Frequency quality analysis

2019

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 2019. 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 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 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 2019 is presented in Table 2.1. Availability of data per year for years 2014 to 2019 can be seen in Table 2.2 [2,3,4,5,6]. In 2019 there was valid measurement data for 98.47 % 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 May, 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 2019

Month	Available data
January	99.89 %
February	99.89 %
March	99.91 %
April	99.94 %
May	83.27 %
June	99.88 %
July	99.89 %
August	99.92 %
September	99.88 %
October	99.75 %
November	99.83 %
December	99.89 %

Table 2.2. The amount of valid measurement data available for years 2014-2019

Year	**Available data**
2014	99.89 %
2015	99.90 %
2016	99.37 %
2017	97.19 %
2018	98.90 %
2019	98.47 %

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 defined in SO GL (System Operation Guideline) Article 131 are also presented in this chapter. The Article 131 is shown in the following page. Regarding Article 131(b), the Nordic synchronous area presently forms one LFC block and LFC area (Load-Frequency Control Block and Area). Therefore the results are calculated for the synchronous area and the FRCE (Frequency Restoration Control Error) is defined as the frequency deviation.

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(a) (i-ii) and 131(b) (i) (1 and 2).

3.1.1 Average frequency

The following figures show the average frequency for the year 2019. 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. Even for the worst month December the average has deviated less than 0.6 mHz from 50 Hz. In other moths the average frequency has been within 0.4 mHz from 50 Hz. In 2018 the average frequency deviated slightly more from 50 Hz than in 2019, since the maximum average frequency deviation in 2018 was less than 0.7 mHz.

***Figure 3.1*. Average frequency for each month in 2019**

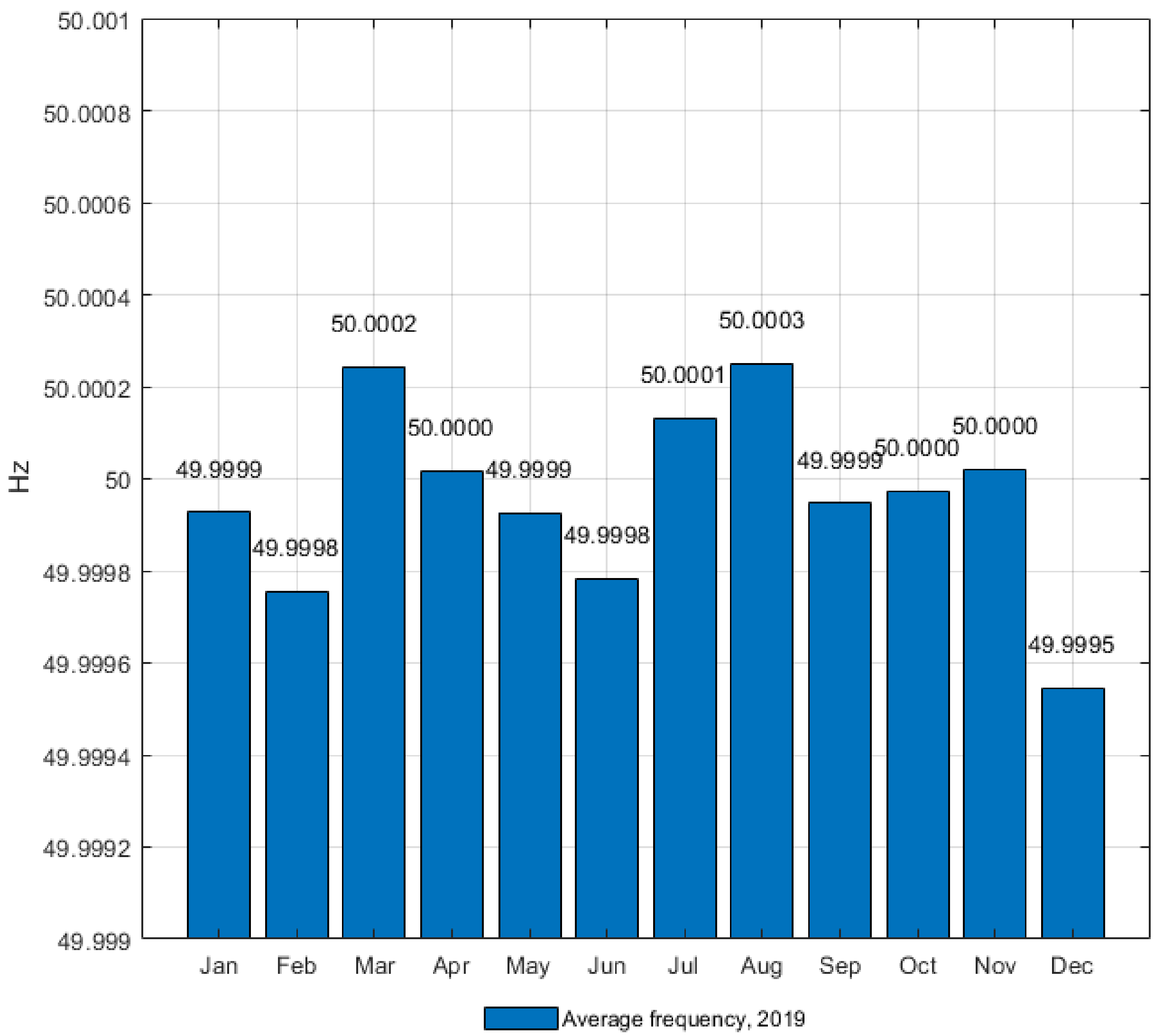


Figure 3.2 represents the average frequencies for every day of the week. The average frequency has had the lowest values on Sundays and highest values on Mondays.

***Figure 3.2**. Average frequency for each day of the week in 2019*

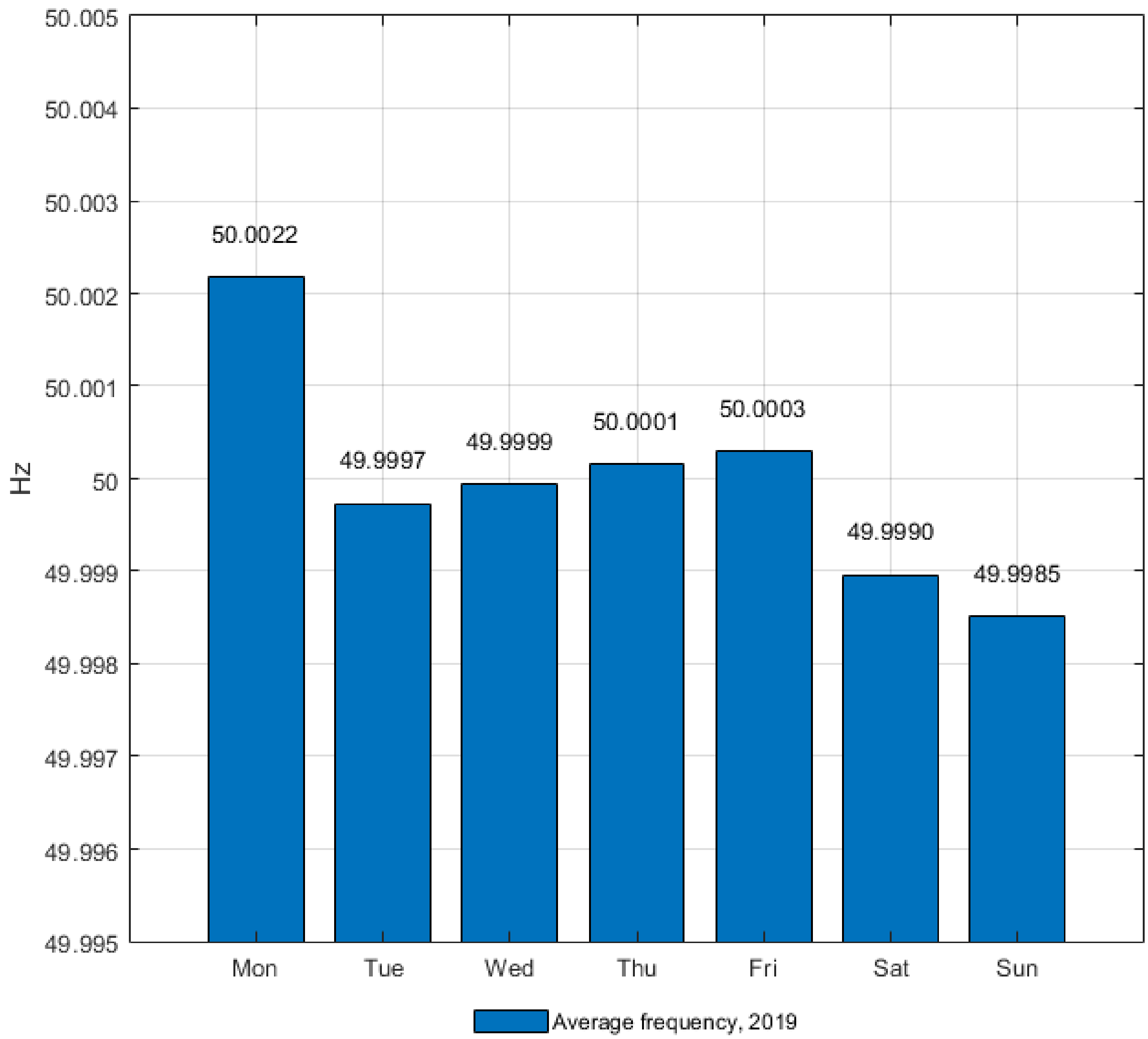


Figure 3.3 shows the average frequencies during each hour of the day. Frequency is generally lower during the night hours from 01 to 04 and in the afternoon from 16 to 18. The frequency is at its highest during the noon, in the evening and around midnight.

Figure 3.3. Average frequency for each hour of the day in 2019

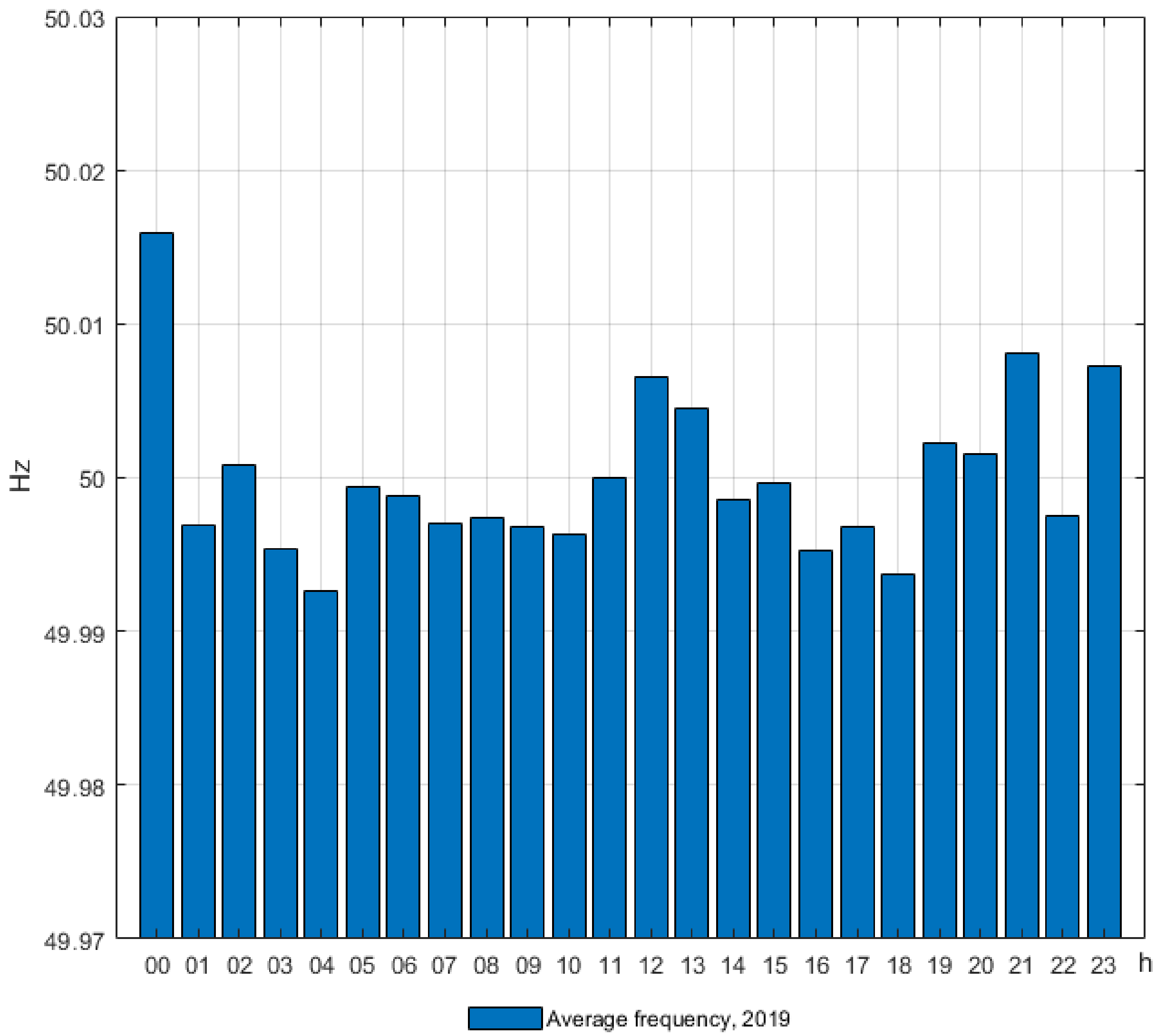
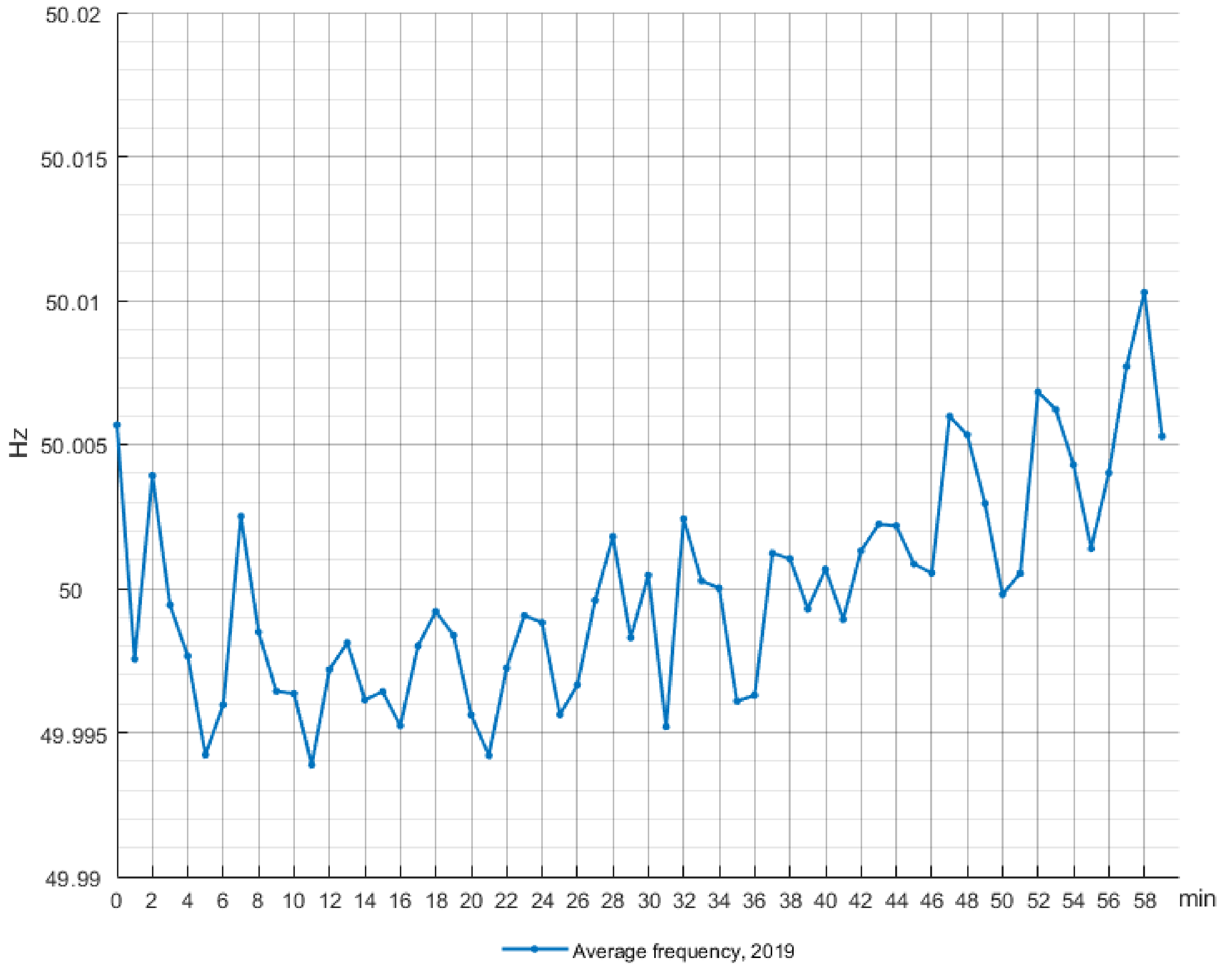


Figure 3.4 shows the average frequency inside the hour. In general the frequency is higher in the latter part of the hour. The difference between consecutive minutes varies between 0-7.5 mHz.

***Figure 3.4**. Average frequency for each minute of the hour in 2019*



3.1.2 Standard deviation

This section includes the figures representing the standard deviation of frequency during the year 2019. 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 2019. The lower standard deviation in July and November indicates that the 1 second frequency values were closer to 50 Hz during those months. From February to June the standard deviation was clearly higher than during other months. In general there was more deviation in frequency values in 2019 than in 2018.

***Figure 3.5**. Standard deviation of the frequency for every month in 2019*

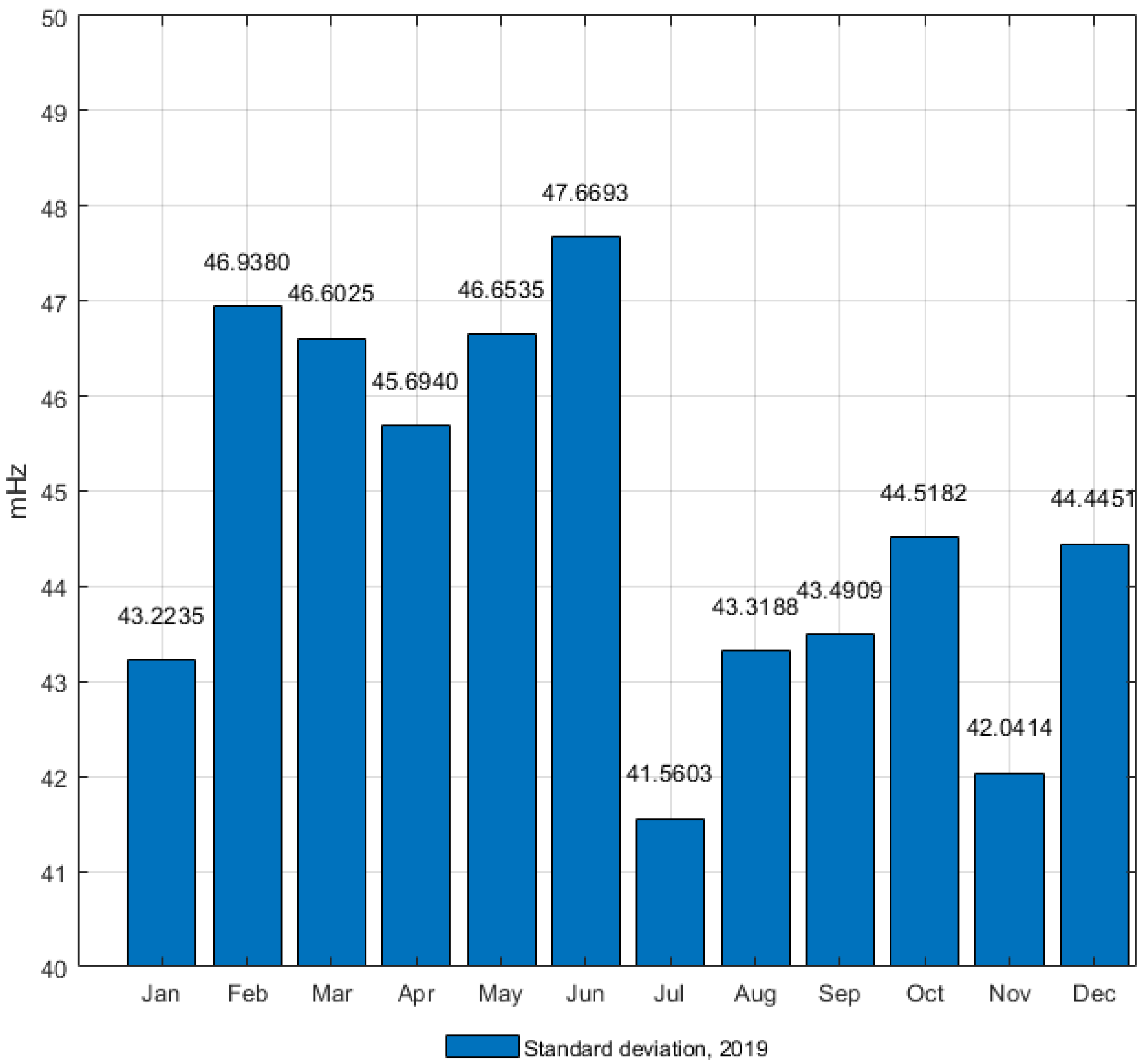


Figure 3.6 represents the standard deviation for every day of the week. Based on standard deviation, the quality of the frequency gets slightly better during the weekdays but gets worse on Saturday. It is noteworthy that all the values are within 3 mHz from each other, where as the monthly variation showed much higher deviation between different months.

Figure 3.6. Standard deviation of the frequency for every day of the week in 2019

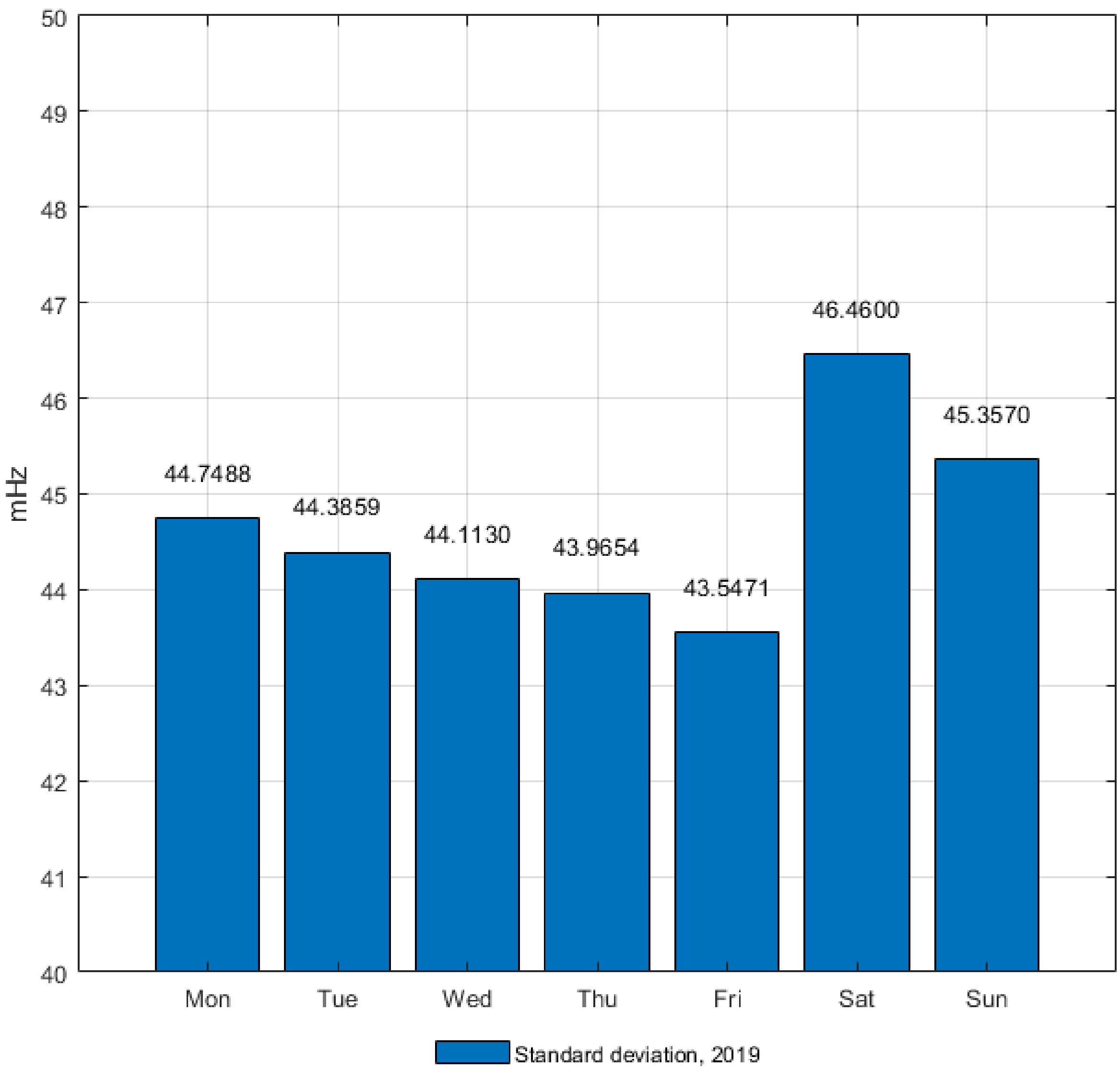


Figure 3.7 shows the standard deviation during a day. The standard deviation varies up to 8.5 mHz from the lowest value during the night to the highest value in the morning. In 2019 rather high standard deviation values occurred during the day hours compared to previous year.

