Frequency quality analysis

2022

FINGRID

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Chapter 1. Introduction

This report presents the results of frequency quality study of the Nordic synchronous system for the year 2022. 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 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 results from Fingrid's previous years' frequency quality analysis. The fourth chapter presents in detail 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. Current Nordic target level for 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 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 at Fingrid's website [1].

The amount of valid measurement data in percentages per month in 2022 is presented in Table 2.1. Availability of data per year for years 2017 to 2022 can be seen in Table 2.2 [2,3,4,5,6]. In 2022 there was valid measurement data for 99.56 % of the time. Some of the data is missing due to telecommunication errors. From the table 2.1, it is clear that the availibility has been worst in March. Other months than March have had good availability and there are no significant differences in availability between those months, according to table 2.1.

Table 2.1. The amount of valid measurement data available per month in 2022

Month	Available data
January	99.97 %
February	99.96 %
March	95.28 %
April	99.96 %
May	99.97 %
June	99.96 %
July	99.96 %
August	99.96 %
September	99.96 %
October	99.84 %
November	99.98 %
December	99.97 %

Table 2.2. The amount of valid measurement data available for years 2017-2022

Year	Available data
2017	97.19 %
2018	98.90 %
2019	98.47 %
2020	97.82 %
2021	99.92 %
2022	99.56 %

Chapter 3. Frequency Quality Indices

This chapter includes frequency quality indices defined and proposed by 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. The Article 131 is shown in the following page.

All input frequency data used to calculate the frequency indices is either 0.1 seconds or averages of the 0.1 second data. For example, a resolution of 1 second means that the average of ten 0.1 second values have 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 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 2022. 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. Average frequency has been very close to 50 Hz, as even for the worst months like May and August the averages have deviated less than 0.45 mHz from 50 Hz. The average frequency in 2022 was a little worse than the year before, since the maximum average frequency deviation in 2021 was close to 0.2 mHz. Also, apart from January, the average frequency has been above 50 Hz every month, which differs from the previous years, where the averages were more evenly distributed around 50 Hz.

***Figure 3.1**. Average frequency for each month in 2022*

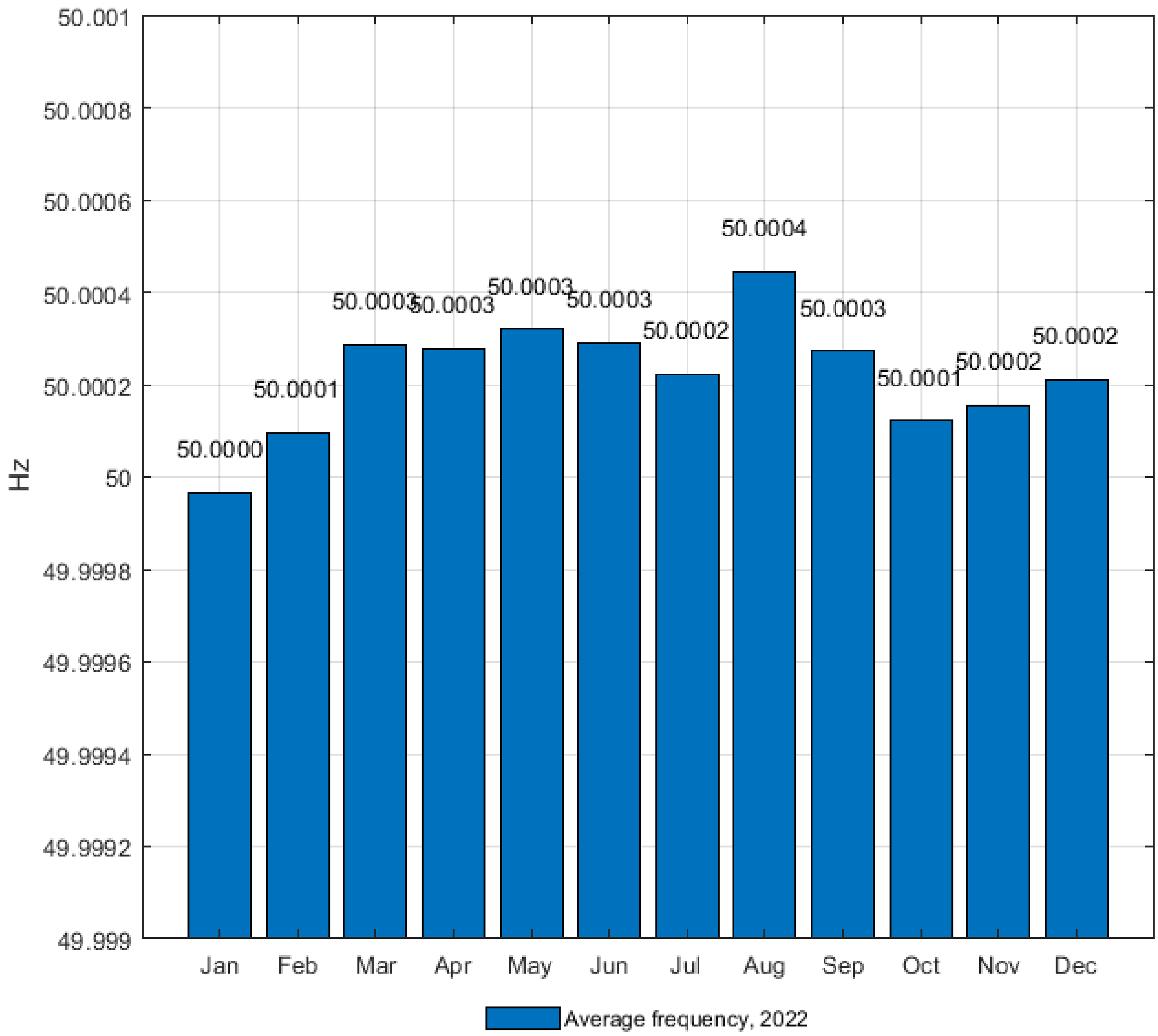


Figure 3.2 shows the average frequencies for each day of the week. The highest average frequency value has occurred on Monday, after which the value of average frequency has decreased steadily before the significant increase on Thursday. On the weekend, the average frequency drops for Saturday and rises again on Sunday.

Figure 3.2*. *Average frequency for each day of the week in 2022

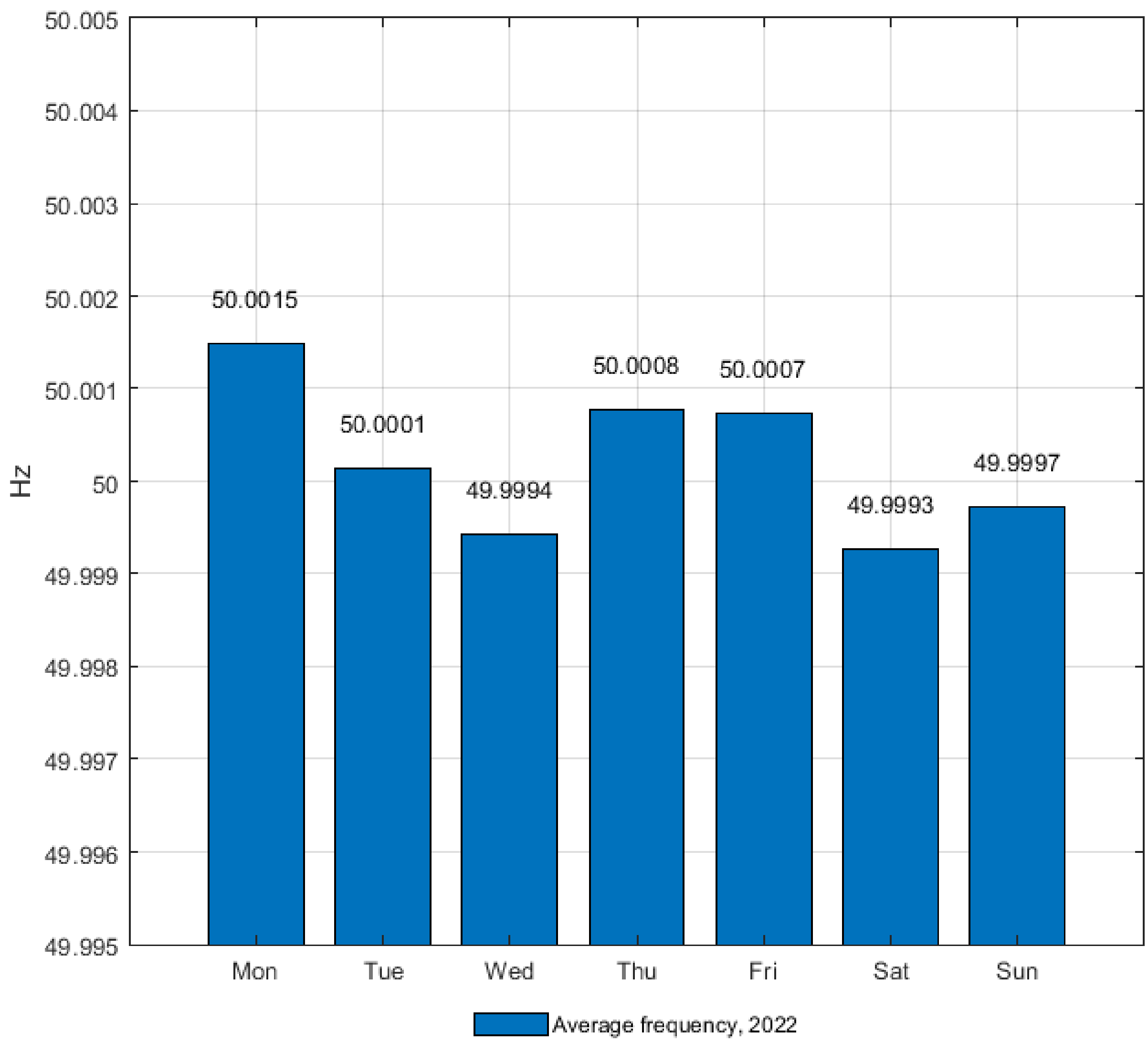


Figure 3.3 shows the average frequencies during each hour of the day. The frequency has been lowest at 7 am and 4 pm. The frequency has been higher around noon, in the evening apart from 10 pm and around midnight.

Figure 3.3. Average frequency for each hour of the day in 2022

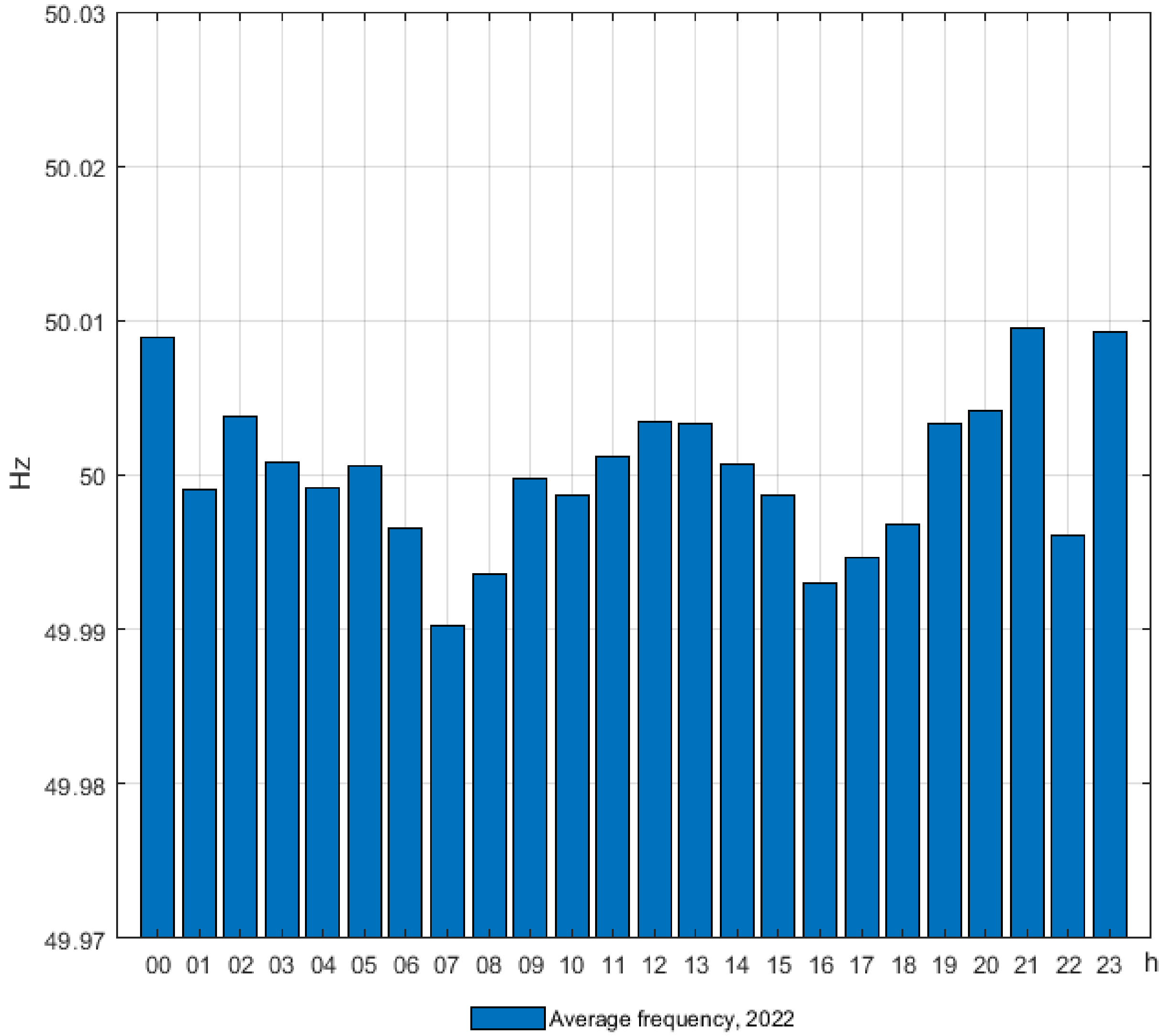
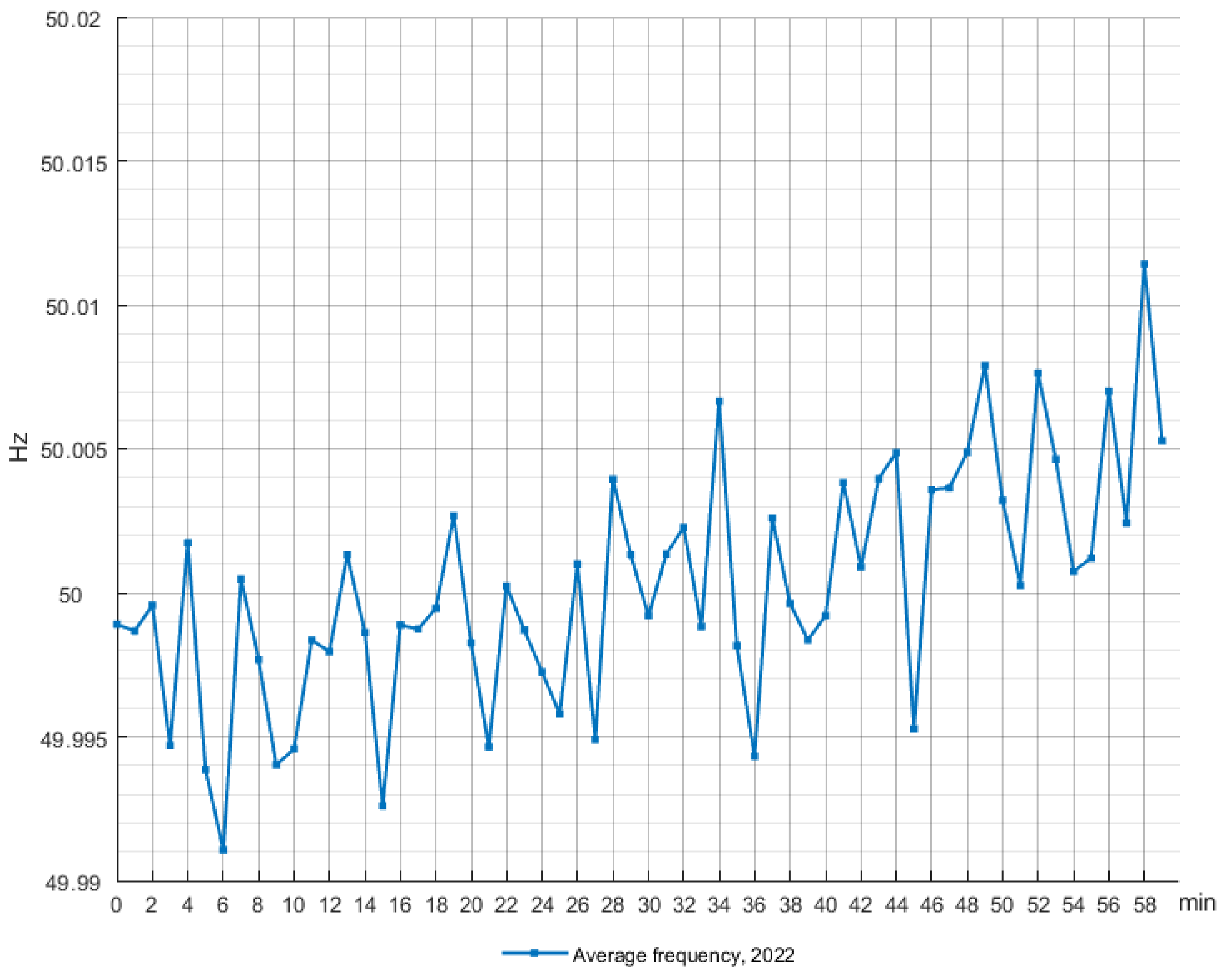


Figure 3.4 shows the average frequency inside the hour. In general, the frequency has been higher in the latter part of the hour. The difference between consecutive minutes varies between 0.1-9.6 mHz. The largest differences have increased slightly from the year 2021. In 2021 the greatest difference was 9.2 mHz.

Figure 3.4*. *Average frequency for each minute of the hour in 2022



3.1.2 Standard deviation

This section includes the figures representing the standard deviation of frequency during the year 2022. 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 2022. The low values of standard deviations in July, November and December indicate that the 1 second frequency values were closer to 50 Hz during those months. In May, the standard deviation were higher than in the other months. Overall, the frequency deviated less in 2022 than in 2021.

***Figure 3.5**. Standard deviation of the frequency for every month in 2022*

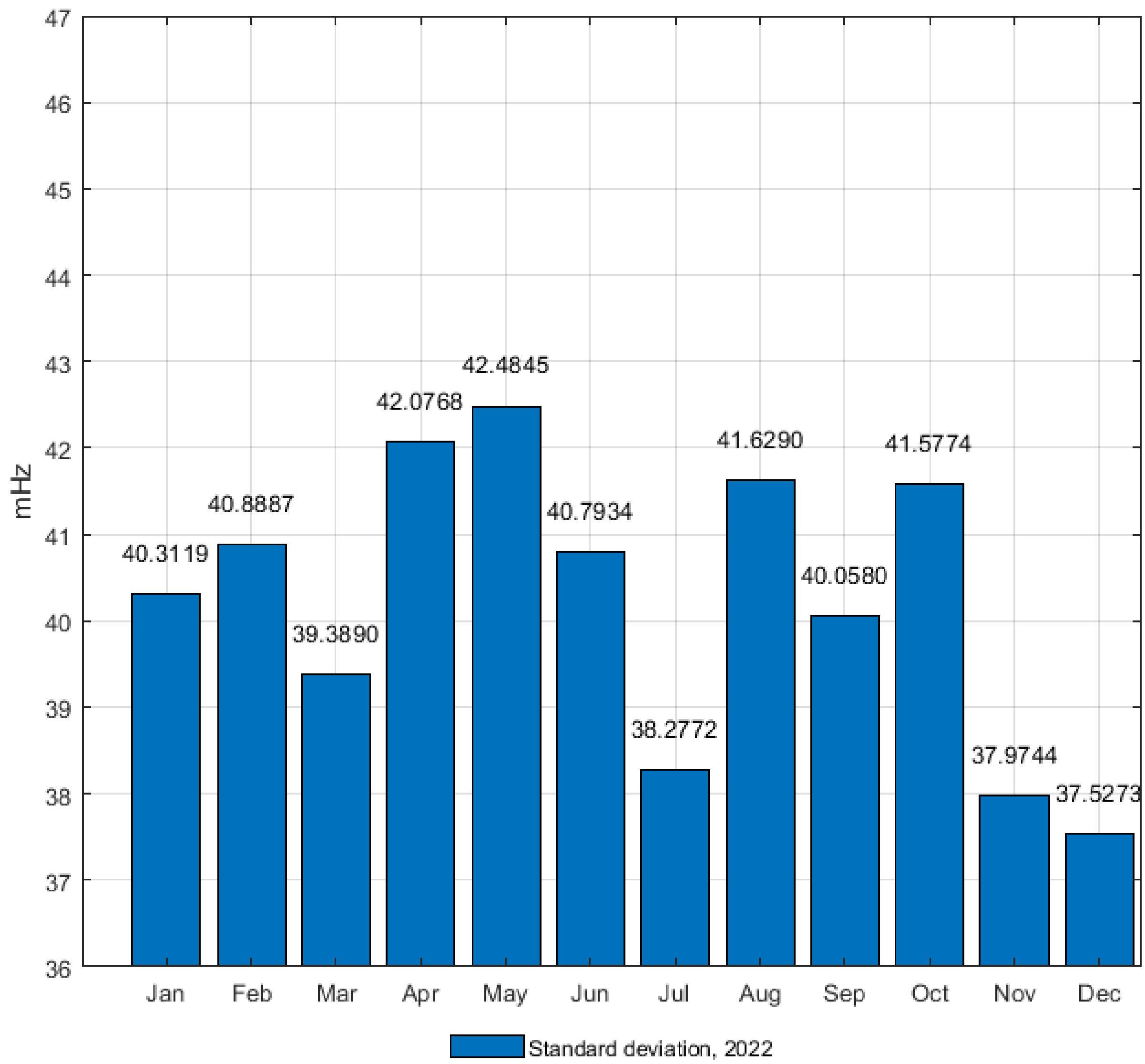


Figure 3.6 represents the standard deviation for each day of the week. Based on standard deviation, frequency quality has been worst on Tuesdays and best on Sundays. The distribution of standard deviation values between different days of the week differs from the previous year, so that it receives values clearly lower than the previous year during the weekend.

***Figure 3.6**. Standard deviation of the frequency for every day of the week in 2022*

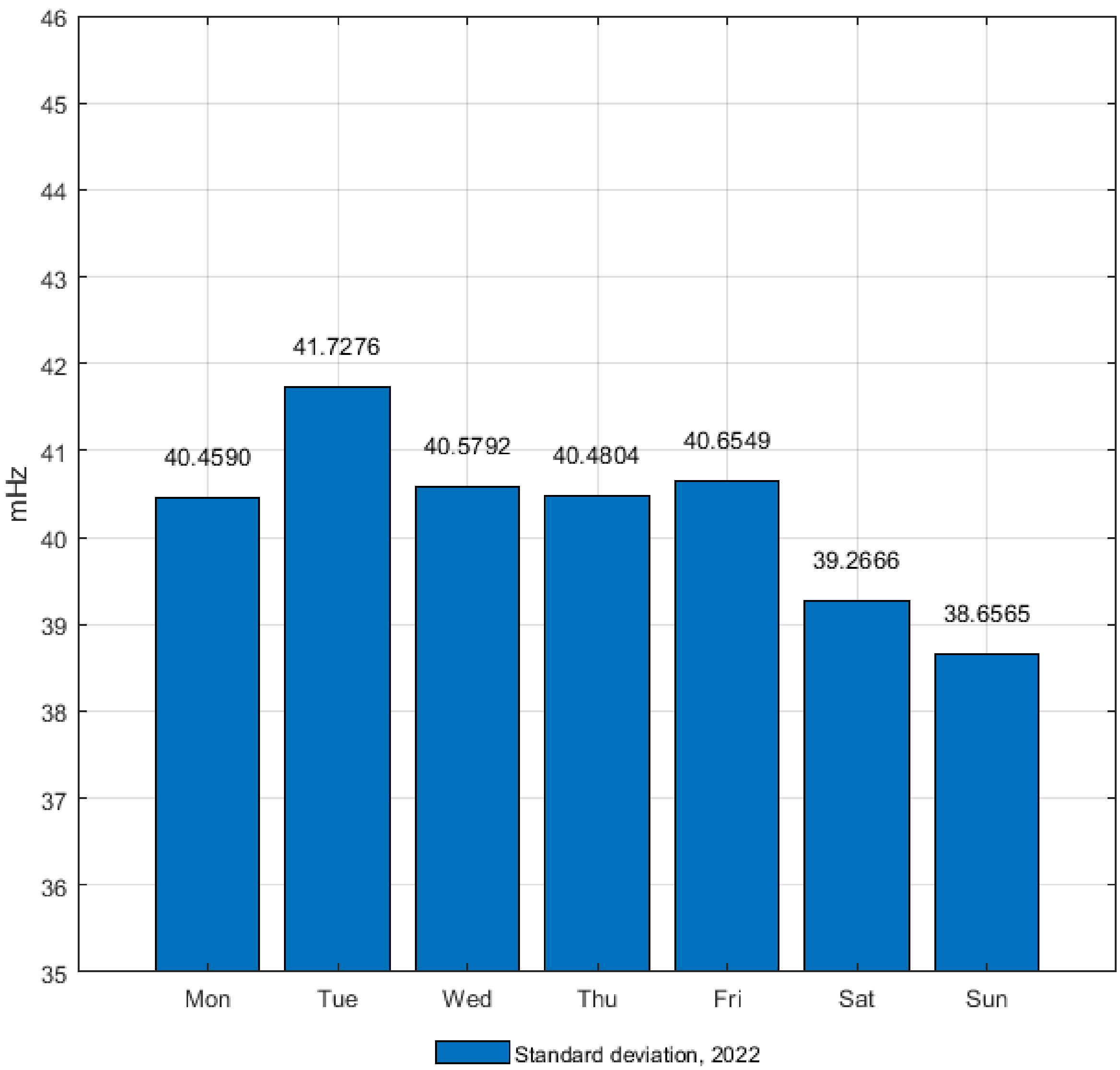


Figure 3.7 shows the standard deviation during the average day. The standard deviation has been higher on average after midnight and lower around the noon. The highest values of standard deviation were experienced in the early morning at 2 am and 5 am. The lowest value was experienced at 2 pm. Compared with the years 2020 and 2021, the values of standard deviation are much smaller around the noon.

***Figure 3.7**. Standard deviation of the frequency for every hour of the day in 2022*

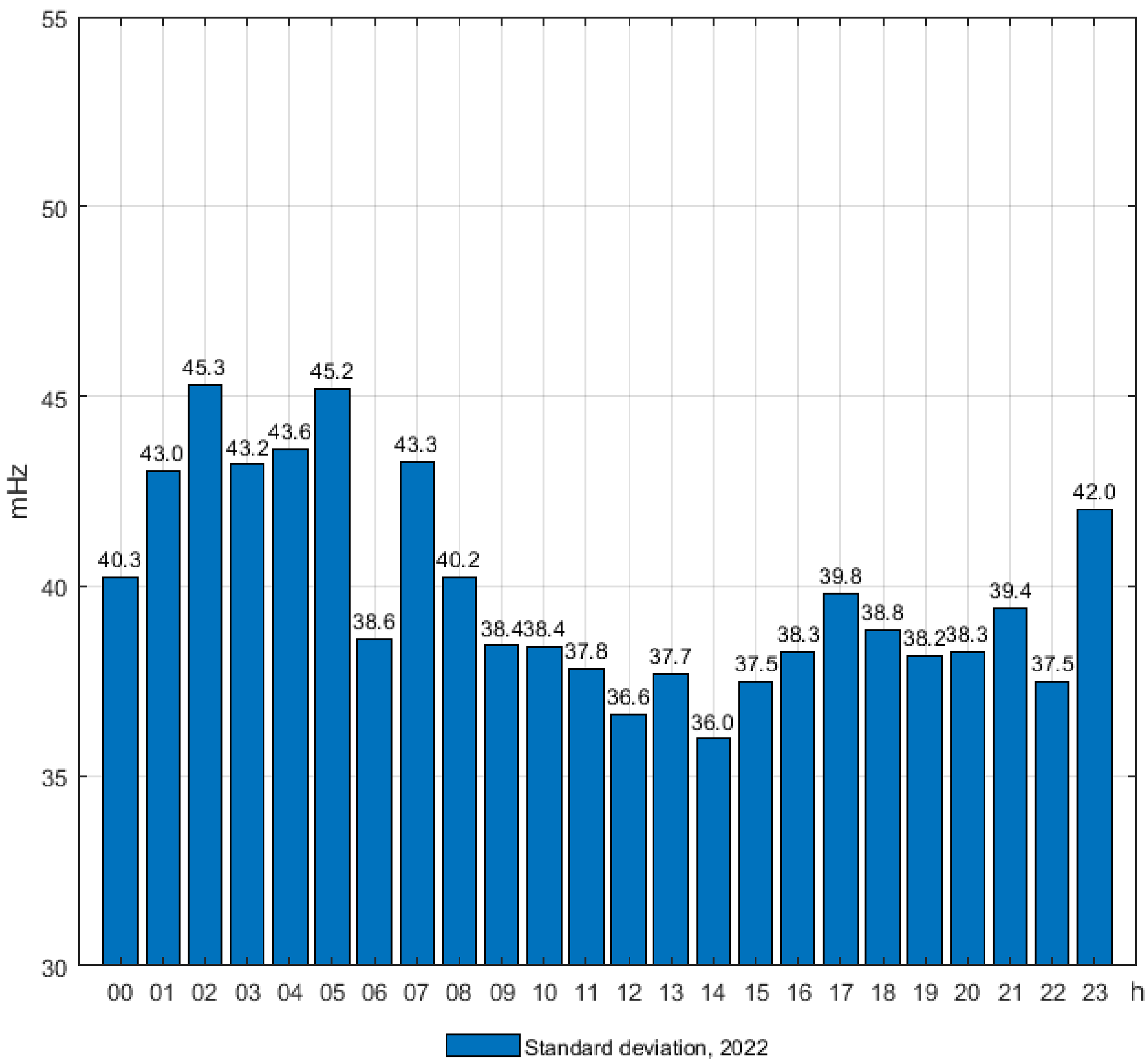
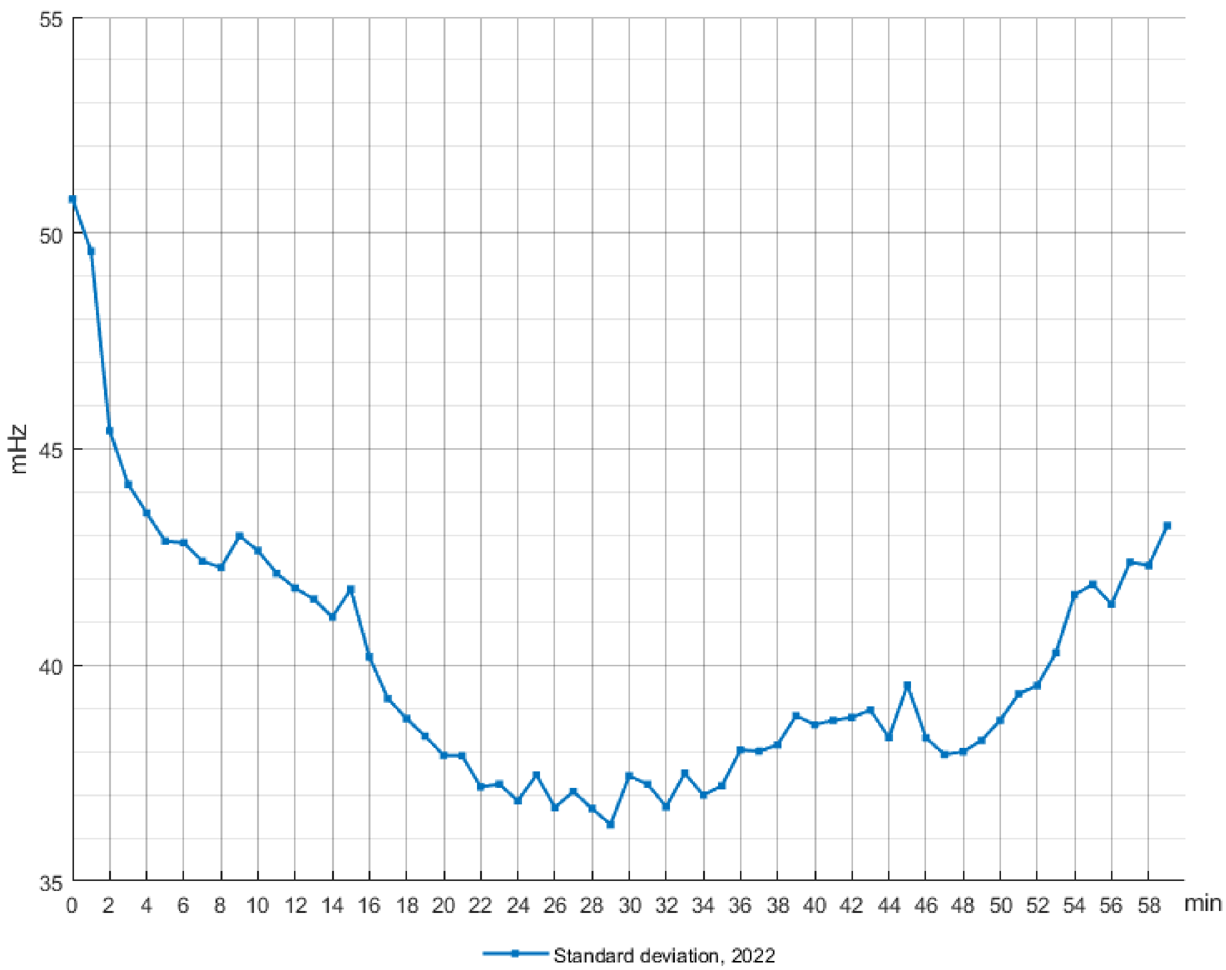


Figure 3.8 represents the standard deviation inside the hour. The standard deviation has the highest values in the beginning of the hour and it has decreased until the half hour mark from where it has increased again. There has also been a slight drop in the standard deviation around the 46th minute.

Figure 3.8*. *Standard deviation of the frequency for every minute of the hour in 2022



3.1.3 Mean value and standard deviation

Mean values and standard deviations of the frequency, according to SOGL Article 131(1)(a) (i) and (ii), month by month for years 2017 to 2022 can be found in Table 3.1 and Table 3.2. Same results are also presented in Figure 3.9. The resolution of the used data was one second.

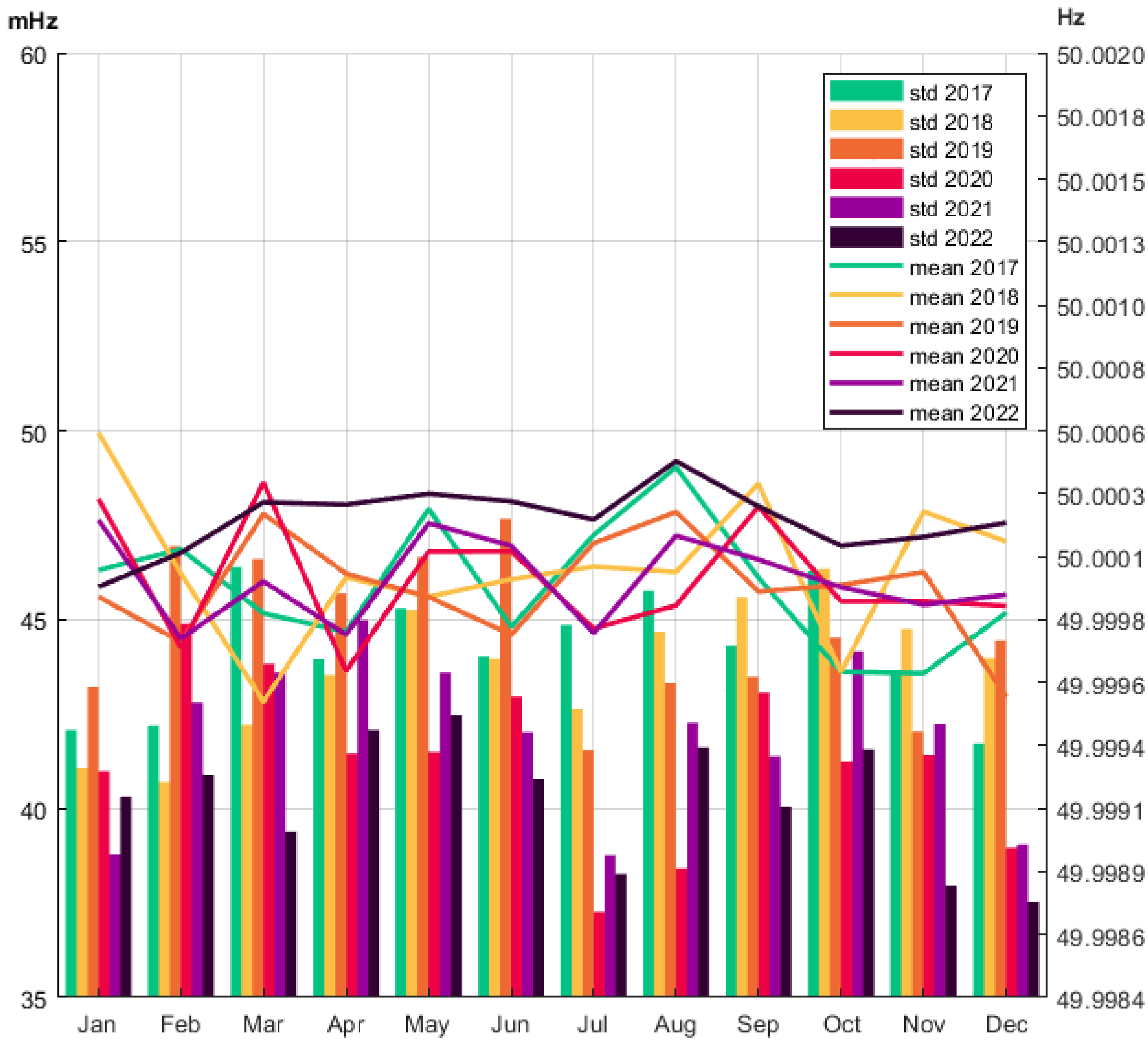
Table 3.1. Mean values and standard deviations for years 2017-2019

	2017		**2018**		**2019**	
Month	**Mean value (Hz)**	**Standard deviation (mHz)**	**Mean value (Hz)**	**Standard deviation (mHz)**	**Mean value (Hz)**	**Standard deviation (mHz)**
January	50.0000	42.1	50.0006	41.1	49.9999	43.2
February	50.0001	42.2	50.0000	40.7	49.9998	46.9
March	49.9999	46.4	49.9995	42.2	50.0002	46.6
April	49.9998	44.0	50.0000	43.5	50.0000	45.7
May	50.0003	45.3	49.9999	45.3	49.9999	46.7
June	49.9998	44.0	50.0000	44.0	49.9998	47.7
July	50.0002	44.9	50.0000	42.6	50.0001	41.6
August	50.0004	45.8	50.0000	44.7	50.0003	43.3
September	50.0000	44.3	50.0004	45.6	49.9999	43.5
October	49.9996	46.3	49.9996	46.3	50.0000	44.5
November	49.9996	43.6	50.0003	44.8	50.0000	42.0
December	49.9999	41.7	50.0001	44.0	49.9995	44.4
Entire year	**50.0000**	**44.2**	**50.0000**	**43.8**	**50.0000**	**44.7**

Table 3.2. Mean values and standard deviations for years 2020-2022

	2020		**2021**		**2022**	
Month	**Mean value (Hz)**	**Standard deviation (mHz)**	**Mean value (Hz)**	**Standard deviation (mHz)**	**Mean value (Hz)**	**Standard deviation (mHz)**
January	50.0003	41.0	50.0002	38.8	50.0000	40.3
February	49.9997	44.9	49.9998	42.8	50.0001	40.9
March	50.0004	43.8	50.0000	43.6	50.0003	39.4
April	49.9996	41.5	49.9998	45.0	50.0003	42.1
May	50.0001	41.5	50.0002	43.6	50.0003	42.5
June	50.0001	43.0	50.0001	42.0	50.0003	40.8
July	49.9998	37.3	49.9998	38.8	50.0002	38.3
August	49.9999	38.4	50.0002	42.3	50.0004	41.6
September	50.0003	43.1	50.0001	41.4	50.0003	40.1
October	49.9999	41.2	50.0000	44.2	50.0001	41.6
November	49.9999	41.4	49.9999	42.3	50.0002	38.0
December	49.9999	39.0	49.9999	39.1	50.0002	37.5
Entire year	**50.0000**	**41.4**	**50.0000**	**42.0**	**50.0002**	**40.3**

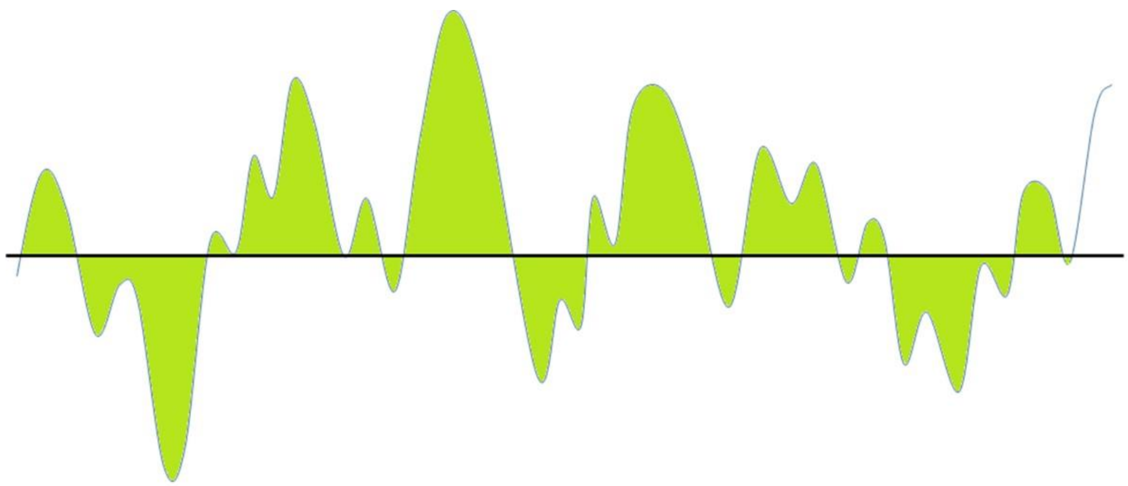
***Figure 3.9**. Mean values and standard deviations for years 2017-2022*



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 portion of half of the normal frequency area (49.9-50.1 Hz). For example, if 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 input frequency data used is 0.1 s. Below Figure 3.10 is also the formula for determining the frequency area.

