Frequency quality analysis

2020

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 2020. The results have been obtained by analyzing data from Fingrid's PMU (Phasor Measurement Unit) measurements. All times are given in Finnish time (CET+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 for the instantaneous frequency data 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 2020 is presented in Table 2.1. Availability of data per year for years 2015 to 2020 can be seen in Table 2.2 [2,3,4,5,6]. In 2020 there was valid measurement data for 97.82 % of the time. Some of the data is missing due to telecommunication errors. There were multiple gaps in the measurement data caused by these errors, which lasted more than half an hour. Majority of them took place in August, which was clearly the worst month when it comes to the availability of the data.

Table 2.1. The amount of valid measurement data available per month in 2020

Month	Available data
January	99.88 %
February	99.84 %
March	99.84 %
April	99.84 %
May	99.72 %
June	99.78 %
July	99.85 %
August	82.21 %
September	97.84 %
October	98.24 %
November	97.21 %
December	99.88 %

Table 2.2. The amount of valid measurement data available for years 2015-2020

Year	Available data
2015	99.90 %
2016	99.37 %
2017	97.19 %
2018	98.90 %
2019	98.47 %
2020	97.82 %

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 2020. 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 March and April the averages have not deviated more than 0.4 mHz from 50 Hz. In the other moths, the average frequency has not deviated more than 0.3 mHz from 50 Hz. The average frequency in 2020 was a little better than the year before, since the maximum average frequency deviation in 2019 was close to 0.5 mHz from 50 Hz.

Figure 3.1. Average frequency for each month in 2020

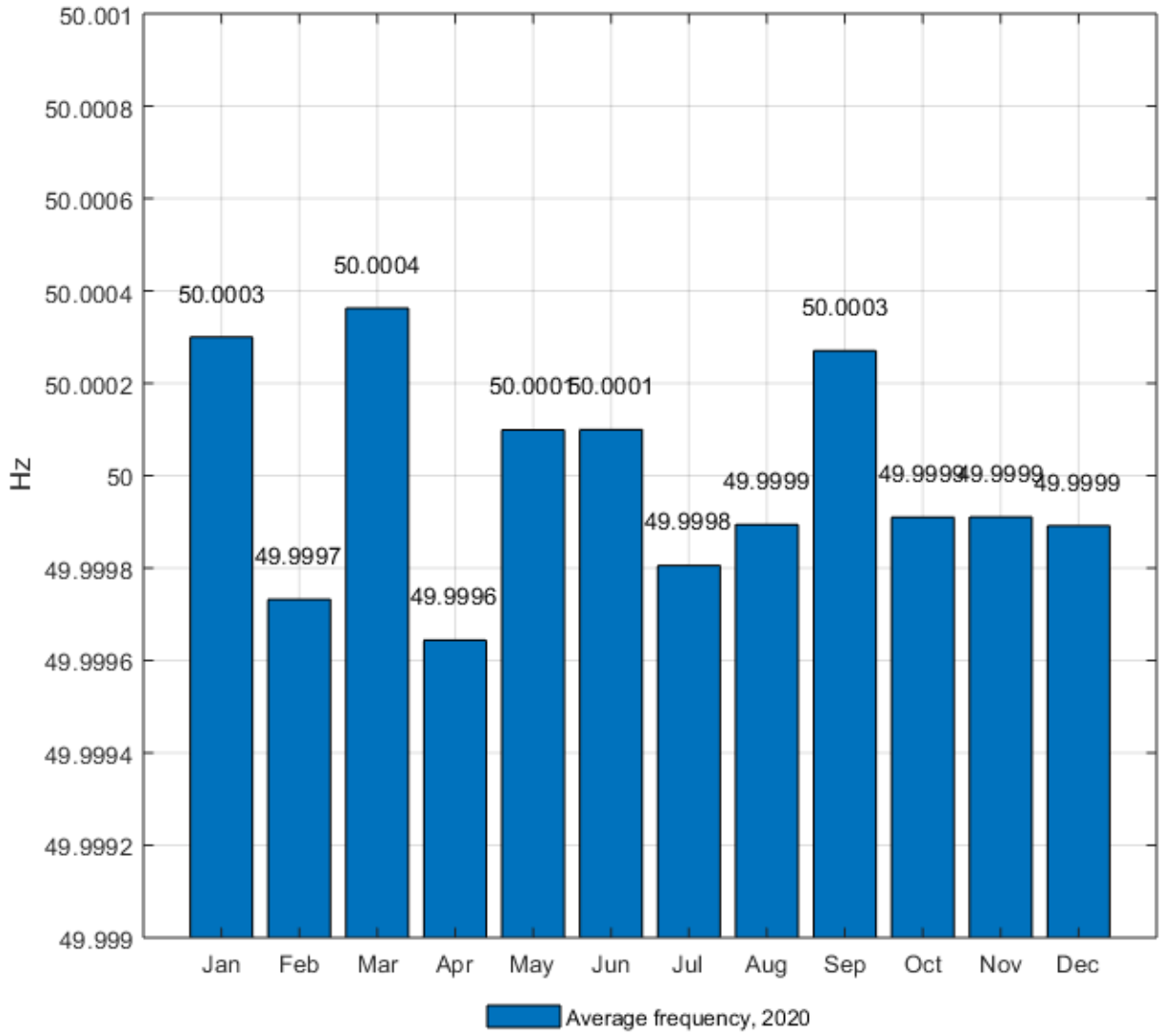


Figure 3.2 represents the average frequencies for every day of the week. On average, the frequency has been lower on the weekends and higher in the beginning of the week and on Wednesdays.

Figure 3.2. Average frequency for each day of the week in 2020

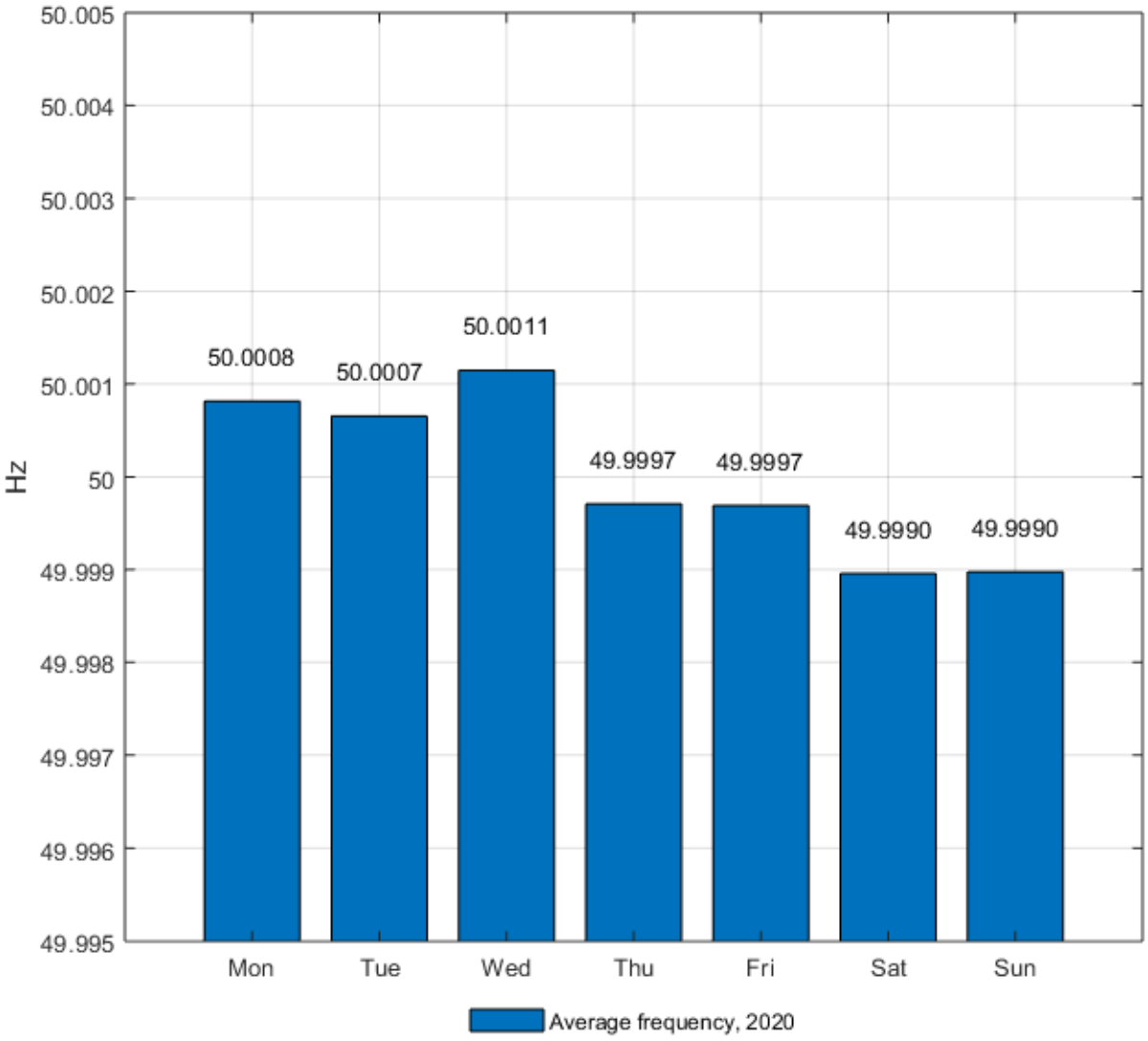


Figure 3.3 shows the average frequencies during each hour of the day. The frequency has been lower during the morning hours hours from 7 a.m. to 11 a.m. and in the afternoon from 16 p.m. to 18 p.m. The frequency has been higher in the early afternoon, in the evening and around midnight.

Figure 3.3. Average frequency for each hour of the day in 2020

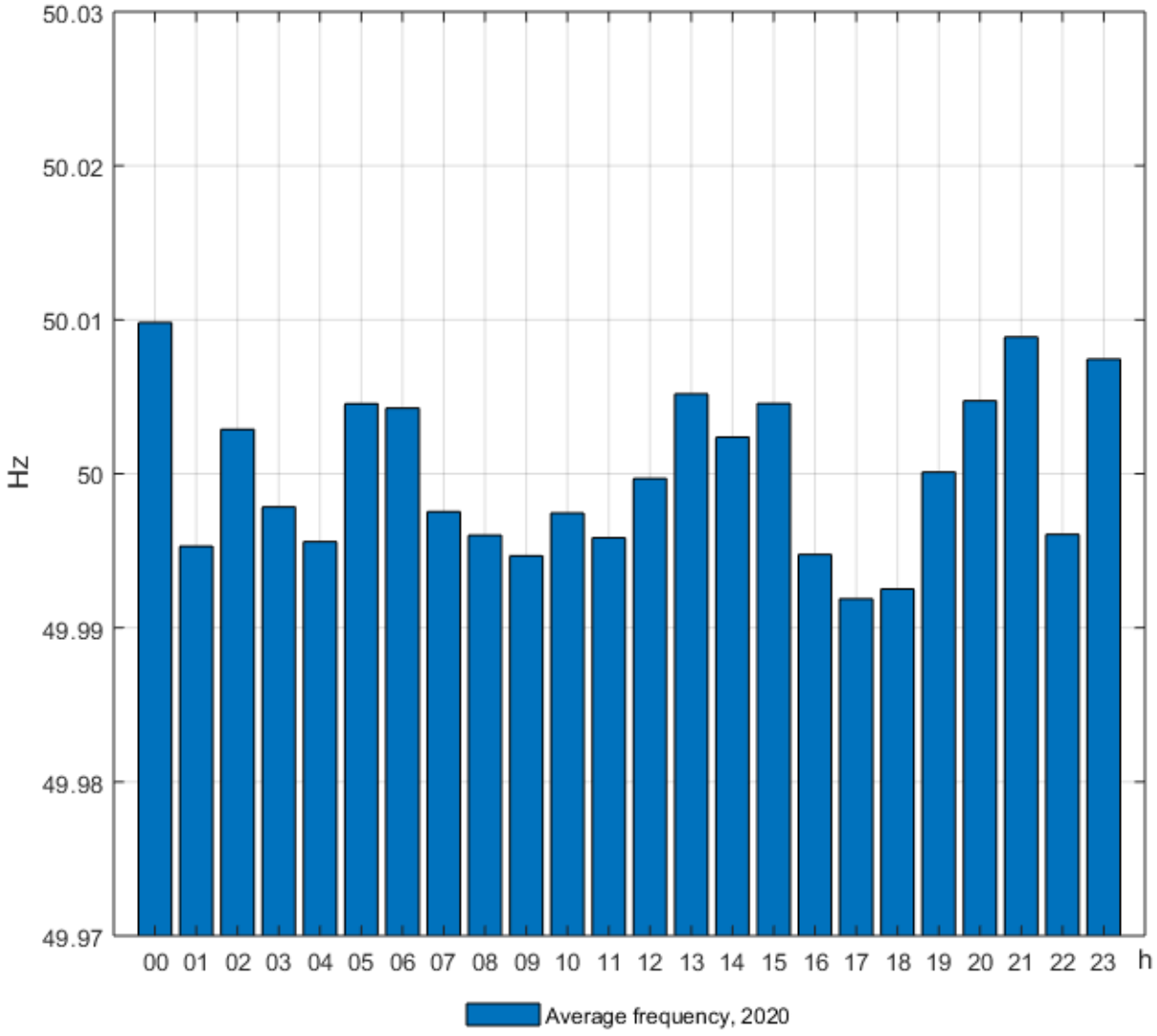
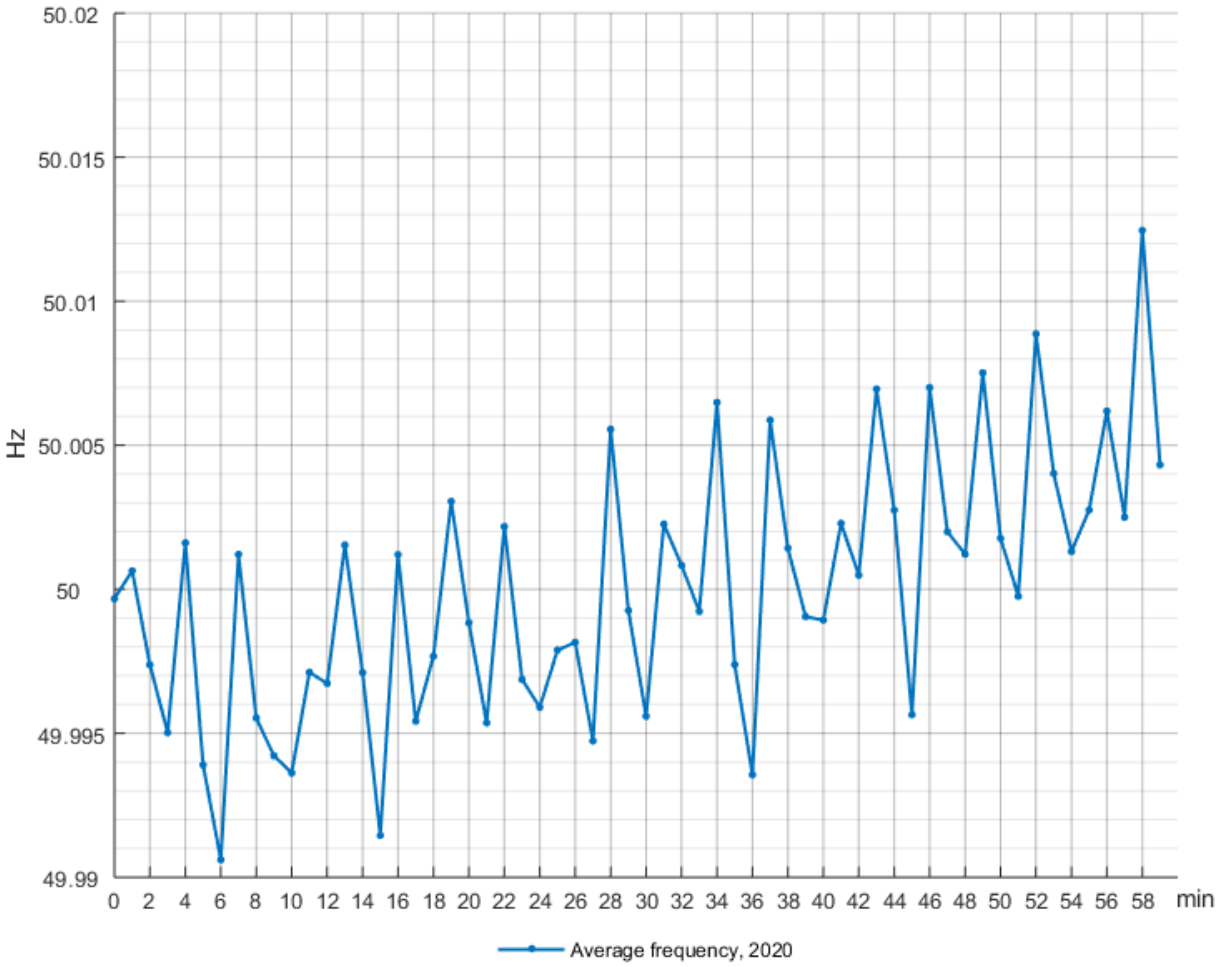


Figure 3.4 shows the average frequency inside the hour. In general, the frequency has been higher in the latter part of the hour. The difference between consecutive minutes varies between 0-12.5 mHz. The differences have increased significantly from year 2019. In 2019 the greatest difference was 7.5 mHz.

Figure 3.4. Average frequency for each minute of the hour in 2020



3.1.2 Standard deviation

This section includes the figures representing the standard deviation of frequency during the year 2020. 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 2020. The low standard deviation in July, August and December indicates that the 1 second frequency values have been closer to 50 Hz during those months. In February the standard deviation has been higher than in the other months. Overall, the frequency has deviated substantially less in 2020 than in 2019.

Figure 3.5. Standard deviation of the frequency for every month in 2020

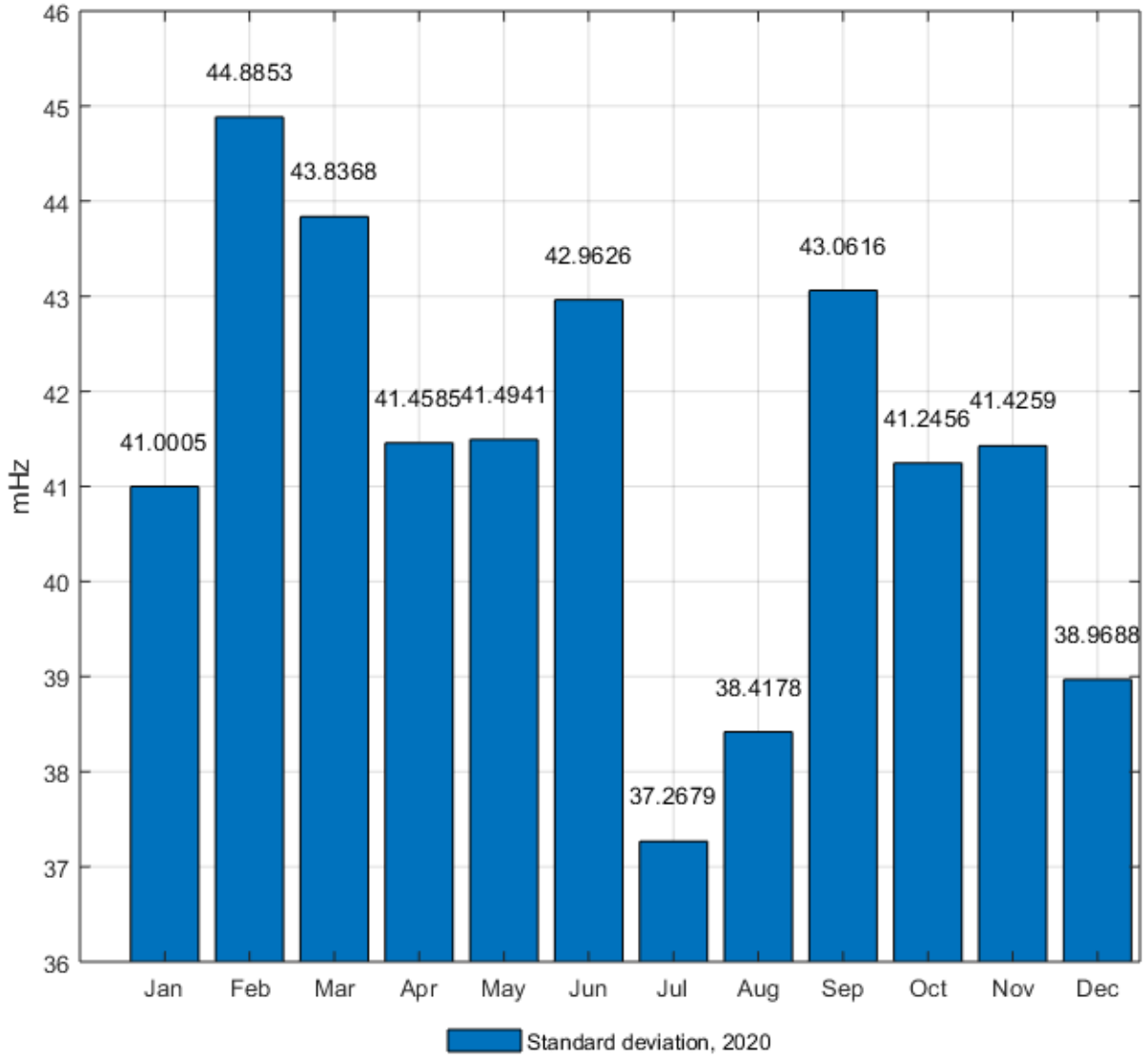


Figure 3.6 represents the standard deviation for every day of the week. Based on standard deviation, the quality of the frequency has been worst in the middle of the week but it has improved towards the weekend. It is noteworthy that all the daily values in the figure are within 2 mHz from each other, where as monthtly deviation figure shows much greater differences between the consecutive months.

Figure 3.6. Standard deviation of the frequency for every day of the week in 2020

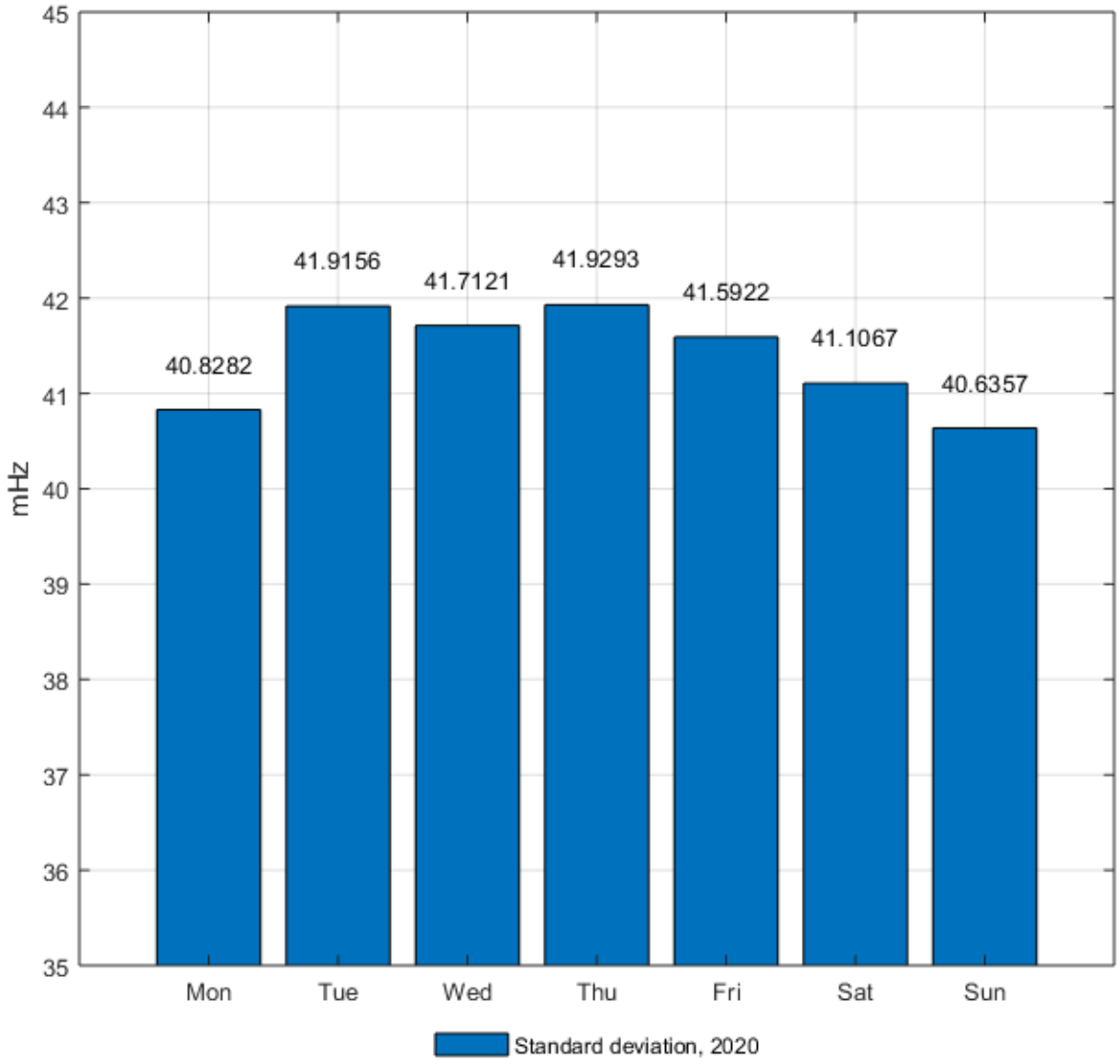


Figure 3.7 shows the standard deviation during the average day. The standard deviation has been higher around noon and lower in the evening. However, the highest and the lowest standard deviation values have occurred in the morning, at 7 am and 9 am.

Figure 3.7. Standard deviation of the frequency for every hour of the day in 2020

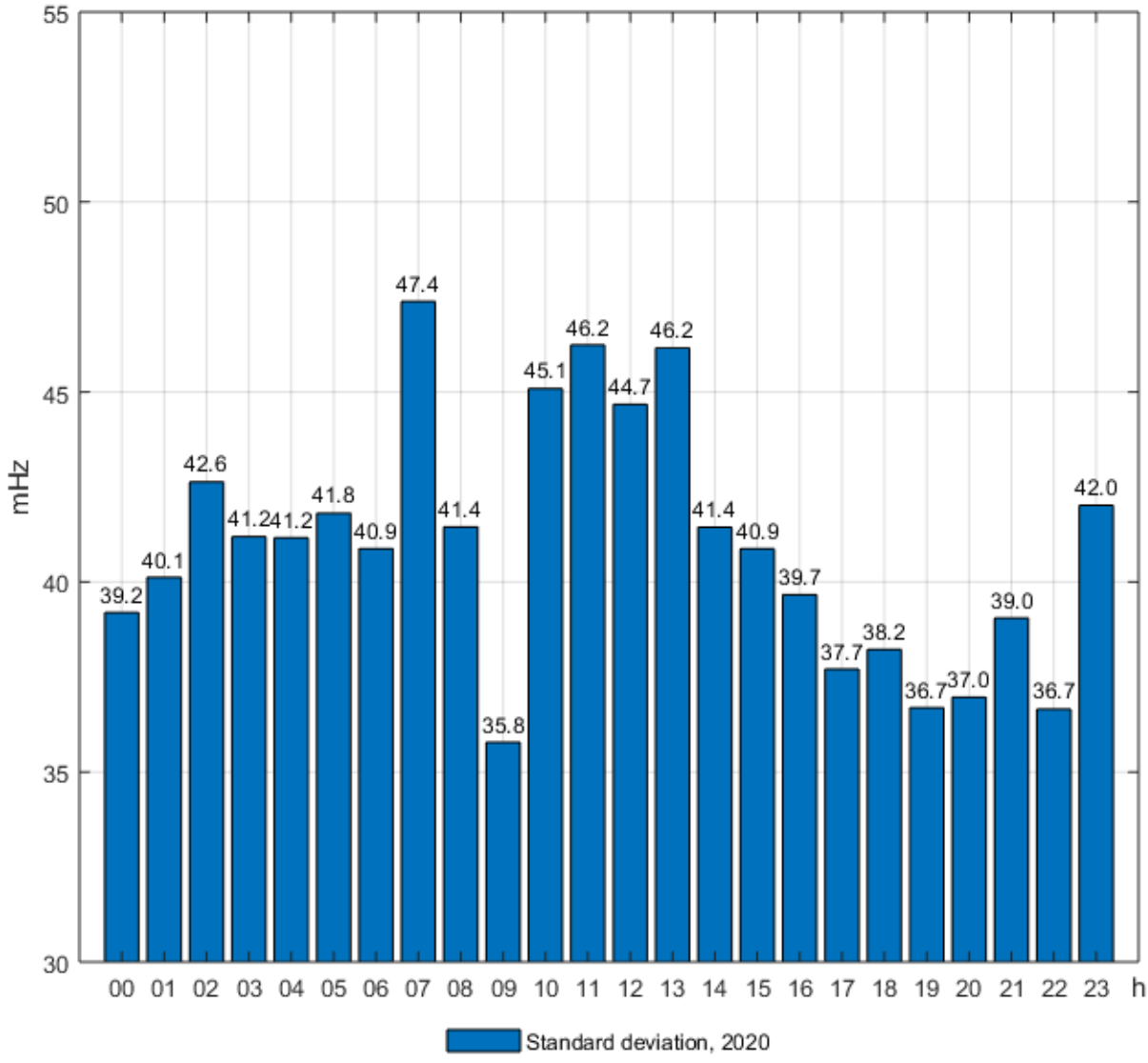
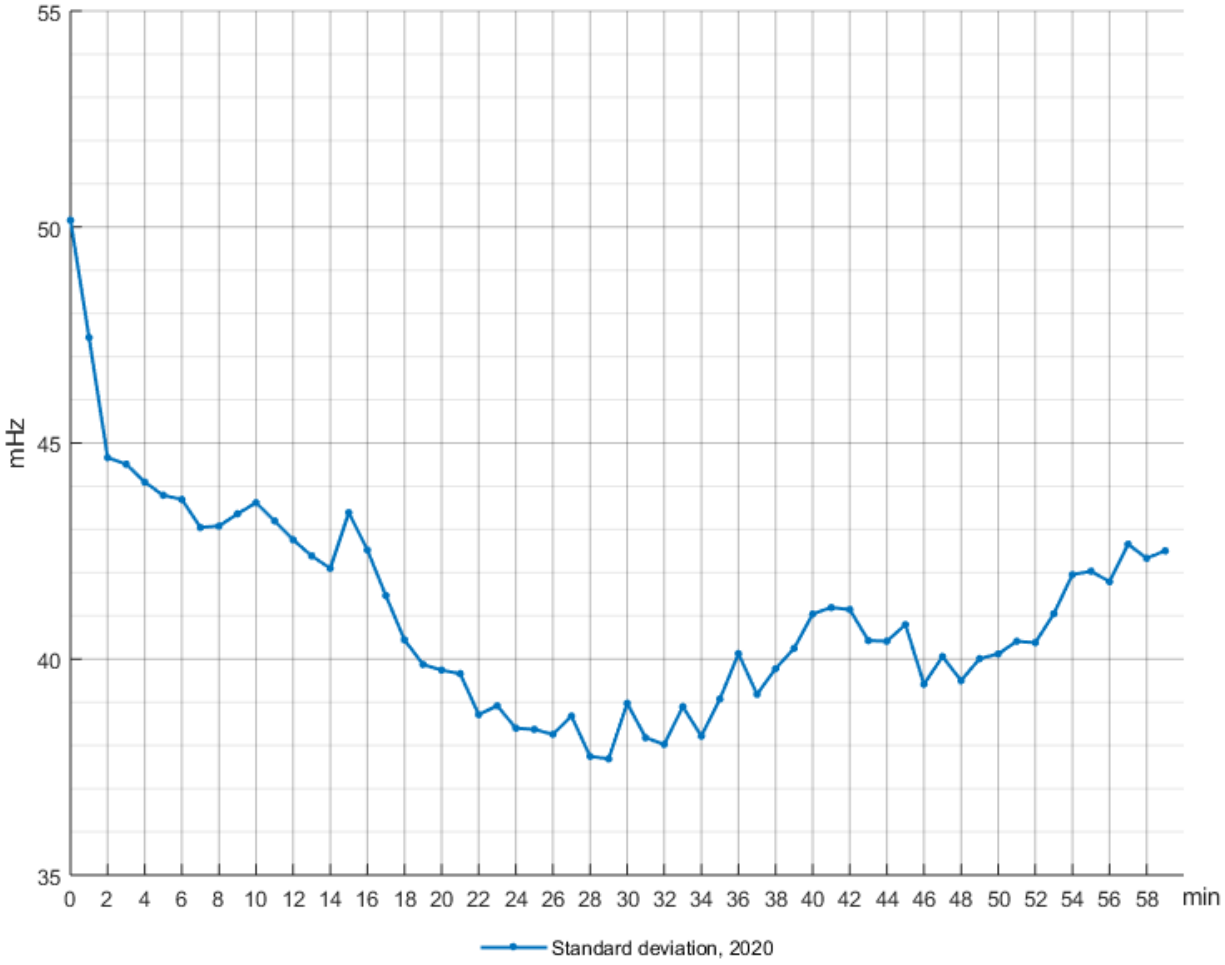


Figure 3.8 represents the standard deviation inside the hour. The standard deviation has had the highest values in the beginning of the hour and it has decreased until the half hour mark from where it has increased again. There has also been a slight drop in the standard deviation around the 46th minute.

Figure 3.8. Standard deviation of the frequency for every minute of the hour in 2020



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 2015 to 2020 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.

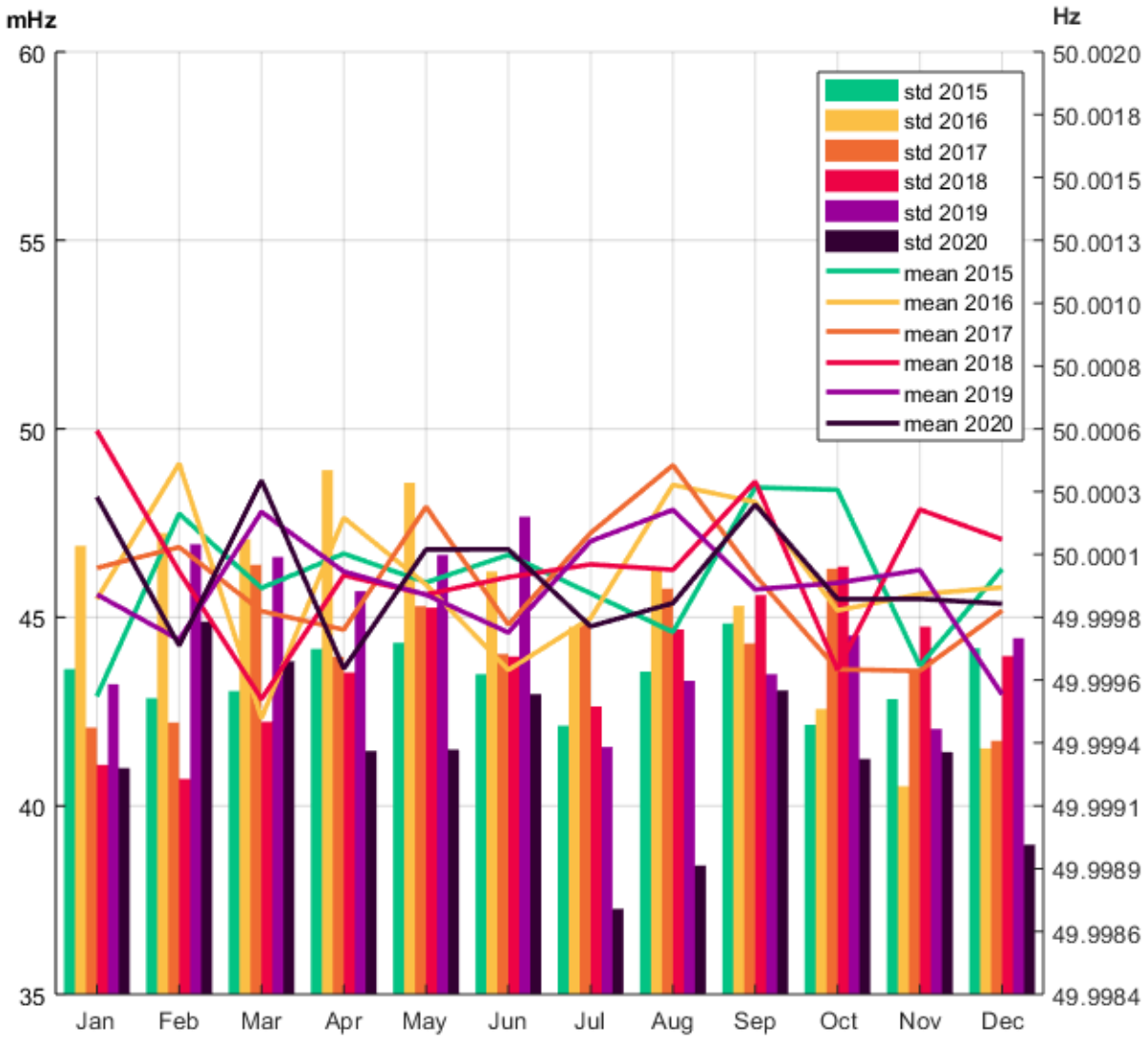
Table 3.1. Mean values and standard deviations for years 2015-2017

	2015		**2016**		**2017**	
Month	**Mean value (Hz)**	**Standard deviation (mHz)**	**Mean value (Hz)**	**Standard deviation (mHz)**	**Mean value (Hz)**	**Standard deviation (mHz)**
January	49.9995	43.6	49.9999	46.9	50.0000	42.1
February	50.0002	42.9	50.0004	47.2	50.0001	42.2
March	50.0000	43.0	49.9995	47.1	49.9999	46.4
April	50.0001	44.2	50.0002	48.9	49.9998	44.0
May	50.0000	44.3	50.0000	48.6	50.0003	45.3
June	50.0001	43.5	49.9996	46.2	49.9998	44.0
July	49.9999	42.1	49.9998	44.8	50.0002	44.9
August	49.9998	43.6	50.0003	46.3	50.0004	45.8
September	50.0003	44.8	50.0003	45.3	50.0000	44.3
October	50.0003	42.2	49.9999	42.6	49.9996	46.3
November	49.9997	42.8	49.9999	40.5	49.9996	43.6
December	50.0000	44.2	50.0000	41.5	49.9999	41.7
Entire year	**50.0000**	**43.4**	**50.0000**	**45.5**	**50.0000**	**44.2**

Table 3.2. 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**

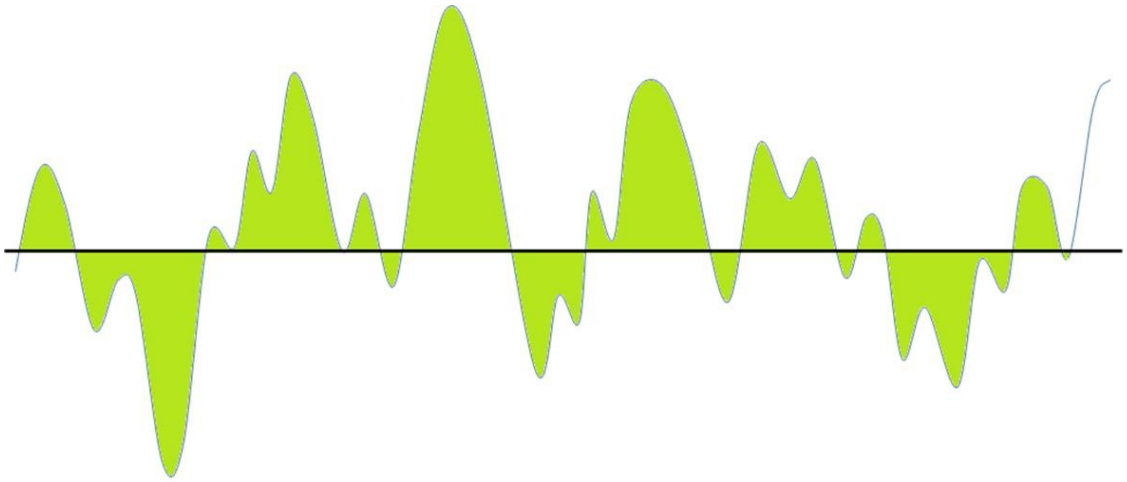
Figure 3.9. Mean values and standard deviations for years 2015-2020



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.