***Figure 3.7**. Standard deviation of the frequency for every hour of the day in 2019*

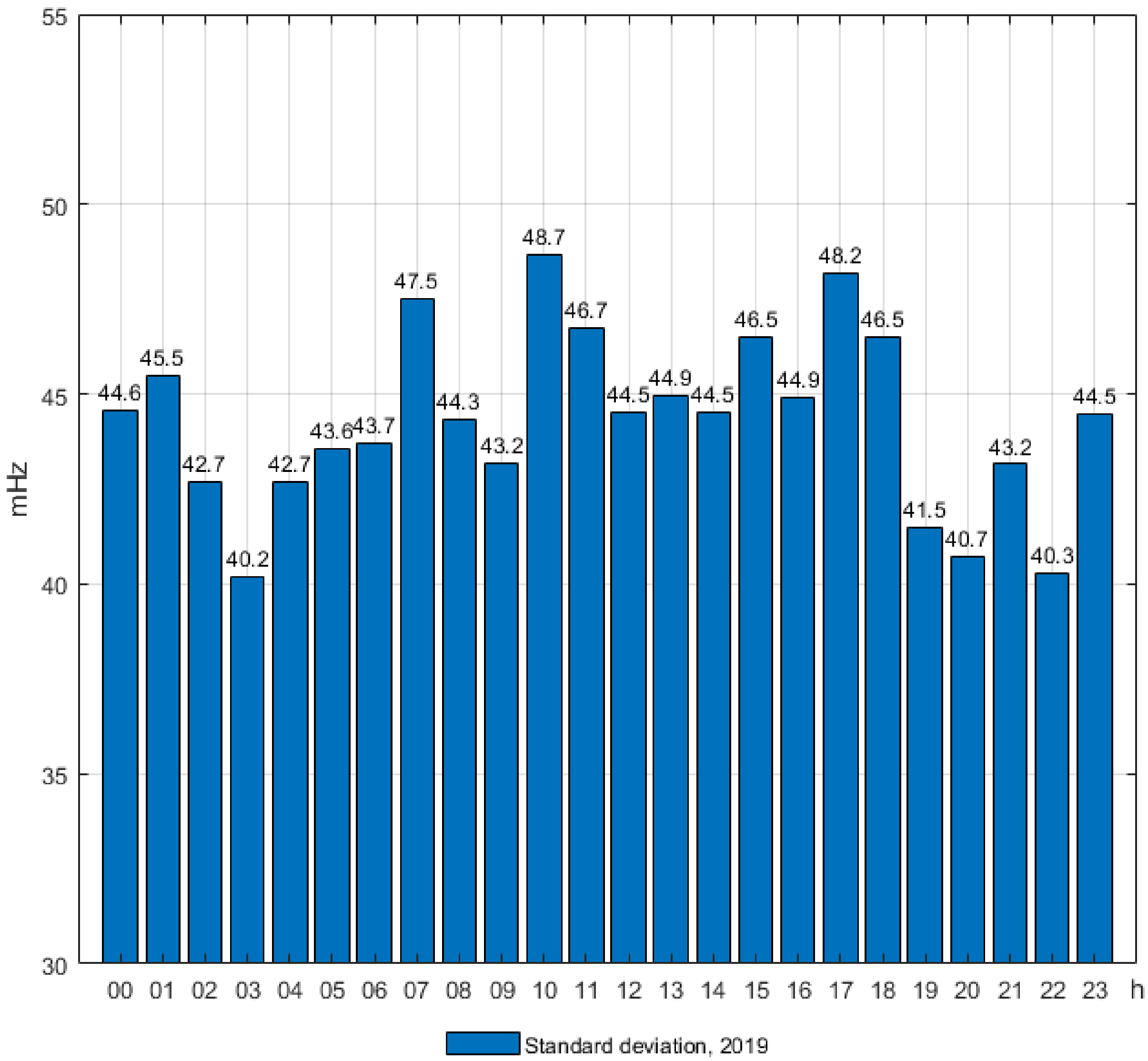
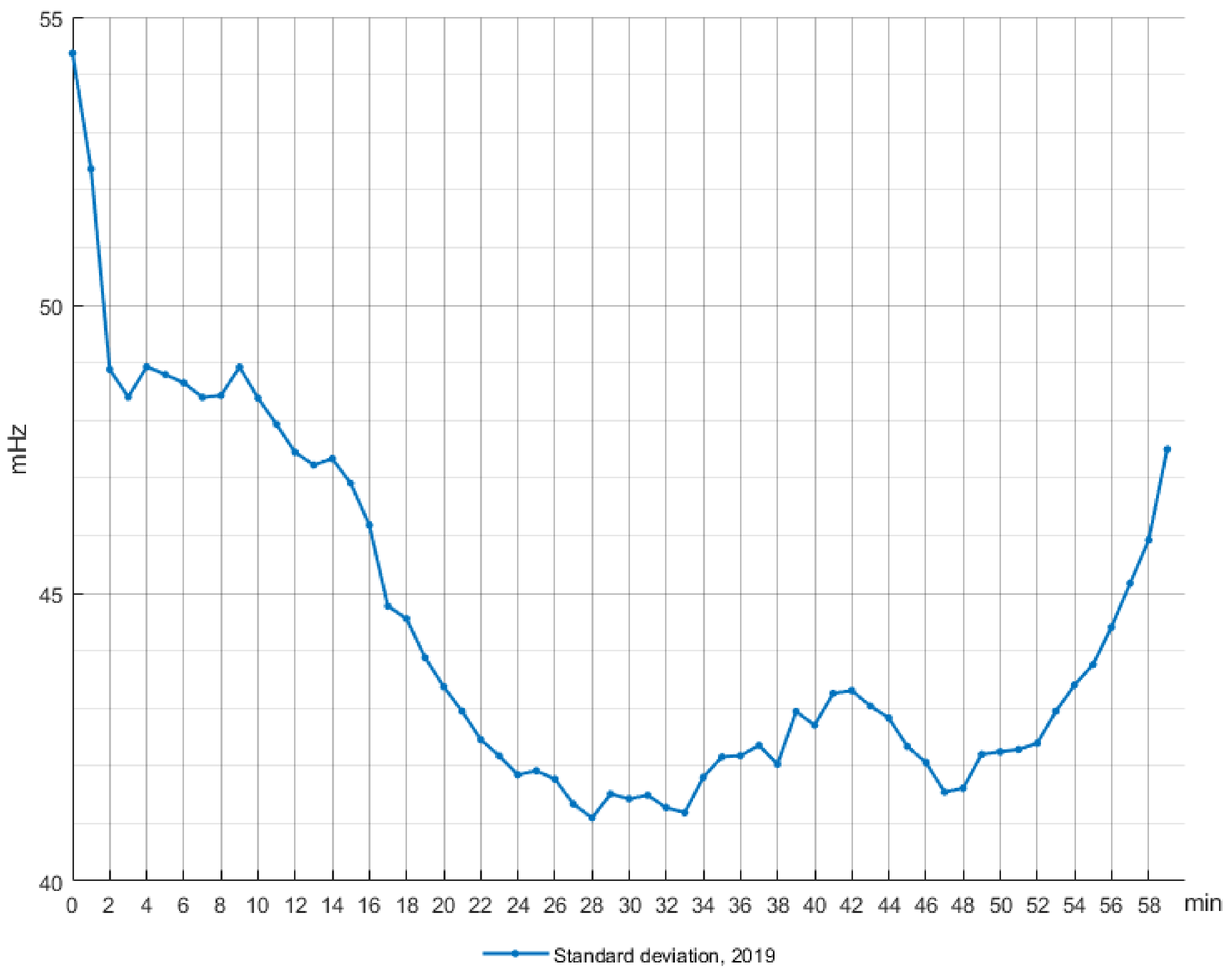


Figure 3.8 represents the standard deviation inside one hour. The standard deviation is at its highest in the beginning of the hour. From the 9th minute the standard deviation starts to drop until the half hour mark from where it starts to increase again. There is also a slight drop in the standard deviation at 47th minute.

Figure 3.8**. **Standard deviation of the frequency for every minute of the hour in 2019



3.1.3 Mean value and standard deviation

Mean values and standard deviations of the frequency, according to SOGL Article 131(a) i and ii), month by month for years 2014 to 2019 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.

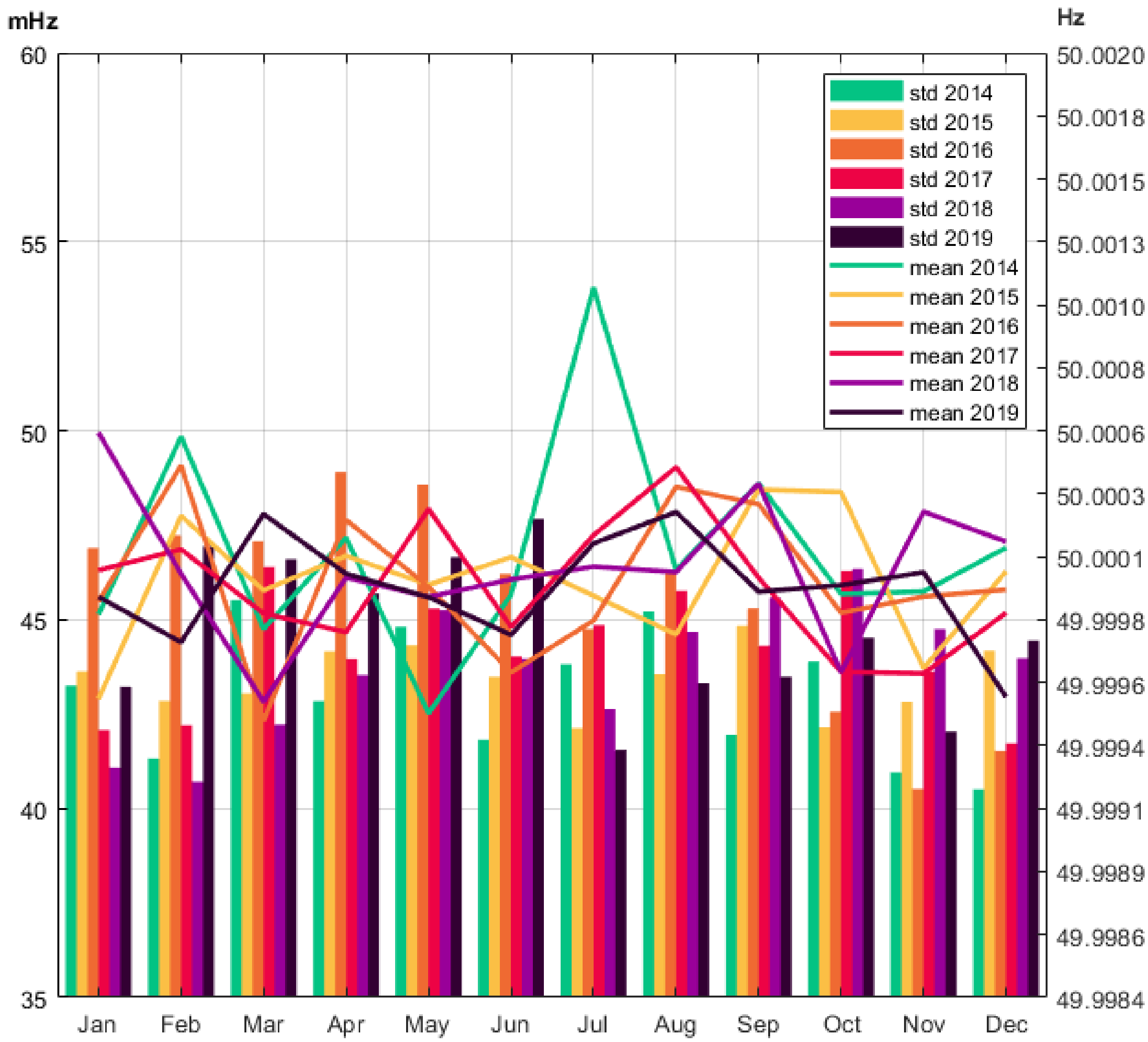
Table 3.1. Mean values and standard deviations for years 2014-2016

	2014		**2015**		**2016**	
Month	**Mean value (Hz)**	**Standard deviation (mHz)**	**Mean value (Hz)**	**Standard deviation (mHz)**	**Mean value (Hz)**	**Standard deviation (mHz)**
January	49.9999	43.3	49.9995	43.6	49.9999	46.9
February	50.0005	41.3	50.0002	42.9	50.0004	47.2
March	49.9998	45.5	50.0000	43.0	49.9995	47.1
April	50.0002	42.8	50.0001	44.2	50.0002	48.9
May	49.9995	44.8	50.0000	44.3	50.0000	48.6
June	49.9999	41.8	50.0001	43.5	49.9996	46.2
July	50.0011	43.8	49.9999	42.1	49.9998	44.8
August	50.0000	45.2	49.9998	43.6	50.0003	46.3
September	50.0004	42.0	50.0003	44.8	50.0003	45.3
October	49.9999	43.9	50.0003	42.2	49.9999	42.6
November	49.9999	41.0	49.9997	42.8	49.9999	40.5
December	50.0001	40.5	50.0000	44.2	50.0000	41.5
Entire year	**50.0001**	**43.1**	**50.0000**	**43.4**	**50.0000**	**45.5**

Table 3.2. 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**

***Figure 3.9**. Mean values and standard deviations for years 2014-2019*

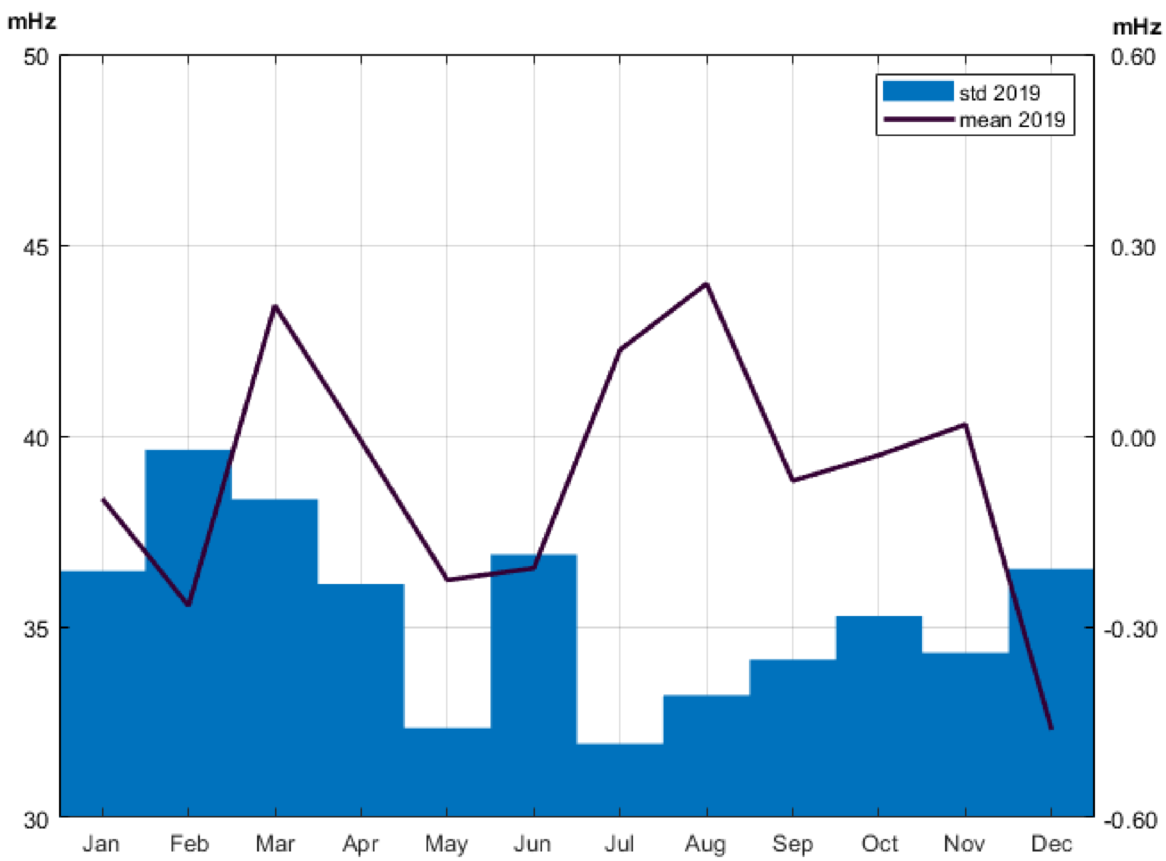


Mean values and standard deviations for frequency deviations as per Article 131(b) (i) for year 2019 can be found in Table 3.3. Results show how much frequency has deviated from nominal 50 Hz value. Visual representation can be found in Figure 3.10. The resolution of the frequency data used in the following table and figure was 15 minutes.

Table 3.3. Mean values and standard deviations of frequency deviations for year 2019

	2019	
Month	**Mean value (mHz)**	**Standard deviation (mHz)**
January	-0.098	36.5
February	-0.267	39.6
March	0.205	38.3
April	-0.008	36.1
May	-0.227	32.3
June	-0.208	36.9
July	0.135	31.9
August	0.239	33.2
September	-0.071	34.1
October	-0.030	35.3
November	0.018	34.3
December	-0.462	36.5
Entire year	**-0.065**	**35.4**

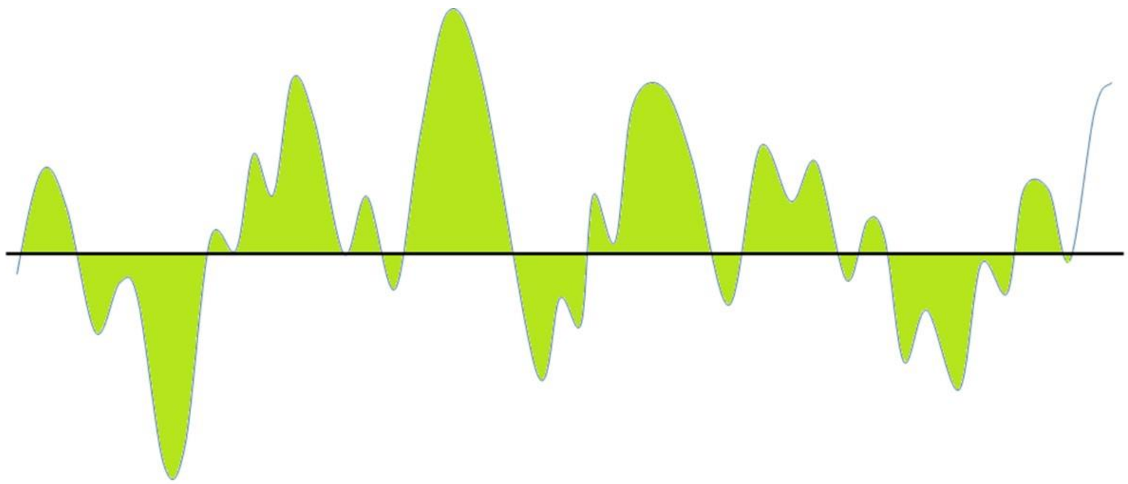
***Figure 3.10**. Mean values and standard deviations of frequency deviations for year 2019*



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 3.11. 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 3.11 is also the formula for calculating the frequency area.

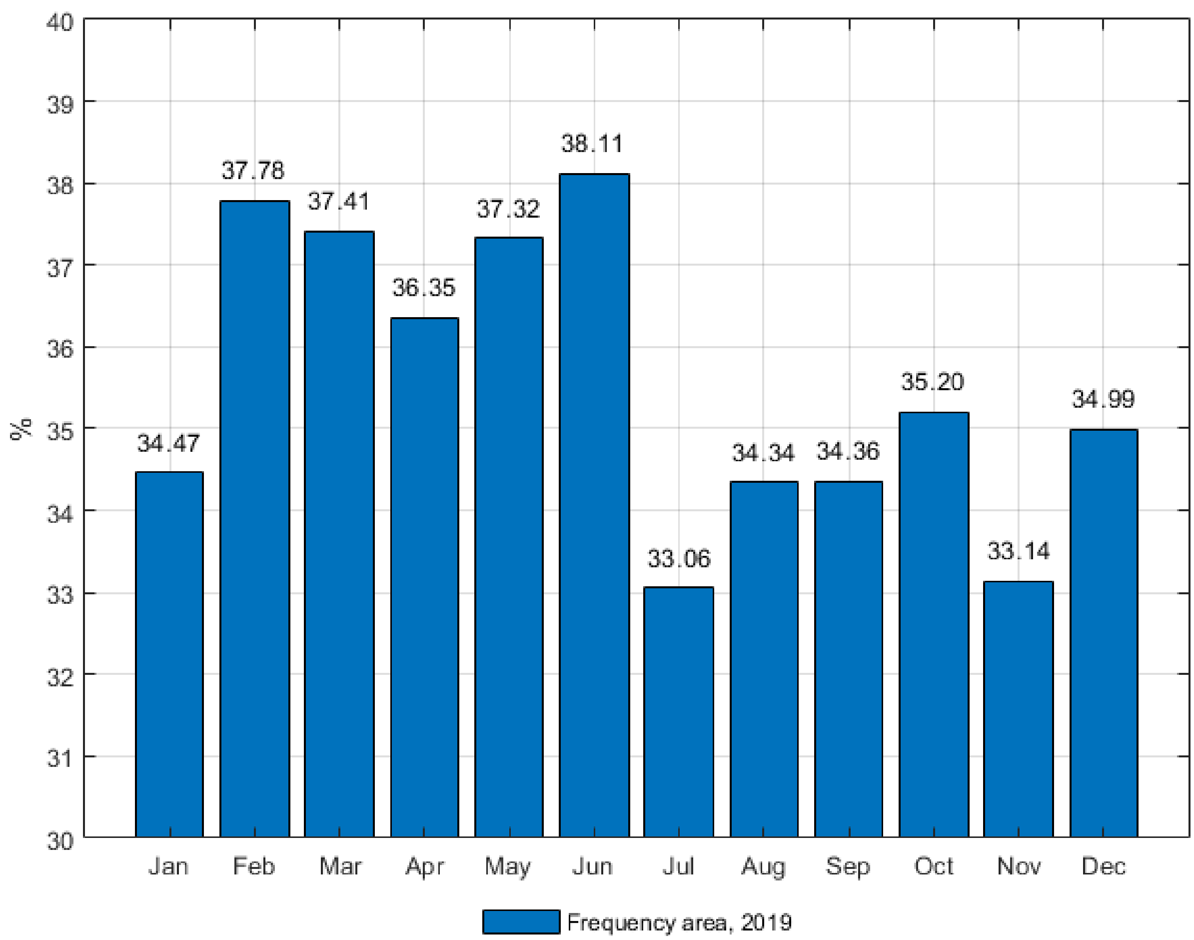
Figure 3.11**. **Frequency quality index: Frequency area [7]



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

Figure 3.12 represents the average frequency area for every month in 2019. From February to June the percentage of the area was considerably larger than on other months. The percentage of the area was smaller on January and the latter half of the year. The result differs a lot from year 2018 when in general the frequency area gained its smallest values on the first half of the year and greatest values on the latter half of the year.

Figure 3.12*. *The average frequency area for every month in 2019



The frequency area during each day of the week can be seen in Figure 3.13. The percentage was smaller on the weekdays and geater on the weekend. The lowest and the highest percentage values can be found on concecutive days, Friday and Saturday.

Figure 3.13. The average frequency area for every day of the week in 2019

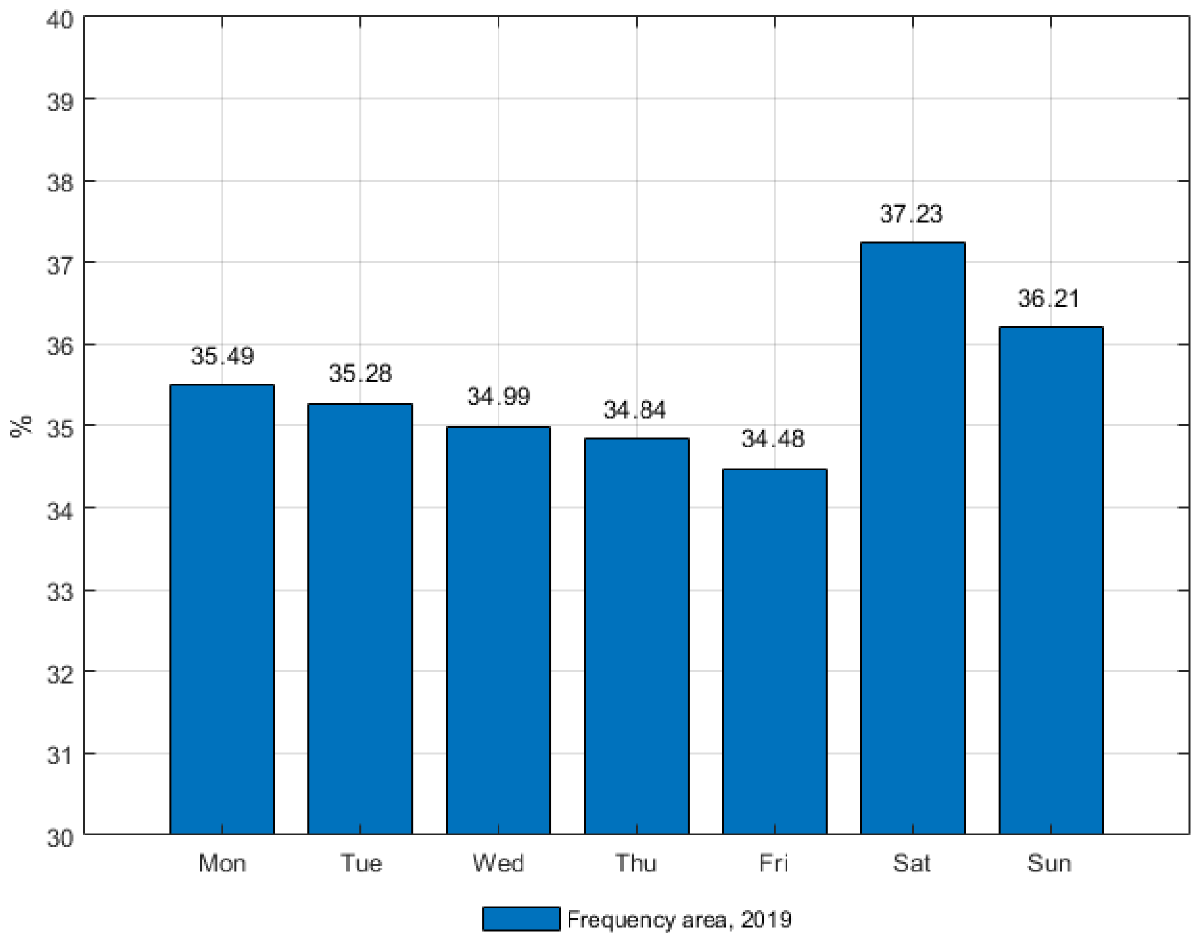


Figure 3.14 has the frequency area for every hour during the day. The figure shows that the deviation of the frequency from 50.0 Hz was generally greater in the late morning and during the day. The percentage of the frequency area was smaller during the evining and night hours apart from a few exeptions.

***Figure 3.14**. The average frequency area for every hour inside the day in 2019*

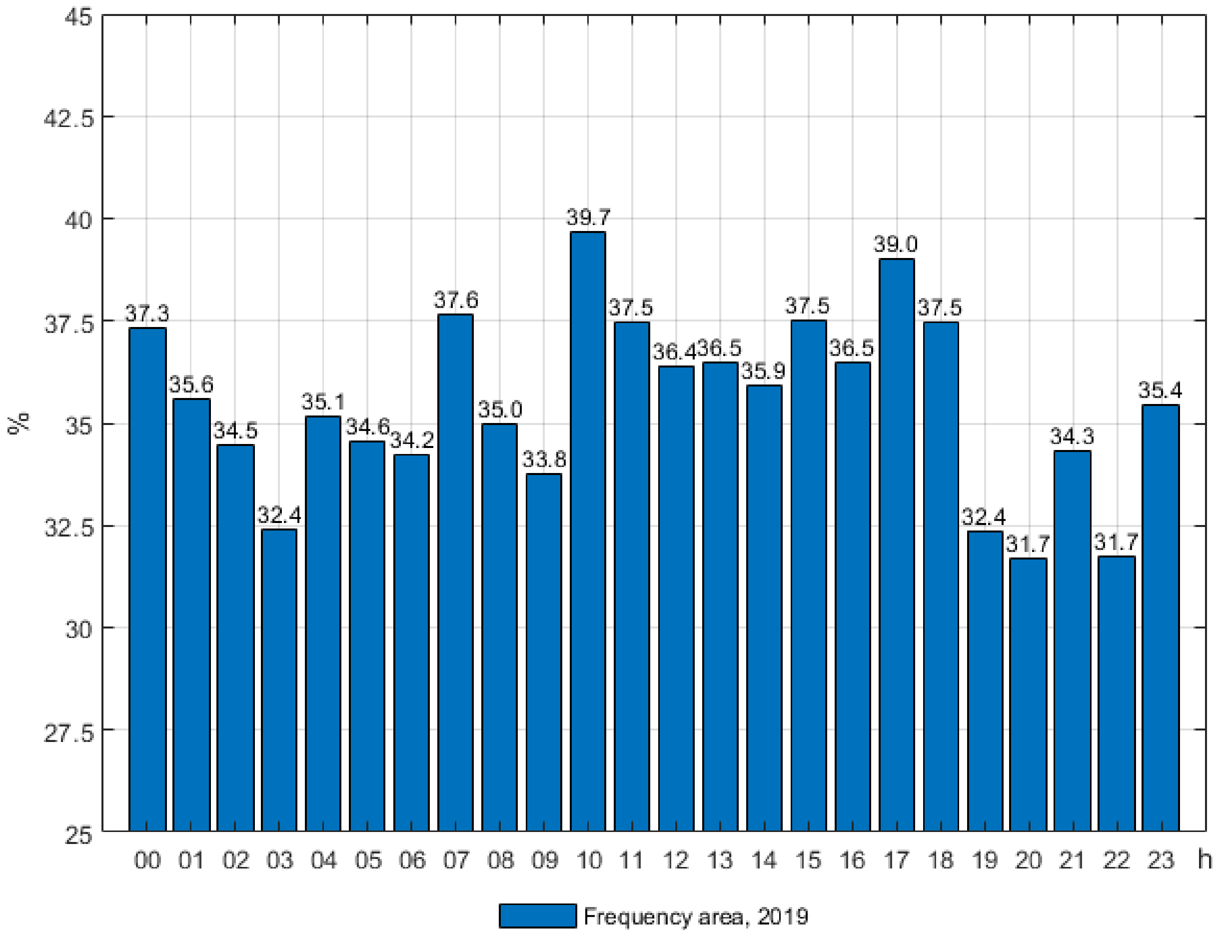
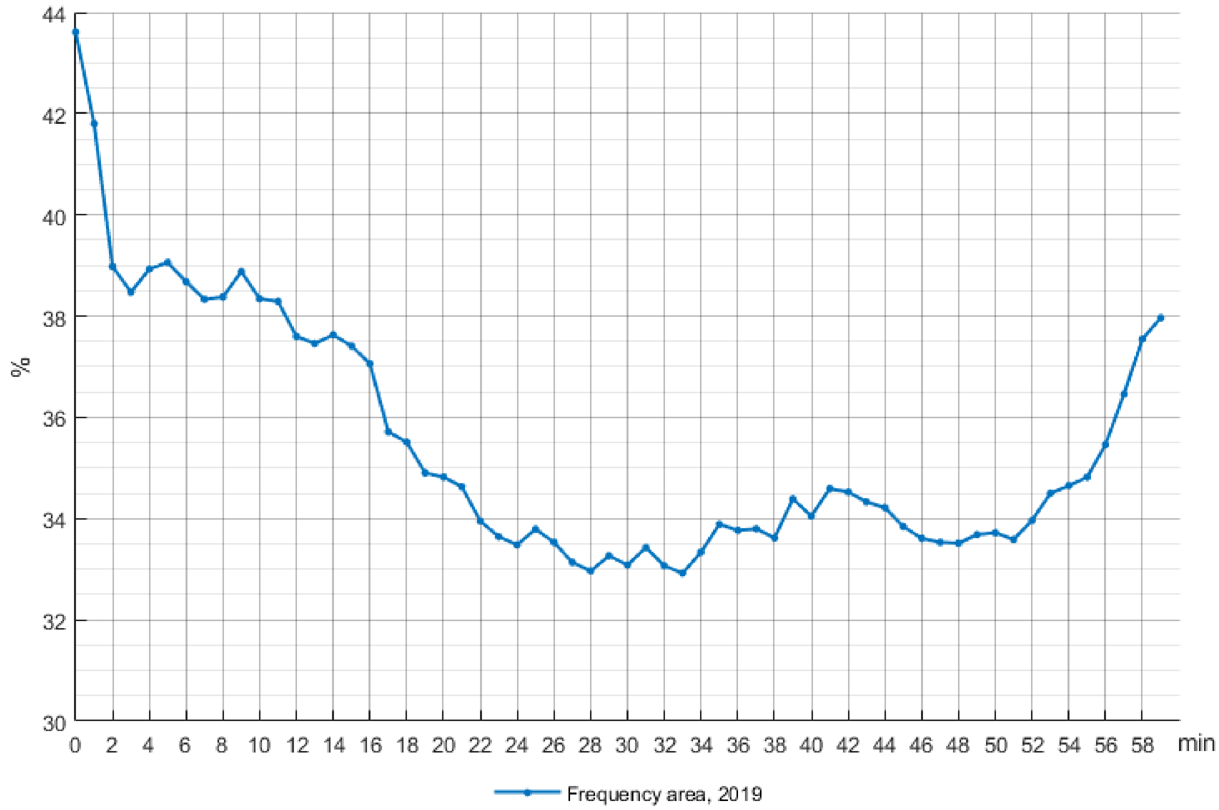


Figure 3.15 represents the frequency area within the hour. The percentage of the frequency area was smaller in the middle of the hour while more deviation occured closer to the hour shift.