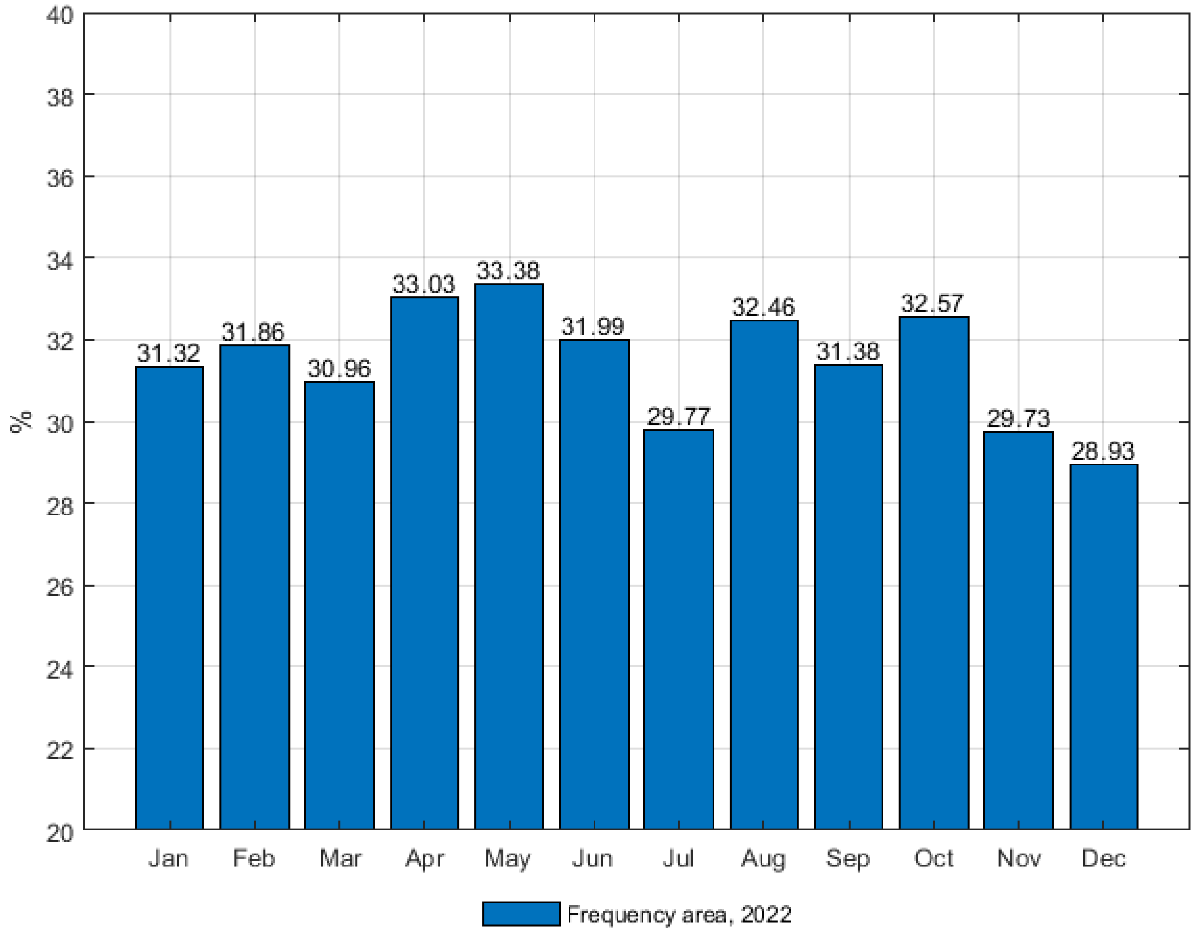
Figure 3.10*. *Frequency quality index: Frequency area [7]



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

Figure 3.11 represents the average frequency area for every month in 2022. The percentage of the area has been largest in May and smallest in December. The values of average monthly frequency area have decreased from 2021.

***Figure 3.11**. The average frequency area for every month in 2022*



The frequency area during each day of the week can be seen in Figure 3.12. The percentage of the area has been very close to equal between different weekdays, if Tuesday is not taken account. Compared with the year 2021, there is clear reduction in percentages of the average frequency area. Also, the values associated with the weekend are smaller than the values of weekdays, which is a new trend compared with the years 2020 and 2021.

***Figure 3.12**. The average frequency area for every day of the week in 2022*

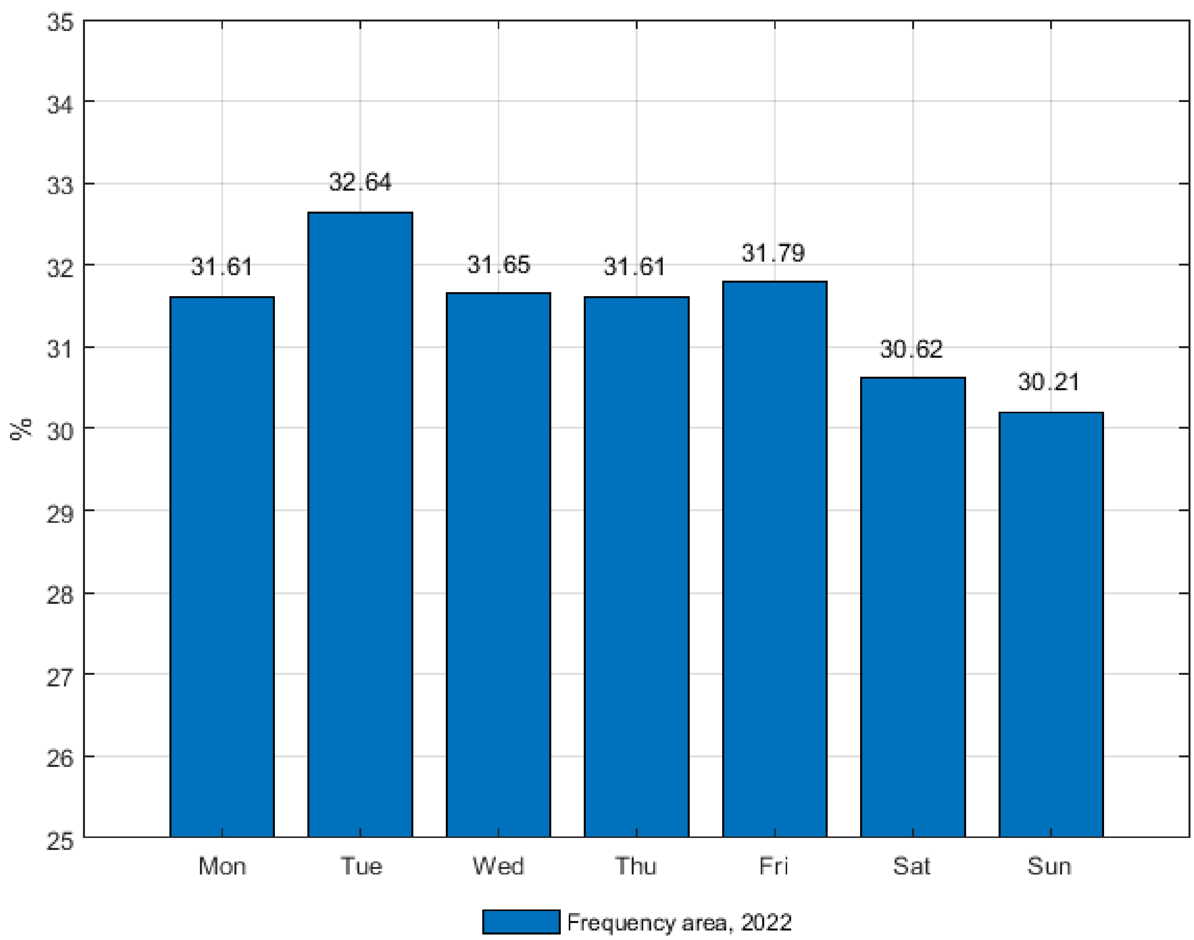


Figure 3.13 has the frequency area for every hour during the day. The figure shows that the deviation of the frequency from 50.0 Hz has been greater on average in the early morning. The percentage of the average frequency area has been smaller around the noon, which differs greatly from the trend of the years 2020 and 2021 where frequency area values increased significantly during this period.

Figure 3.13*. *The average frequency area for every hour inside the day in 2022

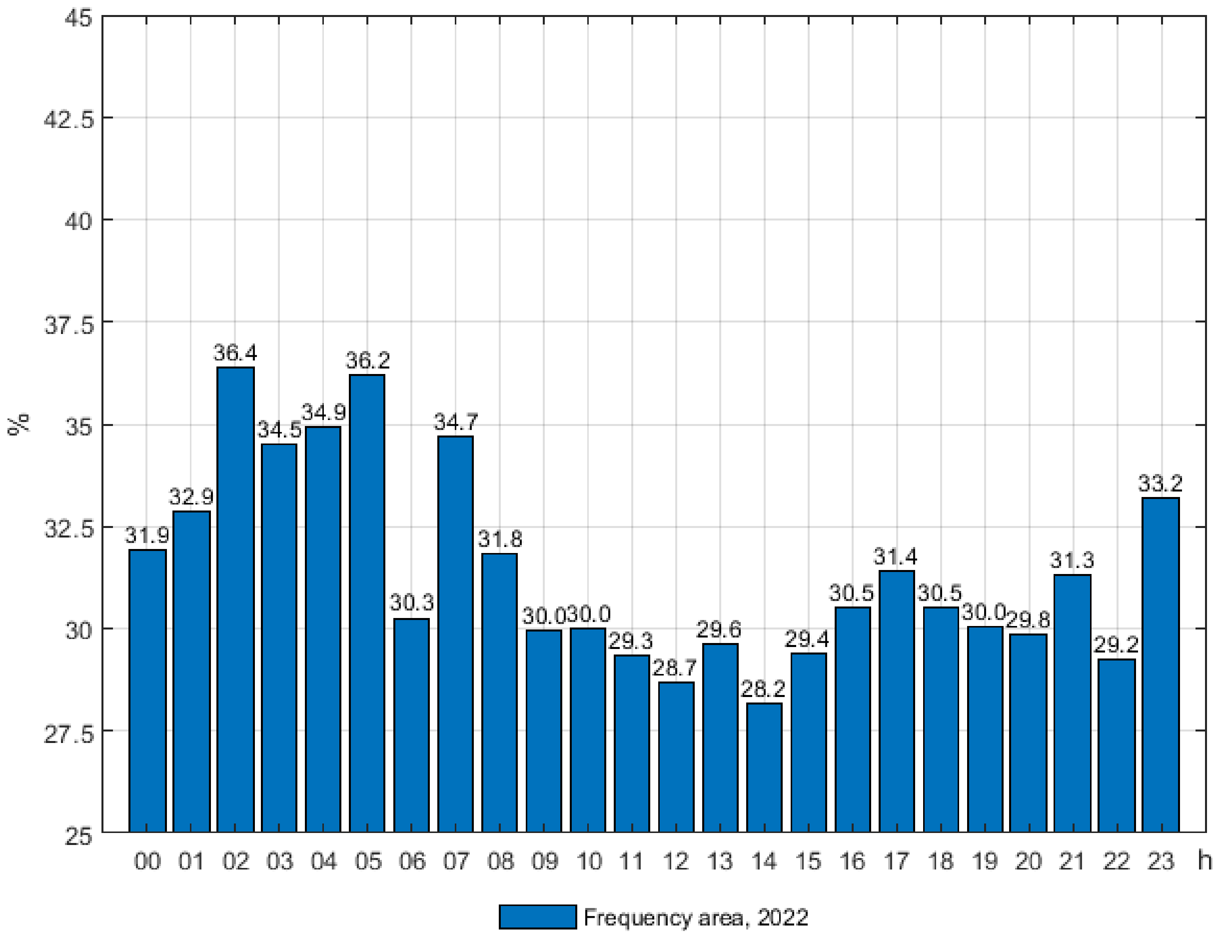
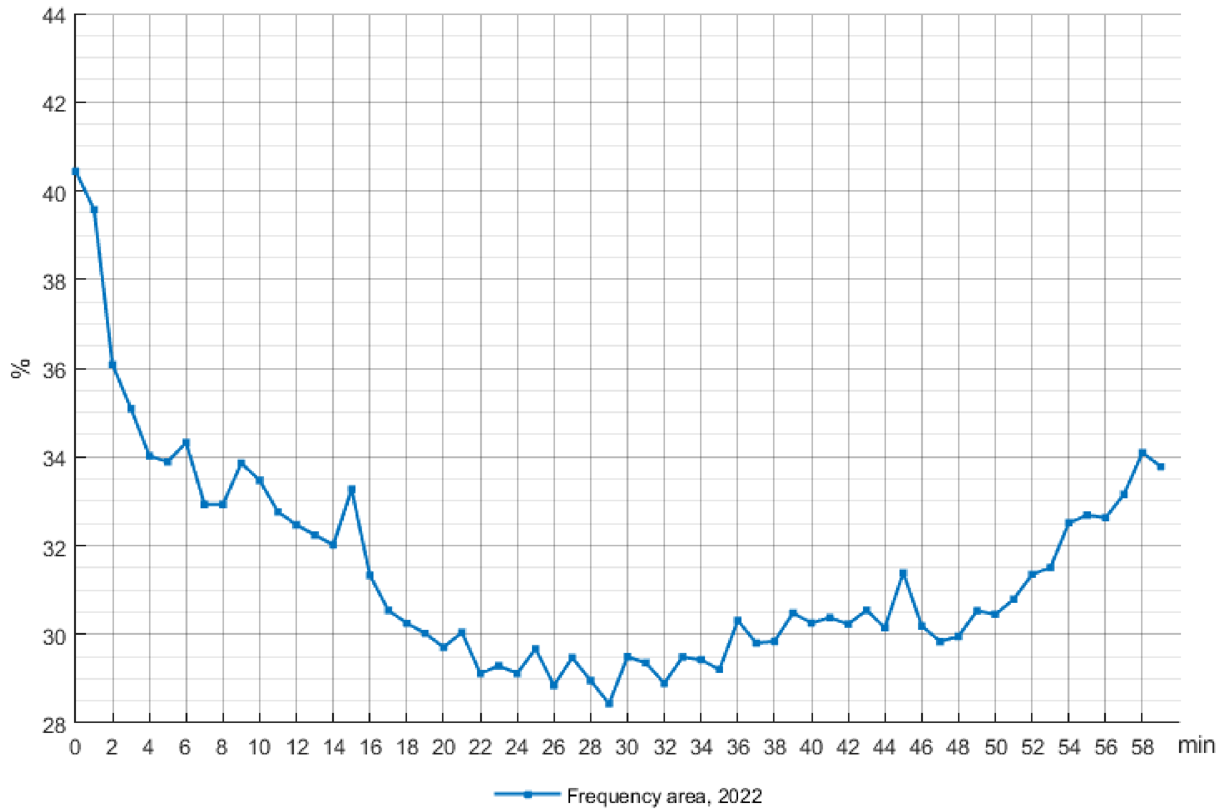


Figure 3.14 represents the frequency area within the hour. The percentage of the frequency area has been smaller in the middle of the hour while more deviation has occurred closer to the hour shift.

***Figure 3.14**. The average frequency area for every minute within the hour in 2022*



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 year 2017 to 2022. All results are summed up in Figure 3.15.

***Table 3.3**. The 1st, 5th, 10th, 90th, 95th and 99th percentiles for year 2017*

	2017					
Month	**1st (Hz)**	**5th (Hz)**	**10th (Hz)**	**90th (Hz)**	**95th (Hz)**	**99th (Hz)**
Jan	49.905	49.932	49.946	50.054	50.069	50.097
Feb	49.903	49.931	49.946	50.055	50.069	50.095
Mar	49.893	49.925	49.941	50.059	50.076	50.108
Apr	49.899	49.928	49.944	50.056	50.071	50.102
May	49.892	49.926	49.943	50.058	50.074	50.105
Jun	49.895	49.927	49.944	50.057	50.073	50.103
Jul	49.897	49.927	49.943	50.058	50.074	50.104
Aug	49.895	49.926	49.942	50.060	50.076	50.106
Sep	49.899	49.929	49.944	50.057	50.074	50.105
Oct	49.892	49.925	49.942	50.059	50.077	50.113
Nov	49.896	49.928	49.944	50.055	50.070	50.100
Dec	49.908	49.932	49.946	50.053	50.068	50.098
Entire year	**49.898**	**49.928**	**49.944**	**50.057**	**50.073**	**50.103**

Table 3.4. The 1st, 5th, 10th, 90th, 95th and 99th percentiles for 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 3.5. The 1st, 5th, 10th, 90th, 95th and 99th percentiles for 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 3.6. The 1st, 5th, 10th, 90th, 95th and 99th percentiles for 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**

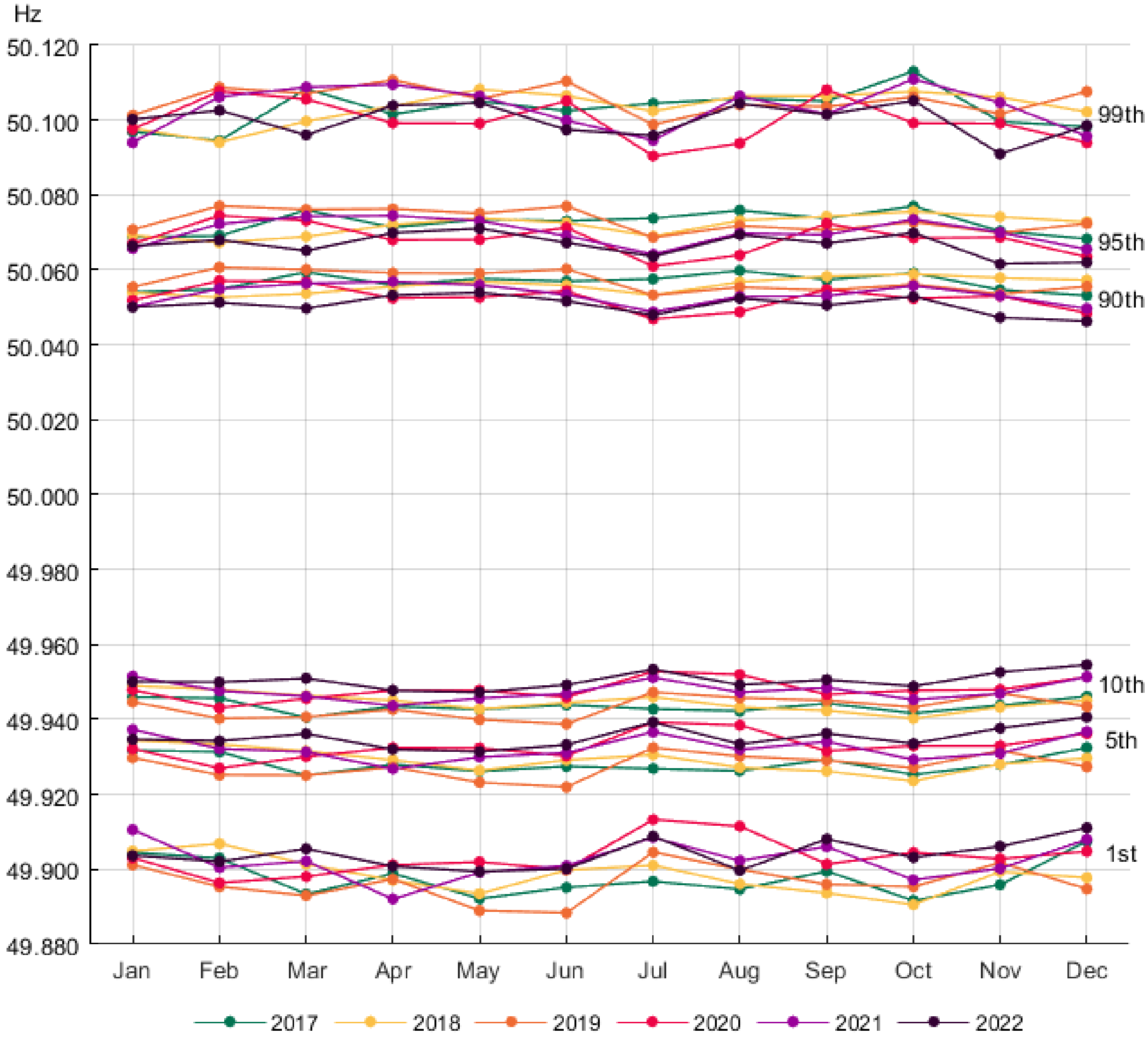
Table 3.7. The 1st, 5th, 10th, 90th, 95th and 99th percentiles for year 2021

	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 3.8. The 1st, 5th, 10th, 90th, 95th and 99th percentiles for 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**

***Figure 3.15**. The 1st, 5th, 10th, 90th, 95th and 99th percentiles for years 2017-2022*



More detailed results for the percentiles of 2022 are shown in the next figures. Figure 3.16 is a visual representation of the given percentiles for each month in 2022. The percentiles in May are furthest from 50 Hz, which indicates that the frequency values are spread around the 50 Hz with a wide distribution. Similarly, in December the percentiles are closest to 50 Hz, which suggests that the frequency deviations have remained within more limited range.

***Figure 3.16**. The 1st, 5th, 10th, 90th, 95th and 99th percentile of the frequency for every month in 2022*

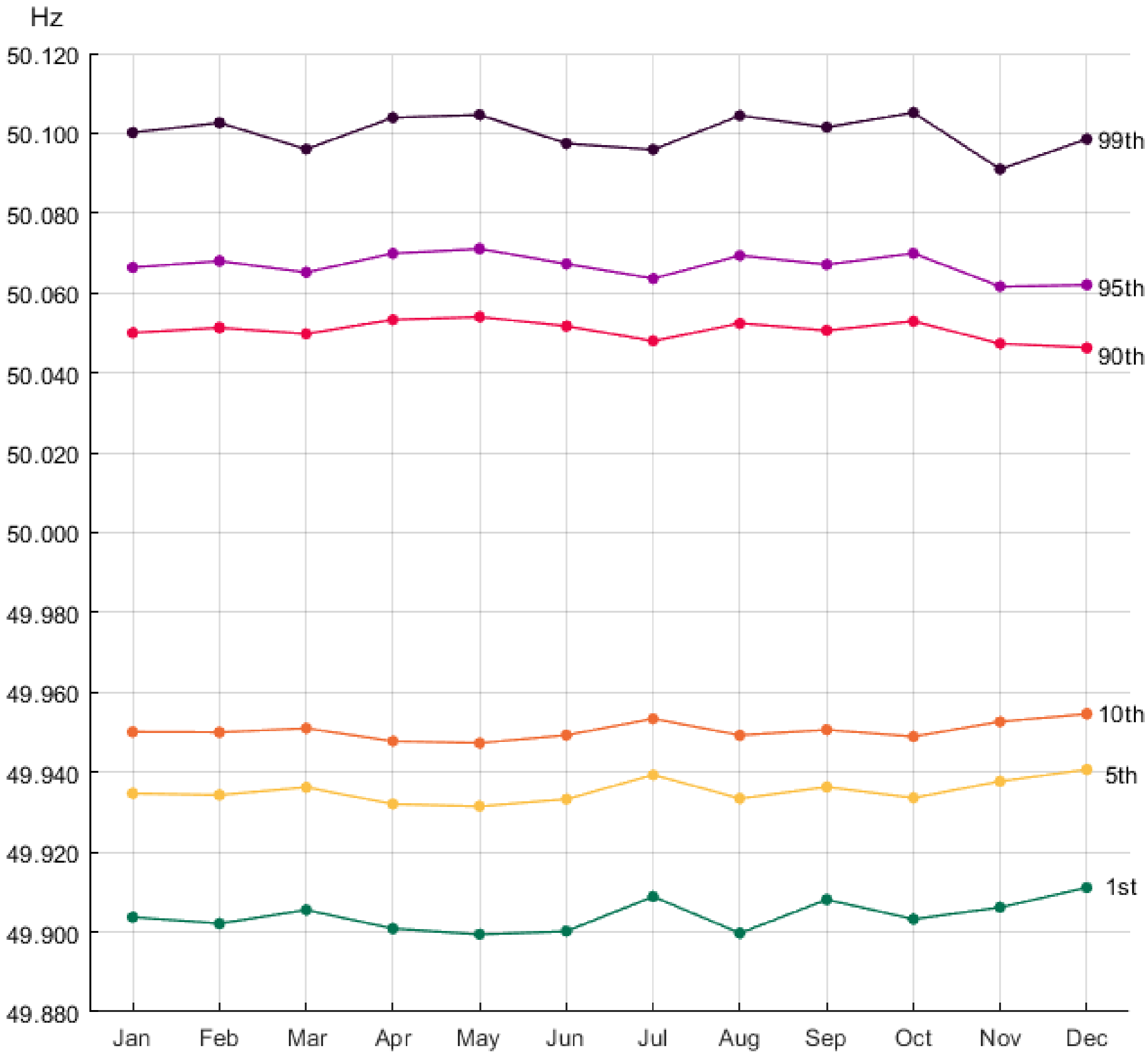


Figure 3.17 shows the percentiles for every day during the week. The percentiles on Tuesday are furthest from 50 Hz, which indicates that the frequency has deviated on a wider range during that day. Apart from subtle variations, the percentiles stay rather constant during the week.

Figure 3.17**. **The 1st, 5th, 10th, 90th, 95th and 99th percentile of the frequency for every day of the week in 2022

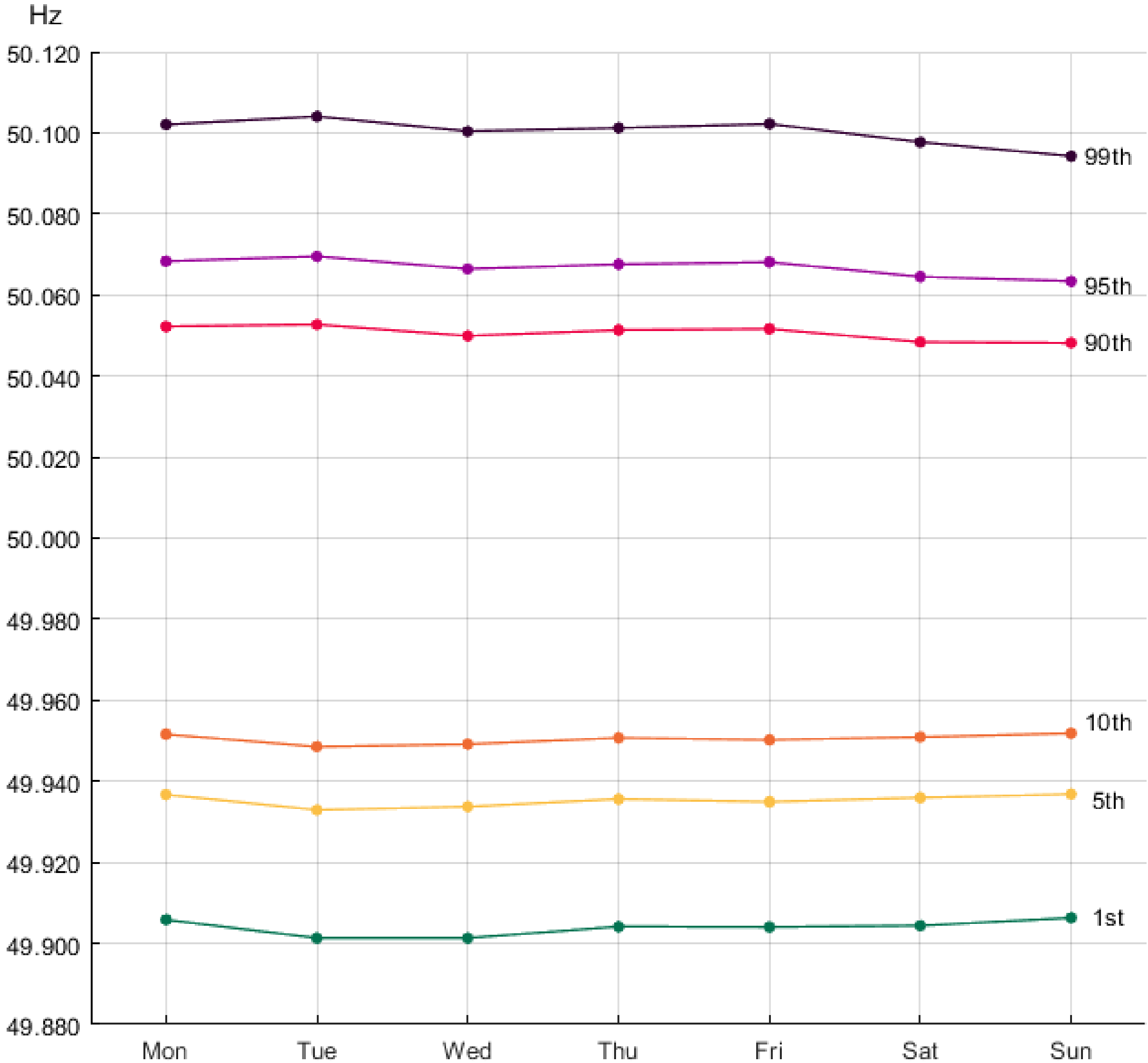


Figure 3.18 represents the percentiles inside the day. All percentiles gain higher values in the midnight, which indicates that there have been more over frequencies and less under frequencies in the midnight. On the next hour the situation is opposite. There have been less over frequencies and more under frequencies at 1 am.

***Figure 3.18**. The 1st, 5th, 10th, 90th, 95th and 99th percentile of the frequency for every hour of the day in 2022*

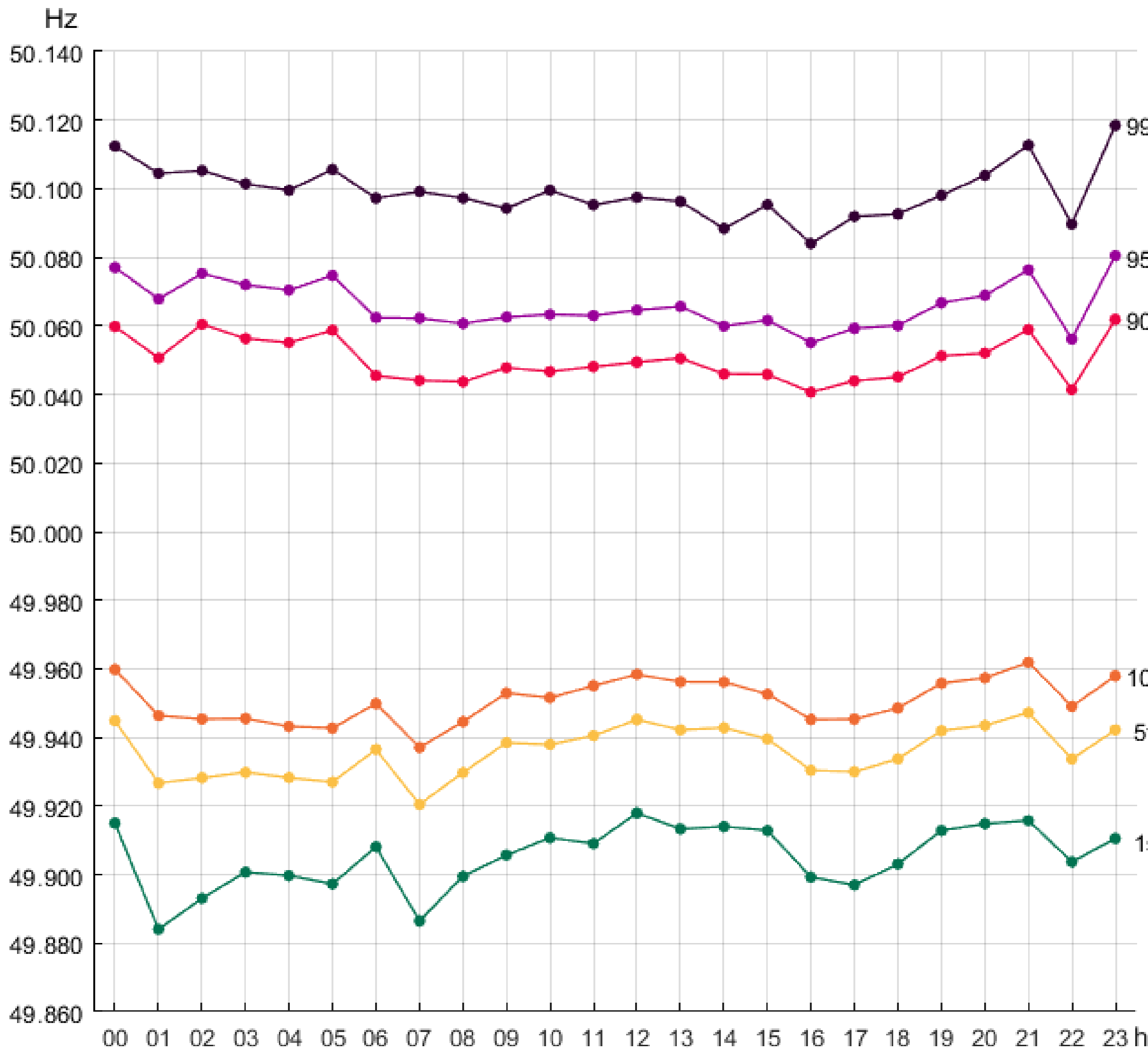
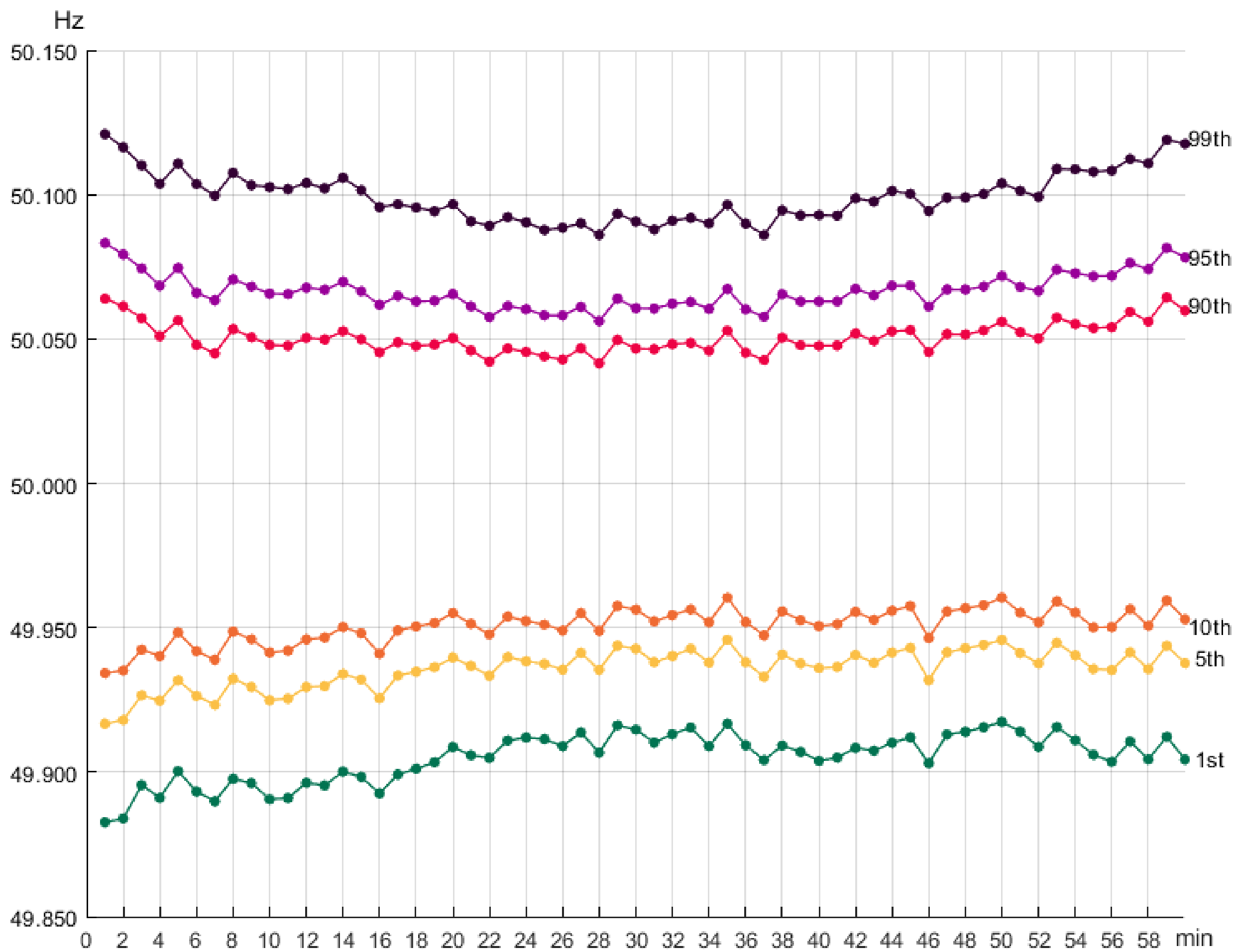


Figure 3.19 shows the percentiles inside the hour. Overall, more frequency deviation has occurred during the hour shift. The 90th, 95th and 99th percentiles gain the highest values during a time interval of few minutes at hour shift. The 10th, 5th and 1st percentiles gain the lowest values at the first minute 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 2022*



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 2022. The cumulative growth of minutes outside the standard frequency range has been quite steady throughout the whole year 2022 and thus more constant than in the preceding two years. The frequency has been outside the standard range less than 9600 minutes, 5334 minutes over 50.1 Hz and 4260 minutes under 49.9 Hz. This means that the current Nordic target level has been reached. The time outside standard frequency range has significantly decreased from 2021.

Figure 3.20. Cumulative minutes outside the standard frequency range in 2022

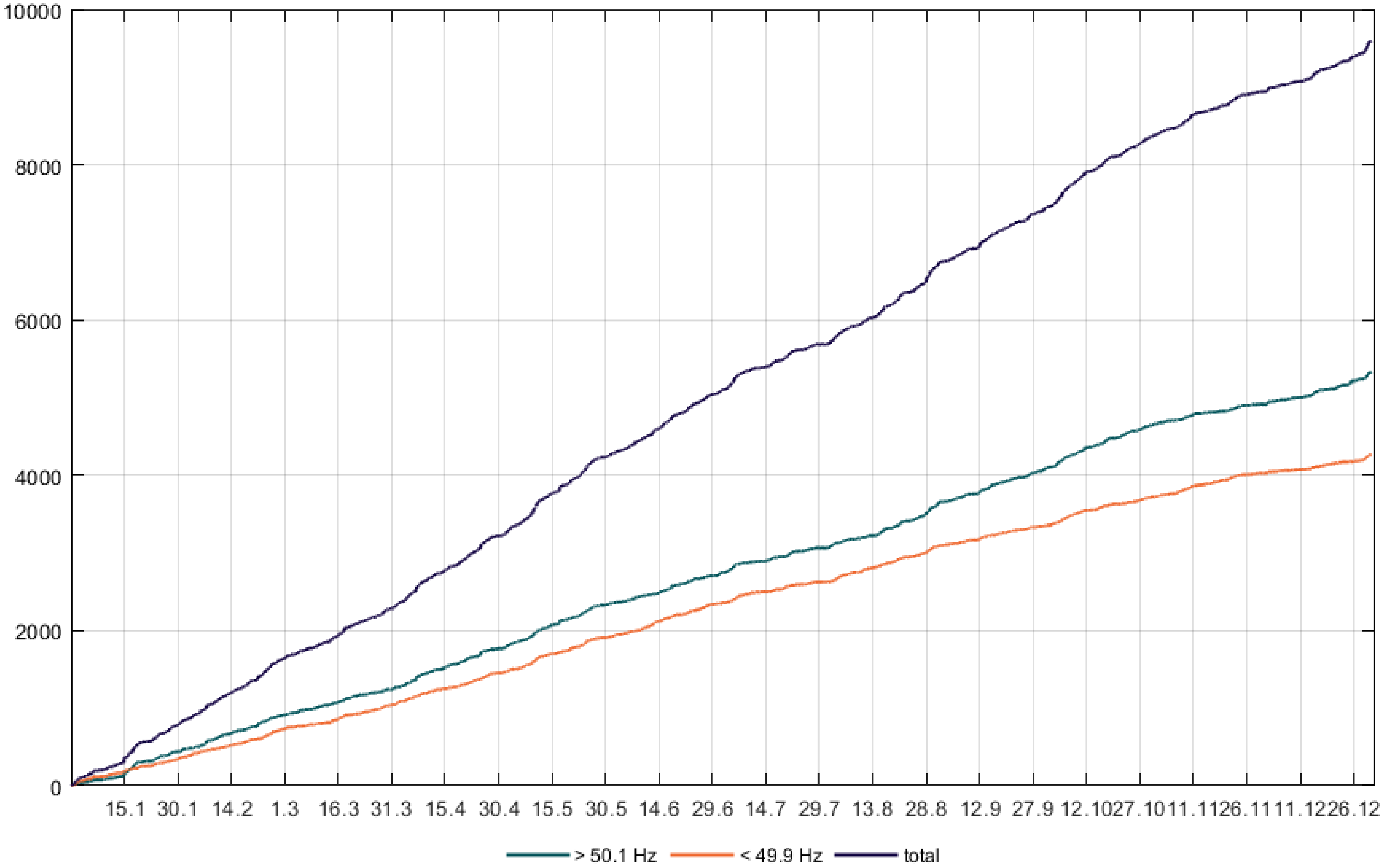
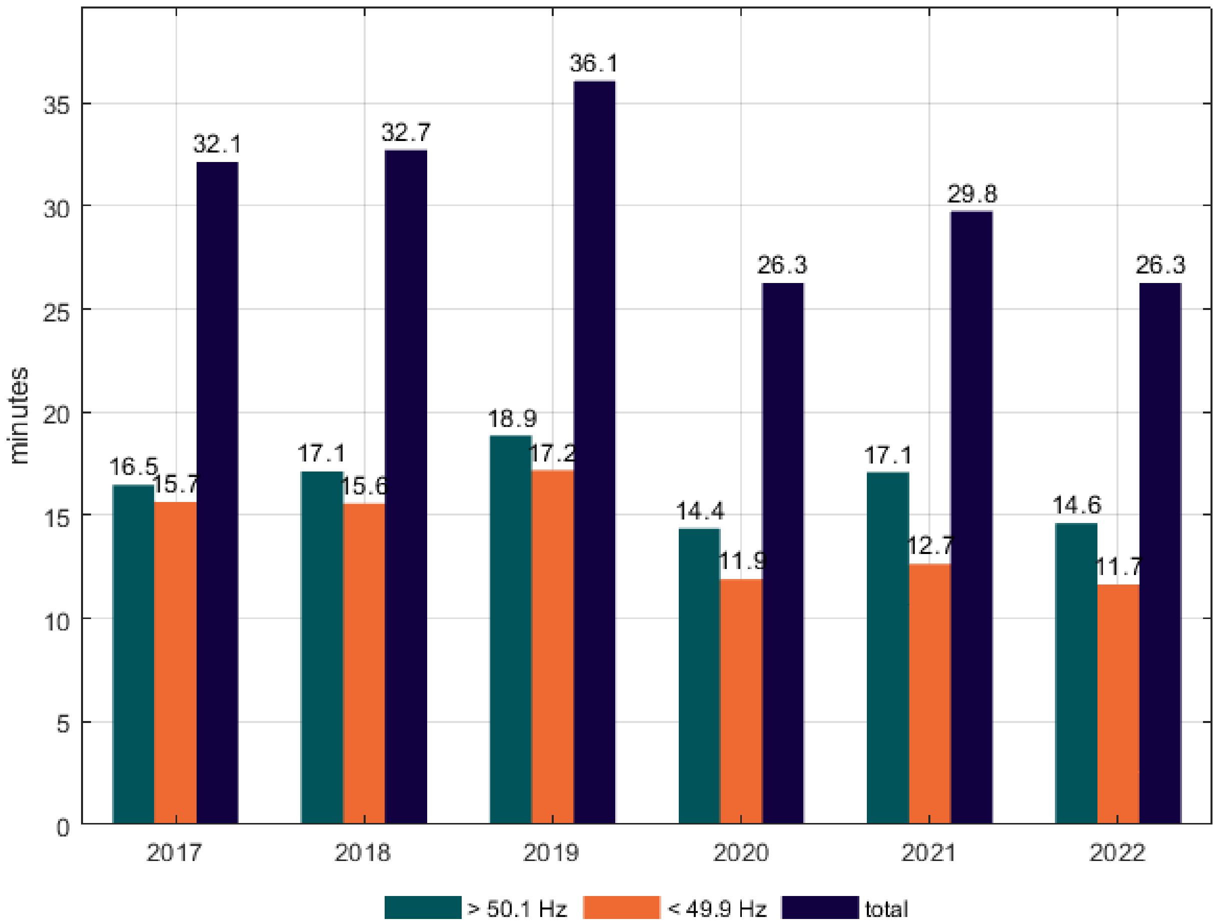


Figure 3.21 represents the daily average number of minutes per year that the frequency was outside the standard frequency range. The number of minutes outside the standard frequency range in 2022 has decreased from the previous year. Every year there have been more over frequencies than under frequencies.