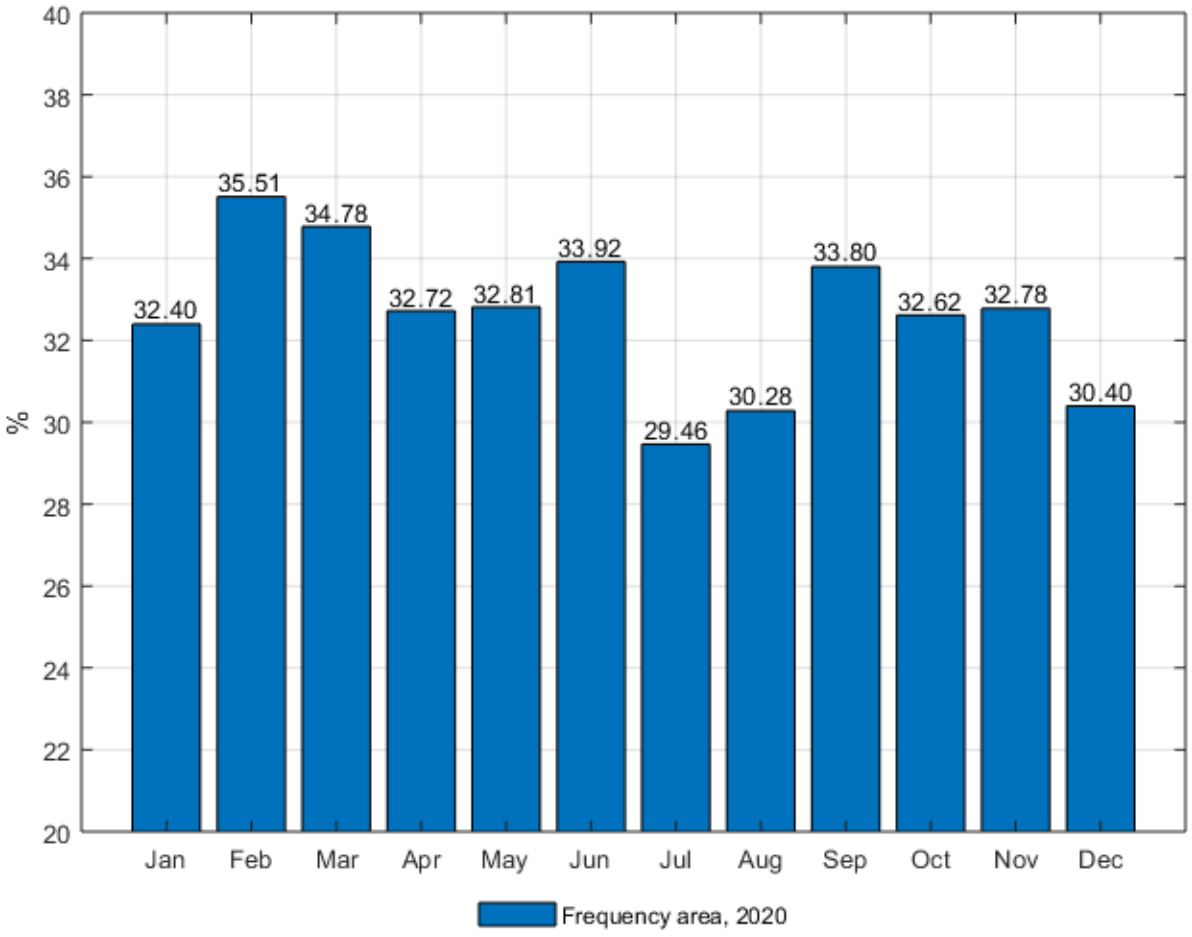
Figure 3.10. Frequency quality index: Frequency area [7]



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

Figure 3.11 represents the average frequency area for every month in 2020. The frequency area has been larger in February and March than in the other months. The percentage of the area has been considerably smaller in July, August and Decenber compared to the other months. The average monthly frequency area was noticeably smaller in 2020 than in 2019.

Figure 3.11. The average frequency area for every month in 2020



The frequency area during each day of the week can be seen in Figure 3.12. The area has been very close to equal between different days but slightly larger in the middle of the week.

Figure 3.12. The average frequency area for every day of the week in 2020

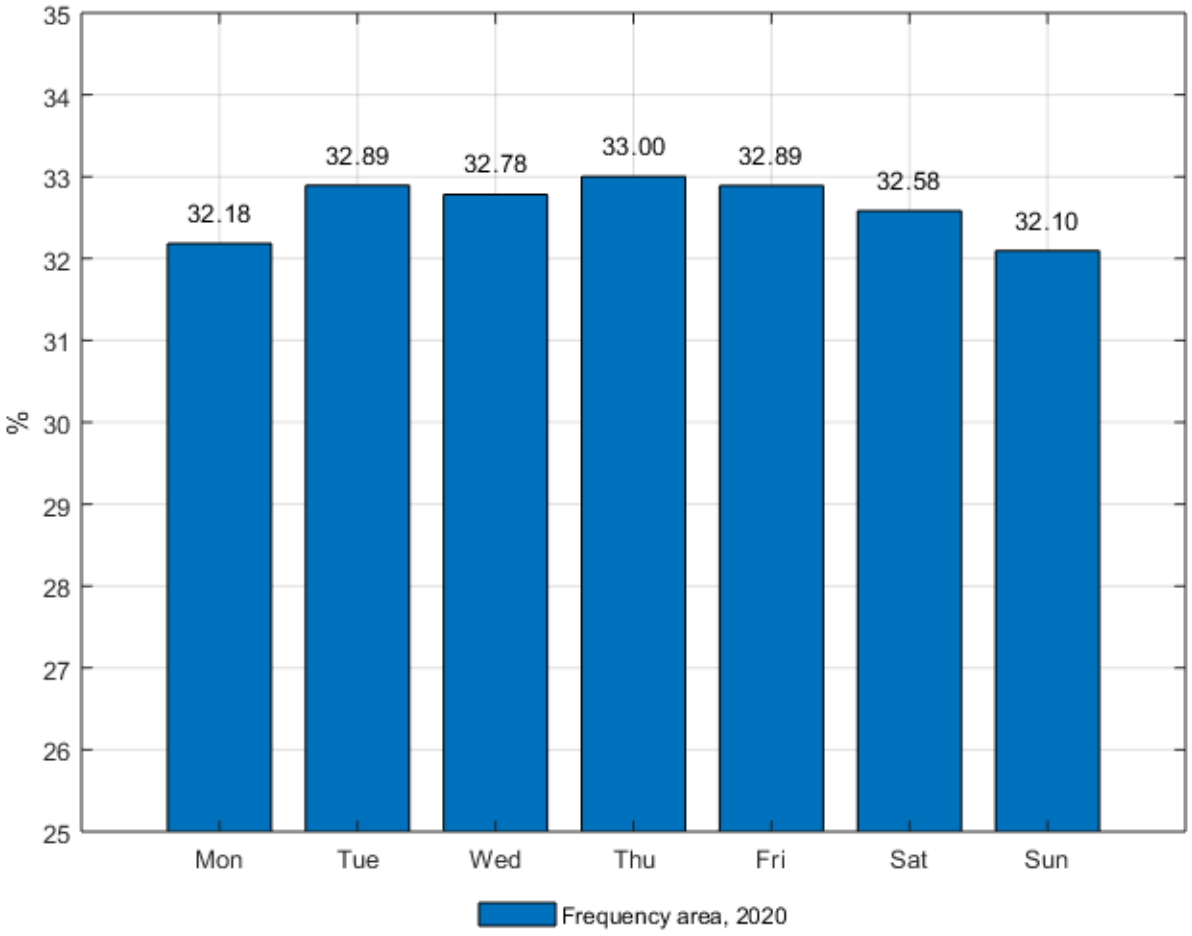


Figure 3.13 has the frequency area for every hour during the day. The figure shows that the deviation of the frequency from 50.0 Hz has been greater in the late morning and in the noon. The percentage of the frequency area has been smaller in the afternoon and especially in the evening.

Figure 3.13. The average frequency area for every hour inside the day in 2020

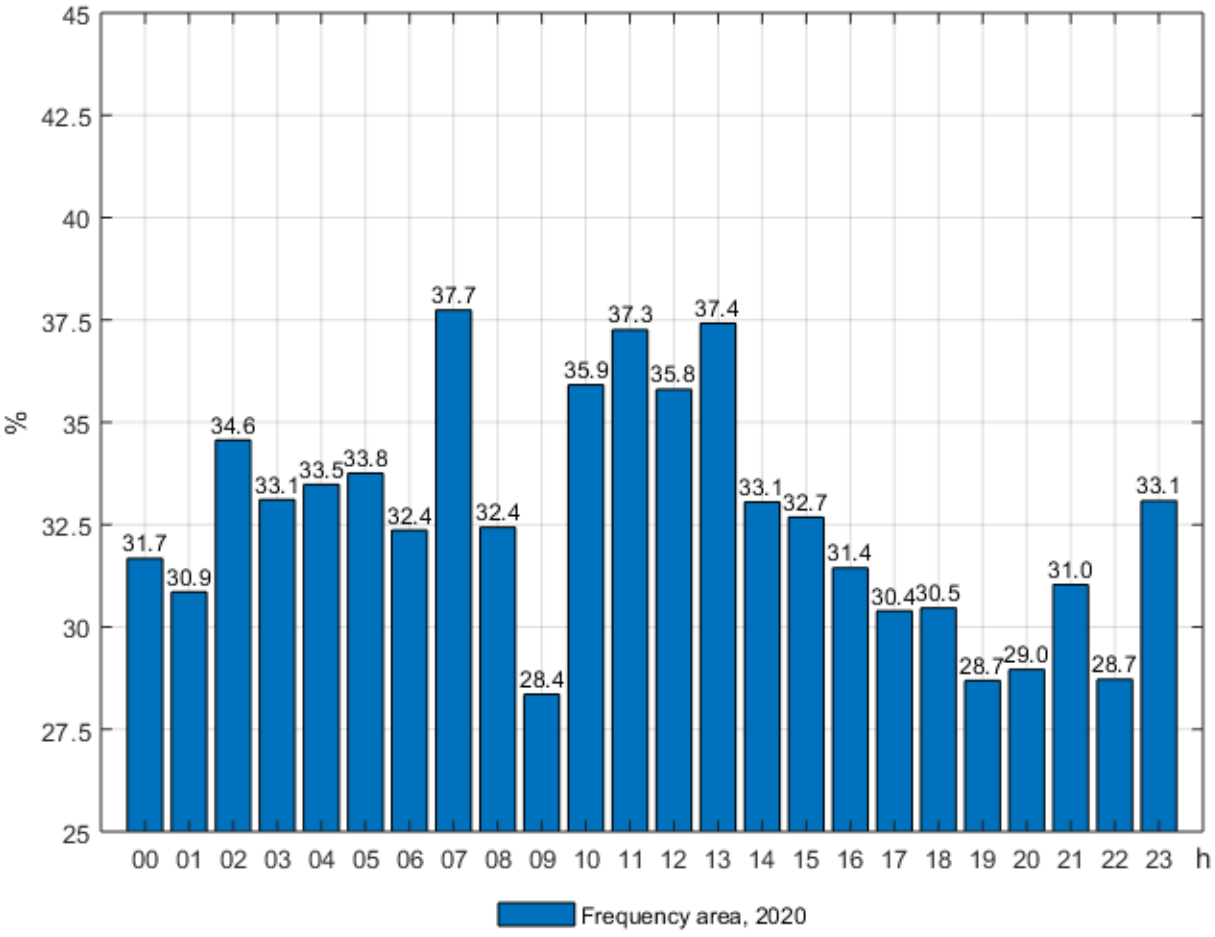
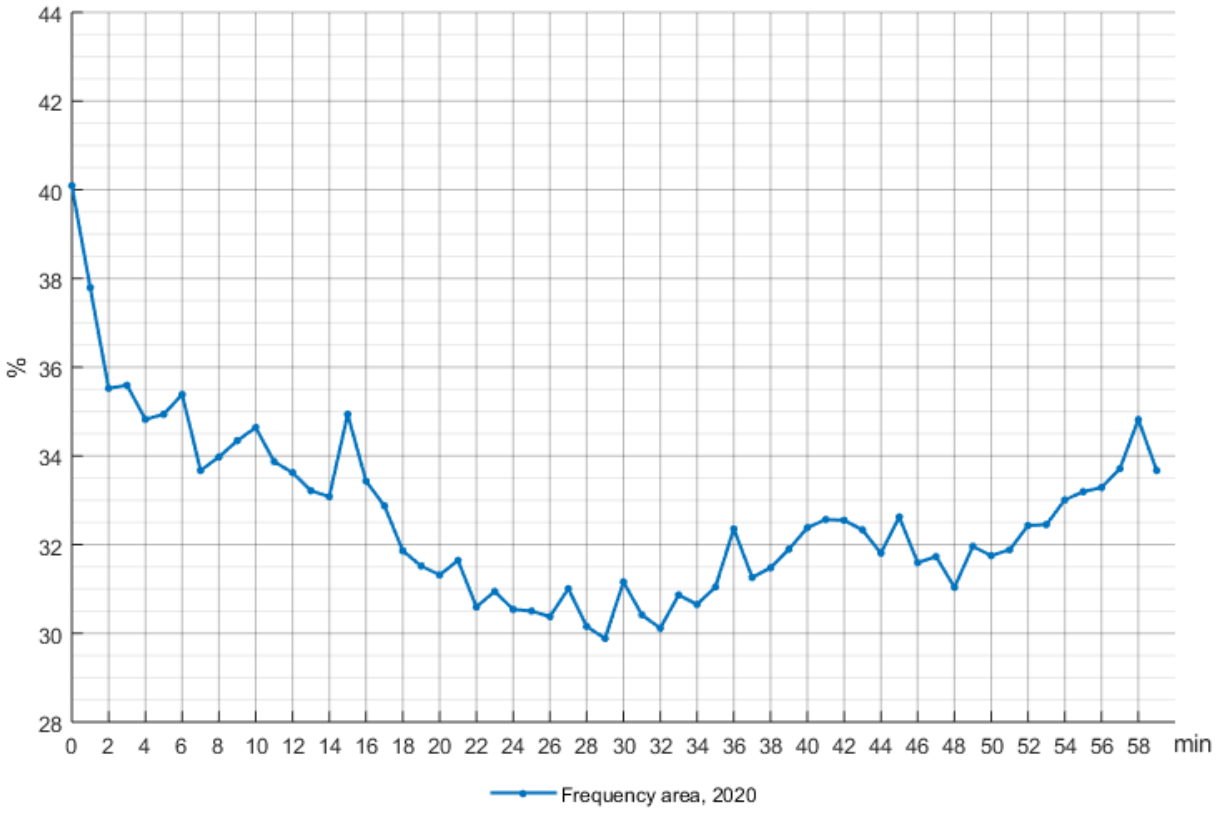


Figure 3.14 represents the frequency area within the hour. The percentage of the frequency area has been smaller in the middle of the hour while more deviation has occurred closer to the hour shift.

Figure 3.14. The average frequency area for every minute within the hour in 2020



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 2015 to 2020. All results are summed up in Figure 3.15.

Table 3.3. The 1st, 5th, 10th, 90th, 95th and 99th percentiles for year 2015

	2015					
Month	**1st (Hz)**	**5th (Hz)**	**10th (Hz)**	**90th (Hz)**	**95th (Hz)**	**99th (Hz)**
Jan	49.900	49.929	49.944	50.055	50.071	50.102
Feb	49.901	49.931	49.946	50.055	50.070	50.101
Mar	49.903	49.931	49.946	50.055	50.071	50.102
Apr	49.900	49.930	49.945	50.057	50.073	50.105
May	49.896	49.927	49.943	50.057	50.072	50.101
Jun	49.900	49.930	49.945	50.056	50.071	50.099
Jul	49.902	49.930	49.945	50.054	50.068	50.095
Aug	49.898	49.929	49.945	50.055	50.072	50.105
Sep	49.900	49.930	49.944	50.058	50.076	50.109
Oct	49.902	49.931	49.946	50.055	50.069	50.095
Nov	49.901	49.930	49.945	50.054	50.070	50.101
Dec	49.900	49.929	49.944	50.057	50.074	50.106
Entire year	**49.900**	**49.930**	**49.945**	**50.056**	**50.071**	**50.102**

Table 3.4. The 1st, 5th, 10th, 90th, 95th and 99th percentiles for year 2016

	2016					
Month	**1st (Hz)**	**5th (Hz)**	**10th (Hz)**	**90th (Hz)**	**95th (Hz)**	**99th (Hz)**
Jan	49.897	49.925	49.940	50.060	50.077	50.110
Feb	49.892	49.925	49.941	50.061	50.078	50.110
Mar	49.896	49.924	49.939	50.061	50.077	50.108
Apr	49.887	49.920	49.937	50.063	50.080	50.111
May	49.887	49.922	49.939	50.062	50.080	50.117
Jun	49.893	49.924	49.941	50.058	50.075	50.108
Jul	49.897	49.927	49.943	50.057	50.073	50.105
Aug	49.896	49.926	49.941	50.060	50.077	50.109
Sep	49.896	49.928	49.943	50.059	50.075	50.106
Oct	49.903	49.931	49.946	50.055	50.070	50.100
Nov	49.905	49.933	49.948	50.052	50.067	50.094
Dec	49.905	49.934	49.948	50.052	50.069	50.103
Entire year	**49.896**	**49.926**	**49.942**	**50.058**	**50.075**	**50.107**

Table 3.5. 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 3.6. 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**

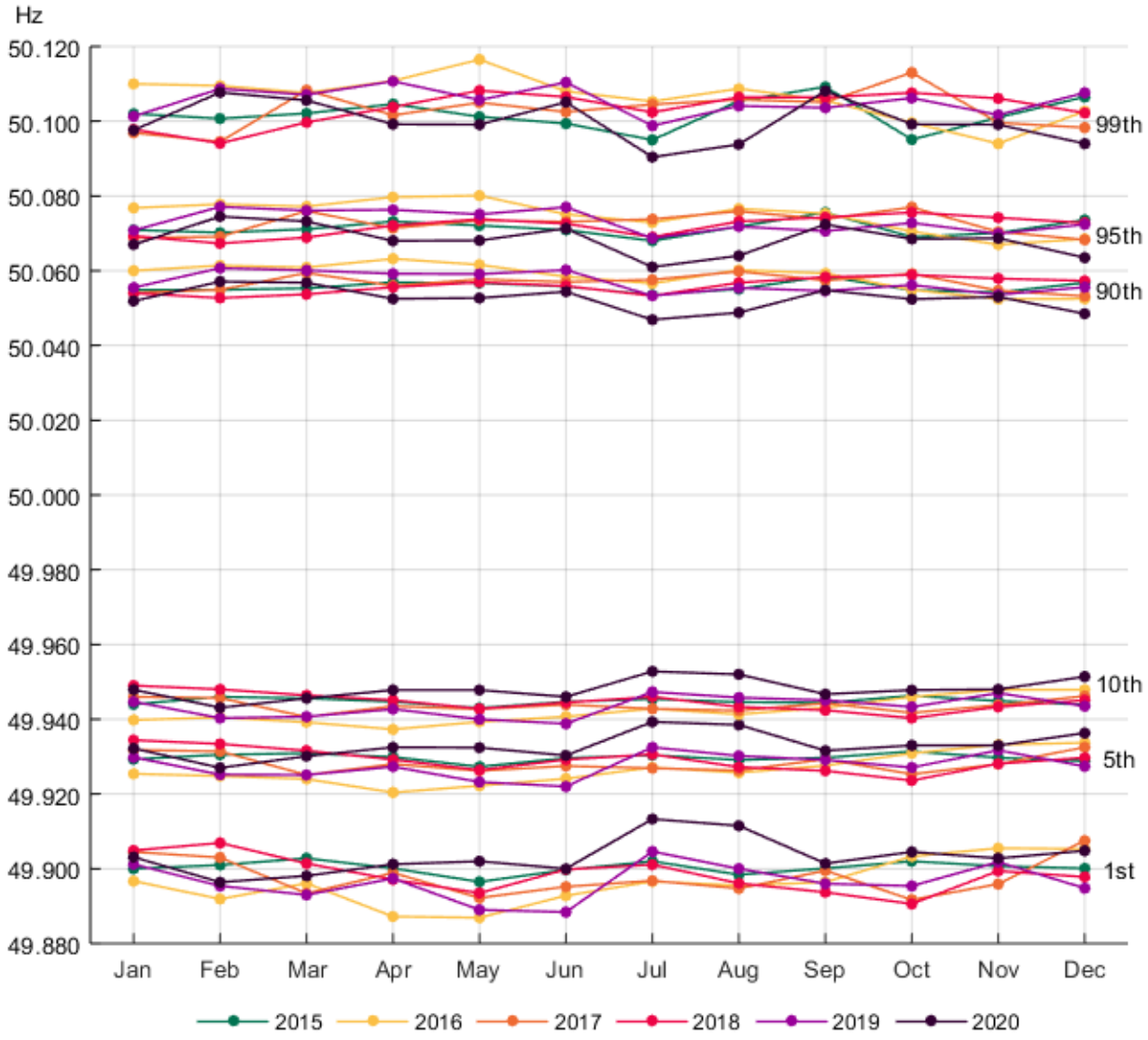
Table 3.7. The 1st, 5th, 10th, 90th, 95th and 99th percentiles for year 2019

	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 3.8. 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**

Figure 3.15. The 1st, 5th, 10th, 90th, 95th and 99th percentiles for years 2015-2020



More detailed results for the percentiles of 2020 are shown in the next figures. Figure 3.16 is a visual representation of the given percentiles for each month in 2020. The percentiles in February are furthest from 50 Hz, which indicates that the frequency has deviated the most during that month. Similarly, in July the percentiles are closest to 50 Hz which suggests that there have been least deviations during that month.

Figure 3.16. The 1st, 5th, 10th, 90th, 95th and 99th percentile of the frequency for every month in 2020

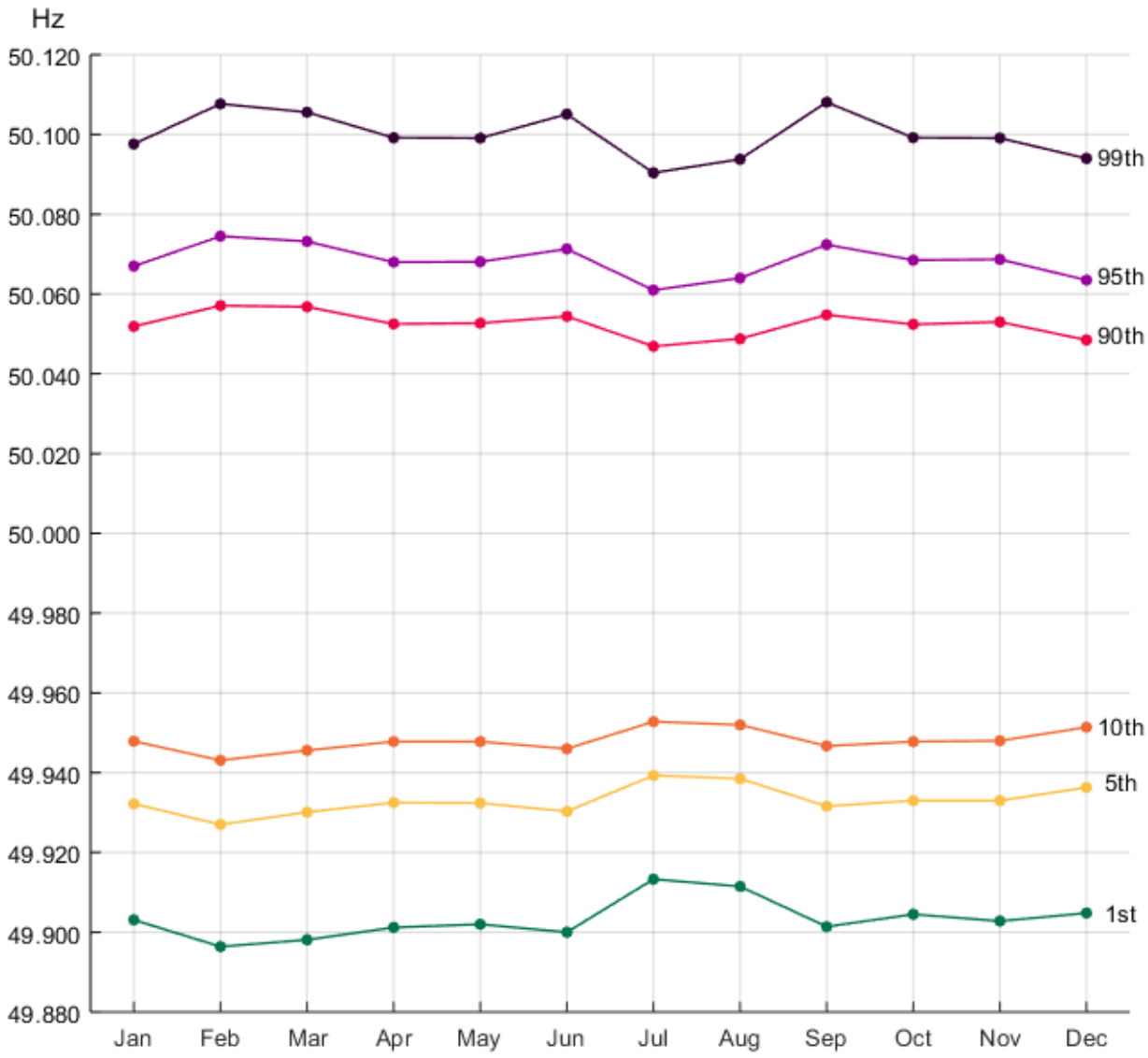


Figure 3.17 shows the percentiles for every day during the week. All percentiles are slightly higher on Wednesday, which indicates that there have been more over frequencies during Wednesdays. Apart from subtle variations, the percentiles stay rather constant during the week.

Figure 3.17. The 1st, 5th, 10th, 90th, 95th and 99th percentile of the frequency for every day of the week in 2020

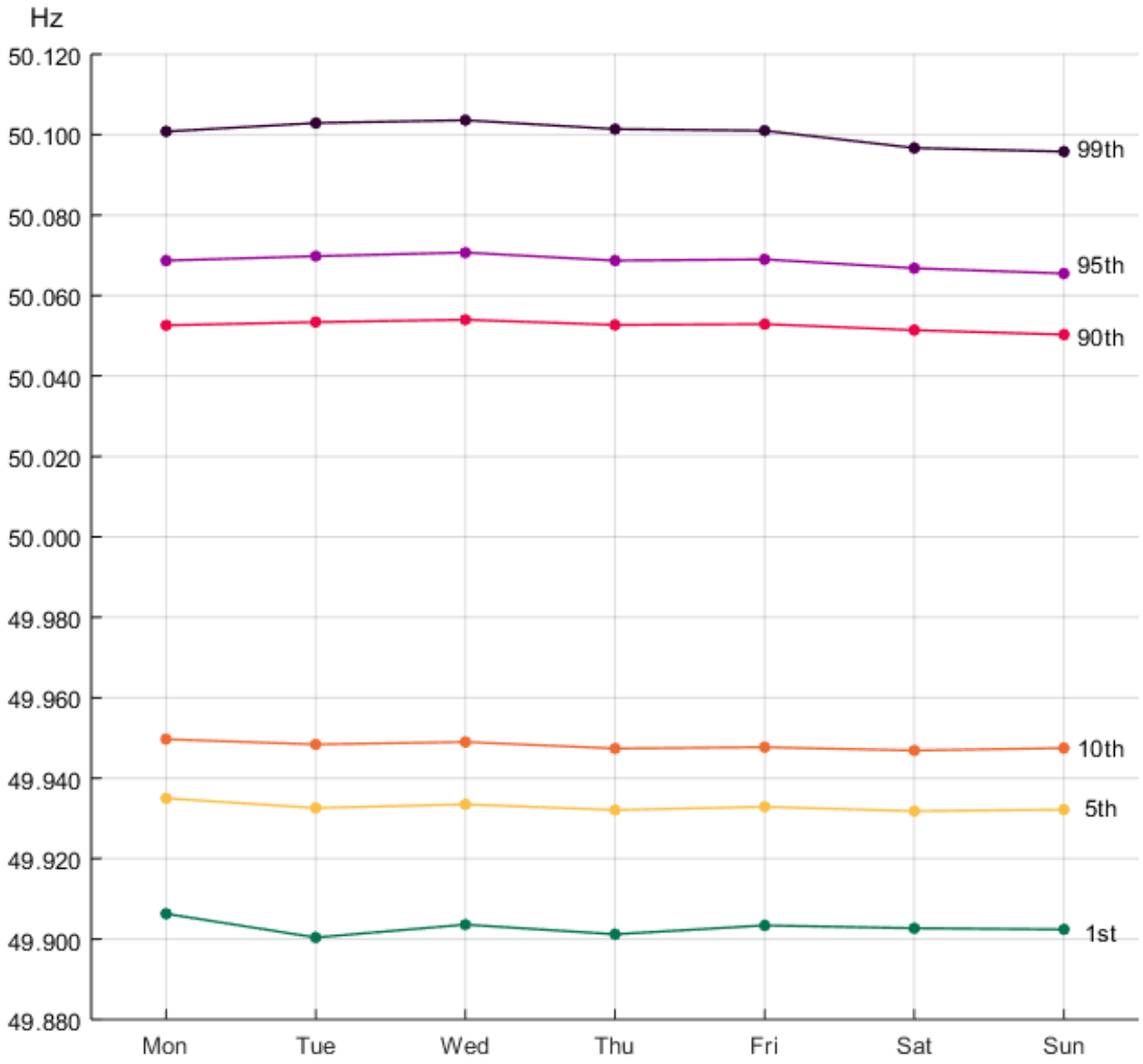


Figure 3.18 represents the percentiles inside the day. All percentiles gain higher values at midnight, which indicates that there have been more over frequencies and less under frequencies at midnight. On the next hour the situation is opposite. There have been less over frequencies and more under frequencies 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 2020

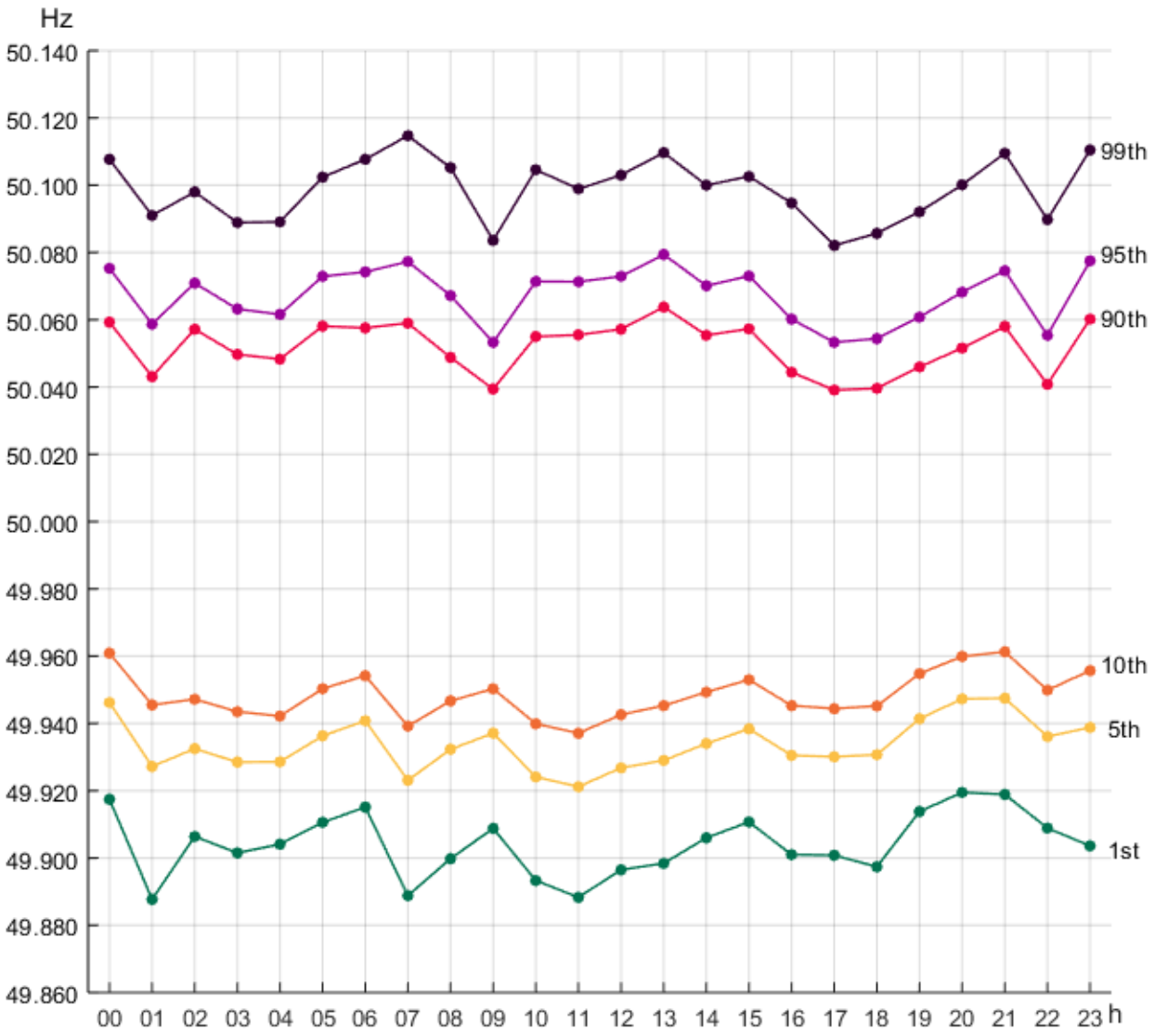
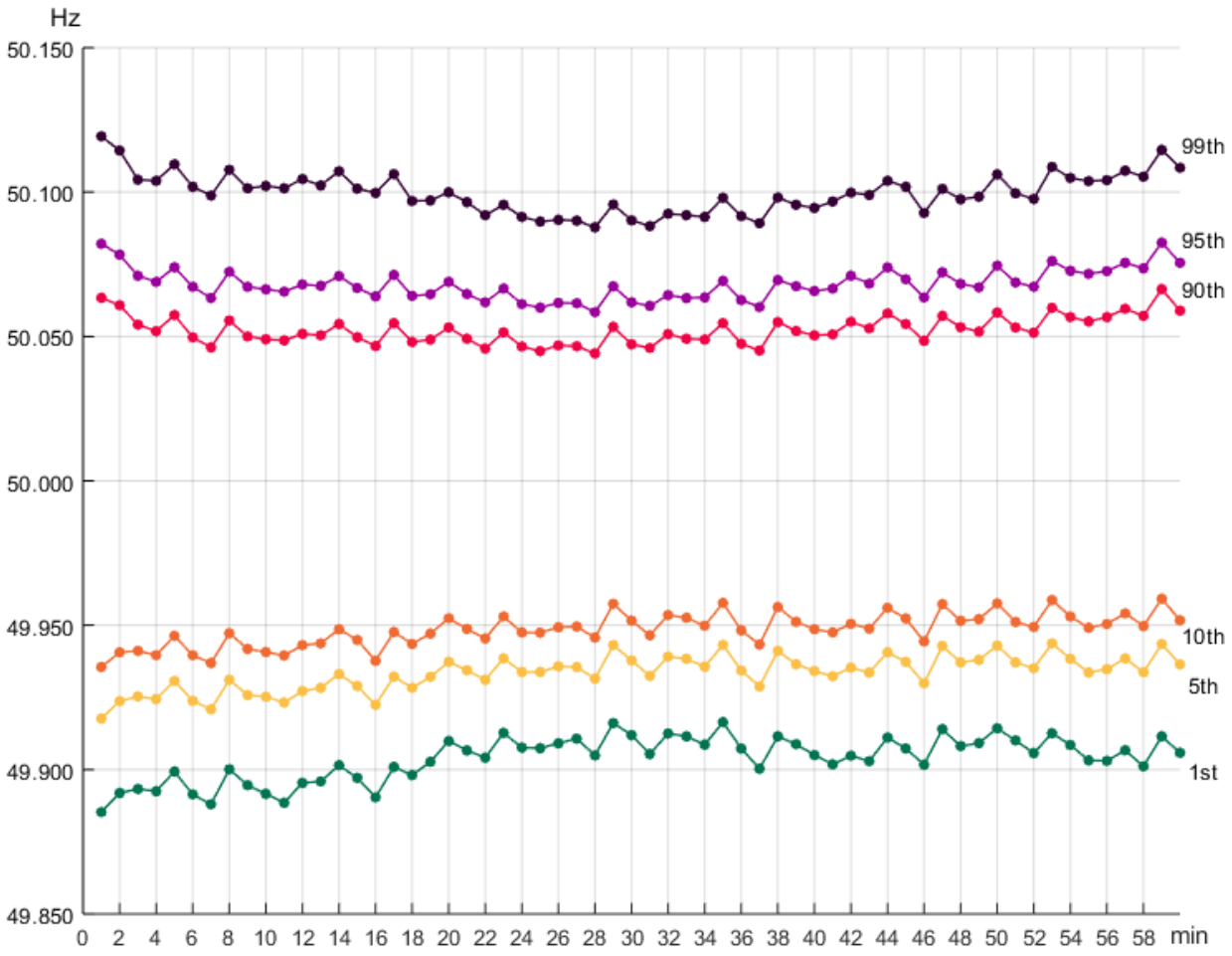


Figure 3.19 shows the percentiles inside the hour. Overall, more frequency deviations have occurred during the hour shift. The 90th, 95th and 99th percentiles gain the highest values and the 10th, 5th and 1st percentiles gain the lowest values at the first minute of the hour. The variation of the percentile values between consecutive minutes has increased from year 2019.