***Figure 3.15**. The average frequency area for every minute within the hour in 2019*



3.3 1st, 5th, 10th, 90th, 95th and 99th percentile of the 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(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 3.4-3.9 contain the results from year 2014 to 2019. All results are summed up in Figure 3.16.

***Table 3.4**. The 1st, 5th, 10th, 90th, 95th and 99th percentiles for year 2014*

	2014					
Month	**1st (Hz)**	**5th (Hz)**	**10th (Hz)**	**90th (Hz)**	**95th (Hz)**	**99th (Hz)**
Jan	49.902	49.930	49.944	50.055	50.071	50.101
Feb	49.904	49.932	49.948	50.053	50.068	50.097
Mar	49.893	49.926	49.942	50.058	50.075	50.106
Apr	49.902	49.931	49.946	50.055	50.071	50.098
May	49.894	49.927	49.943	50.057	50.072	50.103
Jun	49.902	49.931	49.946	50.053	50.068	50.096
Jul	49.900	49.930	49.945	50.058	50.072	50.102
Aug	49.899	49.929	49.944	50.058	50.077	50.113
Sep	49.908	49.934	49.948	50.055	50.071	50.103
Oct	49.897	49.929	49.945	50.056	50.072	50.105
Nov	49.903	49.932	49.947	50.052	50.066	50.094
Dec	49.911	49.935	49.948	50.052	50.067	50.096
Entire year	**49.901**	**49.930**	**49.945**	**50.055**	**50.071**	**50.102**

Table 3.5. 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 3.6. 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 3.7. 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**

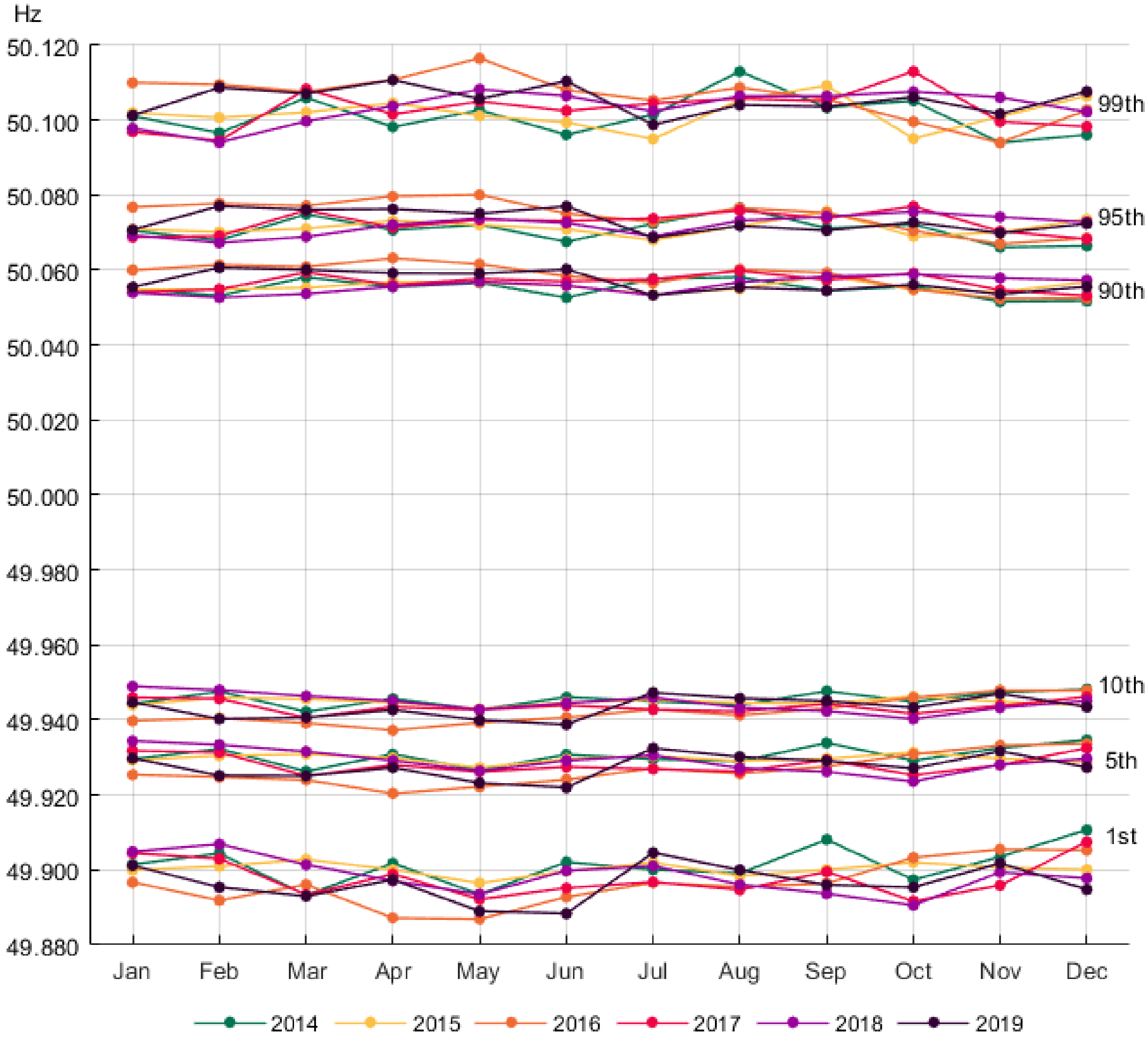
Table 3.8. The 1st, 5th, 10th, 90th, 95th and 99th percentiles for year 2018

	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 3.9. 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**

***Figure 3.16**. The 1st, 5th, 10th, 90th, 95th and 99th percentiles for years 2014-2019*



More detailed results for the percentiles of 2019 are shown in the next figures. Figure 3.17 is a visual representation of the given percentiles for each month in 2019. The percentiles in June were furthest from 50 Hz, which indicates that there were most deviations during that month. Similarly, in July the percentiles were closest to 50 Hz which indicates that there were least deviations during that mont.

***Figure 3.17**. The 1st, 5th, 10th, 90th, 95th and 99th percentile of the frequency for every month in 2019*

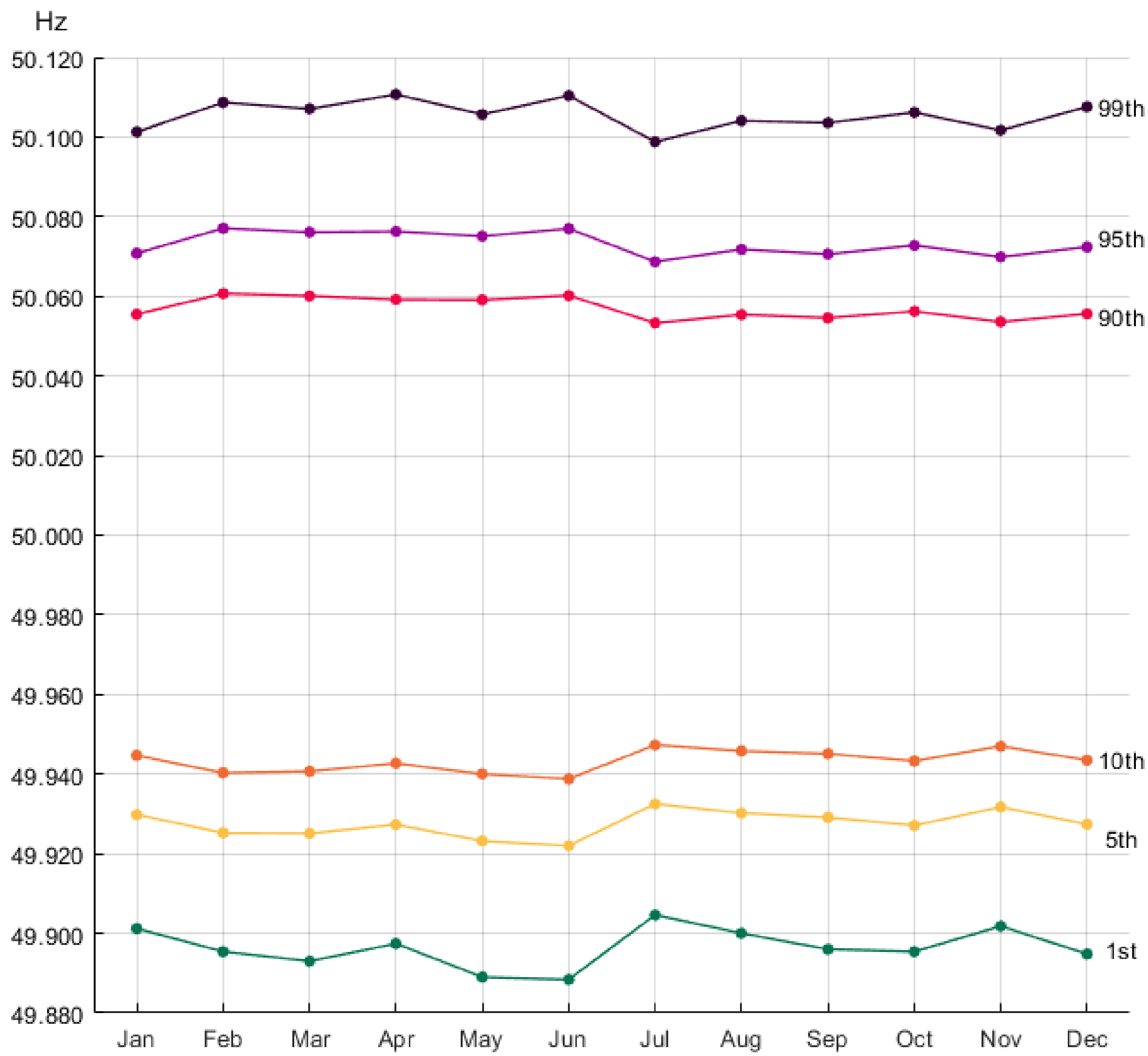


Figure 3.18 shows the percentiles for every day during the week. The 90th, 95th and 99th percentiles were slighly higher and the 10th, 5th and 1st percentiles were slighly lower on Saturday, which indicates that there were more both over and under frequencies during that day. Apart from the weekend, the percentiles stay rather constant.

Figure 3.18. The 1st, 5th, 10th, 90th, 95th and 99th percentile of the frequency for every day of the week in 2019

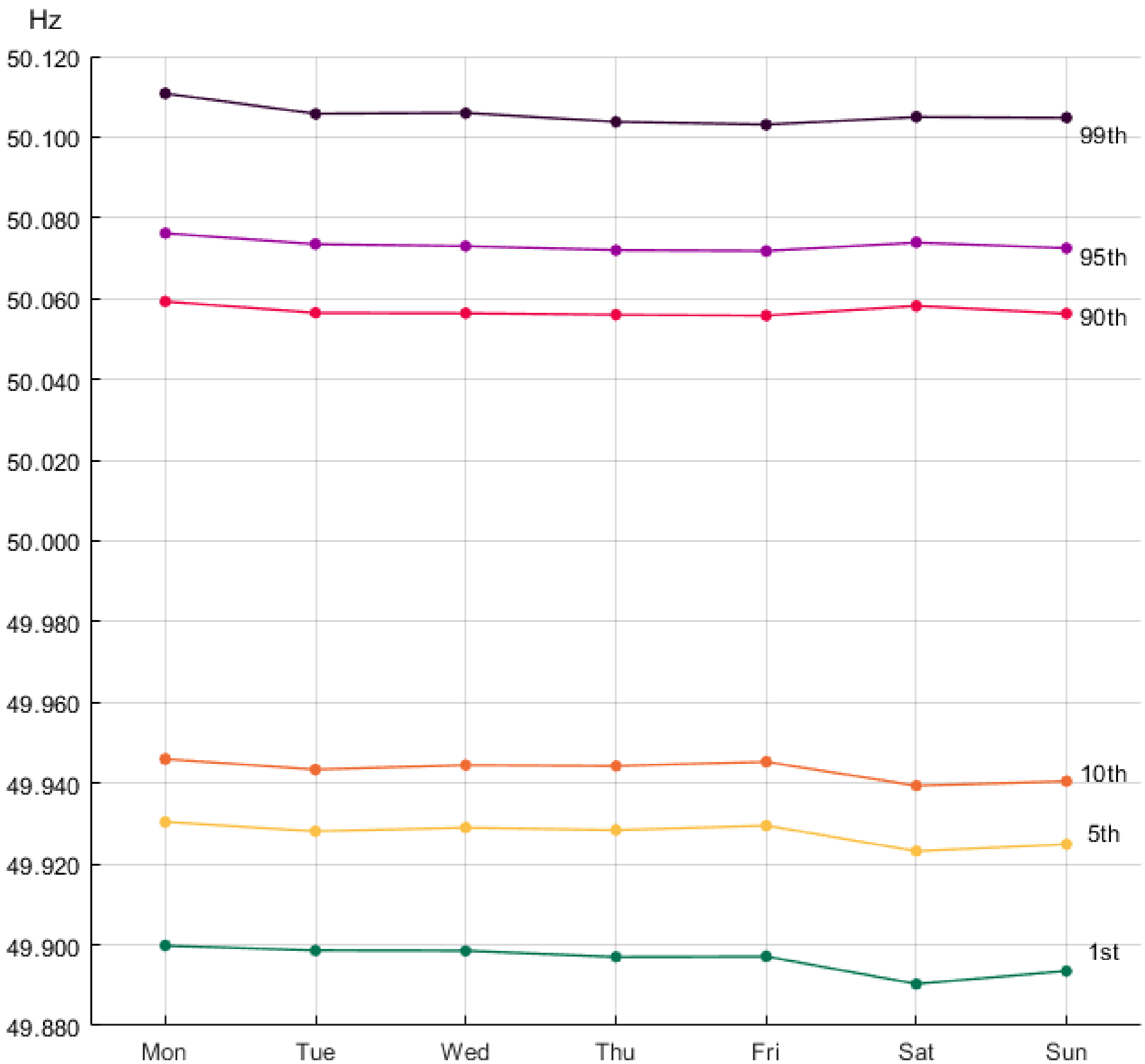
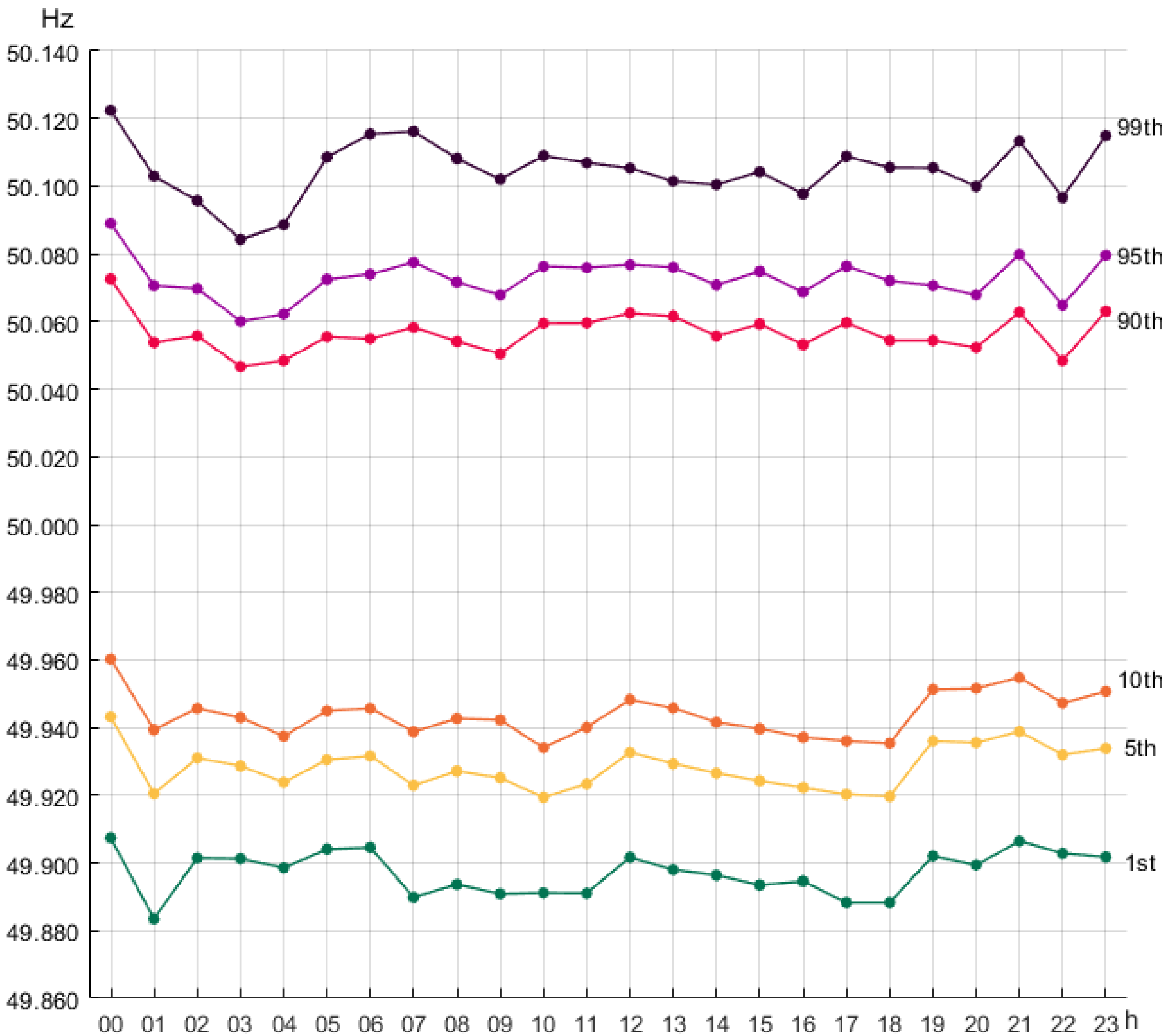


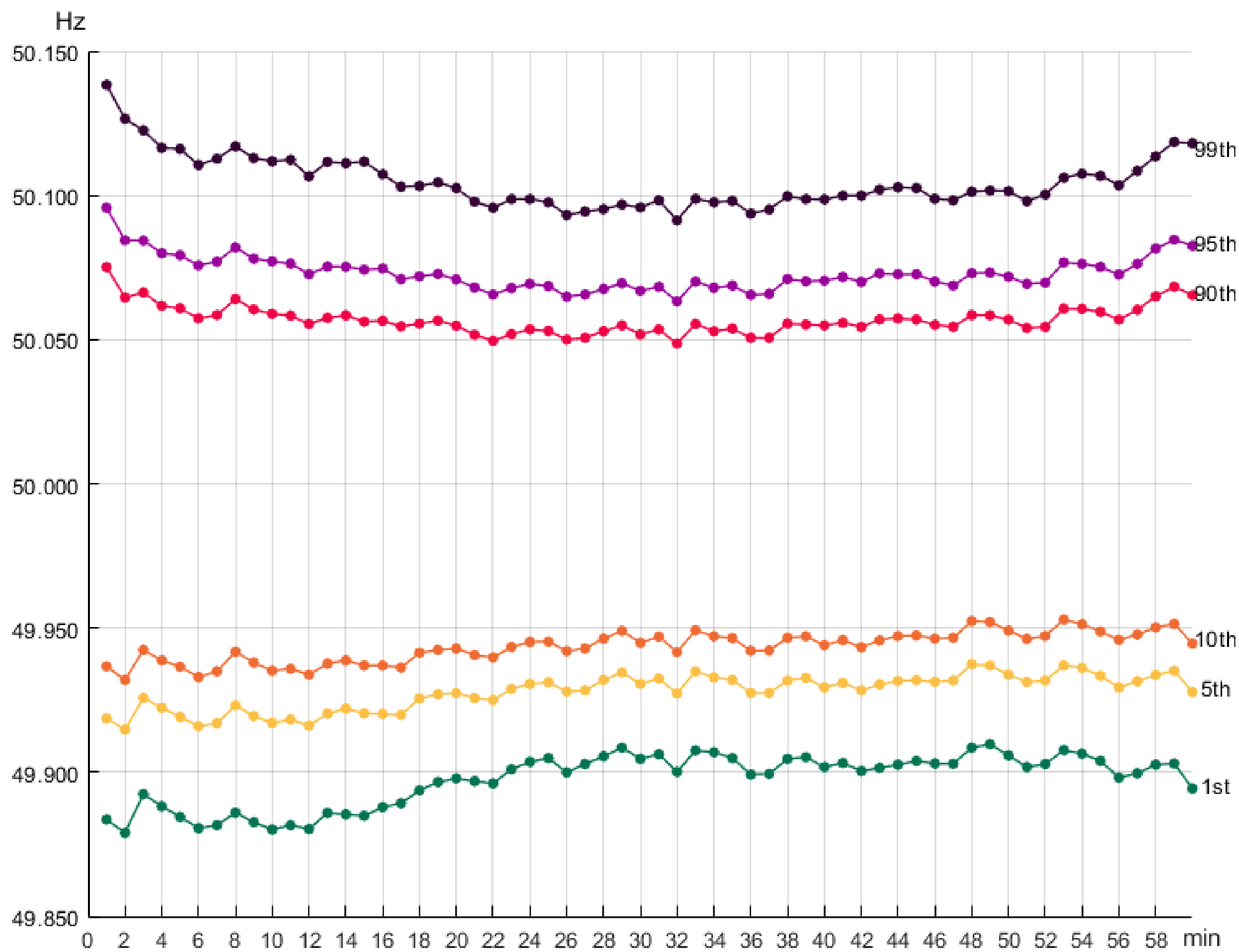
Figure 3.19 represents the percentiles inside the day. All percentiles gain higher frequency values in the midnight, which indicates that there are more over frequencies and less under frequencies in the midnight. On the next hour at 01 the situation is opposite. There are less over frequencies and more under frequencies.

***Figure 3.19**. The 1st, 5th, 10th, 90th, 95th and 99th percentile of the frequency for every hour of the day in 2019*



Variation of the percentiles inside the hour was fairly low. More frequency deviation was experienced during the hour shift. The 90th, 95th and 99th percentiles gained the highest values on the first minute of the hour. The 10th, 5th and 1st percentiles gained the lowest values on the second minute of the hour, so after the first minute over frequencies there were more under frequencies.

***Figure 3.20**. The 1st, 5th, 10th, 90th, 95th and 99th percentile of the frequency for every minute inside the hour in 2019*

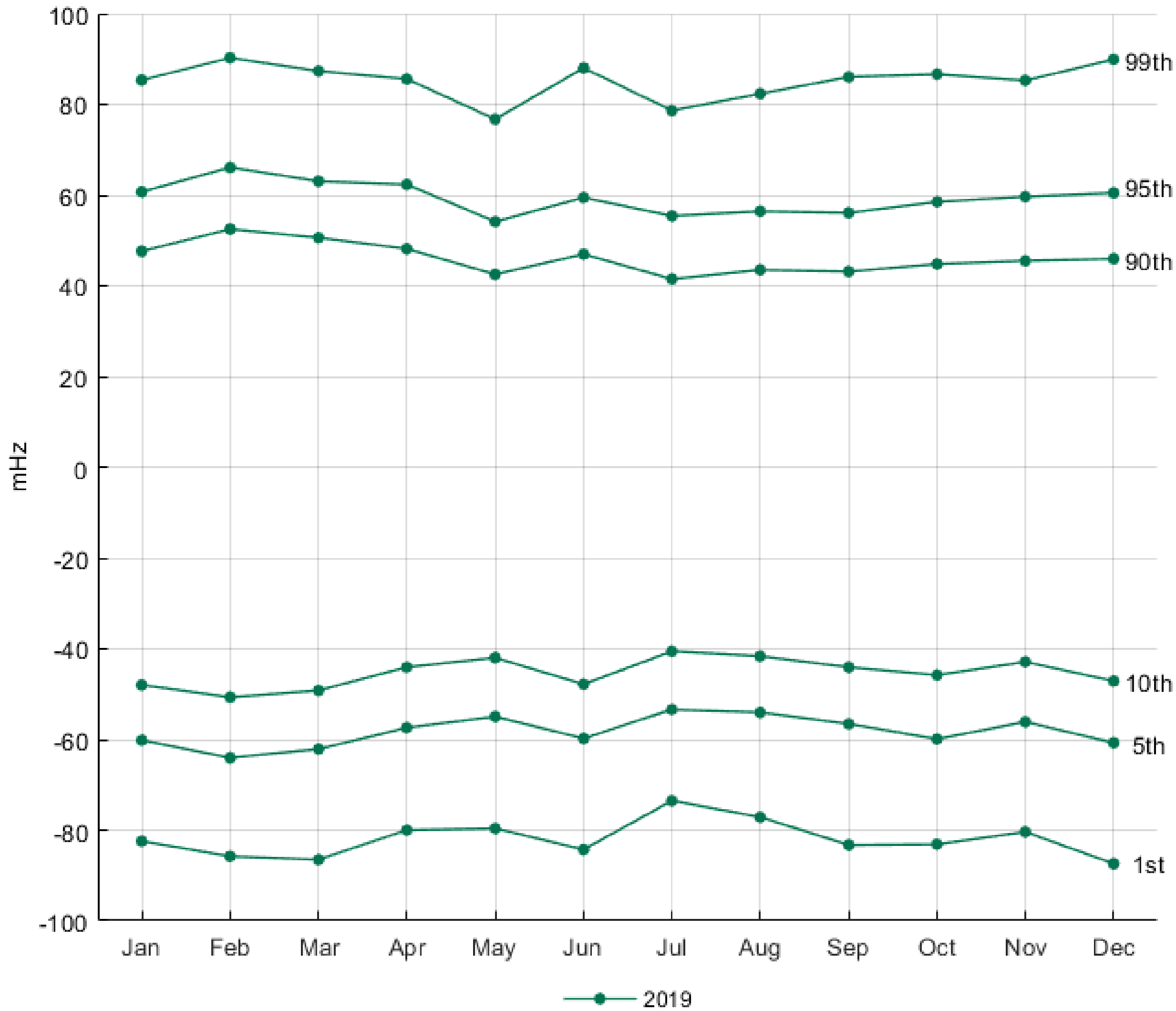


The 1st, 5th, 10th, 90th, 95th and 99th percentiles according to SO GL Article 131(b) i(3) are presented in Table 3.10. Figure 3.21 below the table shows results in graphical form. Results are deviations from nominal 50 Hz value and a frequency data with a resolution of 15 minutes was used.

***Table 3.10**. The 1st, 5th, 10th, 90th, 95th and 99th percentiles for year 2019*

	2019					
Month	**1st (mHz)**	**5th (mHz)**	**10th (mHz)**	**90th (mHz)**	**95th (mHz)**	**99th (mHz)**
Jan	-82.4	-60.2	-48.0	47.6	60.7	85.4
Feb	-85.8	-64.0	-50.7	52.5	66.1	90.2
Mar	-86.5	-62.1	-49.2	50.6	63.1	87.3
Apr	-80.0	-57.4	-44.1	48.2	62.3	85.6
May	-79.6	-55.0	-42.0	42.5	54.1	76.7
Jun	-84.3	-59.8	-47.8	47.0	59.4	88.0
Jul	-73.5	-53.4	-40.6	41.5	55.4	78.6
Aug	-77.1	-54.0	-41.6	43.5	56.4	82.3
Sep	-83.3	-56.6	-44.1	43.1	56.1	86.1
Oct	-83.1	-59.9	-45.8	44.8	58.5	86.7
Nov	-80.4	-56.1	-42.9	45.5	59.6	85.3
Dec	-87.4	-60.7	-47.1	46.0	60.5	89.9
Entire year	**-81.9**	**-58.3**	**-45.3**	**46.1**	**59.4**	**85.2**

***Figure 3.21**. The 1st, 5th, 10th, 90th, 95th and 99th percentiles for year 2019*



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 3.22 shows cumulative minutes outside the standard frequency range in 2019. The curves are fairly linear throughout the year though the growth has been slighly slower during January and in beginning of February. The frequency has been outside the standard range over 1300 minutes, close to 7000 minutes over 50,1 Hz and close to 6300 minutes under 49,9 Hz. The results mean that the current Nordic target level has been exceeded.