Figure 3.21*. *Daily average number of minutes per year that the frequency was outside the standard frequency range in 2017-2022



Same results can be seen in Table 3.9 as percentage of time in and outside the standard frequency range. The availability of data has been taken into account: 100 % corresponds to total time for which 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
2017	1.18 %	1.12 %	97.70 %
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 %

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

***Table 3.10**. Minutes over and below the standard frequency range*

Year	> 50.1 Hz (min)	< 49.9 Hz (min)	Total (min)
2017	6185	5884	12069
2018	6328	5755	12083
2019	6997	6377	13374
2020	5375	4456	9831
2021	6247	4621	10868
2022	5357	4273	9630

Tables 3.11 and 3.12 contain the total time (in minutes) in which the frequency was outside the standard frequency range (49.9-50.1 Hz) month by month for years 2017 to 2022. These results are based on the evaluation criteria defined in SO GL Article 131(1)(a) (iv). The results from previous tables are not entirely comparable due to differences in availability of measurement data. The same information is presented visually in Figure 3.22.

***Table 3.11**. Total time in which the frequency was outside the 49.9-50.1 Hz band in years 2017-2019*

	2017		**2018**		**2019**	
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	362	345	386	340	478	414
February	272	338	272	266	632	519
March	669	611	436	415	650	628
April	471	460	529	501	709	501
May	577	642	582	547	507	633
June	501	549	588	436	719	766
July	569	530	495	419	413	332
August	504	476	608	549	552	444
September	564	442	598	585	515	526
October	703	573	662	708	606	568
November	420	522	596	447	471	387
December	399	266	508	497	637	584
Entire year	**6011**	**5756**	**6258**	**5709**	**6890**	**6302**

Table 3.12. Total time in which the frequency was outside the 49.9-50.1 Hz band in years 2020-2022

	2020		**2021**		**2022**	
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	385	375	299	199	449	363
February	619	506	547	393	454	361
March	598	489	687	390	339	315
April	411	405	682	620	524	413
May	422	399	618	466	568	460
June	563	430	428	407	373	428
July	251	179	322	262	357	285
August	259	179	589	386	555	453
September	614	390	471	295	464	267
October	420	333	717	516	574	374
November	397	359	537	425	255	306
December	320	352	346	275	420	233
Entire year	**5258**	**4396**	**6242**	**4631**	**5334**	**4260**

***Figure 3.22**. Total time in which the frequency was outside the 49.9-50.1 band in years 2017-2022*

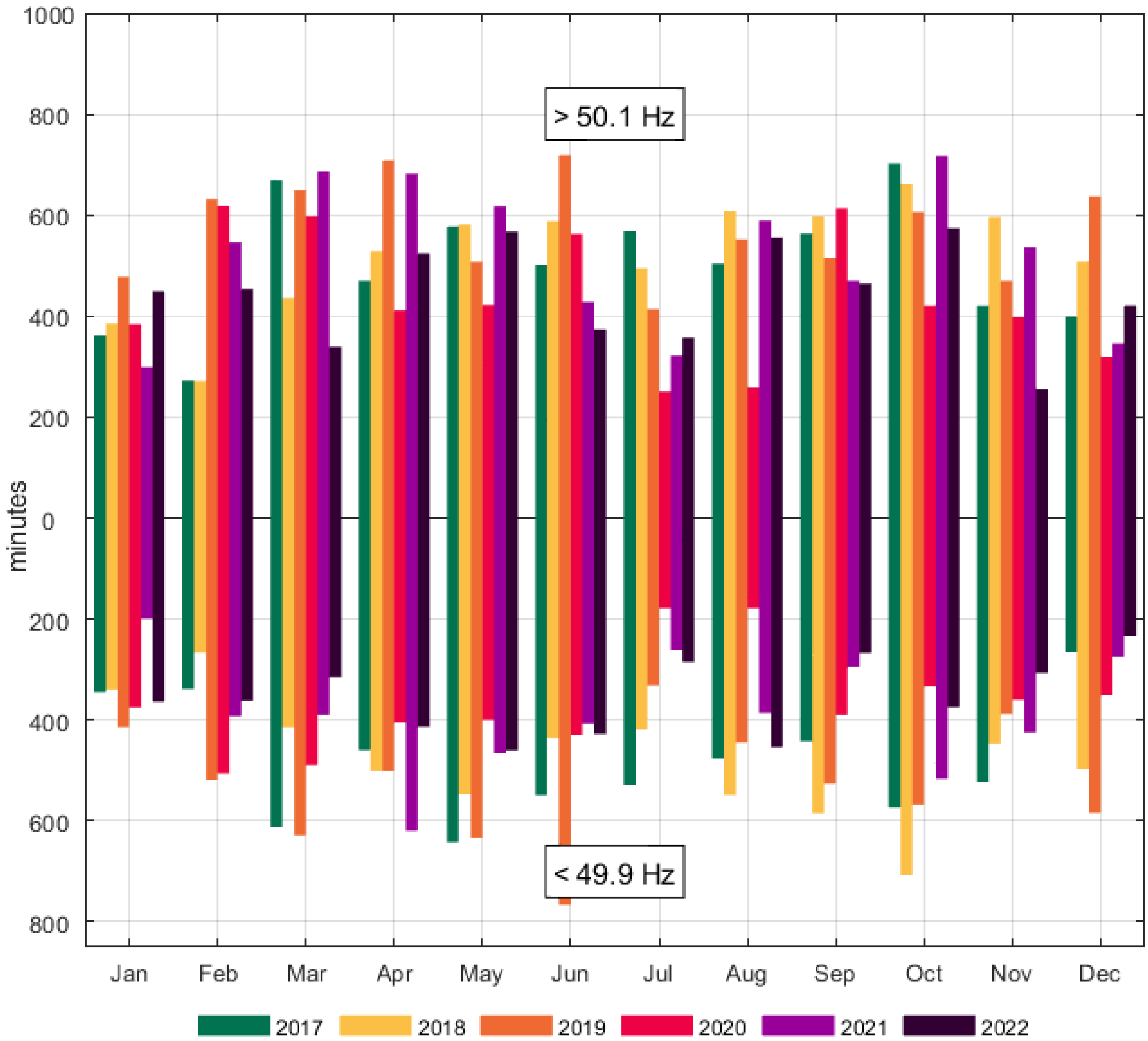


Figure 3.23 shows the daily average in minutes month by month when the frequency has been outside the standard frequency range in the years 2017-2022. In 2022, May had the longest time outside the standard frequency range. March, July, November and December had the best frequency in this comparison.

***Figure 3.23**. Daily average time that the frequency was outside the standard frequency range month by month for years 2017-2022*

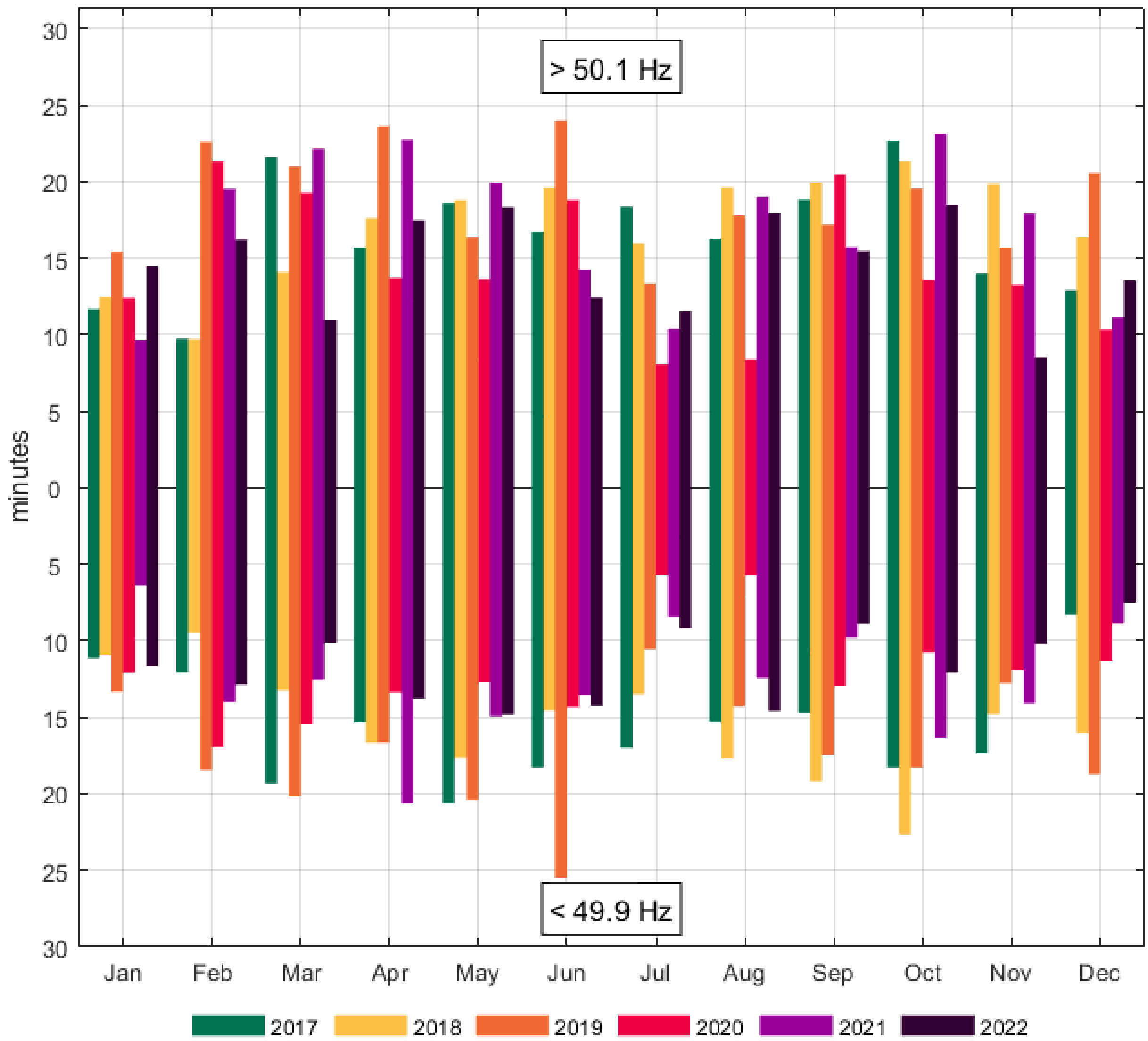


Figure 3.24 represents the daily average time that the frequency was outside the standard frequency range during each day of the week. In 2022 the frequency was outside the standard frequency range the most on Tuesdays and the least on Sundays. Compared with the year 2021 there is a clear reduction on weekends in the amount of time the frequency was outside the standard frequency range.

***Figure 3.24**. Daily average time that the frequency was outside the standard frequency range during each day of the week for years 2017-2022*

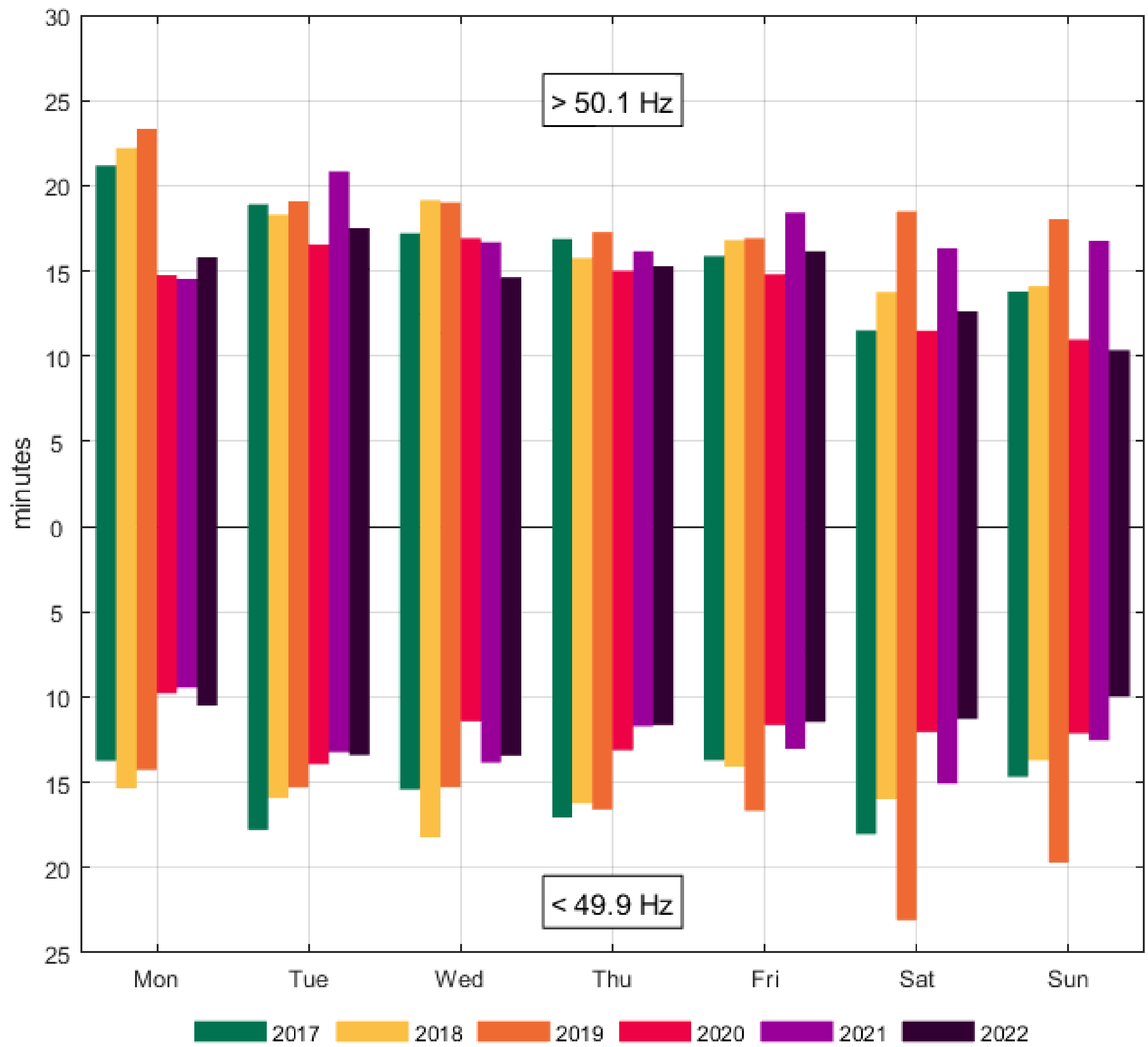


Figure 3.25 represents the daily average time that the frequency was outside the standard frequency range for each hour in a day. In 2022, the frequency has been over 50.1 Hz the most at the hours 0, 21 and 23 and under 49.9 Hz the most at the hours 1, 2 and 7. Frequency stayed inside the standard frequency range best during hours from 12 to 15.

***Figure 3.25**. Daily average time that the frequency was outside the standard frequency range during each hour of the day for years 2017-2022*

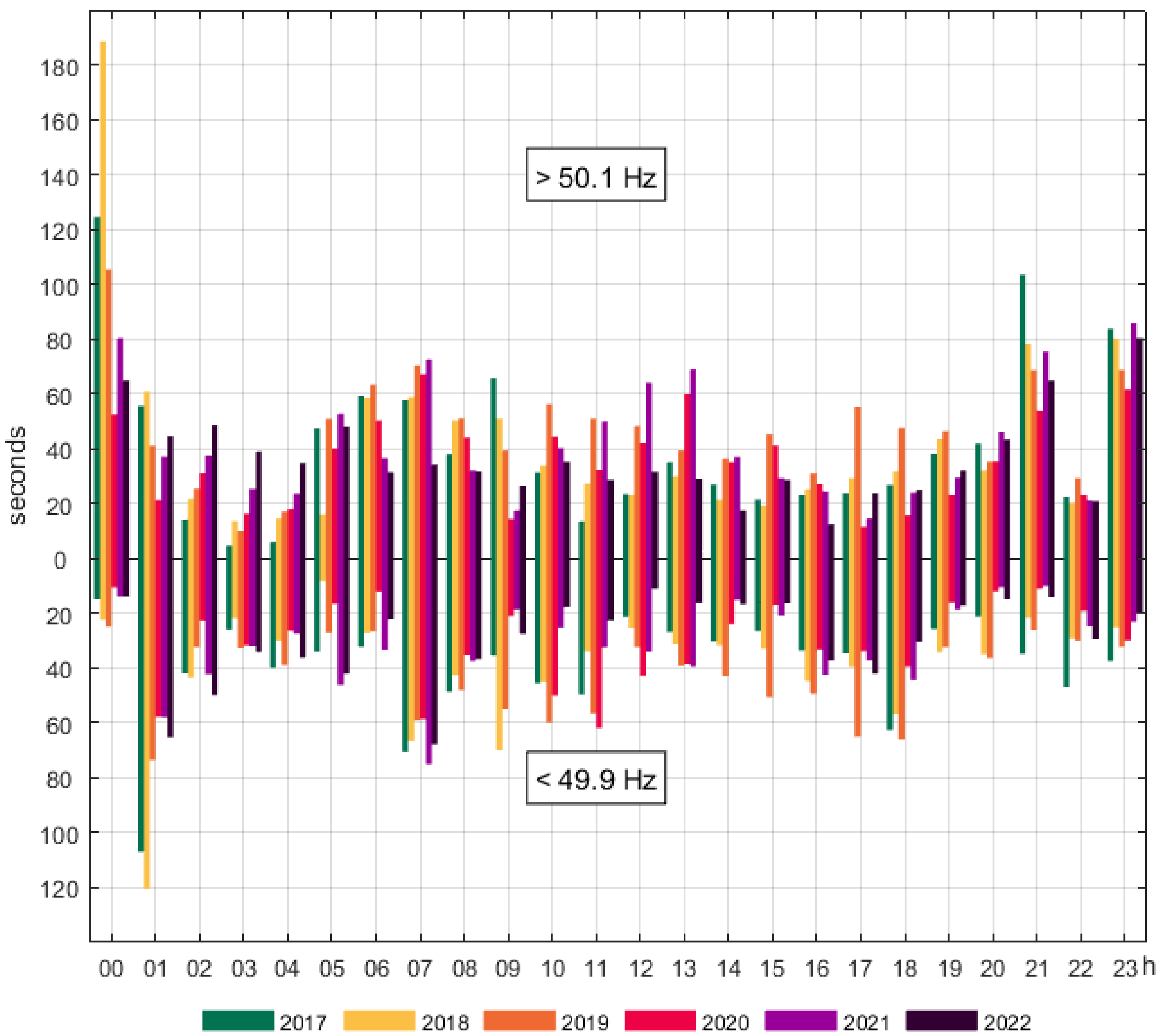


Figure 3.26 shows the daily average time outside the standard frequency range per hour and absolute value of Nordic consumption and production difference. Also transmission difference of HVDC links connecting the Nordic power system to Continental Europe and Russia is presented.

The differences were calculated by subtracting 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 was retrieved from the ENTSO-E Transparency platform website and the transmission powers of the HVDC links were direct measurement data. Hours are given in Finnish time (UTC+2 / UTC+3 in the summer).

In the morning, the peaks for production and consumption differences are around 2200 MWh. At midnight the peak for production difference is around 1660 MWh and for consumption difference the peak is around 1440 MWh. Compared with 2021, the peak in time outside the normal frequency range associated with seven o'clock has decreased by more than a quarter although the hour-related changes in production, consumption and powers of HVDC links have been close to the same level. Also, while comparing the HVDC transmission differences of the years 2020 and 2021 with the year 2022, a new period of growth in values has emerged, reaching its maximum by the hour 11.

***Figure 3.26**. Seconds per hour outside the standard frequency range and the absolute values of Nordic consumption, production and HVDC transmission differences in 2022*

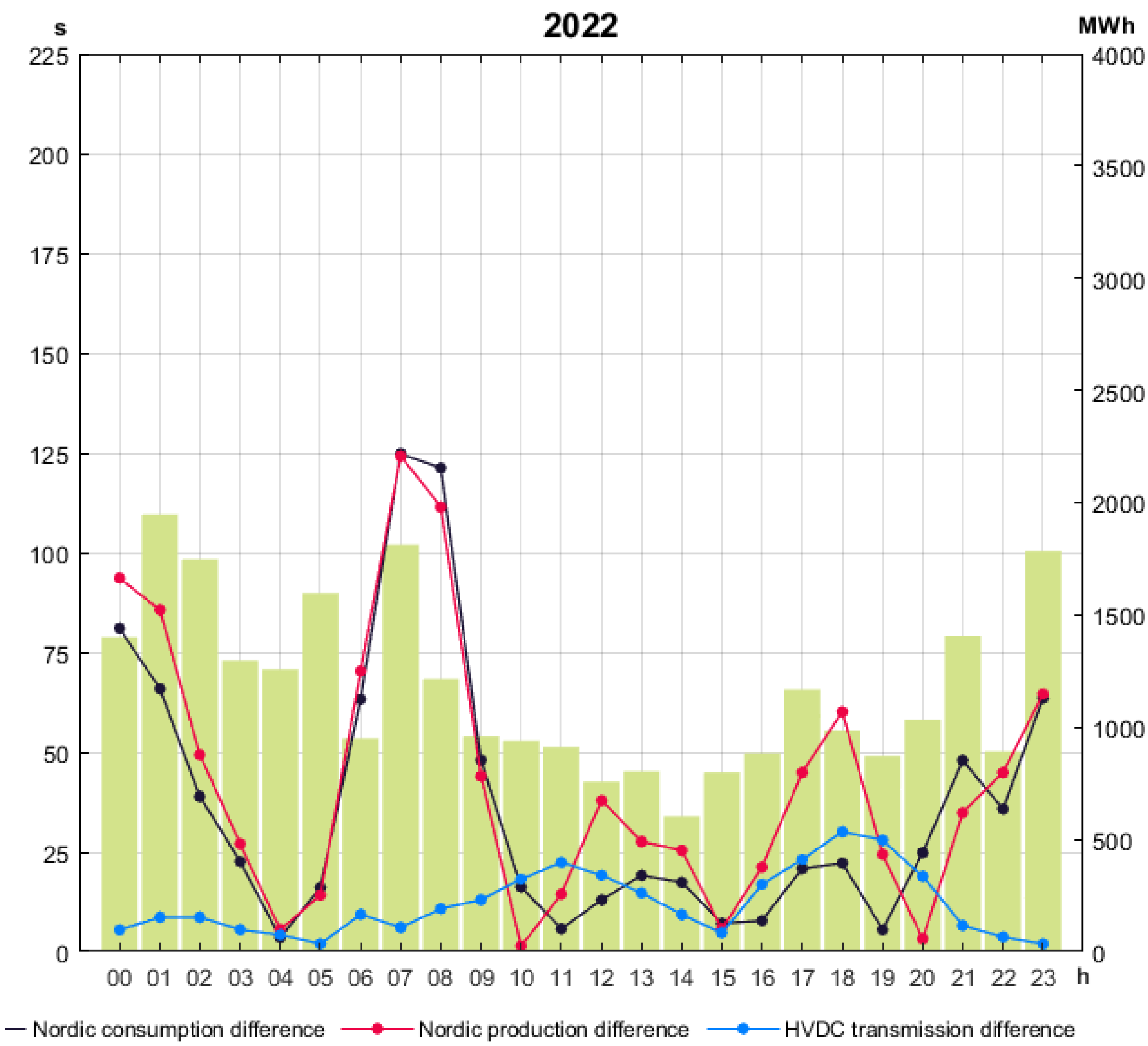


Figure 3.27 illustrates an average hour divided to 60 minutes. For each minute of the average hour there is a value in seconds per hour that frequency has been over or below the standard frequency range. In years 2017-2022 the frequency has been outside the standard frequency range most often in the beginning of the hour. The frequency has stayed 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.

***Figure 3.27**. Number of seconds per hour outside the standard frequency range in 2017-2022 for each minute of an average hour*

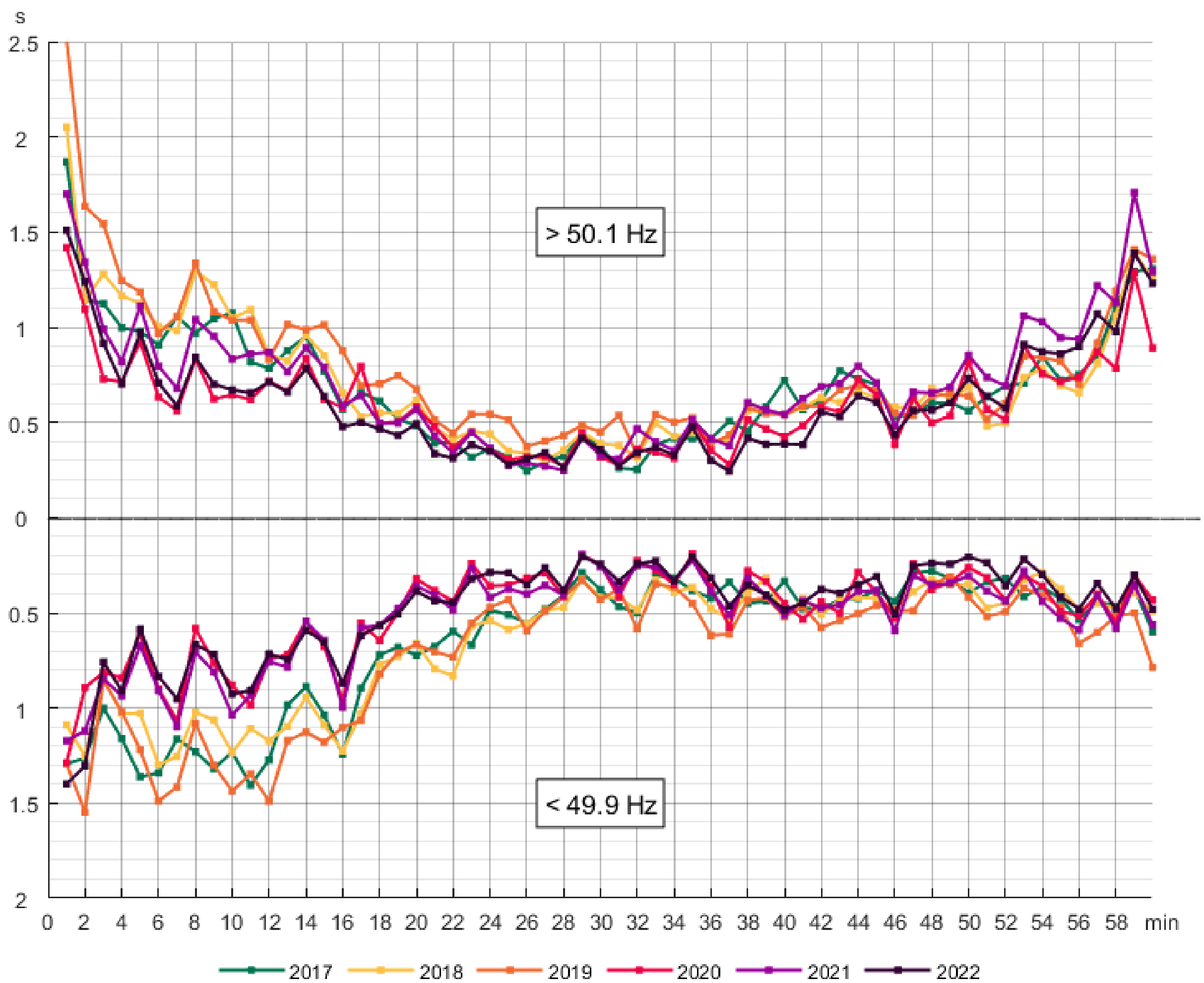
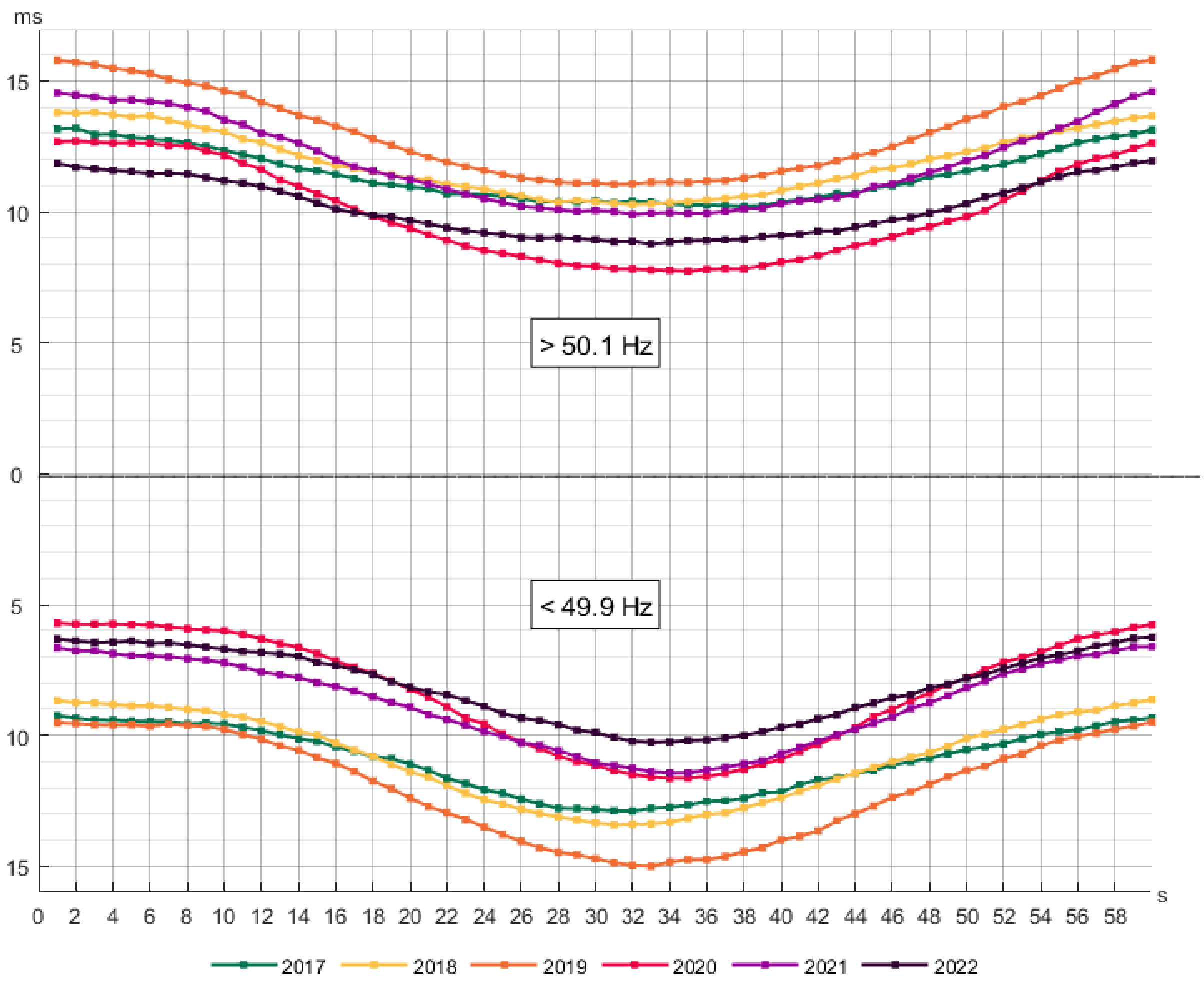


Figure 3.28 illustrates an average minute divided into 60 seconds. For each second of the average minute there is a value in milliseconds per minute that the frequency has been over or below the standard frequency range. There have been more over frequencies at the beginning and at the end of the average minute. Under frequencies have occurred more frequently in the middle of the minute. While comparing the year 2022 with the years 2017-2019 and 2021, there has been major reducement in occurrence of both under and over frequencies inside an average minute.

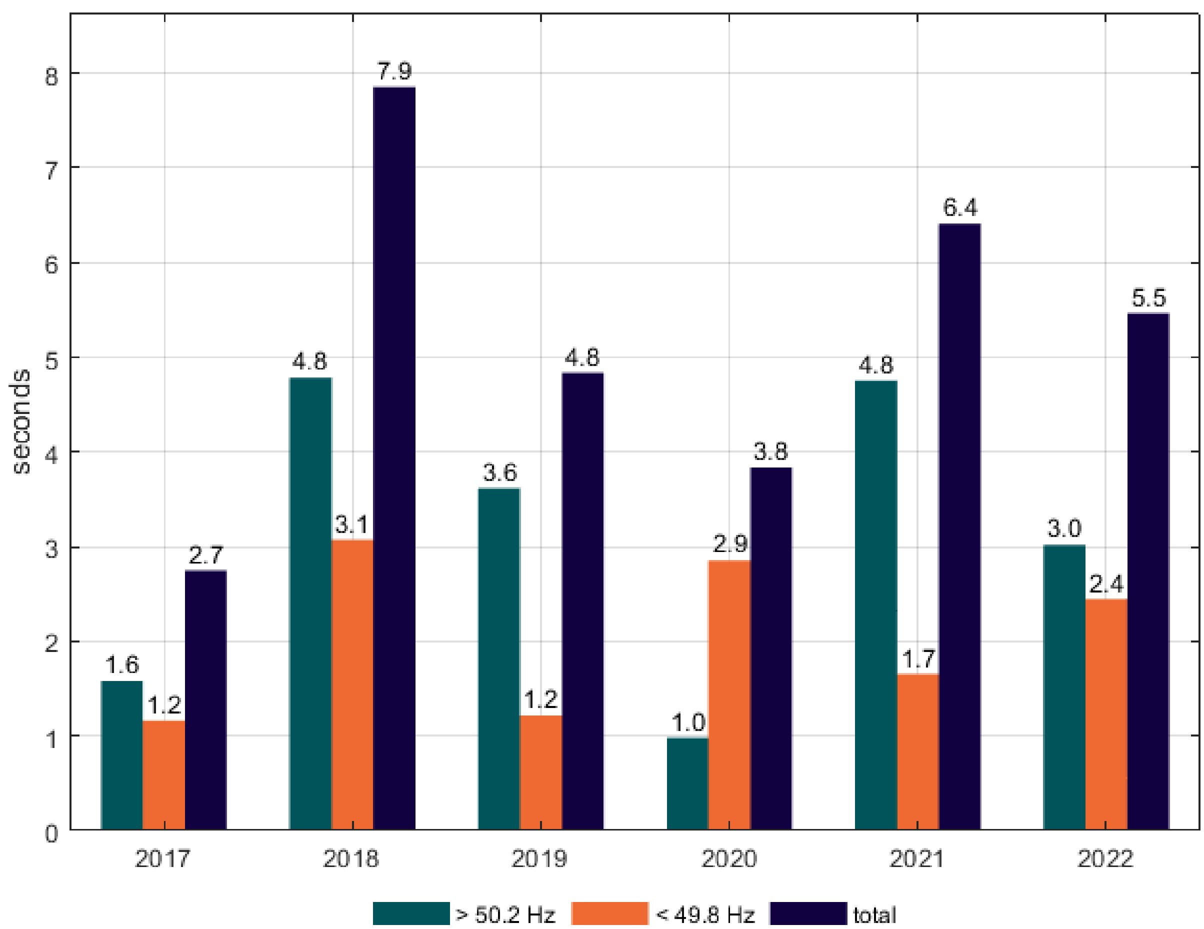
***Figure 3.28**. Number of milliseconds per minute outside the standard frequency range in 2017-2022 for each second of an average minute*



3.4.2 Time outside 49.8-50.2 Hz

Figure 3.29 shows frequency deviations exceeding ±200 mHz as average number of seconds per day. The total time outside 49.8-50.2 Hz was lower in 2022 than in 2021. In 2022, over frequencies exceeding 200 mHz have been more common than under frequencies, which is in line with the trend of the years 2017-2019 and 2021. While examining years 2017 to 2022, the year 2022 had the third largest total time outside 49.8-50.2 Hz.

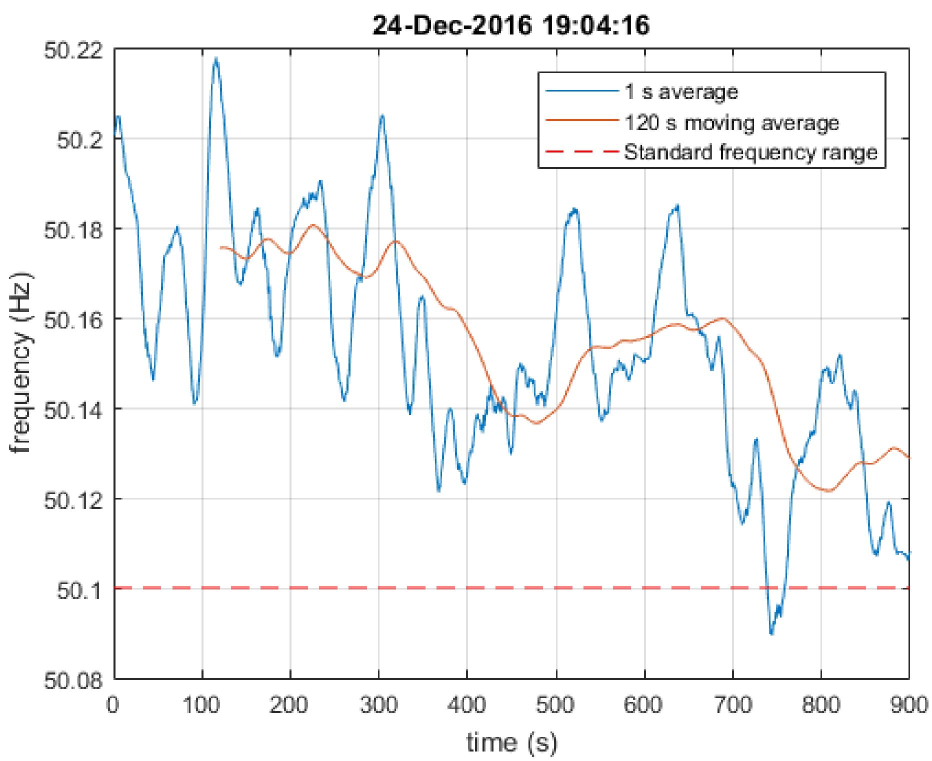
Figure 3.29*. *Average number of seconds per day that the frequency was outside the 49.8-50.2 Hz band for years 2017-2022



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 are 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 was 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 used resolution of the frequency data was 1 second.

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



The number of events in 2017-2022 that the frequency exceeded 49.8-50.2 Hz band and did not even momentarily return to the standard frequency range within 15 minutes are presented in Table 3.13. These results were calculated with 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.*

	2017		**2018**		**2019**		**2020**		**2021**		**2022**	
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	0	0	1	0	0	0
March	0	0	0	0	0	0	0	0	1	0	0	0
April	0	0	0	0	0	0	0	0	0	0	0	0
May	0	0	1	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	0	0	1	0	0	1	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	0	0	1	1	0	0	1	0	2	0	**0**	**0**

Table 3.14 shows the number of events in 2017-2022 that the frequency exceeded the 49.8-50.2 Hz band and the 120 s moving average did not return to the standard frequency range within the next 15 minutes. These results were calculated with 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.

	2017		**2018**		**2019**		**2020**		**2021**		**2022**	
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	1	0	0	0	2	0	0	0
March	0	0	0	0	0	0	0	0	1	0	0	0
April	1	0	0	0	1	0	0	0	0	0	0	0
May	1	0	2	0	0	0	0	0	1	0	0	0
June	1	0	2	0	0	1	0	0	0	0	0	0
July	0	0	1	0	0	0	0	0	0	0	0	0
August	0	0	0	0	0	0	0	0	0	0	0	0
September	0	0	0	1	0	0	1	0	1	0	0	0
October	0	0	0	0	1	0	0	0	0	0	0	0
November	0	0	1	0	0	0	0	0	1	0	0	0
December	0	0	0	1	1	0	0	0	0	0	1	0
Entire year	3	0	6	2	4	1	1	0	6	0	**1**	**0**
Sum	**3**		**8**		**5**		**1**		**6**		**1**	

3.4.3 Time outside 49.0-51.0 Hz

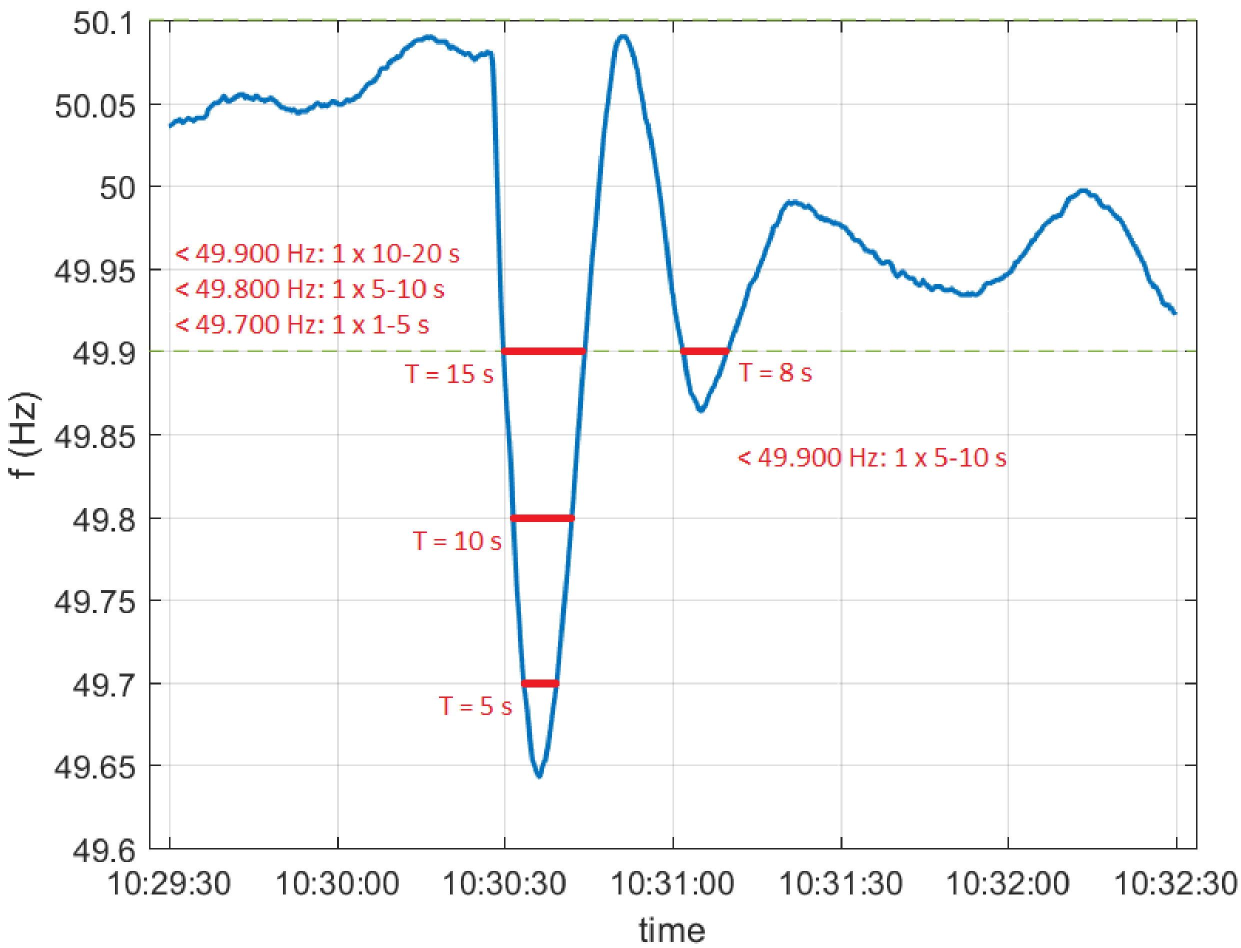
Time outside 49.0 Hz and 51.0 Hz is calculated by counting the number of samples that are below 49.0 Hz or above 51.0 Hz and multiplying the number by the time duration of the sample. The criteria are also defined in SO GL Article 131(1)(a) (v). The resolution of the data used was 1 second.

