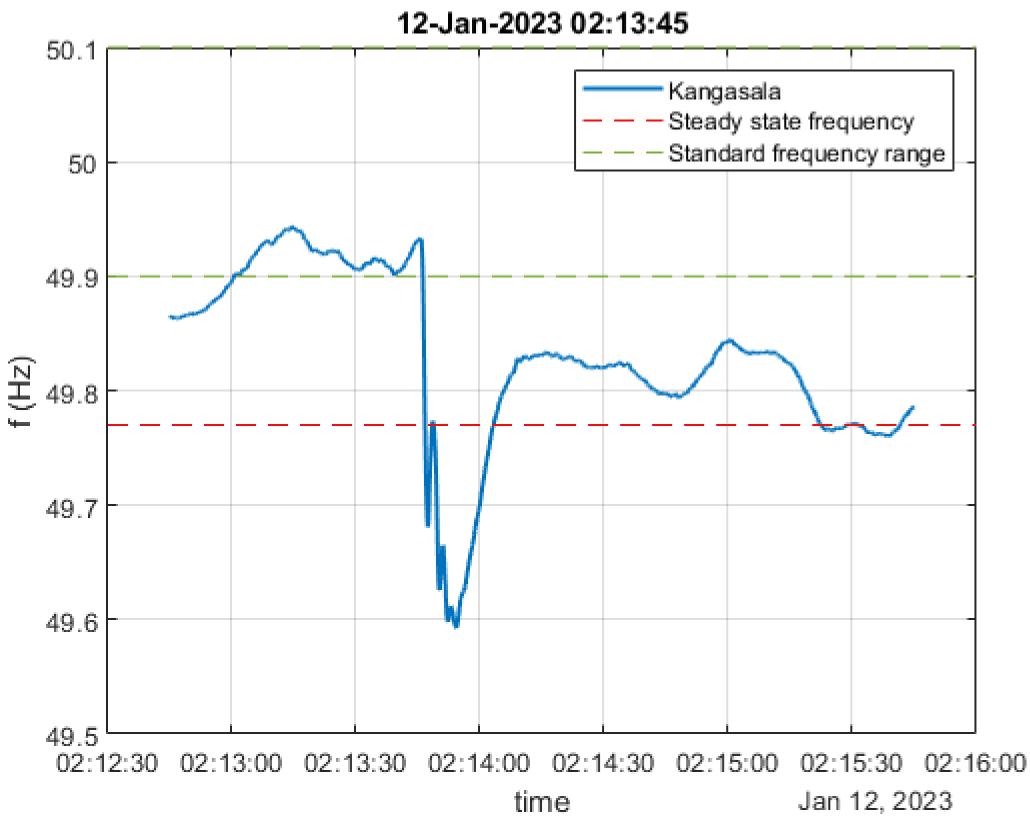


***Table 4.2**. Disturbance 12-Jan-2023 02:13:45*

Date		**12-Jan-2023 02:13:45**	
f_{start}	49.930 Hz	$f_{steady\ state}$	49.770 Hz
$f_{extreme}$	49.593 Hz	$\Delta f_{steady\ state}$	0.160 Hz
Δf	-0.337 Hz	$f_{extreme2}$	49.833 Hz
Δt	8.4 s	$f_{extreme3}$	49.794 Hz
ΔP	1183 MW	damping	16.35 %
E_k	138 GWs	FBF	7405 MW/Hz
cause		HVDC	

***Figure 4.4**. Disturbance 17-Feb-2023 17:09:53*

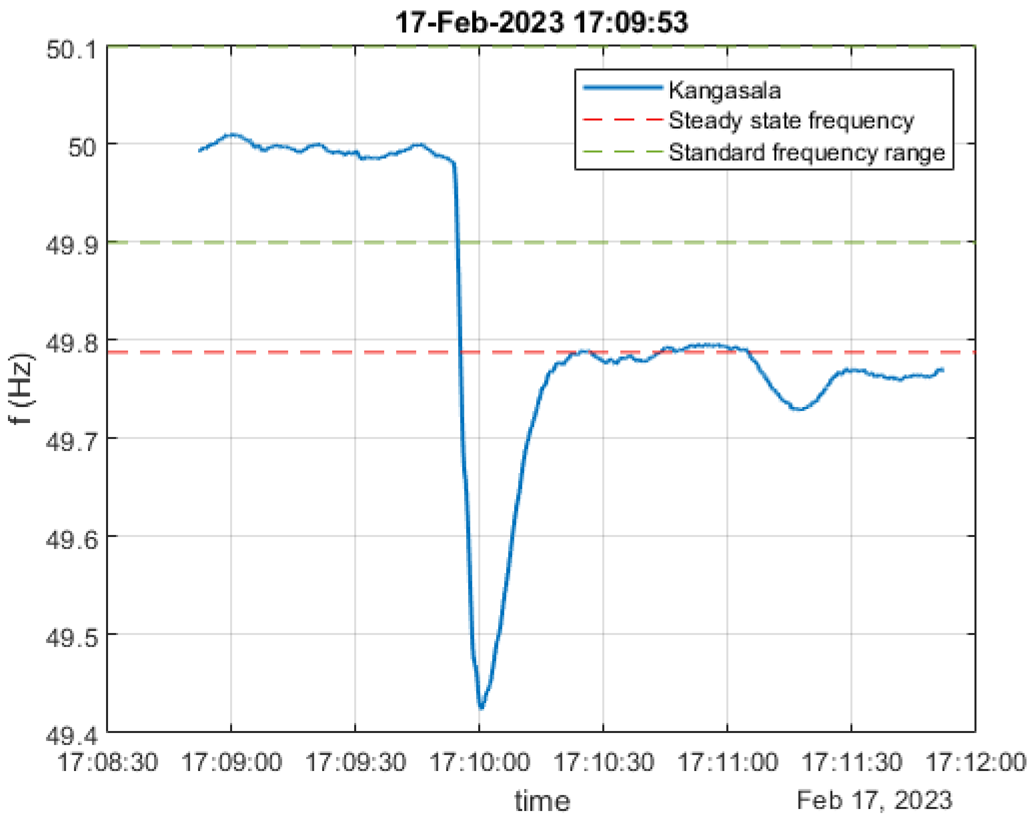


***Table 4.3**. Disturbance 17-Feb-2023 17:09:53*

Date		**17-Feb-2023 17:09:53**	
f_{start}	49.978 Hz	$f_{steady\ state}$	49.788 Hz
$f_{extreme}$	49.425 Hz	$\Delta f_{steady\ state}$	0.190 Hz
Δf	-0.553 Hz	$f_{extreme2}$	49.796 Hz
Δt	6.6 s	$f_{extreme3}$	49.730 Hz
ΔP	1714 MW	damping	17.84 %
E_k	181 GWs	FBF	9024 MW/Hz
cause		HVDC	