Figure 3.19. The 1st, 5th, 10th, 90th, 95th and 99th percentile of the frequency for every minute inside the hour in 2020



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 2020. The cumulative growth of minutes otside the standard frequency range has been fastest in the first half of the year. From the beginning of June untill the end of August the cumulative growth has been drastically slower. After August the growth speed has been similar to the growth speed in the beginning of the year. The frequency has been outside the standard range less than 10 000 minutes: close to 5400 minutes over 50.1 Hz and close to 4500 minutes under 49.9 Hz. The Nordic target for less than 10 000 minutes outside the standard frequency range has been reached. The time outside standard frequency range has significantly reduced from 2019.

Figure 3.20. Cumulative minutes outside the standard frequency range in 2020

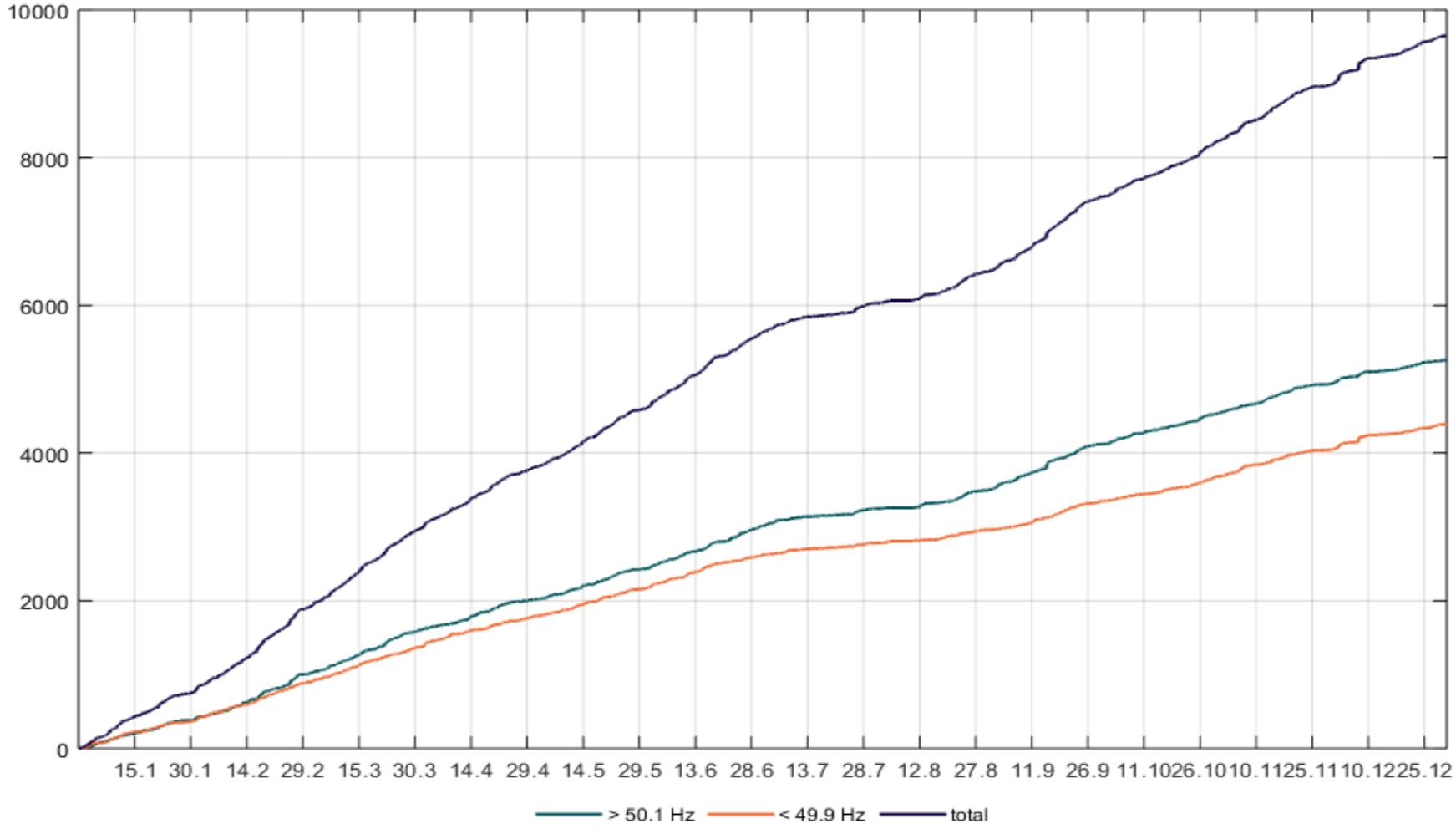
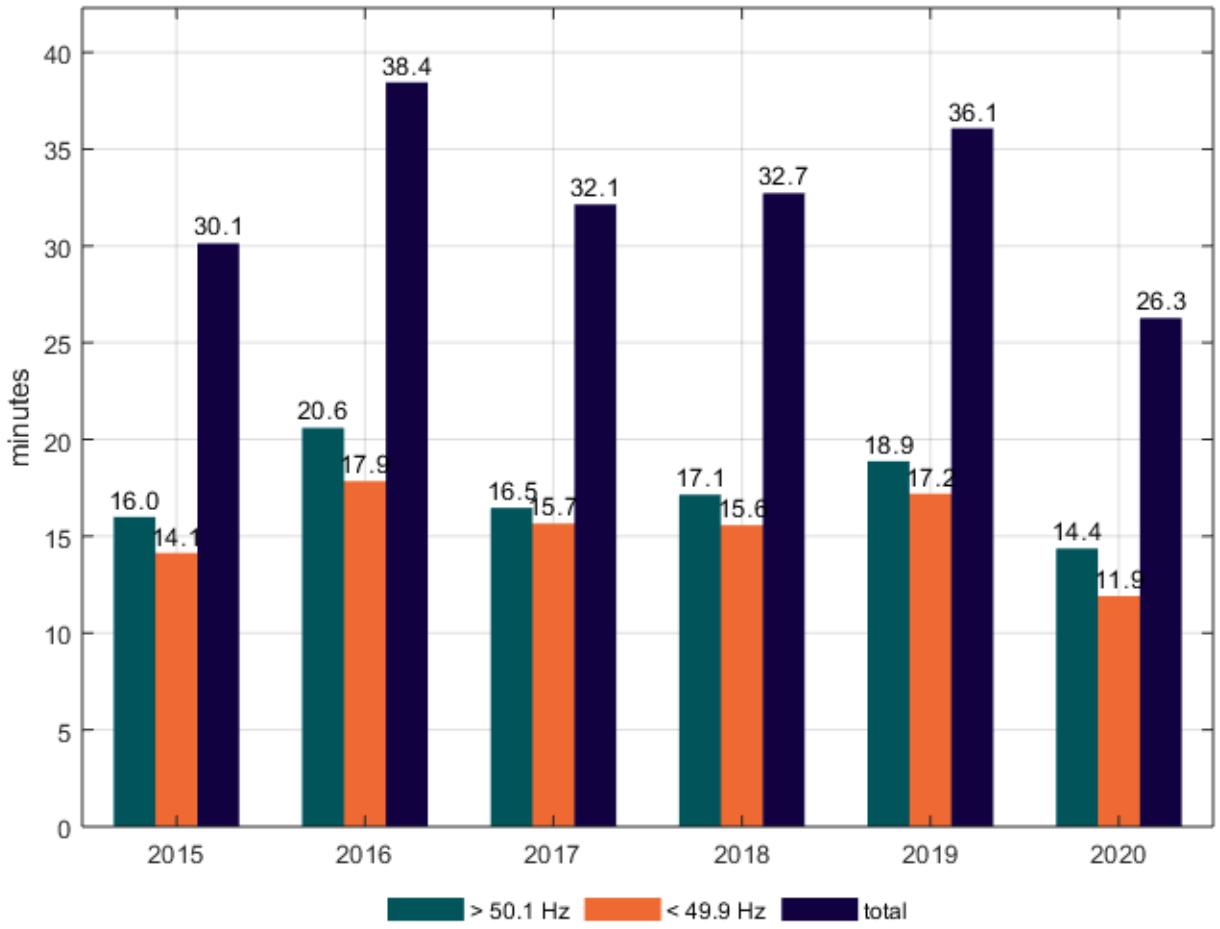


Figure 3.21 represents the daily average number of minutes per year that the frequency was outside the standard frequency range. The number of minutes outside the standard frequency range in 2020 has clearly been lower than on the previous years. Every year there have been more over frequencies than under frequencies.

Figure 3.21. Daily average number of minutes per year that the frequency was outside the standard frequency range in 2015-2020



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
2015	1.11 %	0.98 %	97.91 %
2016	1.44 %	1.25 %	97.31 %
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 %

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 the 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)
2015	5844	5166	11010
2016	7586	6574	14160
2017	6185	5884	12069
2018	6328	5755	12083
2019	6997	6377	13374
2020	5375	4456	9831

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 2015 to 2020. 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 2015-2017

	2015		**2016**		**2017**	
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	498	444	723	526	362	345
February	420	379	687	612	272	338
March	506	376	679	566	669	611
April	544	428	779	809	471	460
May	478	535	962	820	577	642
June	414	438	607	594	501	549
July	323	397	587	537	569	530
August	579	485	704	572	504	476
September	678	428	584	523	564	442
October	314	398	434	362	703	573
November	454	414	288	310	420	522
December	629	443	504	325	399	266
Entire year	**5838**	**5165**	**7539**	**6555**	**6011**	**5756**

Table 3.12. Total time in 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**

Figure 3.22. Total time in which the frequency was outside the 49.9-50.1 band in years 2015-2020

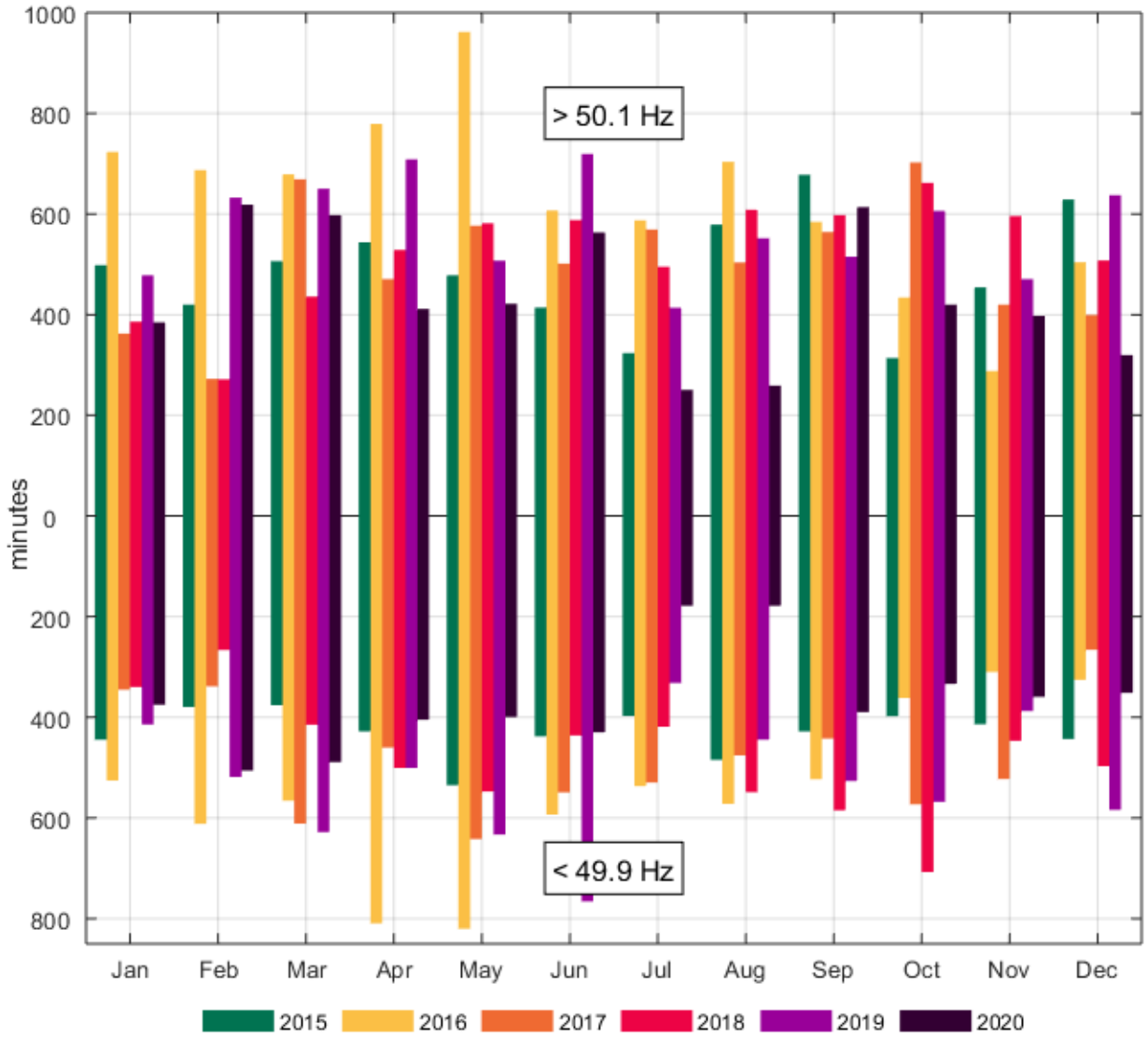


Figure 3.23 shows the daily average in minutes month by month when the frequency has been outside the standard frequency range in years 2015-2020. In 2020, February has had the longest time outside the standard frequency range. July and August have clearly had the best frequency in this comparison.

Figure 3.23. Daily average time that the frequency was outside the standard frequency range month by month for years 2015-2020

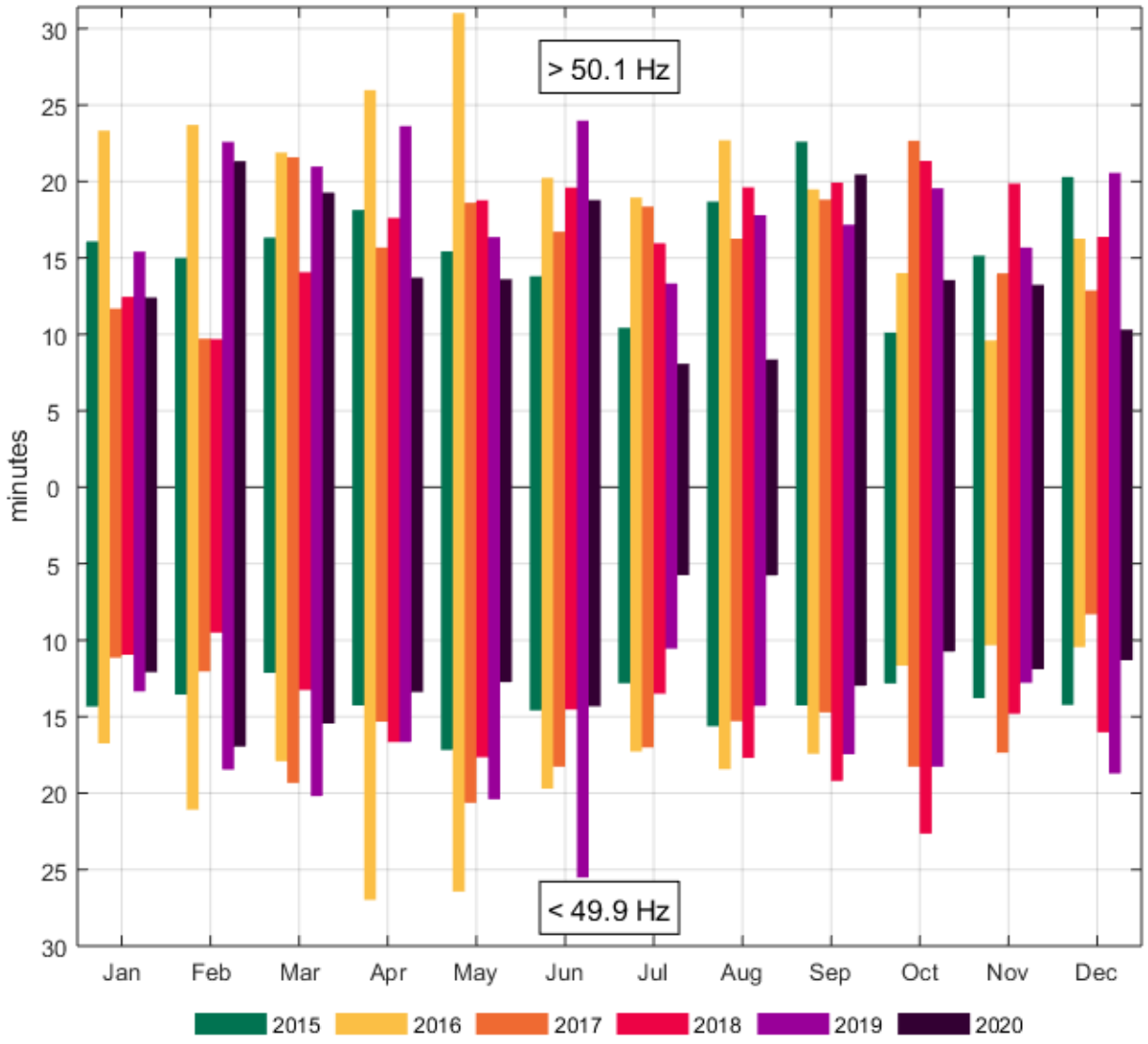


Figure 3.24 represents the daily averge time that the frequency has been outside the standard frequency range during each day of the week. In 2020 the frequency has been outside the standard frequency range the most on Tuesdays and the least on the weekends. The result is almost opposite to year 2019 when the frequency was outside the standard frequency range the most on the weekends.

Figure 3.24. Daily average time that the frequency was outside the standard frequency range during each day of the week for years 2015-2020

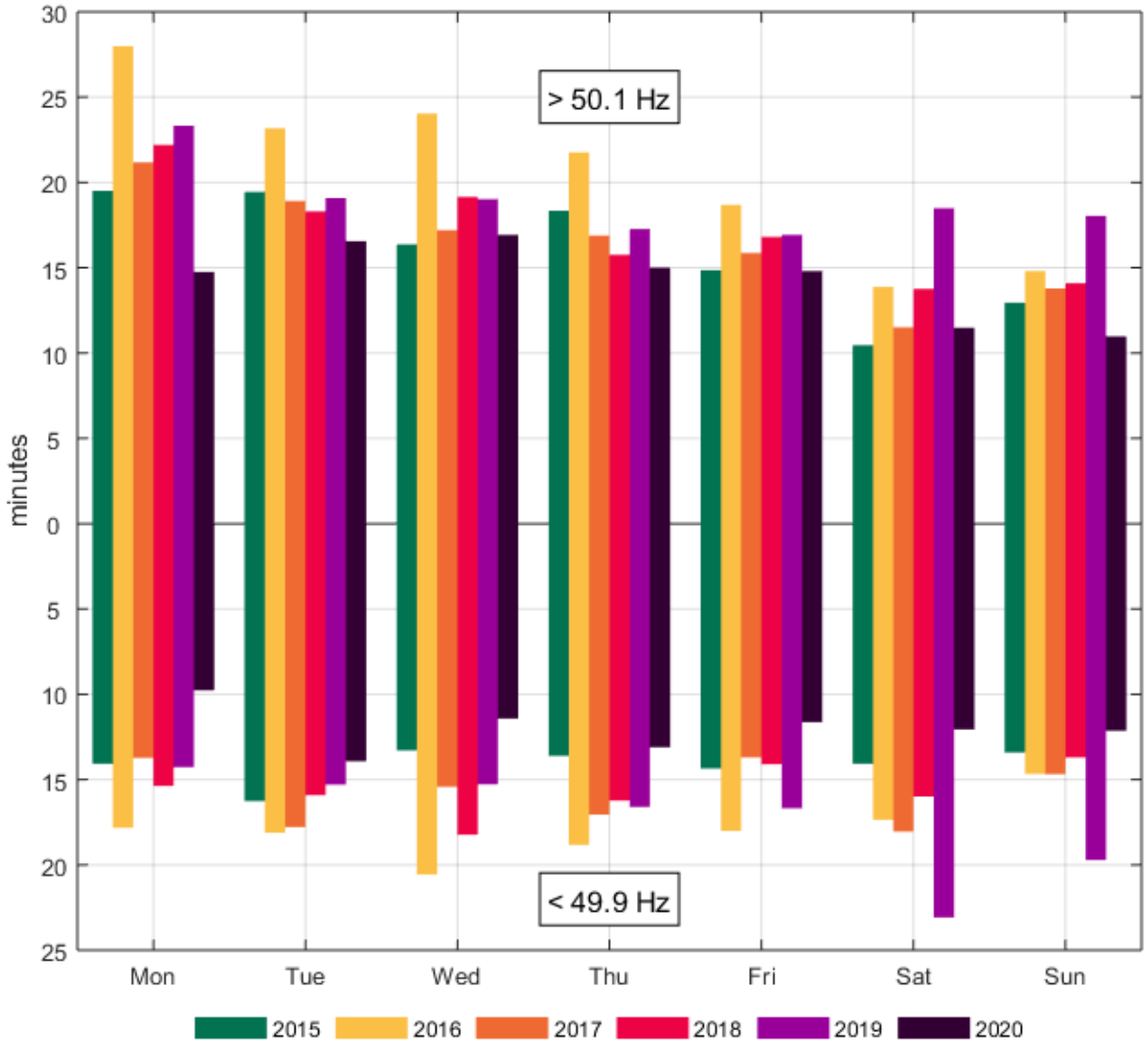


Figure 3.25 represents the daily average time that the frequency was outside the standard frequency range for each hour in the day. The hours are according to the Finnish time (UTC+2 / UTC+3 in the summer). In 2020, the frequency has been over 50.1 Hz the most at the hours 7, 13 and 23 and under 49.9 Hz the most at the hours 1, 7 and 11. The frequency has been outside the standard frequency range more frequently during the morning hours, except for hour 9, and in the early afternoon. Frequency has stayed inside the standard frequency range the best during hours from 2 to 4 and from 17 to 20.

Figure 3.25. Daily average time that the frequency was outside the standard frequency range during each hour of the day for years 2015-2020

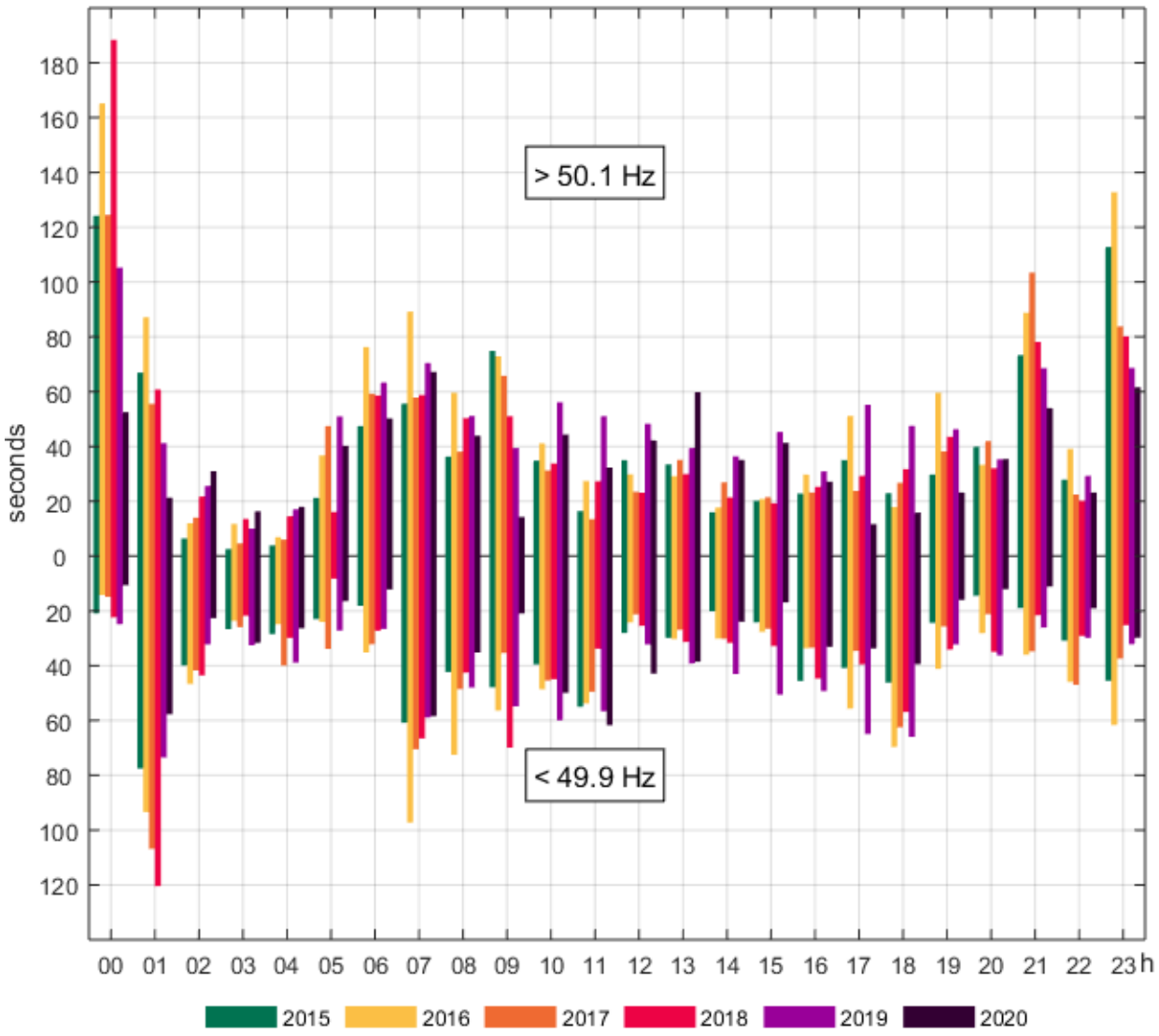


Figure 3.26 shows the daily average time outside the standard frequency range per hour and absolute value of Nordic consumption and production difference. Also transmission difference of HVDC links connecting the Nordic power system to Continental Europe and Russia is presented.

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 Nord Pool 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 Nordic production difference curve peaks close to 2500 MWh while the consumption difference curve peaks close to 2200 MWh. Near midnight the peaks for production and consumption differences are around 1700 MWh. The highest value of frequency deviation occurs in hour 7 when the production and consumption difference curves peak. However, significant deviation also occurs in the early afternoon when the differences in production, consumption and HVDC transmission are not very significant. Compared to the year 2019, the differences in production, consumption and HVDC transmission have decreased substantially.

Figure 3.26. Seconds per hour outside the standard frequency range and the absolute values of Nordic consumption, production and HVDC transmission differences in 2020

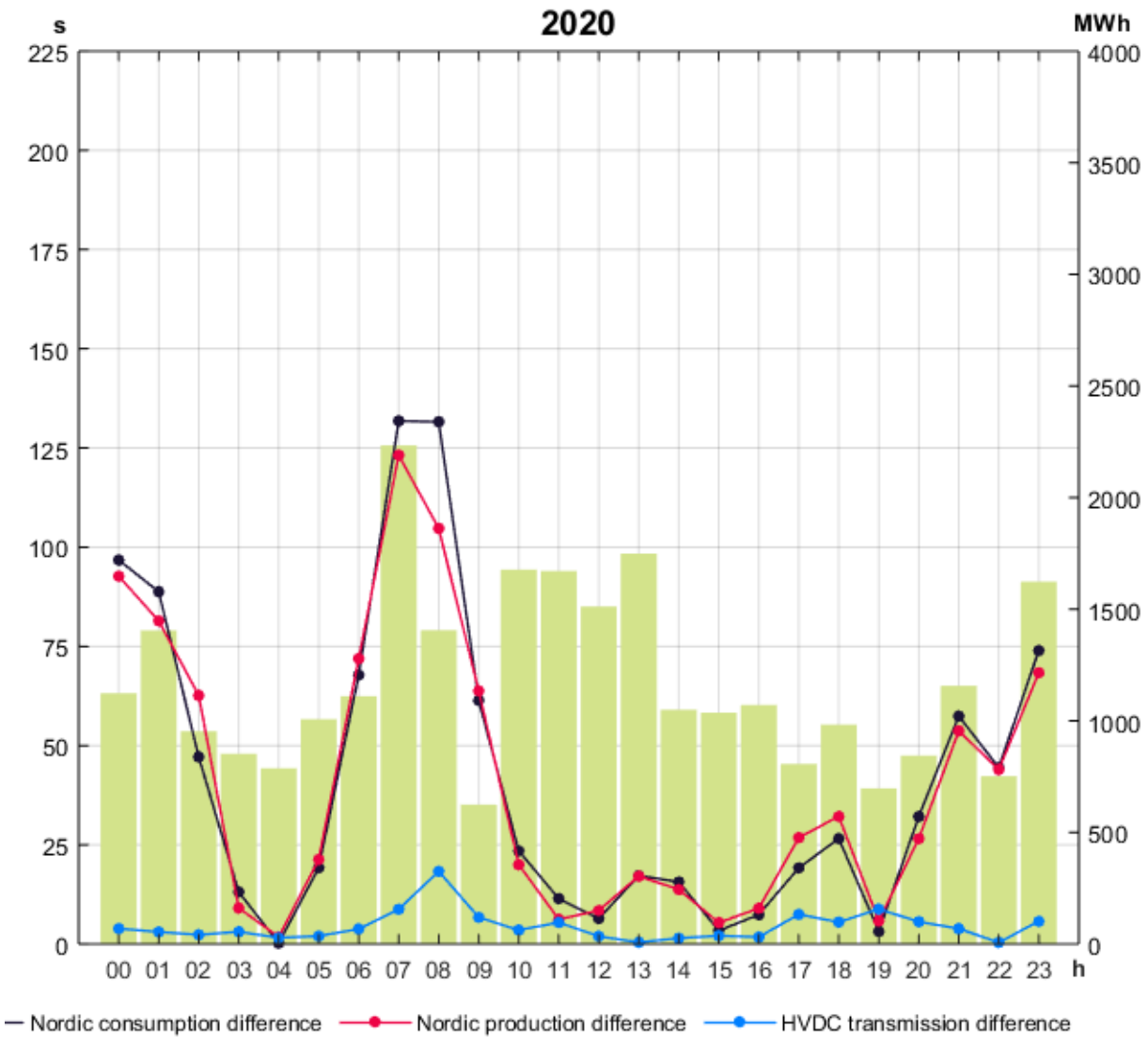


Figure 3.27 illustrates an average hour divided to 60 minutes. For each minute of the average hour there is a value in seconds per hour that frequency has been over or below the standard frequency range. In years 2015-2020 the frequency has been outside the standard frequency range most often in the beginning of the hour. The frequency has stayed best inside the standard frequency range in the middle of the hour. The time outside 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 2015-2020 for each minute of an average hour

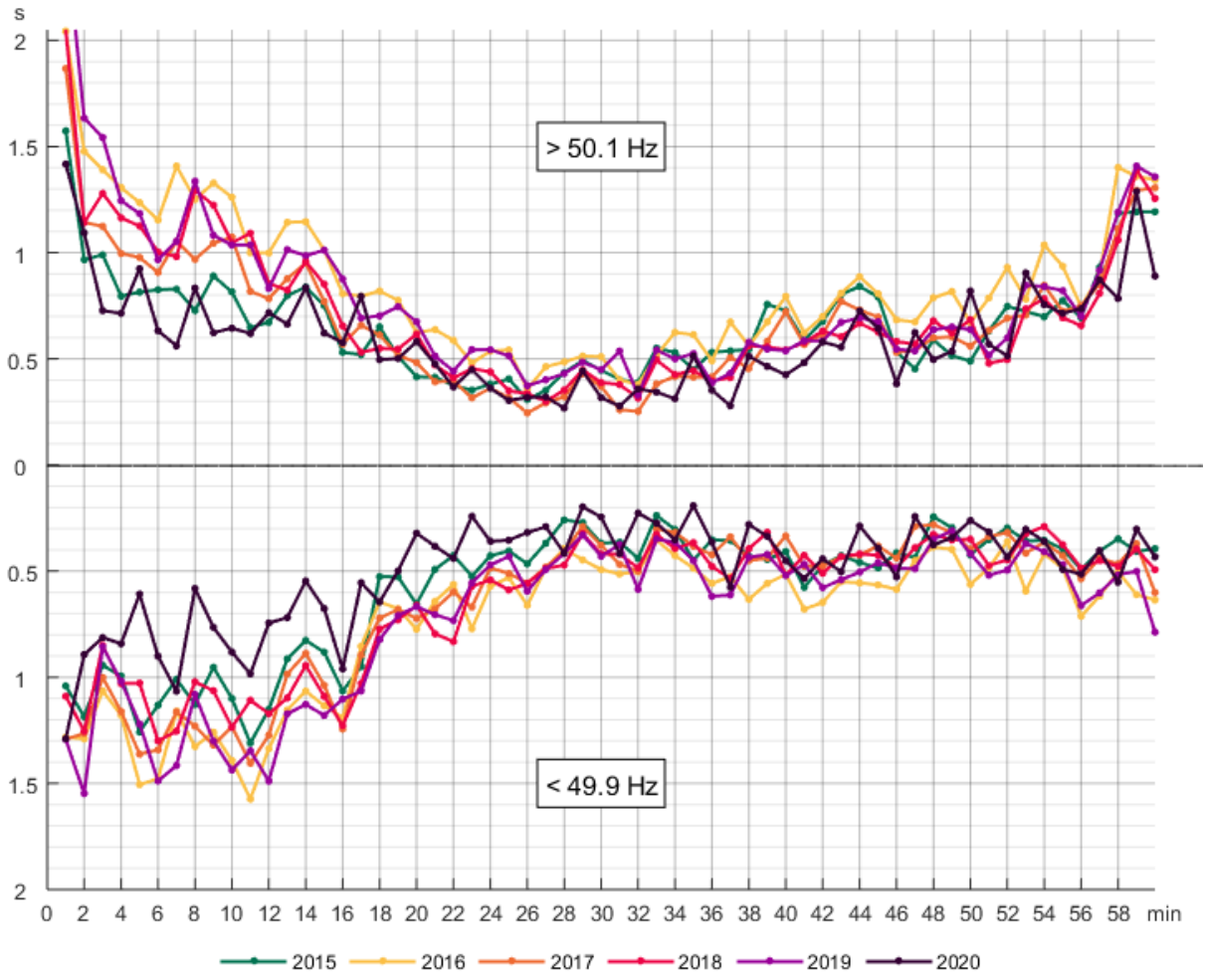
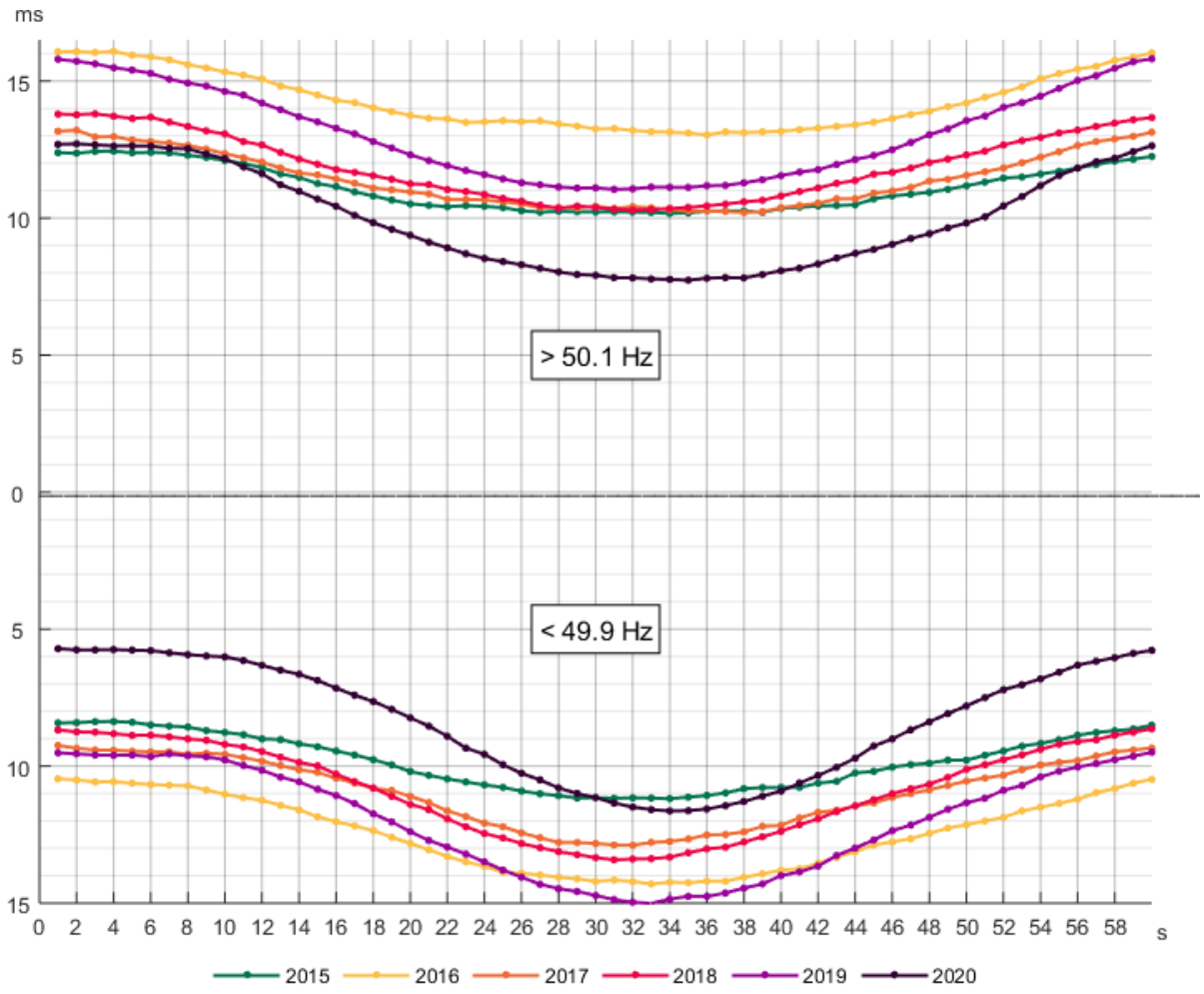


Figure 3.28 illustrates an average minute divided into 60 seconds. For each second of the average minute there is a value in milliseconds per minute that the frequency has been over or below the standard frequency range. There have been more over frequencies at the beginning and at the end of the average minute. Under frequencies have occurred more frequently in the middle of the minute. The 2020 curve has more pronounced shape compared to previous years, but generally less over and under frequencies have occurred in 2020 compared to the previous years.