There were no instances in 2017-2022 where the frequency crossed 49.0 Hz or 51.0 Hz.

3.5 Number of frequency deviations with different durations

In this section, the frequencies outside the standard frequency range have been sorted according to amplitude and duration of the deviation, as well as whether the deviation was over or under the normal frequency range. Figure 3.31 gives an example on 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 10-20 s column and one to 5-10 s column. The other frequency deviation goes also below 49.800 Hz and 49.700 Hz. These will also be counted as one frequency deviation < 49.800 Hz with time from 5-10 s and one < 49.700 Hz with time from 1-5 s. Altogether, the example period is counted as four (4) frequency deviations. Also for example, time window of 5-10 s stands for frequency deviations lasting over five (5) seconds and under or exactly 10 seconds.

***Figure 3.31**. Example on how the number of frequency deviations is calculated [2]*



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 that was used is 0.1 seconds.

Tables 3.15-3.20 provide more detailed information about frequency deviations from year 2017 to 2022. These tables include the durations and amplitudes of the deviations, as well as total amount, maximum duration and average duration of deviations.

Table 3.15. Total number of frequency deviation in 2017

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	14813	5217	3723	5441	3586	840	655	91	34366	895.60	10.24
> 50.2	19	8	17	17	5	1	0	0	67	43.90	8.90
> 50.3	0	1	1	0	0	0	0	0	2	5.10	4.85
< 49.9	14196	5284	3269	4948	3360	755	650	96	32558	995.90	10.29
< 49.8	43	17	36	8	1	0	0	0	105	27.50	4.29
< 49.7	0	1	1	1	0	0	0	0	3	10.70	7.03
< 49.6	0	1	0	0	0	0	0	0	1	2.90	2.90
< 49.5	0	0	0	0	0	0	0	0	0	0.00	0.00

Table 3.16. 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 3.17. 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 3.18. 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 3.19. 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 3.20. 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	0.00

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. Year 2020 has had the smallest number of deviations in the observation period. The number of the frequency deviations of 0-1 seconds have been by far the highest in 2022, although in the same year the values of other time categories have been at least at level of previous years or even lower.

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

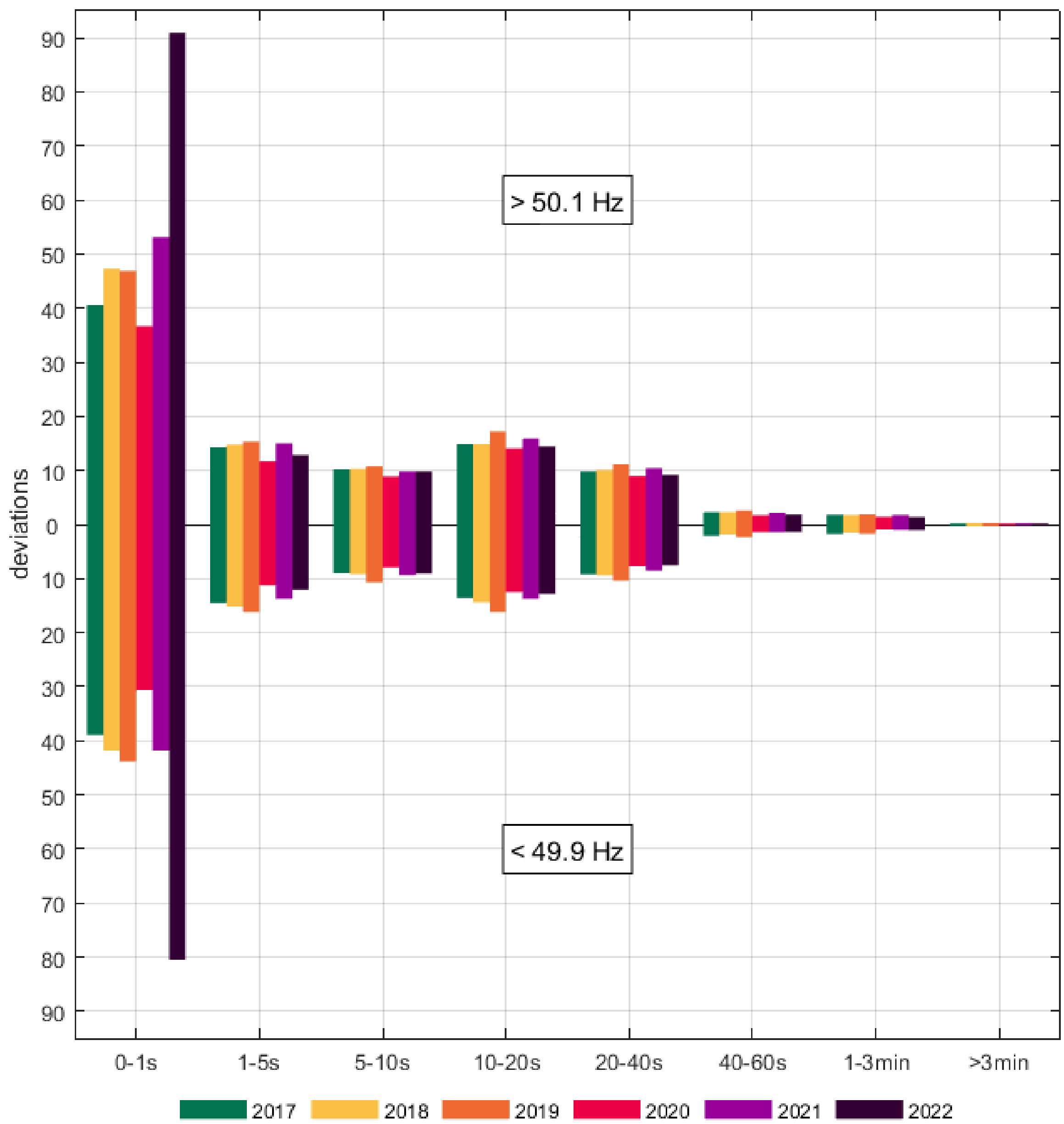
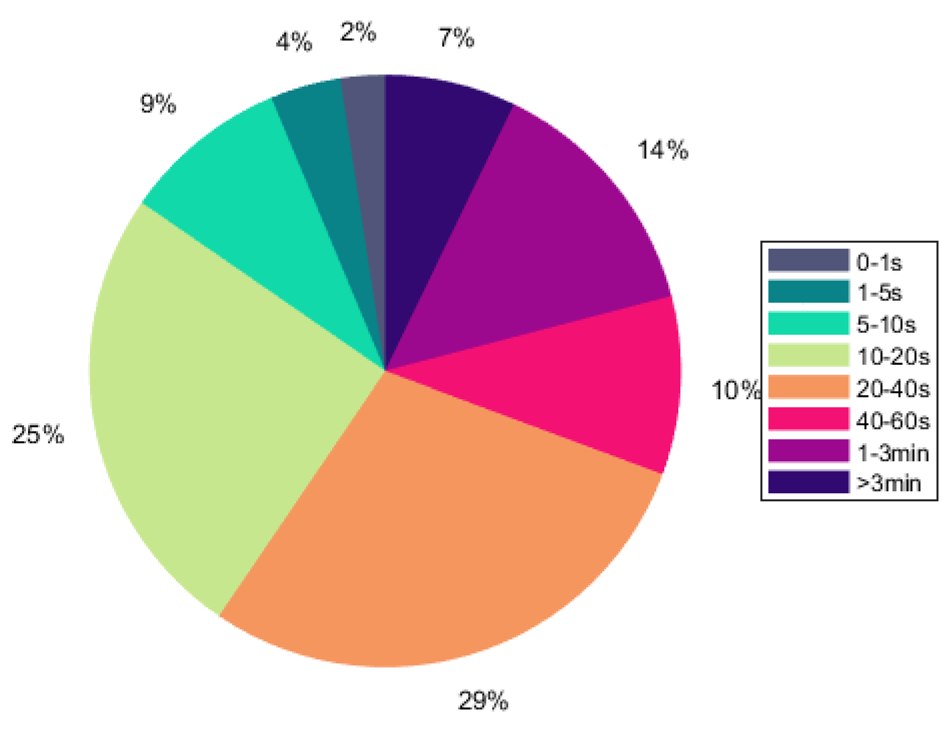


Table 3.21 shows how deviations of different duration affected to the total time outside the standard frequency range in 2022. Times are given in minutes. Pie chart in Figure 3.33 shows in percentages how the total time outside the standard frequency range was divided between deviations of different duration. Deviations with duration of 10-20 s and 20-40 s lasted more than half of the total time outside the standard frequency range.

Table 3.21. Total minutes in 2022 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	123	190	454	1272	1513	531	778	456	5318
< 49.9 Hz	109	179	414	1128	1243	398	538	229	4238
total	232	369	868	2401	2756	929	1316	685	9556

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 the year 2022. Figure 3.34 represents the total number of deviations per duration for each month in 2022. Most of the deviations have lasted only between 0-1 seconds. Most deviations occurred in August and May. January and February had the smallest number of deviations.

***Figure 3.34**. Total number of frequency deviations per duration for each month in 2022*

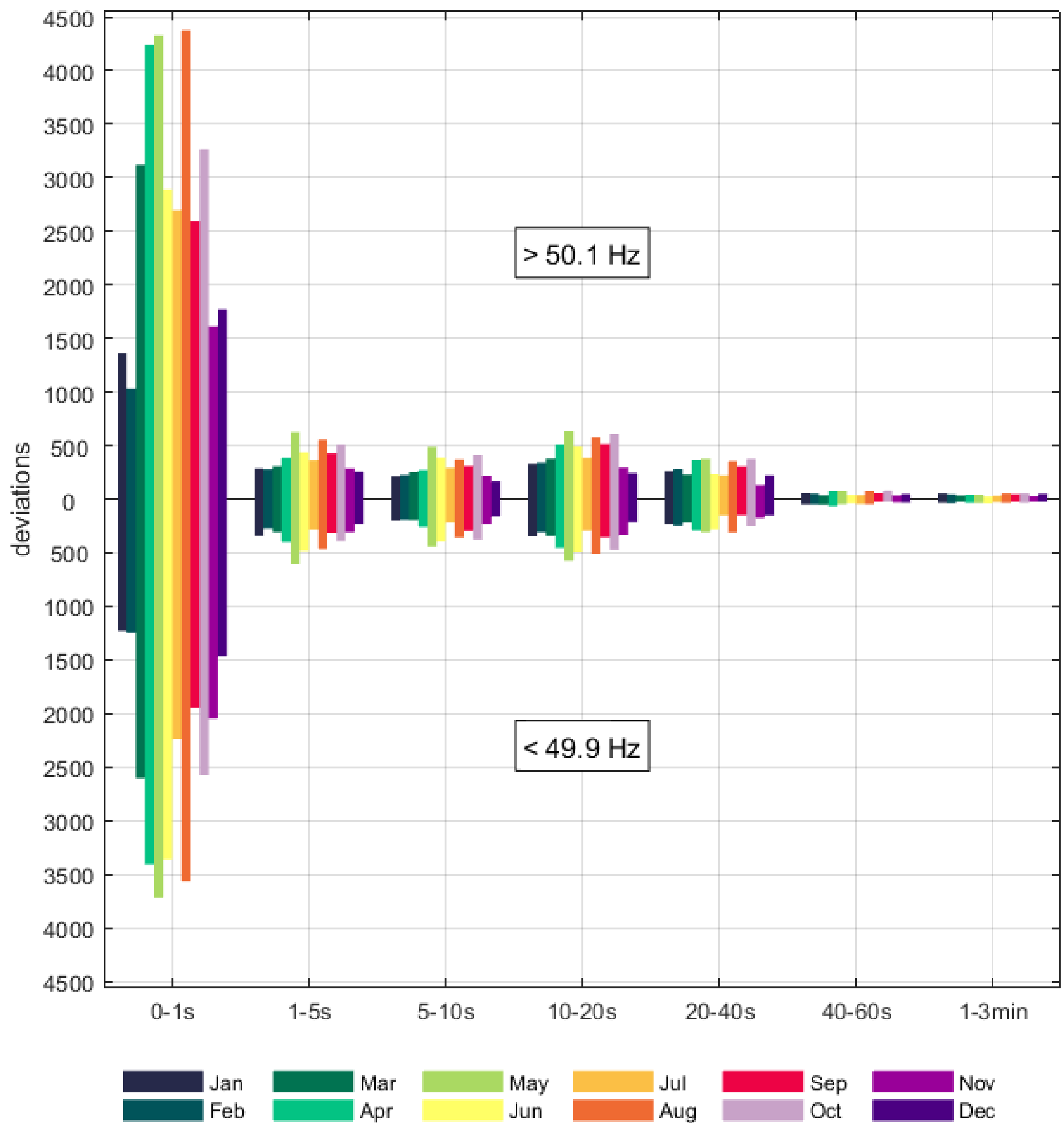
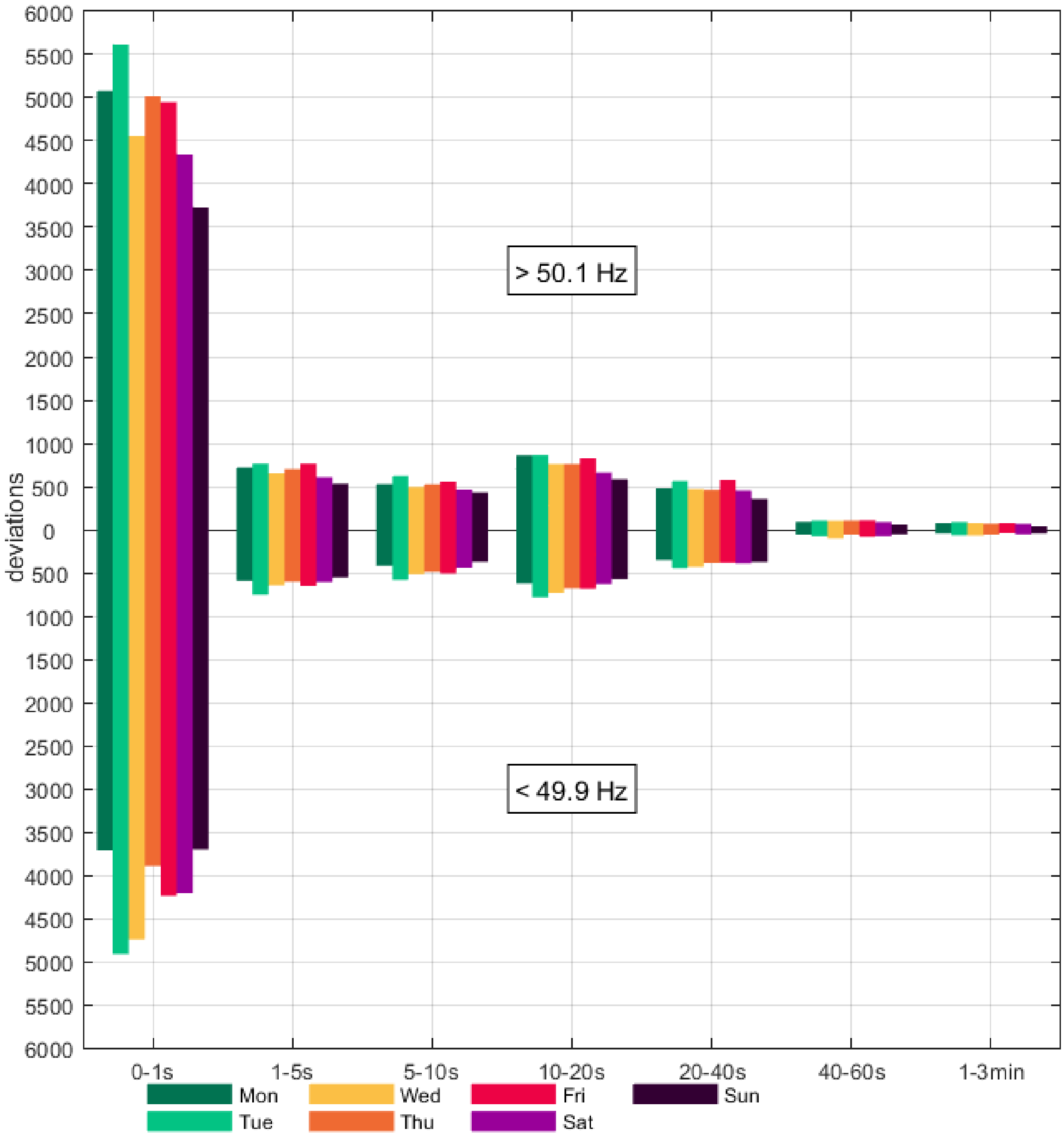


Figure 3.35 shows the number of deviations for every day of the week. Tuesdays had the largest amount of total deviations almost in every time category, expect for deviations lasting 40-60 seconds. Sundays on the other hand had the smallest total amount of deviations in 2022.

***Figure 3.35**. Total number of frequency deviations per duration for each day of the week in 2022*



Figures 3.36 and 3.37 illustrate the number of deviations per duration inside the day. Figure 3.36 includes the hours 0-11 and Figure 3.37 the hours 12-23. Most deviations over the standard frequency range occurred around the midnight. With under frequency deviations, hours 2 am to 5 am, 4 pm to 5 pm and hour 7 am had most deviations.

***Figure 3.36**. Total number of frequency deviations per duration for hours 0-11 in 2022*

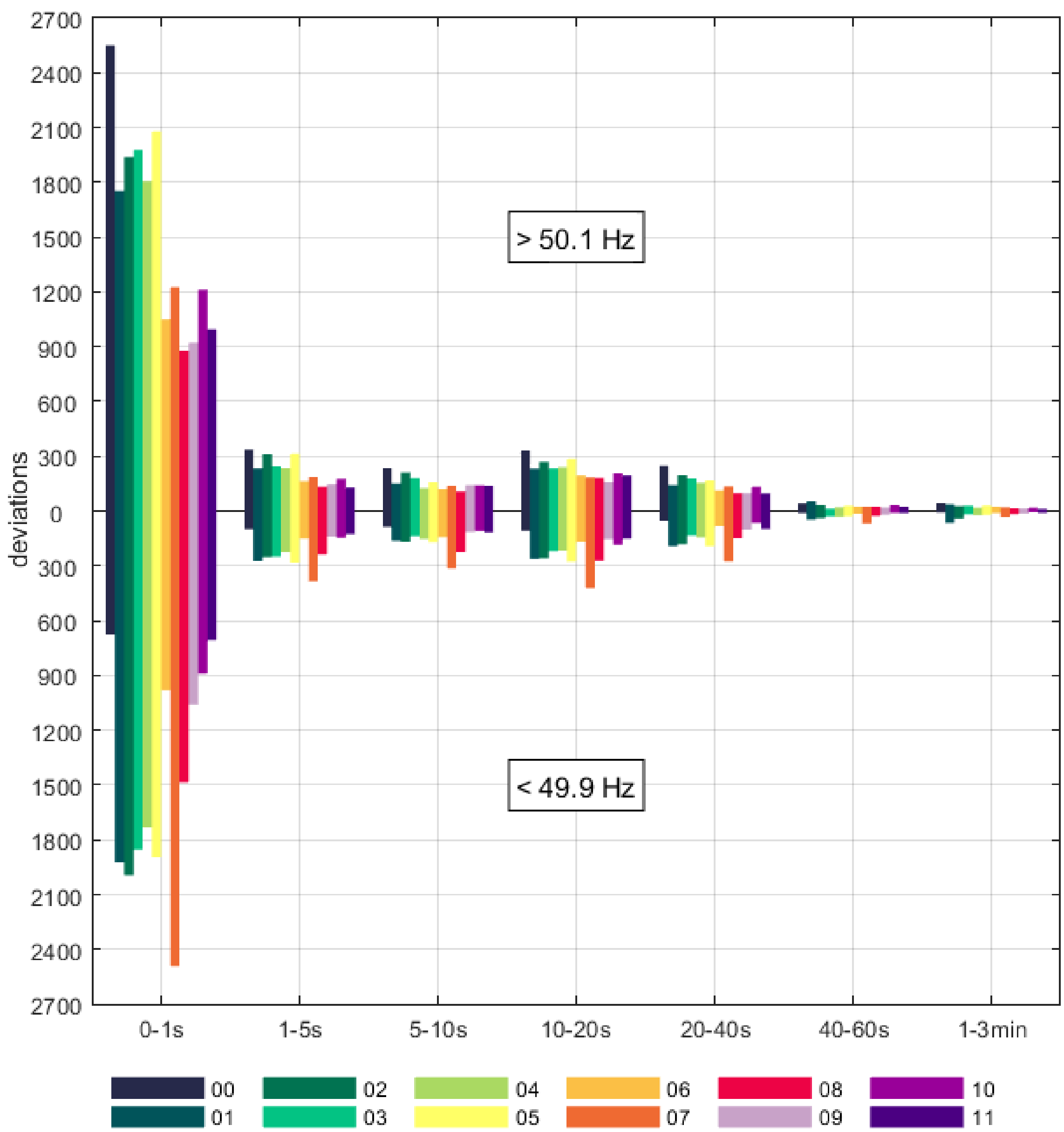


***Figure 3.37**. Total number of frequency deviations per duration for hours 12-23 in 2022*

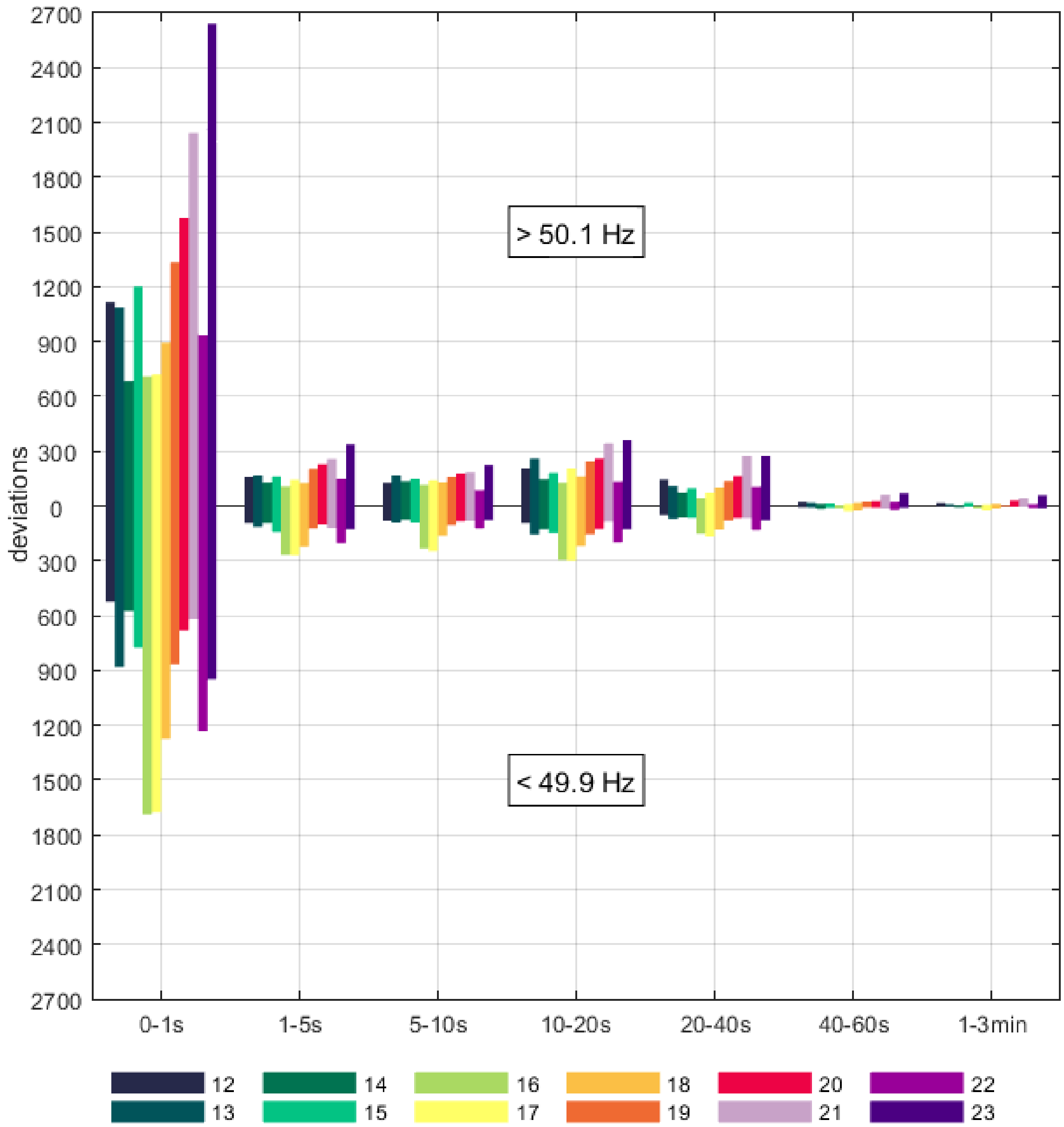
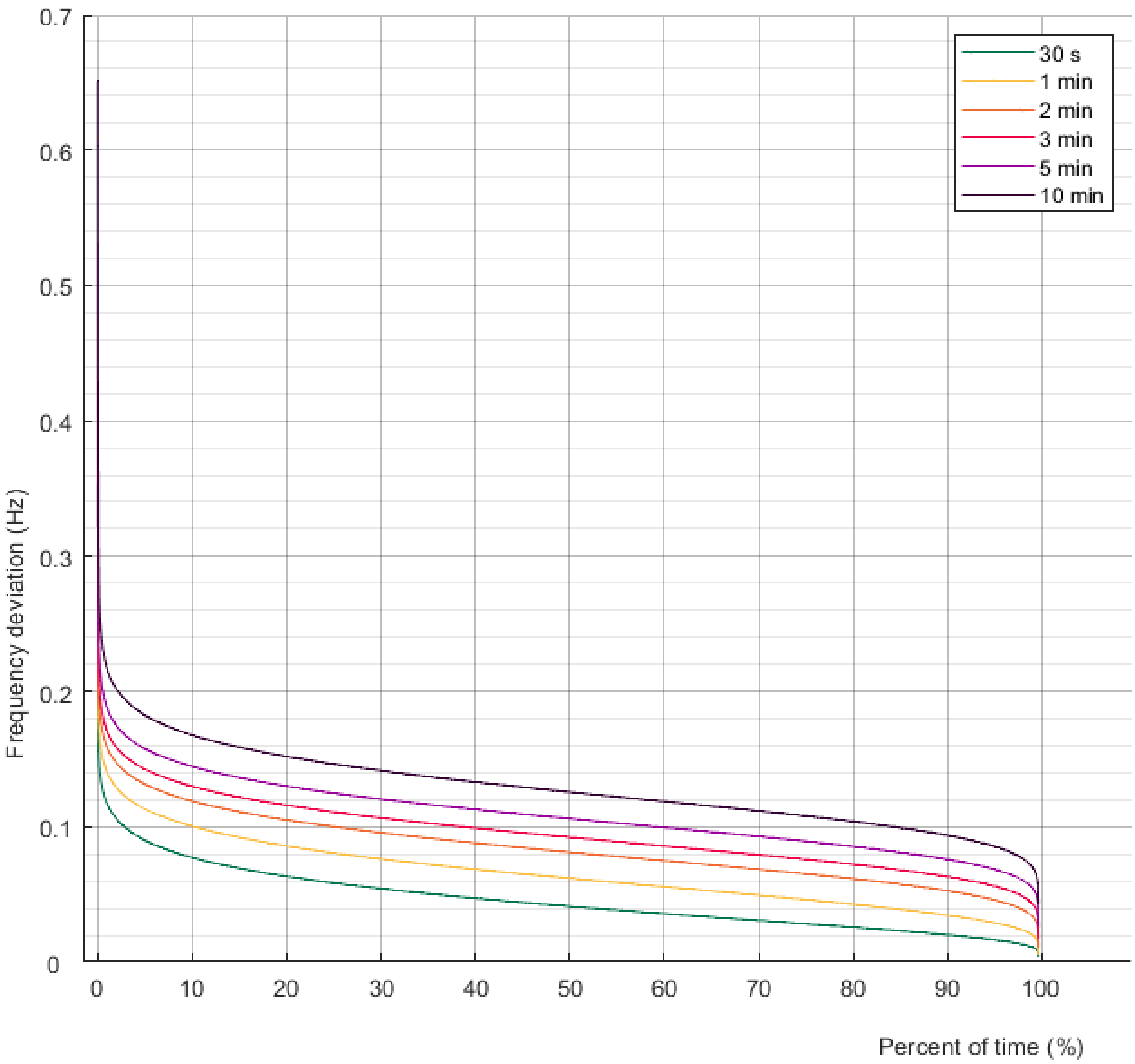


Figure 3.38 represents the duration curve of maximum frequency deviation inside different time windows in year 2022. The time window was slid through the year with a time interval of one second. Studied time windows can be found from legend of the Figure 3.38. Chapter 4 shows in detail the frequency disturbances of over 0.3 Hz which can be seen here as a peak near 0% permanence.

***Figure 3.38**. Duration curve of maximum frequency deviation inside different time windows in 2022*



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 deviations for years between 2017-2022. The number of over frequency deviations decreased slightly from the previous year in all categories except for deviations of more than 15 minutes. With under frequencies, the amount of deviations stayed close to the same level as in 2021. When comparing the year 2022 with the years 2017-2019, the number of deviations has substantially decreased in all categories.

***Figure 3.39**. Total number of longer frequency deviations per duration between 2017-2022*

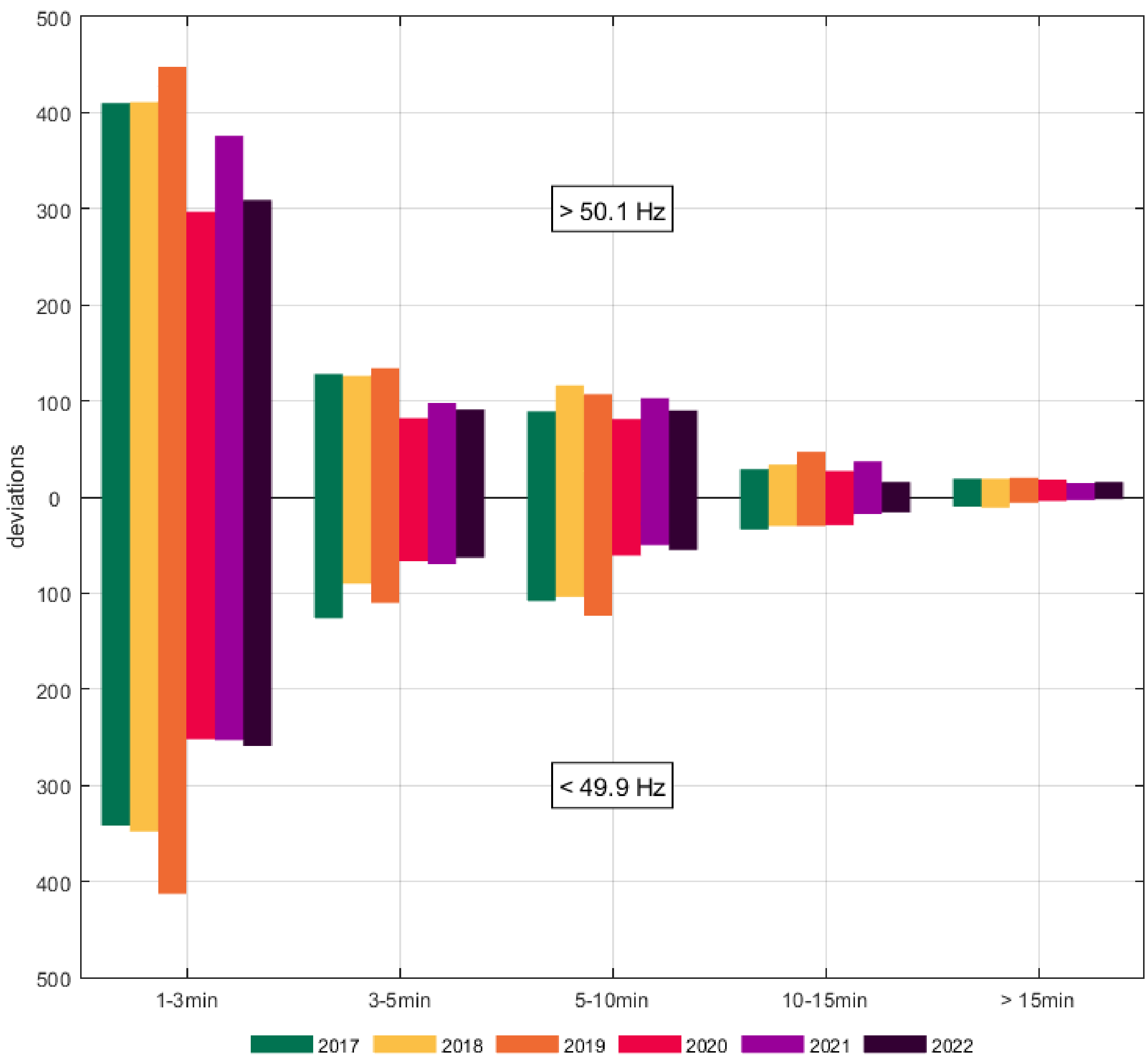


Figure 3.40 shows the total number of longer deviations for each month in 2022. Compared with 2021, there was a clear reduction in the number of 1-10 minute frequency deviations between March and May. On the other hand, the number of the frequency deviations of 1-5 minutes increased between July and September.

***Figure 3.40**. Total number of longer frequency deviations per duration for each month in 2022*

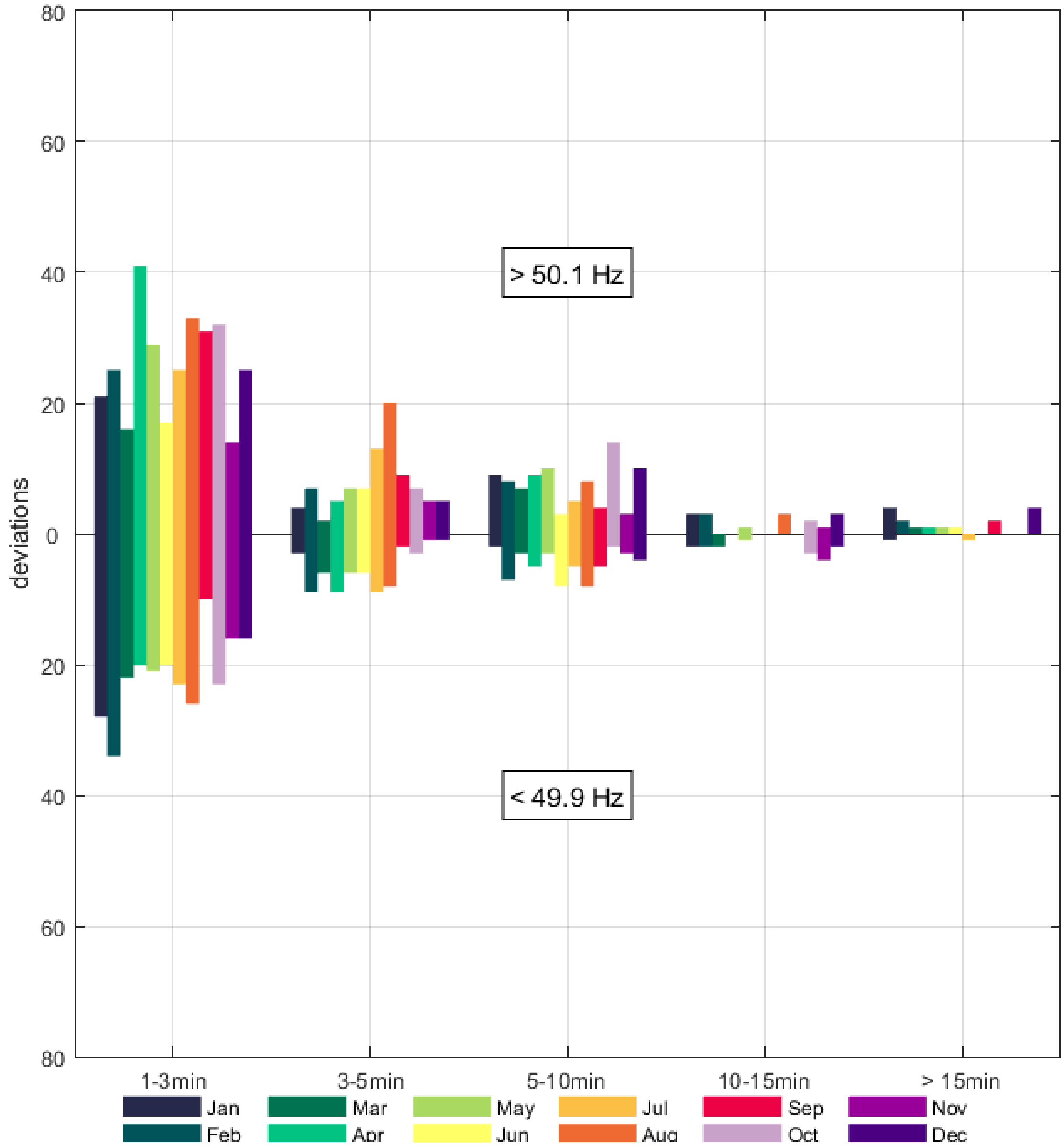
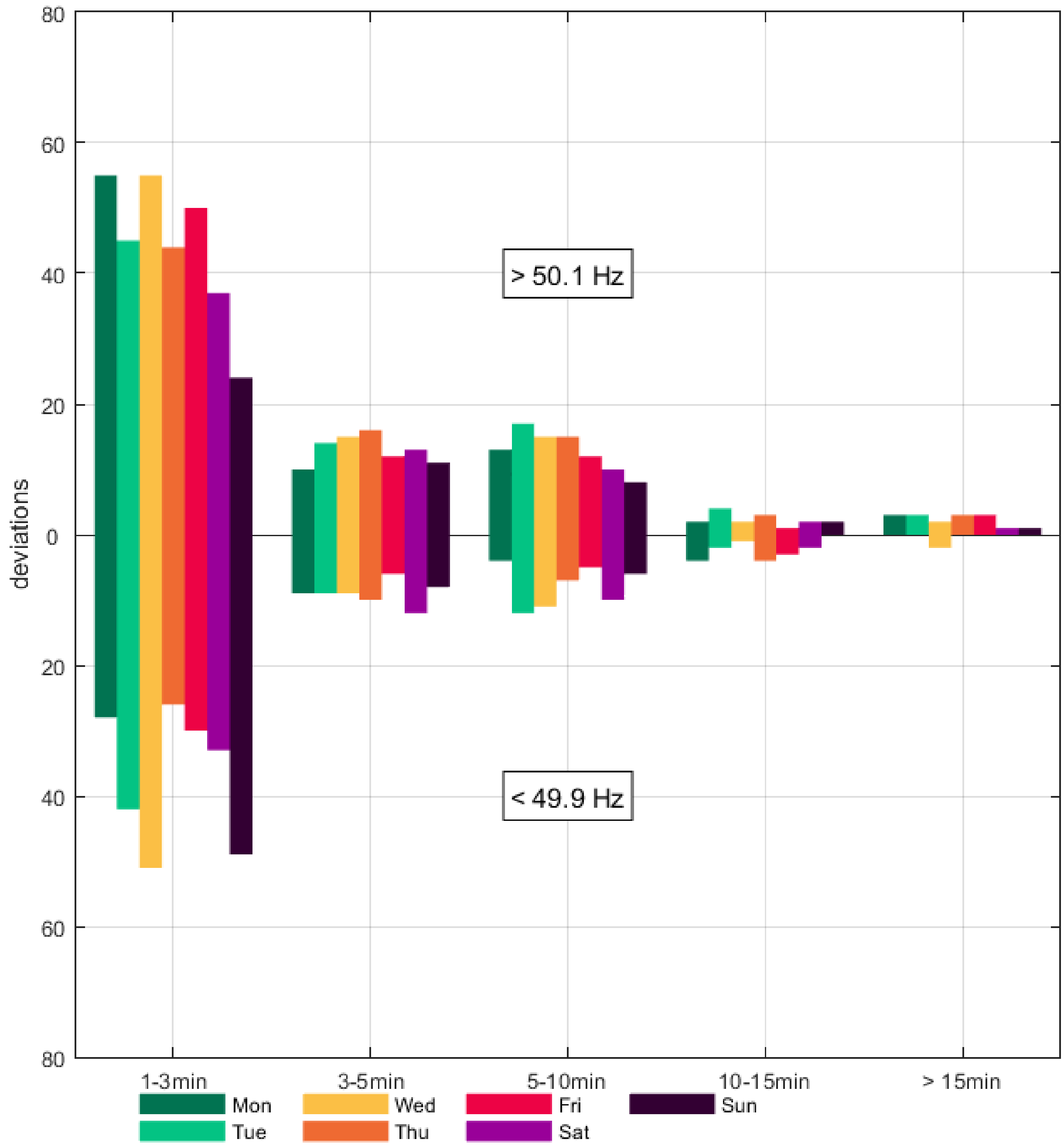


Figure 3.41 represents the number of deviations with different durations during every day of the week in 2022. Compared with 2021, the number of over frequency deviations associated with the end of the week has dropped considerably.

Figure 3.41**. **Total number of longer frequency deviations per duration for each day of the week in 2022



Figures 3.42 and 3.43 illustrate the number and distribution of longer frequency deviations inside the day. Most deviations over the standard frequency range occurred around the midnight. Also, hour 9 pm had significant amount of longer over frequency deviations. With under frequency deviations, hours 1 am to 2 am and hour 7 am had most deviations.