***Figure 4.5**. Disturbance 01-Mar-2023 02:07:04*

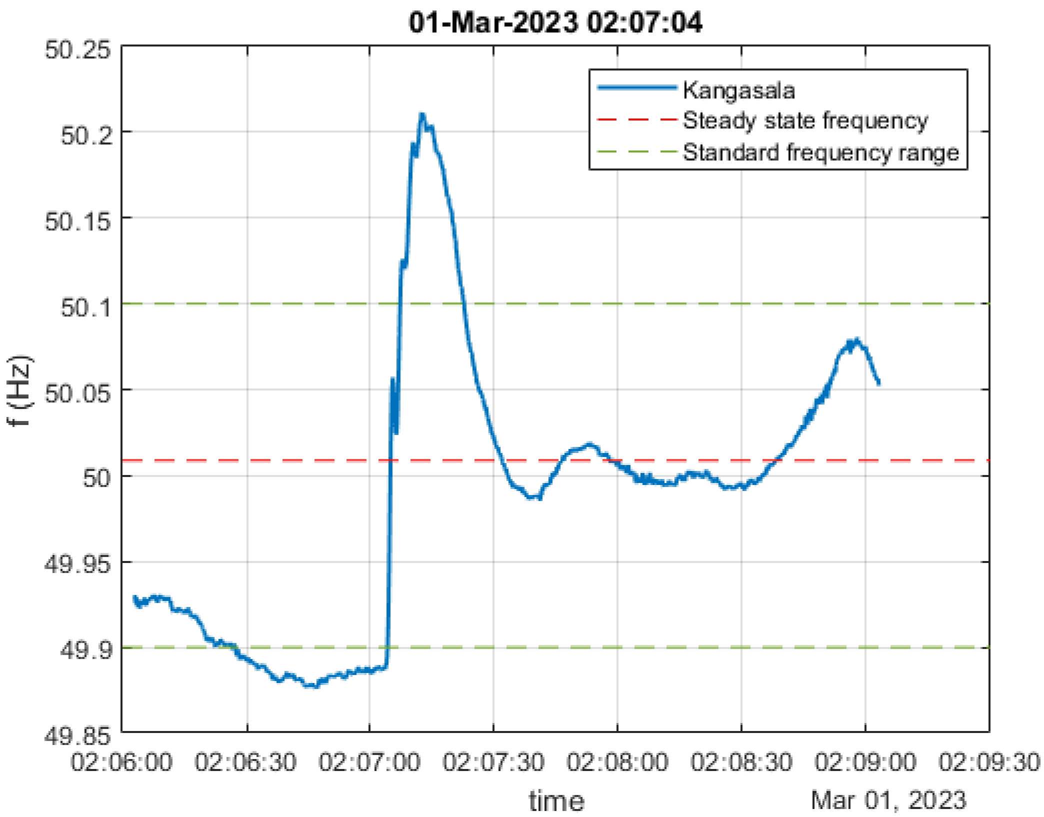


***Table 4.4**. Disturbance 01-Mar-2023 02:07:04*

Date		**01-Mar-2023 02:07:04**	
f_{start}	49.895 Hz	$f_{steady\ state}$	50.009 Hz
$f_{extreme}$	50.211 Hz	$\Delta f_{steady\ state}$	0.114 Hz
Δf	0.316 Hz	$f_{extreme2}$	49.987 Hz
Δt	8.6 s	$f_{extreme3}$	50.019 Hz
ΔP	689 MW	damping	14.28 %
E_k	180 GWs	FBF	6047 MW/Hz
cause		HVDC	

***Figure 4.6**. Disturbance 26-Apr-2023 07:39:59*

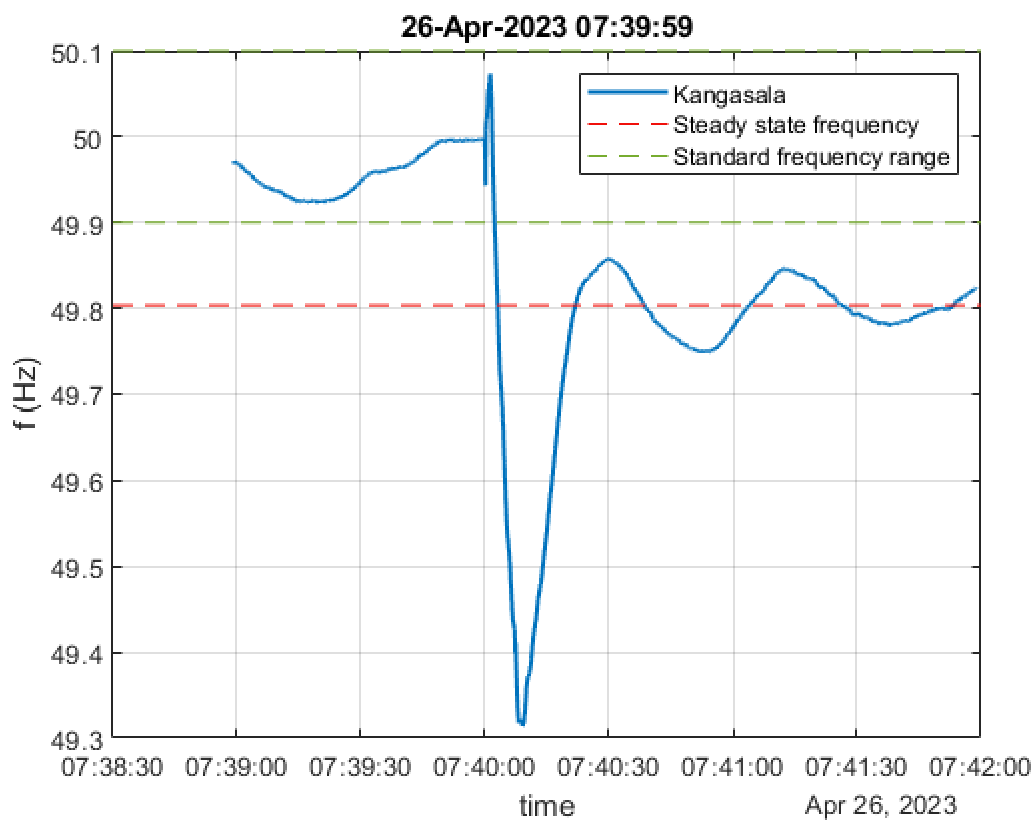


***Table 4.5**. Disturbance 26-Apr-2023 07:39:59*

Date		**26-Apr-2023 07:39:59**	
f_{start}	49.995 Hz	$f_{steady\ state}$	49.804 Hz
$f_{extreme}$	49.316 Hz	$\Delta f_{steady\ state}$	0.191 Hz
Δf	-0.679 Hz	$f_{extreme2}$	49.857 Hz
Δt	9.3 s	$f_{extreme3}$	49.749 Hz
ΔP	1118 MW	damping	19.98 %
E_k	192 GWs	FBF	5845 MW/Hz
cause		Nuclear	