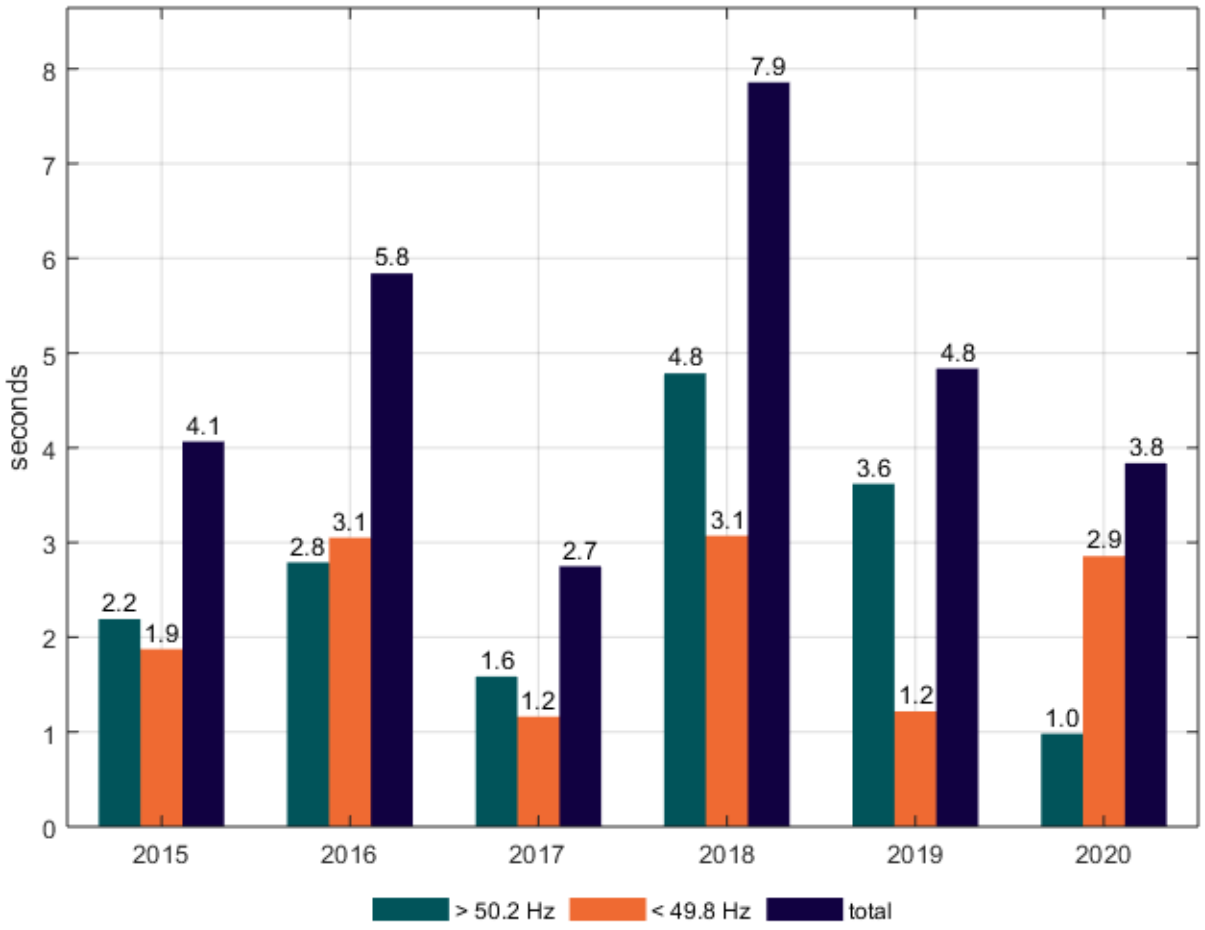
Figure 3.28. Number of milliseconds per minute outside the standard frequency range in 2015-2020 for each second of an average minute



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 2020 than in 2019. In 2020, under frequencies exceeding 200 mHz have been much more common than over frequencies. In the previous years, except for year 2016, over frequencies have been more common.

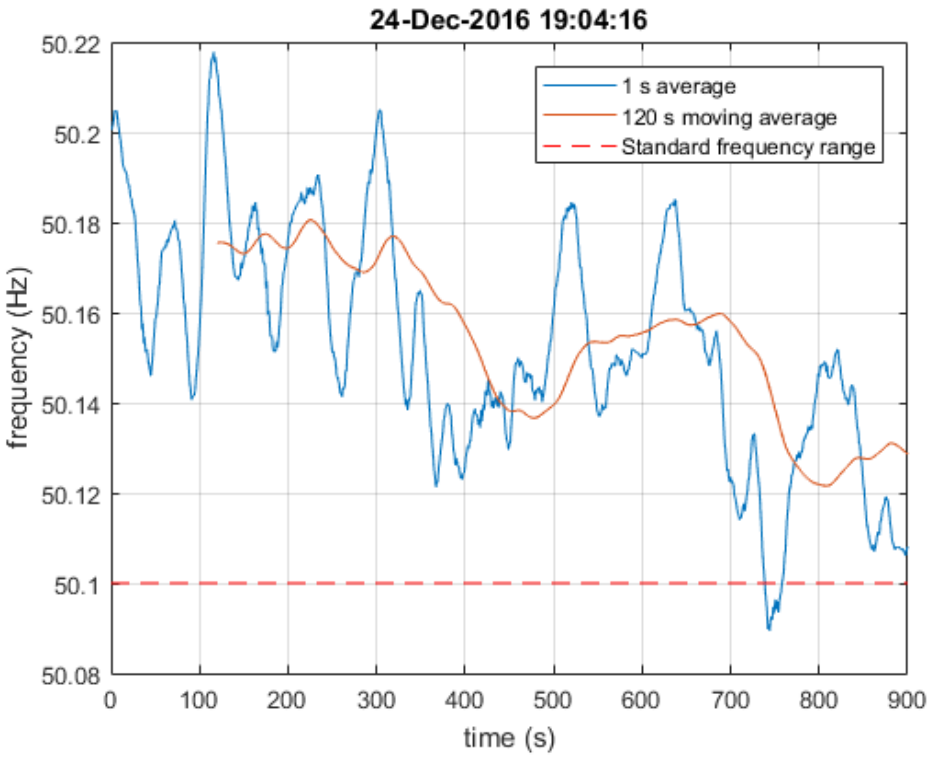
Figure 3.29. Average number of seconds per day that the frequency was outside the 49.8-50.2 Hz band for years 2015-2020



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 2015-2020 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.

	2015		**2016**		**2017**		**2018**		**2019**		**2020**	
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	1	0	0	0	0	0	0	0	0	0
February	0	0	0	0	0	0	0	0	0	0	0	0
March	0	0	0	0	0	0	0	0	0	0	0	0
April	0	0	0	0	0	0	0	0	0	0	0	0
May	0	0	0	0	0	0	1	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	0	0	0	0	1	0	0	1	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	0	0	0	1	1	0	0	**1**	**0**

Table 3.14 shows the number of events in 2015-2020 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.

	2015		**2016**		**2017**		**2018**		**2019**		**2020**	
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	1	0	3	0	0	0	0	0	0	0	0	0
February	2	0	0	1	0	0	0	0	1	0	0	0
March	0	0	0	0	0	0	0	0	0	0	0	0
April	4	0	1	0	1	0	0	0	1	0	0	0
May	0	0	0	0	1	0	2	0	0	0	0	0
June	0	0	0	0	1	0	2	0	0	1	0	0
July	0	0	1	0	0	0	1	0	0	0	0	0
August	2	0	0	0	0	0	0	0	0	0	0	0
September	1	0	1	0	0	0	0	1	0	0	1	0
October	0	0	2	0	0	0	0	0	1	0	0	0
November	0	0	0	0	0	0	1	0	0	0	0	0
December	0	0	1	0	0	0	0	1	1	0	0	0
Entire year	10	0	9	1	3	0	6	2	4	1	**1**	**0**
Sum	**10**		**10**		**3**		**8**		**5**		**1**	

3.4.3 Time outside 49.0-51.0 Hz

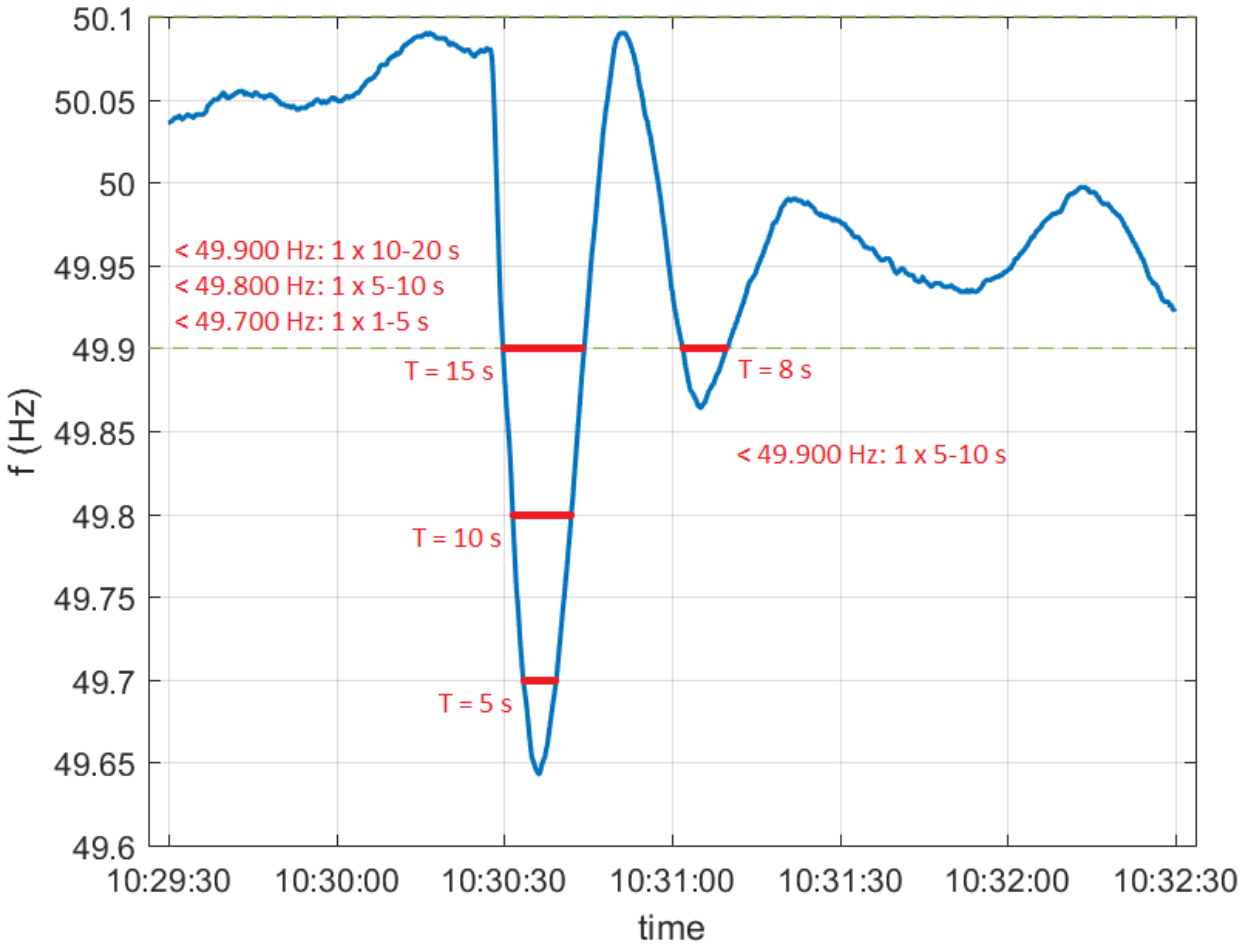
Time outside 49.0 Hz and 51.0 Hz is calculated by counting the number of samples that are below 49.0 Hz or above 51.0 Hz and multiplying the number by the time duration of the sample. The criteria are also defined in SO GL Article 131(1)(a) (v). The resolution of the data used was 1 second.

There were no instances in 2015-2020 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 [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 that was used is 0.1 seconds.

Tables 3.15-3.20 provide more detailed information about frequency deviations from year 2015 to 2020. 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 2015

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	16558	5750	3730	5174	3166	827	610	115	35930	1173.70	9.52
> 50.2	52	26	23	22	6	3	0	0	132	53.90	6.31
> 50.3	1	2	0	0	0	0	0	0	3	2.70	1.73
< 49.9	14642	5590	3165	4648	2958	725	519	98	32345	734.50	9.32
< 49.8	38	15	20	29	5	0	0	0	107	27.10	6.59
< 49.7	0	3	7	1	0	0	0	0	11	11.60	6.34
< 49.6	0	1	2	0	0	0	0	0	3	6.20	5.50
< 49.5	0	0	0	0	0	0	0	0	0	0.00	0.00

Table 3.16. Total number of frequency deviation in 2016

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	18827	6452	4288	6553	4249	955	857	150	42331	1418.20	10.45
> 50.2	44	30	43	20	11	0	1	0	149	75.70	7.10
> 50.3	1	8	0	0	0	0	0	0	9	4.70	2.88
< 49.9	17236	6454	3875	5762	3992	850	652	119	38940	549.50	9.82
< 49.8	52	36	43	27	5	2	2	0	167	69.50	6.87
< 49.7	1	2	3	2	0	0	0	0	8	11.90	6.43
< 49.6	0	1	1	0	0	0	0	0	2	5.60	4.35
< 49.5	0	0	0	0	0	0	0	0	0	0.00	0.00

Table 3.17. 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 3.18. 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 3.19. 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 3.20. 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

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 where as years 2016 and 2019 have had the most deviations in the observation period.

Figure 3.32. Daily average number of frequency deviations per duration

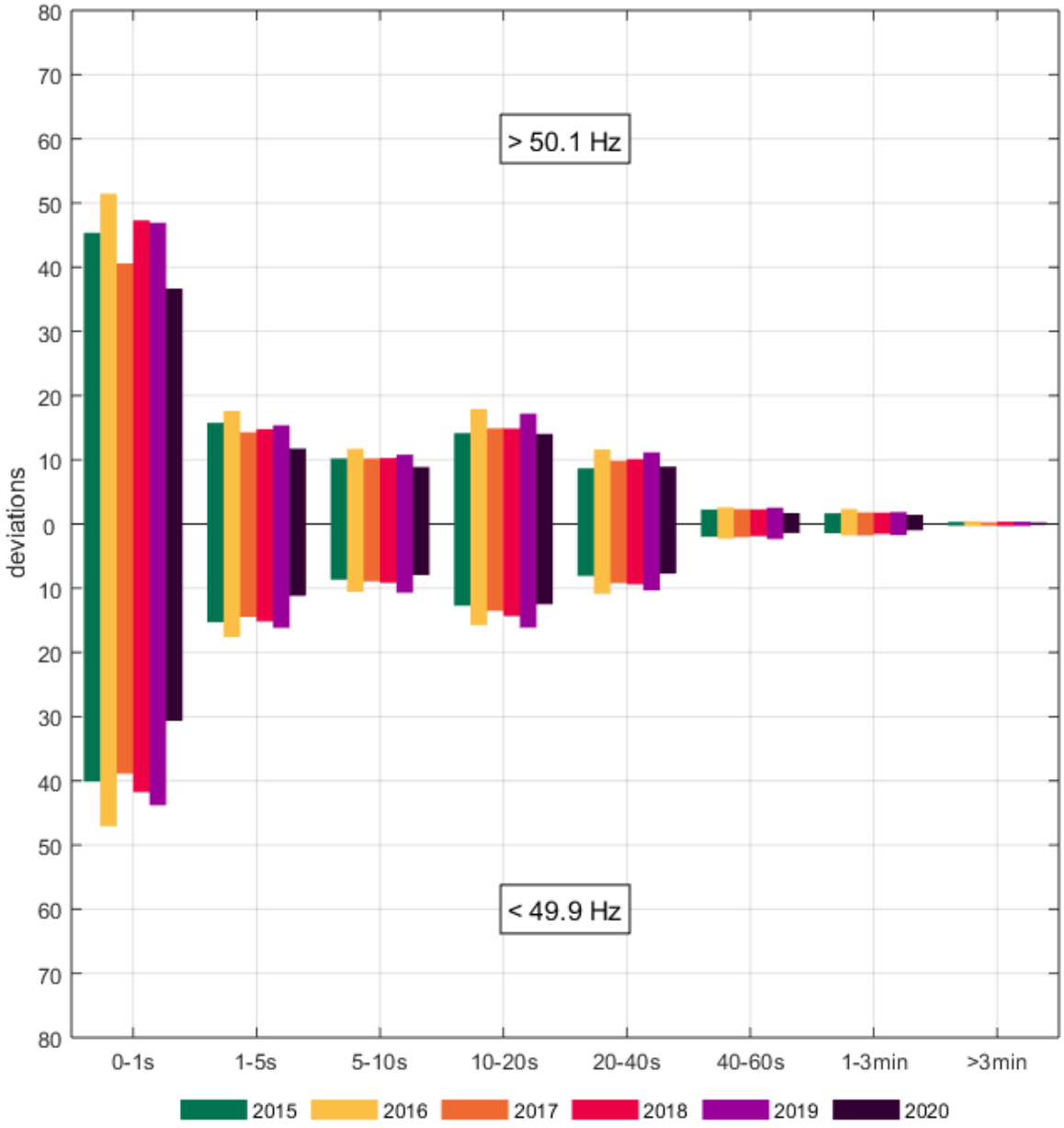
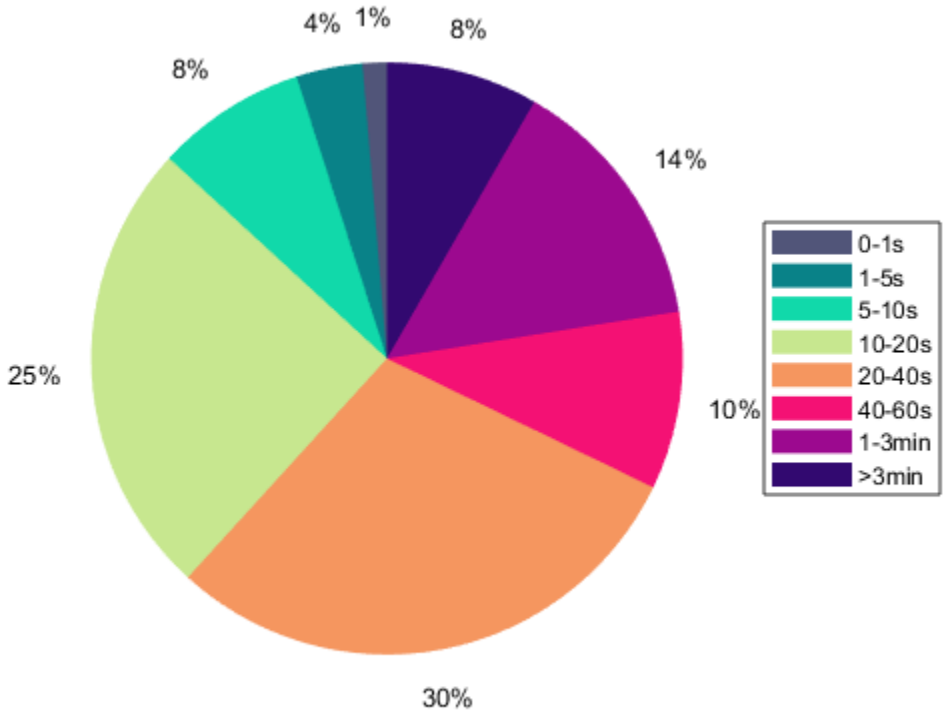


Table 3.21 shows how deviations of different duration affected to the total time outside the standard frequency range in 2020. Times are given in minutes. Pie chart in Figure 3.33 shows in percentages how the total time outside the standard frequency range was divided between deviations of different 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 2020 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	67	174	407	1246	1493	500	809	438	5134
< 49.9 Hz	58	166	366	1107	1284	411	520	341	4252
total	125	340	773	2353	2777	911	1329	779	9386

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 2020. Figure 3.34 represents the total number of deviations per duration for each month in 2020. Most of the deviations have lasted only between 0-1 seconds. Clearly the most deviations have occurred in September. Also February, March and June have been prominent in the number of deviations. July has had the smallest number of deviations.

Figure 3.34. Total number of frequency deviations per duration for each month in 2020

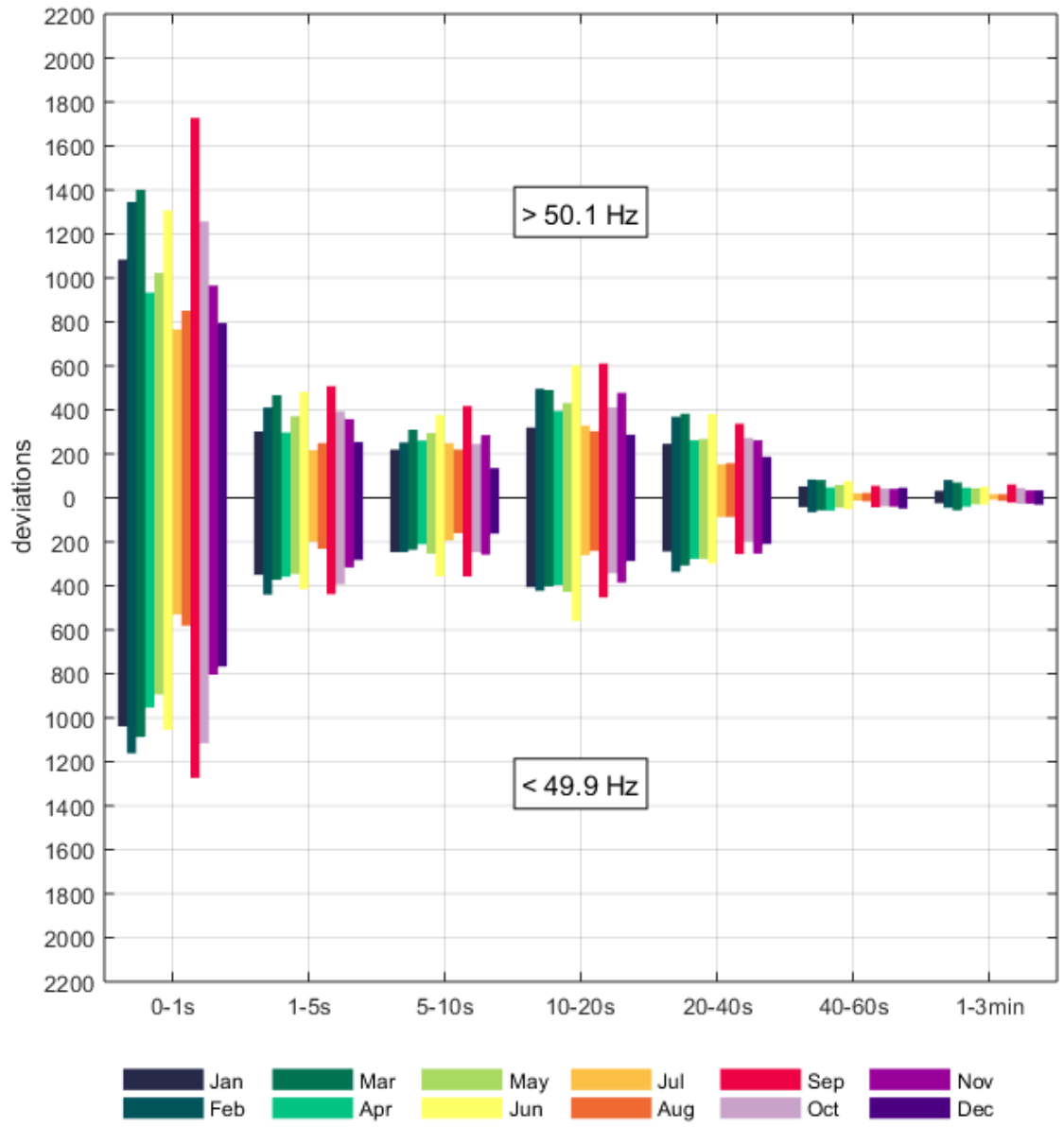
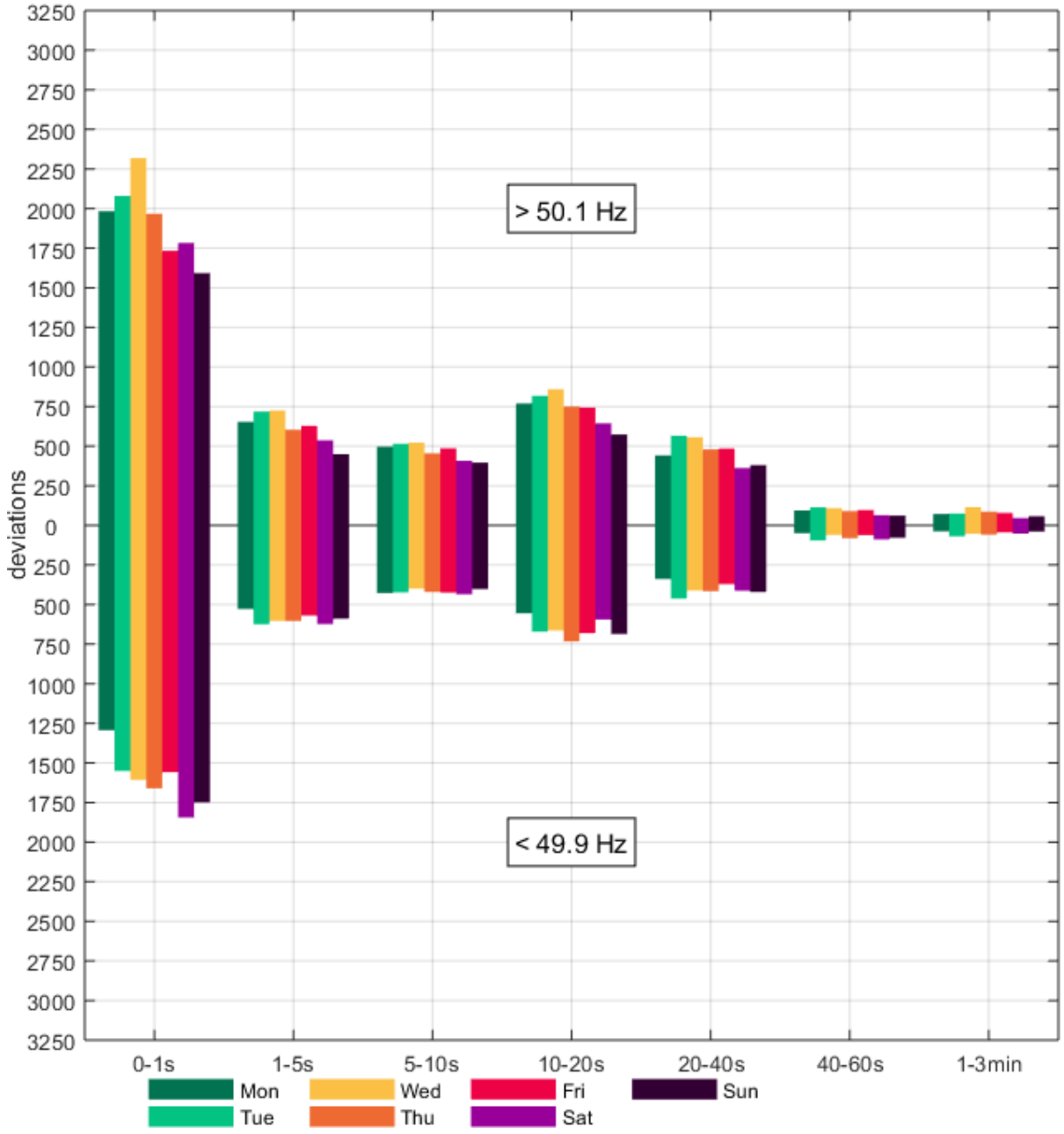


Figure 3.35 shows the number of deviations for every day of the week. Deviations of all durations have been common on Tuesday and Wednesday. Under 49.9 Hz deviations lasting 0-1 s have been most common on the weekend.

Figure 3.35. Total number of frequency deviations per duration for each day of the week in 2020



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 have occurred around midnigth, in the late morning and in the afternoon. Also evening hour 21 morning hour 7 have clearly had more deviations.

Figure 3.36. Total number of frequency deviations per duration for hours 0-11 in 2020

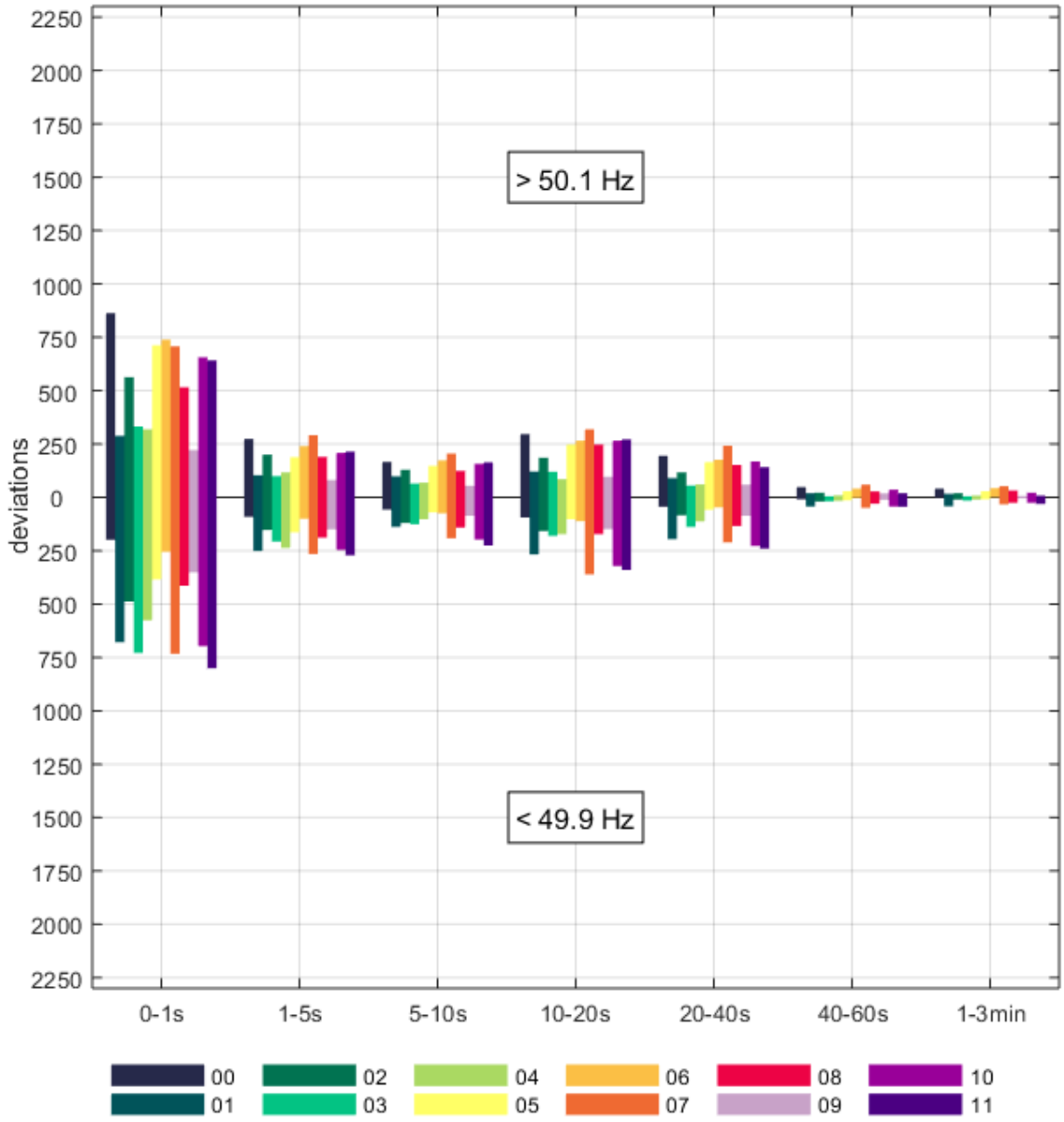


Figure 3.37. Total number of frequency deviations per duration for hours 12-23 in 2020

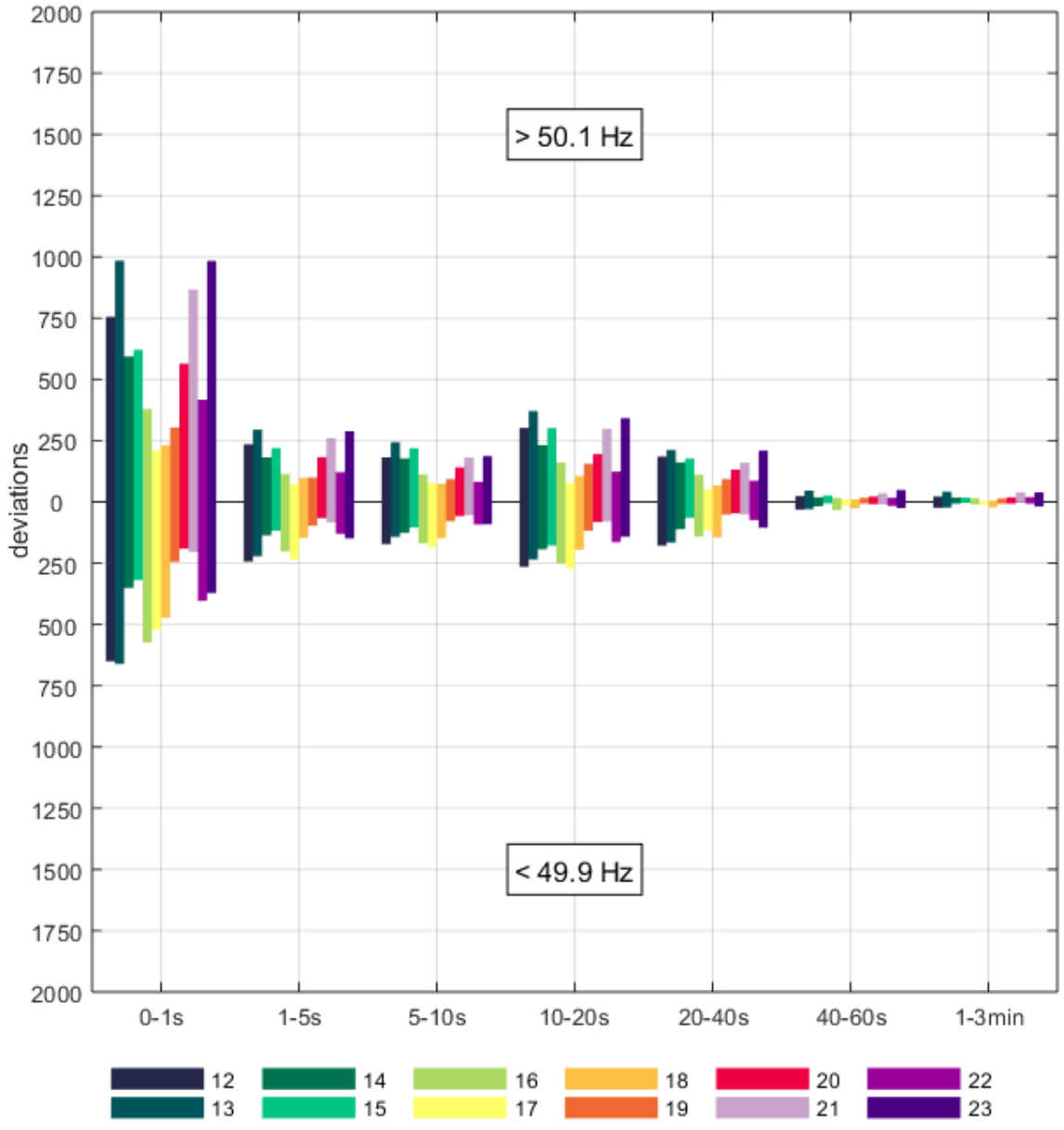
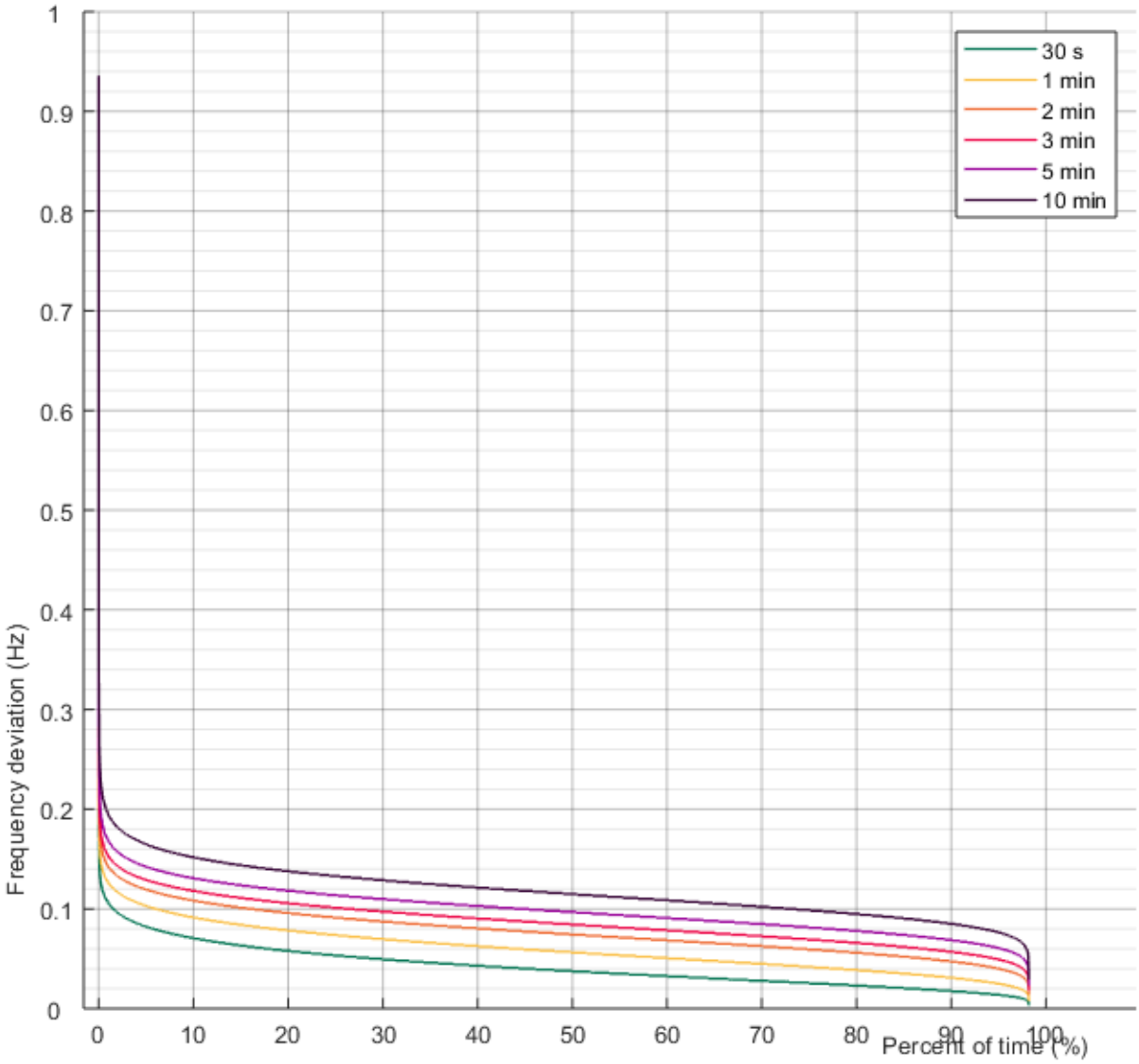


Figure 3.38 represents the duration curve of maximum frequency deviation inside different time windows in year 2020. The time window was slid through the year with a time interval of one second. Studied time windows can be found from legend of the Figure 3.38. Chapter 4 shows in detail the frequency 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 2020



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 2015-2020. The number of deviations has subtantially decreased from the previous years in every duration category.