***Figure 3.42**. Total number of longer frequency deviations per duration for hours 0-11 in 2022*

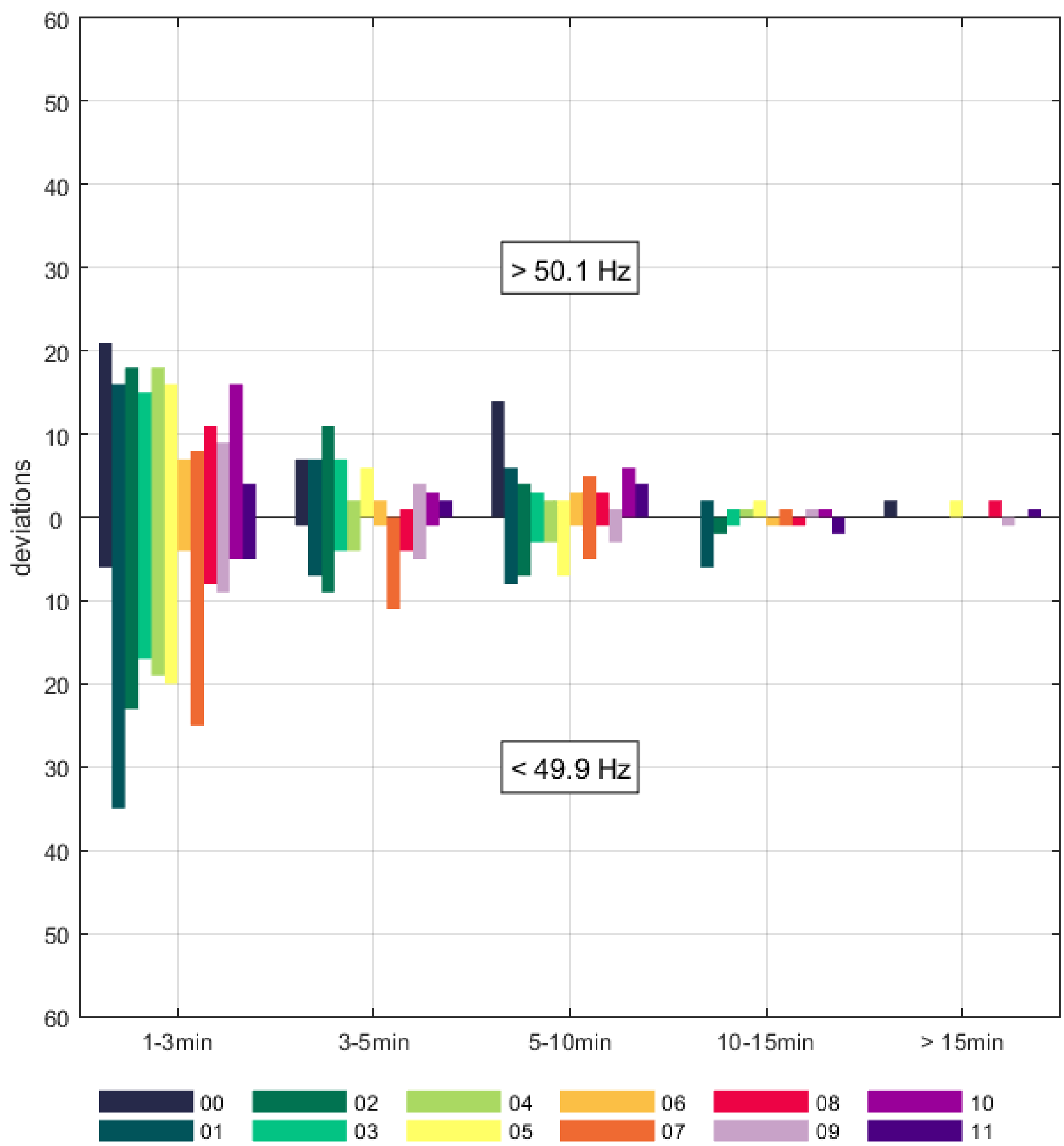
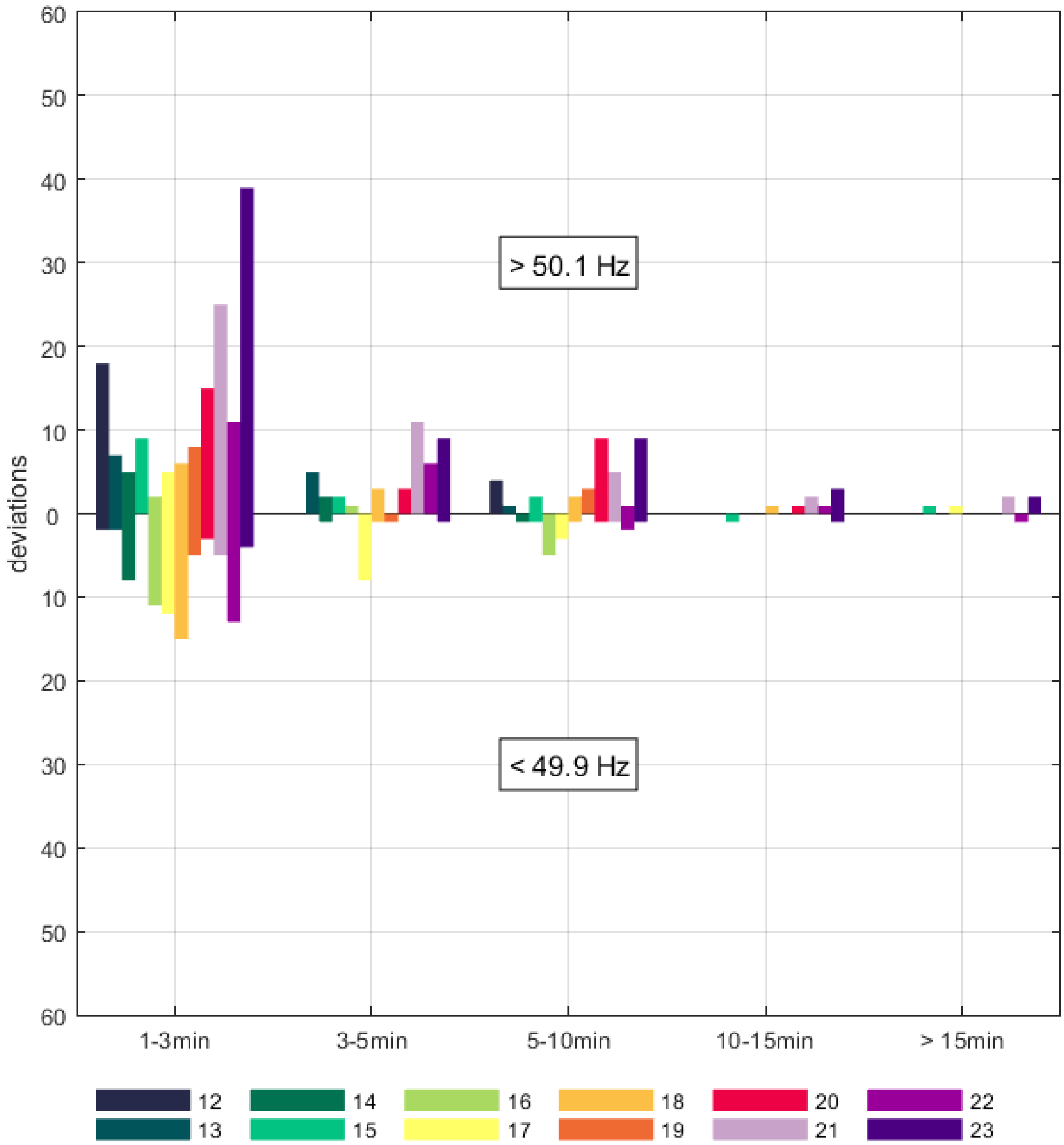


***Figure 3.43**. Total number of longer frequency deviations per duration for hours 12-23 in 2022*



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 on how many times per given time period Frequency Containment Reserve for Disturbances (FCR-D) is activated. The crossings are calculated separately for the number of occasions the frequency goes over and under the frequency range. The resolution of the frequency is one second.

3.6.1 Number of 49.9-50.1 Hz crossings

Figure 3.44 shows the daily average numbers of threshold crossings from 2017 to 2022. Year 2022 had the second lowest number of crossings right after year 2020. Every year there have been slightly 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 frequency data used in threshold crossing calculation is lower and thus can not detect all crossings.

***Figure 3.44**. Daily average number of threshold crossings for years 2017-2022*

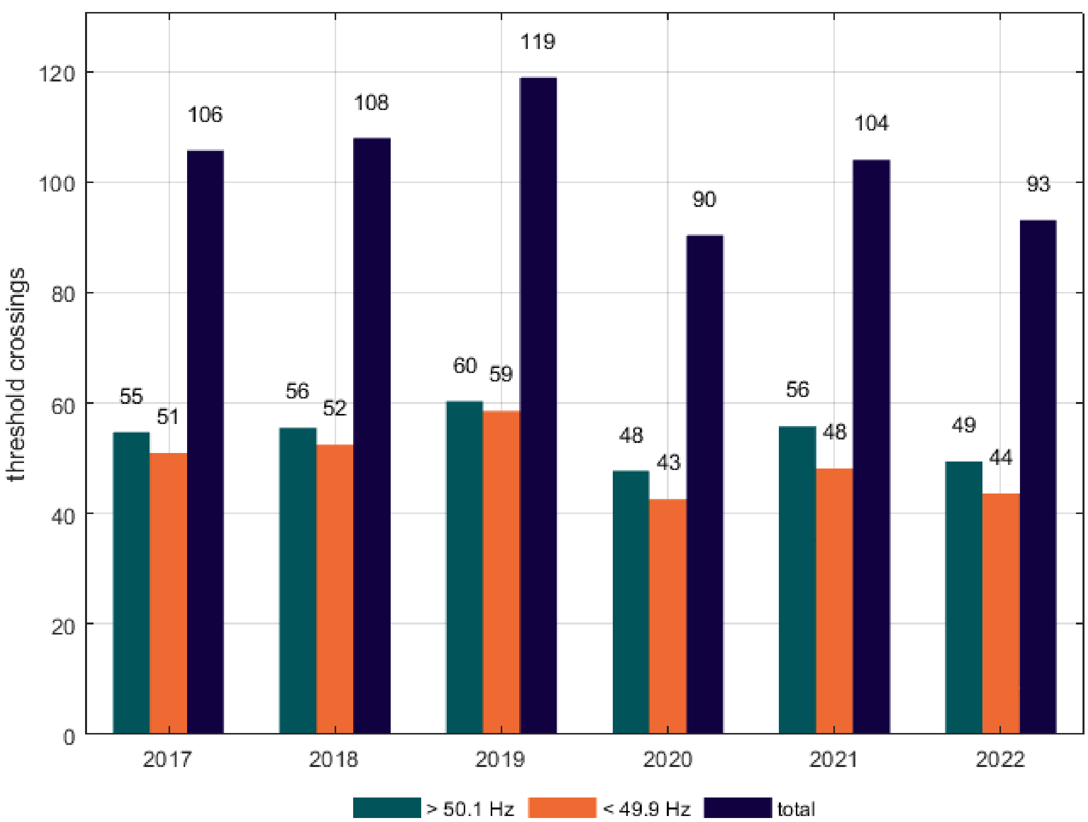


Figure 3.45 represents the daily average number of threshold crossings for each month in 2022. The frequency crossed the threshold most often in May, August and October. November and December had the smallest number of threshold crossings.

***Figure 3.45**. Daily average number of threshold crossings for every month in 2022*

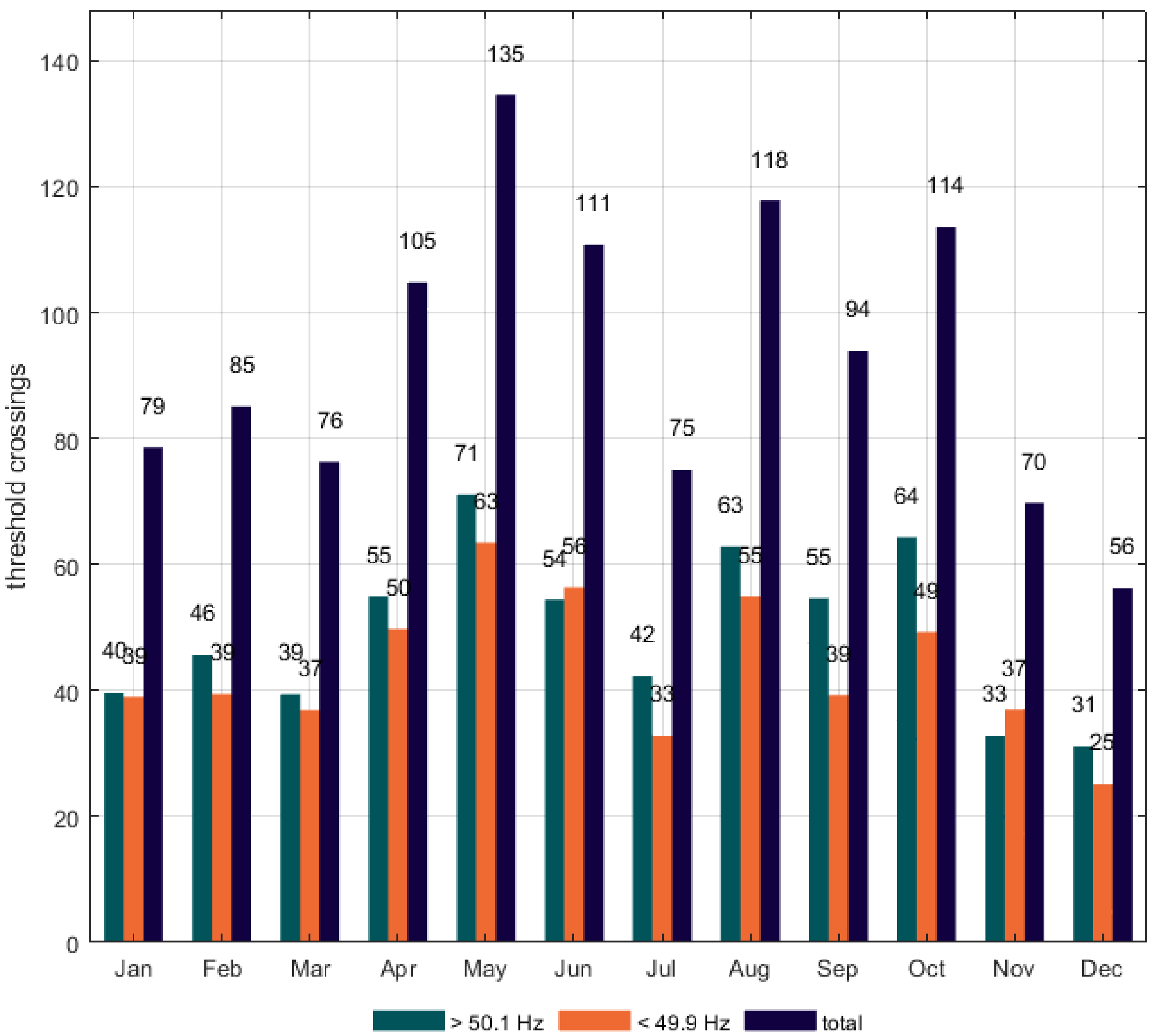
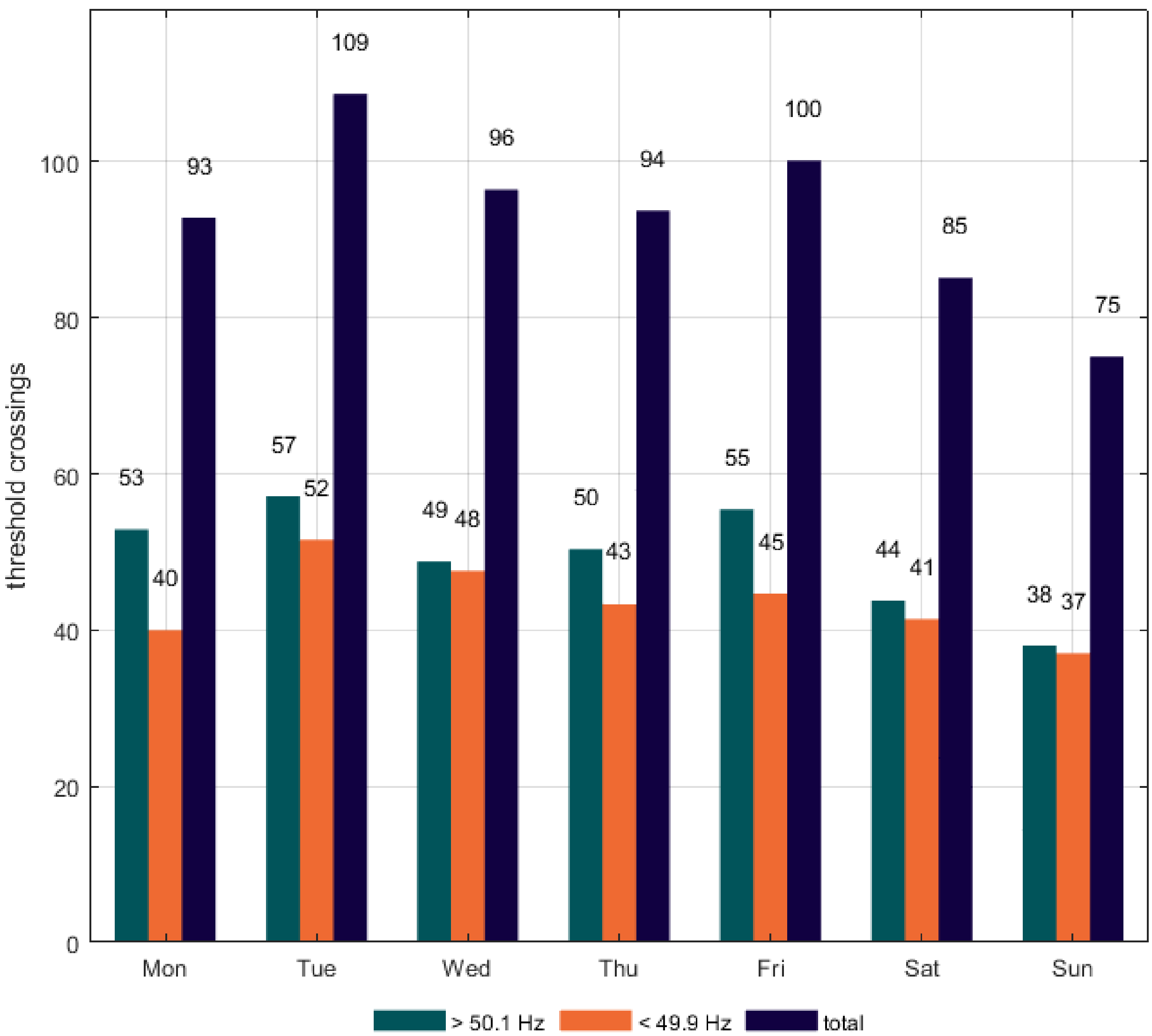


Figure 3.46 shows the number of threshold crossings for each day of the week in 2022.The number of crossings has been highest on Tuesdays and lowest on Sundays.

***Figure 3.46**. Daily average number of threshold crossings for every day of the week in 2022*



The hourly number of threshold crossings inside an average day is presented in Figure 3.47. The smallest number of threshold crossings occurred at 2 pm. The most crossings were experienced at 7 am. Compared with the year 2021, the number of threshold crossings decreased substantially around the noon.

***Figure 3.47**. Average number of threshold crossings for every hour of the day in 2022*

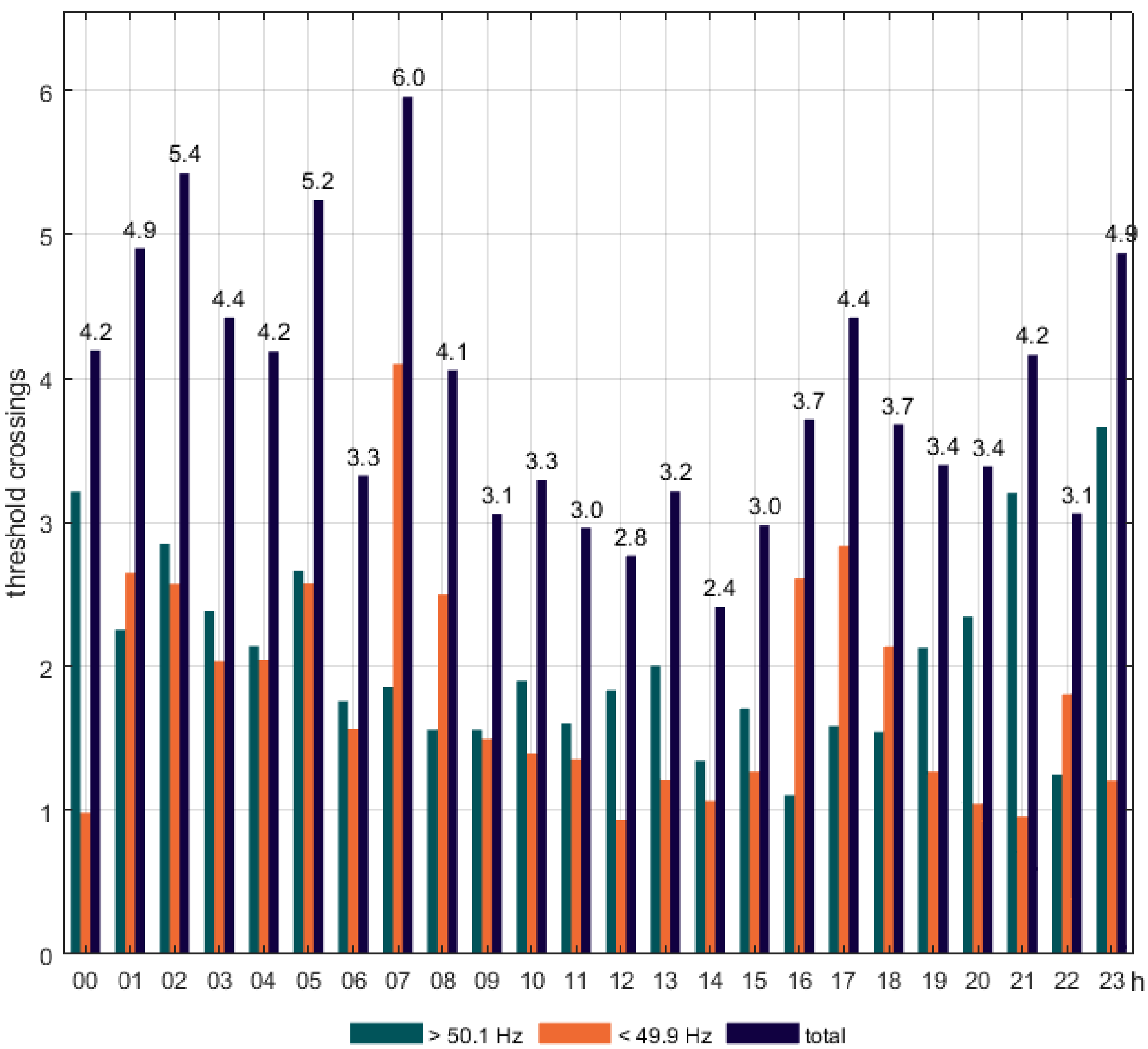
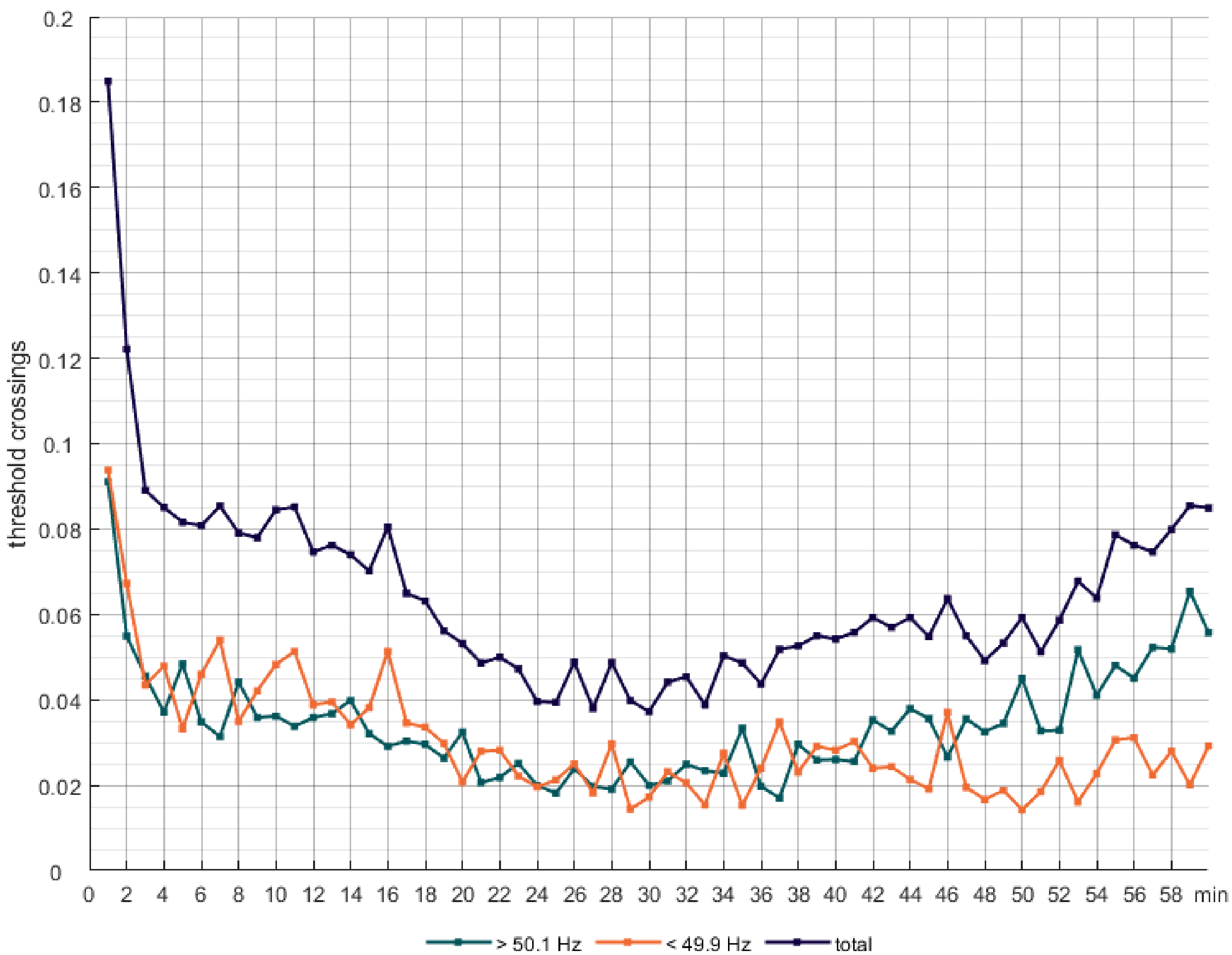


Figure 3.48 represents the average number of threshold crossings for every minute inside the hour. Most crossings occurred in the first minutes of the hour. During the first 30 minutes of the hour, the frequency crossed 51.1 Hz almost as often as 49.9 Hz, whereas more crossings of 50.1 Hz took place in the latter part of the hour.

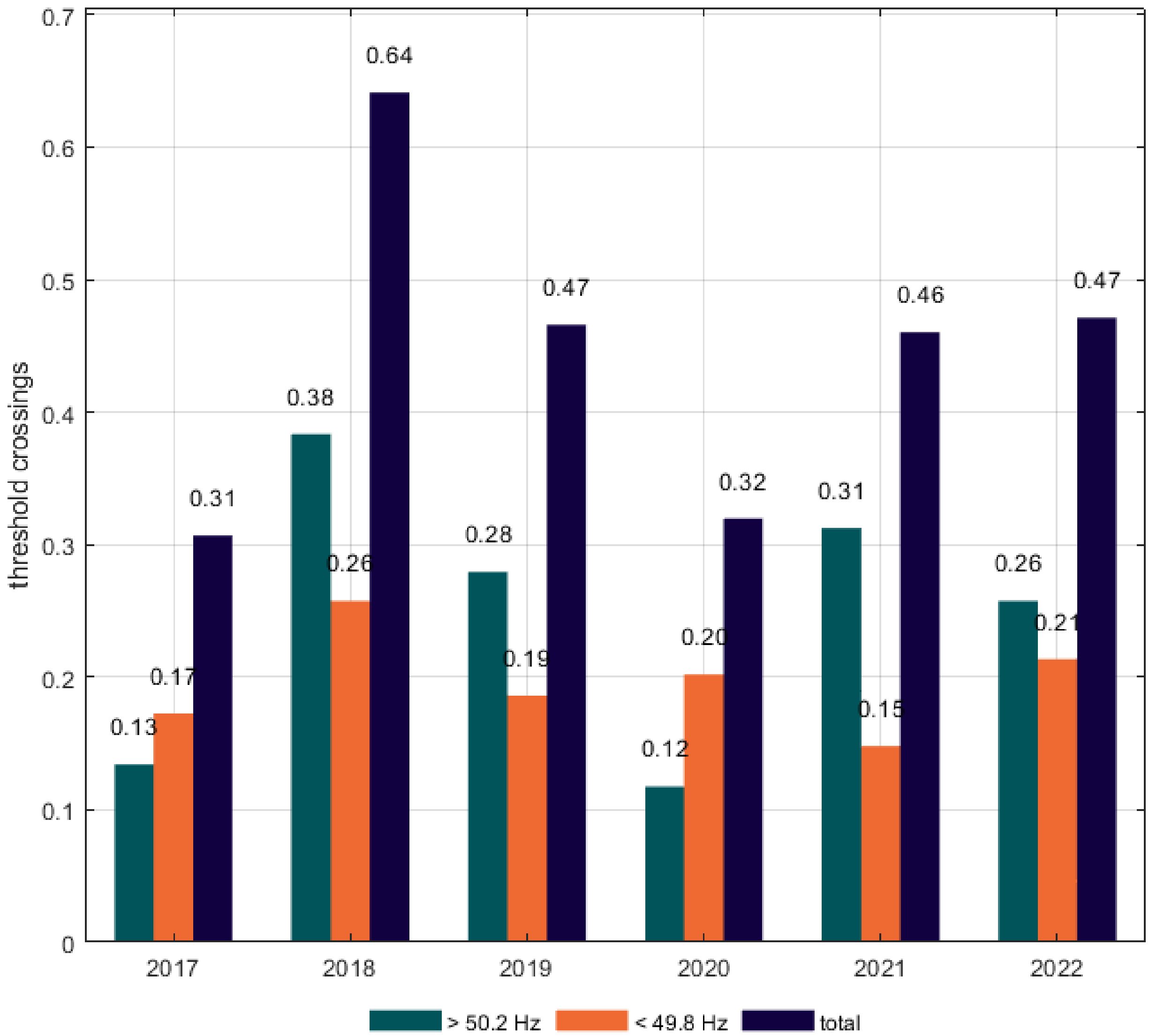
***Figure 3.48**. Average number of threshold crossings for every minute of the hour in 2022*



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 2022, the total number of crossings were at the same level as previous year.

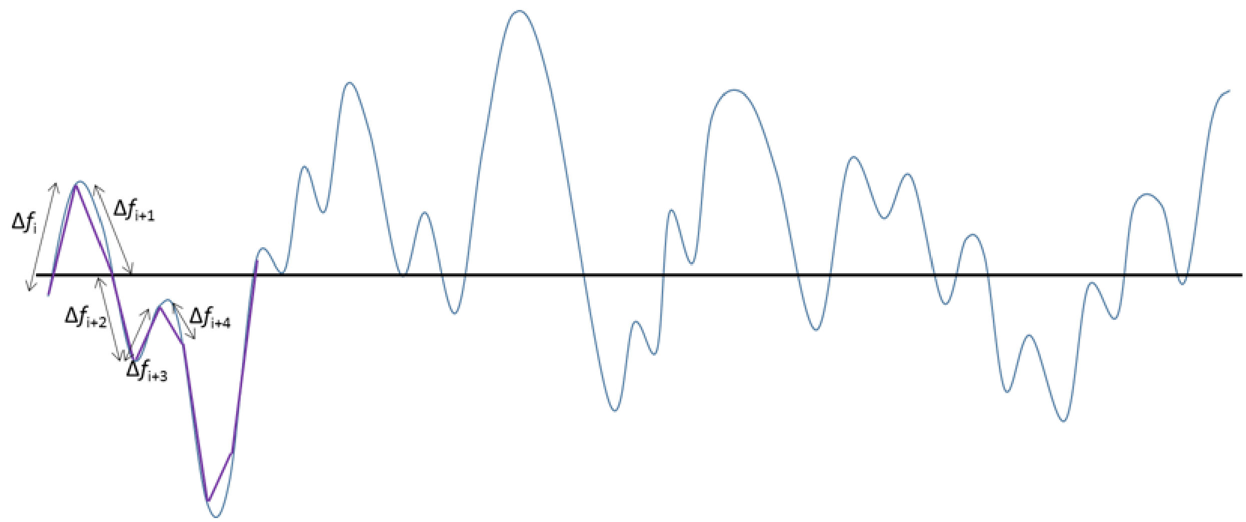
***Figure 3.49**. Daily average number of threshold crossings larger than ±200 mHz for years 2017-2022*



3.7 Length of frequency path

The length of the path that frequency takes shows how much the frequency travels around the 50.0 Hz, as can be seen from 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).

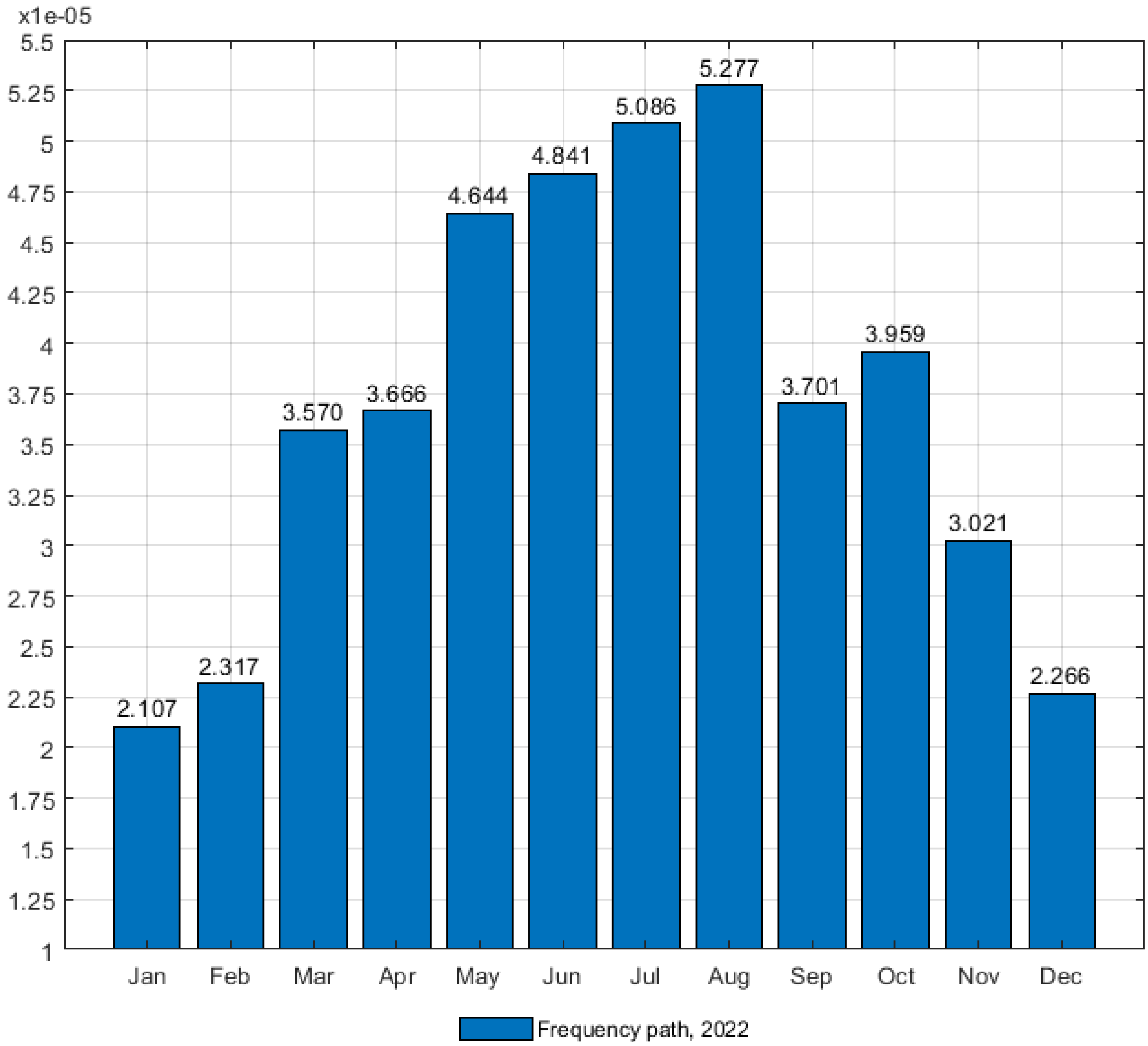
Figure 3.50**. **Frequency quality index: Length of the frequency path [7]



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

Figure 3.51 represents the frequency path for each month in 2022. The path length has steadily increased from January to August. In August the frequency path achieves its peak value, after which it starts to reduce towards the end of the year. The peak value of frequency path has increased by 76 % since 2021 and the average of frequency path from all months has increased around 39 %.

***Figure 3.51**. Length of the frequency path month by month in 2022*



The frequency path for every day of the week shows 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 between Wednesday and Friday. The peak of frequency path length occurred on Monday.

***Figure 3.52**. Length of the frequency path for every day of the week in 2022*

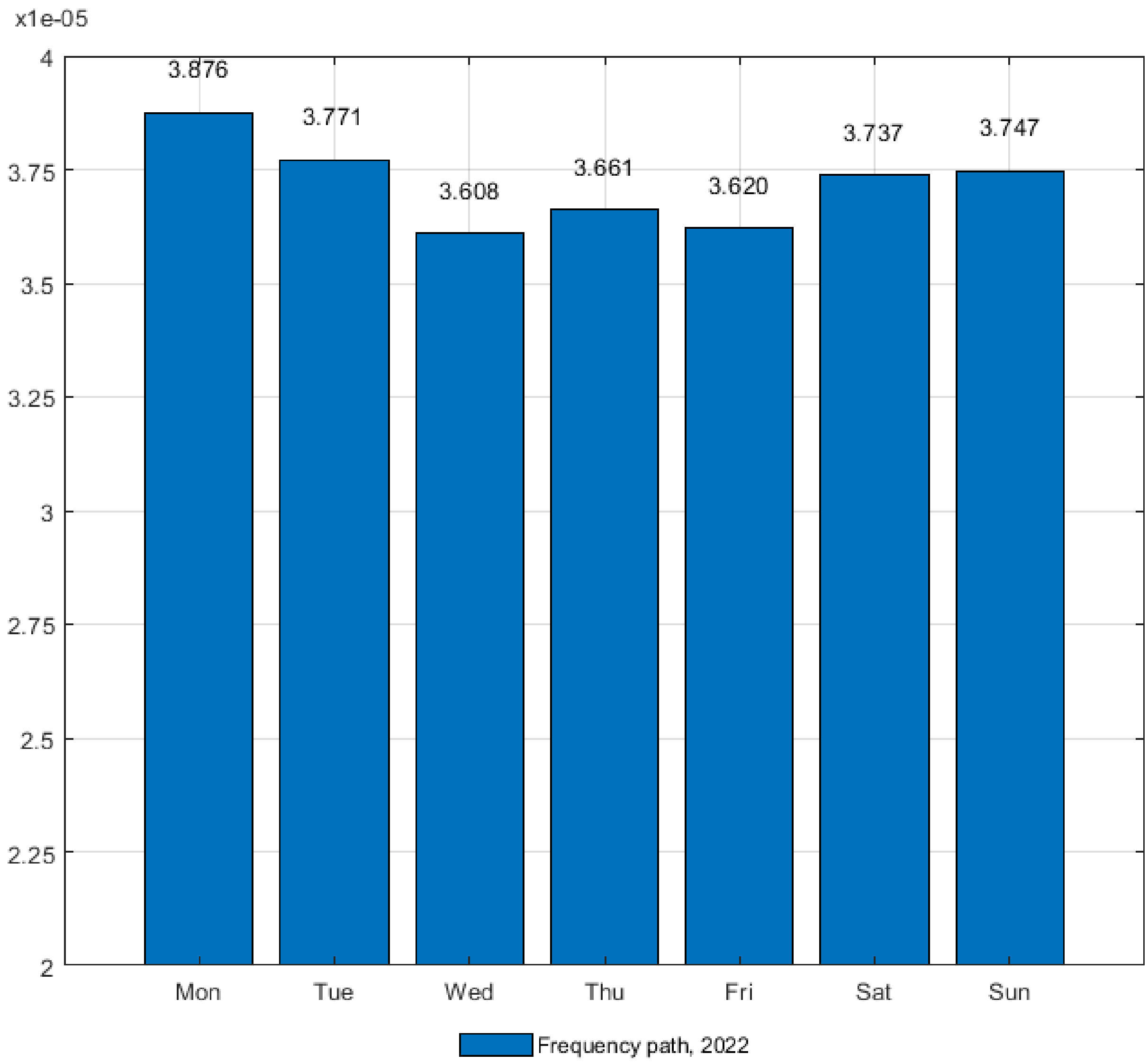


Figure 3.53 shows the frequency path during the day. Compared with the years 2017-2021, the deviation in the length of the frequency path between different hours of the day has increased significantly.