Figure 3.22. Cumulative minutes outside the standard frequency range in 2019

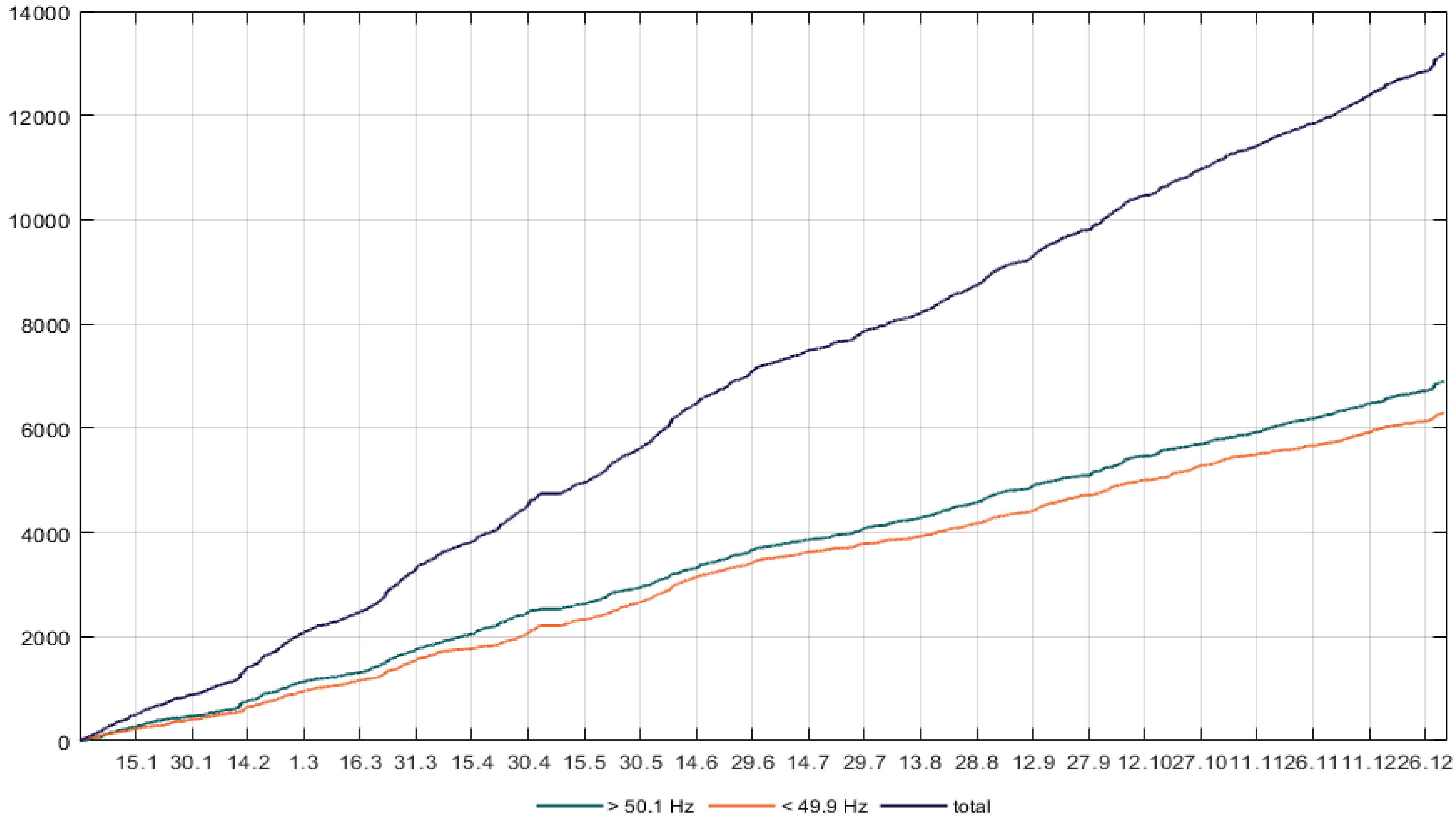
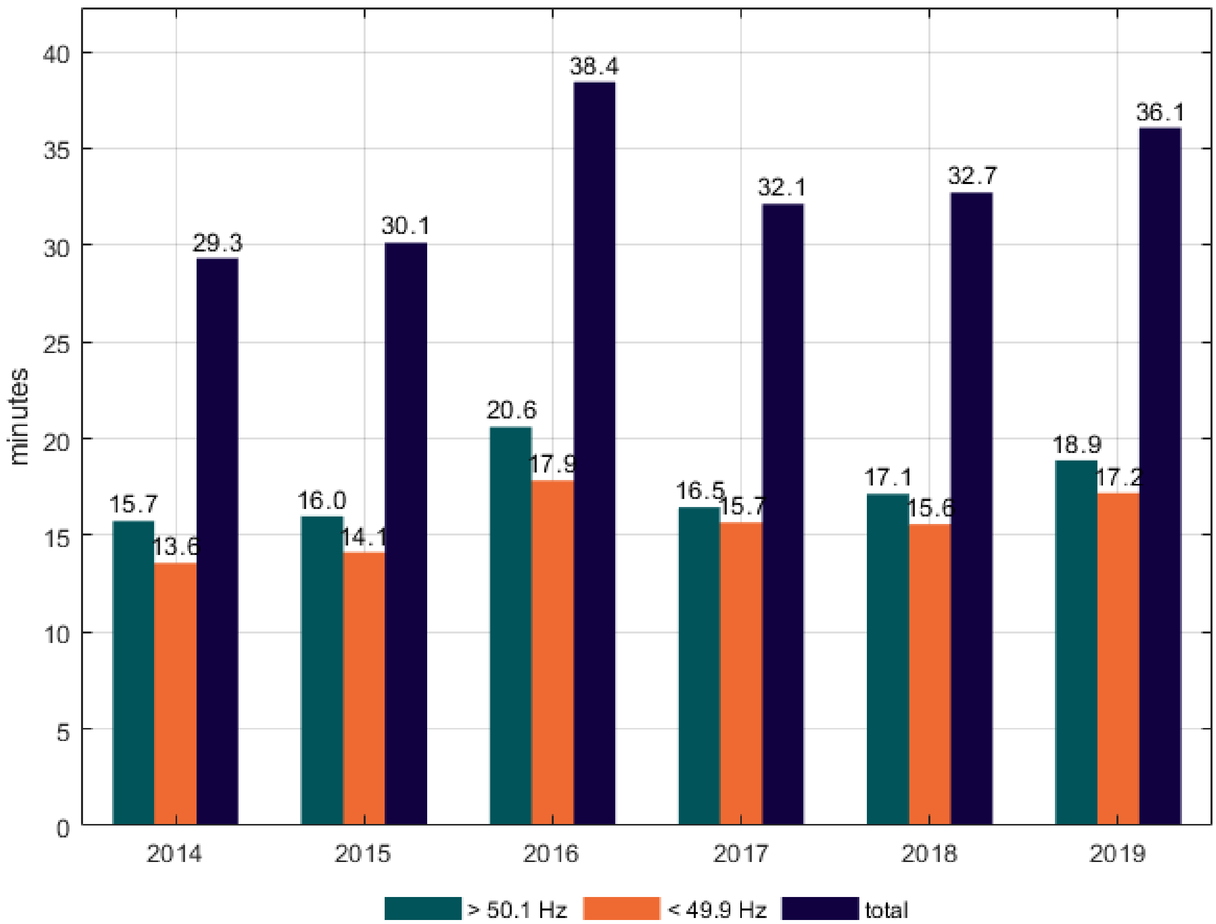


Figure 3.23 represents the daily average number of minutes per year that the frequency was outside the standard frequency range. The number of minutes outside the standard frequency range in 2019 is clearly higher than on the previous years except for 2016 when the total number was over 38 minutes. Every year there has been more over frequencies than under frequencies.

***Figure 3.23**. Daily average number of minutes per year that the frequency was outside the standard frequency range in 2014-2019*



Same results can be seen in Table 3.11 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 3.11. Percentage of time over, below and inside the standard frequency range

Year	> 50.1 Hz	< 49.9 Hz	49.9 Hz - 50.1 Hz
2014	1.09 %	0.94 %	97.96 %
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 %

Table 3.12 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 3.12. Minutes over and below the standard frequency range

Year	> 50.1 Hz (min)	< 49.9 Hz (min)	Total (min)
2014	5755	4959	10714
2015	5844	5166	11010
2016	7586	6574	14160
2017	6185	5884	12069
2018	6328	5755	12083
2019	6997	6377	13374

Tables 3.13 and 3.14 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 2014 to 2019. These results are based on the evaluation criteria defined in SO GL Article 131(a) (iv). The results from the previous tables are not entirely comparable due to differences in availability of measurement data. The same information is presented visually in Figure 3.24.

Table 3.13. Total time in which the frequency was outside the 49.9-50.1 Hz band in years 2014-2016

	2014		**2015**		**2016**	
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	474	409	498	444	723	526
February	324	309	420	379	687	612
March	629	616	506	376	679	566
April	387	391	544	428	779	809
May	517	608	478	535	962	820
June	340	383	414	438	607	594
July	487	444	323	397	587	537
August	830	471	579	485	704	572
September	516	247	678	428	584	523
October	583	506	314	398	434	362
November	303	353	454	414	288	310
December	359	218	629	443	504	325
Entire year	**5749**	**4954**	**5838**	**5165**	**7539**	**6555**

Table 3.14. 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**

***Figure 3.24**. Total time in which the frequency was outside the 49.9-50.1 band in years 2014-2019*

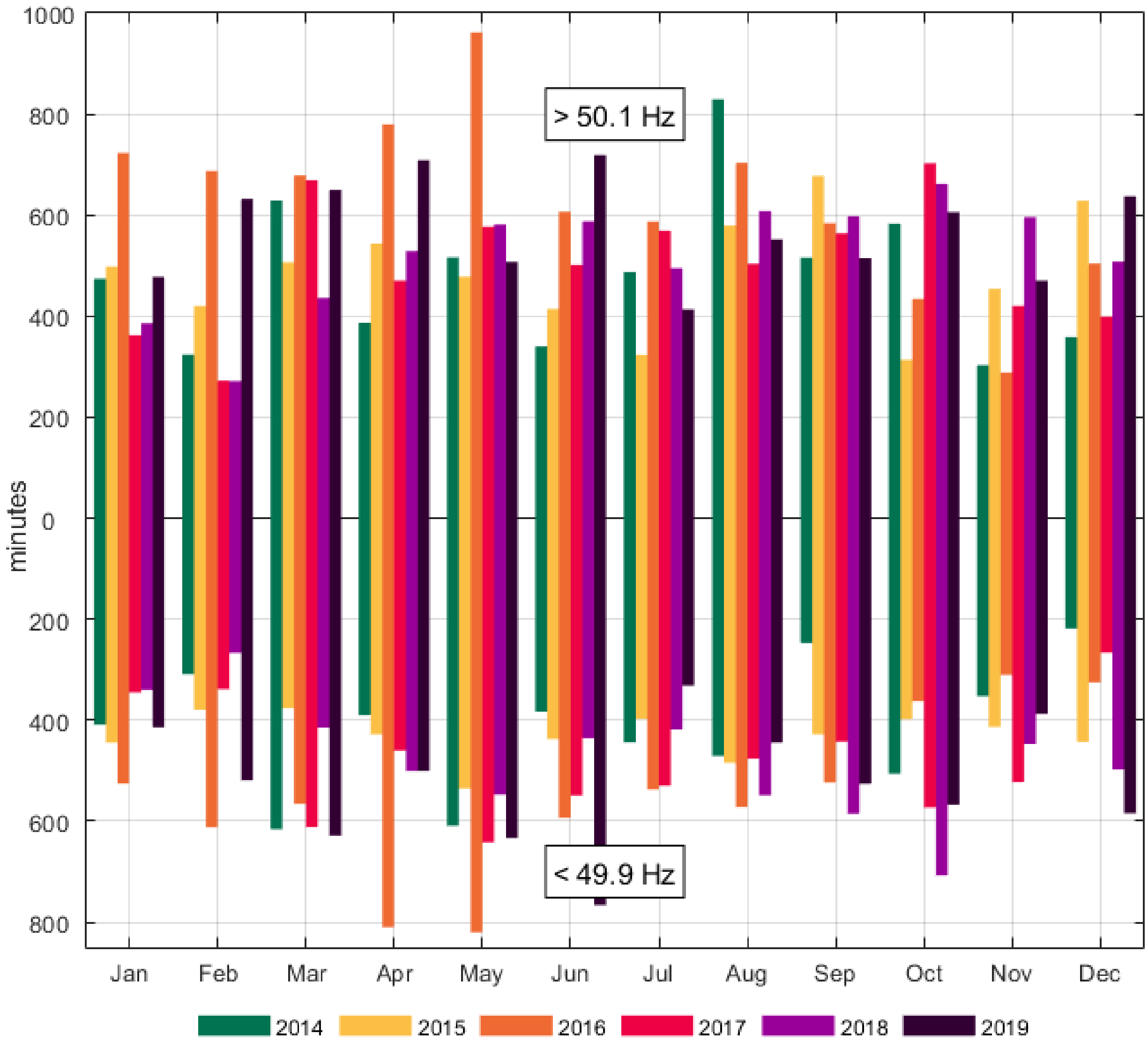


Figure 3.25 shows the daily average in minutes month by month when frequency was outside the standard frequency range in years 2014-2019. In 2019, June had the longest time outside the standard frequency range. July had the best frequency in this comparison.

***Figure 3.25**. Daily average time that the frequency was outside the standard frequency range month by month for years 2014-2019*

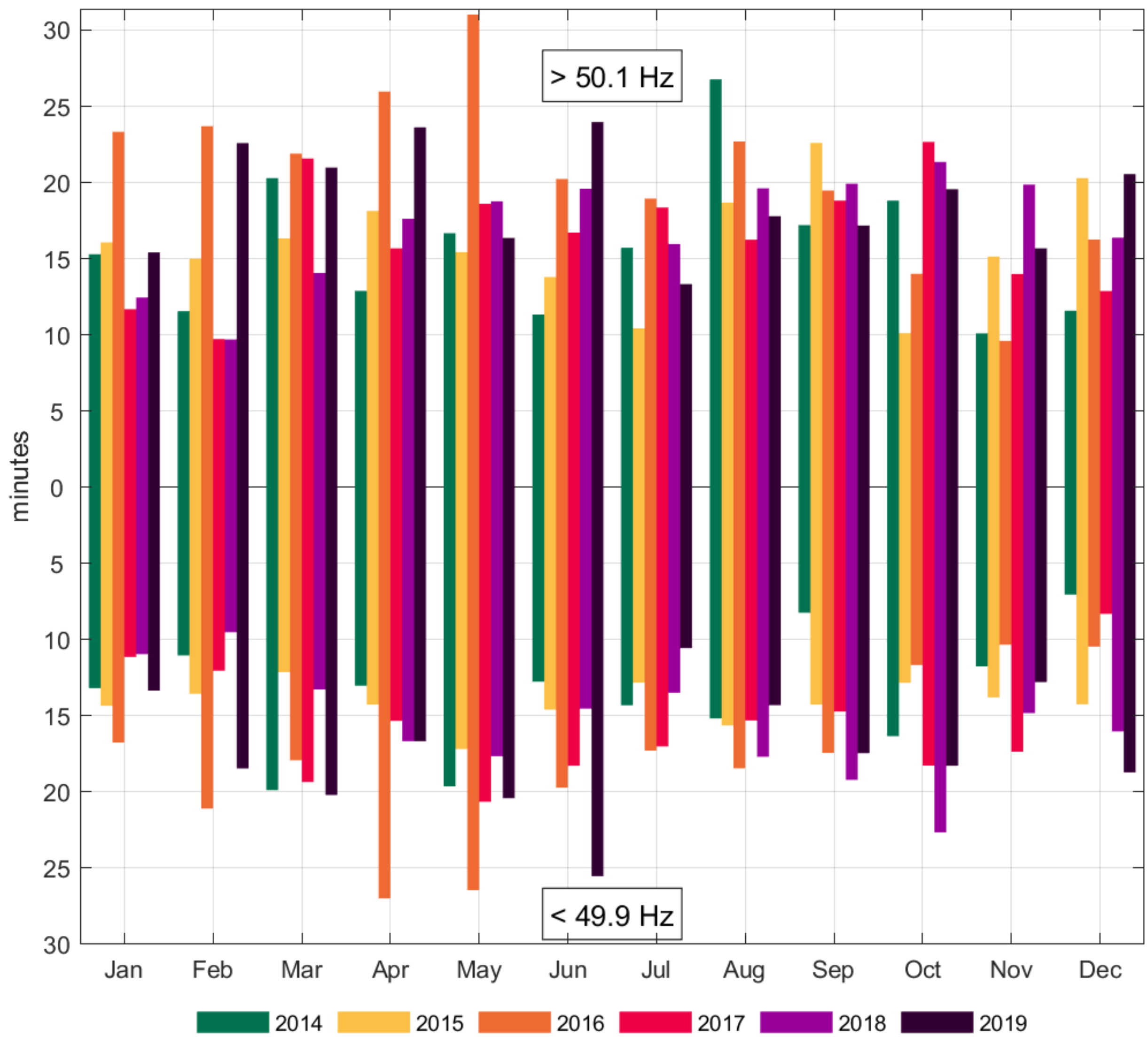


Figure 3.26 represents the daily averge time that the frequency was outside the standard frequency range during each day of the week. On the previous years the frequency has been outside the standard frequency range mostly during the weekdays. However, in 2019 the frequency has been more time outside the standard frequency range during the weekend and on Monday than on other weekdays.

Figure 3.26. Daily average time that the frequency was outside the standard frequency range during each day of the week for years 2014-2019

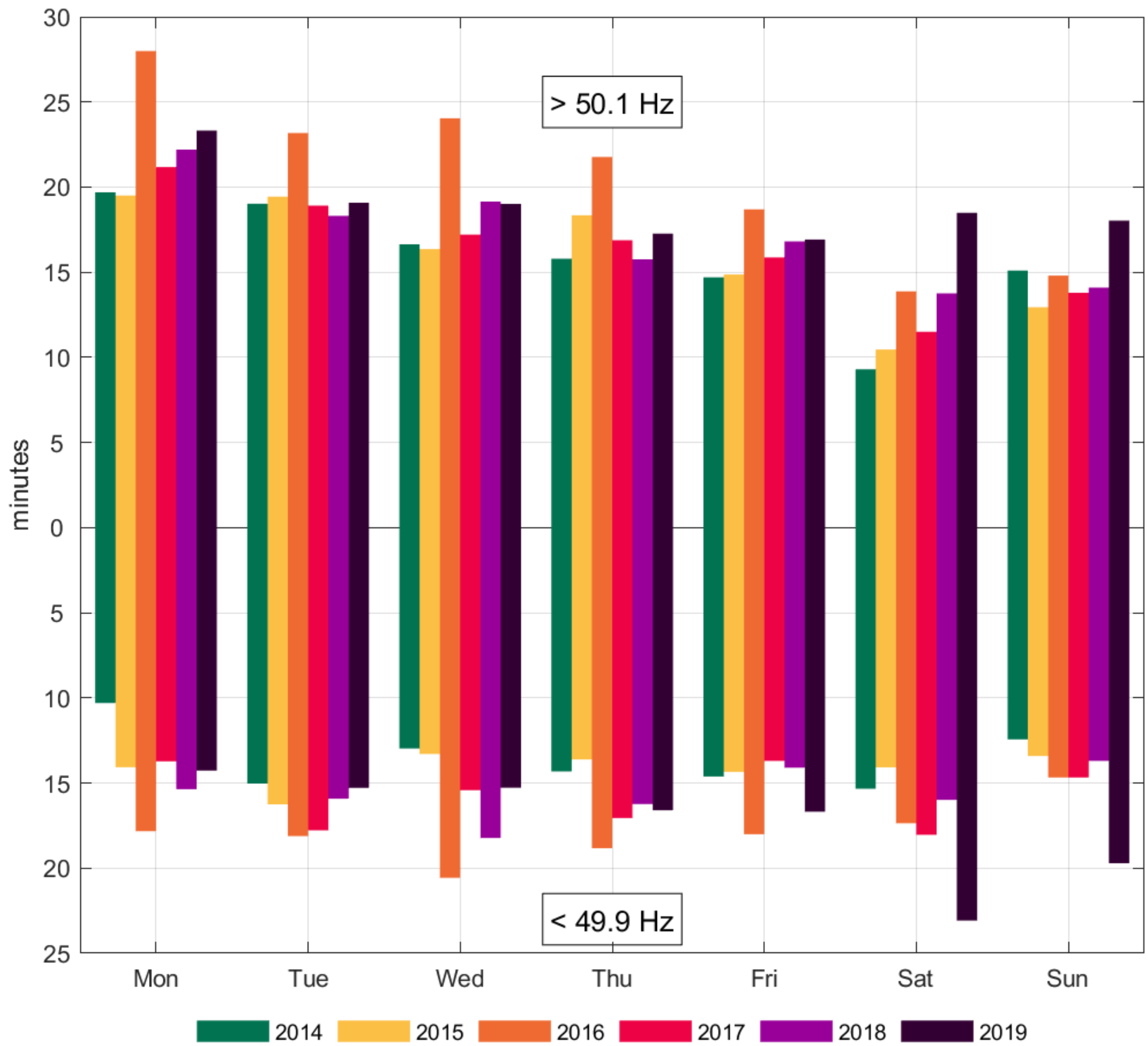


Figure 3.27 represents the daily average time that the frequency was outside the standard frequency range for each hour in the day. The hours are according to the Finnish time (UTC+2 / UTC+3 in the summer). In 2019 the frequency has been over 50.1 Hz the most at the hours 21, 23 and 0 and under 49.9 Hz the most at the hours 1, 17 and 19. In 2019 and the previous years, the frequency has been outside the standard frequency range more frequently during the morning hours as well as in the evening and midnight. Frequency has stayed inside the standard frequency range best during hours from 2 to 4. In 2019 the hours 10-18 have clearly been worse in terms of time outside 49.9-50.1 Hz compared to the previous years.

***Figure 3.27**. Daily average time that the frequency was outside the standard frequency range during each hour of the day for years 2014-2019*

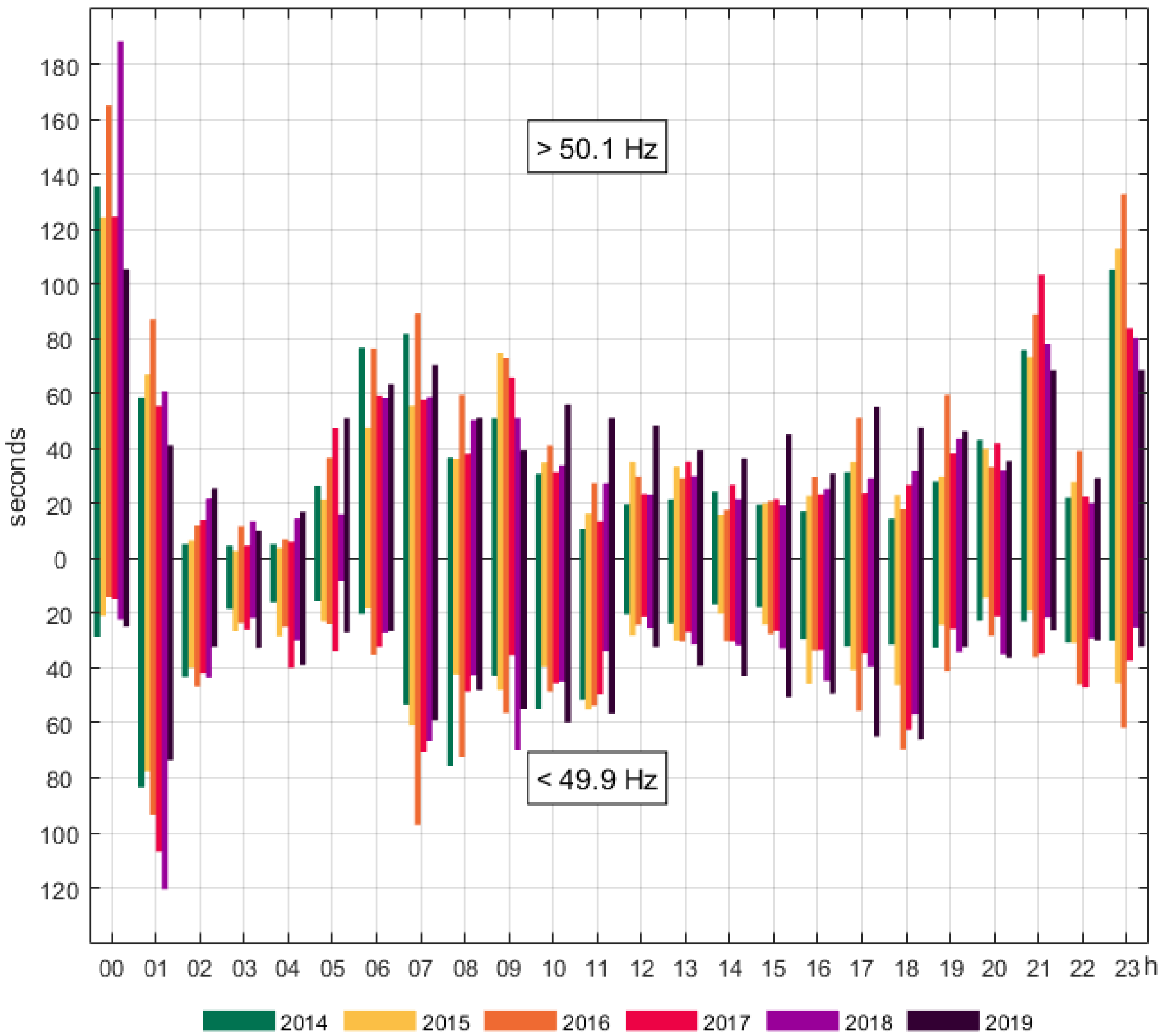


Figure 3.28 shows the daily average time outside the standard frequency range per hour and absolute value of Nordic consumption and production difference. Also transmission difference of HVDC links connecting the Nordic power system to Continental Europe and Russia is presented.