Figure 3.39. Total number of longer frequency deviations per duration between 2015-2020

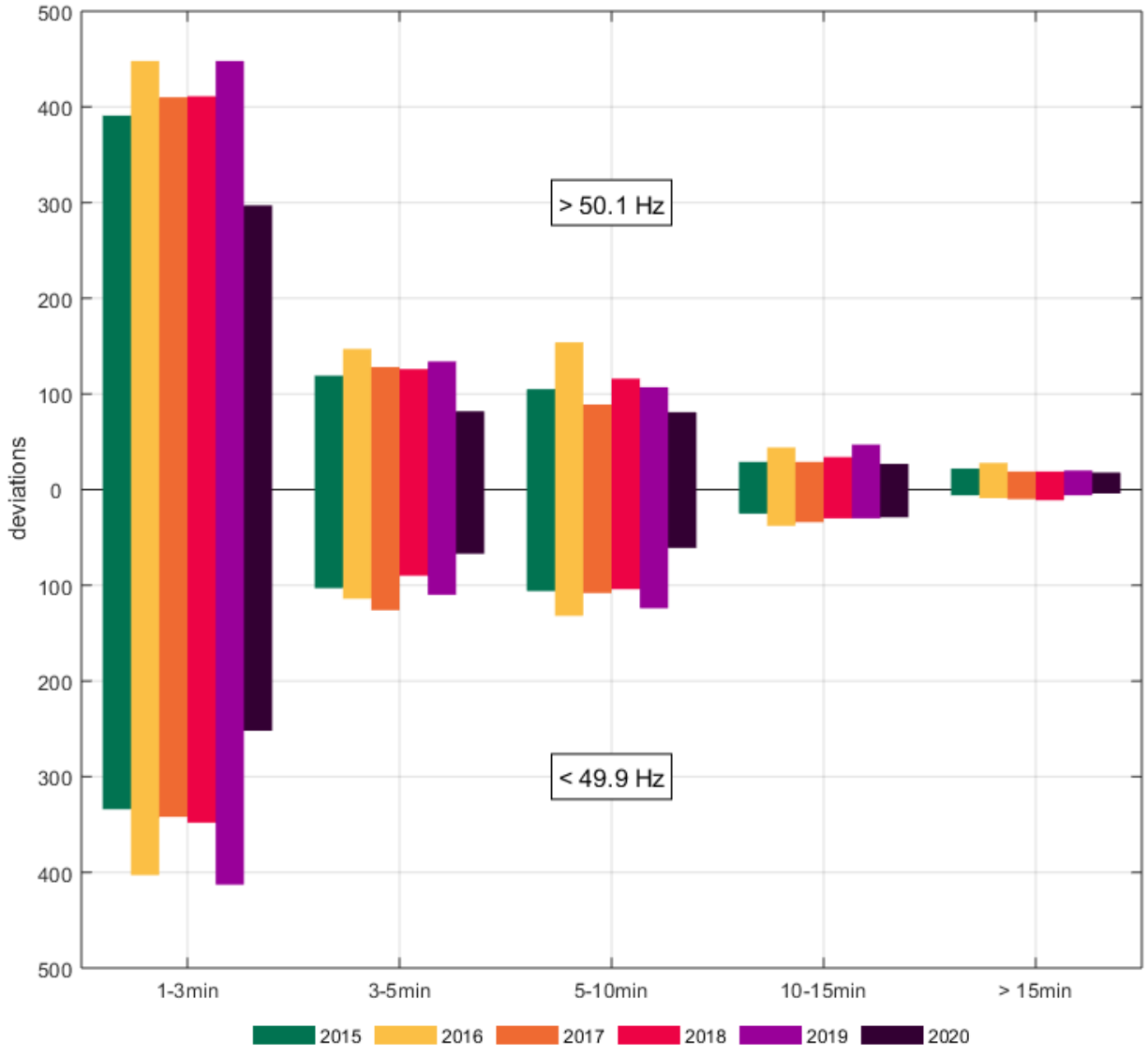


Figure 3.40 shows the total number of longer deviations for each month in 2020. March has had the most deviations lasting between 1-3, 3-5 and 5-10 minutes.

Figure 3.40. Total number of longer frequency deviations per duration for each month in 2020

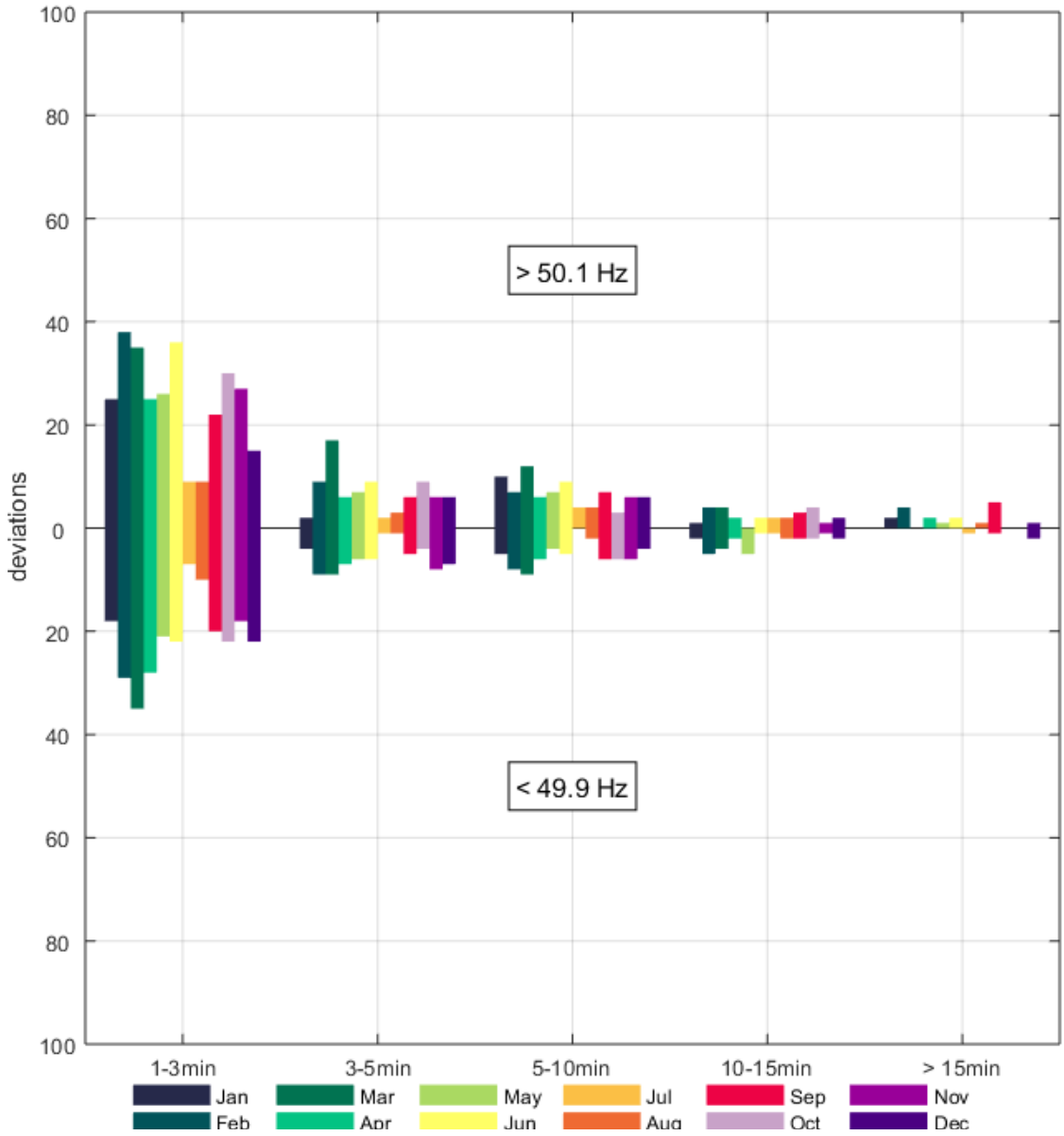
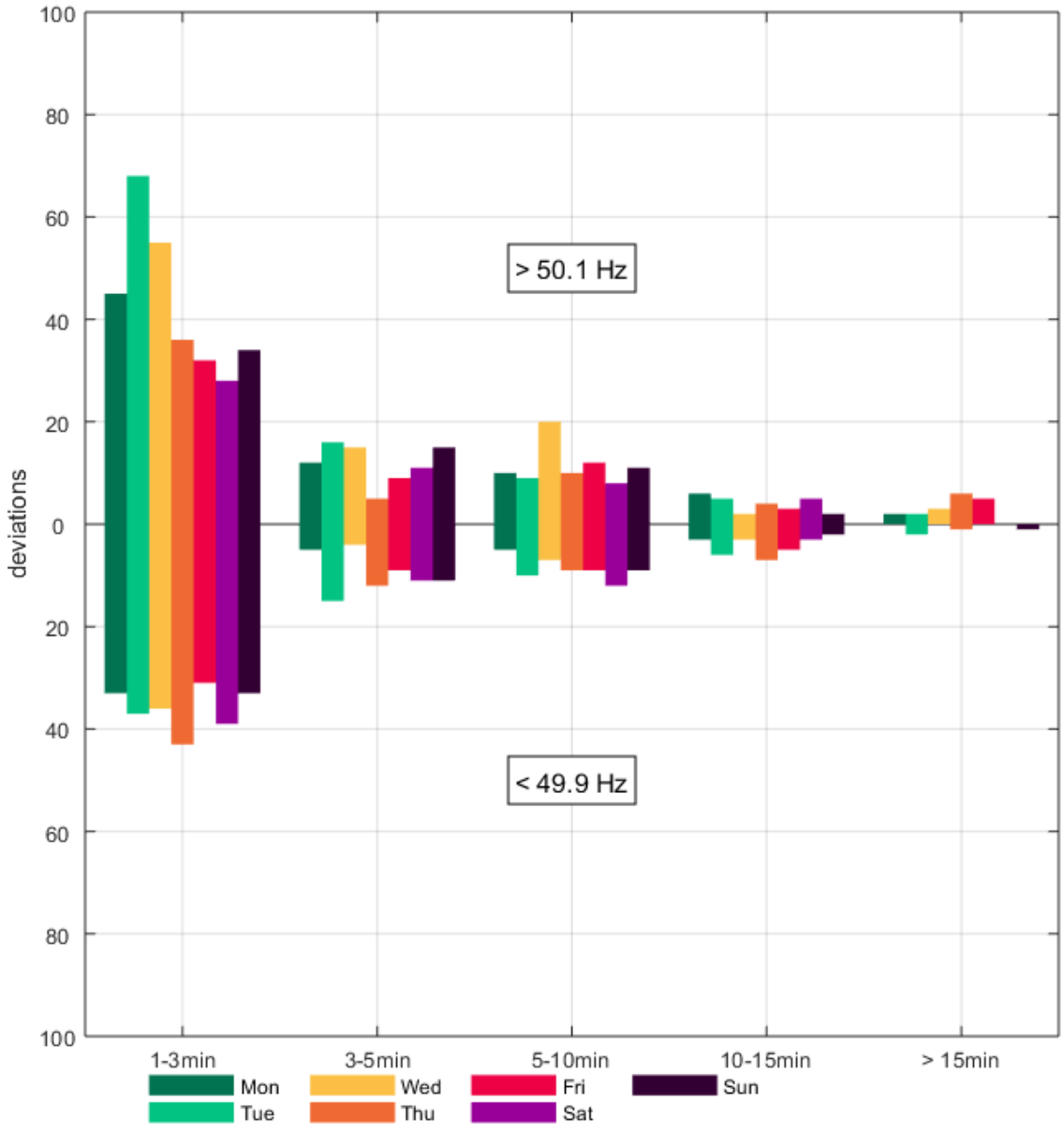


Figure 3.41 represents the number of deviations with different durations during every day of the week in 2020. There have been more over frequencies in the beginning of the week. Especially Tuesday and Wednesday have had a large number of deviations over 50.1 Hz lasting between 1-3 minutes.

Figure 3.41. Total number of longer frequency deviations per duration for each day of the week in 2020



Figures 3.42 and 3.43 follow the same pattern as the figures representing the shorter durations with most deviations taking place in the late morning and in the early afternoon.

Figure 3.42. Total number of longer frequency deviations per duration for hours 0-11 in 2020

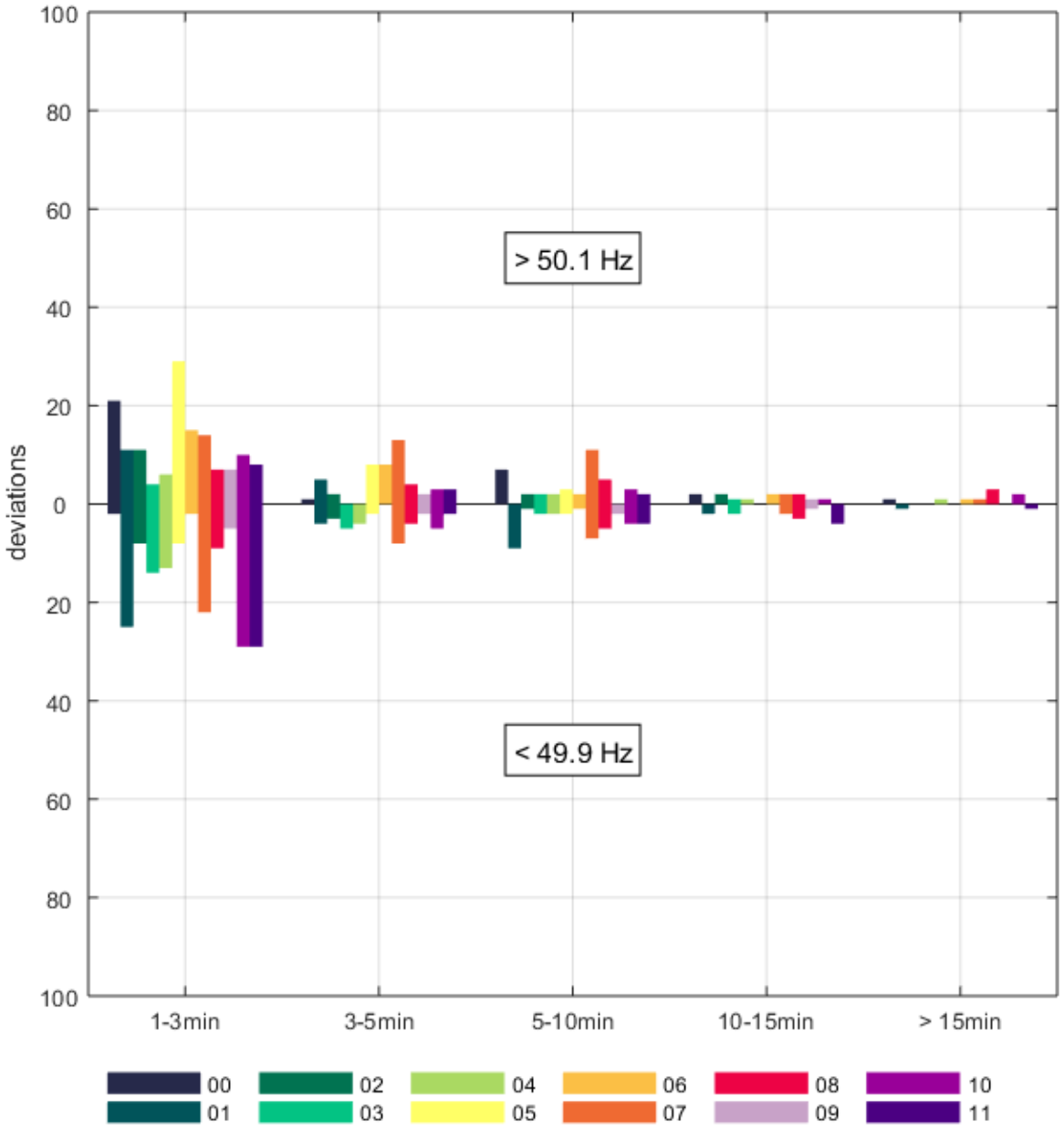
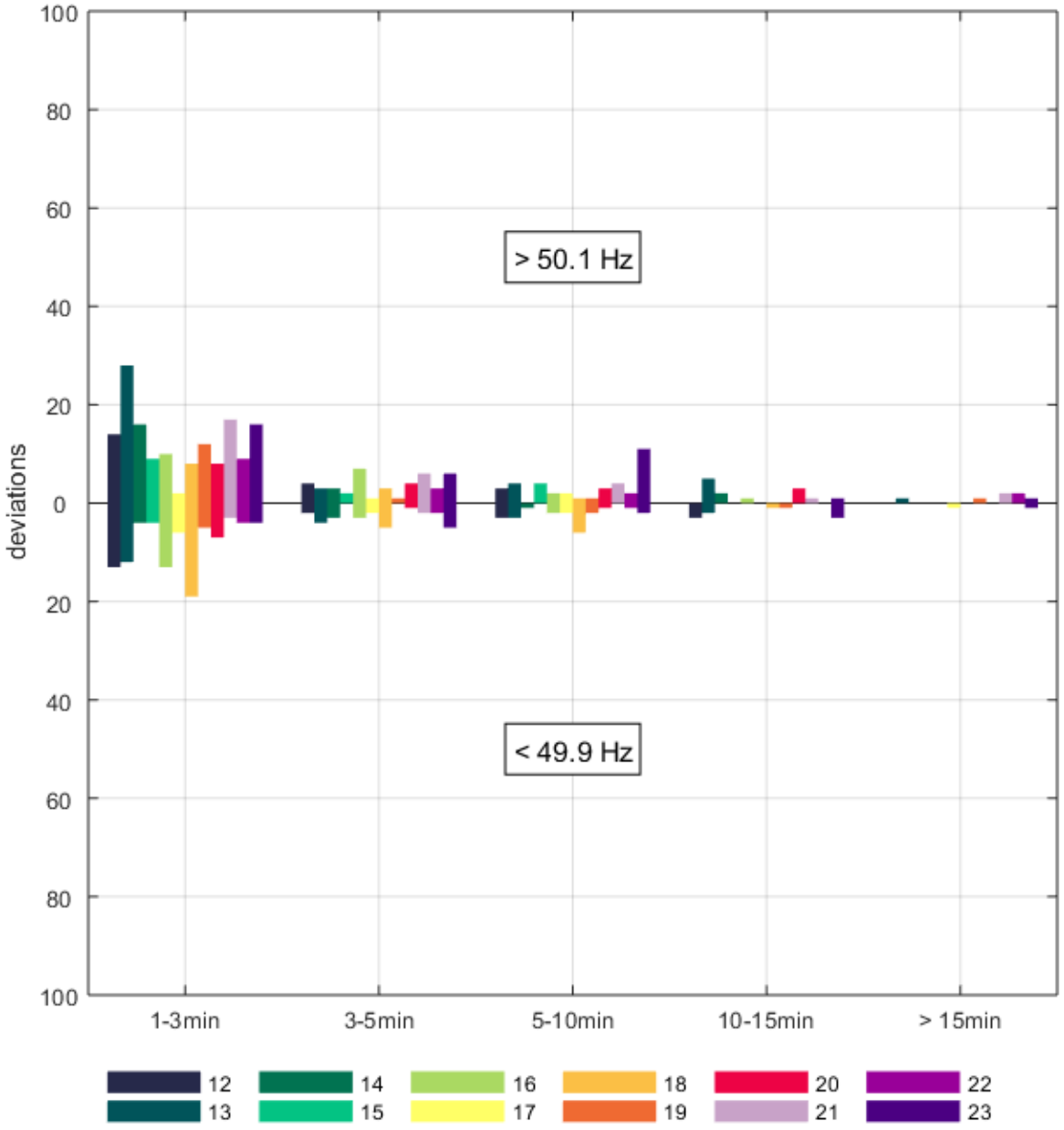


Figure 3.43. Total number of longer frequency deviations per duration for hours 12-23 in 2020



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 over and under frequency deviations from 2015 to 2020. In 2020 there were less crossings than in the previous years. Every year there have been slightly more threshold crossings over 50.1 Hz than under 49.9 Hz.

Figure 3.44. Daily average number of frequency deviations for years 2015-2020

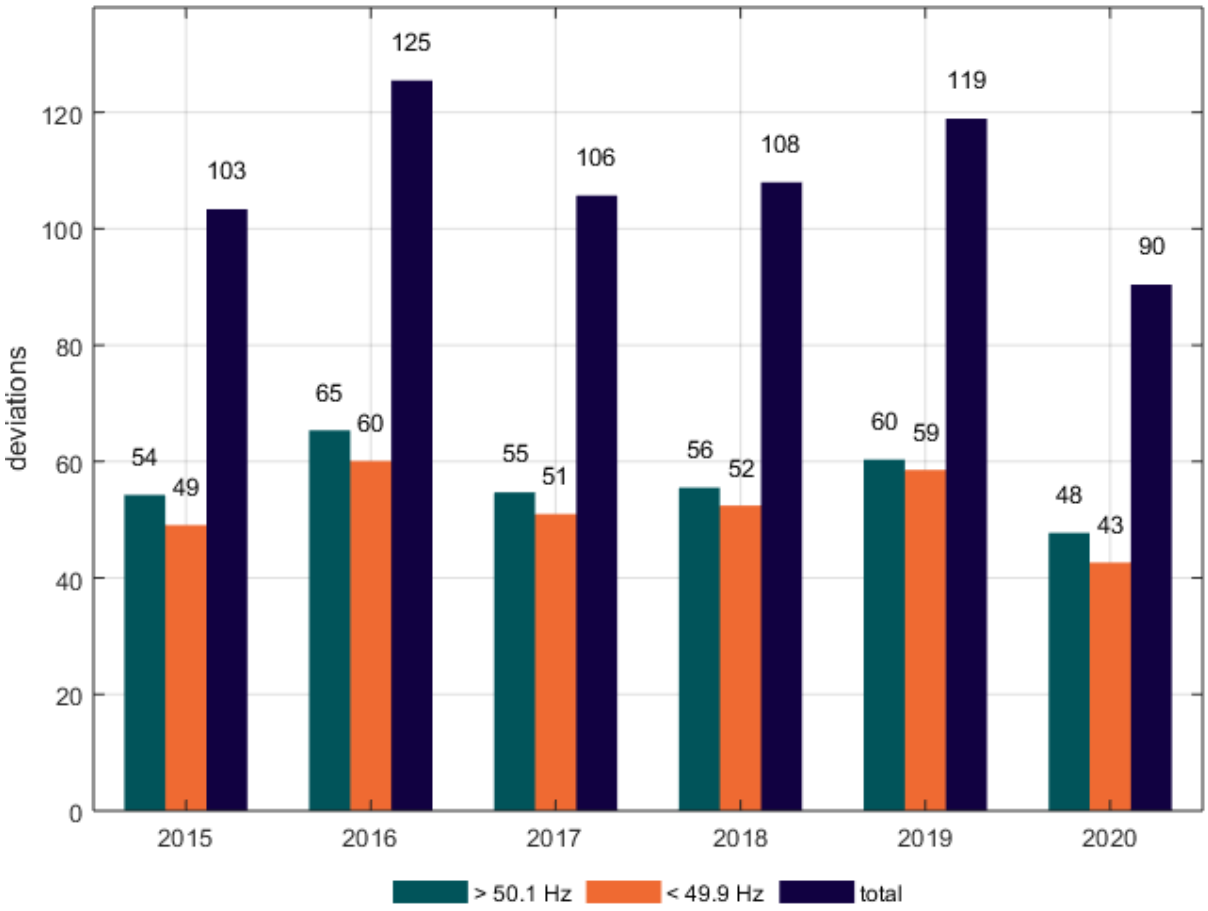


Figure 3.45 represents the daily average number of threshold crossings for each month in 2020. The frequency has crossed the threshold most often in February, June and September. July and Augus have had the smallest number of threshold crossings.

Figure 3.45. Daily average number of threshold crossings for every month in 2020

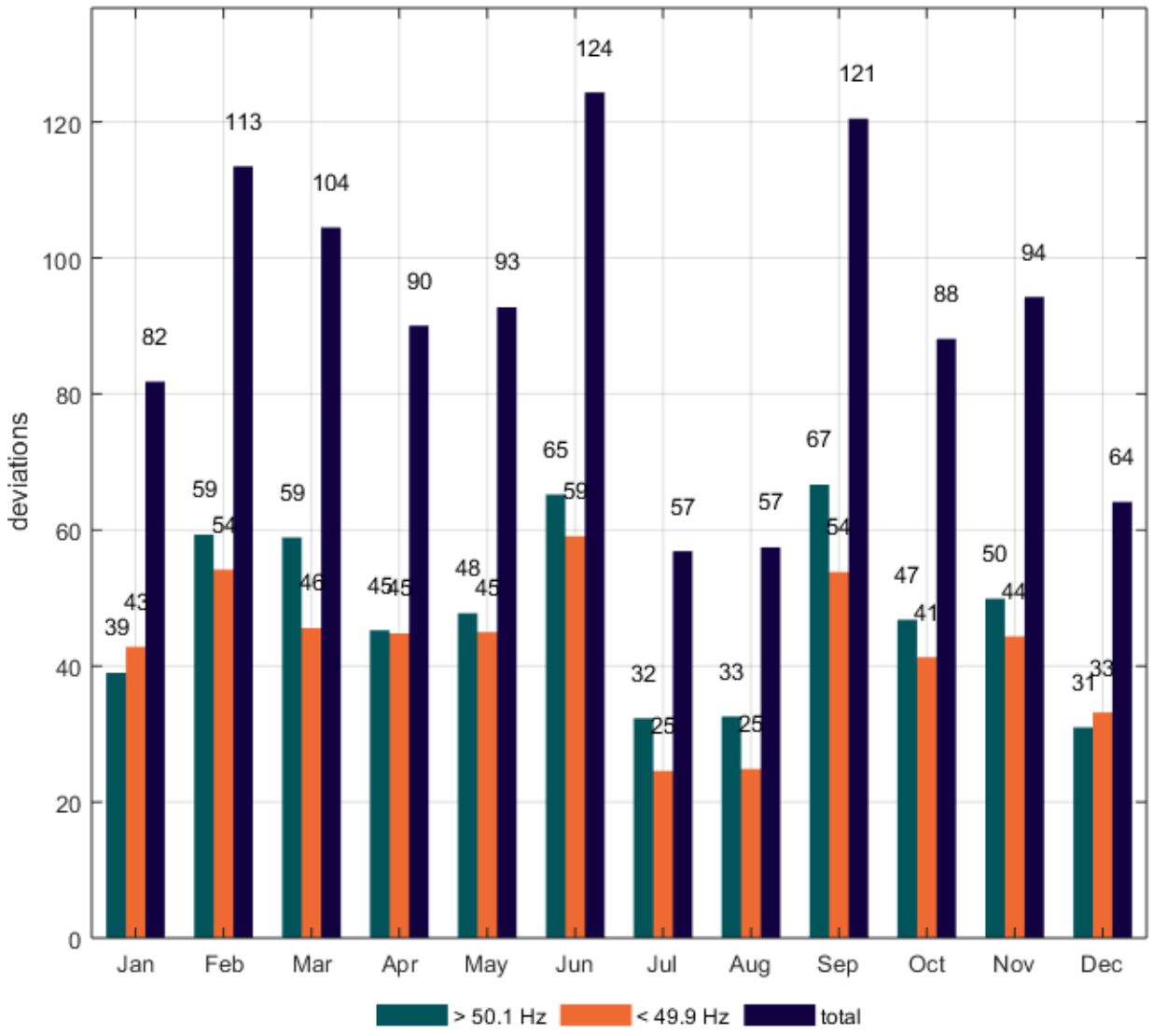
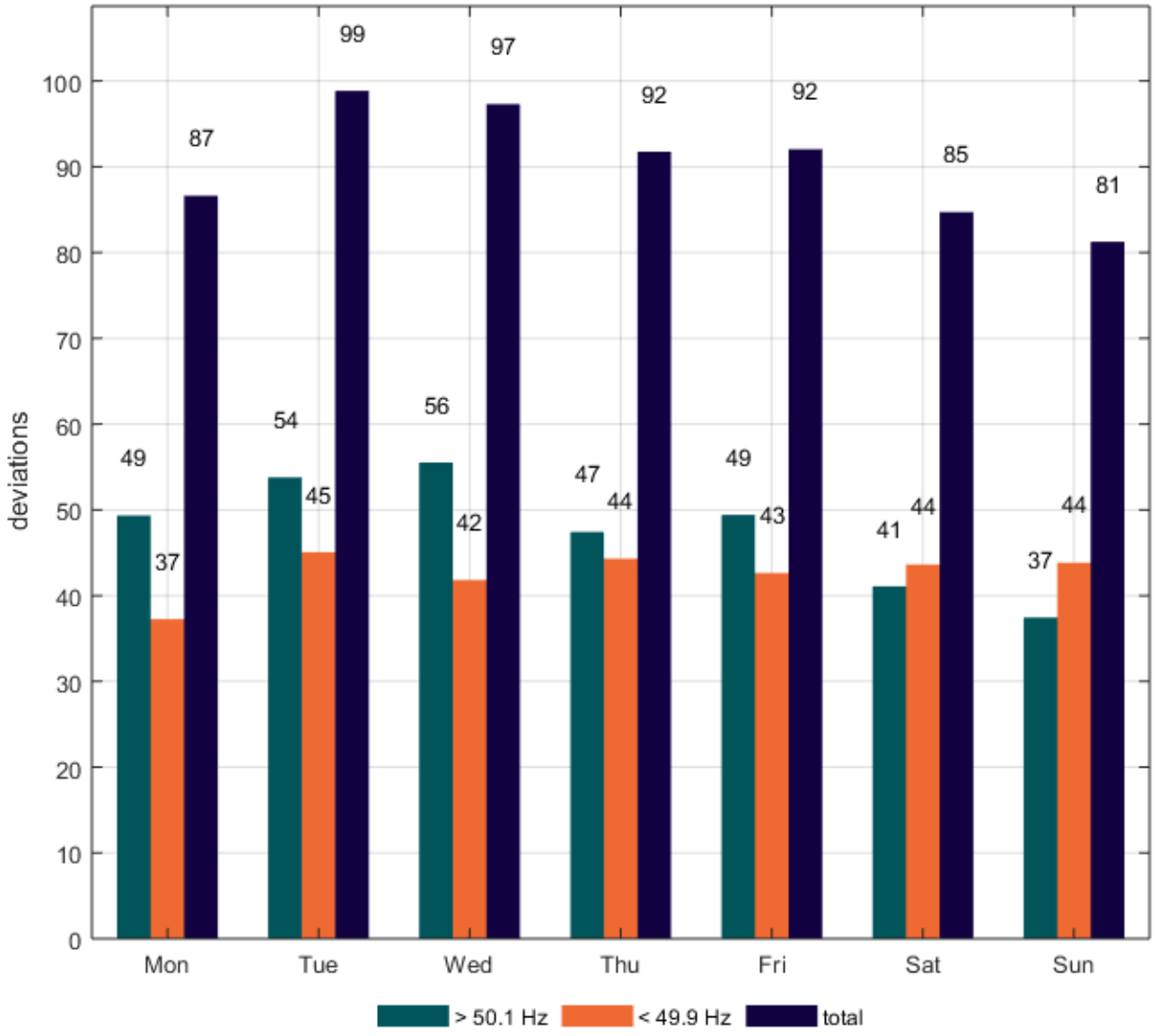


Figure 3.46 shows the number of threshold crossings for each day of the week in 2020.The number of crossings has been highest on Tuesdays and degreased towards the end of the week.

Figure 3.46. Daily average number of threshold crossings for every day of the week in 2020



The hourly number of threshold crossings inside the average day is in Figure 3.47. The smallest number of threshold crossings has occurred at 9 am. The most crossings were experienced in the morning at 7 am and from 10 am to 13 am.