Figure 4.7. Disturbance 08-Jun-2023 13:38:54

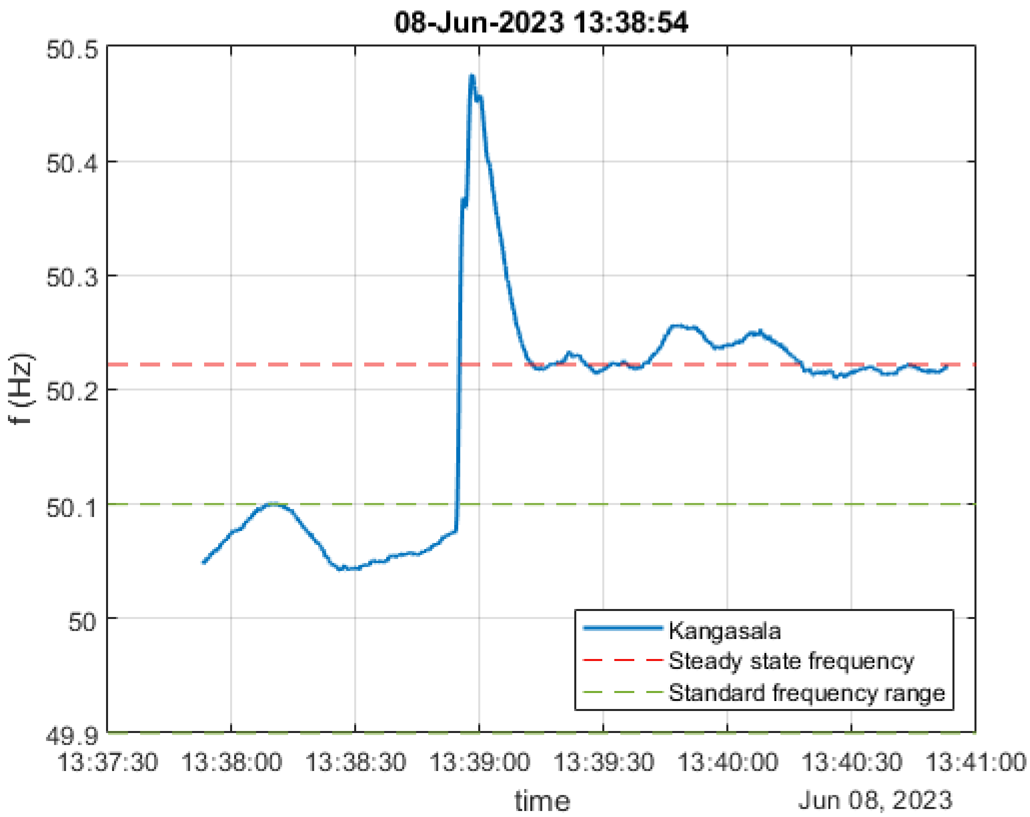


Table 4.6. Disturbance 08-Jun-2023 13:38:54

Date		**08-Jun-2023 13:38:54**	
f_{start}	50.079 Hz	$f_{steady\ state}$	50.222 Hz
$f_{extreme}$	50.475 Hz	$\Delta f_{steady\ state}$	0.143 Hz
Δf	0.396 Hz	$f_{extreme2}$	50.214 Hz
Δt	4.0 s	$f_{extreme3}$	50.256 Hz
ΔP	1299 MW	damping	16.07 %
E_k	170 GWs	FBF	9063 MW/Hz
cause		HVDC	