Figure 3.53*. *Length of the frequency path for every hour of the day in 2022

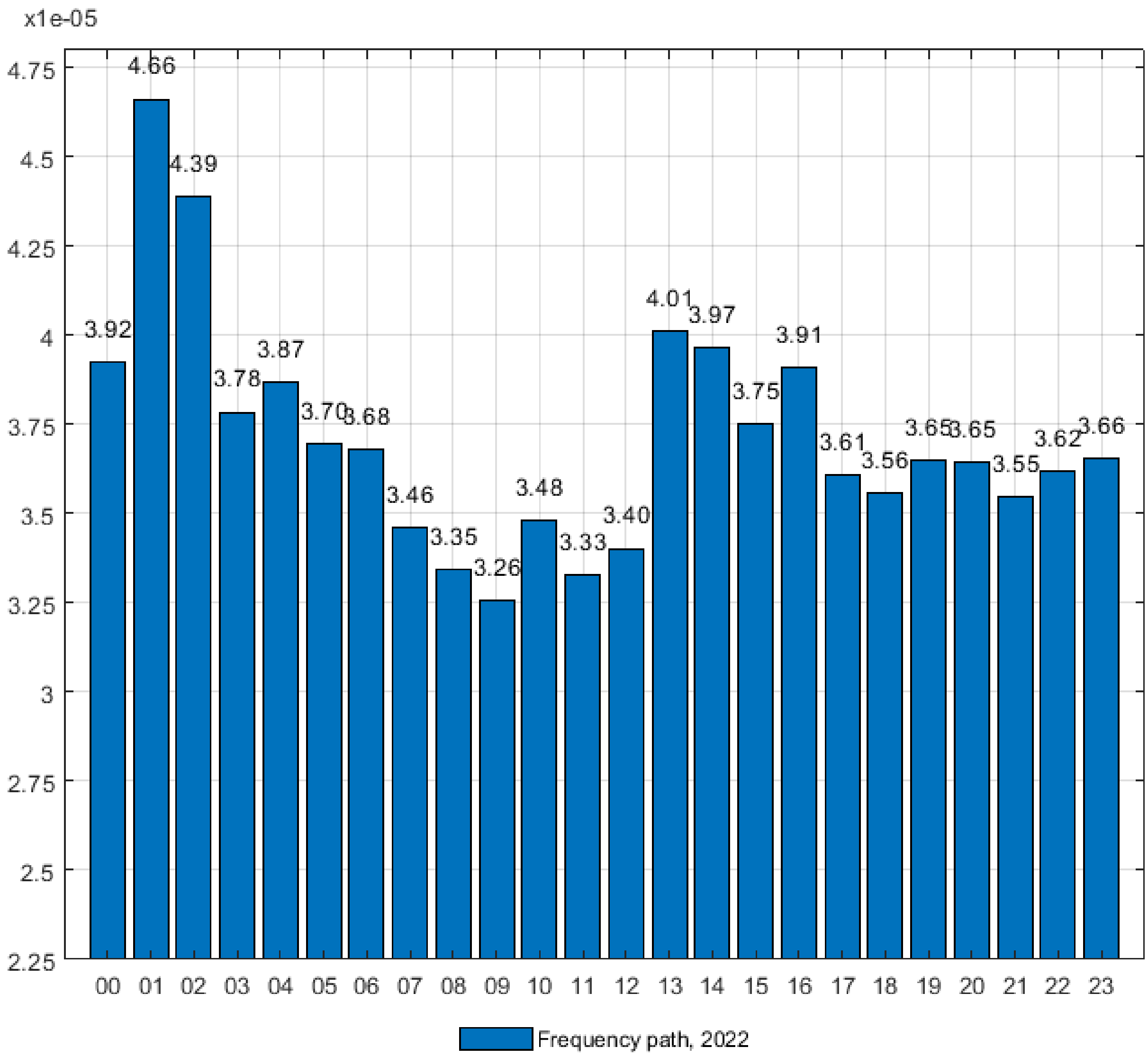
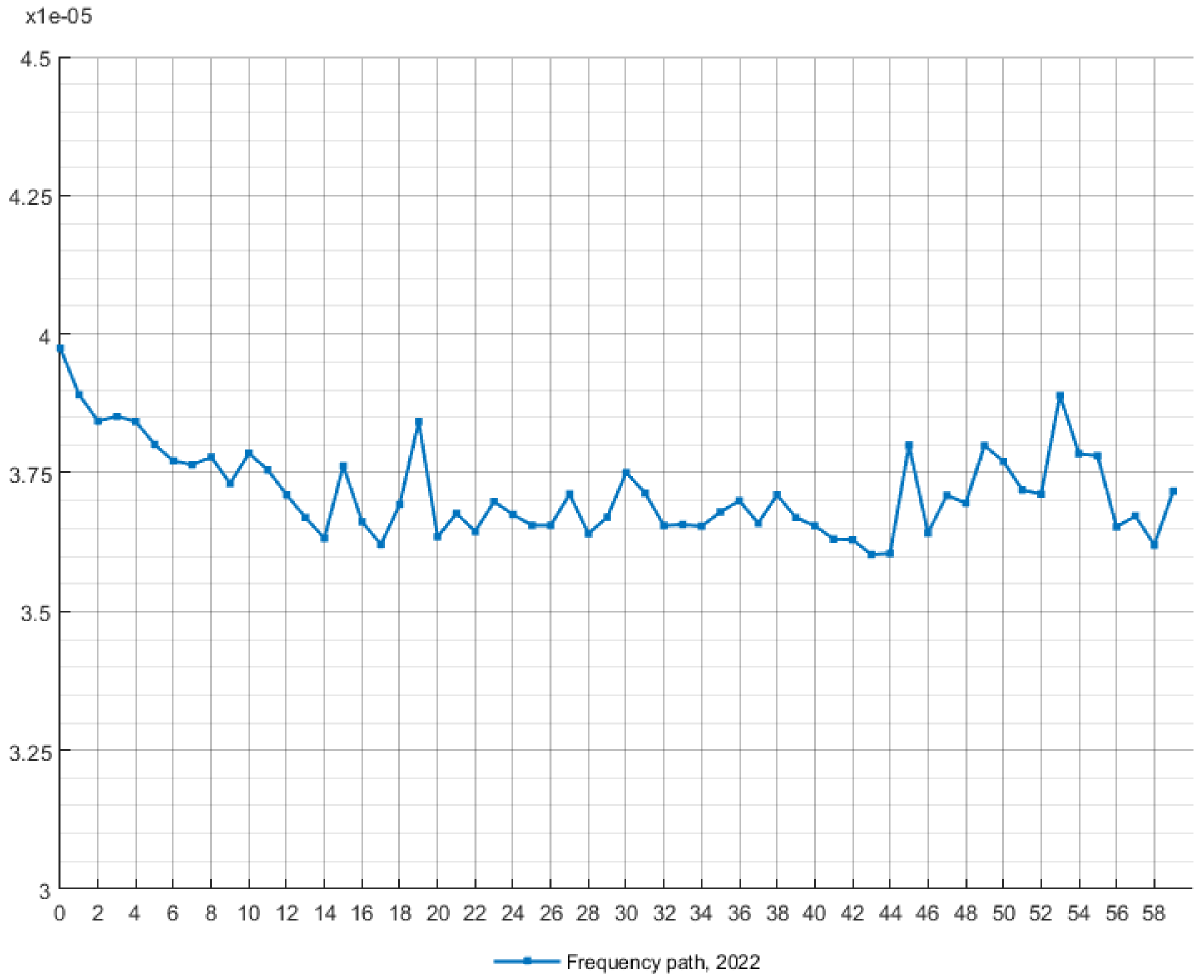


Figure 3.54 represents the average frequency path for every minute inside the hour. The amount of variation inside the hour has increased while comparing the year 2022 with the years 2017-2021, although all of the years peak within the hour shift.

***Figure 3.54**. Length of the frequency path for every minute of the hour in 2022*



3.8 Amount of frequency oscillation

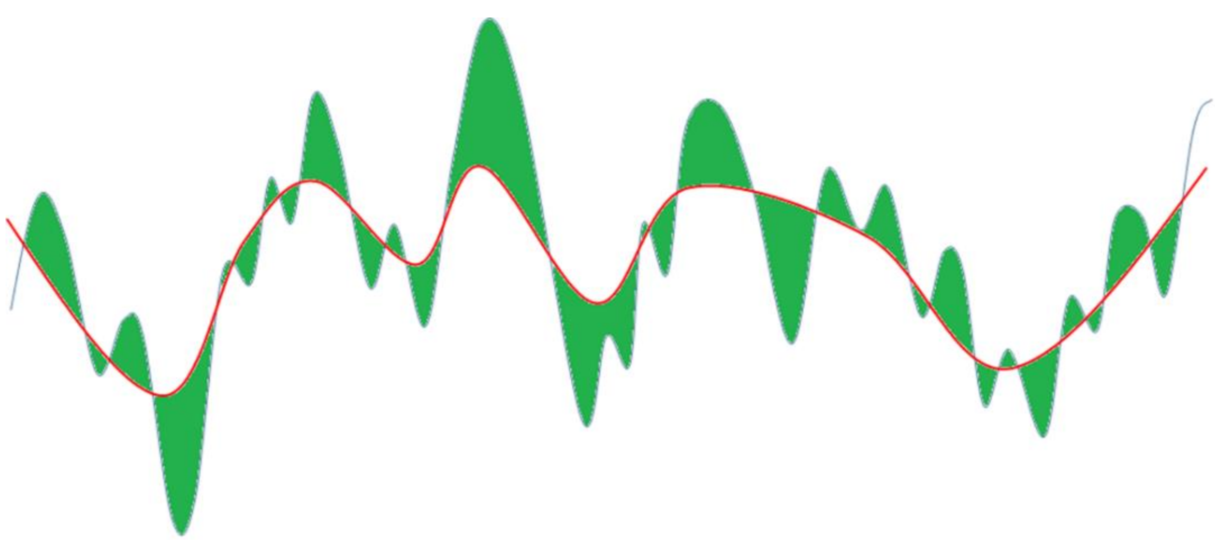
Frequency of the Nordic synchronous system oscillates constantly. Time period of the oscillation is approximately 40 to 90 seconds. This behavior is a natural characteristic of the system but it can be influenced through adequate settings of system reserves. Oscillation has an increasing effect on the 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 Fourier transform which can be used to decompose time series signals such as frequency measurements into sinusoidal frequency components. In other words, 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 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. Area between the filtered frequency signal and the original signal is used to represent the amount of oscillation. The approach is shown in Figure 3.55.

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



Filtering band used in all studies was 30-240 s. Choice is based on comparison between different bands in the 2011 and 2012 oscillation analysis [8]. 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, Fourier transform was calculated for time intervals of one hour. The actually 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 measurement frequency had to stay at least at 4 Hz. If these requirements were not fulfilled that hour was skipped and removed from the calculations.

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

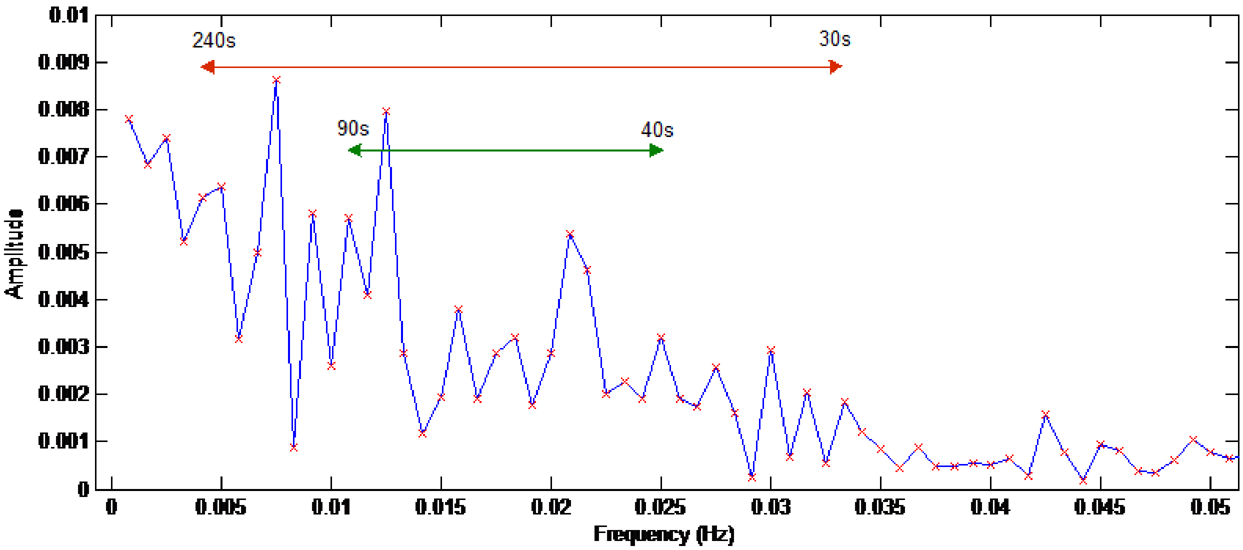
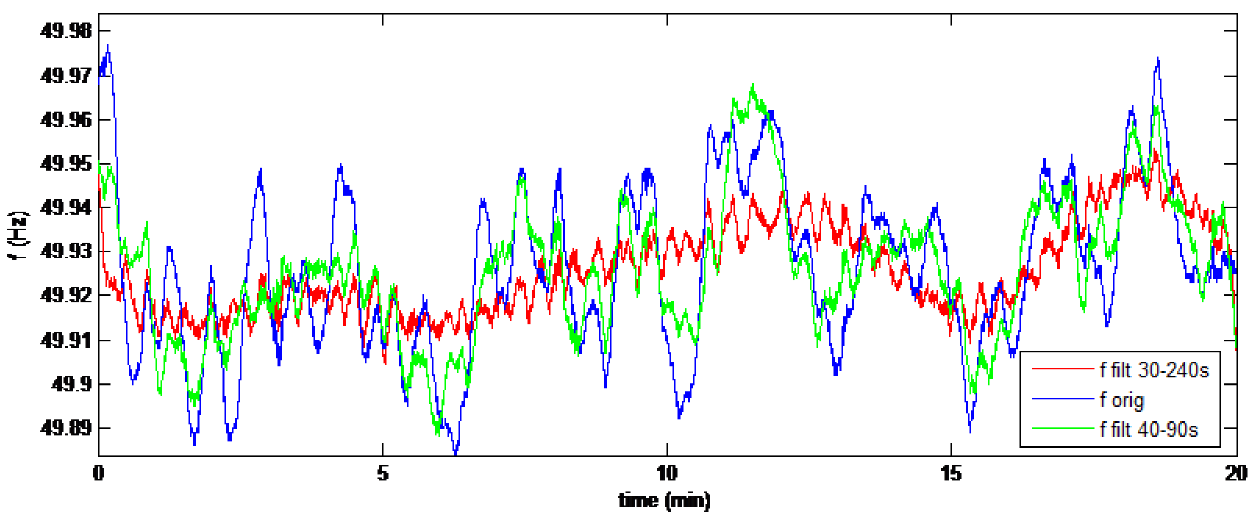


Figure 3.57. Original frequency (blue), frequency with 40-90 s band filtered (green) and frequency with 30-240 s band filtered (red). First 20 minutes of December 2012 are shown (UTC+2) [8]



3.8.2 Amount of oscillation

Figure 3.58 shows hourly values and 24 hour moving averages for the amount of oscillation in 2022. The 24 hour moving averages were calculated if there was enough eligible data for at least 12 hours in the frame of 24 hours.

Gaps in the following curves indicate that there were not enough eligible data for the calculations.

The 24 h moving average had the highest values in the beginning of October. Compared with the year 2021, the amount of oscillation remained on steadier level between different months in 2022. The amount of frequency oscillation has increased substantially from the previous years.

Figures 3.59 and 3.60 contain the previously mentioned 24 hour moving averages for years 2017-2019 and 2020-2022, respectively. In calculations of years 2017-2022, 12 hours of eligible data was required.

Figure 3.58. Amount of oscillation in 2022

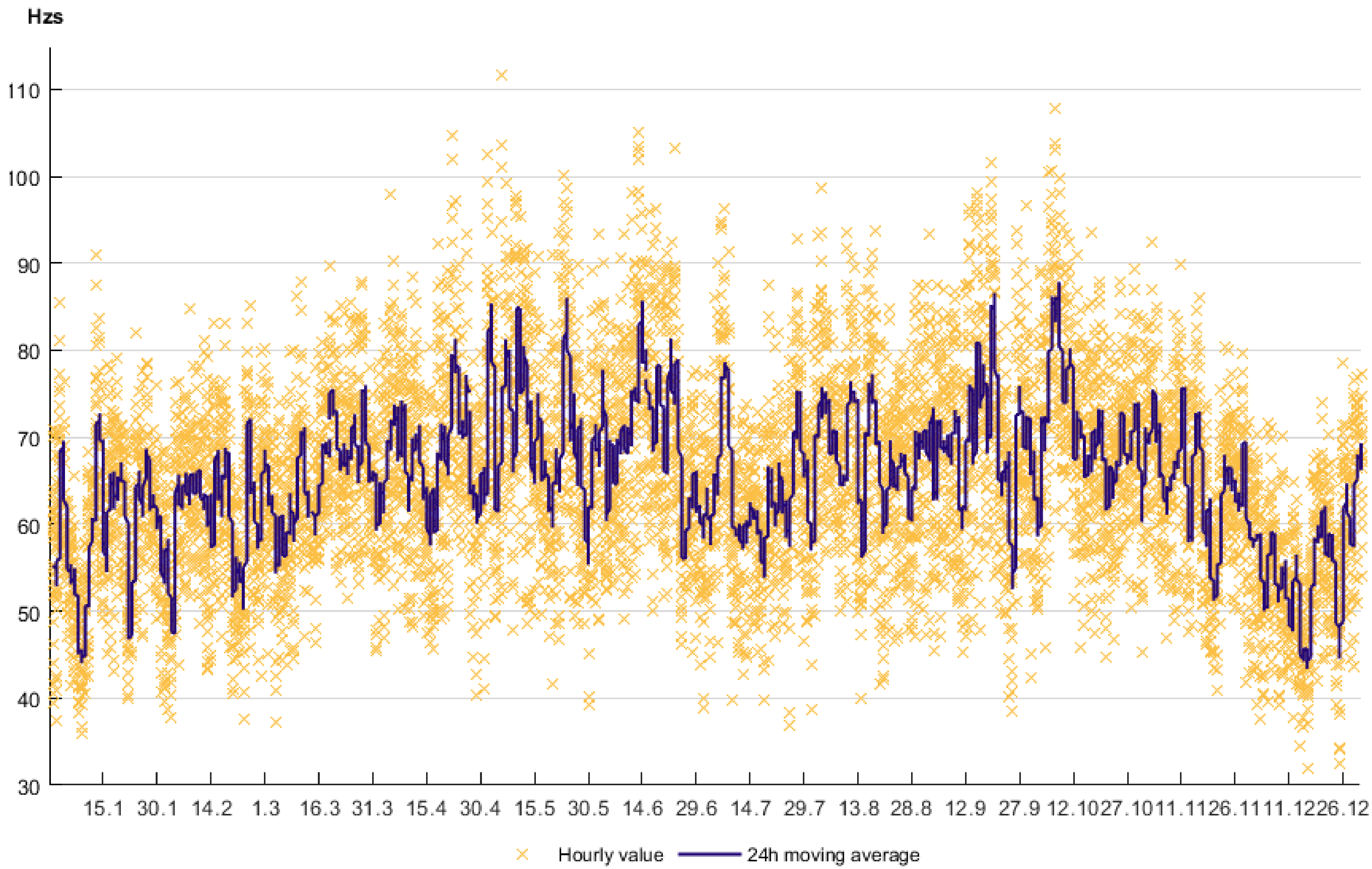


Figure 3.59. Amount of oscillation in 2017-2019

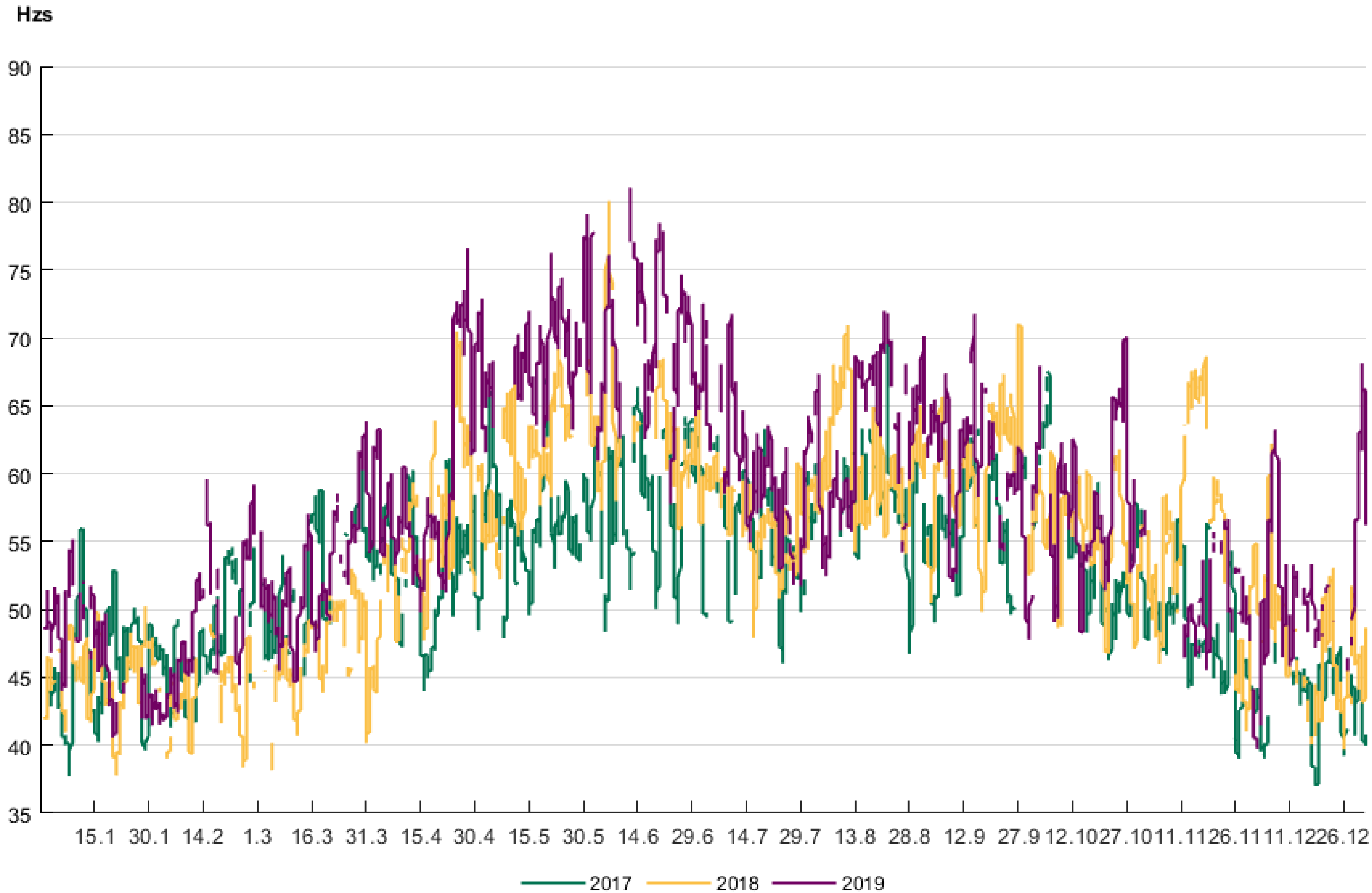
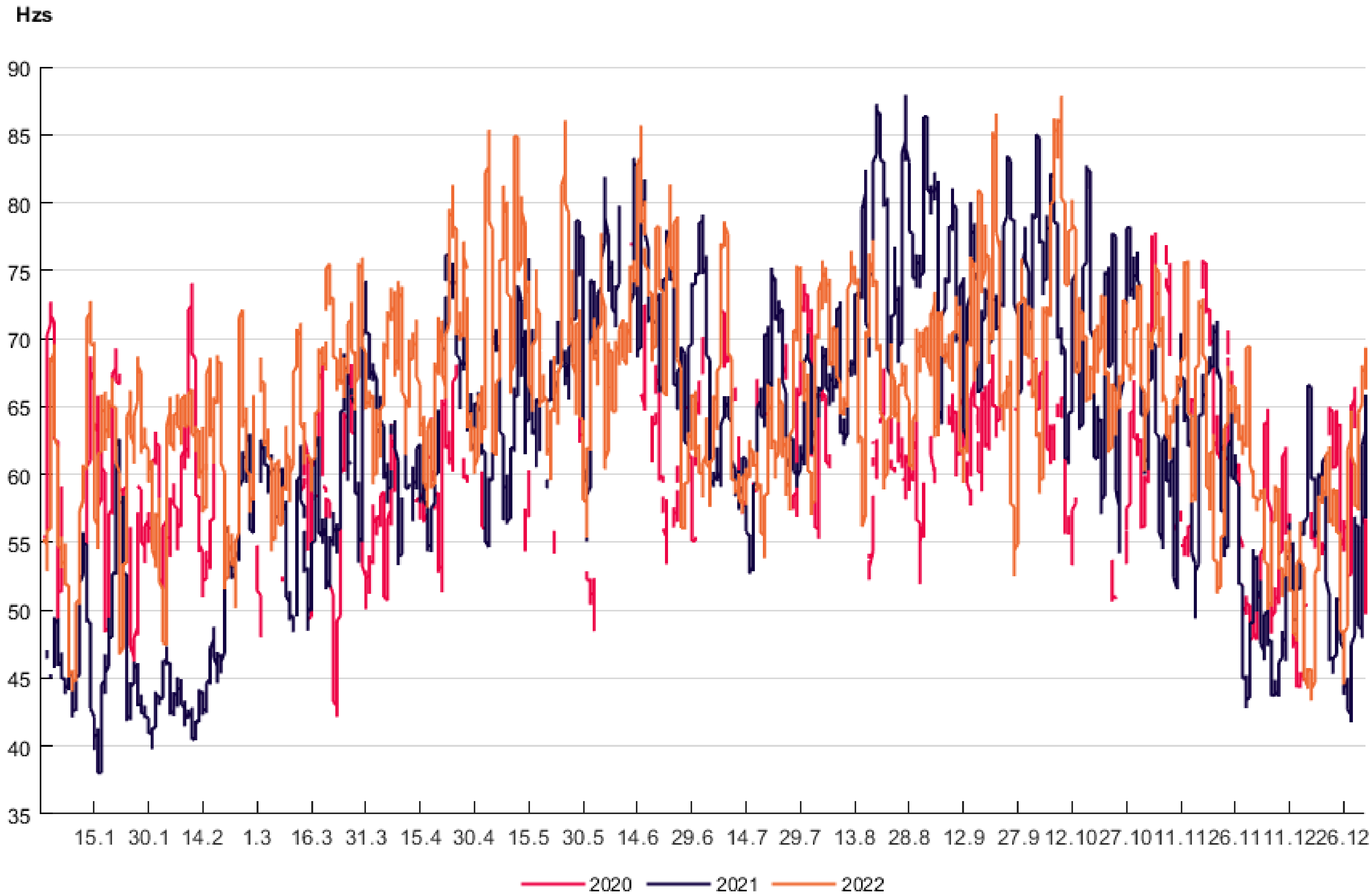


Figure 3.60. Amount of oscillation in 2020-2022



Mean value of the oscillation and standard deviation for each month from 2017 to 2022 are shown in Table 3.22 and 3.23. Figure 3.61 represents the same information in a visual form. The frequency oscillated the most in May and October. Frequency oscillated significantly more in 2022 in comparison with the previous years. The last three years have been among the worst years in terms of oscillation.

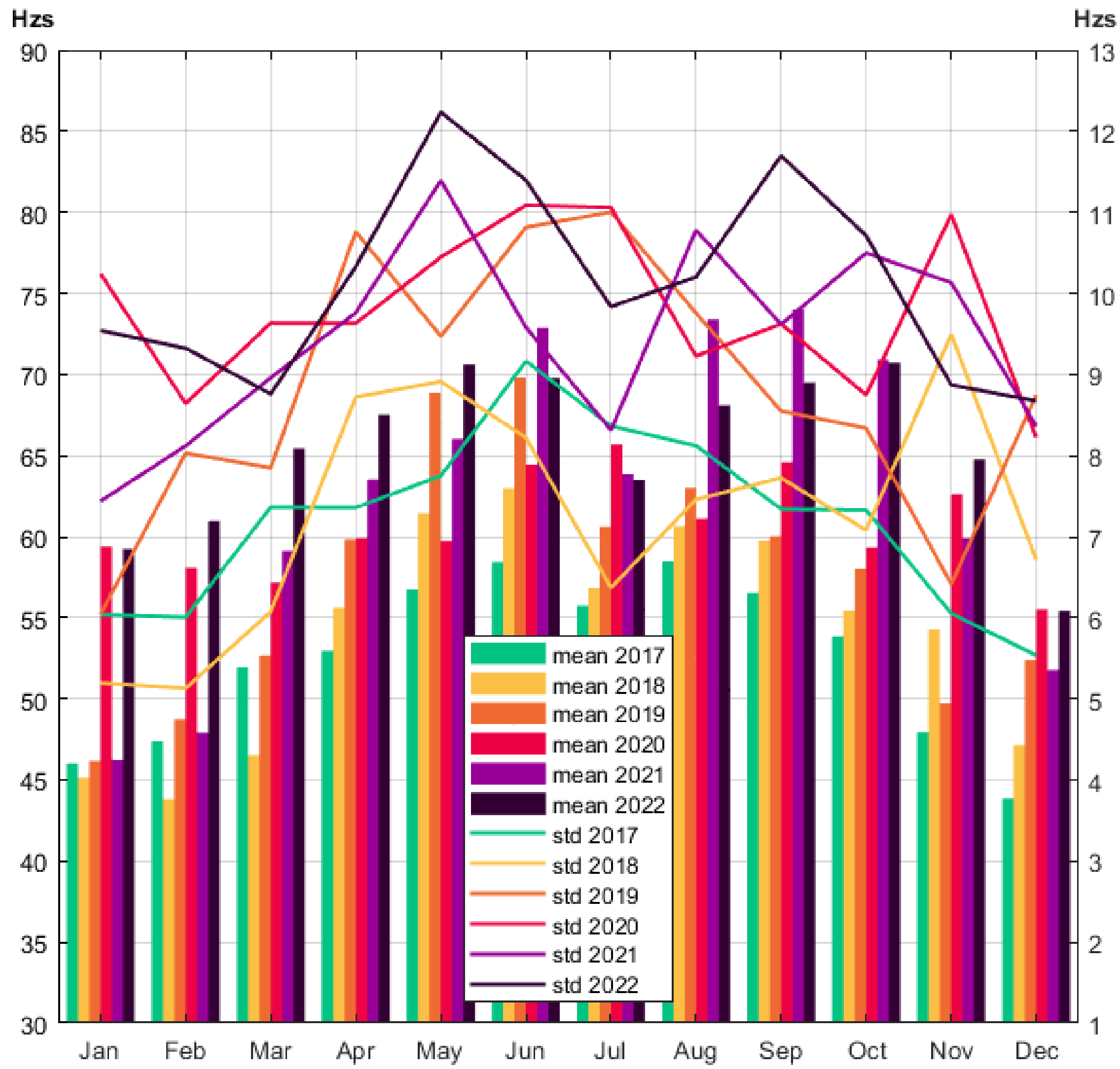
Table 3.22. Mean values and standard deviations for oscillation in years 2017-2019

	Mean value (Hzs)			**Standard deviation (Hzs)**		
Month	**2017**	**2018**	**2019**	**2017**	**2018**	**2019**
January	46.0	45.1	46.2	6.0	5.2	6.0
February	47.4	43.8	48.7	6.0	5.1	8.0
March	52.0	46.5	52.7	7.4	6.1	7.8
April	52.9	55.6	59.8	7.4	8.7	10.8
May	56.8	61.4	68.9	7.7	8.9	9.5
June	58.4	63.0	69.8	9.2	8.2	10.8
July	55.7	56.9	60.6	8.4	6.4	11.0
August	58.5	60.6	63.0	8.1	7.5	9.8
September	56.5	59.8	60.0	7.3	7.7	8.5
October	53.8	55.4	58.0	7.3	7.1	8.3
November	47.9	54.3	49.7	6.1	9.5	6.4
December	43.9	47.1	52.4	5.5	6.7	8.7
Entire year	**52.5**	**54.1**	**57.5**	**7.2**	**7.3**	**8.8**

Table 3.23. Mean values and standard deviations for oscillation in years 2020-2022

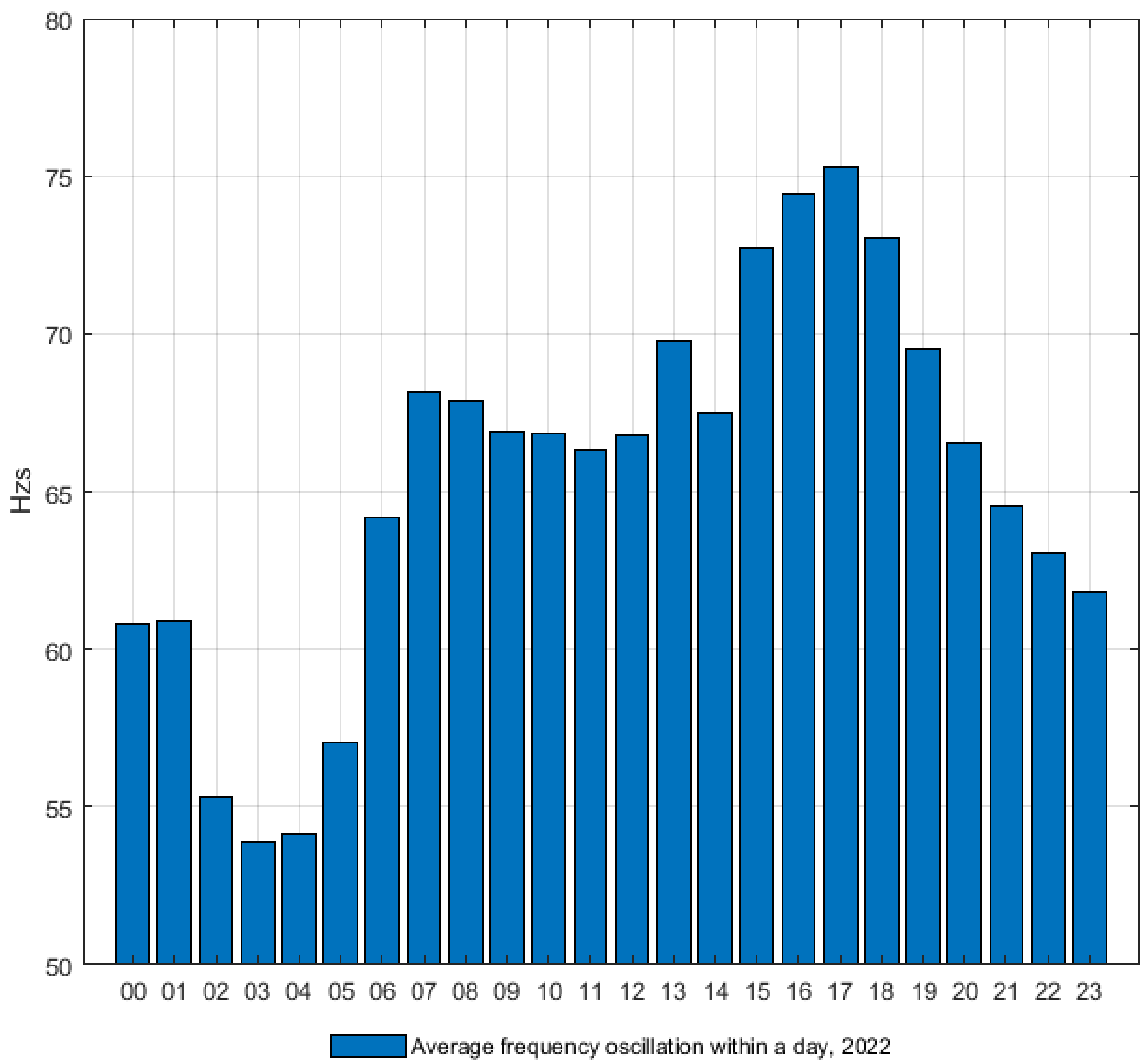
	Mean value (Hzs)			**Standard deviation (Hzs)**		
Month	**2020**	**2021**	**2022**	**2020**	**2021**	**2022**
January	59.4	46.2	59.2	10.2	7.4	9.5
February	58.1	47.9	61.0	8.6	8.1	9.3
March	57.2	59.1	65.4	9.6	9.0	8.8
April	59.9	63.5	67.5	9.6	9.8	10.3
May	59.7	66.0	70.6	10.4	11.4	12.2
June	64.4	72.9	69.8	11.1	9.6	11.4
July	65.7	63.9	63.5	11.1	8.3	9.8
August	61.1	73.4	68.1	9.2	10.8	10.2
September	64.6	74.0	69.5	9.6	9.6	11.7
October	59.3	70.9	70.7	8.7	10.5	10.7
November	62.6	59.9	64.8	11.0	10.1	8.9
December	55.5	51.8	55.4	8.2	8.4	8.7
Entire year	**60.6**	**62.5**	**65.5**	**9.8**	**9.4**	**10.1**

***Figure 3.61**. Mean values (left y-axis) and standard deviations (right y-axis) for oscillation in years 2017-2022*



Average oscillation within a day in 2022 can be seen in fig 3.62. The amount of oscillation has peaked in the late afternoon. Least oscillation was experienced in the night from 2 am to 5 am. Although the total amount of oscillation has increased substantially from the years 2018-2021, the pattern which the bars form, has stayed close to the same during the past years.

Figure 3.62*. *Average frequency oscillation within a day in 2022

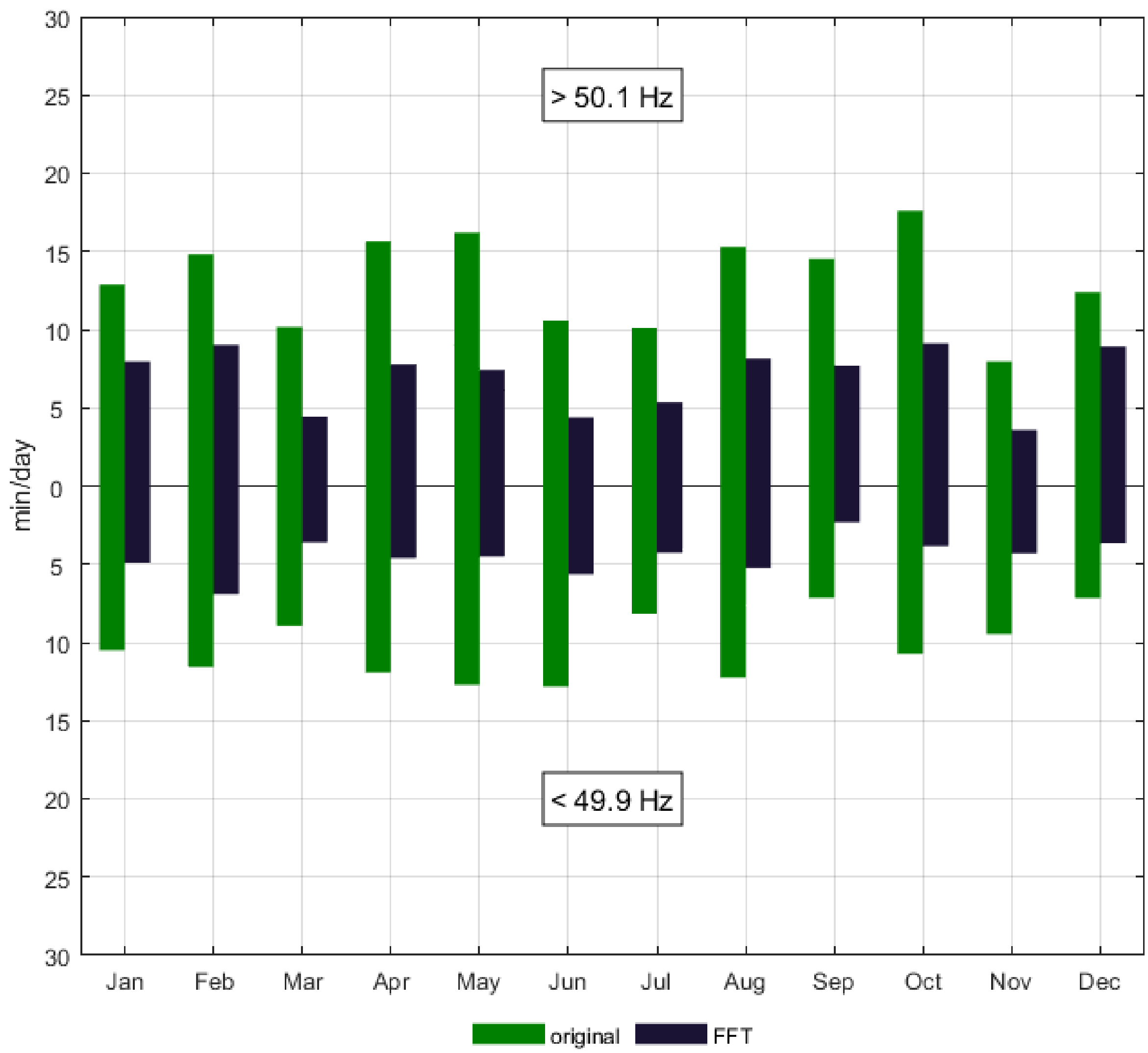


3.8.3 Influence of oscillation on frequency variations

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 2022 without filtering and after applying FFT-filtering. Figure 3.63 shows the average only for minutes per day outside the standard frequency range that had enough consecutive samples for one hour periods for the FFT-algorithm.

***Figure 3.63*. Average time per day outside the standard frequency range in 2022**



In Figure 3.64, the reduction of time outside the standard frequency range through filtering is presented as percentages of the original values. The results show that filtering leads to significant reduction in time outside the standard frequency range. For September, the reduction of time outside the standard frequency range is over 65 % with under frequencies. Compared with the years 2020-2021, the total reduction in time outside the standard frequency range has stayed inside narrower range.