Figure 3.47. Average number of threshold crossings for every hour of the day in 2020

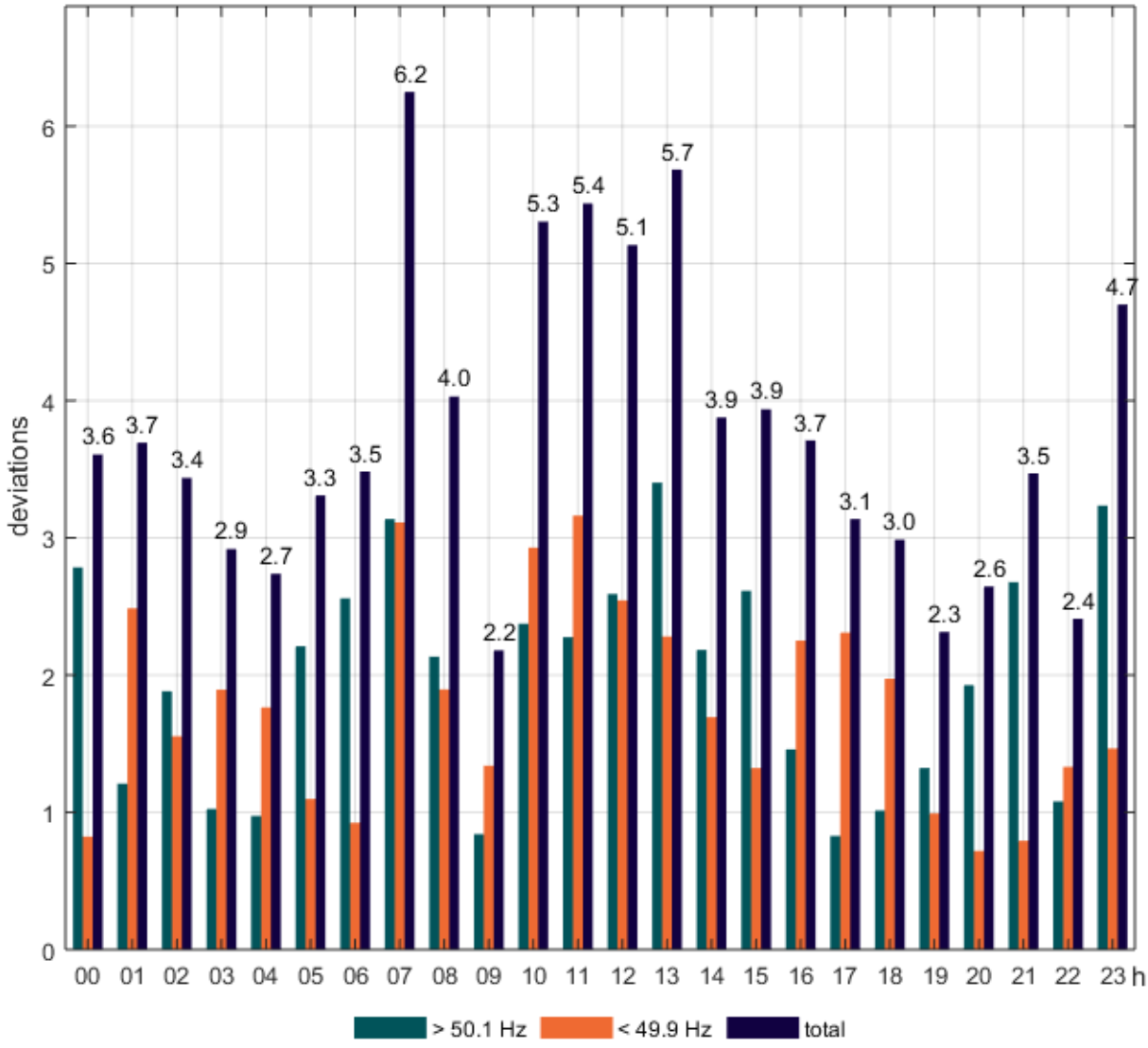
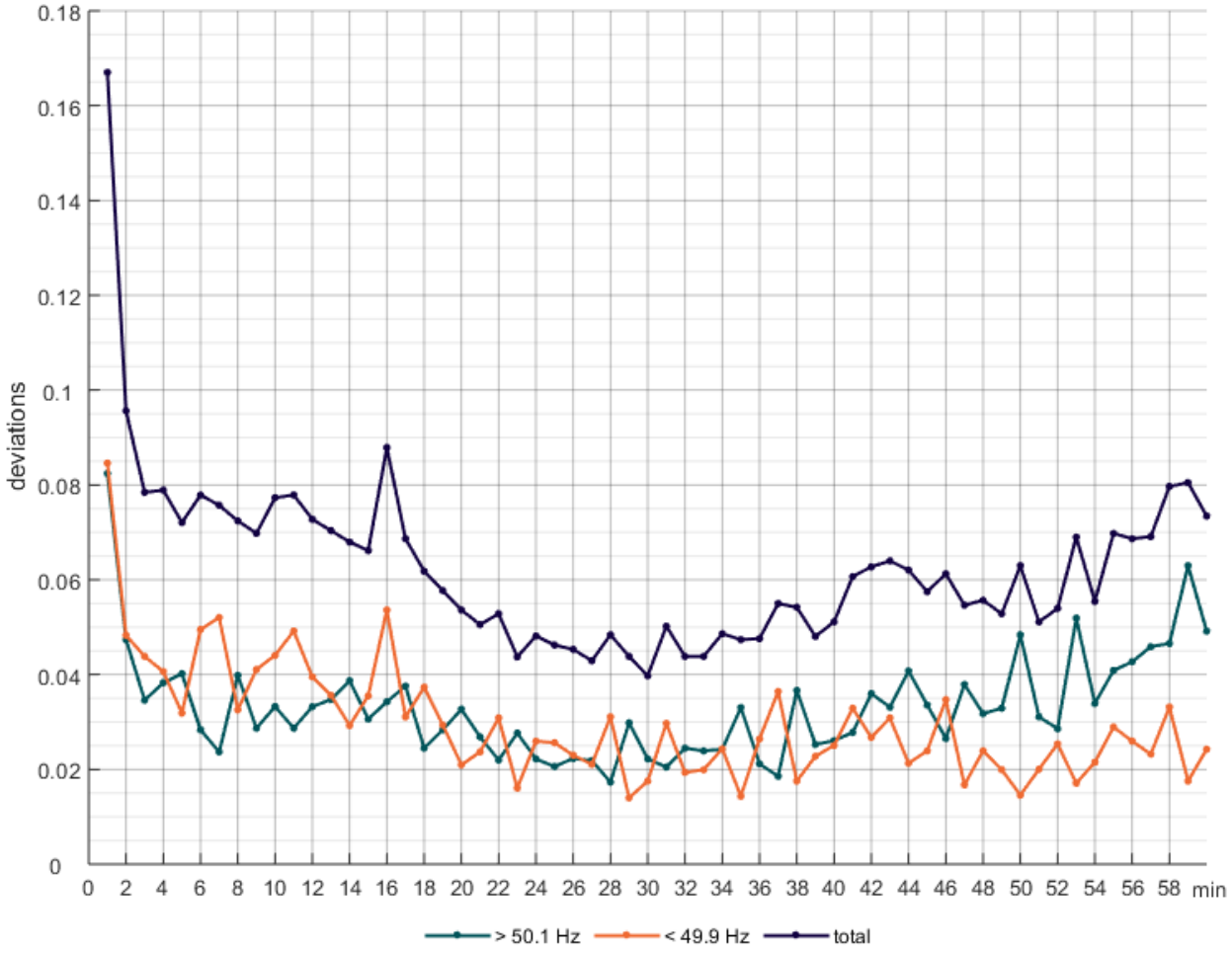


Figure 3.48 represents the average number of threshold crossings for every minute inside the hour. Most crossings have occurred in the first minutes of the hour. During the first 30 minutes of the hour, the frequency has crossed 49.9 Hz more often, whereas more crossings of 50.1 Hz have taken place in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

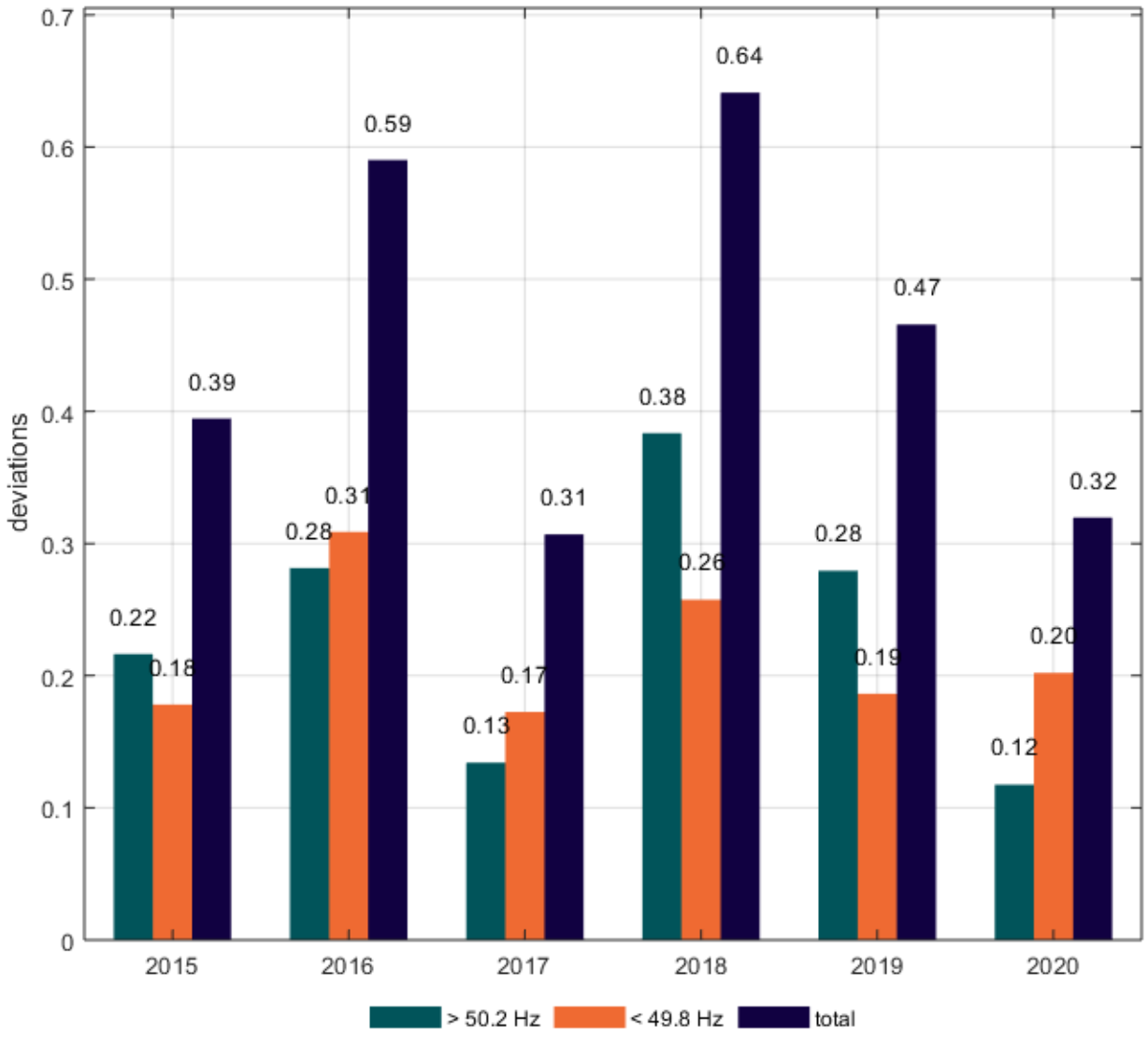
Figure 3.48. Average number of threshold crossings for every minute of the hour in 2020



3.6.2 Number of 49.8-50.2 Hz crossings

Figure 3.49 represents the average number of frequency deviations per day that exceeded ±200 mHz. In 2020 the number of crossings was lower compared to the previous years, except year 2017.

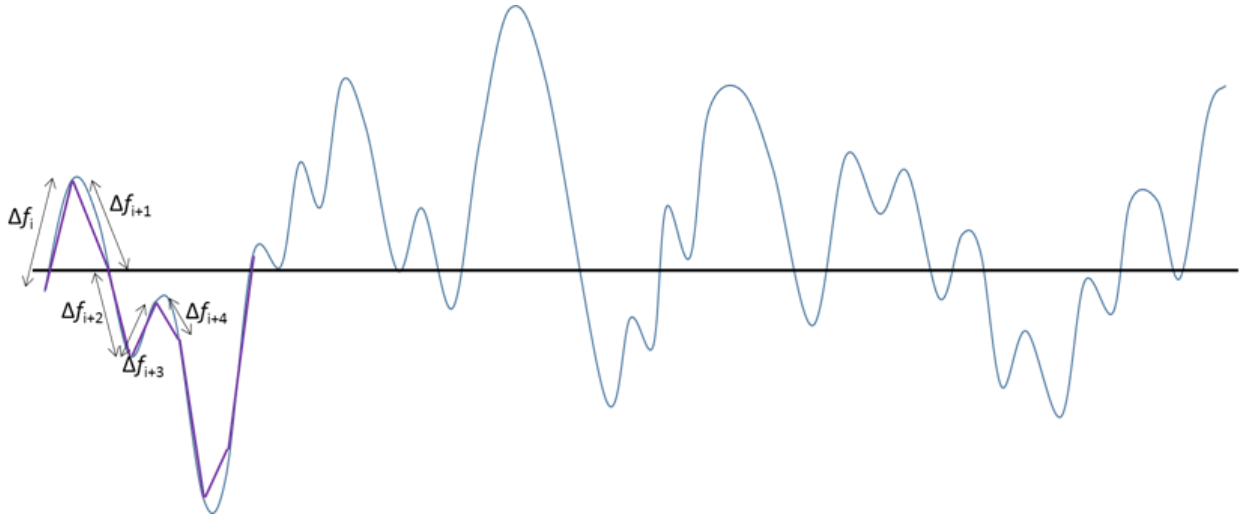
Figure 3.49. Daily average number of frequency deviations larger than ±200 mHz for years 2015-2020



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).

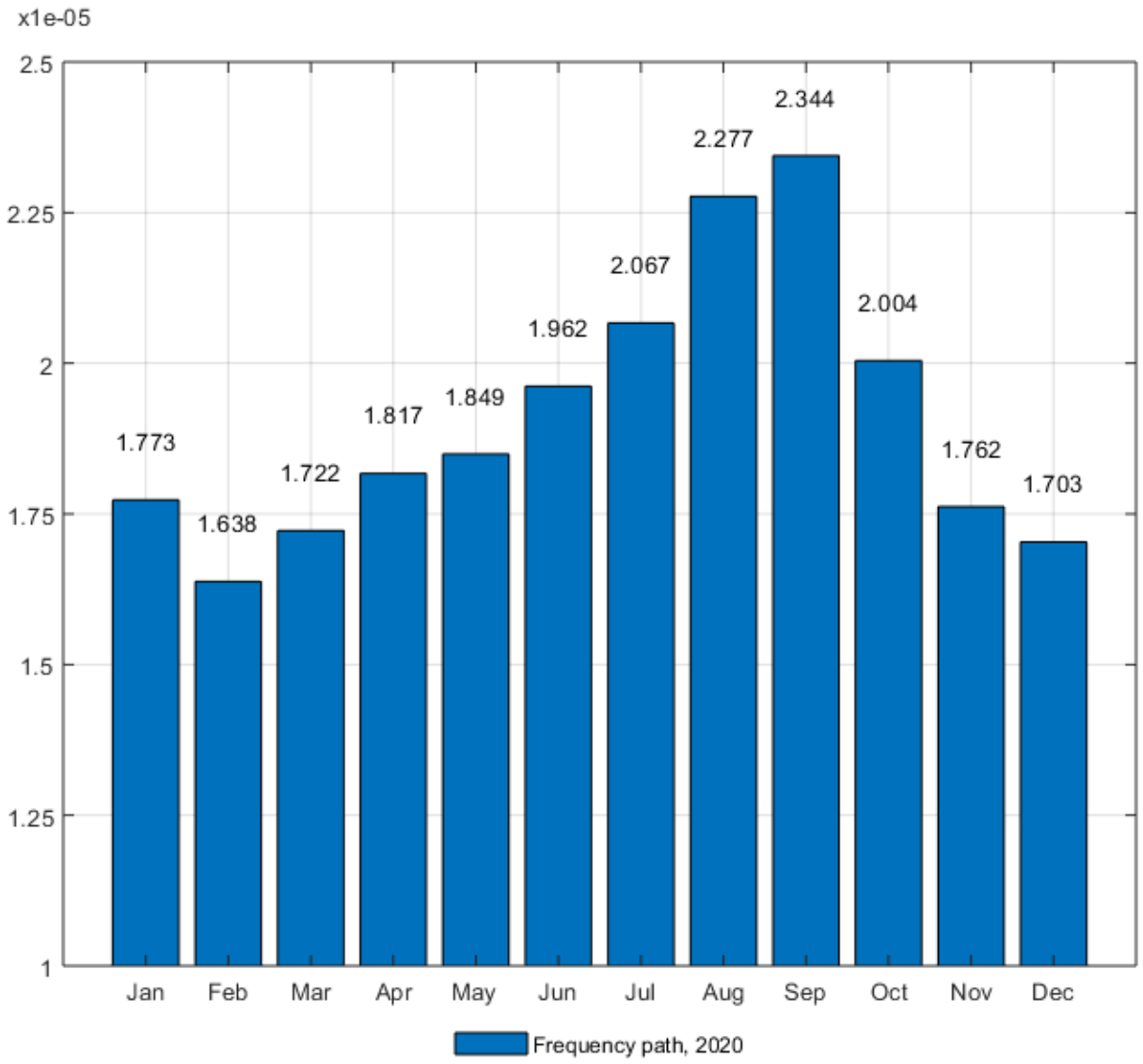
Figure 3.50. Frequency quality index: Length of the frequency path [7]



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

Figure 3.51 represents the frequency path for each month in 2020. The path length has steadily increased from February to September. After September the path length has decreased towards the end of the year.

Figure 3.51. Length of the frequency path month by month in 2020



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 on the weekends than on the weekdays.

Figure 3.52. Length of the frequency path for every day of the week in 2020

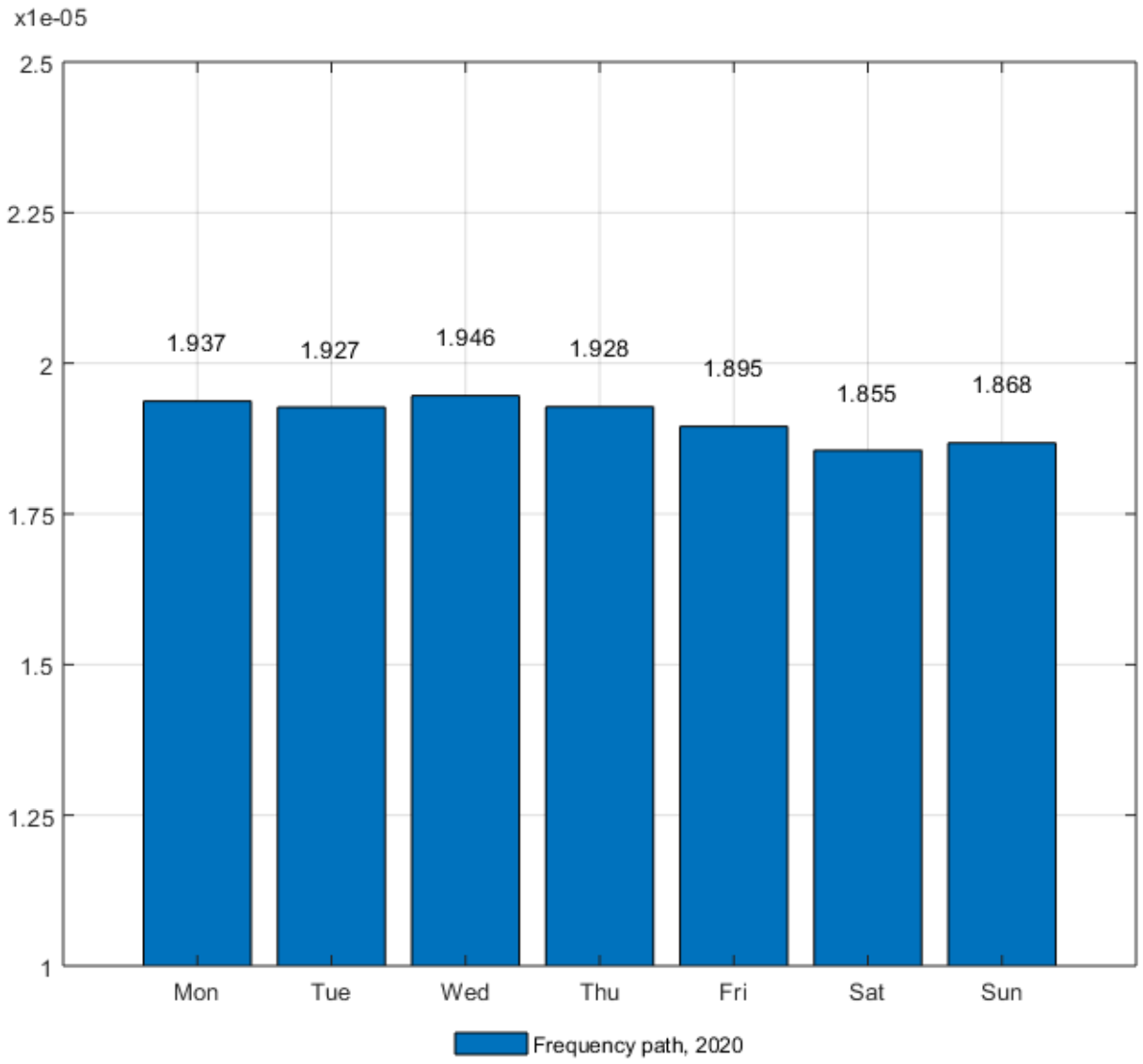


Figure 3.53 shows the frequency path during the day. In the late afternoon and in the late evening the length of the frequency path has increased to some extent but otherwise the pathlength has stayed relatively constant throughout the day.

Figure 3.53. Length of the frequency path for every hour of the day in 2020

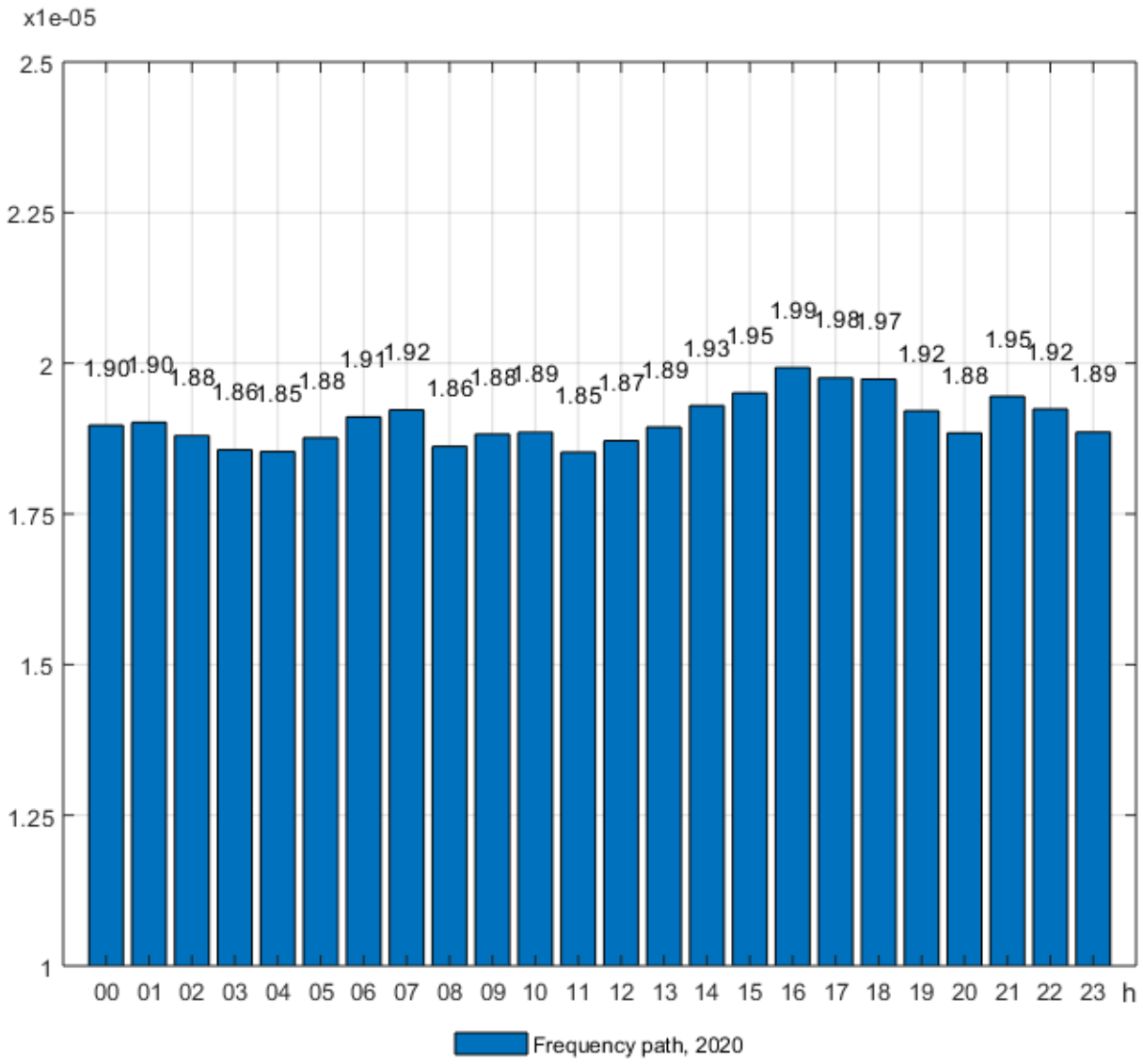
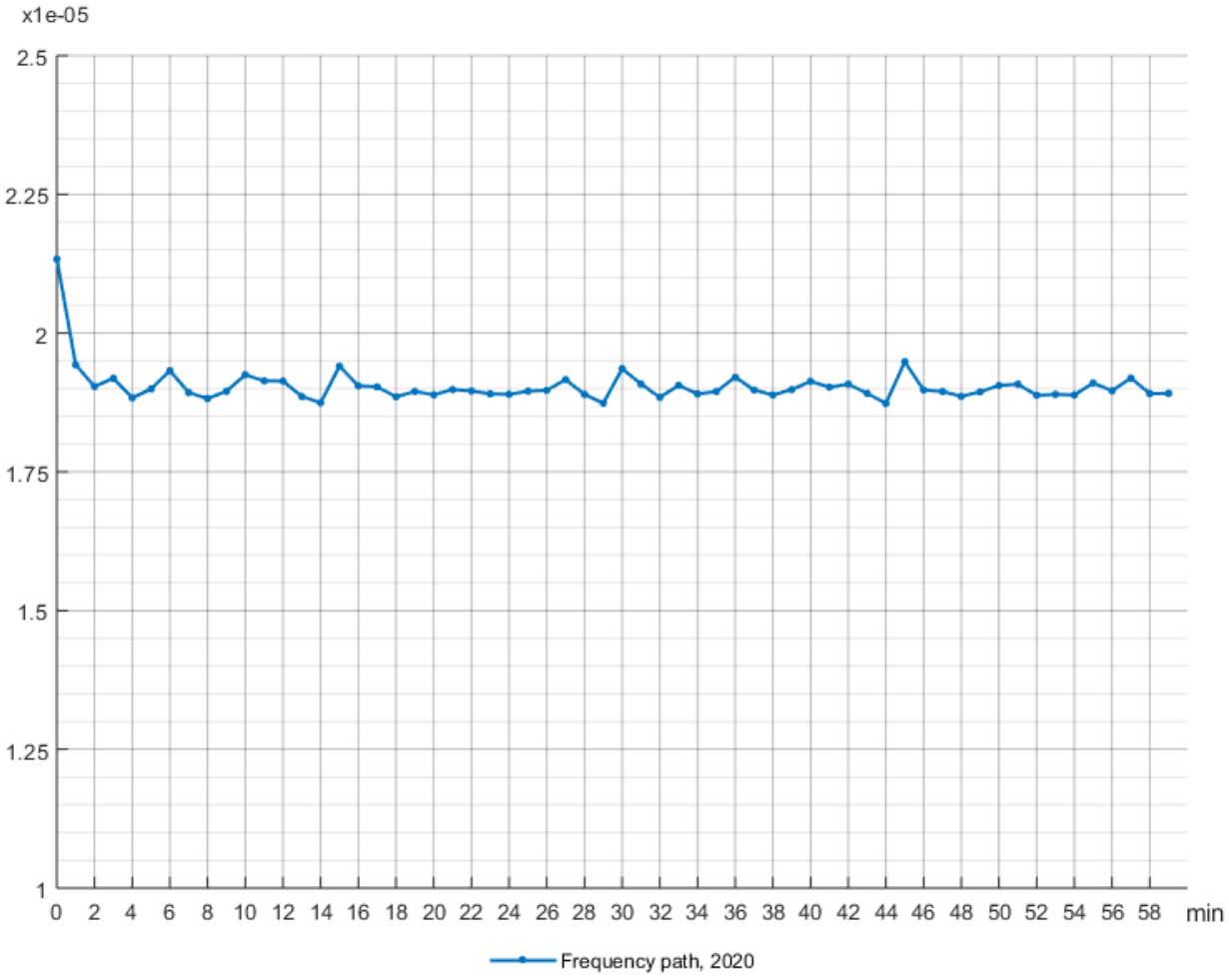


Figure 3.54 represents the average frequency path for every minute inside the hour. The path has been longer during the first minutes of the hour, but otherwise it has stayed pretty even throughout the hour.

Figure 3.54. Length of the frequency path for every minute of the hour in 2020



3.8 Amount of frequency oscillation

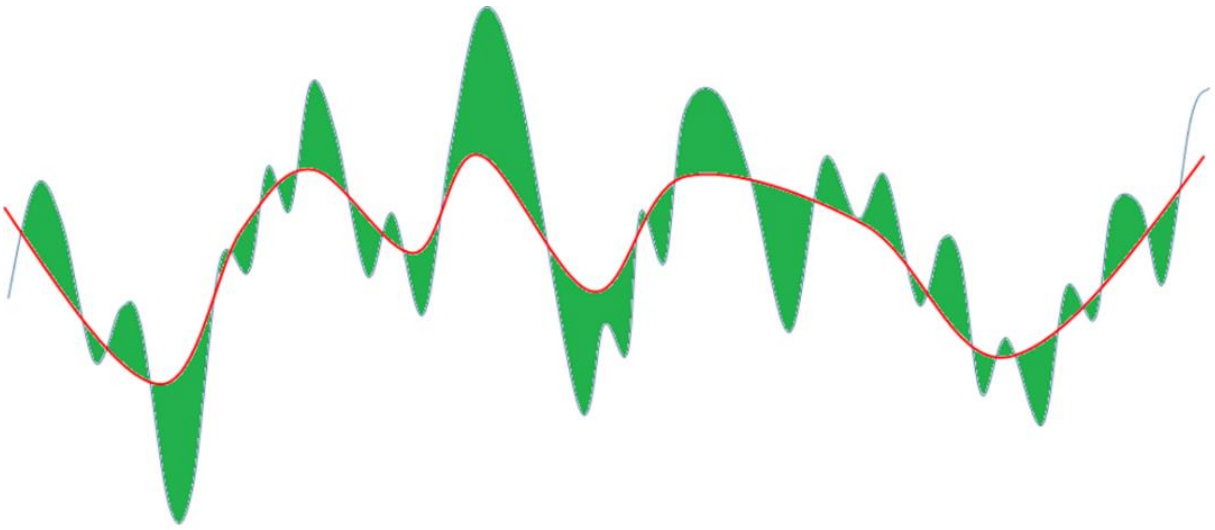
Frequency of the Nordic synchronous system oscillates constantly. Time period of the oscillation is approximately 40 to 90 seconds. This behavior is a natural characteristic of the system but it can be influenced through adequate settings of system reserves. Oscillation has an increasing effect on the 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 [4,5,6,8,9], 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 [8].

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]

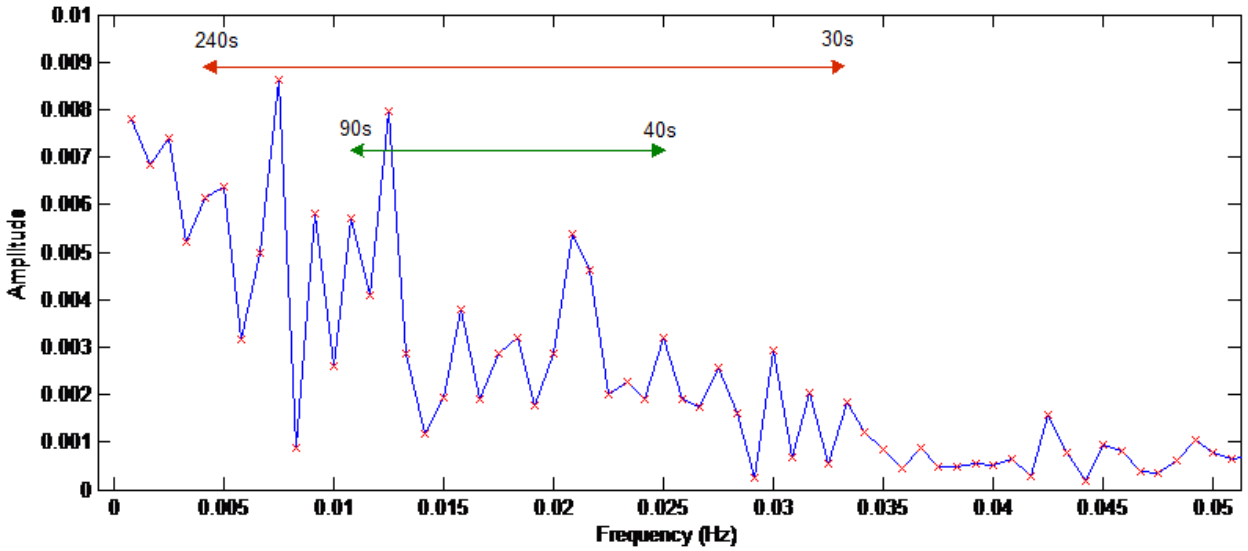
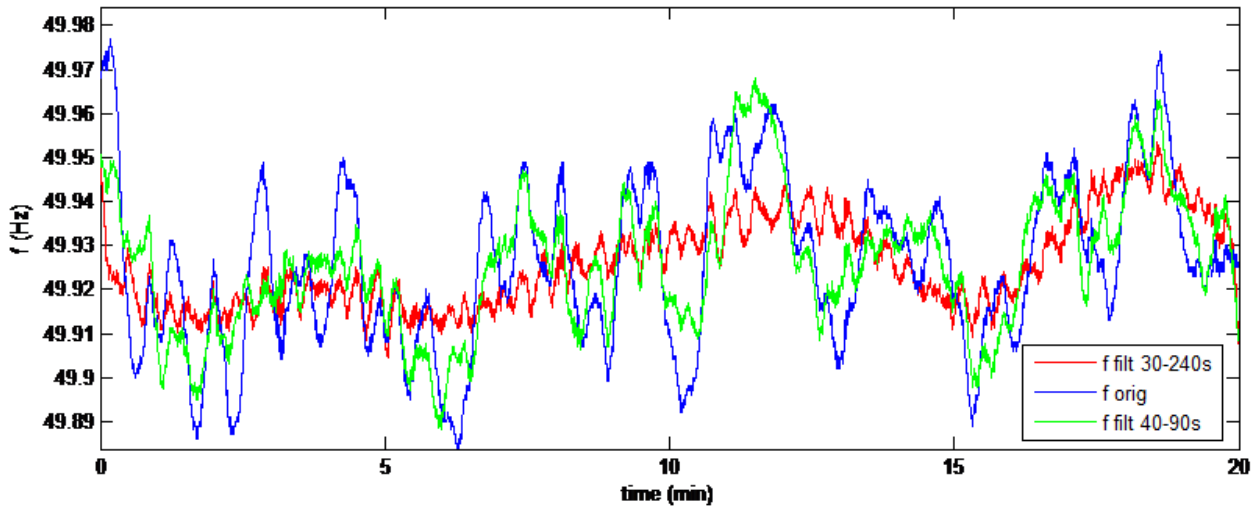


Figure 3.57. Original frequency (blue), frequency with 40-90 s band filtered (green) and frequency with 30-240 s band filtered (red). First 20 minutes of December 2012 are shown (UTC+2) [8]



3.8.2 Amount of oscillation

Figure 3.58 shows hourly values and 24 hour moving averages for the amount of oscillation in 2020. 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 has had the highest values in November. Otherwise the average of the moving average value has stayed aroud 60 Hzs. The amount of frequency oscillation has increased substantially from the previous years. Moreover, the variation in the frequency oscillation values has also increased.

Figures 3.59 and 3.60 contain the previously mentioned 24 hour moving averages for years 2015-2017 and 2018-2020, respectively. In the calculations for year 2015 it was required that there had to be enough eligible data for at least 22 hours in the frame of 24 hours. For 2016-2020, 12 hours of eligible data was required.