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 3 700 MWh while the consumption difference curve peaks close to 2 600 MWh. Near midnight the peaks for production and consumption differences are around 1800-2600 MWh. Highest values of frequency deviations are also found during morning and midnight hours. Differences in HVDC transmission follow very much the same pattern as production and consumption difference. HVDC transmission difference has increased from year 2018 but the production and consumption difference have decreased from the previous year. [6]

Figure 3.28. Seconds per hour outside the standard frequency range and the absolute values of Nordic consumption, production and HVDC transmission differences in 2019

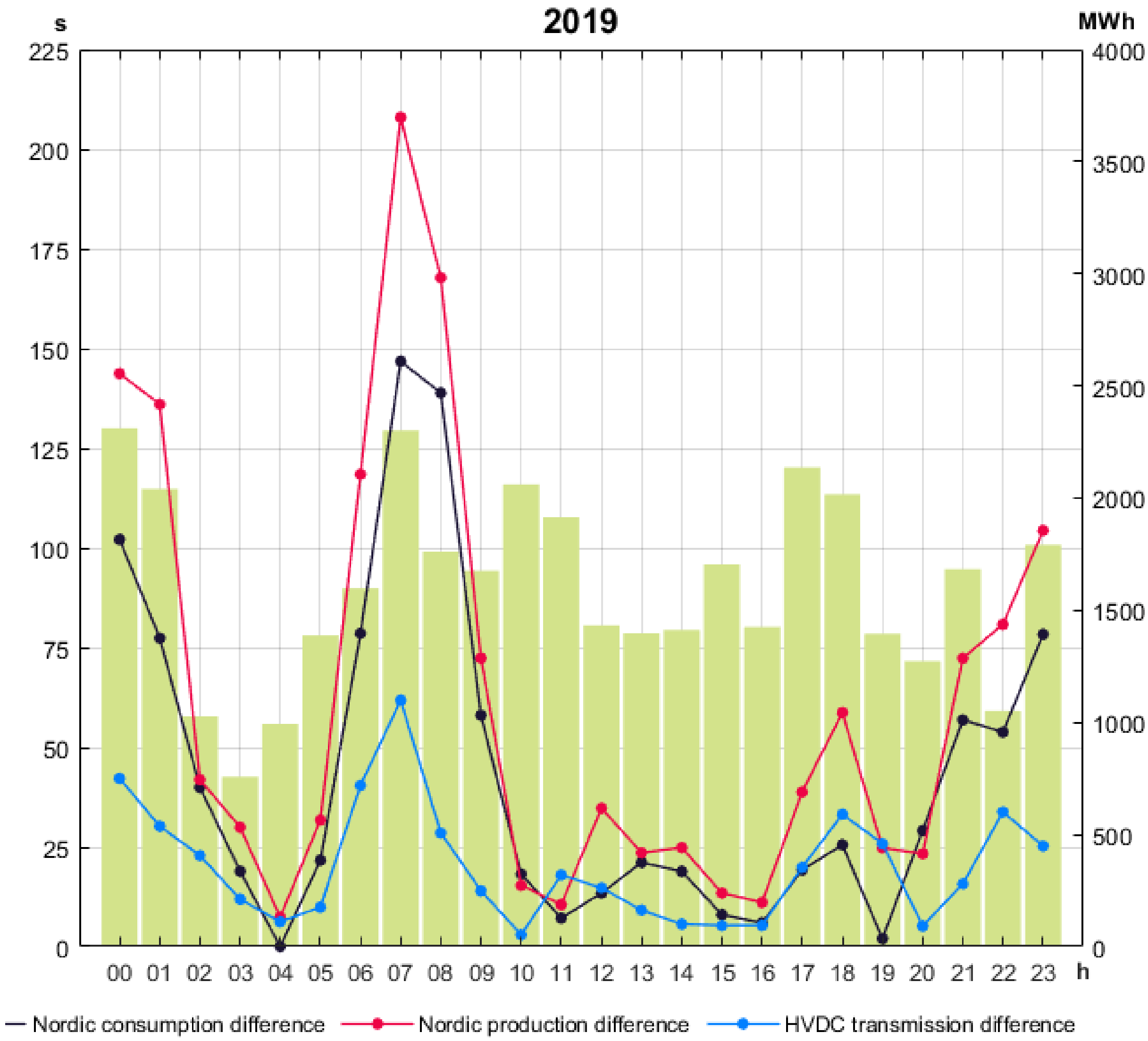


Figure 3.29 illustrates an average hour divided into 60 minutes. For each minute of the average hour there is a value in seconds per hour that frequency has been over or below the standard frequency range. In years 2014-2019 frequency has been outside the standard frequency range more often during the beginning of the average hour. Frequency has stayed best inside the standard frequency range in the middle of hour. The time above the standard frequency range has increased again towards the end of the average hour.

***Figure 3.29**. Number of seconds per hour outside the standard frequency range in 2014-2019 for each minute of an average hour*

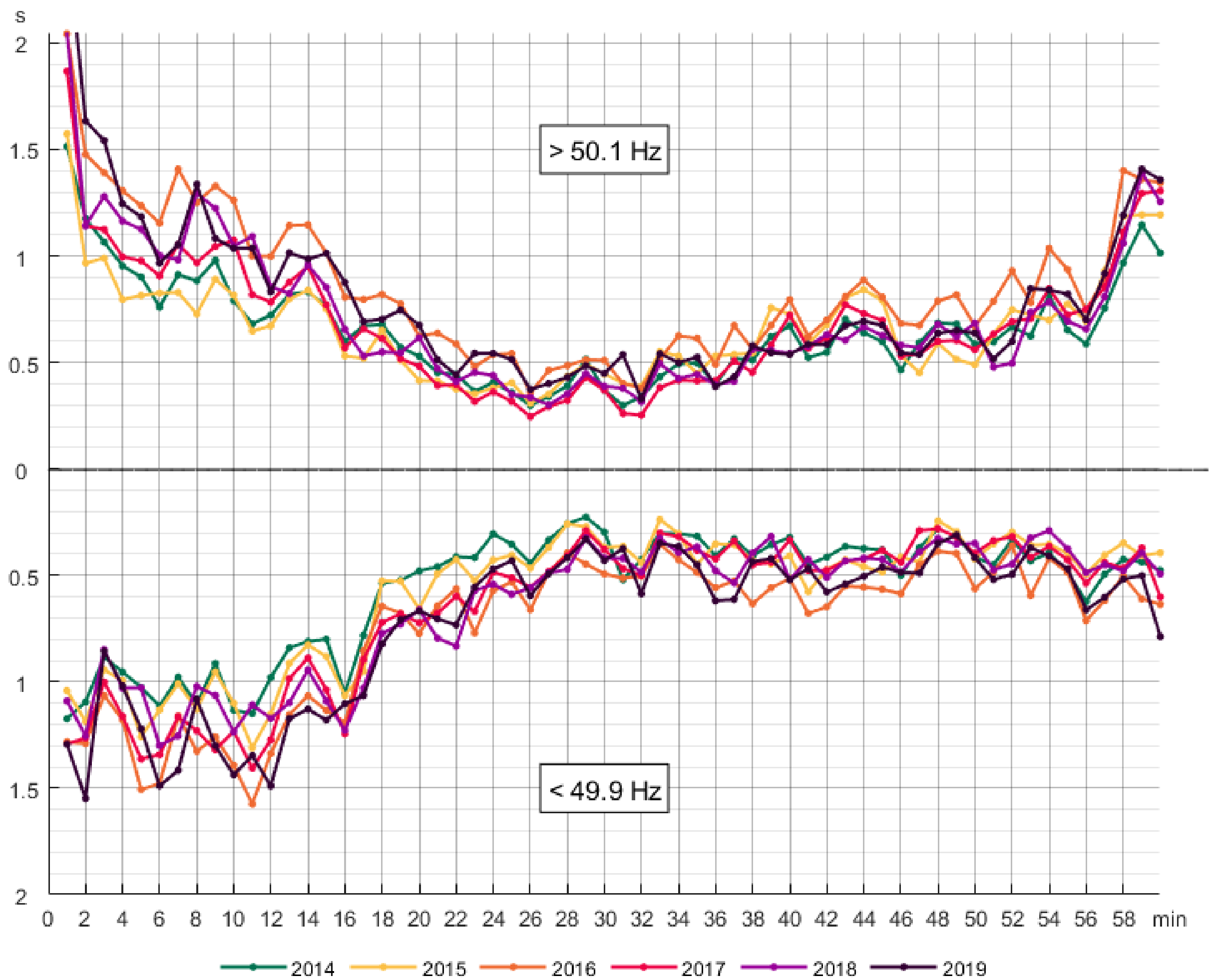
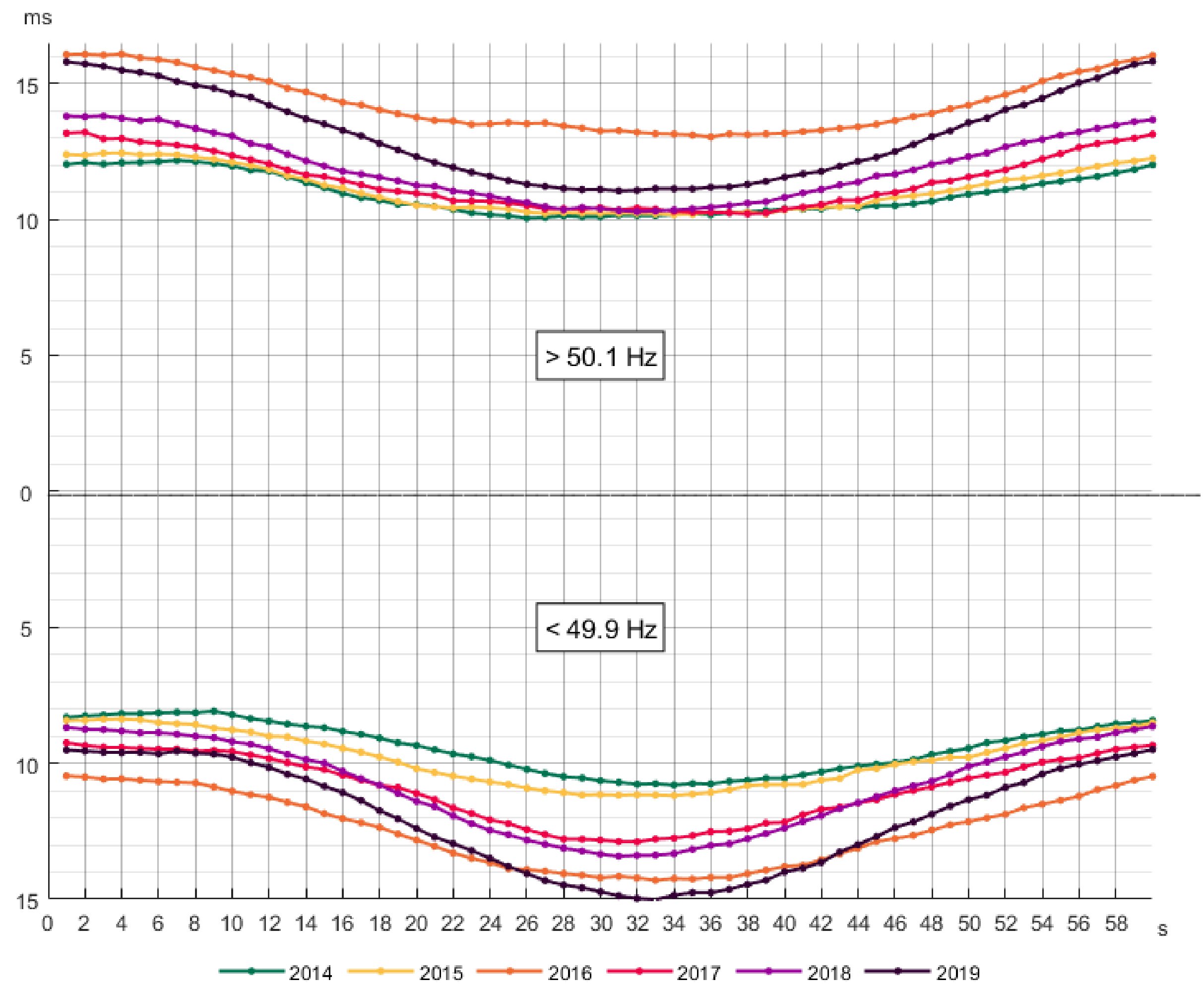


Figure 3.30 illustrates an average minute divided to 60 seconds. For each second of the average minute there is a value in milliseconds per minute that frequency has been over or below the standard frequency range. Overall, the shape of the curve has been fairly smooth, but there has been slightly more 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 2019 curve follows the same pattern as the previous years but the shape of the curve is more pronounced.

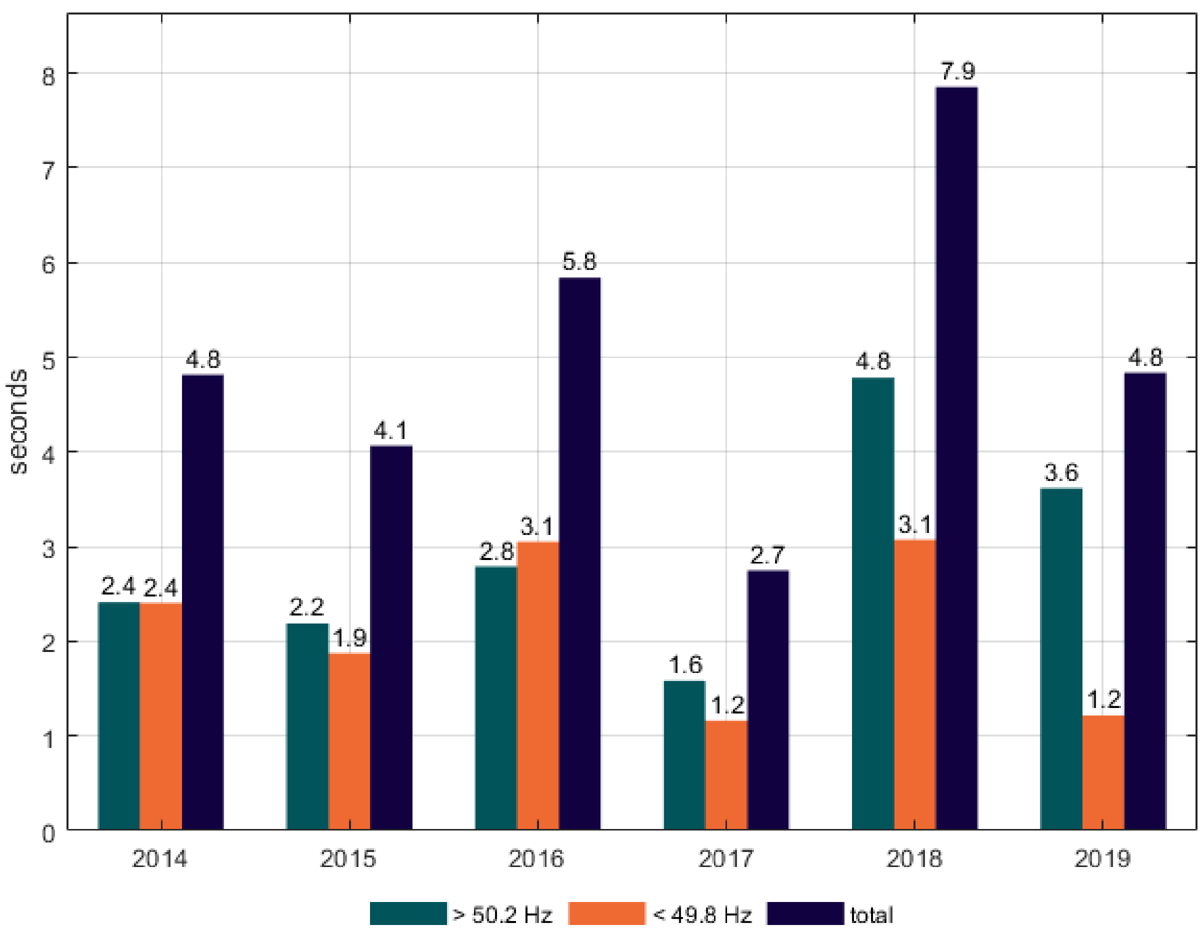
***Figure 3.30**. Number of milliseconds per minute outside the standard frequency range in 2014-2019 for each second of an average minute*



3.4.2 Time outside 49.8-50.2 Hz

Figure 3.31 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 2019 than in 2018. Before year 2018 the share of over and under frequencies has been around equal. However, over frequencies exceeding 200 mHz have been considerably more common than under frequencies in 2018 and 2019.

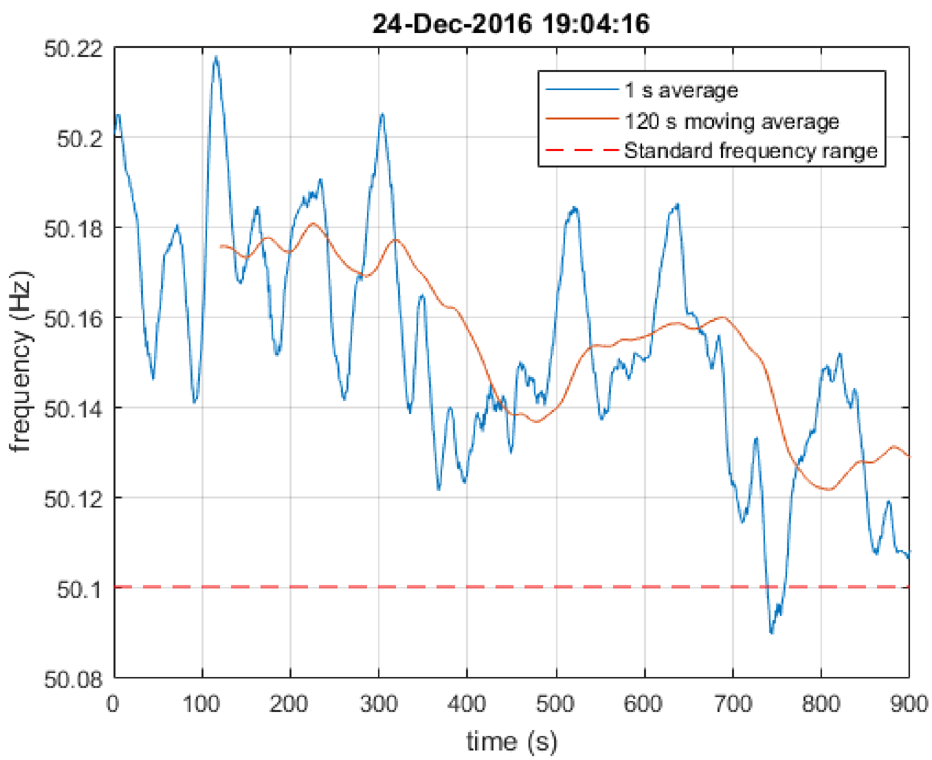
***Figure 3.31**. Average number of seconds per day that the frequency was outside the 49.8-50.2 Hz band for years 2014-2019*



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 (1a 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 3.32, 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 3.32**. Comparison of methods for calculating the number of events, where df > 200 mHz and not restored within 15 min*



The number of events in 2014-2019 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 3.15. These results were calculated with method 1.

Table 3.15. 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.

	2014		**2015**		**2016**		**2017**		**2018**		**2019**	
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	1	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	0	0	1	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	0	0	1	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	0	0	1	0	0	0	1	1	**0**	**0**

Table 3.16 shows the number of events in 2014-2019 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 3.16. 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.

	2014		**2015**		**2016**		**2017**		**2018**		**2019**	
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	3	0	0	0	0	0	0	0
February	0	0	2	0	0	1	0	0	0	0	1	0
March	0	0	0	0	0	0	0	0	0	0	0	0
April	0	0	4	0	1	0	1	0	0	0	1	0
May	0	0	0	0	0	0	1	0	2	0	0	0
June	0	0	0	0	0	0	1	0	2	0	0	1
July	0	0	0	0	1	0	0	0	1	0	0	0
August	0	0	2	0	0	0	0	0	0	0	0	0
September	1	0	1	0	1	0	0	0	0	1	0	0
October	0	1	0	0	2	0	0	0	0	0	1	0
November	0	0	0	0	0	0	0	0	1	0	0	0
December	1	0	0	0	1	0	0	0	0	1	1	0
Entire year	2	1	10	0	9	1	3	0	6	2	**4**	**1**
Sum	**3**		**10**		**10**		**3**		**8**		**5**	

3.4.3 Time outside 49.0-51.0 Hz

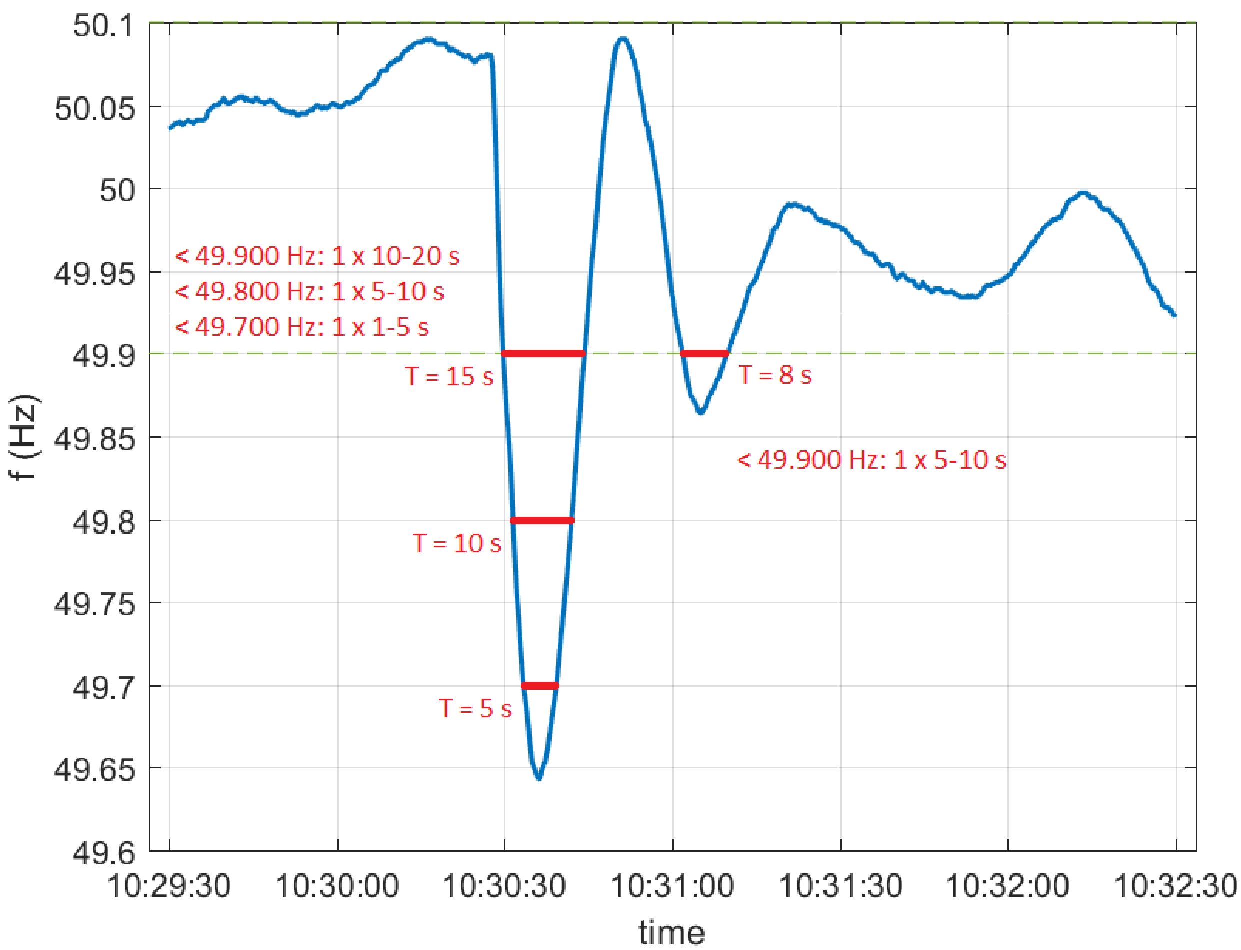
Time outside 49.0 Hz and 51.0 Hz is calculated by counting the number of samples that are below 49.0 Hz or above 51.0 Hz and multiplying the number by the time duration of the sample. The criteria are also defined in SO GL Article 131(a) (v). The resolution of the data used was 1 second.

There were no instances in 2014-2019 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 3.33 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 3.33**. 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 3.17-3.22 provide more detailed information about frequency deviations from year 2014 to 2019. These tables include the durations and amplitudes of the deviations, as well as total amount, maximum duration and average duration of deviations.

Table 3.17. Total number of frequency deviation in 2014

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	13658	5475	3522	4731	2965	799	667	138	31955	1377.20	10.52
> 50.2	39	18	21	18	8	1	2	0	107	117.40	6.76
> 50.3	1	2	0	0	0	0	0	0	3	3.80	2.98
< 49.9	11490	4960	3007	4248	2735	683	543	95	27761	1178.00	10.37
< 49.8	41	23	18	29	4	1	1	0	117	63.10	10.31
< 49.7	0	1	2	1	0	0	0	0	4	10.40	6.90
< 49.6	0	0	1	0	0	0	0	0	1	6.70	6.70
< 49.5	0	1	0	0	0	0	0	0	1	4.00	4.00

Table 3.18. 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 3.19. 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 3.20. 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 3.21. 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 3.22. 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

Figure 3.34 is a visual representation of the data in Tables 3.17-3.22. The number of deviations is now given as a daily average instead of total number per year. The number of short-lasting deviations rose from 2014 to 2016 and decreased again in 2017. In 2018 and 2019 the number of deviations increased again. Years 2016 and 2019 have the most deviations in the observation period.

***Figure 3.34**. Daily average number of frequency deviations per duration*

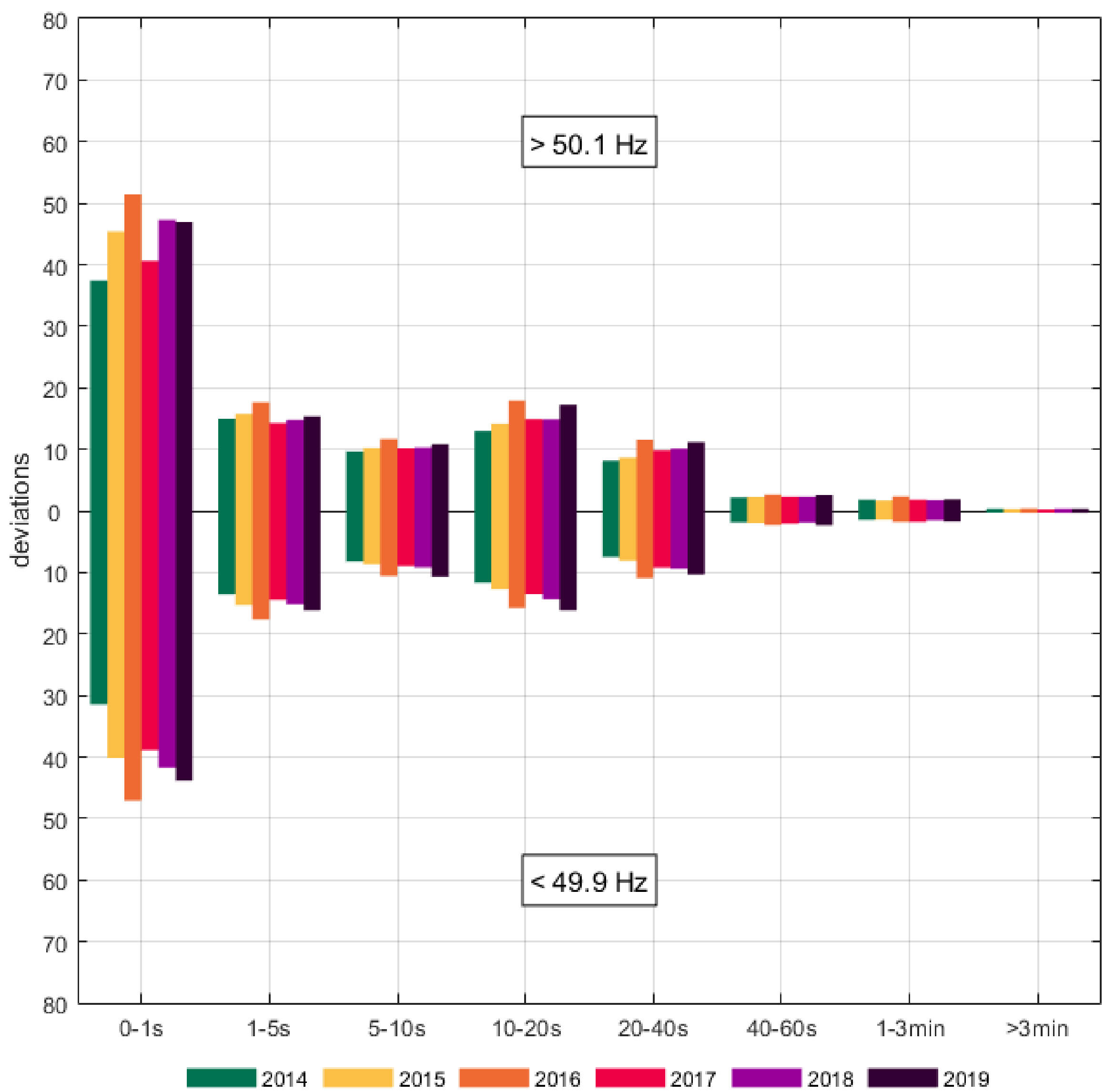
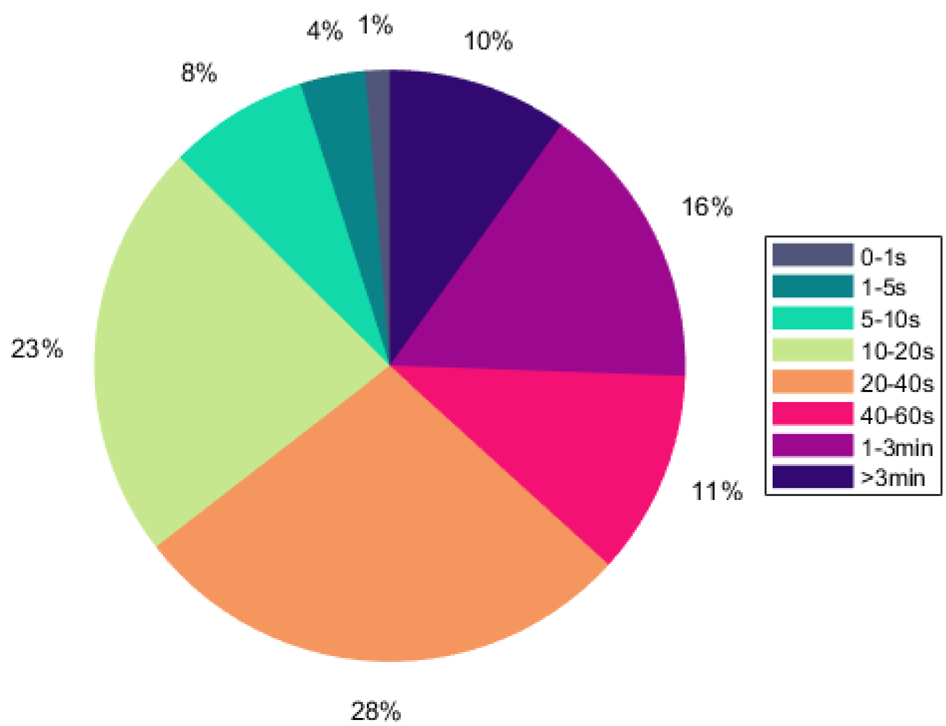


Table 3.23 shows how deviations of different duration affected to the total time outside the standard frequency range in 2019. Times are given in minutes. Pie chart in Figure 3.35 shows in percentages how the total time outside the standard frequency range was divided between deviations of different 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 3.23. Total minutes in 2019 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	87	224	499	1517	1858	748	1057	747	6737
< 49.9 Hz	84	234	489	1427	1716	687	960	521	6118
total	171	458	988	2944	3574	1435	2018	1268	12855

Figure 3.35. 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 2019. Figure 3.36 represents the total number of deviations per duration for each month in 2019. Most of the deviations lasted only between 0-1 seconds. Clearly the most deviations occurred in June. Also the spring moths from February to May were prominent in the number of deviations. The least amount of deviations occurred in November.