***Figure 3.64*. Reduction in time per month outside the standard frequency range after filtering in 2022**

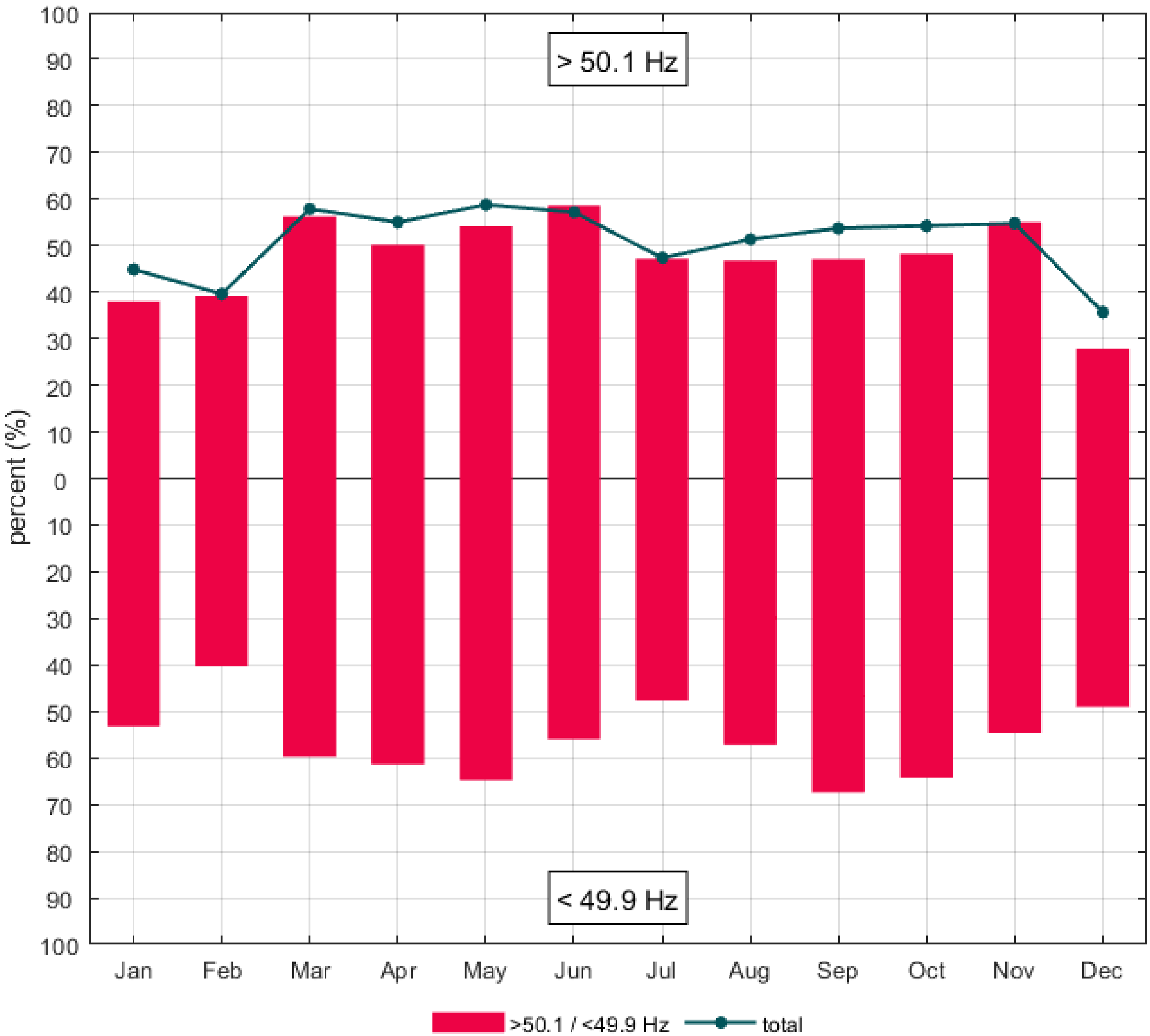
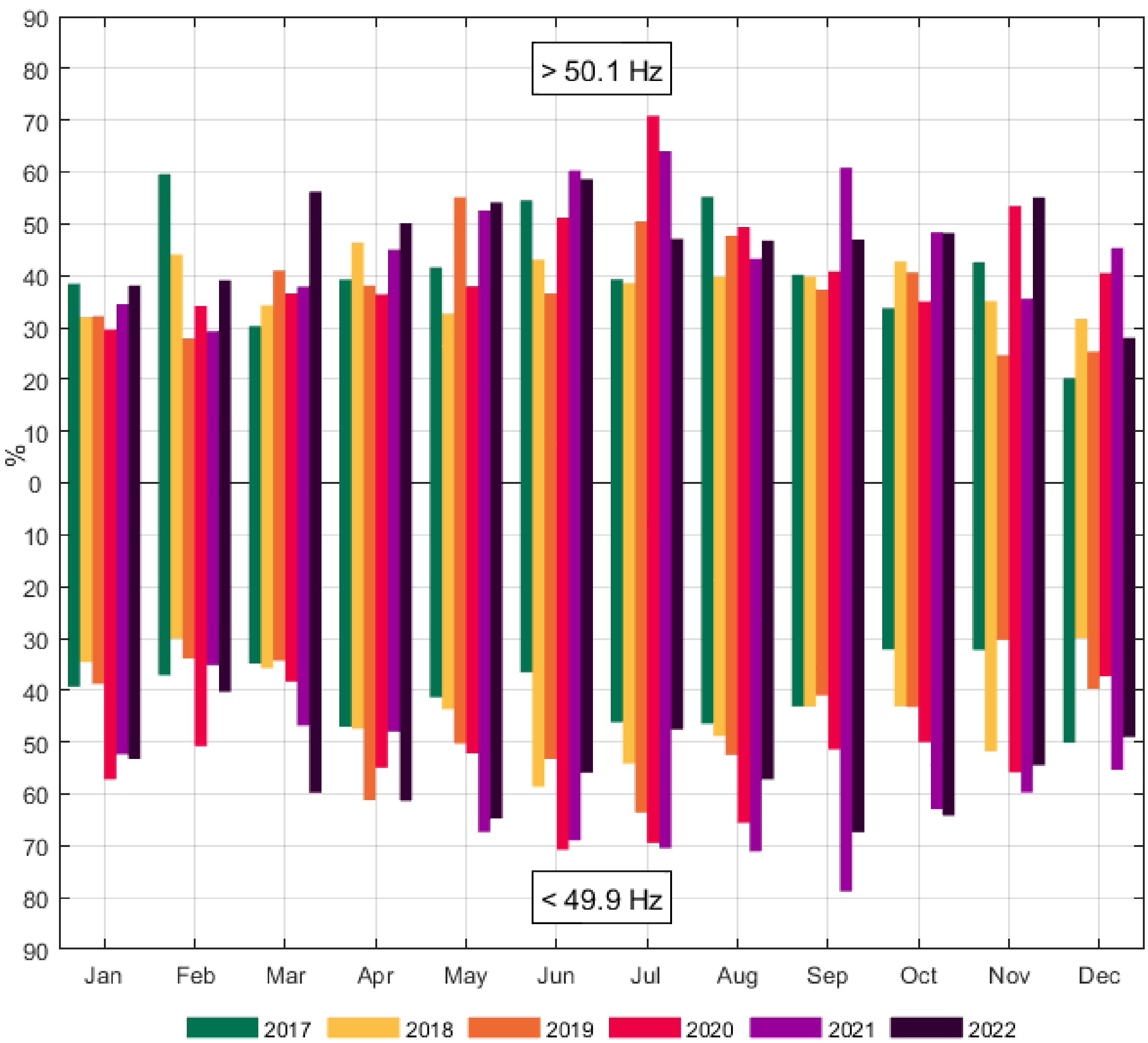


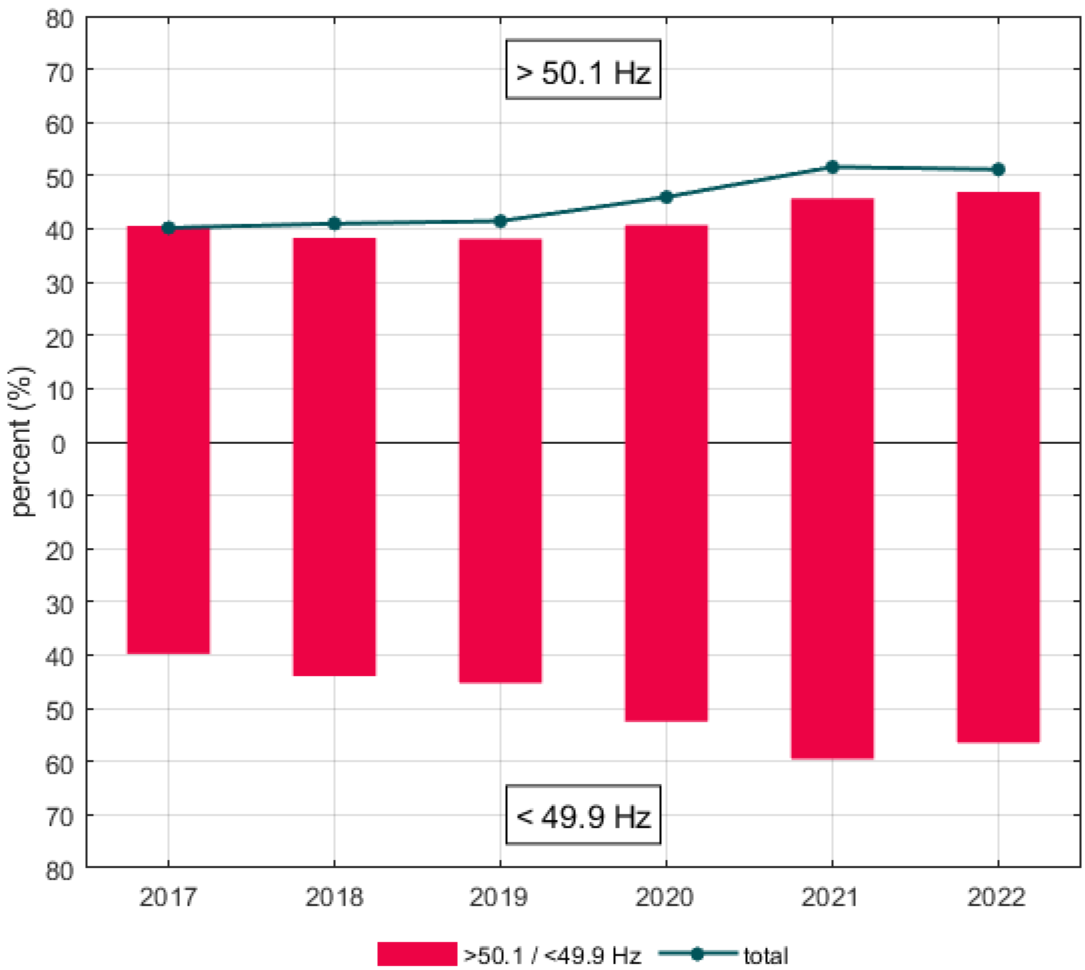
Figure 3.65 represents the reduction in time outside the standard frequency range in percentages month by month for years 2017 to 2022.

***Figure 3.65**. Reduction in time per month outside the standard frequency range after filtering in years 2017-2022*



In addition to the monthly values presented in the previous figure, results for the entire year in 2017-2022 are shown below in Figure 3.66. Filtering the oscillation reduces duration of frequency deviations around 50 % in year 2022. Slight yearly growth in reduction can be seen from 2017 up to 2021, before the leveling of the growth in the year 2022. The reduction is about 10 % more for under frequency deviations in year 2022, which is a smaller value than in 2021.

***Figure 3.66*. Reduction in time outside the standard frequency range after filtering for years 2017-2022**



3.9 Frequency step around the hour shift

The frequency step around the hour shift is defined by the difference between the highest and the 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 2022. Of the total samples in a period, the 1st, 5th, 10th, 50th, 90th, 95th and 99th percentile 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]

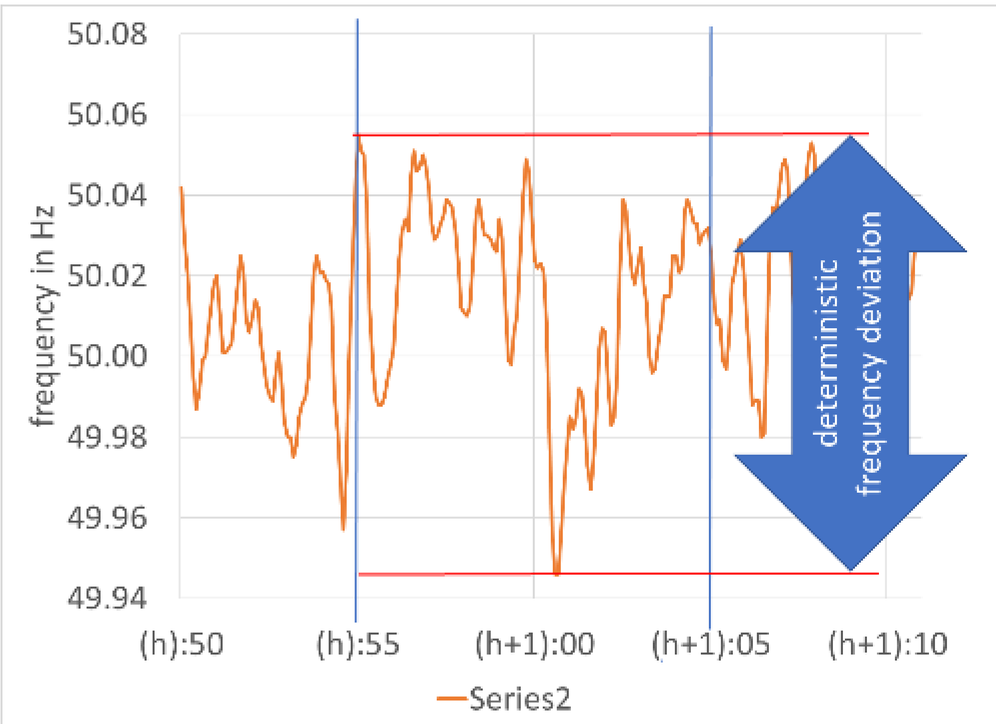


Figure 3.68 represents the deterministic frequency deviation per month in 2022. The 50th percentile stays below zero for the entire year, which indicates that the highest frequency took place before the lowest in more than half of the hour shifts.

***Figure 3.68**. The 1st, 5th, 10th, 50th, 90th, 95th, and 99th percentile of deterministic frequency deviation for every month in 2022*

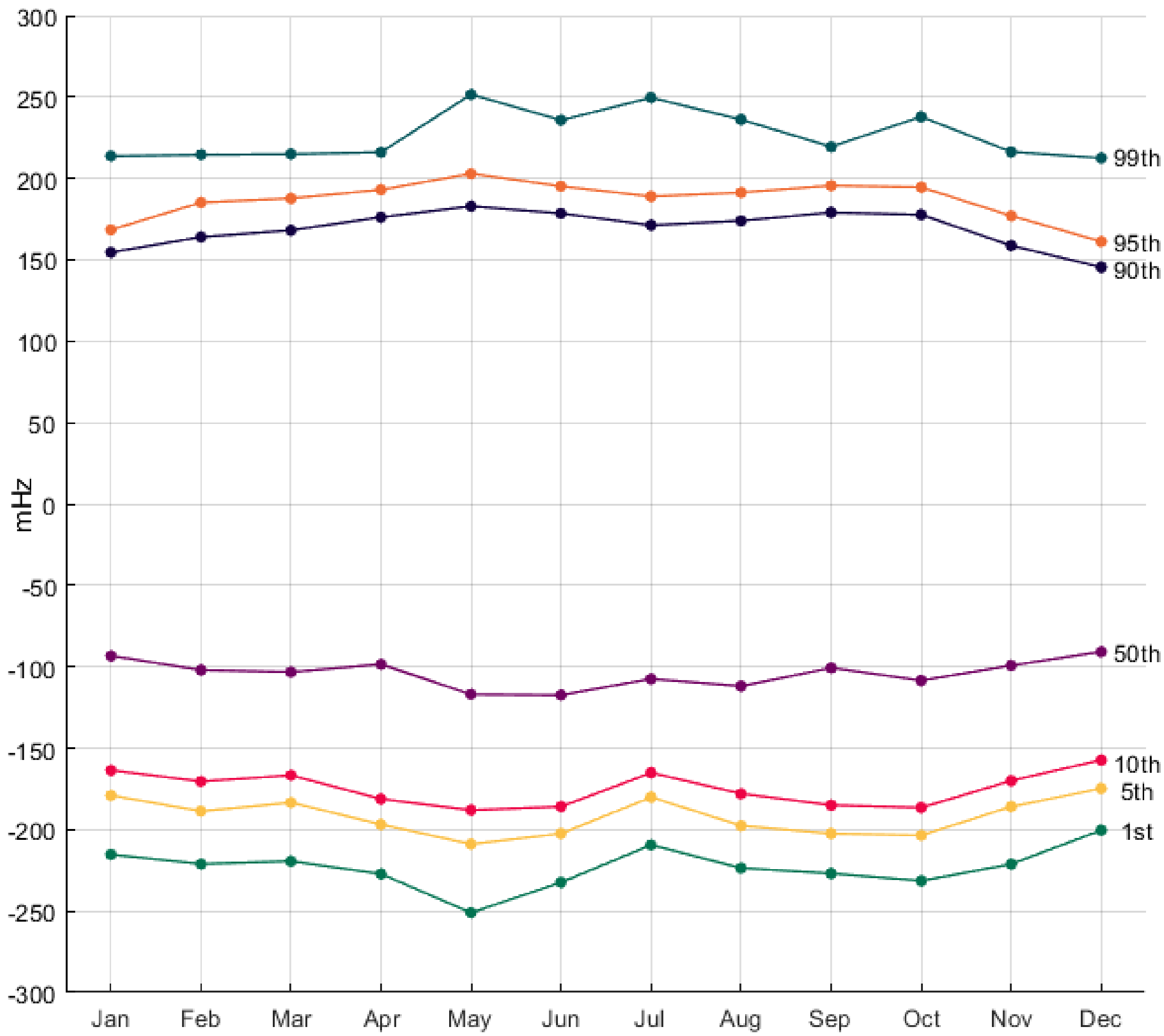
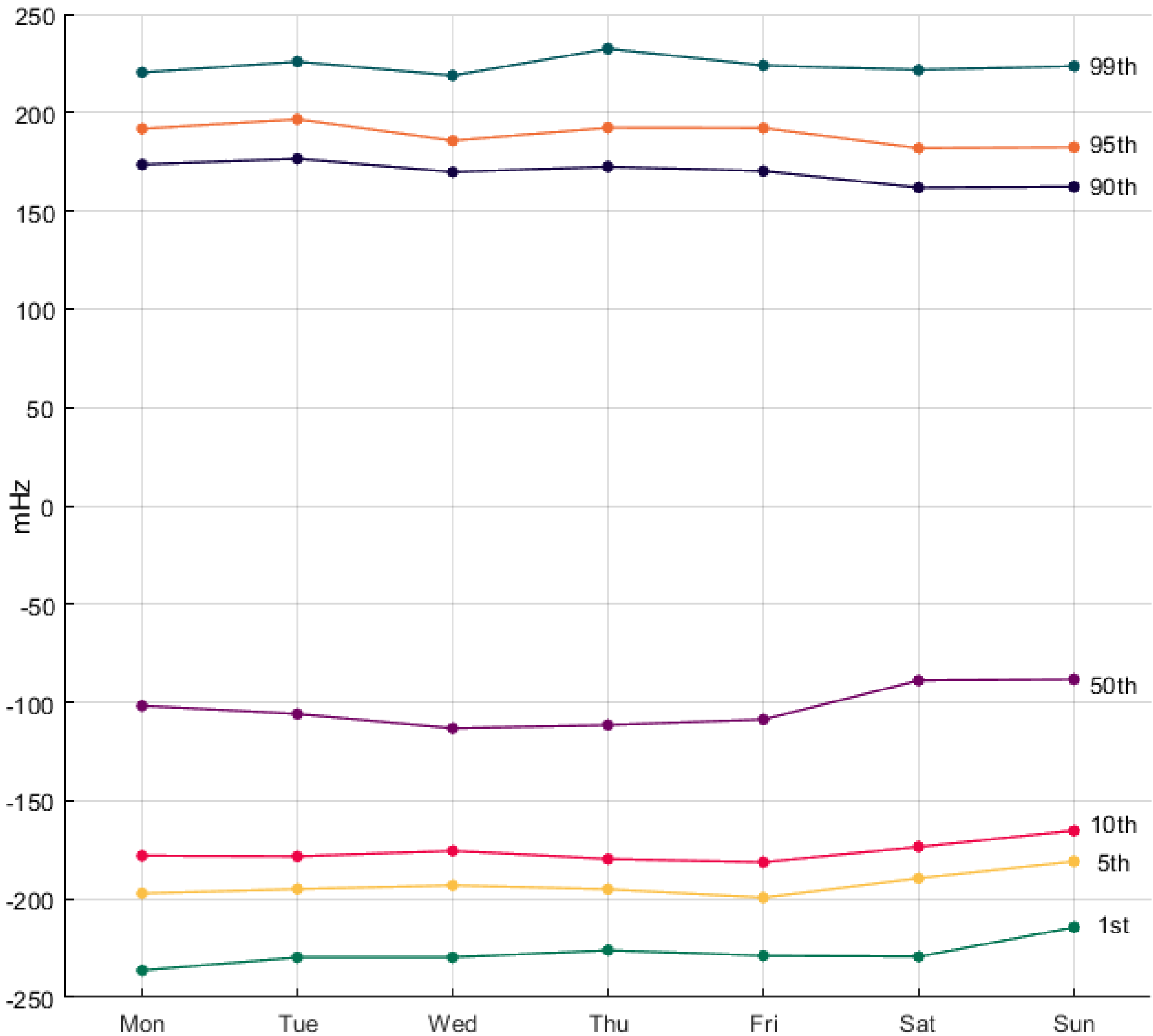


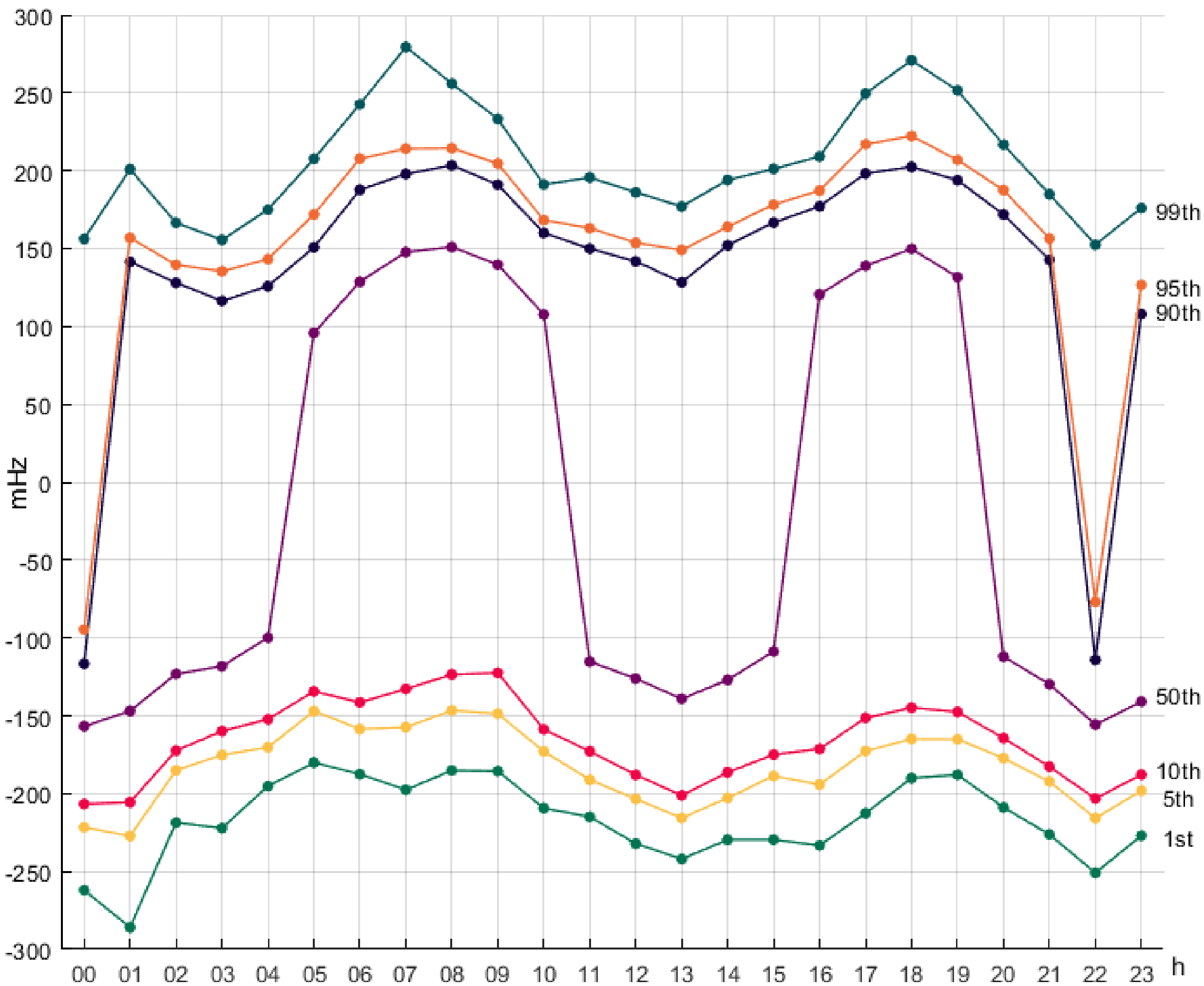
Figure 3.69 shows the percentiles around the hour shift for every day of the week in 2022. The 5th, 10th and 50th percentile have been slightly higher on the weekends.

***Figure 3.69**. The 1st, 5th, 10th, 50th, 90th, 95th, and 99th percentile of deterministic frequency deviation for every day of the week in 2022*



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 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 those hours.

***Figure 3.70**. The 1st, 5th, 10th, 50th, 90th, 95th, and 99th percentile of deterministic frequency deviation for every hour of the day in 2022*

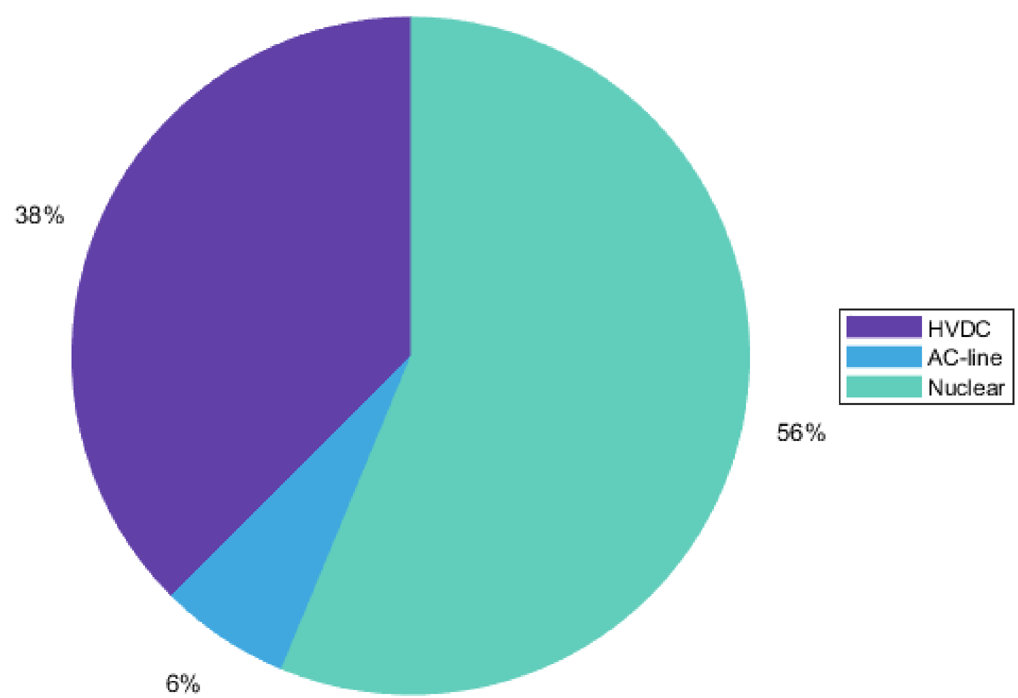


Chapter 4. Frequency disturbances exceeding 300 mHz frequency deviation

This chapter offers information of the major frequency disturbances in the Nordic synchronous system in the year 2022. Over 300 mHz frequency deviations according to Fingrid's PMU located in Kangasala are included. Measurement frequency for the PMU was 10 Hz. This data describes at a fair accuracy frequency of the whole Nordic system.

Nine of the over ±300 mHz disturbances were caused by nuclear power plants, six by failures in HVDC links and one due to fault in AC-line. Figure 4.1 represents the share of factors causing over 300 mHz deviations. In 2022 the number of 300 mHz deviations increased roughly by 50 % from the previous year.

***Figure 4.1**. Shares of factors causing over 300 mHz disturbances in the Nordic synchronous system in 2022*



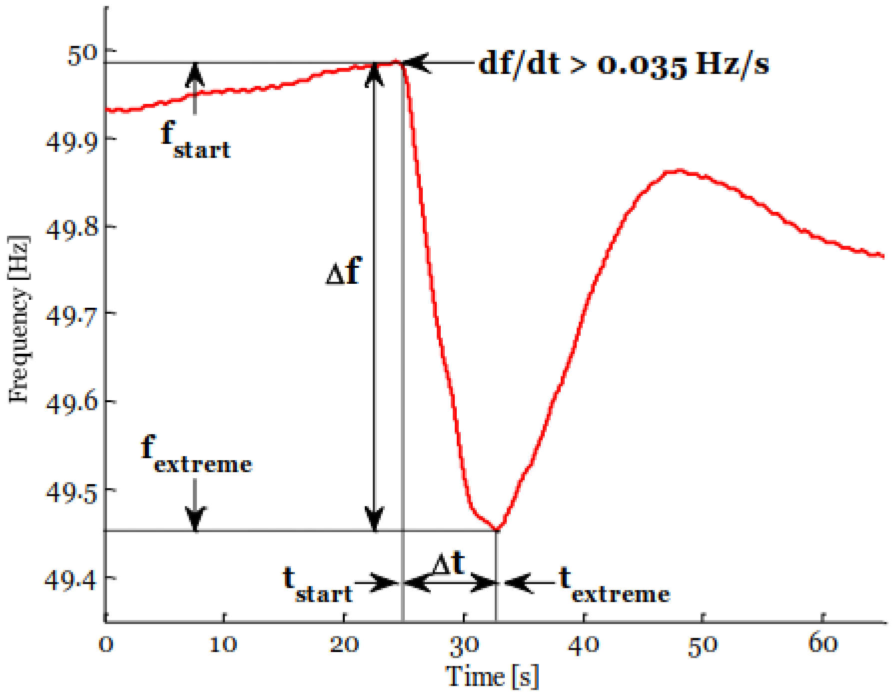
The largest under frequency deviation was caused by nuclear power plant. The amplitude of this deviation was -0.587 Hz and it was reported on 24 September. Largest over frequency deviation occurred on 21 August and its amplitude was 0.461 Hz. This deviation was caused by a fault in HVDC link.

The following part of the chapter will go into more detail on every disturbance that took place in 2022. This will include figures of the frequency when the major disturbances have occurred and information about the disturbance in table form. Table 4.1 contains a short summary of the studied disturbances. Times presented are in the Finnish time (UTC+2 / UTC+3 in the summer). The information given are 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 frequency after disturbance = $| (f_{extreme3} - f_{extreme2}) / (f_{extreme2} - f_{extreme}) |$
- Frequency Bias Factor (FBF) = $\Delta P / \Delta f_{steady\ state}$

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 in 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. Values for kinetic energy are given because it affects to the system inertia which describes system's ability to oppose changes in frequency. Higher kinetic energy provides higher inertia and therefore better ability to oppose frequency deviations. [9] More detailed descriptions of the events listed in Table 4.1 are presented afterwards in Figures 4.3-18 and Tables 4.2-17.

Table 4.1. List of disturbance events in 2022

Event date	Δf (Hz)	ΔP (MW)	Δt (s)	E_k (GWs)	Cause	Page
02-Jan-2022 01:14:06	-0.448	1317	6.3	183	HVDC	105
06-Jan-2022 22:29:32	-0.309	1165	8.7	231	Nuclear	106
29-Jan-2022 17:04:49	-0.339	1124	8.1	204	HVDC	107
22-Mar-2022 17:27:12	0.439	1410	8.3	239	HVDC	108
24-Apr-2022 10:29:53	-0.381	982	13.7	183	Nuclear	109
26-Apr-2022 10:37:38	-0.359	958	18.5	209	Nuclear	110
05-Jul-2022 05:56:26	0.312	664	7.2	172	HVDC	111
02-Aug-2022 12:04:56	0.378	958	5.8	188	HVDC	112
21-Aug-2022 21:13:01	0.461	1410	3.5	178	HVDC	113
29-Aug-2022 11:54:23	-0.379	888	7.9	191	Nuclear	114
05-Sep-2022 13:54:14	-0.313	-	9.4	178	AC-line	115
24-Sep-2022 21:36:00	-0.587	1389	11.5	195	Nuclear	116
12-Oct-2022 11:30:22	-0.478	1347	12.2	214	Nuclear	117
09-Nov-2022 11:09:54	-0.323	718	18.1	211	Nuclear	118
09-Nov-2022 11:43:06	-0.457	1275	6.9	211	Nuclear	119
29-Dec-2022 22:30:01	-0.353	1321	9.0	169	Nuclear	120

Figure 4.3. Disturbance 02-Jan-2022 01:14:06

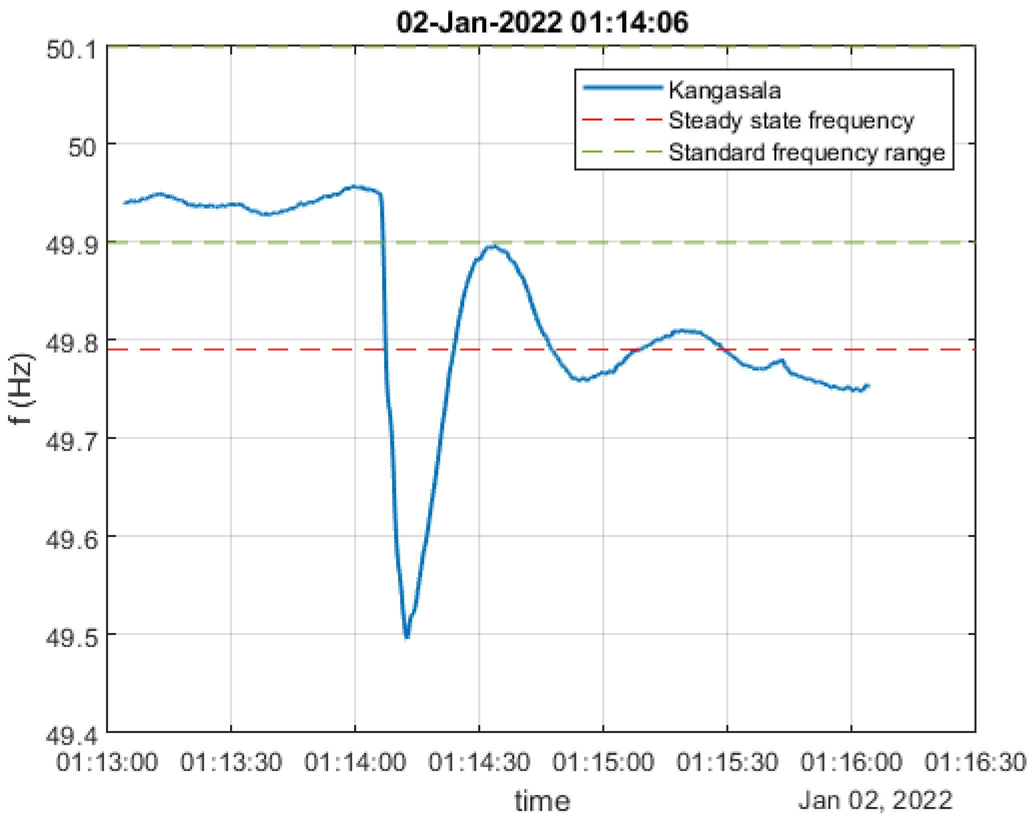


Table 4.2. Disturbance 02-Jan-2022 01:14:06

Date		**02-Jan-2022 01:14:06**	
f_{start}	49.945 Hz	$f_{steady\ state}$	49.791 Hz
$f_{extreme}$	49.497 Hz	$\Delta f_{steady\ state}$	0.154 Hz
Δf	-0.448 Hz	$f_{extreme2}$	49.896 Hz
Δt	6.3 s	$f_{extreme3}$	49.759 Hz
ΔP	1317 MW	damping	34.37 %
E_k	183 GWs	FBF	8550 MW/Hz
cause		HVDC	

Figure 4.4. Disturbance 06-Jan-2022 22:29:32

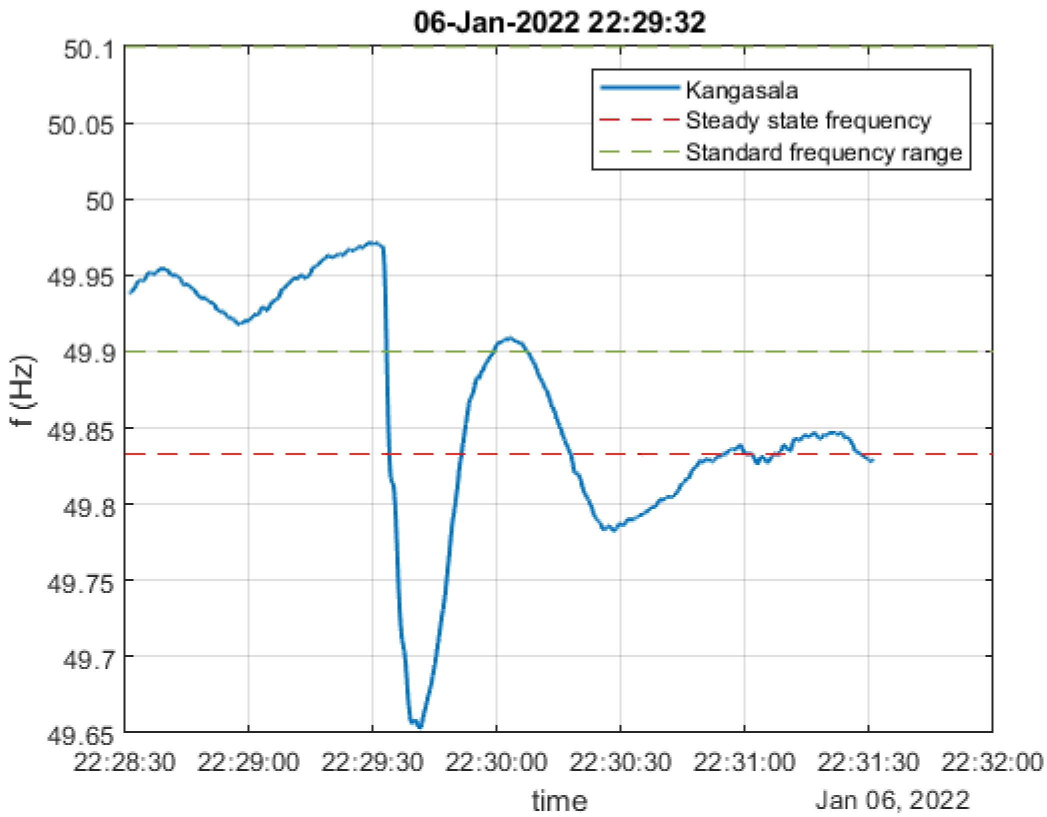


Table 4.3. Disturbance 06-Jan-2022 22:29:32

Date		**06-Jan-2022 22:29:32**	
f_{start}	49.962 Hz	$f_{steady\ state}$	49.833 Hz
$f_{extreme}$	49.653 Hz	$\Delta f_{steady\ state}$	0.129 Hz
Δf	-0.309 Hz	$f_{extreme2}$	49.909 Hz
Δt	8.7 s	$f_{extreme3}$	49.783 Hz
ΔP	1165 MW	damping	49.22 %
E_k	231 GWs	FBF	9010 MW/Hz
cause		Nuclear	

Figure 4.5. Disturbance 29-Jan-2022 17:04:49

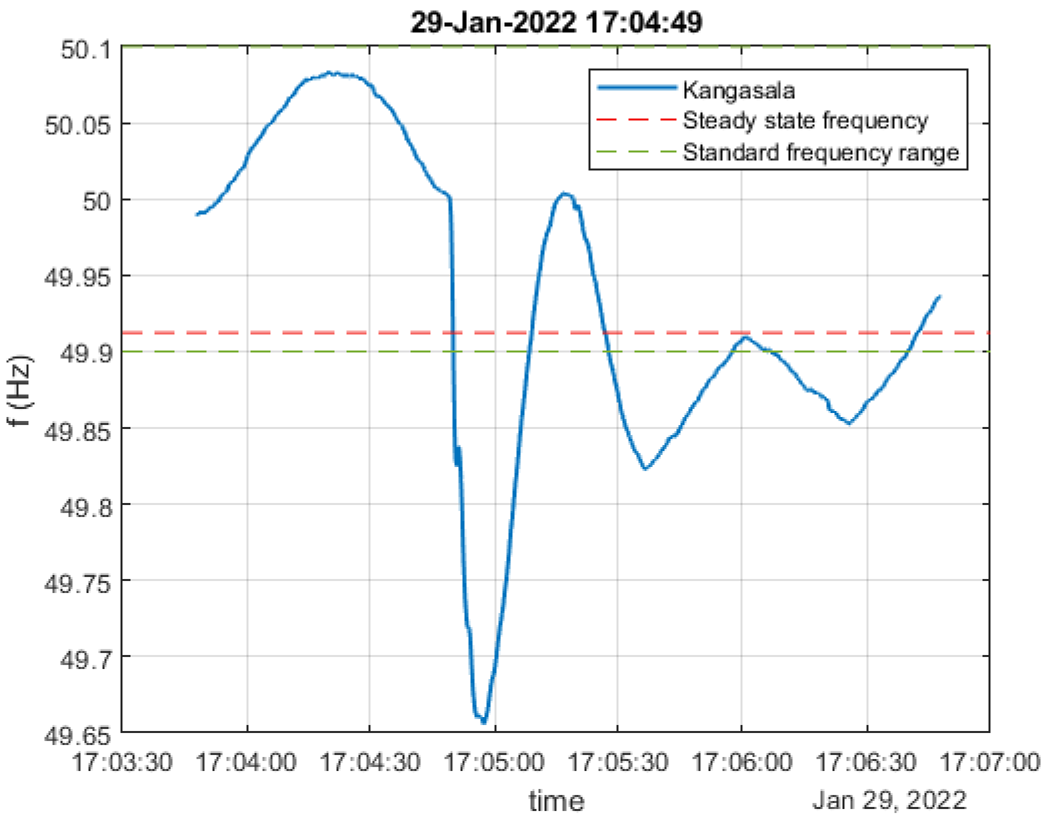


Table 4.4. Disturbance 29-Jan-2022 17:04:49

Date		**29-Jan-2022 17:04:49**	
f_{start}	49.996 Hz	$f_{steady\ state}$	49.912 Hz
$f_{extreme}$	49.656 Hz	$\Delta f_{steady\ state}$	0.084 Hz
Δf	-0.339 Hz	$f_{extreme2}$	50.004 Hz
Δt	8.1 s	$f_{extreme3}$	49.823 Hz
ΔP	1124 MW	damping	52.02 %
E_k	204 GWs	FBF	13458 MW/Hz
cause		HVDC	

Figure 4.6. Disturbance 22-Mar-2022 17:27:12

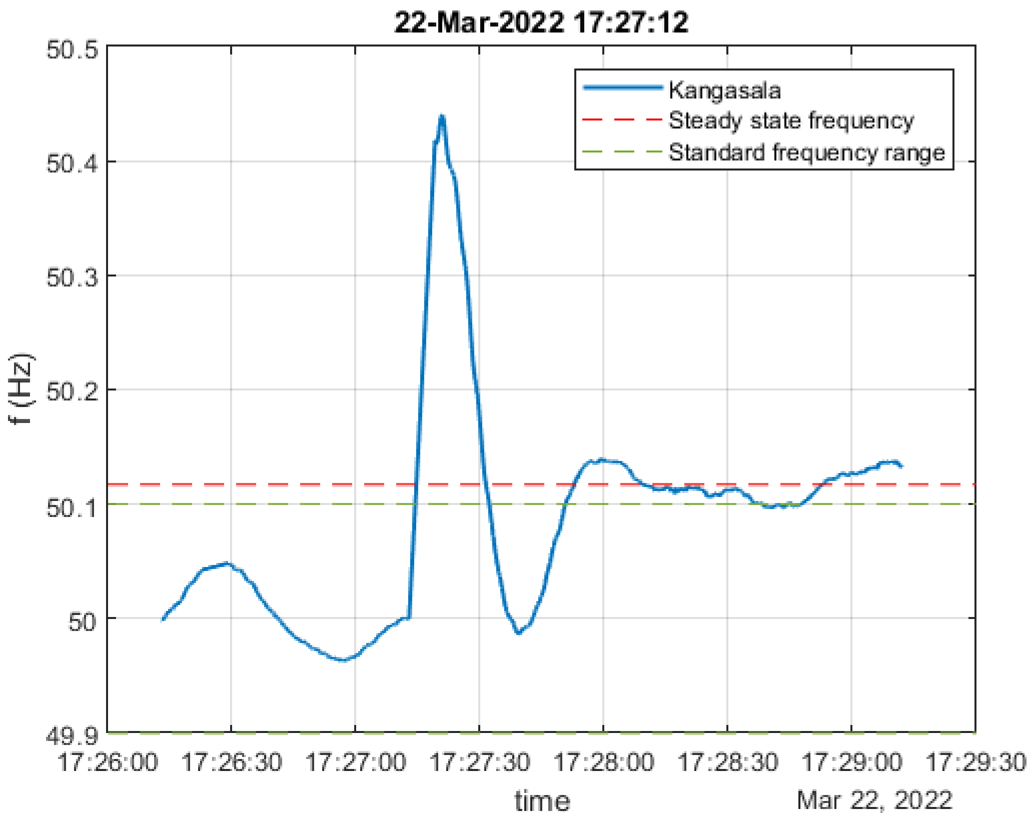


Table 4.5. Disturbance 22-Mar-2022 17:27:12

Date		**22-Mar-2022 17:27:12**	
f_{start}	50.000 Hz	$f_{steady\ state}$	50.117 Hz
$f_{extreme}$	50.439 Hz	$\Delta f_{steady\ state}$	0.117 Hz
Δf	0.439 Hz	$f_{extreme2}$	49.987 Hz
Δt	8.3 s	$f_{extreme3}$	50.139 Hz
ΔP	1410 MW	damping	33.72 %
E_k	239 GWs	FBF	12011 MW/Hz
cause		HVDC	