Figure 3.58. Amount of oscillation in 2020

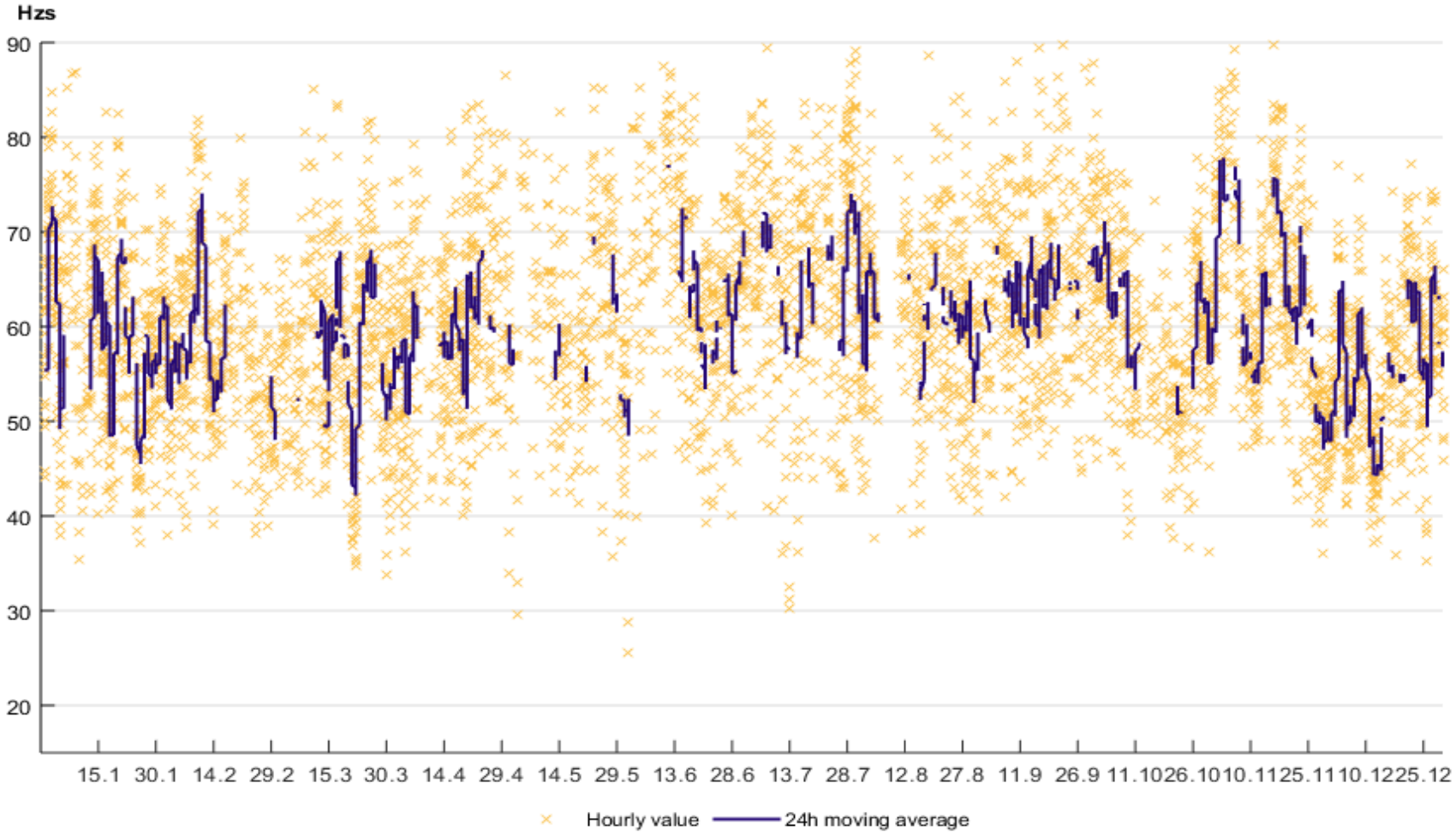


Figure 3.59. Amount of oscillation in 2015-2017

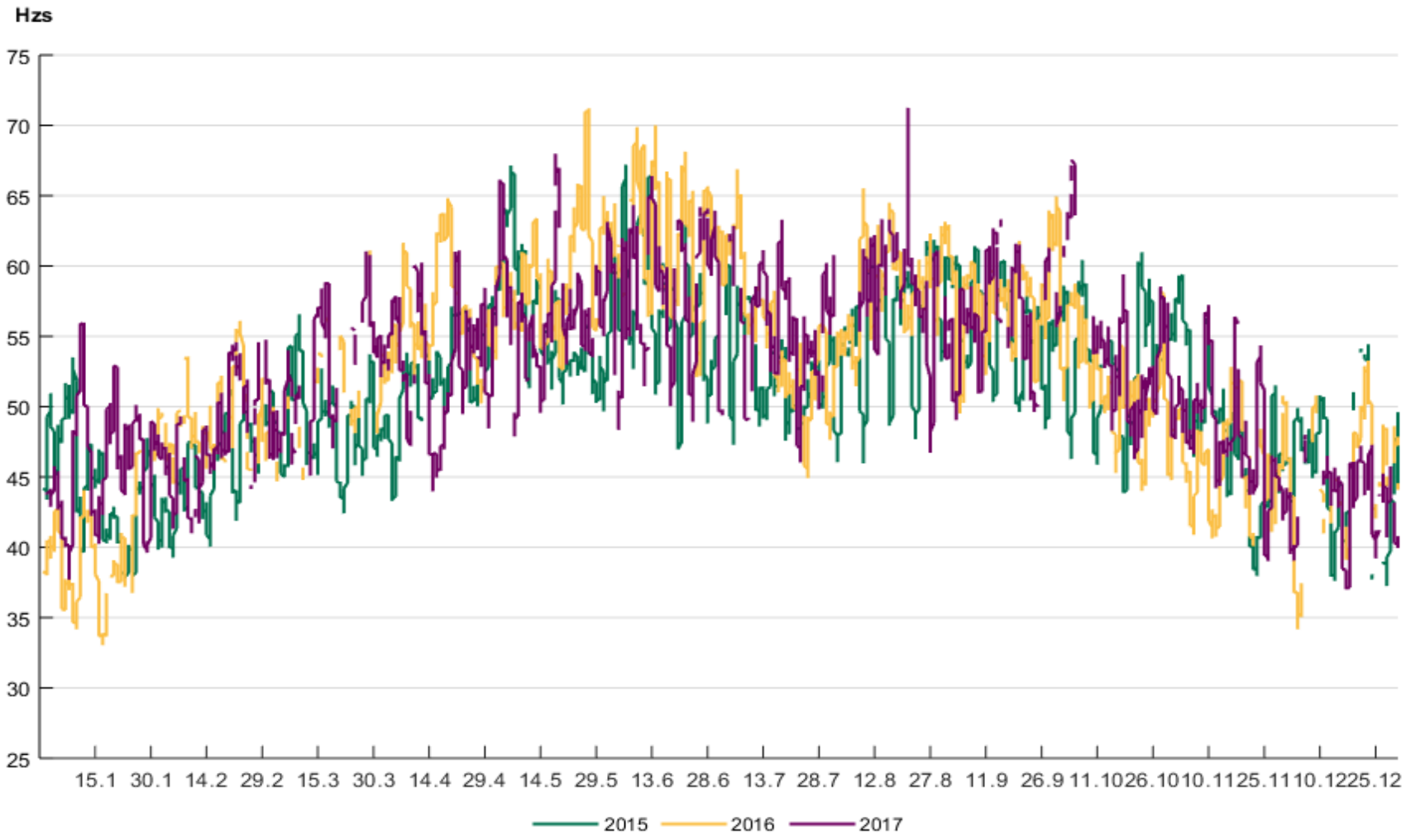
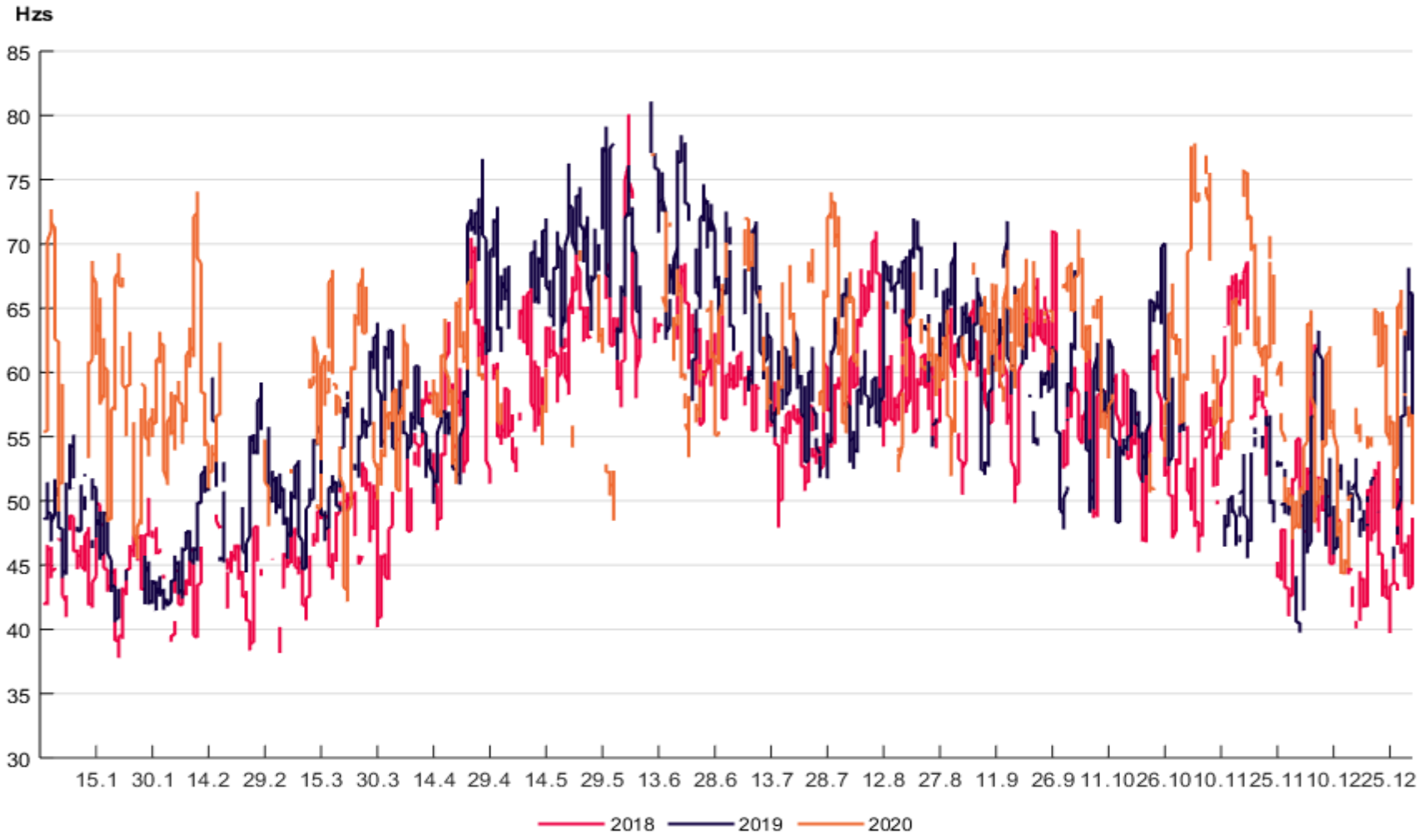


Figure 3.60. Amount of oscillation in 2018-2020



Mean value of the oscillation and standard deviation for each month from 2015 to 2020 are shown in Table 3.22 and 3.23. Figure 3.61 represents the same information in a visual form. The frequency has oscillated the most from May to July. Frequency oscillated significantly more in 2020 in comparison to the previous years. The last three years have been among the worst years in terms of oscillation.

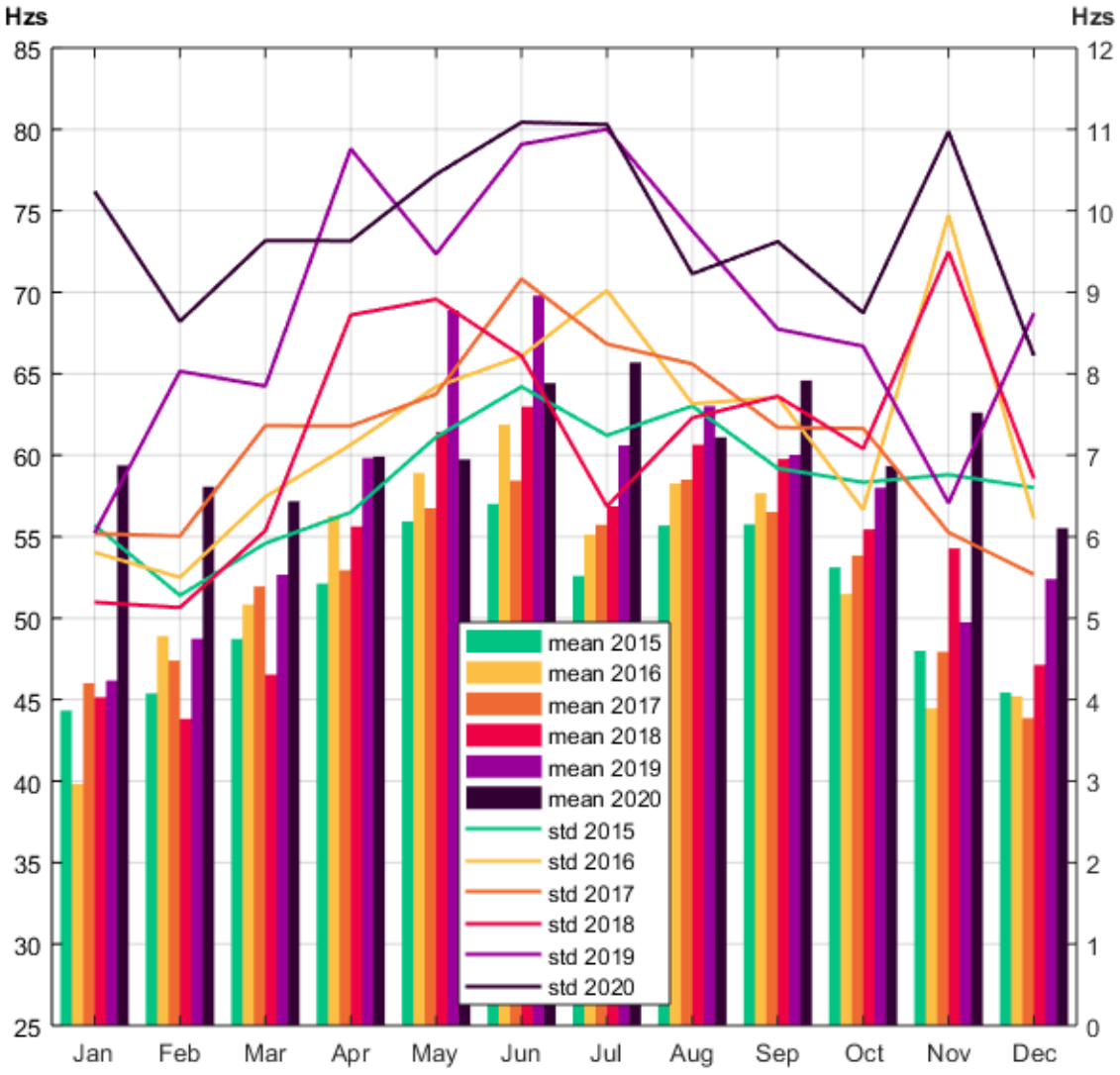
Table 3.22. Mean values and standard deviations for oscillation in years 2015-2017

	Mean value (Hzs)			**Standard deviation (Hzs)**		
Month	**2015**	**2016**	**2017**	**2015**	**2016**	**2017**
January	44.3	39.8	46.0	6.1	5.8	6.0
February	45.4	48.9	47.4	5.3	5.5	6.0
March	48.7	50.8	52.0	5.9	6.5	7.4
April	52.1	56.3	52.9	6.3	7.1	7.4
May	55.9	58.9	56.8	7.2	7.8	7.7
June	57.0	61.9	58.4	7.8	8.2	9.2
July	52.6	55.1	55.7	7.2	9.0	8.4
August	55.7	58.3	58.5	7.6	7.6	8.1
September	55.8	57.7	56.5	6.8	7.7	7.3
October	53.1	51.5	53.8	6.7	6.3	7.3
November	48.0	44.5	47.9	6.8	9.9	6.1
December	45.4	45.2	43.9	6.6	6.2	5.5
Entire year	**51.2**	**52.4**	**52.5**	**6.7**	**7.3**	**7.2**

Table 3.23. Mean values and standard deviations for oscillation in years 2018-2020

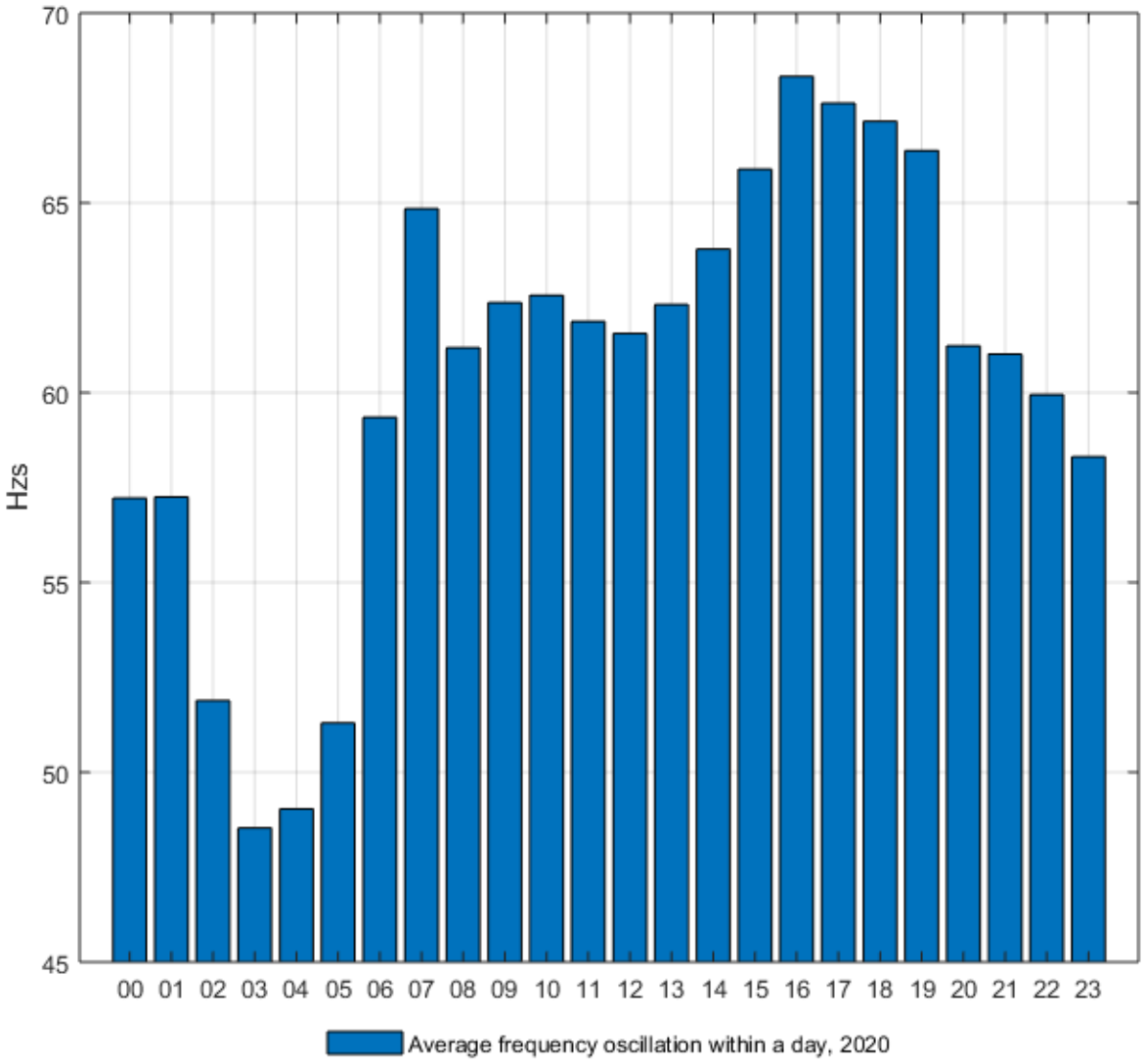
	Mean value (Hzs)			Standard deviation (Hzs)		
Month	**2018**	**2019**	**2020**	**2018**	**2019**	**2020**
January	45.1	46.2	59.4	5.2	6.0	10.2
February	43.8	48.7	58.1	5.1	8.0	8.6
March	46.5	52.7	57.2	6.1	7.8	9.6
April	55.6	59.8	59.9	8.7	10.8	9.6
May	61.4	68.9	59.7	8.9	9.5	10.4
June	63.0	69.8	64.4	8.2	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**

Figure 3.61. Mean values (left y-axis) and standard deviations (right y-axis) for oscillation in years 2015-2020



Average oscillation within a day in 2020 can be seen in fig 3.62. The amount of oscillation has peaked in the late afternoon. The least oscillation has occurred in the night from 2 am to 5 am.

Figure 3.62. Average frequency oscillation within a day in 2020

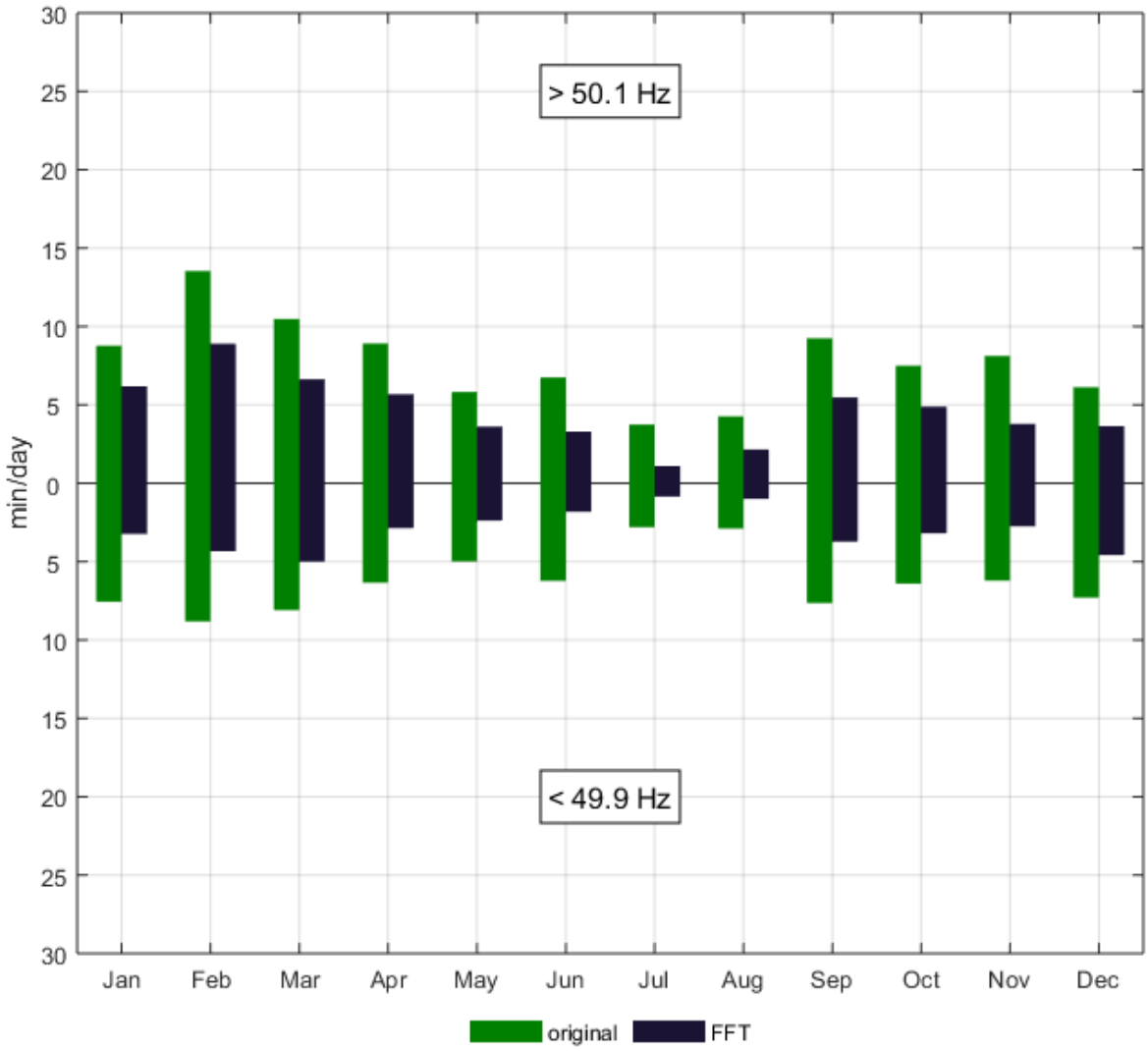


3.8.3 Influence of oscillation on frequency variations

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 2020 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 2020



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 of time outside the standard frequency range. For July, the reduction of time outside the standard frequency range is 70 %. For most of the months, the reduction of under frequencies is more than 50 %.

Figure 3.64. Reduction in time per month outside the standard frequency range after filtering in 2020

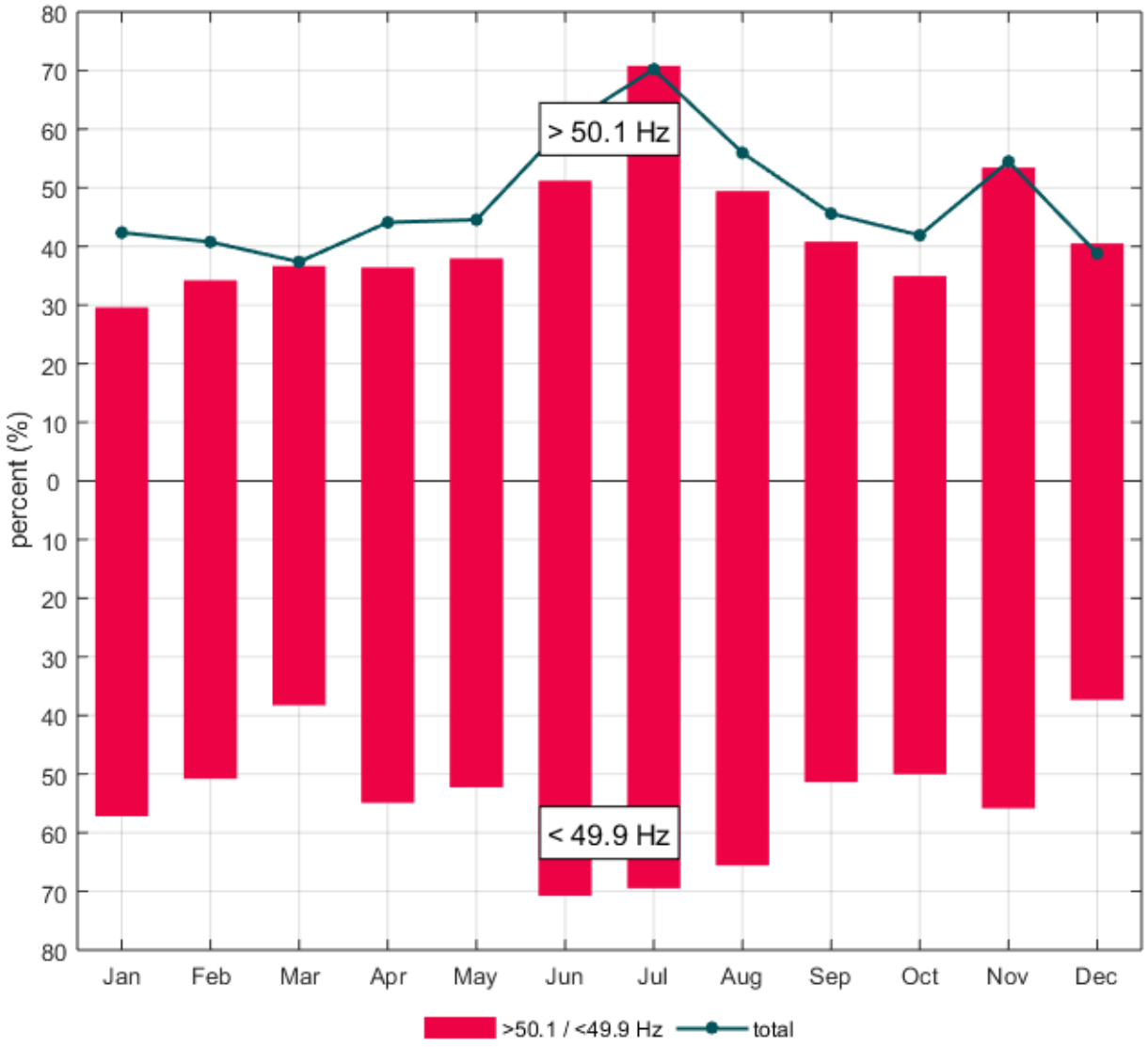
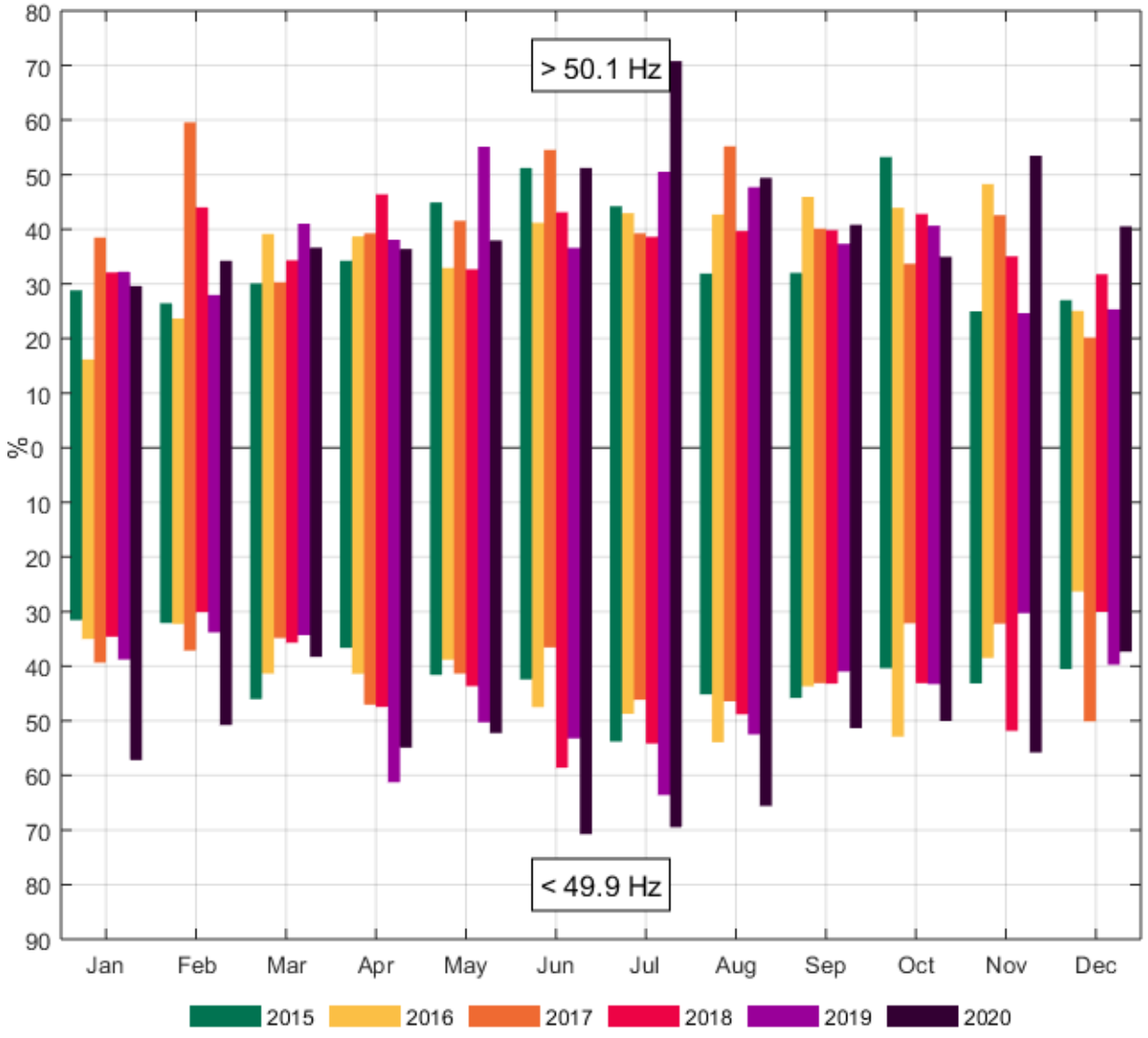


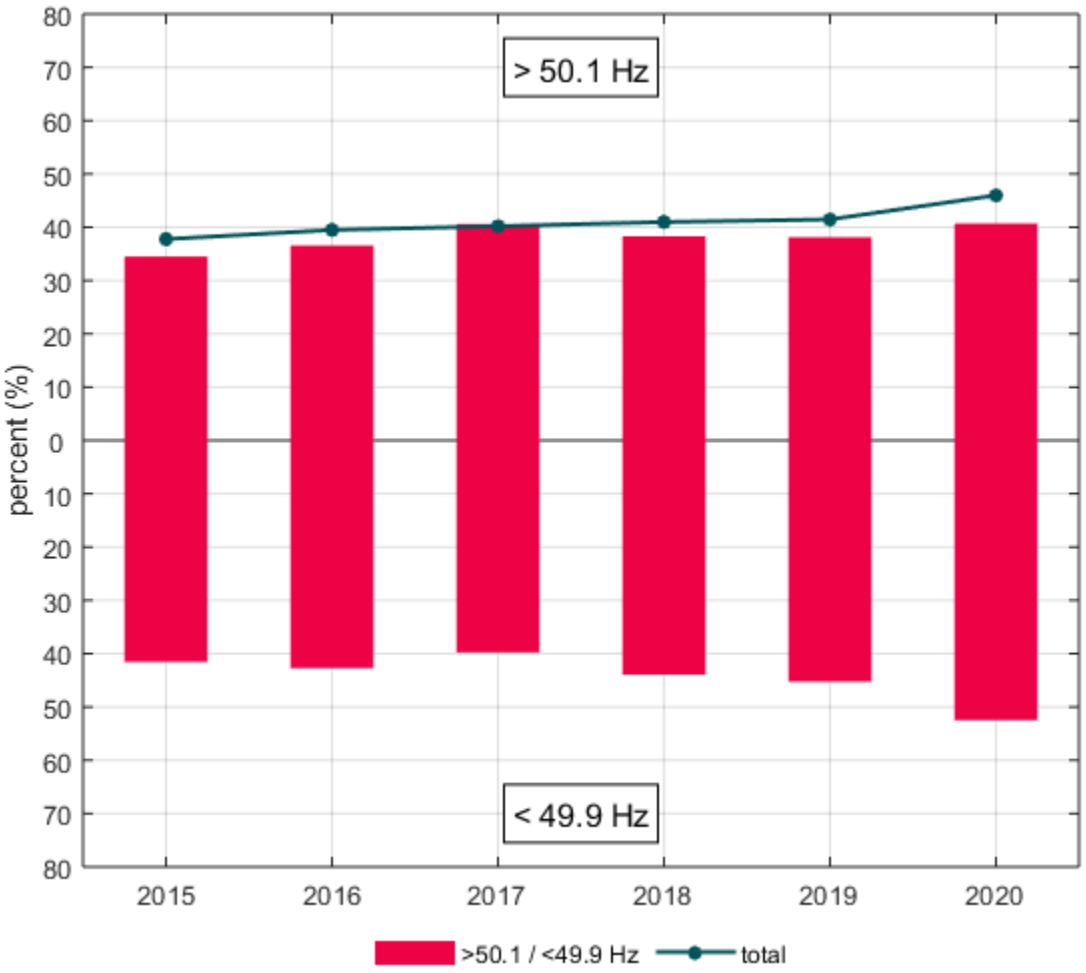
Figure 3.65 represents the reduction in time outside the standard frequency range in percentages month by month for years 2015 to 2020.

Figure 3.65. Reduction in time per month outside the standard frequency range after filtering in years 2015-2020



In addition to the monthly values presented in the previous figure, results for the entire year in 2015-2020 are shown below in Figure 3.66. Filtering the oscillation reduces duration of frequency deviations around 45 %. Slight yearly growth in reduction can bee seen from 2015 onwards. The reduction is about 10% more for under frequency deviations.

Figure 3.66. Reduction in time outside the standard frequency range after filtering for years 2015-2020



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 2020. 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]

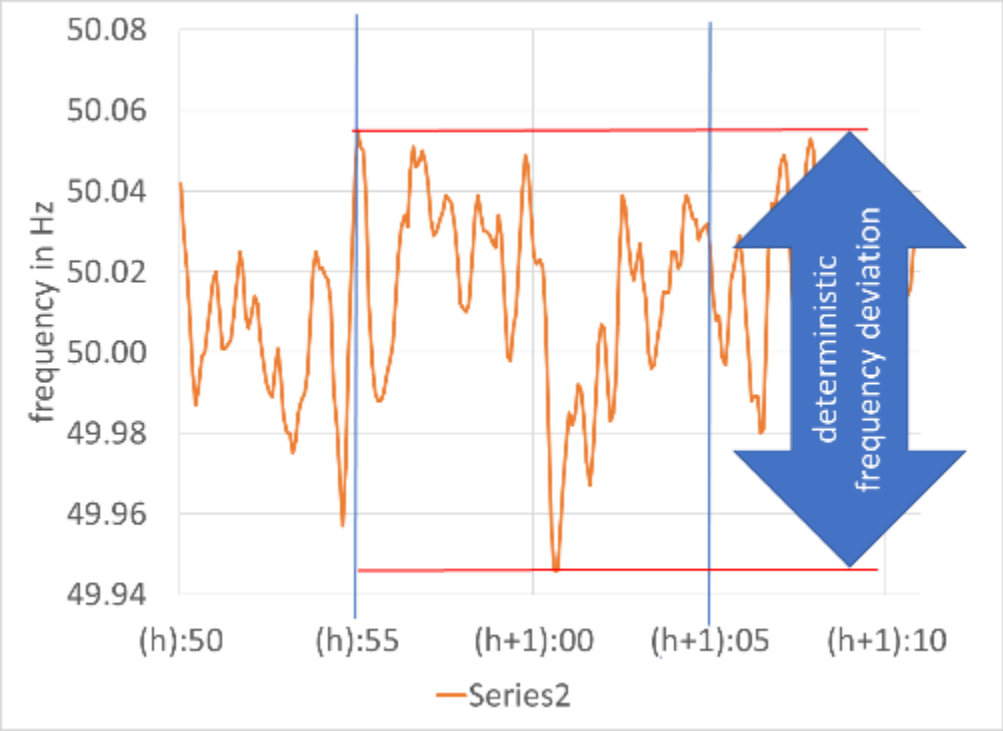


Figure 3.68 represents the deterministic frequency deviation per month in 2020. The 50th percentile stays below zero for the entire year, which indicates that the highest frequency took place before the lowest in more than half of the hour shifts.