***Figure 4.8**. Disturbance 25-Jun-2023 21:08:32*

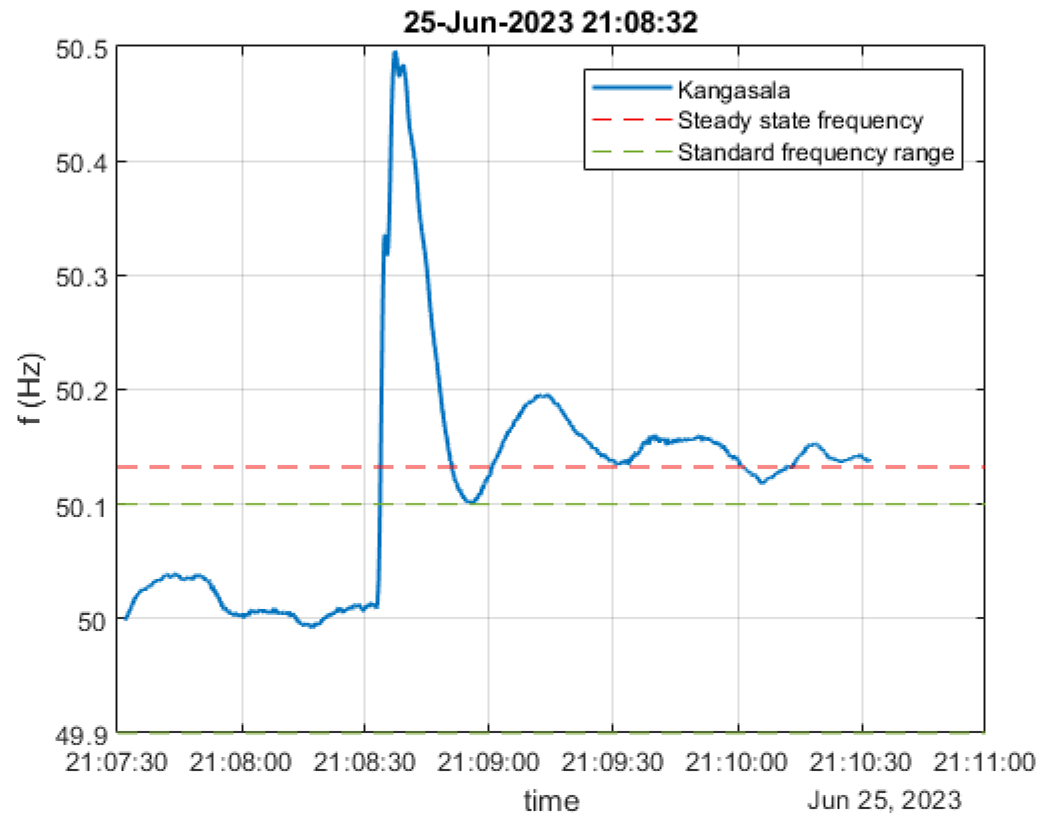


***Table 4.7**. Disturbance 25-Jun-2023 21:08:32*

Date		**25-Jun-2023 21:08:32**	
f_{start}	50.012 Hz	$f_{steady\ state}$	50.133 Hz
$f_{extreme}$	50.495 Hz	$\Delta f_{steady\ state}$	0.121 Hz
Δf	0.483 Hz	$f_{extreme2}$	50.101 Hz
Δt	4.4 s	$f_{extreme3}$	50.195 Hz
ΔP	1399 MW	damping	23.85 %
E_k	196 GWs	FBF	11592 MW/Hz
cause		HVDC	

***Figure 4.9**. Disturbance 25-Jul-2023 08:56:18*

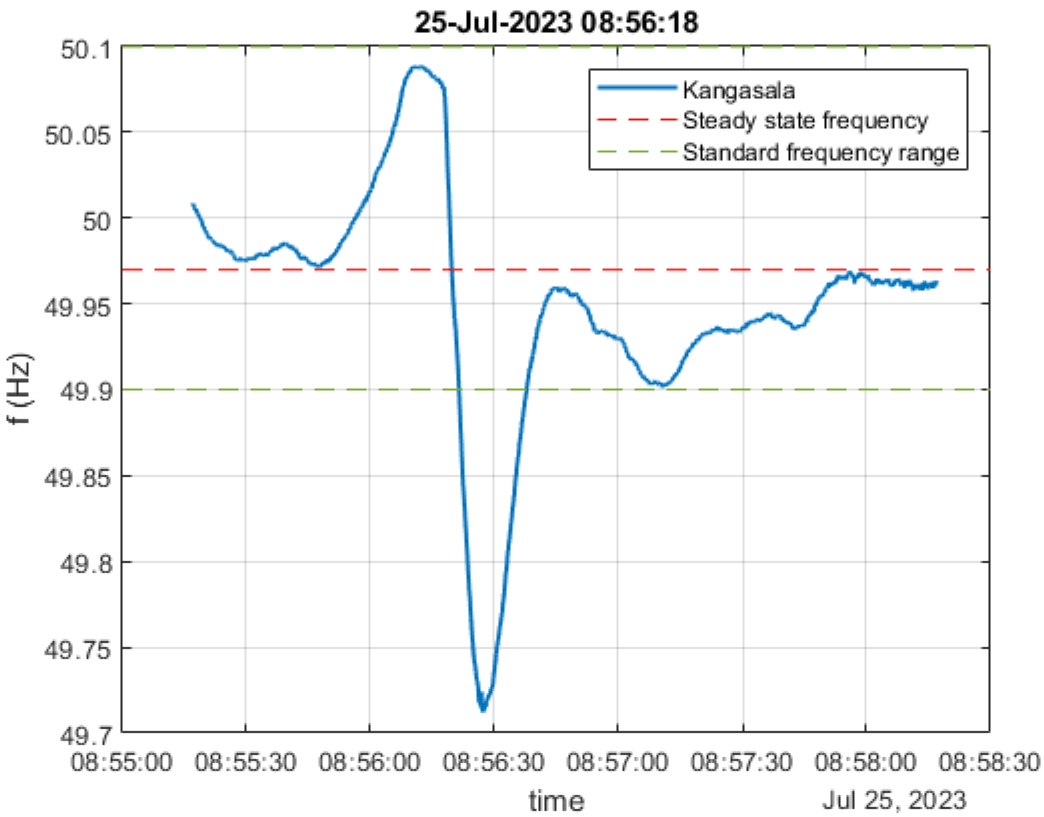


***Table 4.8**. Disturbance 25-Jul-2023 08:56:18*

Date		**25-Jul-2023 08:56:18**	
f_{start}	50.069 Hz	$f_{steady\ state}$	49.970 Hz
$f_{extreme}$	49.713 Hz	$\Delta f_{steady\ state}$	0.099 Hz
Δf	-0.356 Hz	$f_{extreme2}$	49.959 Hz
Δt	9.3 s	$f_{extreme3}$	49.902 Hz
ΔP	809 MW	damping	23.33 %
E_k	195 GWs	FBF	8166 MW/Hz
cause		Nuclear	