Figure 4.7. Disturbance 24-Apr-2022 10:29:53

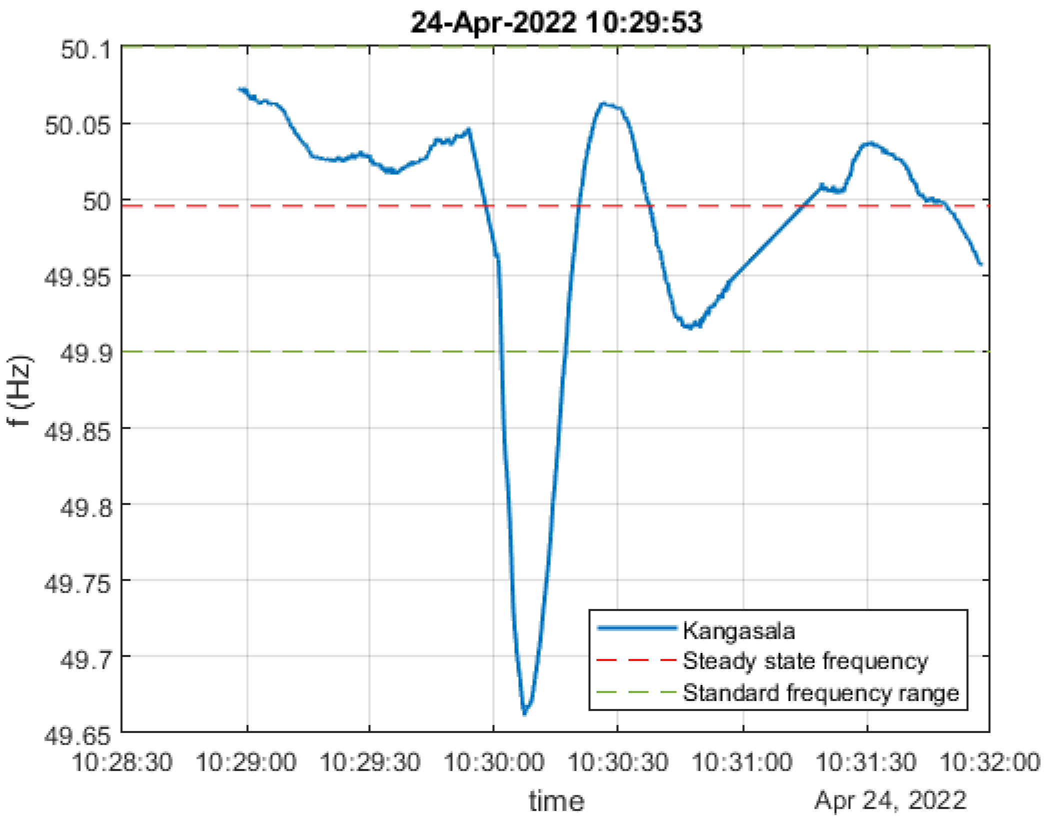


Table 4.6. Disturbance 24-Apr-2022 10:29:53

Date		**24-Apr-2022 10:29:53**	
f_{start}	50.044 Hz	$f_{steady\ state}$	49.995 Hz
$f_{extreme}$	49.663 Hz	$\Delta f_{steady\ state}$	0.049 Hz
Δf	-0.381 Hz	$f_{extreme2}$	50.063 Hz
Δt	13.7 s	$f_{extreme3}$	49.915 Hz
ΔP	982 MW	damping	37.01 %
E_k	183 GWs	FBF	20041 MW/Hz
cause		Nuclear	

Figure 4.8. Disturbance 26-Apr-2022 10:37:38

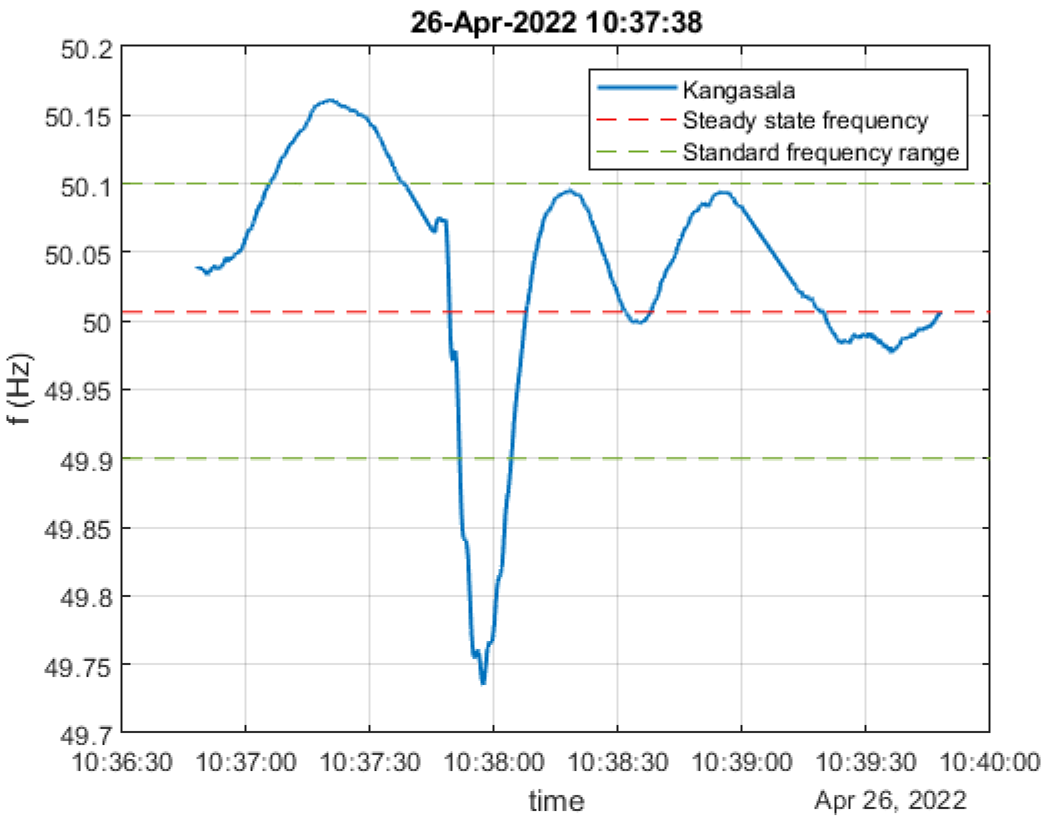


Table 4.7. Disturbance 26-Apr-2022 10:37:38

Date		**26-Apr-2022 10:37:38**	
f_{start}	50.095 Hz	$f_{steady\ state}$	50.007 Hz
$f_{extreme}$	49.736 Hz	$\Delta f_{steady\ state}$	0.089 Hz
Δf	-0.359 Hz	$f_{extreme2}$	50.096 Hz
Δt	18.5 s	$f_{extreme3}$	49.998 Hz
ΔP	958 MW	damping	27.00 %
E_k	209 GWs	FBF	10814 MW/Hz
cause		Nuclear	

***Figure 4.9**. Disturbance 05-Jul-2022 05:56:26*

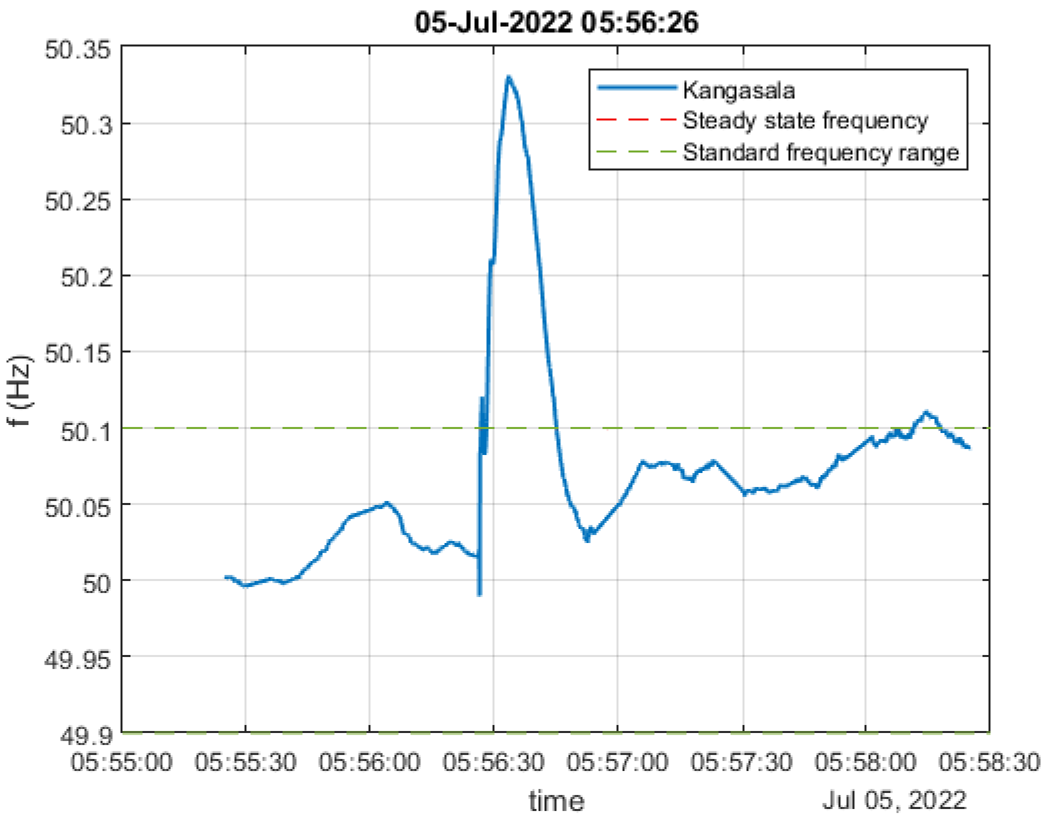


***Table 4.8**. Disturbance 05-Jul-2022 05:56:26*

Date		**05-Jul-2022 05:56:26**	
f_{start}	50.018 Hz	$f_{steady\ state}$	50.100 Hz
$f_{extreme}$	50.330 Hz	$\Delta f_{steady\ state}$	0.082 Hz
Δf	0.312 Hz	$f_{extreme2}$	50.026 Hz
Δt	7.2 s	$f_{extreme3}$	50.078 Hz
ΔP	664 MW	damping	17.19 %
E_k	172 GWs	FBF	8066 MW/Hz
cause		HVDC	

***Figure 4.10**. Disturbance 02-Aug-2022 12:04:56*

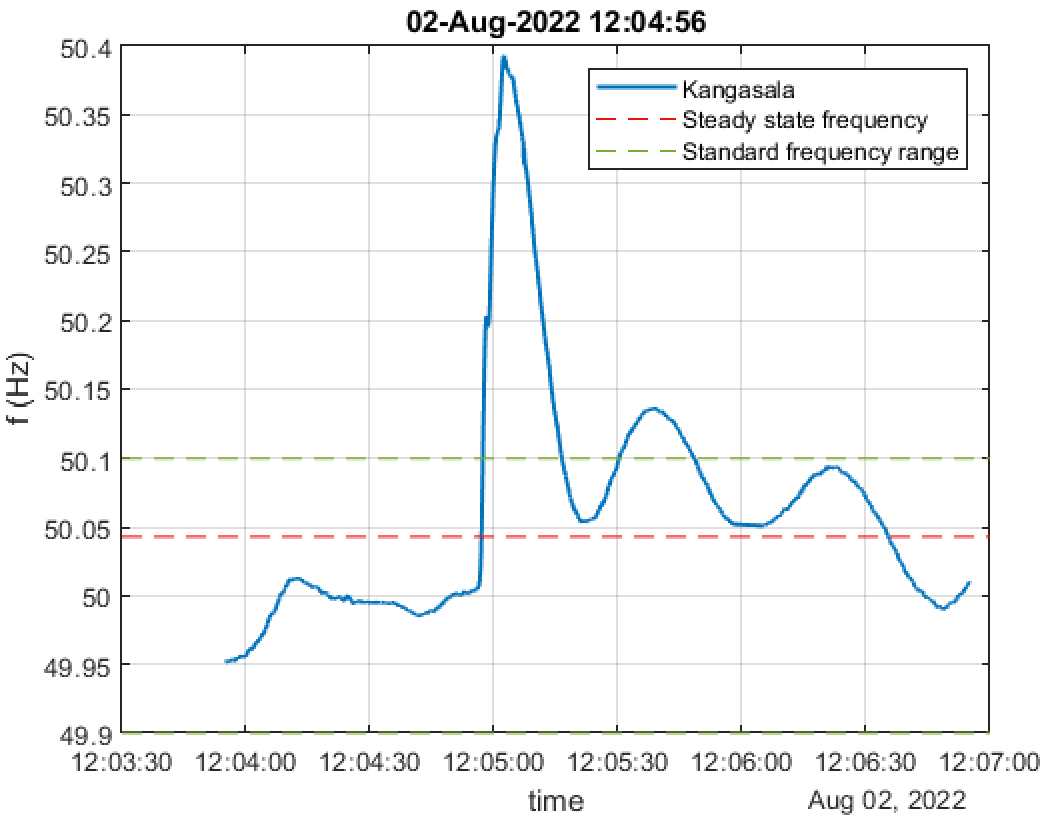


***Table 4.9**. Disturbance 02-Aug-2022 12:04:56*

Date		**02-Aug-2022 12:04:56**	
f_{start}	50.014 Hz	$f_{steady\ state}$	50.043 Hz
$f_{extreme}$	50.392 Hz	$\Delta f_{steady\ state}$	0.029 Hz
Δf	0.378 Hz	$f_{extreme2}$	50.052 Hz
Δt	5.8 s	$f_{extreme3}$	49.990 Hz
ΔP	958 MW	damping	17.96 %
E_k	188 GWs	FBF	32992 MW/Hz
cause		HVDC	

***Figure 4.11**. Disturbance 21-Aug-2022 21:13:01*

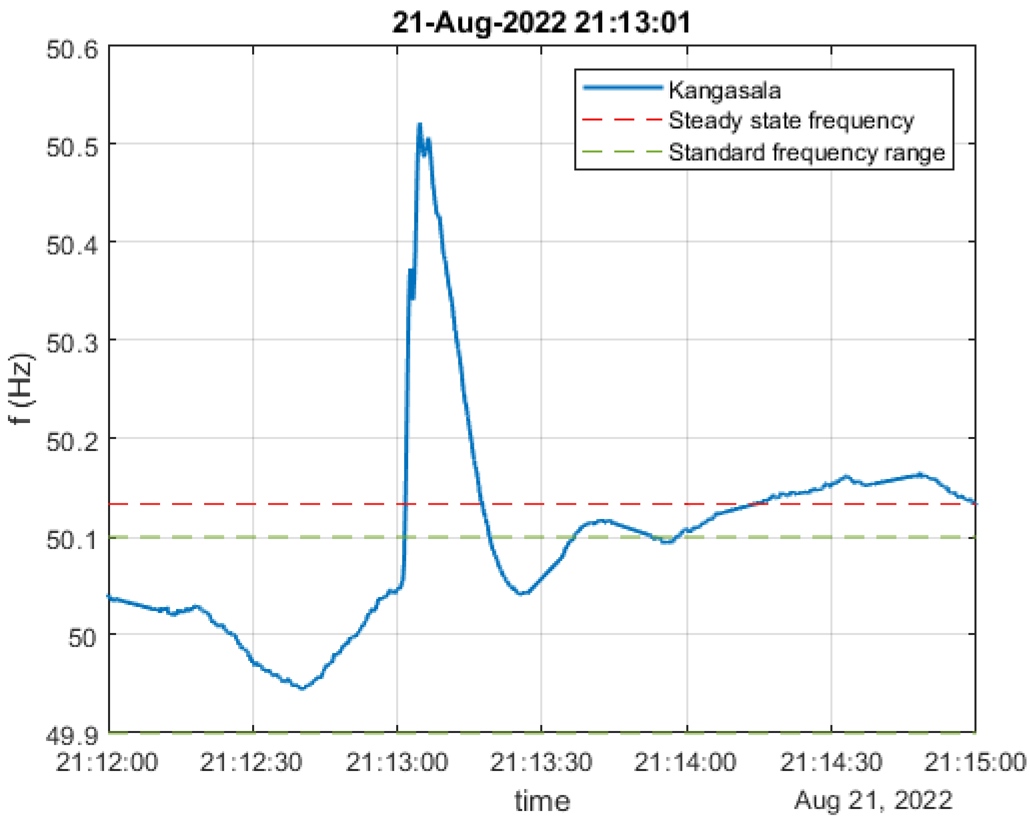


***Table 4.10**. Disturbance 21-Aug-2022 21:13:01*

Date		**21-Aug-2022 21:13:01**	
f_{start}	50.057 Hz	$f_{steady\ state}$	50.133 Hz
$f_{extreme}$	50.518 Hz	$\Delta f_{steady\ state}$	0.076 Hz
Δf	0.461 Hz	$f_{extreme2}$	50.042 Hz
Δt	3.5 s	$f_{extreme3}$	50.146 Hz
ΔP	1410 MW	damping	21.88 %
E_k	178 GWs	FBF	18560 MW/Hz
cause		HVDC	

Figure 4.12. Disturbance 29-Aug-2022 11:54:23

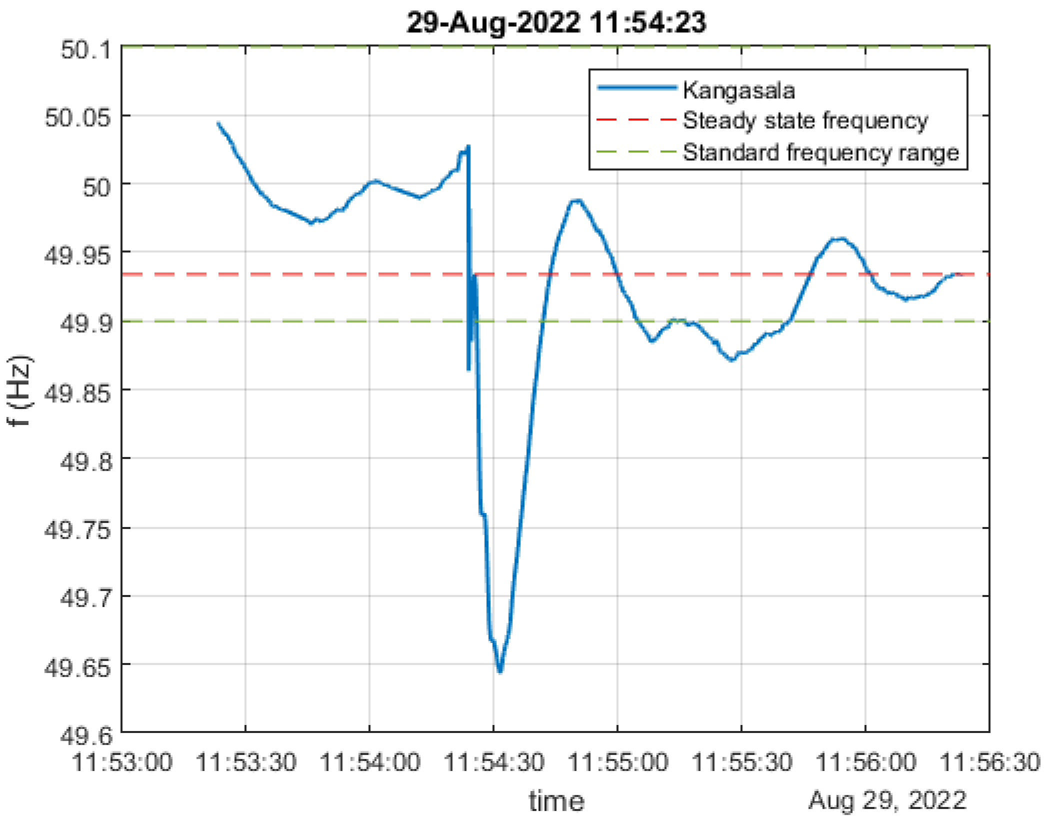


Table 4.11. Disturbance 29-Aug-2022 11:54:23

Date		**29-Aug-2022 11:54:23**	
f_{start}	50.024 Hz	$f_{steady\ state}$	49.934 Hz
$f_{extreme}$	49.644 Hz	$\Delta f_{steady\ state}$	0.090 Hz
Δf	-0.379 Hz	$f_{extreme2}$	49.988 Hz
Δt	7.9 s	$f_{extreme3}$	49.871 Hz
ΔP	888 MW	damping	33.95 %
E_k	191 GWs	FBF	9904 MW/Hz
cause		Nuclear	

Figure 4.13. Disturbance 05-Sep-2022 13:54:14

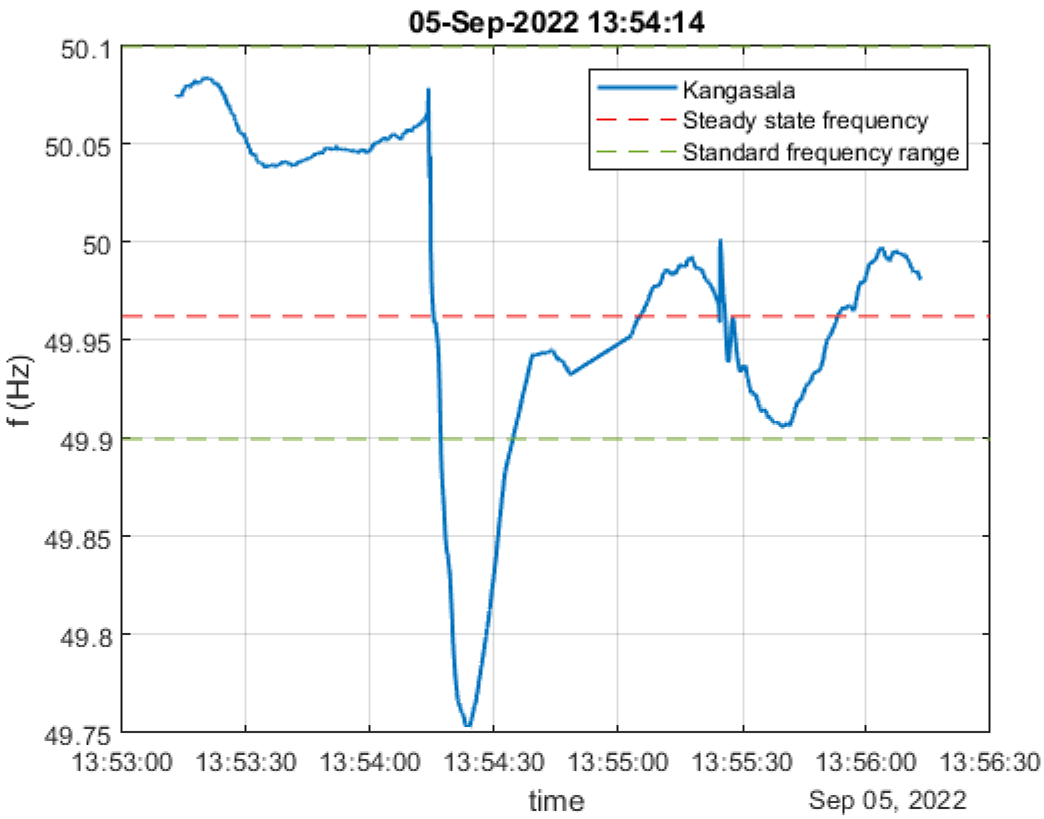


Table 4.12. Disturbance 05-Sep-2022 13:54:14

Date		**05-Sep-2022 13:54:14**	
f_{start}	50.067 Hz	$f_{steady\ state}$	49.962 Hz
$f_{extreme}$	49.754 Hz	$\Delta f_{steady\ state}$	0.105 Hz
Δf	-0.313 Hz	$f_{extreme2}$	49.993 Hz
Δt	9.4 s	$f_{extreme3}$	49.906 Hz
ΔP	-	damping	36.15 %
E_k	178 GWs	FBF	-
cause		AC-line	

Figure 4.14. Disturbance 24-Sep-2022 21:36:00

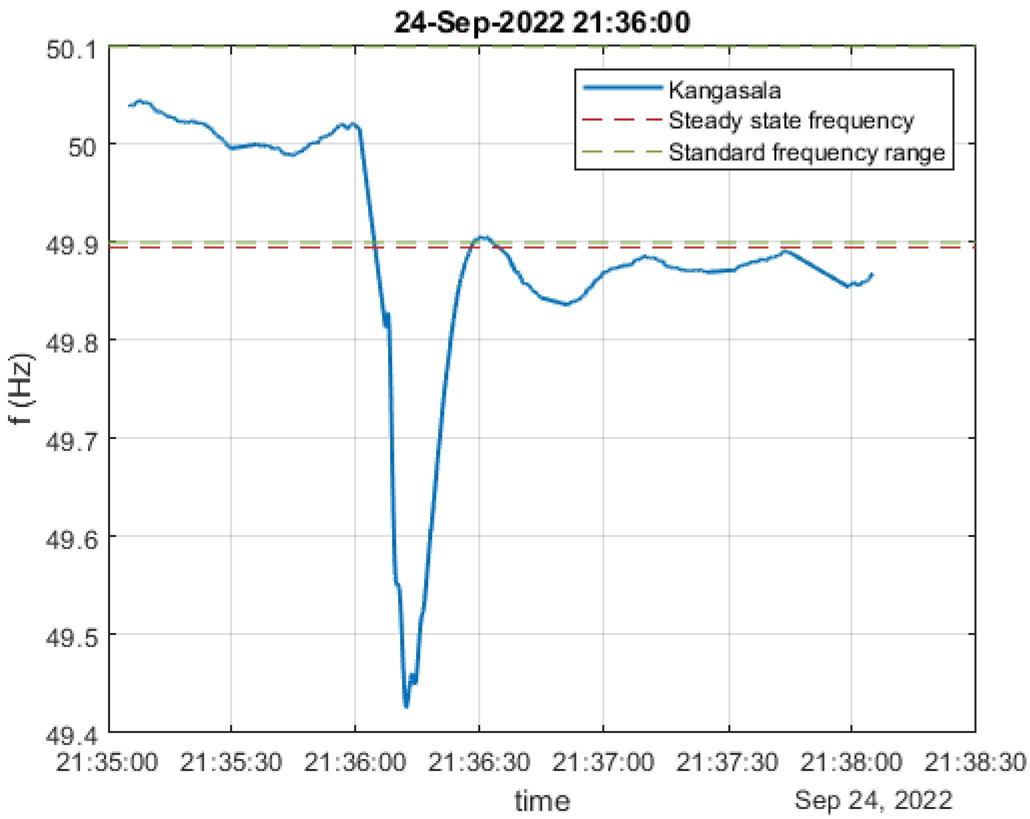


Table 4.13. Disturbance 24-Sep-2022 21:36:00

Date		24-Sep-2022 21:36:00	
f_{start}	50.014 Hz	$f_{steady\ state}$	49.895 Hz
$f_{extreme}$	49.427 Hz	$\Delta f_{steady\ state}$	0.119 Hz
Δf	-0.587 Hz	$f_{extreme2}$	49.905 Hz
Δt	11.5 s	$f_{extreme3}$	49.837 Hz
ΔP	1389 MW	damping	14.40 %
E_k	195 GWs	FBF	11657 MW/Hz
cause		Nuclear	

***Figure 4.15**. Disturbance 12-Oct-2022 11:30:22*

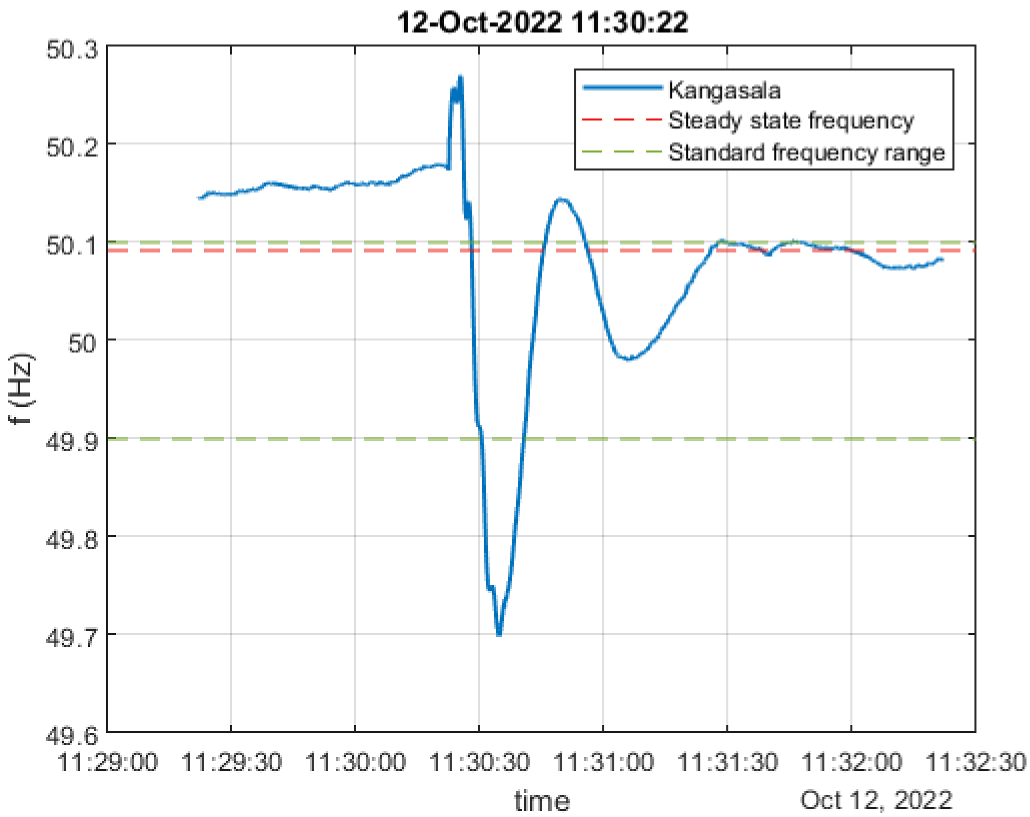


***Table 4.14**. Disturbance 12-Oct-2022 11:30:22*

Date		**12-Oct-2022 11:30:22**	
f_{start}	50.178 Hz	$f_{steady\ state}$	50.092 Hz
$f_{extreme}$	49.700 Hz	$\Delta f_{steady\ state}$	0.086 Hz
Δf	-0.478 Hz	$f_{extreme2}$	50.144 Hz
Δt	12.2 s	$f_{extreme3}$	49.980 Hz
ΔP	1347 MW	damping	36.94 %
E_k	214 GWs	FBF	15661 MW/Hz
cause		Nuclear	

Figure 4.16. Disturbance 09-Nov-2022 11:09:54

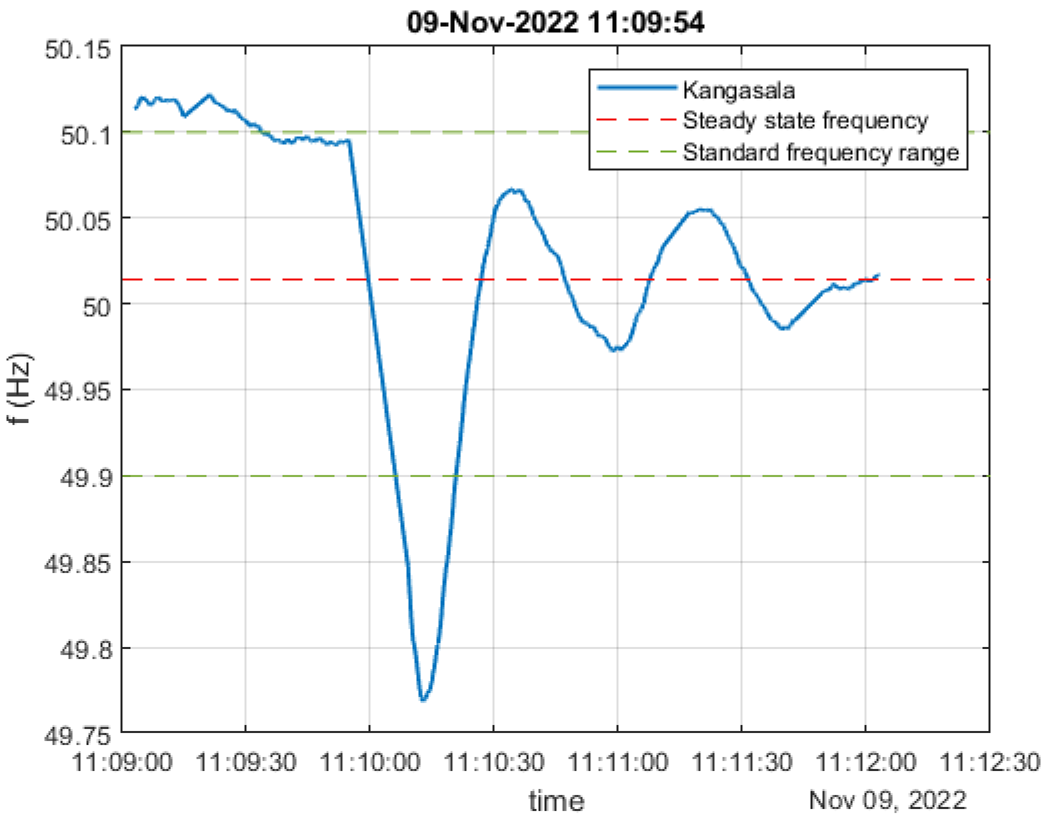


Table 4.15. Disturbance 09-Nov-2022 11:09:54

Date		**09-Nov-2022 11:09:54**	
f_{start}	50.092 Hz	$f_{steady\ state}$	50.014 Hz
$f_{extreme}$	49.769 Hz	$\Delta f_{steady\ state}$	0.078 Hz
Δf	-0.323 Hz	$f_{extreme2}$	50.067 Hz
Δt	18.1 s	$f_{extreme3}$	49.973 Hz
ΔP	718 MW	damping	31.54 %
E_k	211 GWs	FBF	9197 MW/Hz
cause		Nuclear	

***Figure 4.17**. Disturbance 09-Nov-2022 11:43:06*

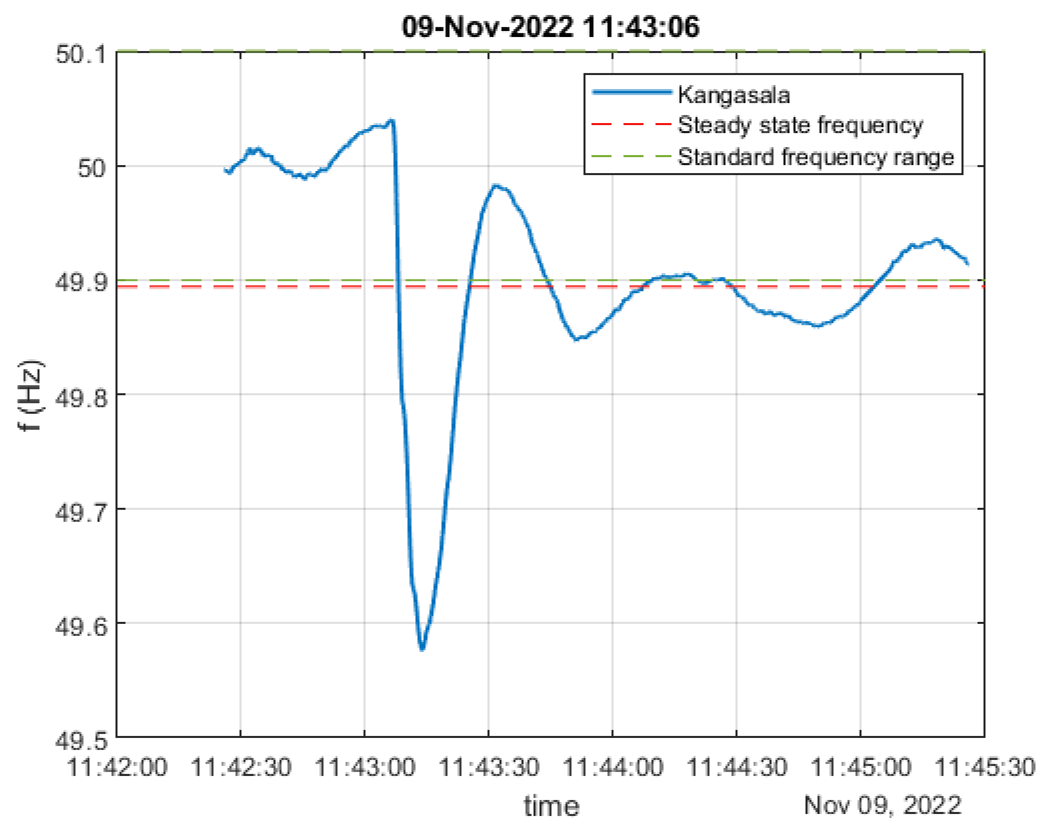


***Table 4.16**. Disturbance 09-Nov-2022 11:43:06*

Date		**09-Nov-2022 11:43:06**	
f_{start}	50.034 Hz	$f_{steady\ state}$	49.894 Hz
$f_{extreme}$	49.577 Hz	$\Delta f_{steady\ state}$	0.140 Hz
Δf	-0.457 Hz	$f_{extreme2}$	49.982 Hz
Δt	6.9 s	$f_{extreme3}$	49.847 Hz
ΔP	1275 MW	damping	33.35 %
E_k	211 GWs	FBF	9095 MW/Hz
cause		Nuclear	

***Figure 4.18**. Disturbance 29-Dec-2022 22:30:01*

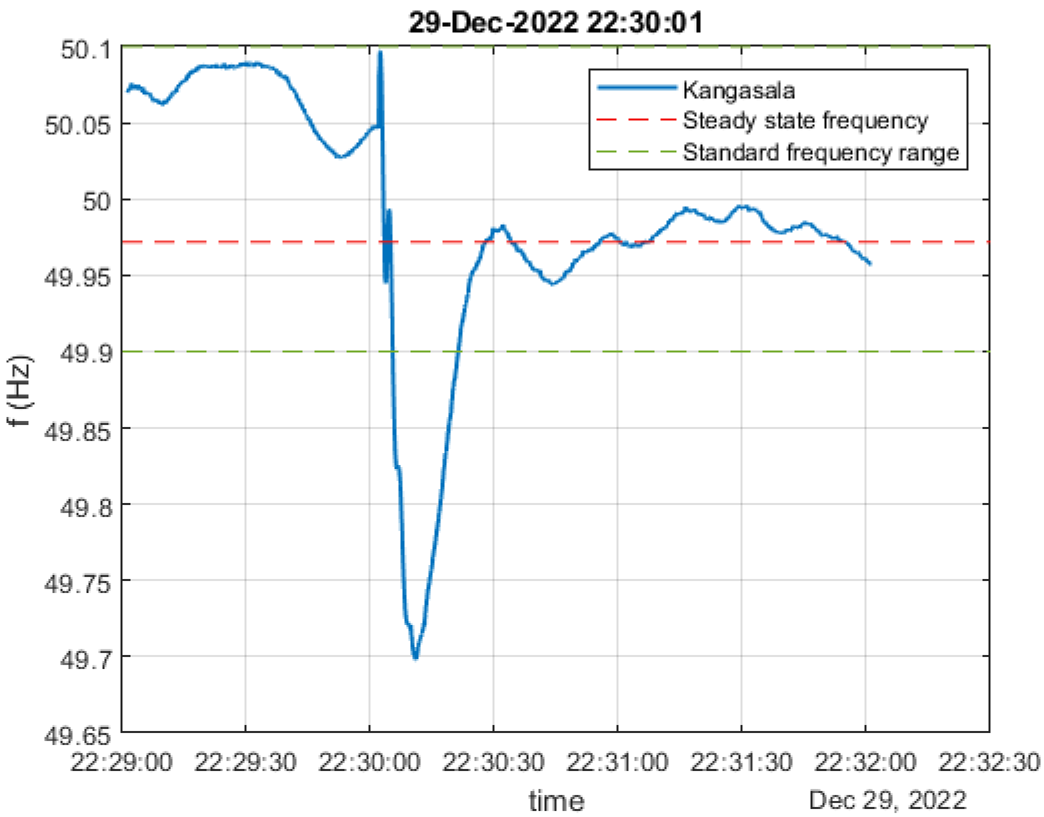


***Table 4.17**. Disturbance 29-Dec-2022 22:30:01*

Date		**29-Dec-2022 22:30:01**	
f_{start}	50.051 Hz	$f_{steady\ state}$	49.972 Hz
$f_{extreme}$	49.698 Hz	$\Delta f_{steady\ state}$	0.080 Hz
Δf	-0.353 Hz	$f_{extreme2}$	49.982 Hz
Δt	9.0 s	$f_{extreme3}$	49.944 Hz
ΔP	1321 MW	damping	13.54 %
E_k	169 GWs	FBF	16610 MW/Hz
cause		Nuclear	

Chapter 5. Summary

The aim of this report was to analyse frequency variation and oscillation in the Nordic synchronous system in 2022. While comparing with the preceding year 2021, the overall quality of frequency was better in 2022 than in 2021, if the amount of oscillation and the number of over 300 mHz disturbances are excluded from the criteria. 2022 does also well in comparison with the other years presented in this report. For example, the time outside the standard frequency range and the number of threshold crossings of the normal frequency range returned to the level of the year 2020 which has been a record year in terms of frequency quality in the preceding five-year period.

November and December were the best months in terms of frequency quality, when standard deviation, time outside the standard frequency range, the number of threshold crossings and the amount of under 3 minutes 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. While comparing the days of the week, Sunday was the best day of the week and Tuesday the worst when the quality of frequency is evaluated.

In the hourly analysis, there seems to be a change of trend, since the hour 7 is not standing out in terms of bad frequency quality as clearly as it has in the past. In the two preceding years the hour 7 has for example had the largest daily average time outside the standard frequency range and standard deviation, while in this year those indexes achieve same levels of peak values around and after the midnight as hour 7 has in the past. Also the frequency quality around the noon has improved when comparing the year 2022 with the years 2020-2021. Within an average hour, the quality of the frequency was worse closer the hour shift and especially at the beginning of the hour.

The amount of oscillation in 2022 has been higher than the levels of the previous years. The mean value of oscillation was the highest in May and October and the standard deviation in May and September. Compared with the years 2017-2019 and 2021, the oscillation’s 24 h moving average deviates in a narrower range and thus resembles more the behaviour of the year 2020. Removal of the oscillation by filtering the frequency data clearly reduces frequency deviations. The reduction is around 50 % with the FFT-filtering method, which is about the same as in the previous year. The reduction is generally higher for under frequency deviations.

There were 16 frequency disturbances in 2022, where the deviation exceeded 300 mHz. Most of the disturbances were caused by nuclear power plants. The number of frequency deviations exceeding 300 mHz increased by over 50 % from the previous year. The average number of these deviations has been around 6 deviations per year between the years 2017-2020, so there seems to be a growing trend in the number of larger frequency deviations.

Chapter 6. Sources

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