***Figure 3.36**. Total number of frequency deviations per duration for each month in 2019*

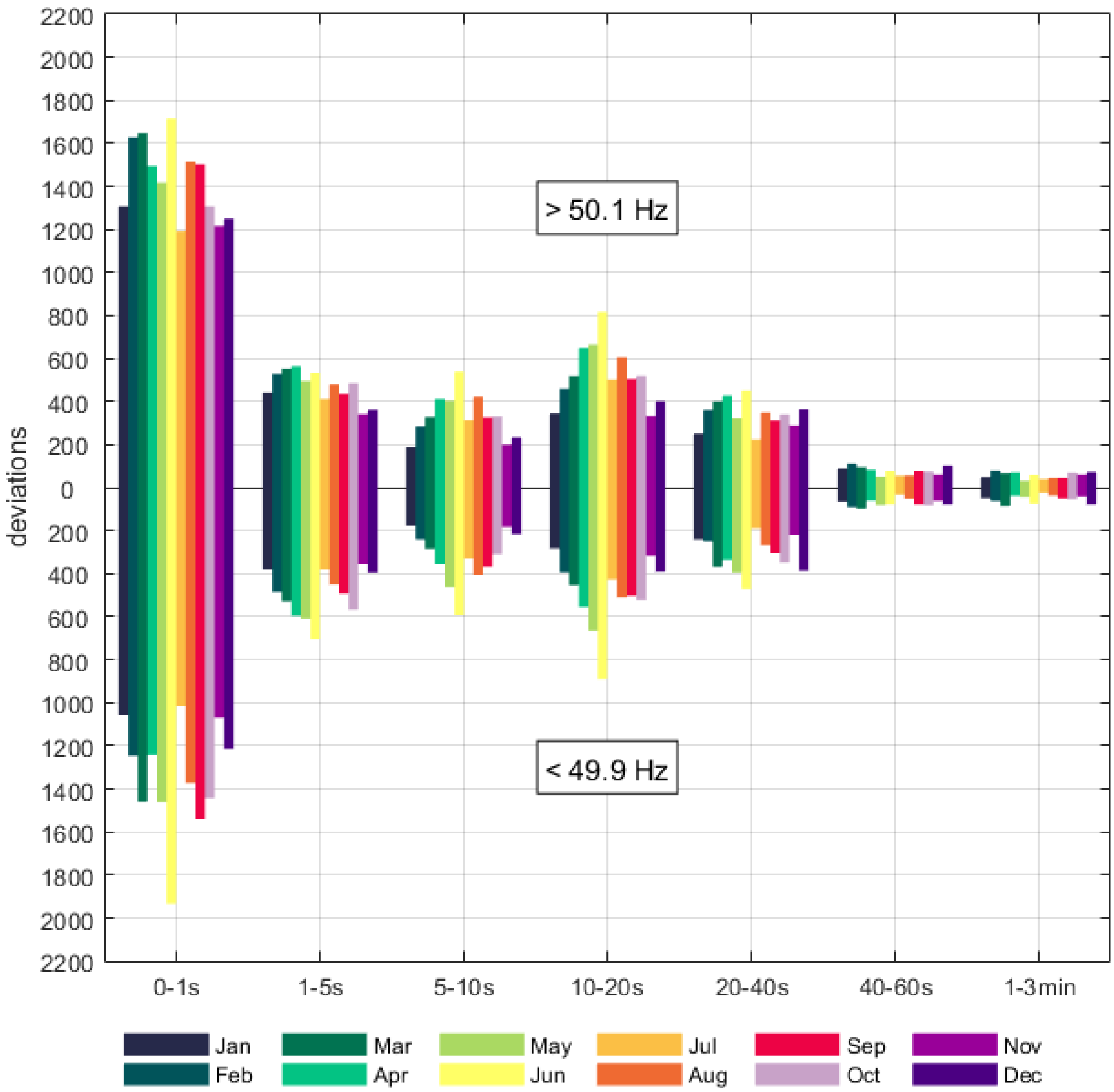
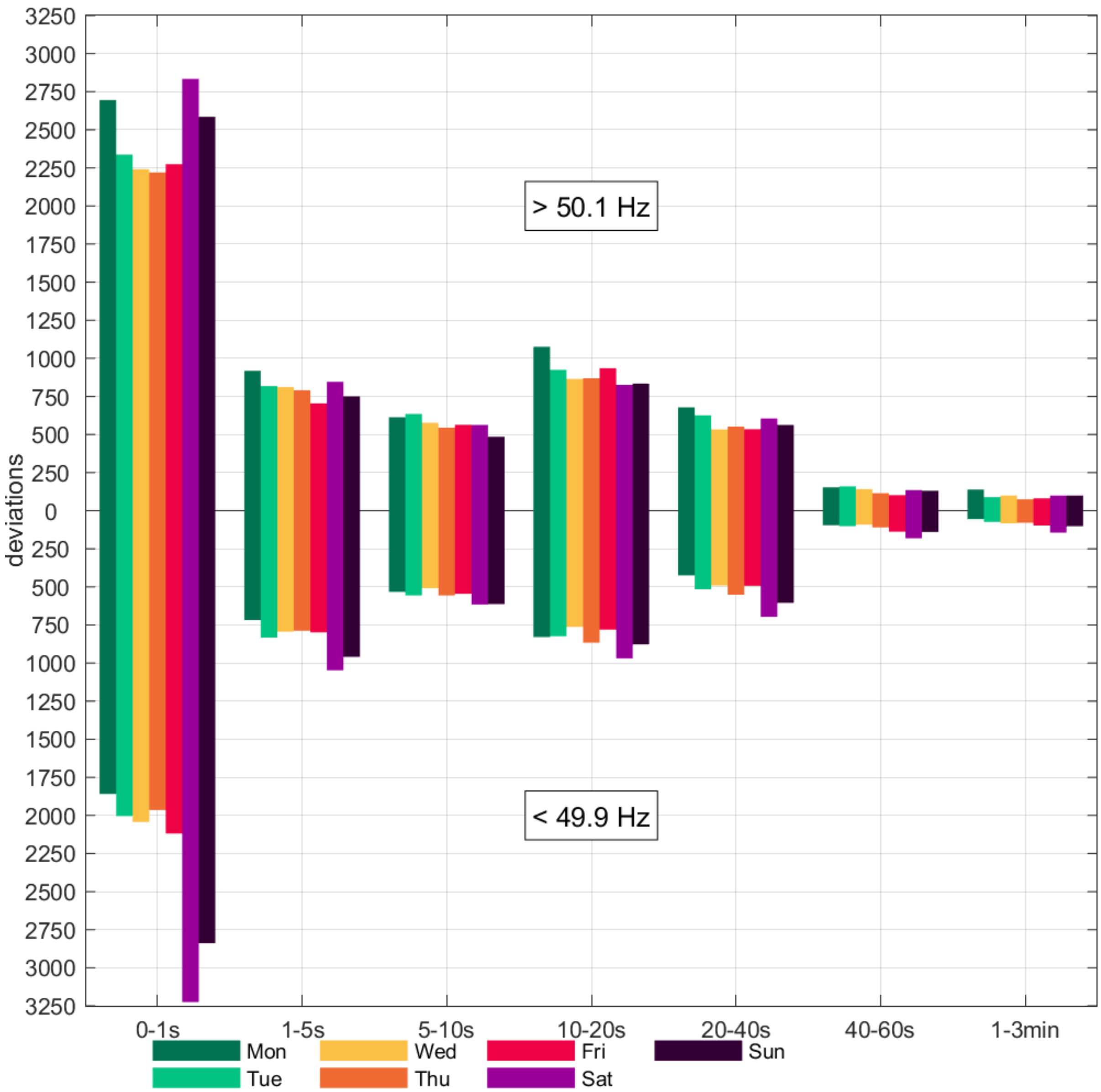


Figure 3.37 shows the number of deviations for every day of the week. Short 50.1 Hz and 49.9 Hz deviations lasting 0-1 s were clearly the most common on Saturday and Sunday. Moreover, under 49.9 Hz deviations of all durations were always most common on the weekend. 50.1 Hz deviations lasting more than 1 s were in general most common on Monday and Tuesday.

Figure 3.37**. **Total number of frequency deviations per duration for each day of the week in 2019



Figures 3.38 and 3.39 illustrate the number of deviations per duration inside the day. Figure 3.38 includes hours from 0-11 and Figure 3.39 the hours from 12-23. By far the most deviations above the standard frequency range occurred in the midnight and in the last hours of the day. More deviations also occurred during the morning and evening hours.

***Figure 3.38**. Total number of frequency deviations per duration for hours 0-11 in 2019*

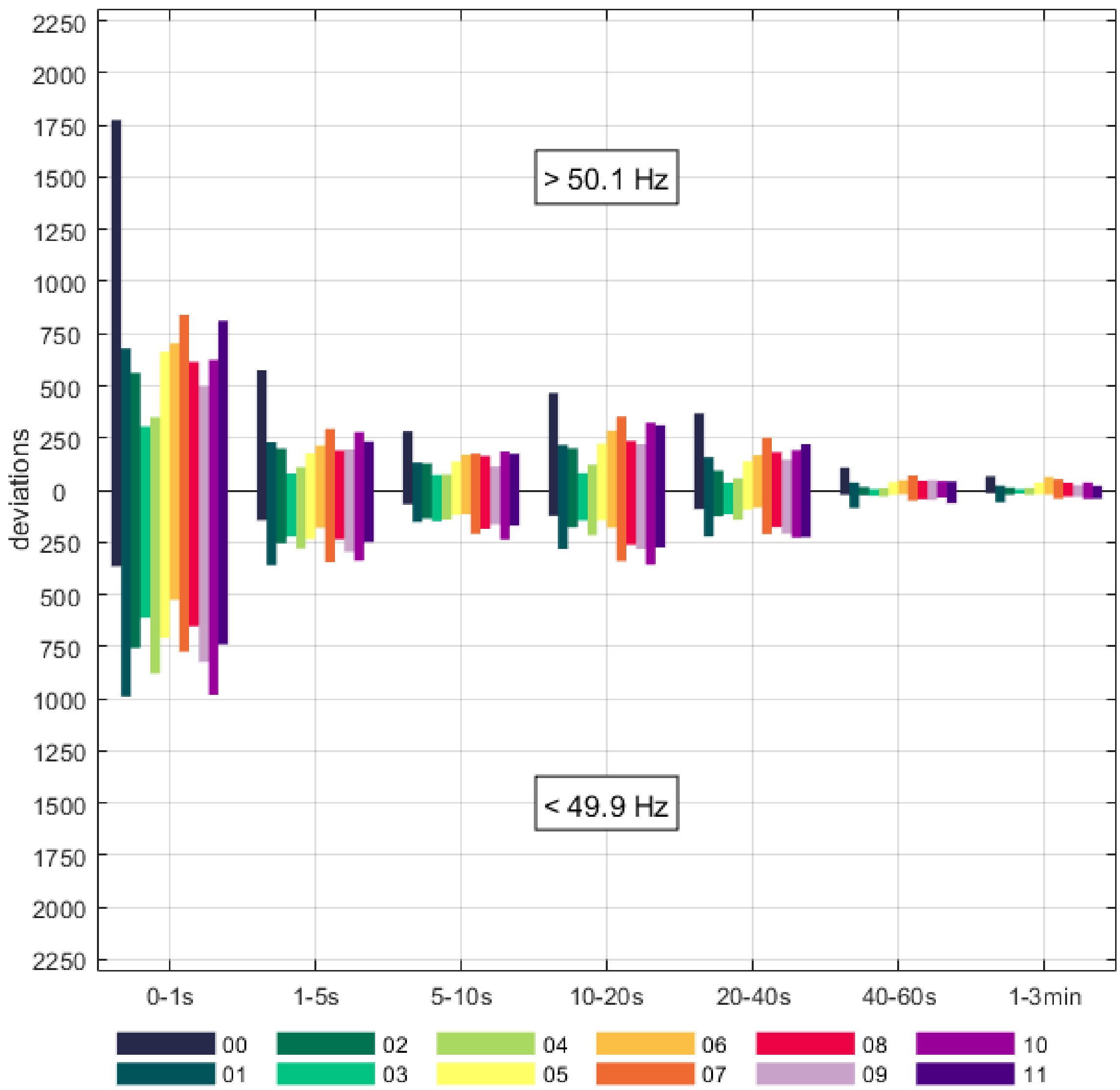


***Figure 3.39**. Total number of frequency deviations per duration for hours 12-23 in 2019*

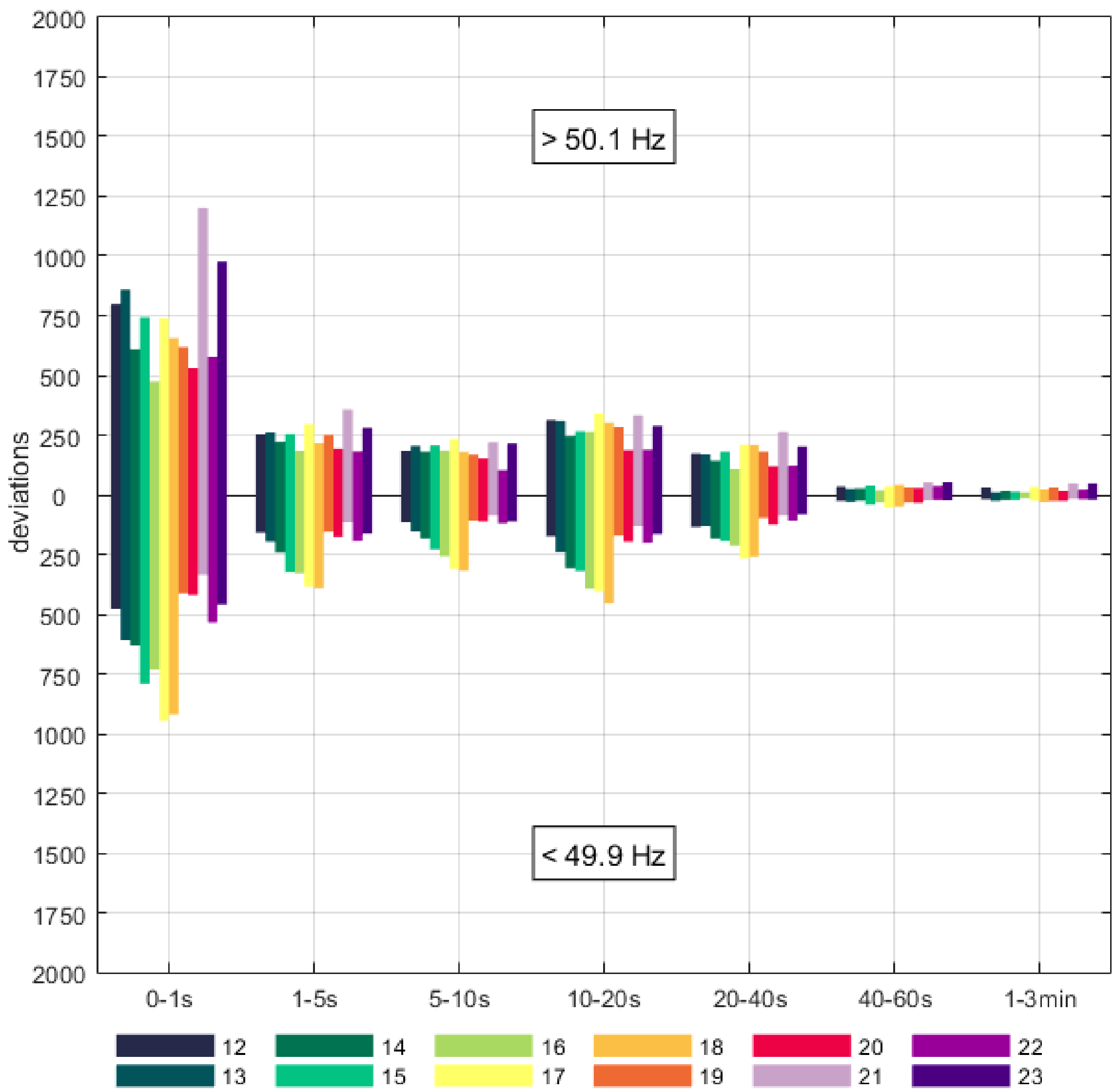
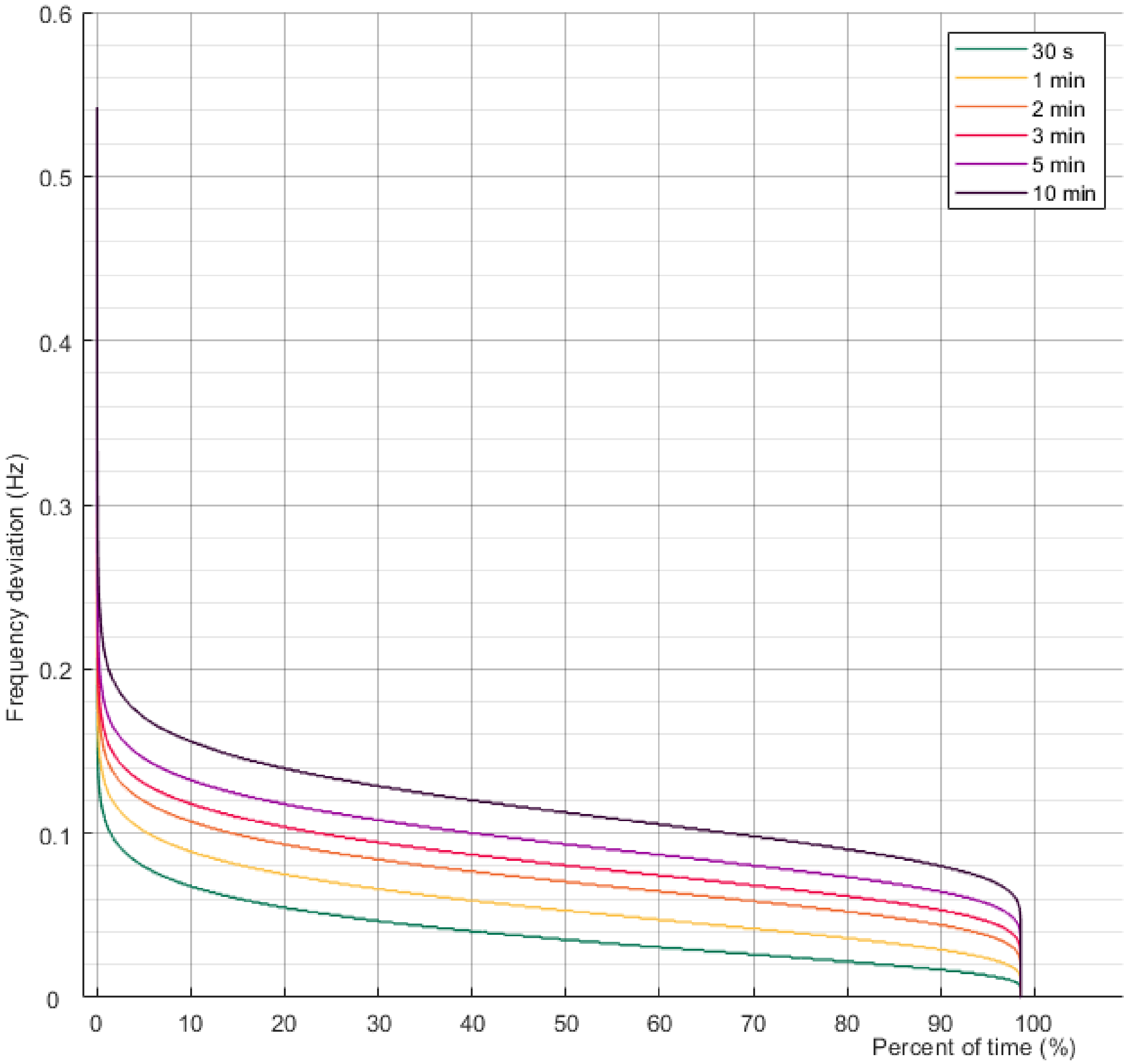


Figure 3.40 represents the duration curve of maximum frequency deviation inside different time windows in year 2019. The time window was slid through the year with a time interval of one second. Studied time windows can be found from the legend of the Figure 3.40. Chapter 4 shows in detail frequency disturbances of over 0.3 Hz which can be seen here as a peak near 100% permanence.

***Figure 3.40**. Duration curve of maximum frequency deviation inside different time windows in 2019*



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 in the calculations for these durations was one minute. Figure 3.41 shows the total number of deviations for years between 2014-2019. The number of 1-3 minute deviations has increased from previous years but the number of longer deviations is on par with the other years. Compared to two previous years the number of deviations has increased in every time category except for over 15 minute deviations.

***Figure 3.41**. Total number of longer frequency deviations per duration between 2014-2019*

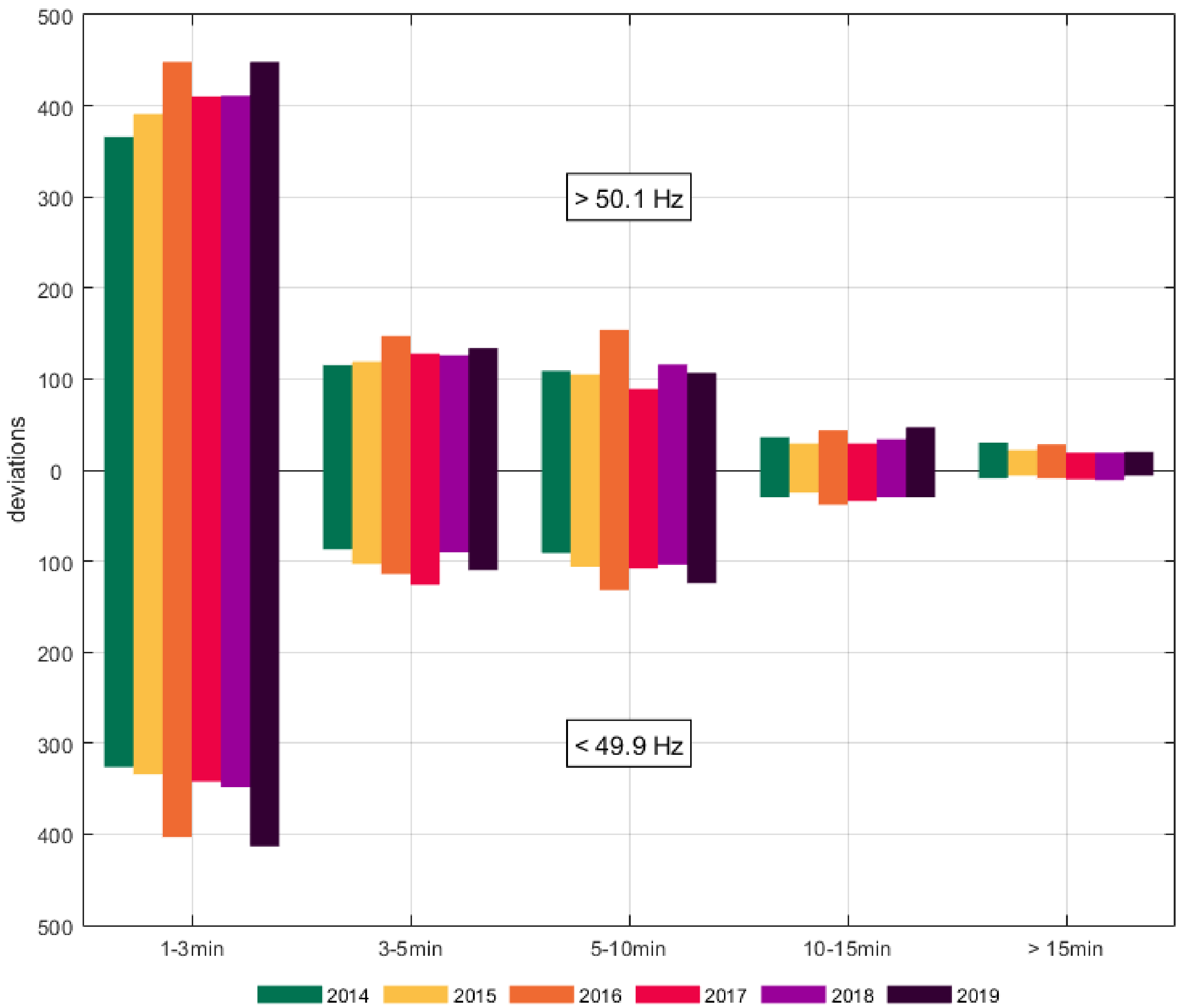


Figure 3.42 shows the total number of longer deviations for each month in 2019. March had the most deviations lasting between 1-3 minutes and December had the most deviations lasting between 5-10 minutes.