***Figure 4.10**. Disturbance 06-Aug-2023 06:46:56*

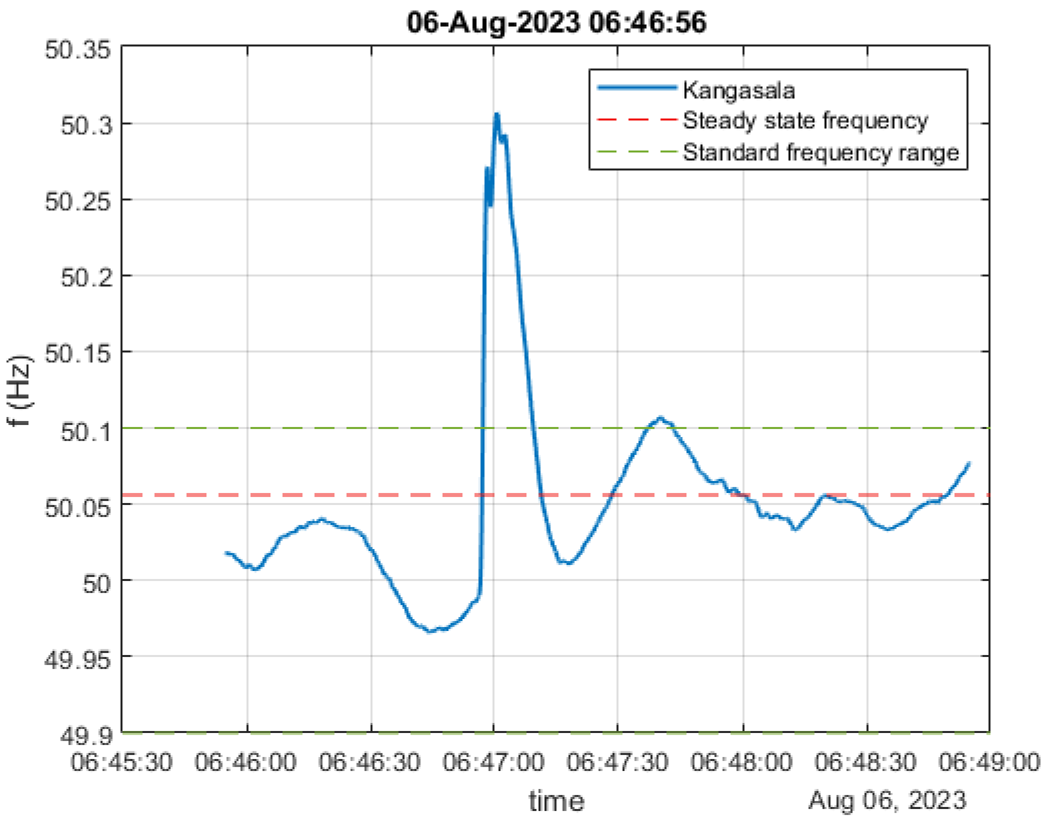


***Table 4.9**. Disturbance 06-Aug-2023 06:46:56*

Date		**06-Aug-2023 06:46:56**	
f_{start}	49.996 Hz	$f_{steady\ state}$	50.056 Hz
$f_{extreme}$	50.306 Hz	$\Delta f_{steady\ state}$	0.060 Hz
Δf	0.310 Hz	$f_{extreme2}$	50.011 Hz
Δt	4.1 s	$f_{extreme3}$	50.107 Hz
ΔP	1002 MW	damping	32.61 %
E_k	175 GWs	FBF	16627 MW/Hz
cause		HVDC	

***Figure 4.11**. Disturbance 07-Aug-2023 11:13:29*

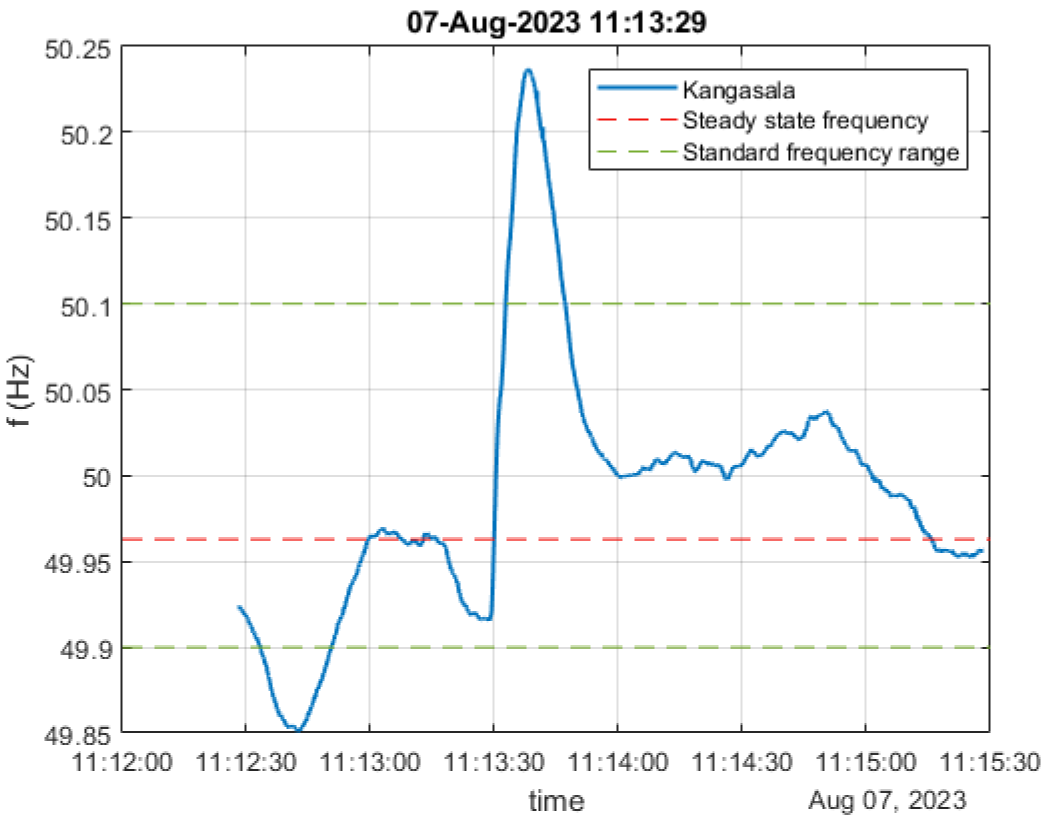


***Table 4.10**. Disturbance 07-Aug-2023 11:13:29*

Date		**07-Aug-2023 11:13:29**	
f_{start}	49.922 Hz	$f_{steady\ state}$	49.963 Hz
$f_{extreme}$	50.236 Hz	$\Delta f_{steady\ state}$	0.041 Hz
Δf	0.314 Hz	$f_{extreme2}$	49.998 Hz
Δt	8.8 s	$f_{extreme3}$	49.953 Hz
ΔP	539 MW	damping	19.03 %
E_k	164 GWs	FBF	13234 MW/Hz
cause		HVDC	