Figure 3.68. The 1st, 5th, 10th, 50th, 90th, 95th, and 99th percentile of deterministic frequency deviation for every month in 2020

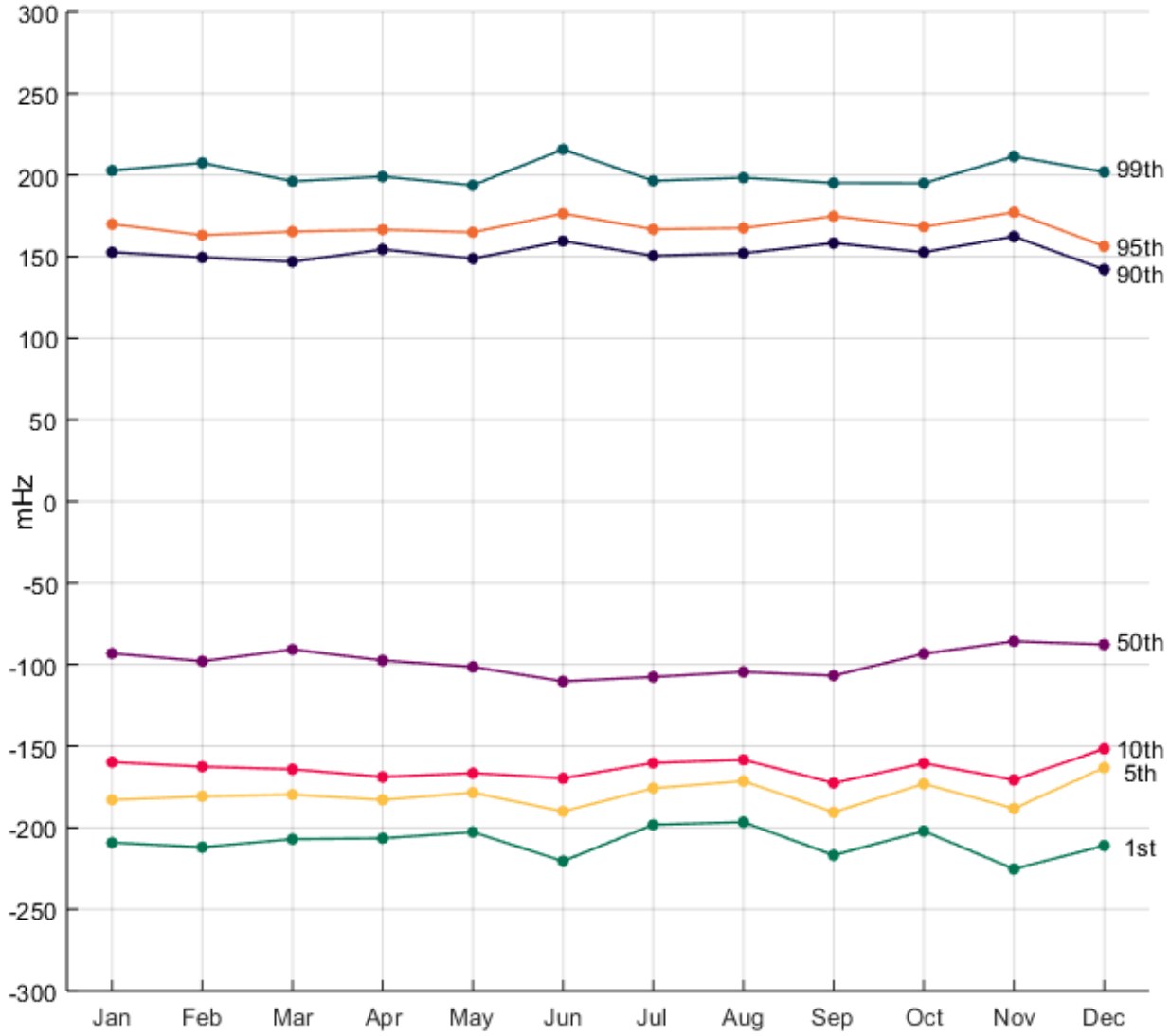
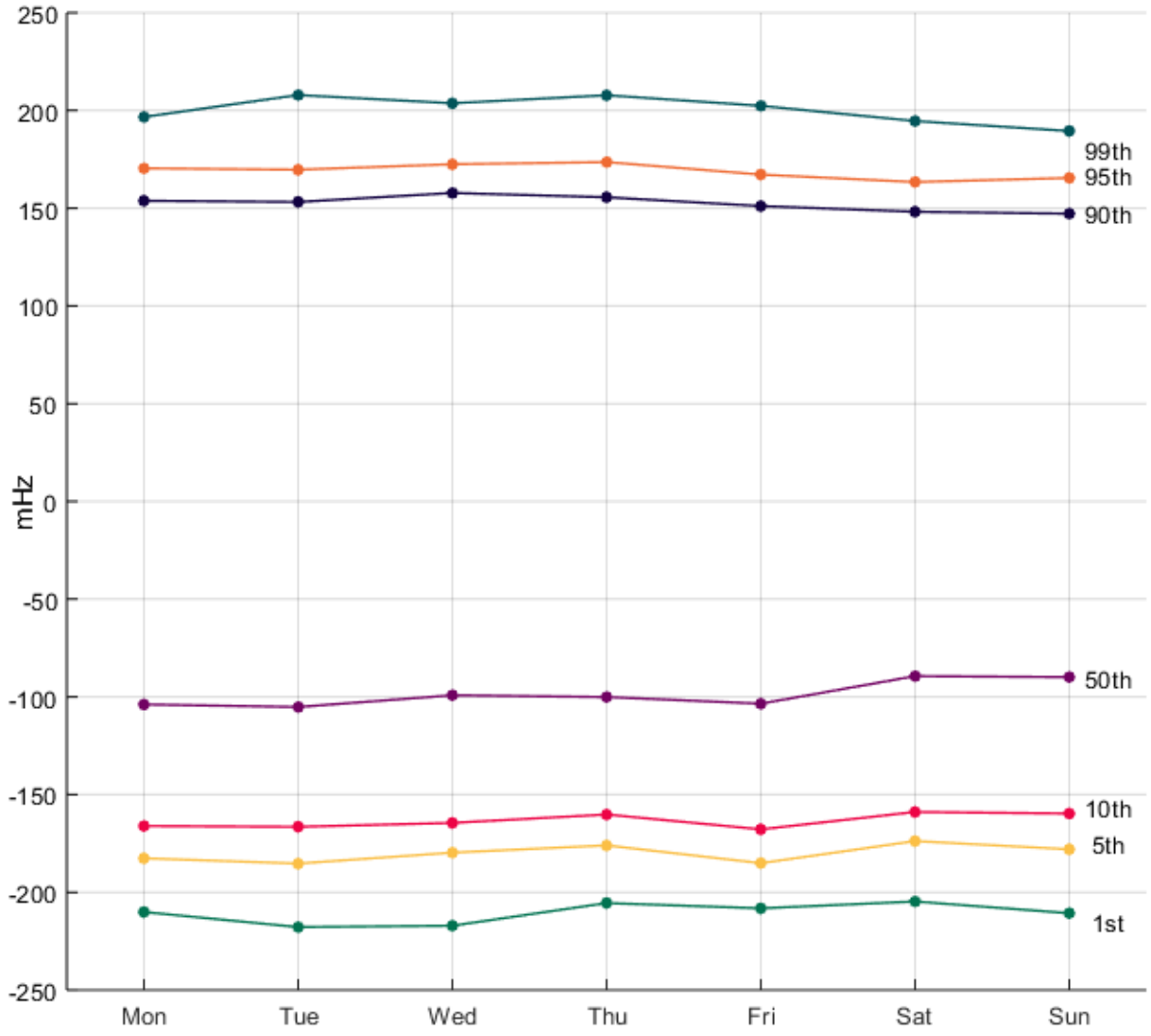


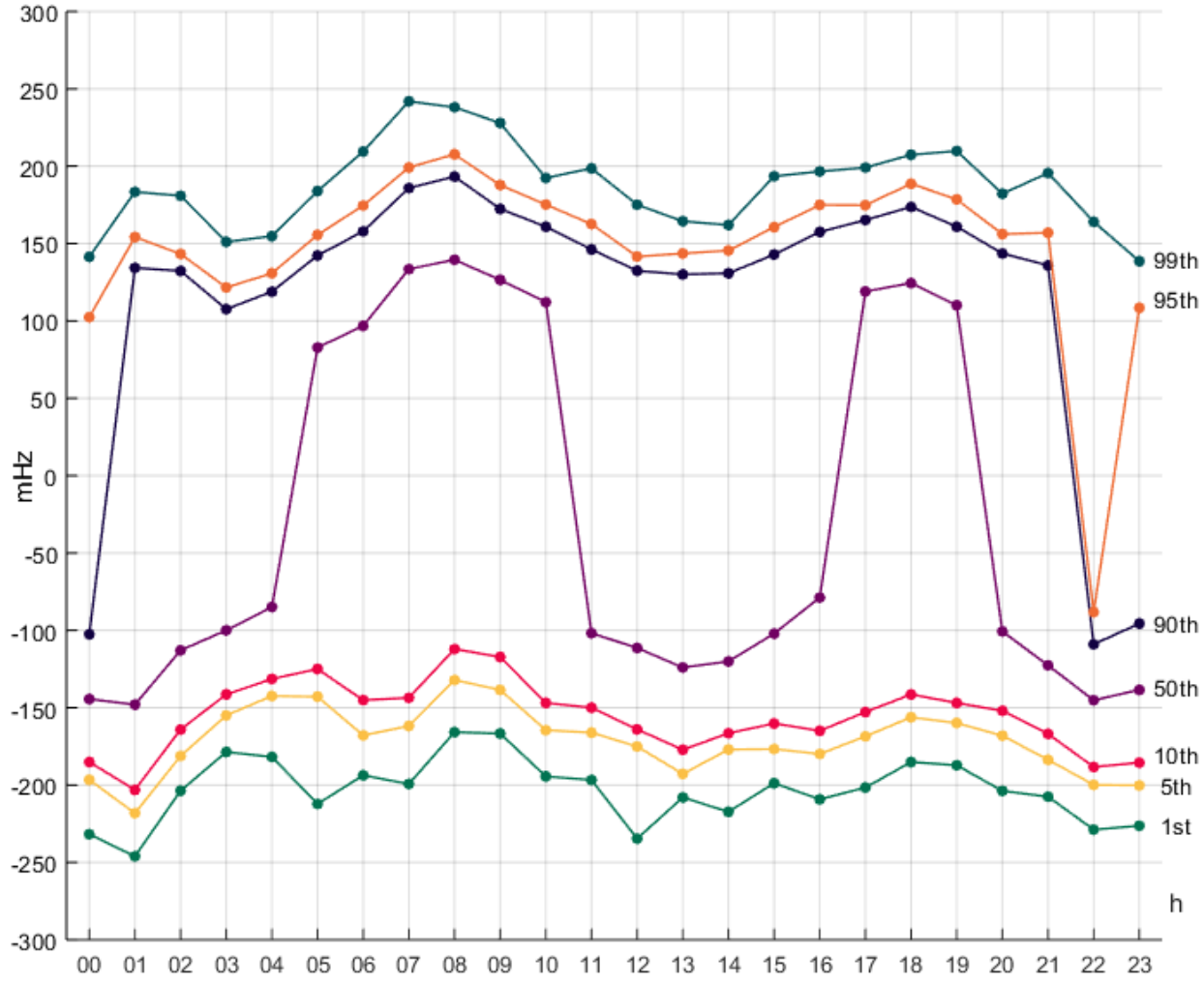
Figure 3.69 shows the percentiles around the hour shift for every day of the week in 2020. The 5th, 10th and 50th percentile have been slightly higher on the weekends.

Figure 3.69. The 1st, 5th, 10th, 50th, 90th, 95th, and 99th percentile of deterministic frequency deviation for every day of the week in 2020



The percentiles of the frequency step around the hour shift for each hour of the day is presented in Figure 3.70. During morning hours from 5 to 10 and in the evening from 17 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 2020



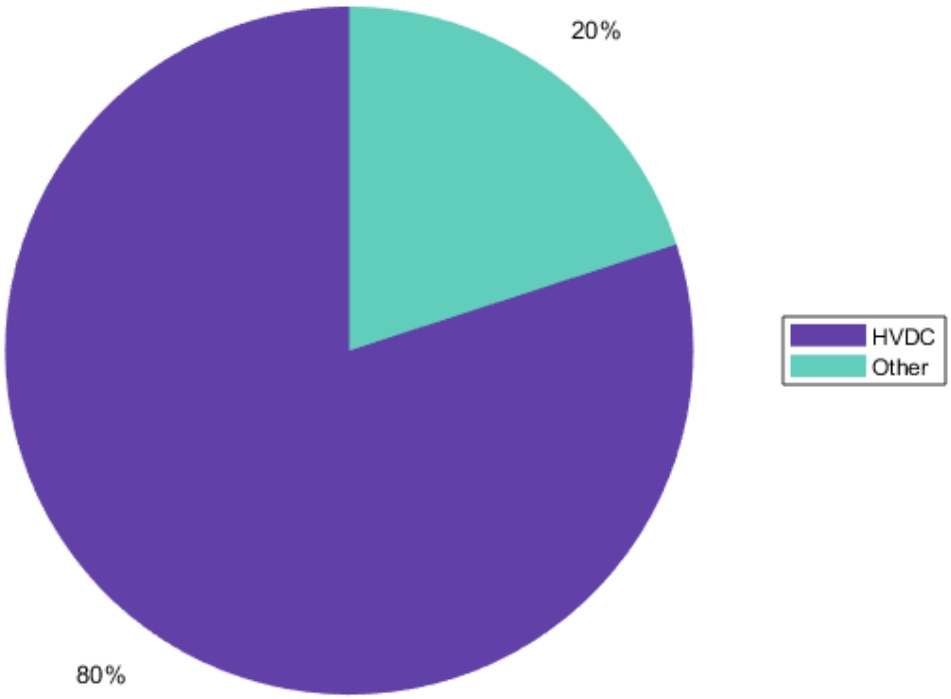
Chapter 4. Frequency disturbances exceeding 300 mHz frequency deviation

This chapter offers information of the major frequency disturbances in the Nordic synchronous system in the year 2020. Over 300 mHz frequency deviations are included.

Measurement data used for this study is from Fingrid's PMU located in Kangasala. Measurement frequency for the PMU is 10 Hz. This data describes at a fair accuracy the frequency of the whole Nordic system.

Four of the over ±300 mHz disturbances were caused by failures in HVDC links and one was caused by other reasons. Figure 4.1. represents the share of factors causing over 300 mHz deviations. In 2020 there were as many over 300 mHz disturbances as in 2019.

Figure 4.1**. **Shares of factors causing over 300 mHz disturbances in the Nordic synchronous system in 2020



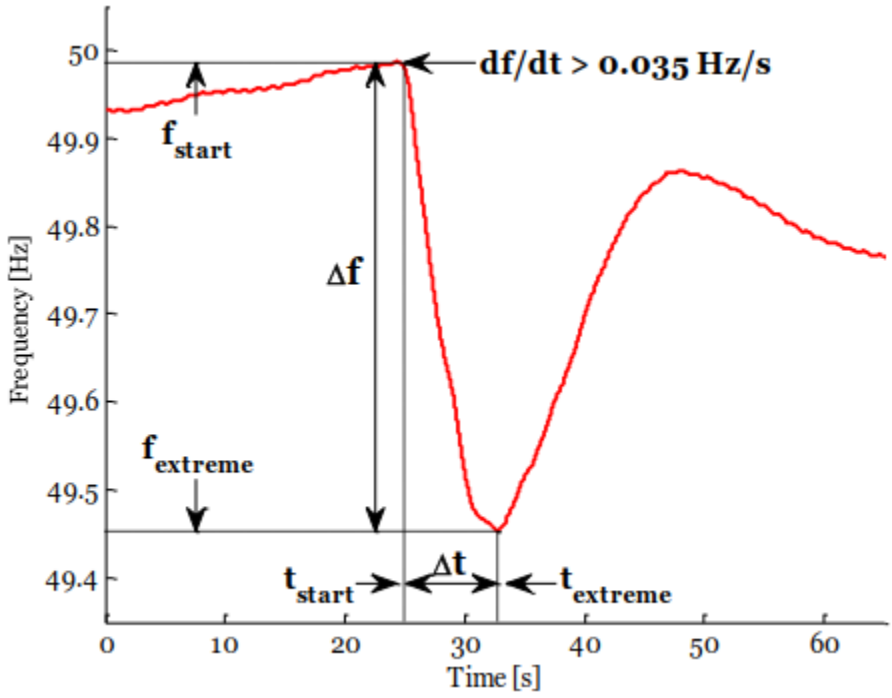
The largest over and under frequency deviations were caused by faults in an HVDC link on 10 September. First, an over frequency deviation of 0.442 Hz was reported. After the over frequency deviation an under frequency deviation of -0.634 Hz occurred.

The following part of the chapter will go into more detail on every disturbance that took place in 2020. 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]



Occasionally included disturbances can have Δf-values below 300 mHz. Δf is defined to be the absolute value between fstart and fextreme as seen in Figure 4.2. In some cases there can be a frequency deviation at a later moment that is higher than Δf and exceeds the ±300 mHz deviation. In 2020 there were no such cases. [10]

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. In 2020 there were no over 300 mHz disturbances with a gradient smaller than 0.035 Hz/s meaning that no disturbances were excluded because of too small a gradient.

Kinetic energy (Ek) is an estimation of the rotation energy of synchronously connected generators in the Nordic synchronous system. Kinetic energy is related to the system inertia which describes the system's ability to oppose changes in frequency. Higher kinetic energy provides higher inertia and therefore better ability to oppose frequency deviations. [10] More detailed descriptions of the events listed in Table 4.1 are presented afterwards in Figures 4.3-24 and Tables 4.2-23.

Table 4.1. List of disturbance events in 2020

Event date	Δf (Hz)	ΔP (MW)	Δt (s)	E_k (GWs)	Cause	Page
10-May-2020 20:56:12	0.318	666	7.5	178	HVDC	105
04-Jun-2020 23:09:44	-0.304	N/A	8.6	164	Other	106
07-Jun-2020 08:06:41	0.356	734	6.9	144	HVDC	107
10-Sep-2020 10:11:21	0.442	1470	5.8	171	HVDC	108
10-Sep-2020 10:12:07	-0.634	1409	6.4	168	HVDC	109

Figure 4.3. Disturbance 10-May-2020 20:56:12

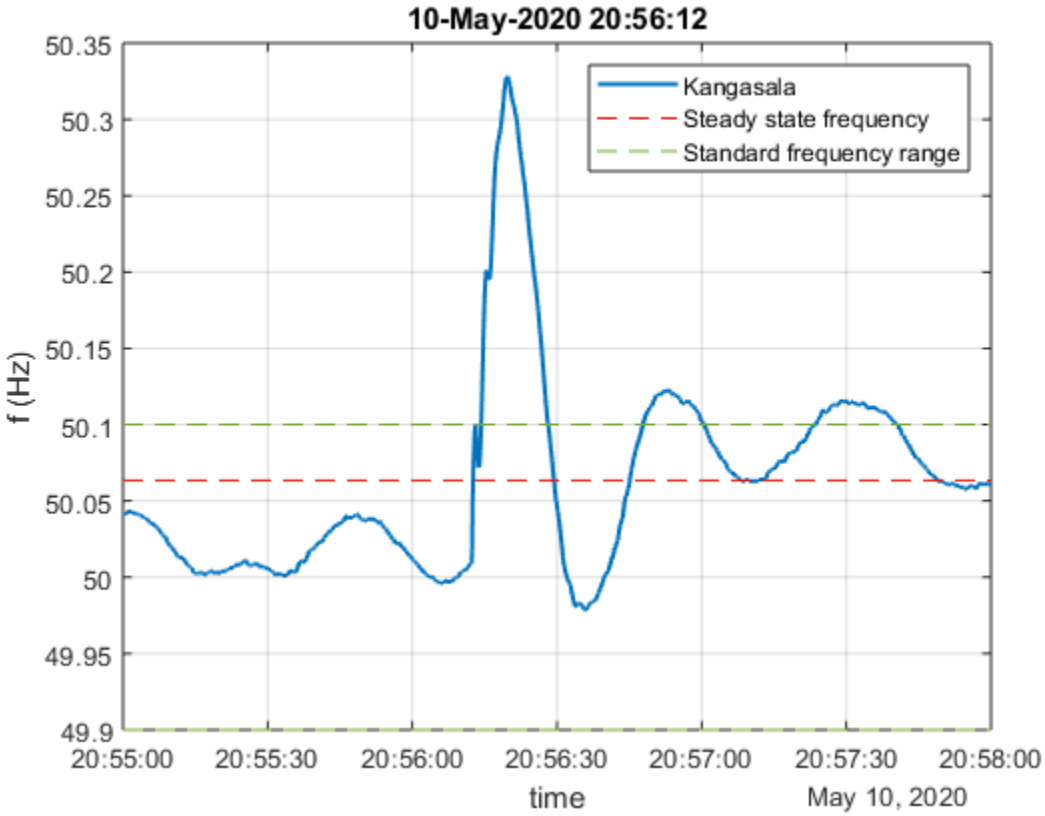


Table 4.2. Disturbance 10-May-2020 20:56:12

Date		**10-May-2020 20:56:12**	
f_{start}	50.010 Hz	$f_{steady\ state}$	50.064 Hz
$f_{extreme}$	50.328 Hz	$\Delta f_{steady\ state}$	0.053 Hz
Δf	0.318 Hz	$f_{extreme2}$	49.979 Hz
Δt	7.5 s	$f_{extreme3}$	50.122 Hz
ΔP	666 MW	damping	41.14 %
E_k	178 GWs	FBF	12501 MW/Hz
cause		HVDC	

Figure 4.4. Disturbance 04-Jun-2020 23:09:44

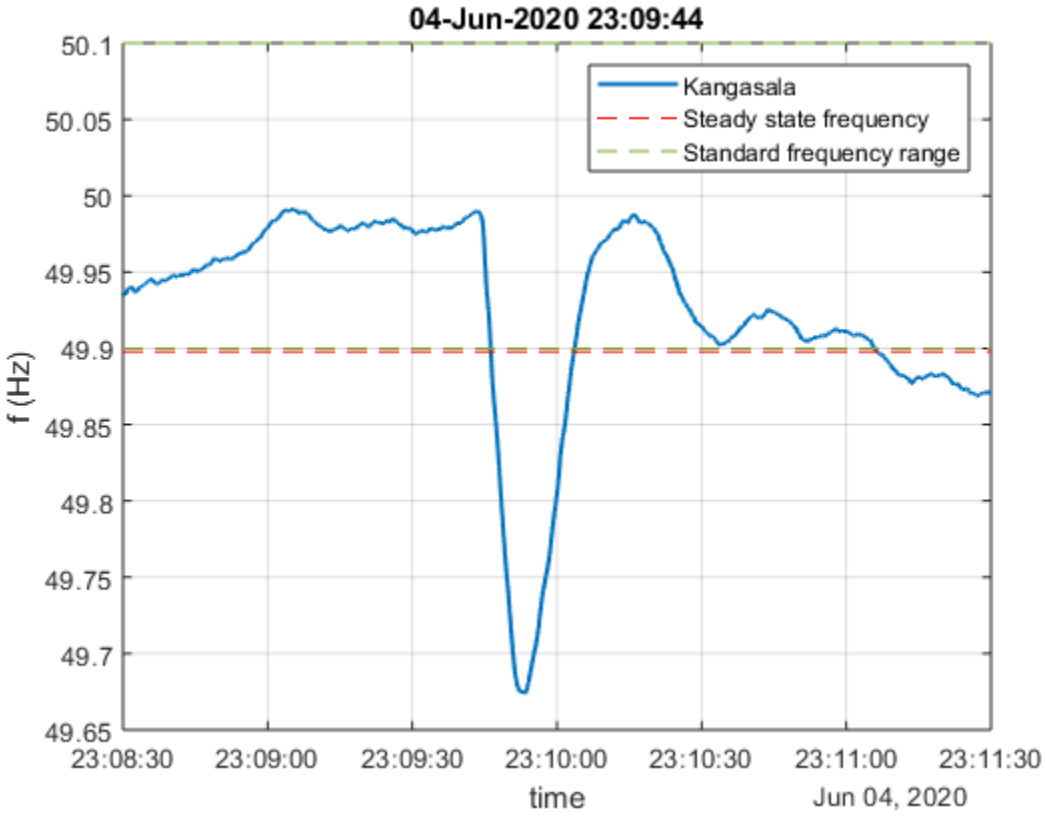


Table 4.3. Disturbance 04-Jun-2020 23:09:44

Date		**04-Jun-2020 23:09:44**	
f_{start}	49.978 Hz	$f_{steady\ state}$	49.898 Hz
$f_{extreme}$	49.674 Hz	$\Delta f_{steady\ state}$	0.080 Hz
Δf	-0.304 Hz	$f_{extreme2}$	49.988 Hz
Δt	8.6 s	$f_{extreme3}$	49.877 Hz
ΔP	N/A	damping	35.27 %
E_k	164 GWs	FBF	N/A
cause		Other	

Figure 4.5. Disturbance 07-Jun-2020 08:06:41

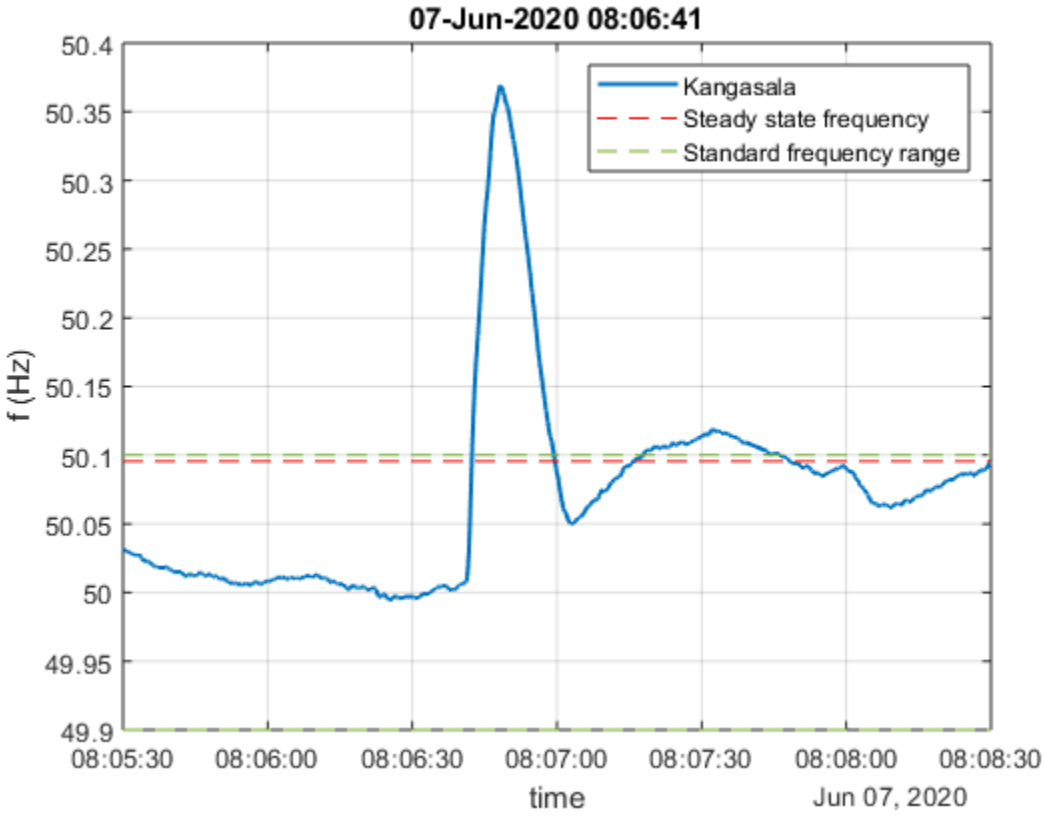


Table 4.4. Disturbance 07-Jun-2020 08:06:41

Date		**07-Jun-2020 08:06:41**	
f_{start}	50.013 Hz	$f_{steady\ state}$	50.095 Hz
$f_{extreme}$	50.369 Hz	$\Delta f_{steady\ state}$	0.082 Hz
Δf	0.356 Hz	$f_{extreme2}$	50.050 Hz
Δt	6.9 s	$f_{extreme3}$	50.119 Hz
ΔP	734 MW	damping	21.60 %
E_k	144 GWs	FBF	8905 MW/Hz
cause		HVDC	

Figure 4.6. Disturbance 10-Sep-2020 10:11:21

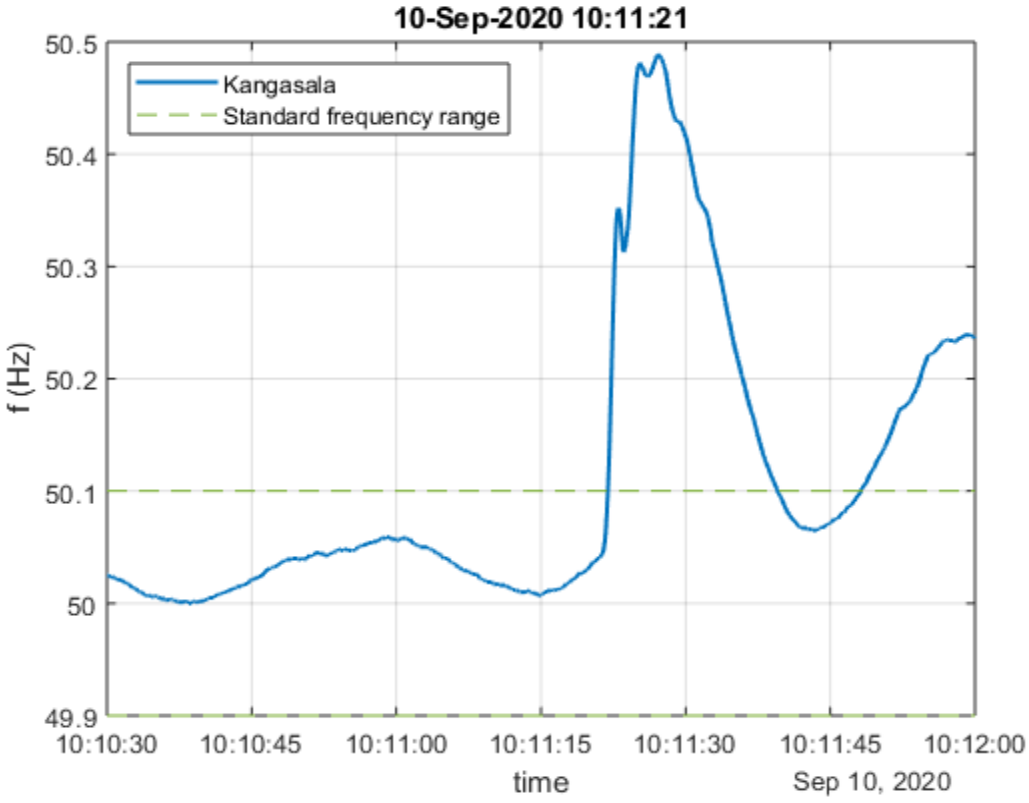


Table 4.5. Disturbance 10-Sep-2020 10:11:21

Date		**10-Sep-2020 10:11:21**	
f_{start}	50.046 Hz	$f_{steady\ state}$	N/A*
$f_{extreme}$	50.488 Hz	$\Delta f_{steady\ state}$	N/A*
Δf	0.442 Hz	$f_{extreme2}$	50.065 Hz
Δt	5.8 s	$f_{extreme3}$	50.239 Hz
ΔP	1470 MW	damping	69.88 %
E_k	171 GWs	FBF	N/A*
cause		HVDC	

*not applicable due to a second disturbance at 10:12:07, see next page

Figure 4.7. Disturbance 10-Sep-2020 10:12:07

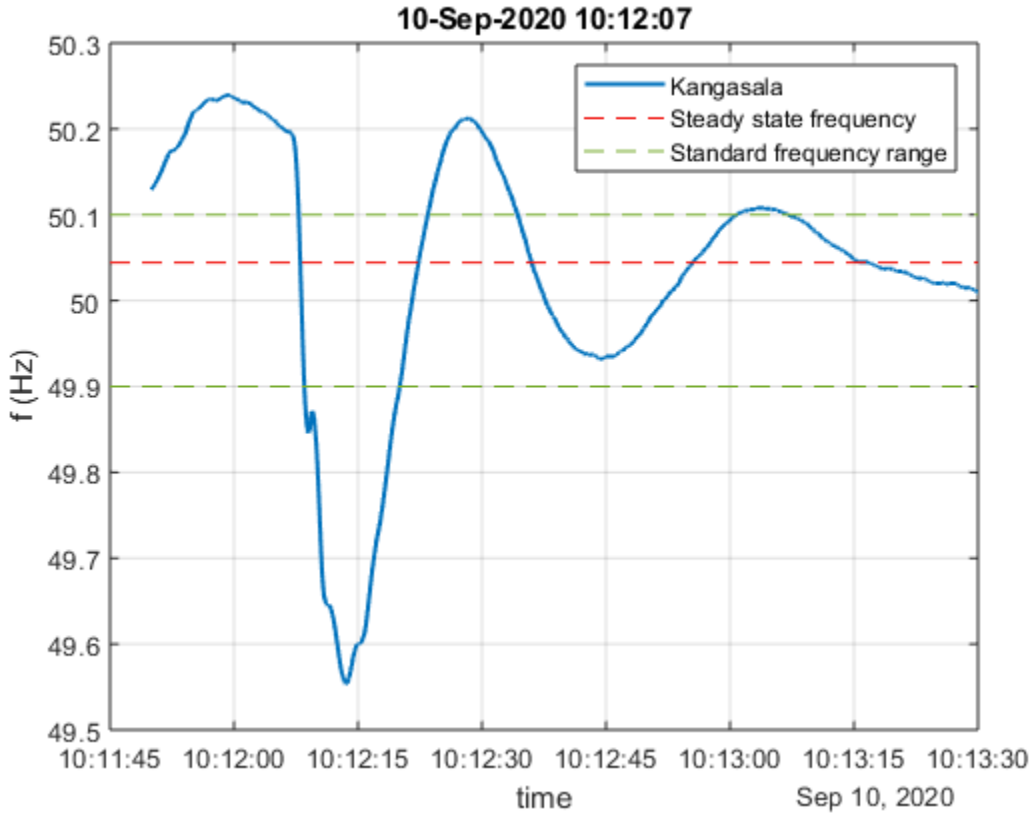


Table 4.6. Disturbance 10-Sep-2020 10:12:07

Date		**10-Sep-2020 10:12:07**	
f_{start}	50.189 Hz	$f_{steady\ state}$	50.044 Hz
$f_{extreme}$	49.555 Hz	$\Delta f_{steady\ state}$	0.144 Hz
Δf	-0.634 Hz	$f_{extreme2}$	50.212 Hz
Δt	6.4 s	$f_{extreme3}$	49.932 Hz
ΔP	1409 MW	damping	42.60 %
E_k	168 GWs	FBF	9763 MW/Hz
cause		HVDC	

Chapter 5. Summary

The aim of this report is to analyze frequency quality in the Nordic synchronous system in 2020. Various indices were used to assess frequency quality, and the results were compared to the previous years. The overall quality of the frequency was better in 2020 than in 2019. In many categories, 2020 had the best frequency in the whole five-year observation period.

The average duration and the number of frequency deviations varied on a monthly and daily basis. The time outside the standard frequency range and the total number of frequency deviations with different durations decreased significantly from 2019. July and August were clearly the best months in terms of frequency quality. In terms of time outside the standard frequency range and the number of deviations, the quality of the frequency was worst in February, March, and September. Most deviations in the frequency occurred in the middle of the week.

In the hourly analysis, most deviations occurred in the late morning and early afternoon. Deviations around midnight decreased in comparison to the previous years. The highest number of threshold crossings and the longest time outside the standard frequency range occurred at 7 am. Inside an average hour the quality of the frequency was worse closer the hour shift and especially in the beginning of the hour.

The amount of frequency oscillation increased significantly from 2019. The amount was also higher compared to any of the previous years. In the past years, the frequency has oscillated less during winter and more from spring to autumn. However, in 2020 the amount of frequency oscillation was high throughout the year. On an average day, the largest amount of oscillation occurred in the late afternoon. Removal of the oscillation by filtering the frequency data clearly reduced the frequency deviations. Reduction with the FFT-filtering method was around 40 % for over frequency deviations and 50 % for under frequency deviations.

The time outside 49.8-50.2 Hz decreased from the previous year. The number of 200 mHz deviations also decreased. There were five frequency disturbances exceeding 300 mHz in 2020. Most of the disturbances were caused by failures in HVDC connections. The number of frequency deviations exceeding 300 mHz was the same as in 2019.

Chapter 6. Sources

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

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[3] Lindberg D.: "Frequency quality analysis for year 2016", Fingrid Oyj, 22.9.2017

[4] Lindberg D.: "Frequency quality analysis for year 2017", Fingrid Oyj, 28.8.2018

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

[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] Commission Regulation (EU) 2017/1485 of 2 August 2017 (System Operation Guideline), available at https://www.entsoe.eu/major-projects/network-code-development/system-operation

[10] Nordic report: Future system inertia, ENTSO-E, 2015, available at http://www.entsoe.eu