***Figure 3.42**. Total number of longer frequency deviations per duration for each month in 2019*

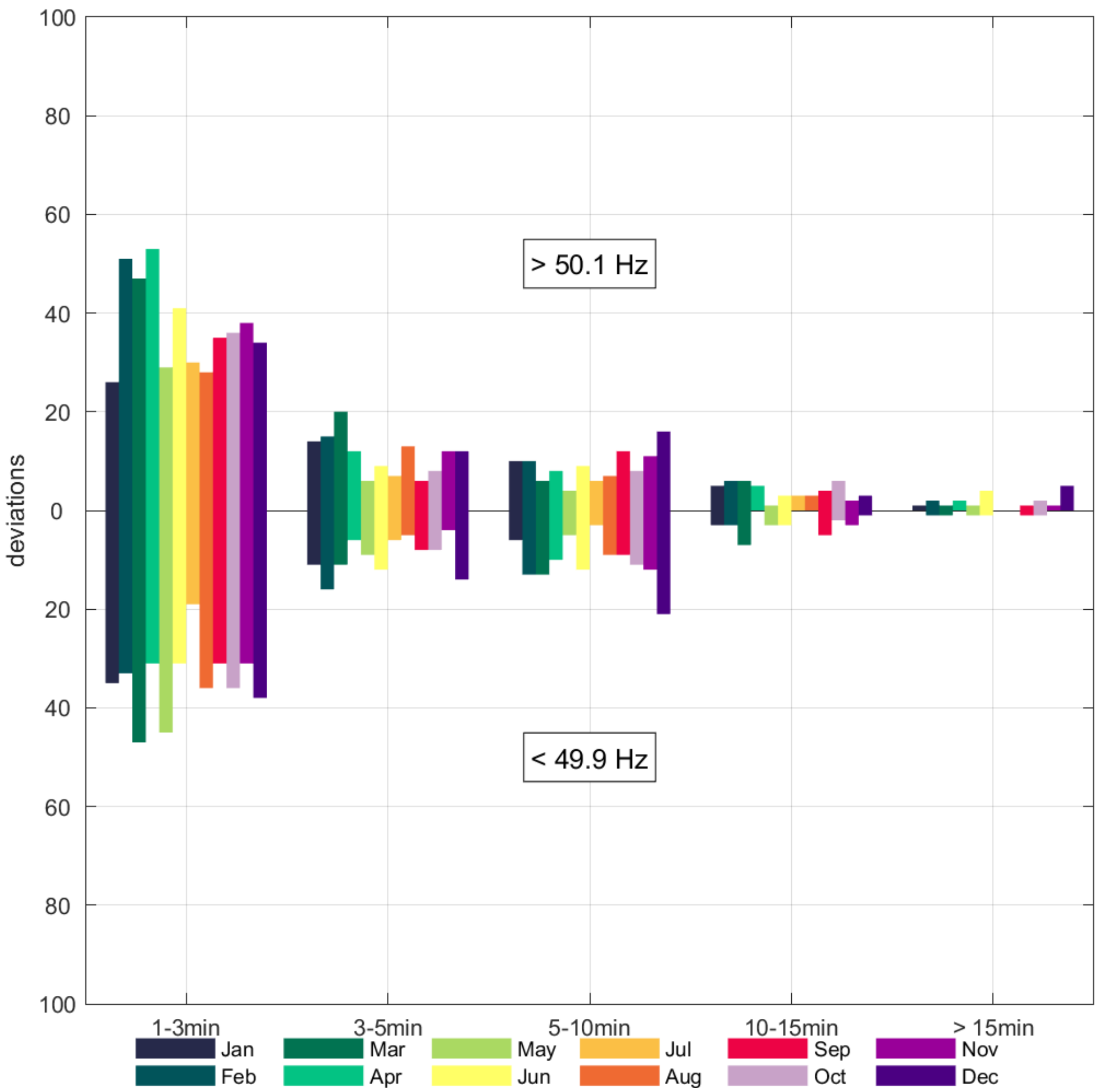
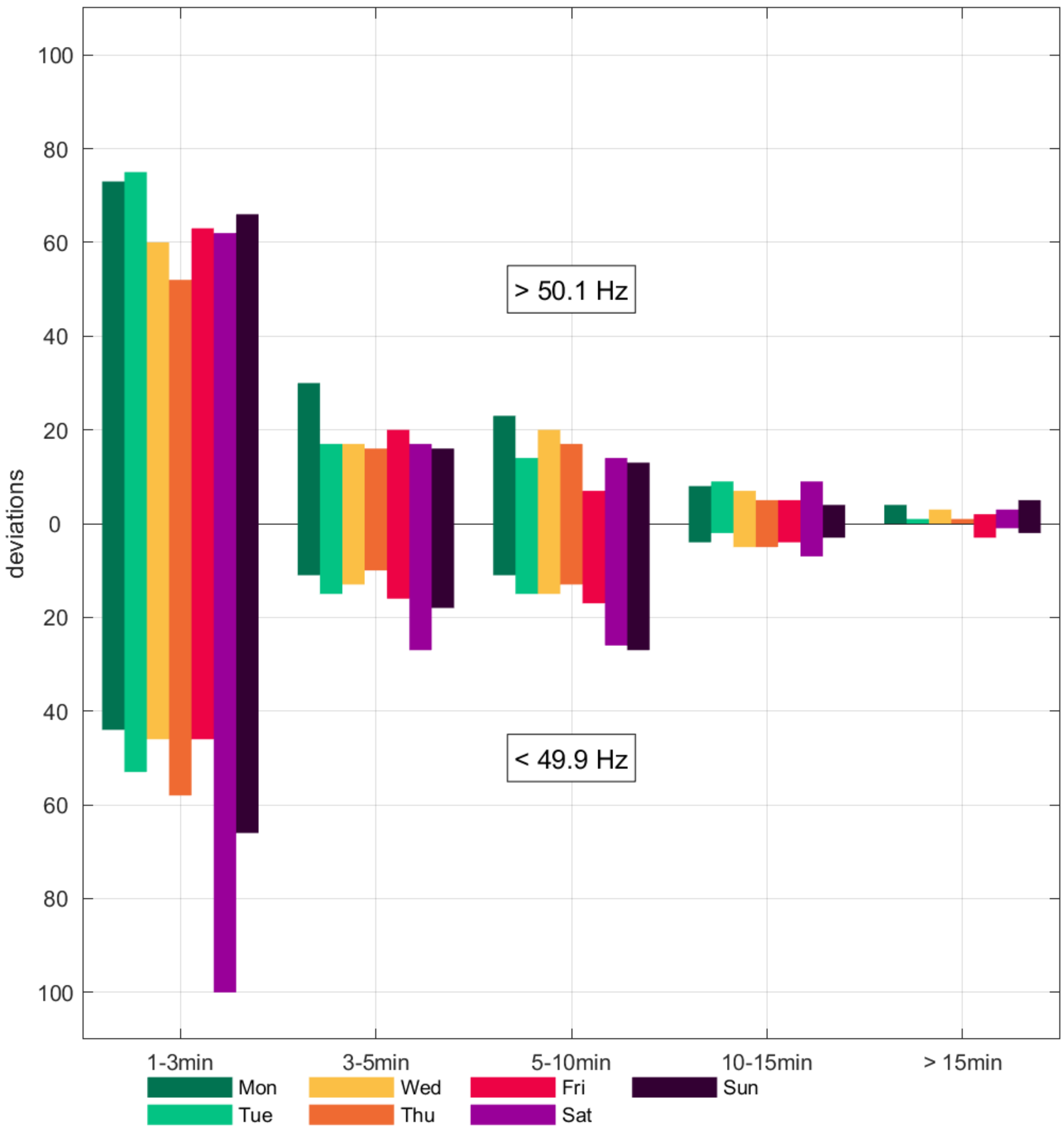


Figure 3.43 represents the number of deviations with different durations during every day of the week in 2019. Beginning of the week had more over frequencies while under frequencies were more common on the weekend. Especially Saturday had a remarkable number of deviations under 49.9 Hz lasting between 1-3 minutes.

***Figure 3.43**. Total number of longer frequency deviations per duration for each day of the week in 2019*



Figures 3.44 and 3.45 follow the same pattern as the figures representing the shorter durations with most deviations taking place around midnight, in the morning and during evening hours.

***Figure 3.44**. Total number of longer frequency deviations per duration for hours 0-11 in 2019*

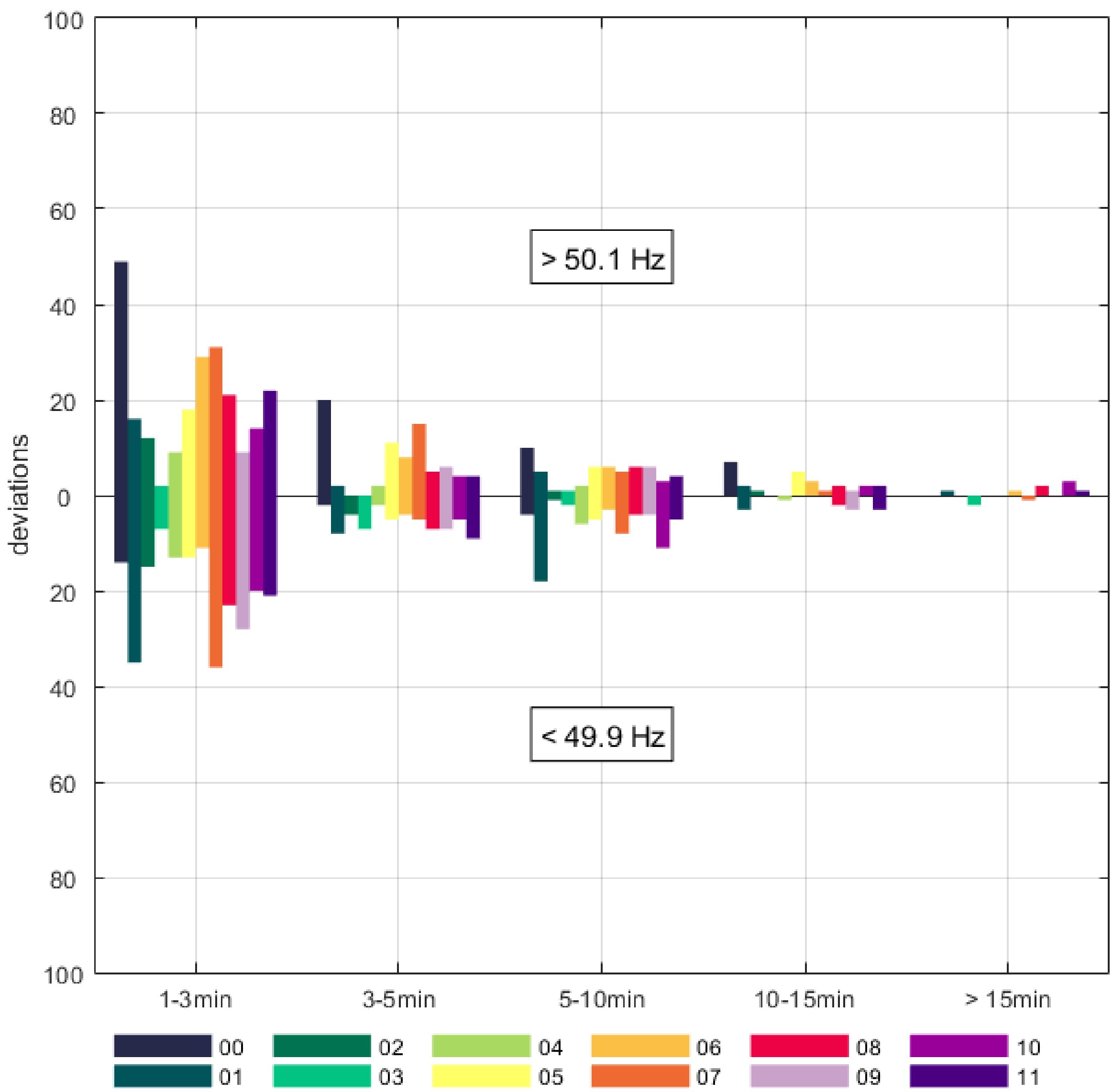
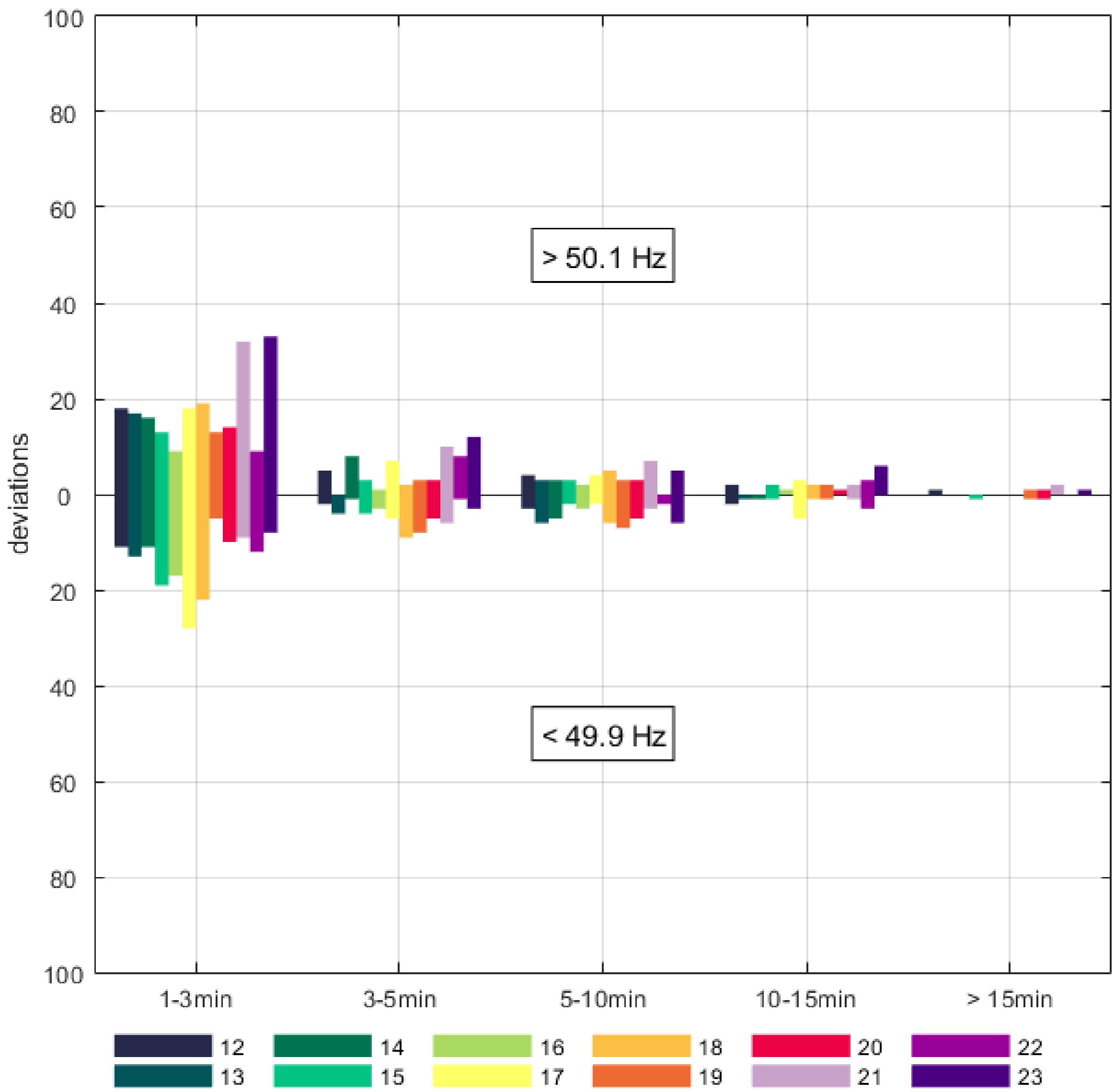


***Figure 3.45**. Total number of longer frequency deviations per duration for hours 12-23 in 2019*



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 FCR-D (Frequency Containment Reserve for Disturbances) 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 3.46 shows the daily average numbers of over and under frequency deviations from 2014 to 2019. In 2019 there were more crossings than in previous years, except for year 2016. Every year there has been slightly more threshold crossings over 50.1 Hz than under 49.9 Hz.

***Figure 3.46**. Daily average number of frequency deviations for years 2014-2019*

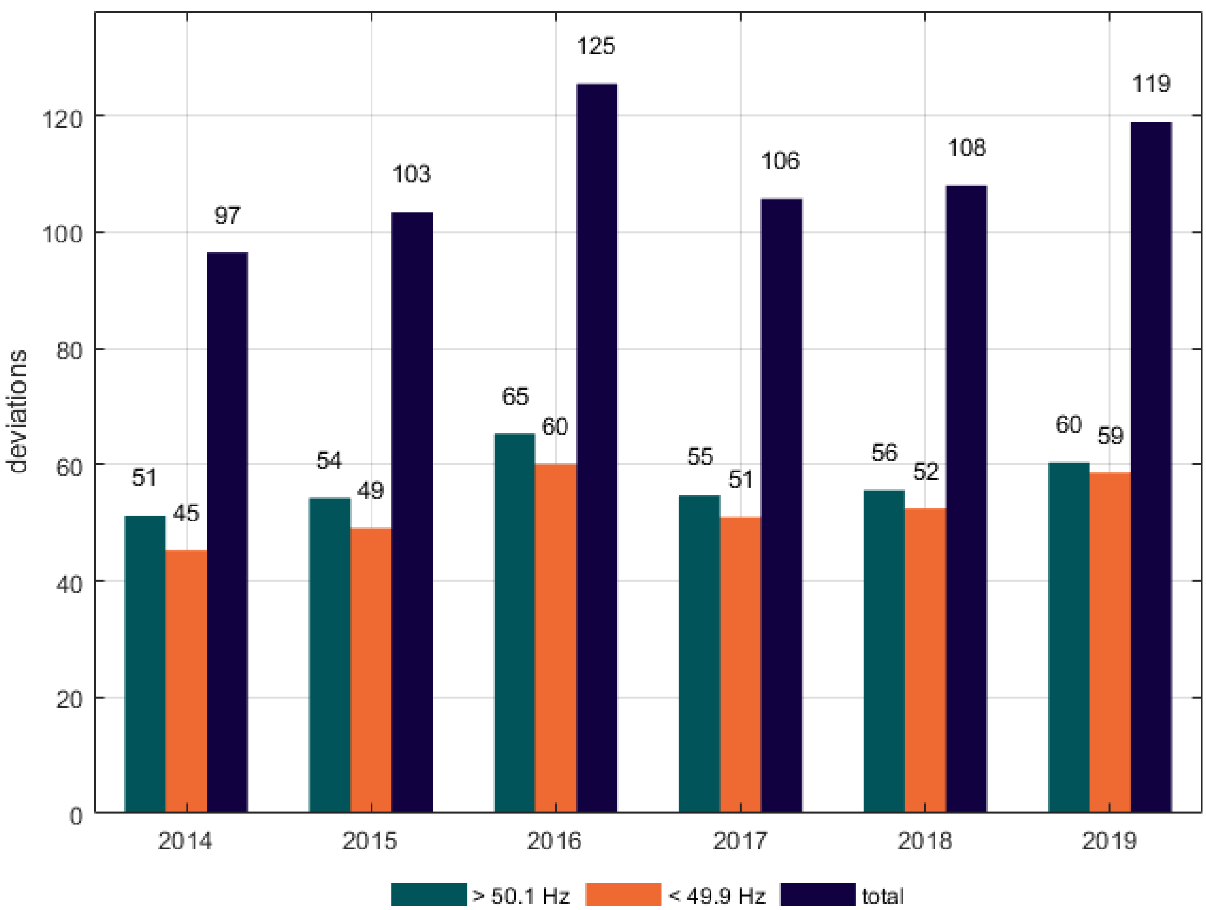


Figure 3.47 represents the daily average number of threshold crossings for each month in 2019. The frequency crossed the threshold most often between April and June. Least frequncy crossings occurred in January and November. In total, there has been slightly more crossings over 50.1 Hz than crossings under 49.9 Hz.

***Figure 3.47**. Daily average number of threshold crossings for every month in 2019*

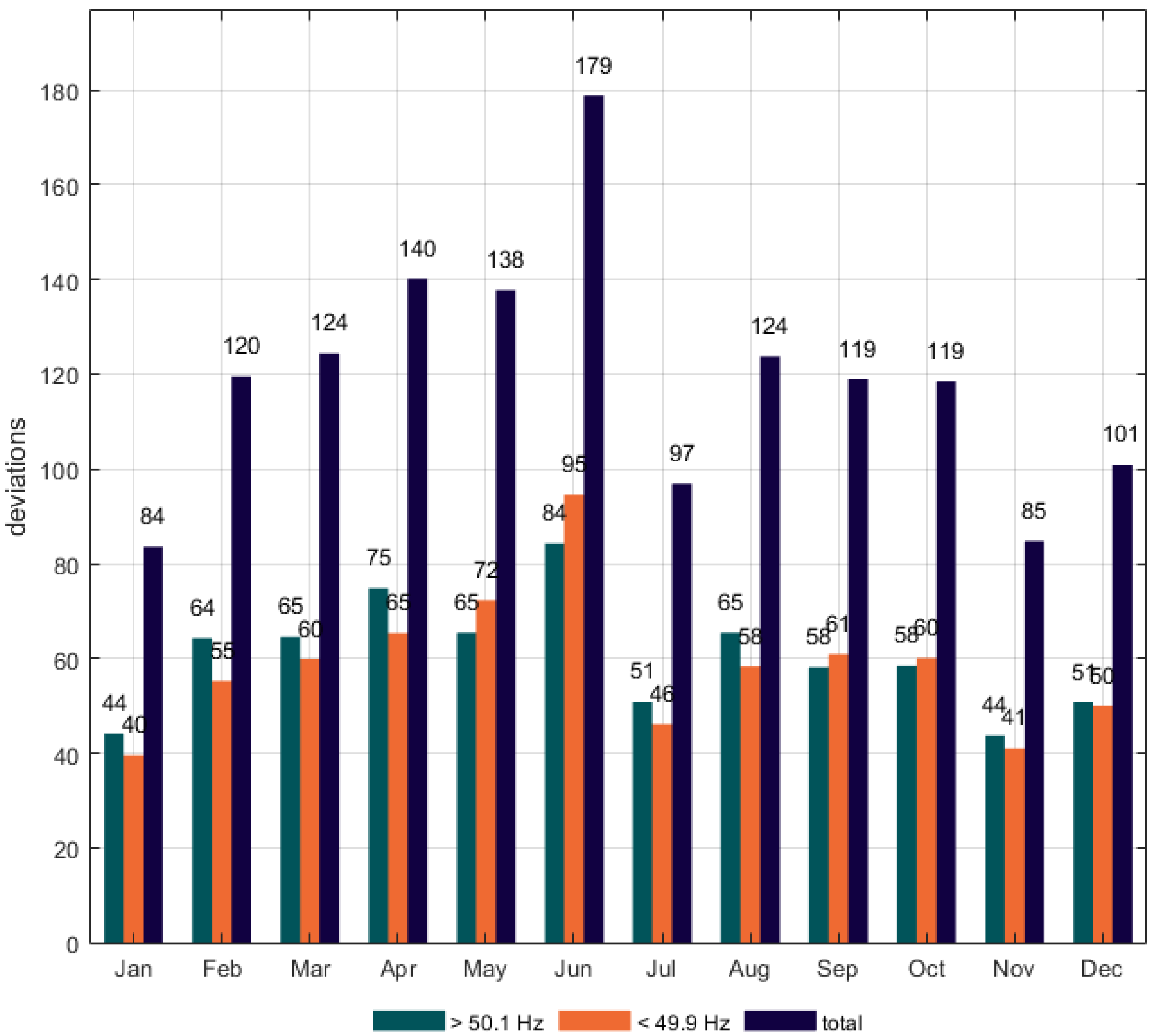
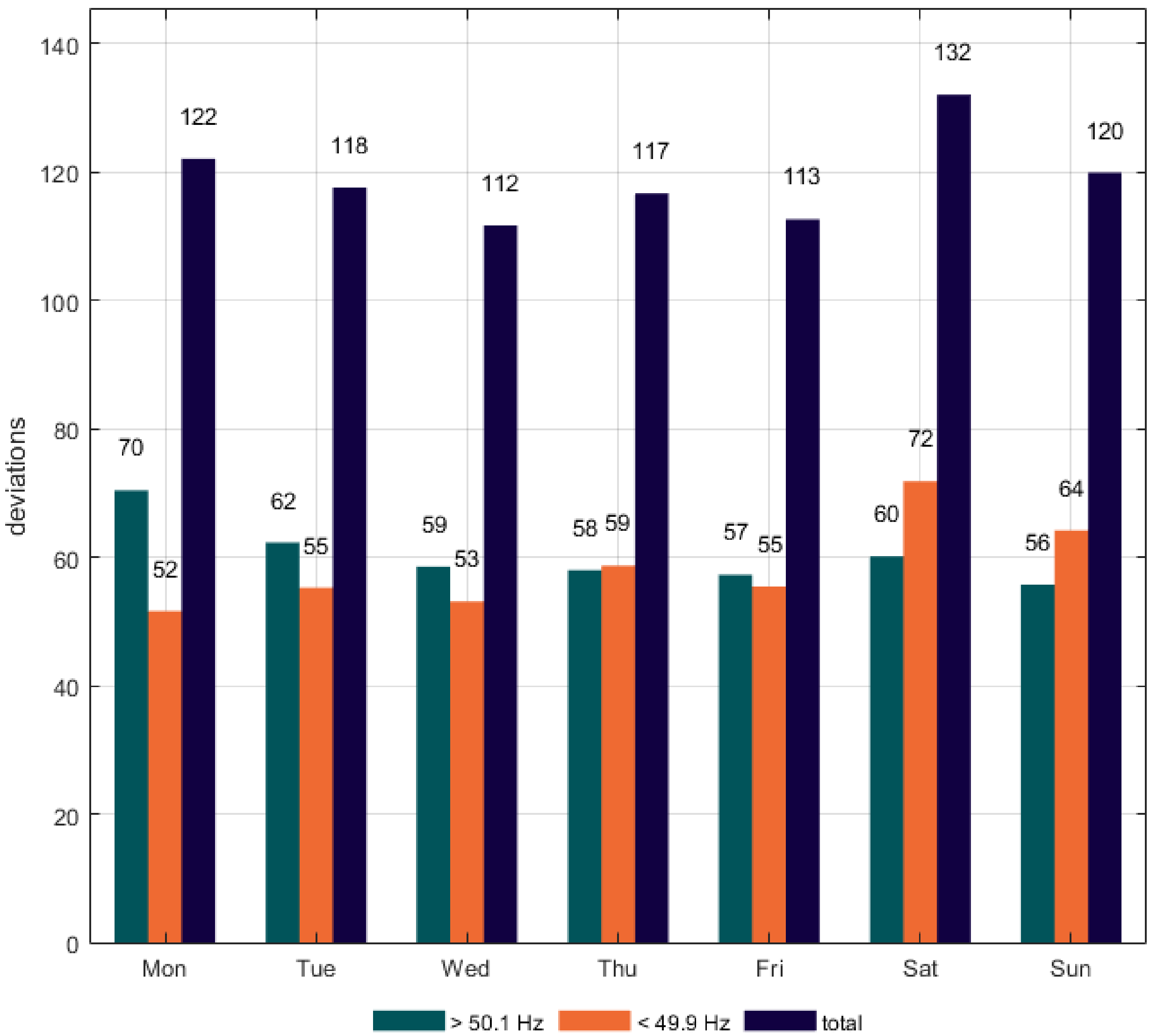


Figure 3.48 shows the number of threshold crossings for each day of the week in 2019. Figure 3.48 shows the number of threshold crossings for each day of the week in 2019. The number of crossings was highest on Saturday.

***Figure 3.48**. Daily average number of threshold crossings for every day of the week in 2019*



The hourly number of threshold crossings inside an average day is in Figure 3.49. The least amount of threshold crossings occured in the night from 2 to 6 and in the evening from 19 to 22. Close to the midnight and in the morning and aftenoon the frequency crossed the threshold more often.

***Figure 3.49**. Average number of threshold crossings for every hour of the day in 2019*

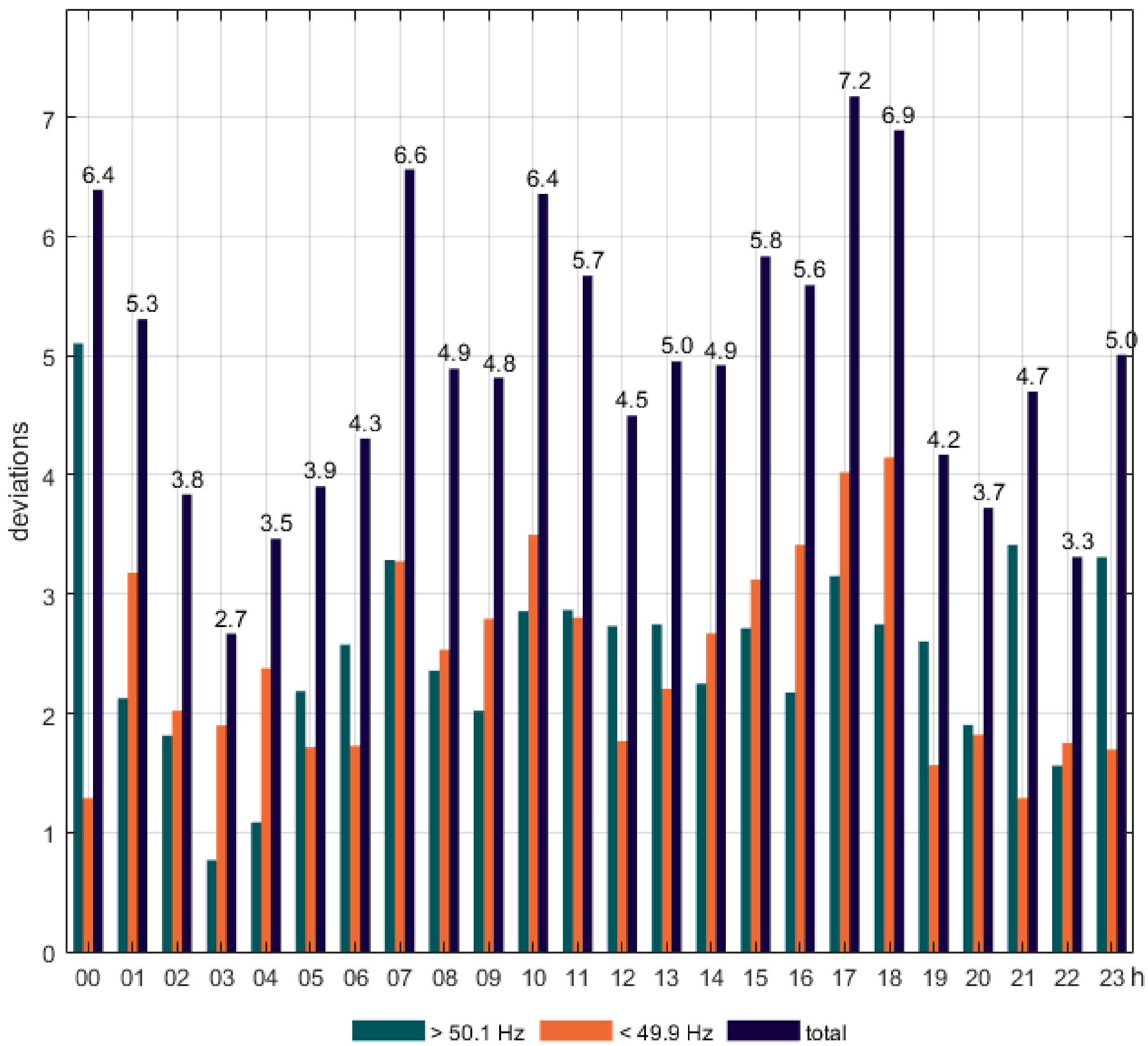
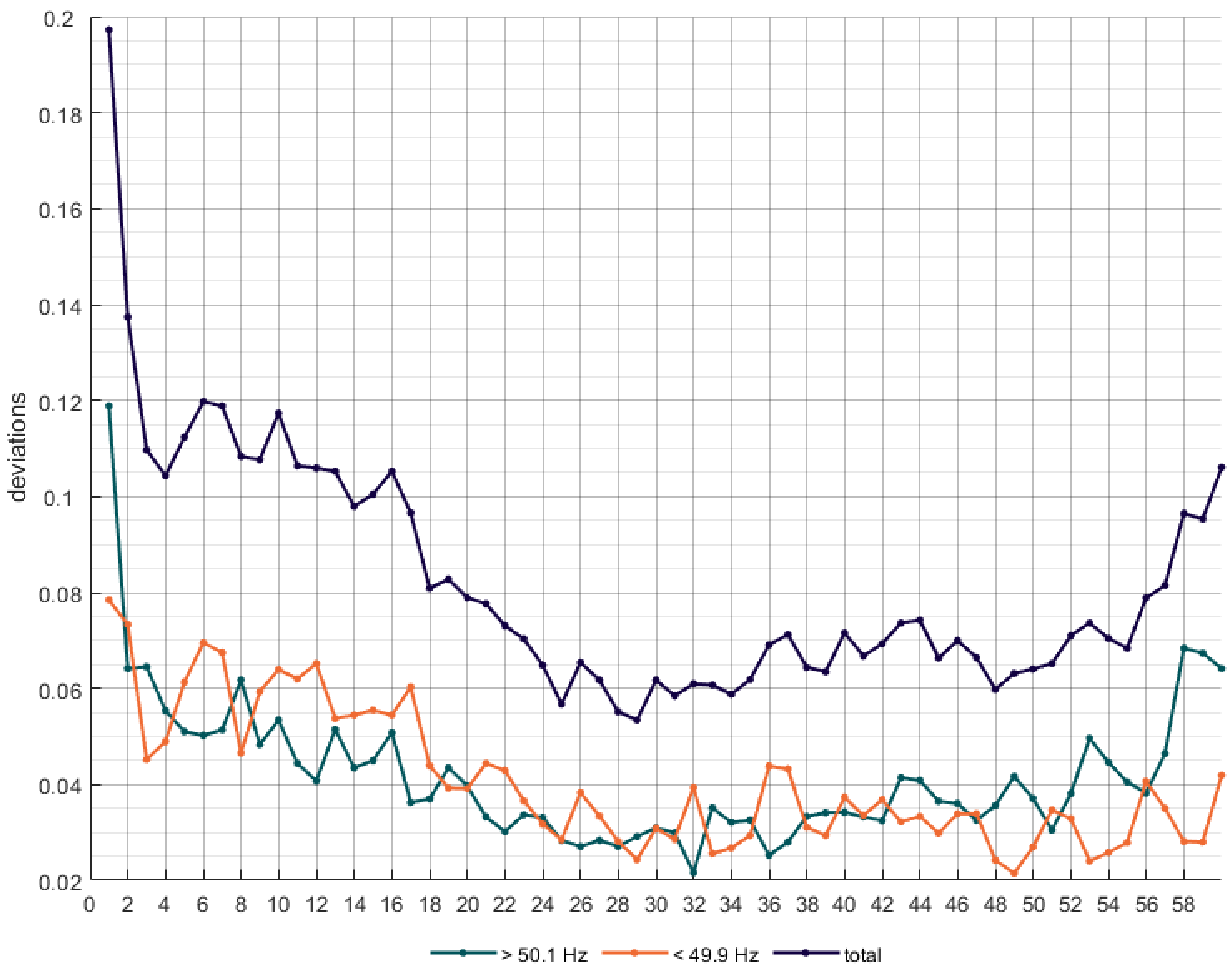


Figure 3.50 represents the average number of threshold crossings for every minute inside the hour. Most crossings took place within the first minutes of the hour. During the first 30 minutes of the hour, the frequency crossed 49.9 Hz more often, while more crossings of 50.1 Hz took place in the latter part of the hour.