Figure 4.12. Disturbance 06-Sep-2023 05:39:51

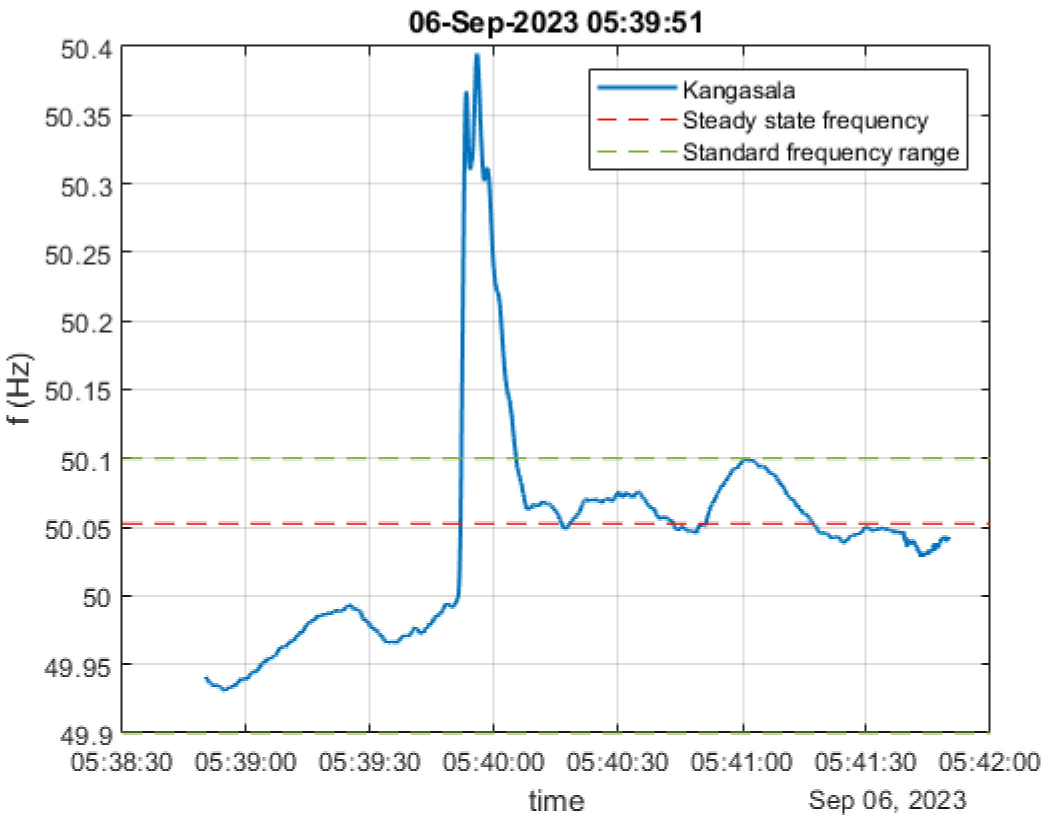


Table 4.11. Disturbance 06-Sep-2023 05:39:51

Date		**06-Sep-2023 05:39:51**	
f_{start}	50.003 Hz	$f_{steady\ state}$	50.053 Hz
$f_{extreme}$	50.393 Hz	$\Delta f_{steady\ state}$	0.050 Hz
Δf	0.390 Hz	$f_{extreme2}$	50.046 Hz
Δt	4.5 s	$f_{extreme3}$	50.099 Hz
ΔP	757 MW	damping	15.33 %
E_k	159 GWs	FBF	15151 MW/Hz
cause		HVDC	

***Figure 4.13**. Disturbance 06-Sep-2023 14:21:09*

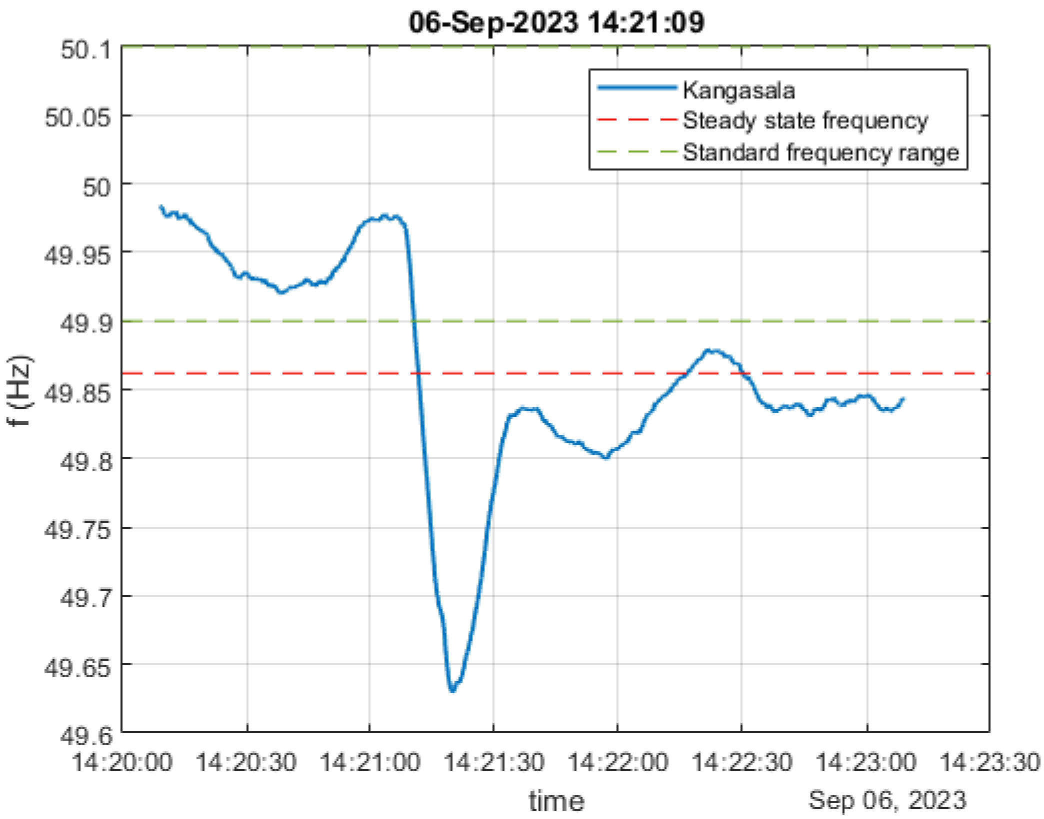


***Table 4.12**. Disturbance 06-Sep-2023 14:21:09*

Date		**06-Sep-2023 14:21:09**	
f_{start}	49.941 Hz	$f_{steady\ state}$	49.862 Hz
$f_{extreme}$	49.630 Hz	$\Delta f_{steady\ state}$	0.080 Hz
Δf	-0.311 Hz	$f_{extreme2}$	49.872 Hz
Δt	10.4 s	$f_{extreme3}$	49.831 Hz
ΔP	1038 MW	damping	17.07 %
E_k	189 GWs	FBF	13046 MW/Hz
cause		Nuclear	

Figure 4.14. Disturbance 19-Sep-2023 12:30:32

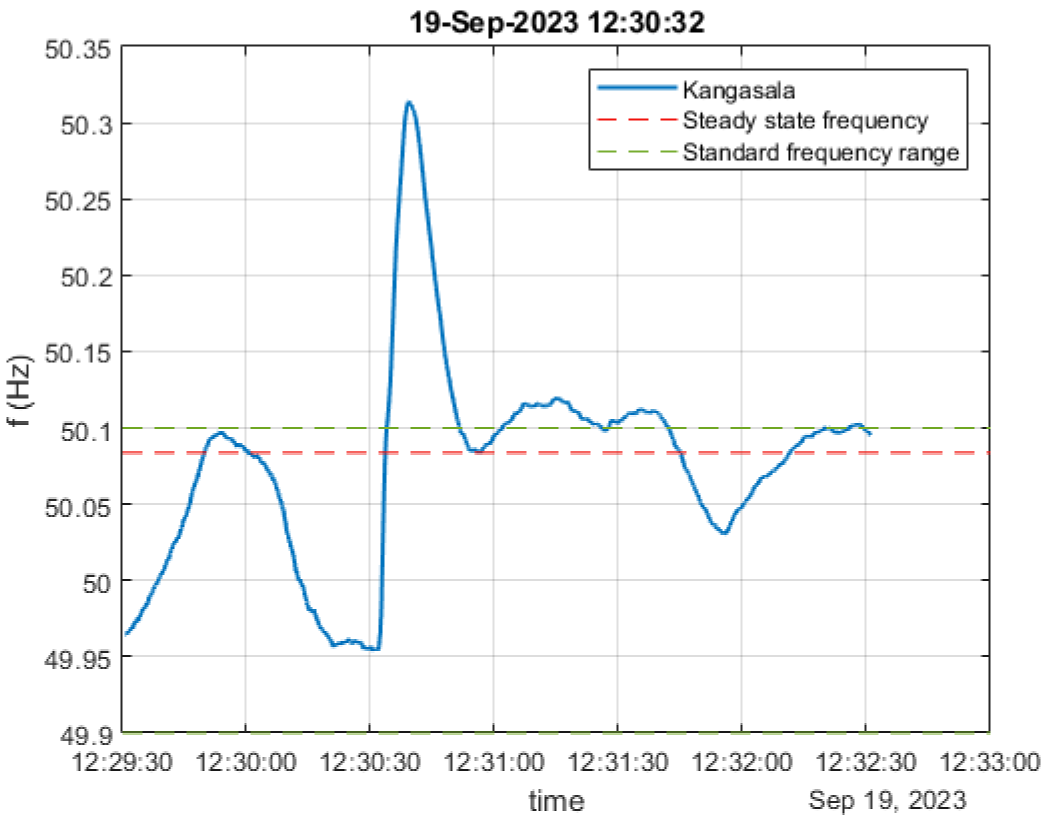


Table 4.13. Disturbance 19-Sep-2023 12:30:32

Date		**19-Sep-2023 12:30:32**	
f_{start}	49.964 Hz	$f_{steady\ state}$	50.084 Hz
$f_{extreme}$	50.313 Hz	$\Delta f_{steady\ state}$	0.120 Hz
Δf	0.349 Hz	$f_{extreme2}$	50.084 Hz
Δt	6.9 s	$f_{extreme3}$	50.031 Hz
ΔP	570 MW	damping	23.04 %
E_k	166 GWs	FBF	4768 MW/Hz
cause		HVDC	

Figure 4.15. Disturbance 19-Nov-2023 19:10:56

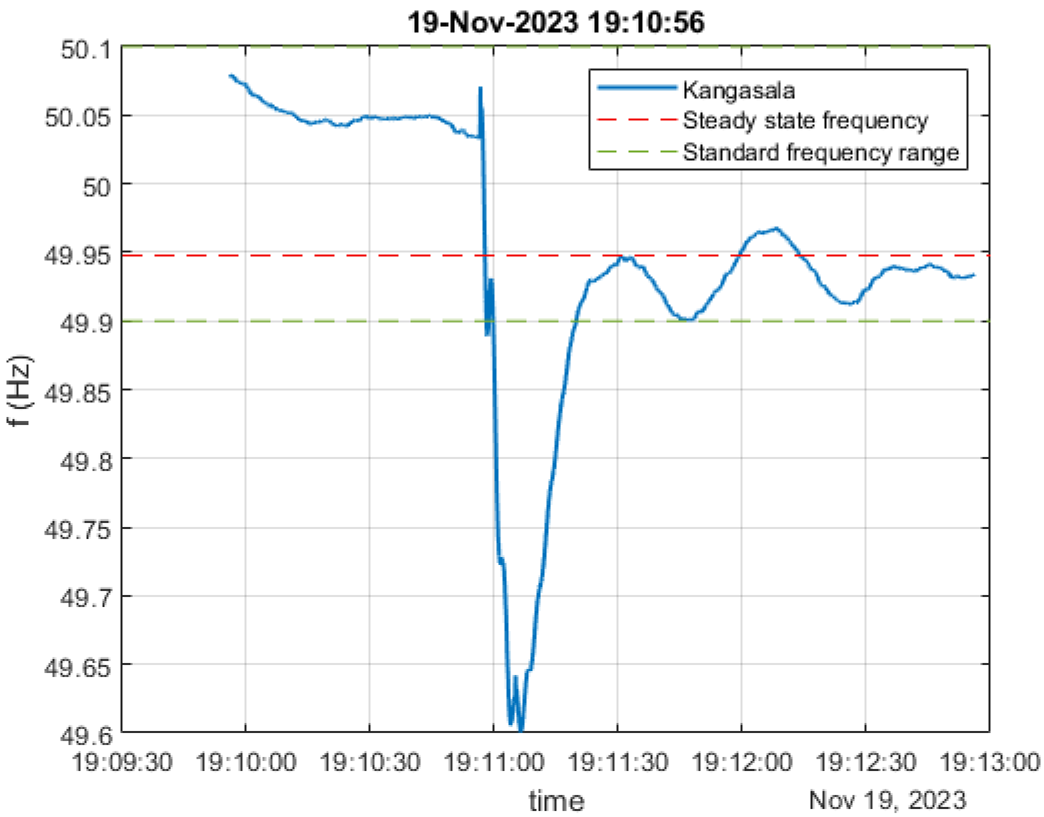


Table 4.14. Disturbance 19-Nov-2023 19:10:56

Date		**19-Nov-2023 19:10:56**	
f_{start}	50.036 Hz	$f_{steady\ state}$	49.948 Hz
$f_{extreme}$	49.601 Hz	$\Delta f_{steady\ state}$	0.089 Hz
Δf	-0.435 Hz	$f_{extreme2}$	49.966 Hz
Δt	10.0 s	$f_{extreme3}$	49.912 Hz
ΔP	1313 MW	damping	14.72 %
E_k	246 GWs	FBF	14809 MW/Hz
cause		Nuclear	

Figure 4.16*. *Disturbance 25-Nov-2023 02:39:21

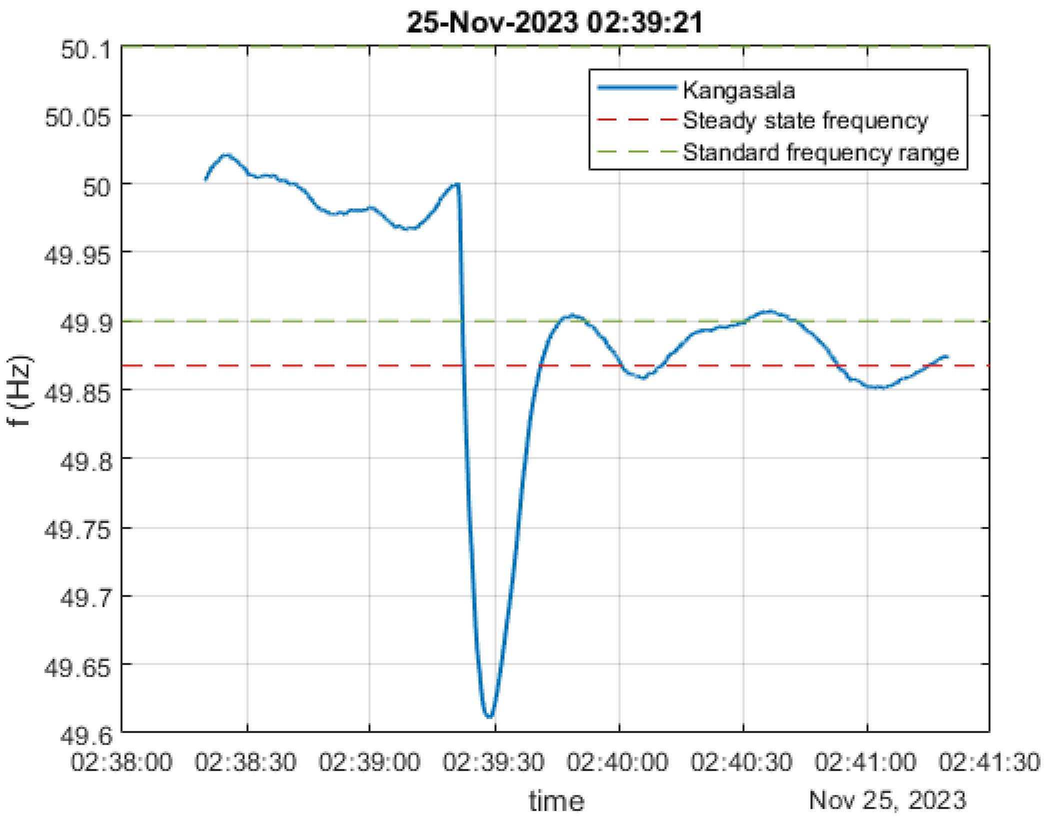


Table 4.15*. *Disturbance 25-Nov-2023 02:39:21

Date		**25-Nov-2023 02:39:21**	
f_{start}	49.993 Hz	$f_{steady\ state}$	49.867 Hz
$f_{extreme}$	49.611 Hz	$\Delta f_{steady\ state}$	0.126 Hz
Δf	-0.382 Hz	$f_{extreme2}$	49.904 Hz
Δt	7.4 s	$f_{extreme3}$	49.858 Hz
ΔP	1242 MW	damping	15.77 %
E_k	205 GWs	FBF	9851 MW/Hz
cause		Nuclear	

Chapter 5. Summary

The aim of this report was to analyze frequency variation and oscillation in the Nordic synchronous system in 2023. The overall quality of frequency was similar to the year 2022. These two years have many common trends that differ from the past years in the observation period. Some differences between the years 2023 and 2022 do exist. For example, long deviations over 3 minutes have been more common in 2023, and time outside 49.8-50.2 Hz is larger.

July and December were the best months in terms of frequency quality, when standard deviation, frequency area, time outside the standard frequency range, and frequency deviations are used as criteria. By using the same criteria, May clearly stands out as the worst month of the year in terms of frequency quality. September is another month where the quality of frequency has been low. When comparing the days of the week, the frequency quality was better from Friday to Sunday and worse from Monday to Thursday, with every criteria available. This is a similar trend to the previous year. However, before 2022, this kind of trend had not been present.

In the hourly analysis, the trend is also similar to 2022. Hour 7 is not standing out as clearly in terms of bad frequency as it was in the previous years. Also, the frequency quality around noon stays at a better level compared to the years 2020 and 2021. The worst hours are from 2 to 5 am and at 7 am. Within an average hour, the quality of the frequency was worse closer to the hour shift and especially at the beginning of the hour. This has been a common trend throughout all the years examined.

The amount of oscillation in 2023 is similar to that in 2022. Oscillation has increased steadily from 2018 to 2022. The mean value of oscillation was the highest in May and September. Removal of the oscillation by filtering the frequency data clearly reduces the time outside the standard frequency range. The reduction is a bit under 50% with the FFT-filtering method, which is slightly less than in the previous two years.

There were 14 frequency disturbances in 2023, where the deviation exceeded 300 mHz. The majority was caused by failures in HVDC links, and the rest by failures in nuclear power plants. This is different from past years since previously, nuclear power plant failures have been the most common reason for large deviations. The number of frequency deviations exceeding 300 mHz is similar to 2022 but has increased compared to years 2017-2020 where there have been around 6 deviations per year.

Chapter 6. Sources

[1] Frequency measurement data, Fingrid Oyj, available at https://data.fingrid.fi (Organizations / Fingrid / Frequency - historical data)

[2] Keskinen K.: "Frequency quality analysis for year 2018", Fingrid Oyj, 6.9.2019

[3] Valli V.: "Frequency quality analysis for year 2019", Fingrid Oyj, 17.9.2020

[4] Valli V.: "Frequency quality analysis for year 2020", Fingrid Oyj, 14.9.2021

[5] Pesonen J.: "Frequency quality analysis for year 2021", Fingrid Oyj, 15.8.2022

[6] Pesonen J.: "Frequency quality analysis for year 2022", Fingrid Oyj, 22.8.2023

[7] Frequency quality phase 2 Project Report, NAG (Nordic Analysis Group), 16.5.2017 internal report

[8] Kuivaniemi M.: "40-90 second oscillation analysis for years 2011 and 2012", Fingrid Oyj, 30.8.2013

[9] Nordic report: “Future system inertia”, ENTSO-E, 2015, available at https://www.entsoe.eu/publications/system-operations-reports/