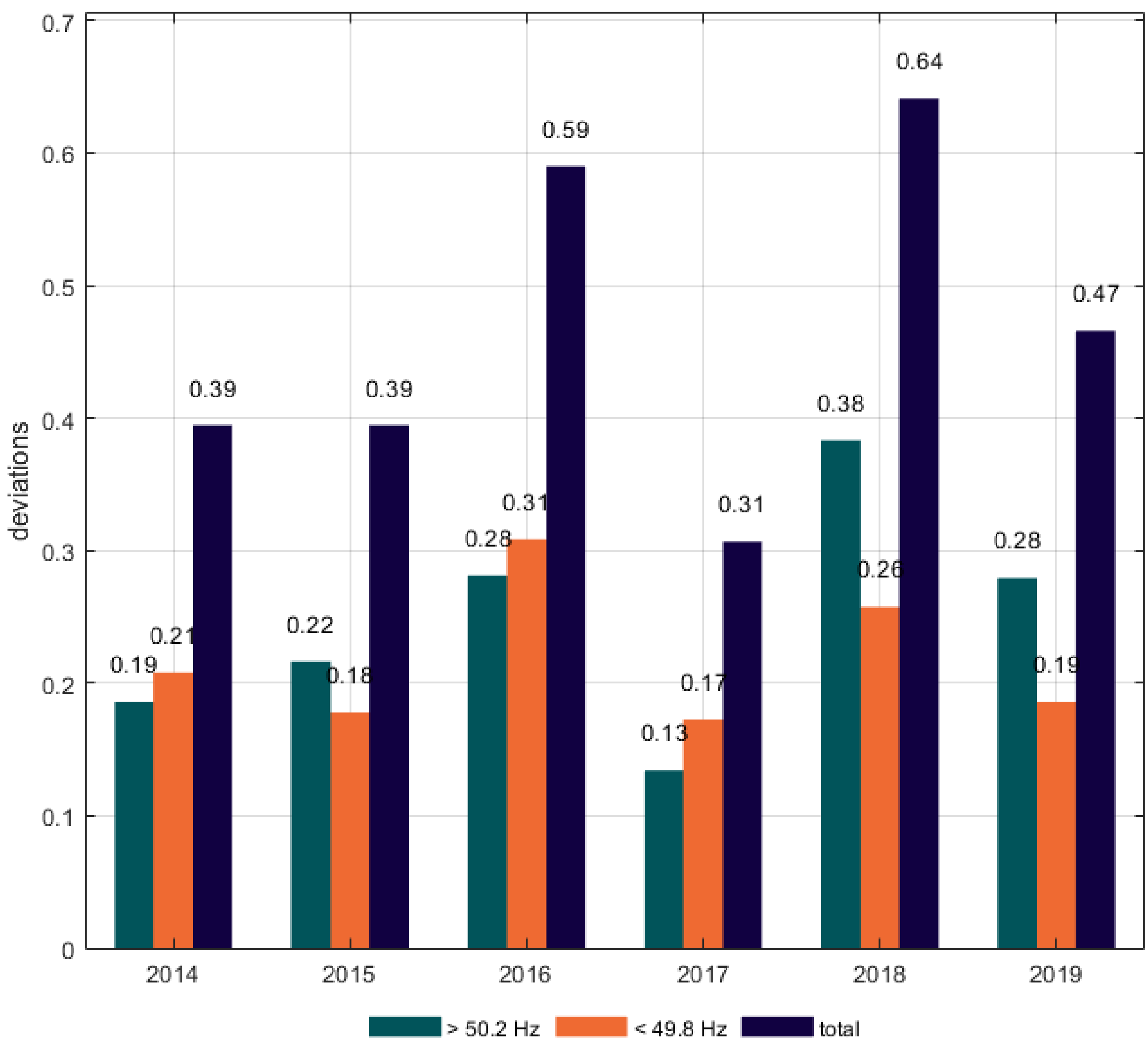
***Figure 3.50**. Average number of threshold crossings for every minute of the hour in 2019*



3.6.2 Number of 49.8-50.2 Hz crossings

Figure 3.51 represents the average number of frequency deviations per day that exceeded ±200 mHz. In 2019 the number of crossings was lower compared to years 2016 and 2018 but higher compared to the other years.

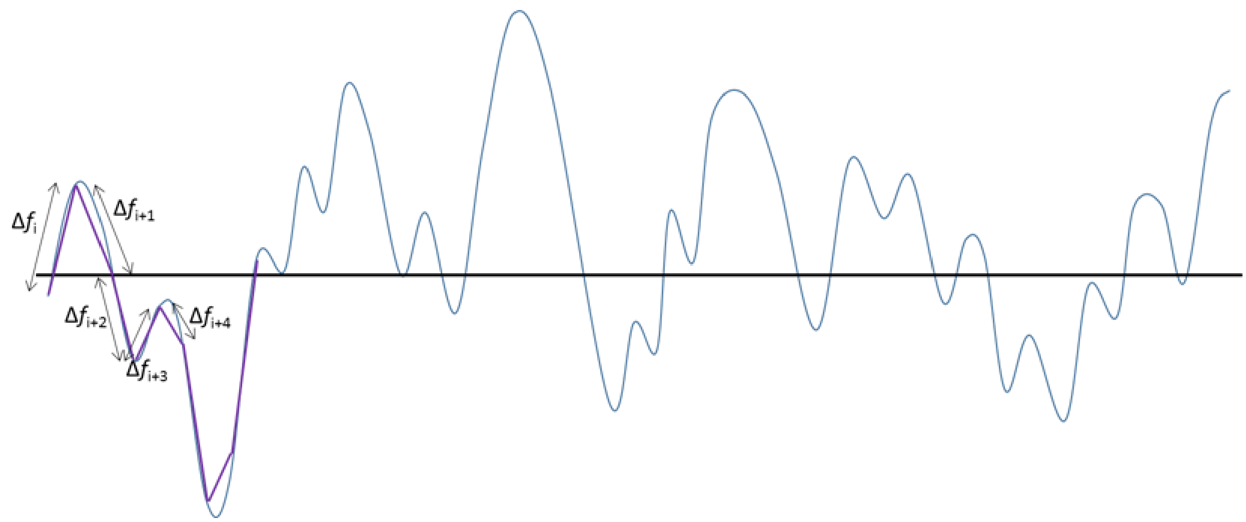
***Figure 3.51**. Daily average number of frequency deviations larger than ±200 mHz for years 2014-2019*



3.7 Length of frequency path

The length of the path that the frequency takes shows how much the frequency travels around 50.0 Hz, as can be seen in Figure 3.52. 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 3.52 is the formula for the frequency path, where Δt is the length of the time step (in this case 0.1 s).

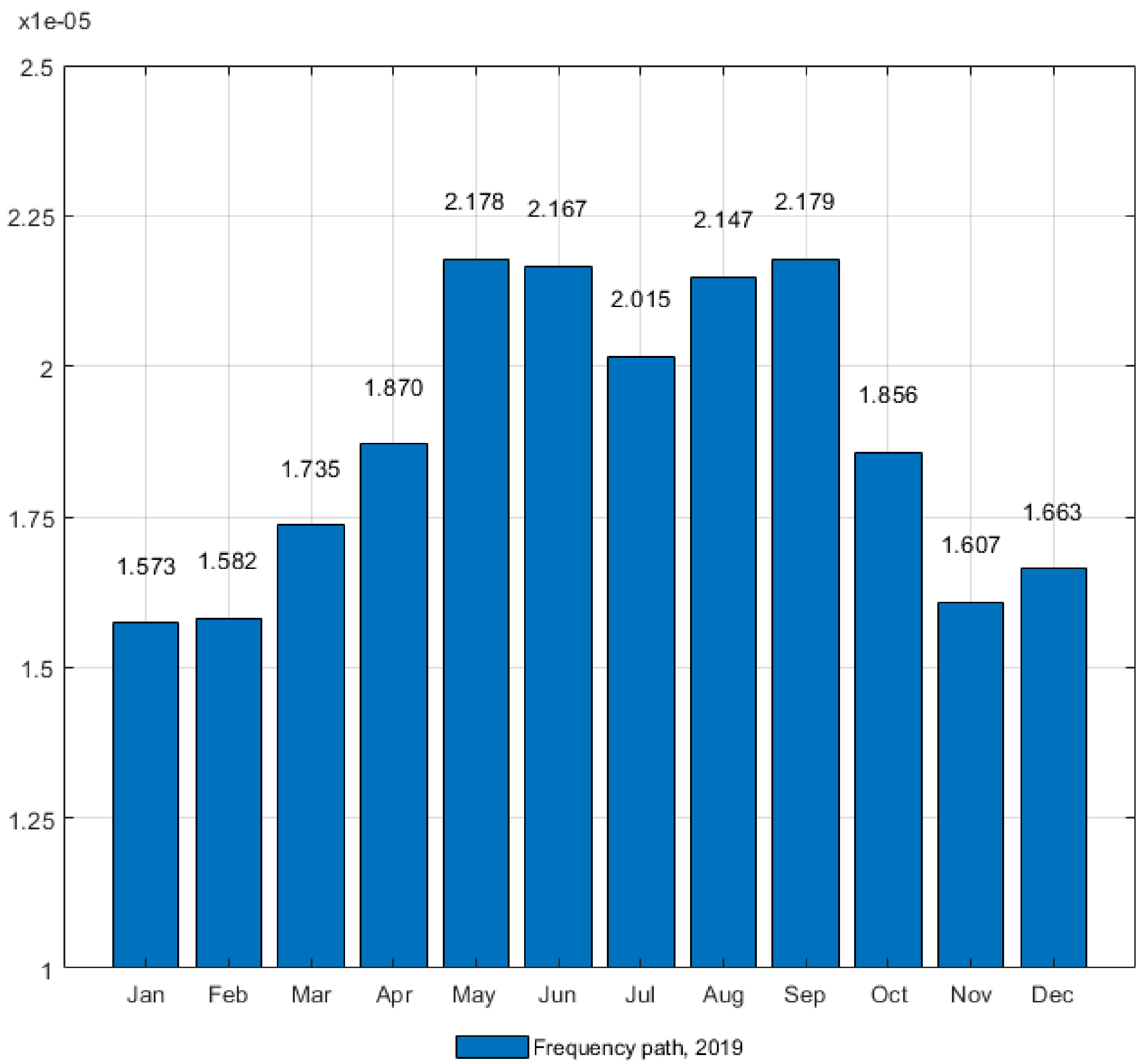
Figure 3.52. Frequency quality index: Length of the frequency path [7]



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

Figure 3.53 represents the frequency path for each month in 2019. The path length increased from February to April. In May the length of the frequency path peaked for the first time. In the summer months the frequecy path stayed relatively long and in Septenmber the path length peaked again. In October the path length decreased steeply and stayed shorter the rest of the year.

***Figure 3.53**. Length of the frequency path month by month in 2019*



The frequency path for every day of the week is shown in Figure 3.54. There has been rather little variation in the frequency path length between the days.

***Figure 3.54**. Length of the frequency path for every day of the week in 2019*

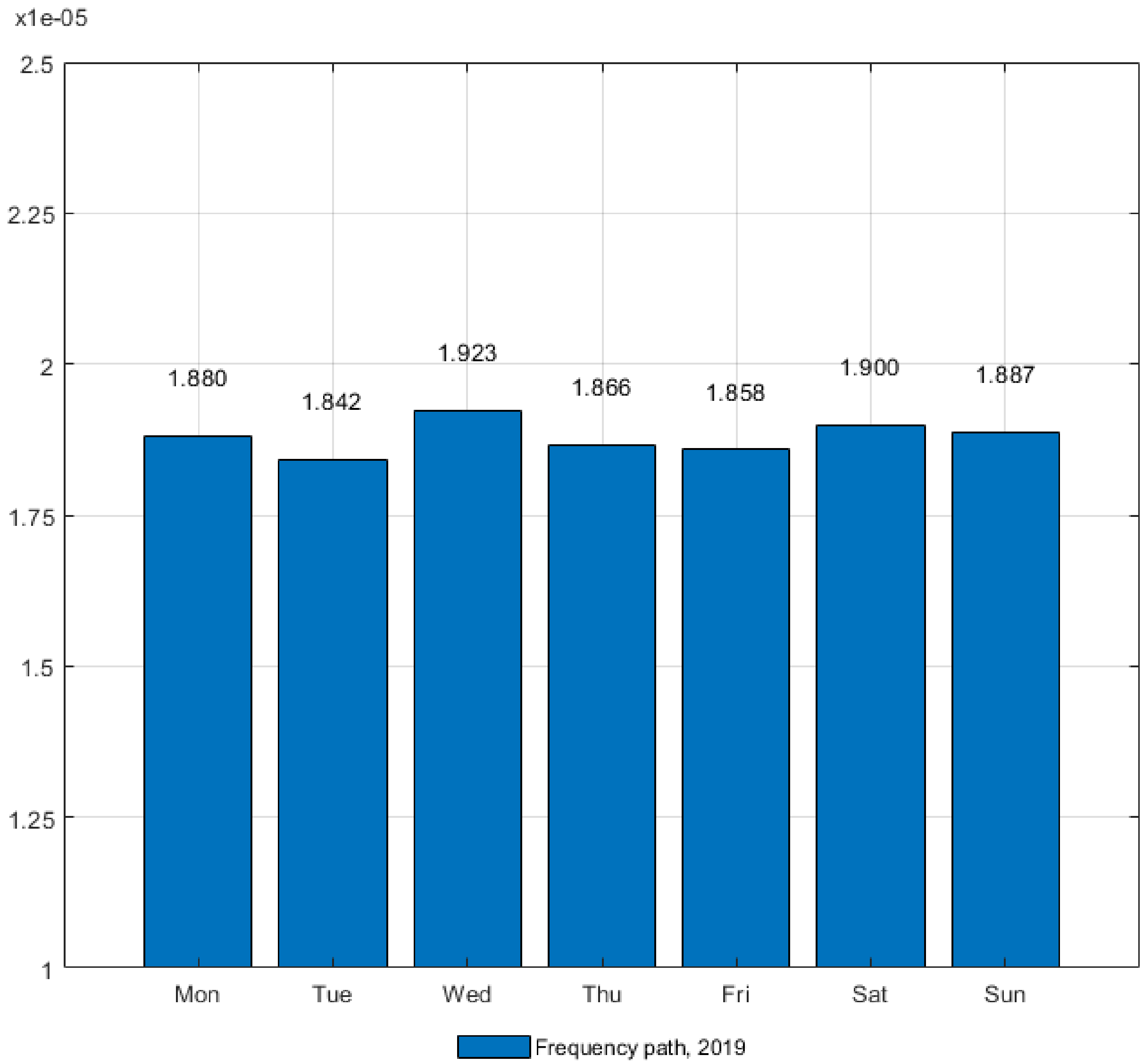


Figure 3.55 shows the frequency path during the day. The path was longer closer to the shift of the day and around afternoon. The frequency path was generally shorter around noon, except for hour 11 when the length of the frequency path peaks.

***Figure 3.55**. Length of the frequency path for every hour of the day in 2019*

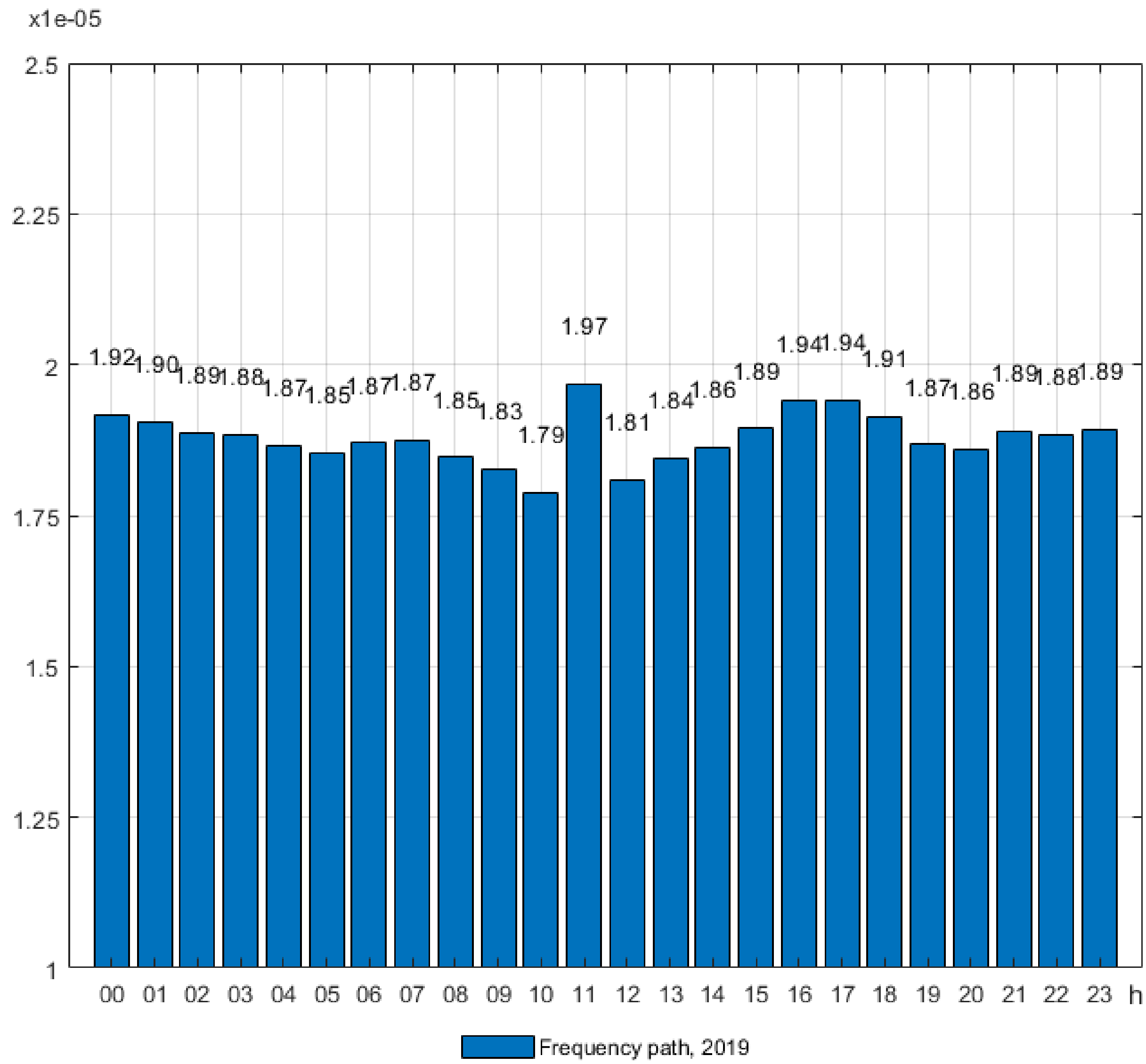
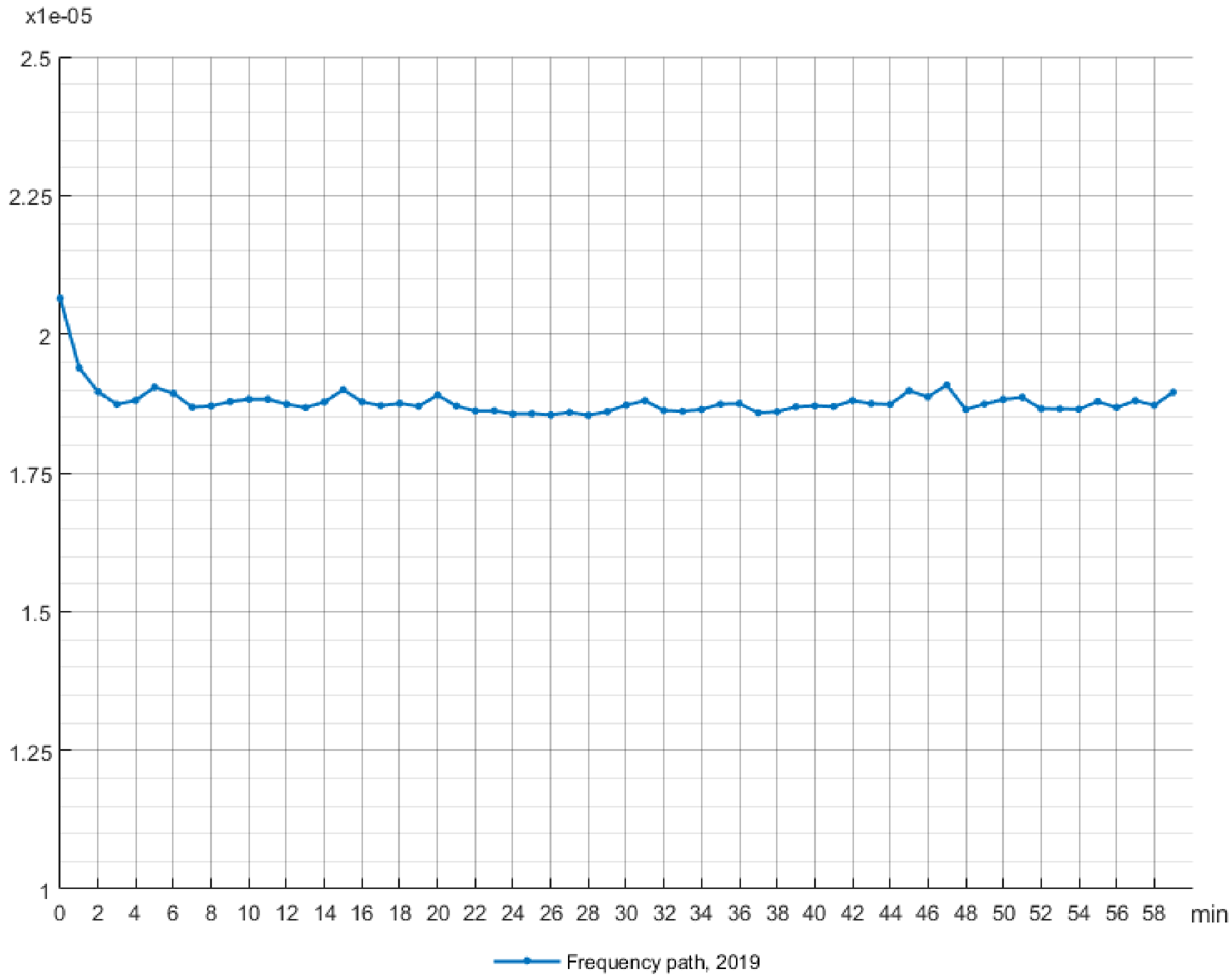


Figure 3.56 represents the average frequency path for every minute inside the hour. The path was longer during the first minutes of the hour, but otherwise it stayed pretty even throughout the hour.

***Figure 3.56**. Length of the frequency path for every minute of the hour in 2019*



3.8 Amount of frequency oscillation

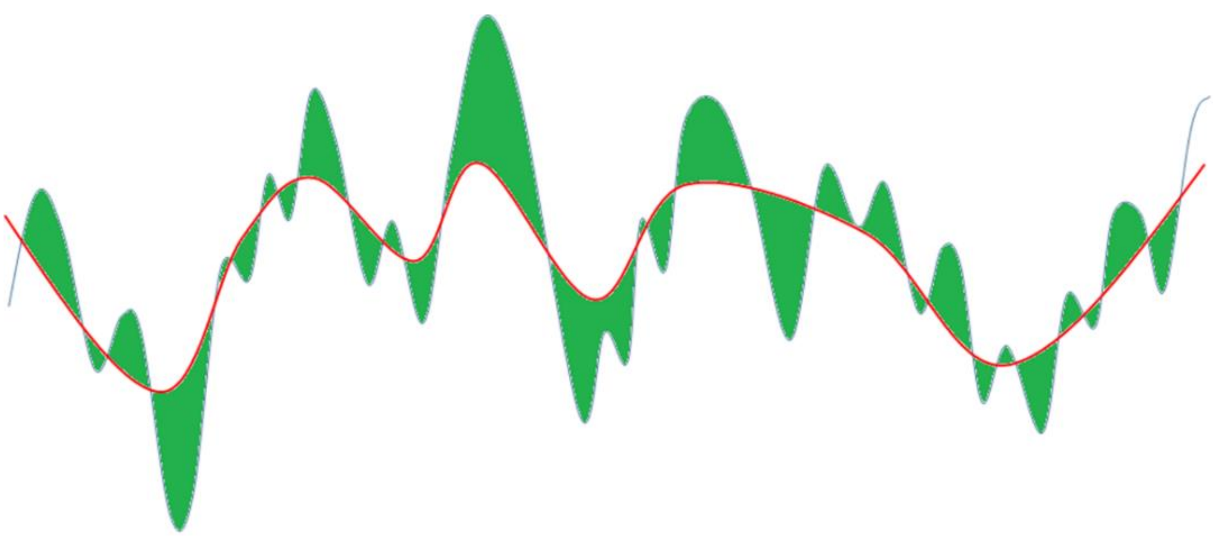
Frequency of the Nordic synchronous system oscillates constantly. The time period of the oscillation is approximately 40 to 90 seconds. This behavior is a natural characteristic of the system but it can be influenced through adequate settings of system reserves. Oscillation has an increasing effect on 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 3.57 [7].

***Figure 3.57**. 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 3.58. Frequency bands corresponding to the 40-90 s and 30-240 s bands are marked on the figure. Figure 3.59 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 3.58. 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]

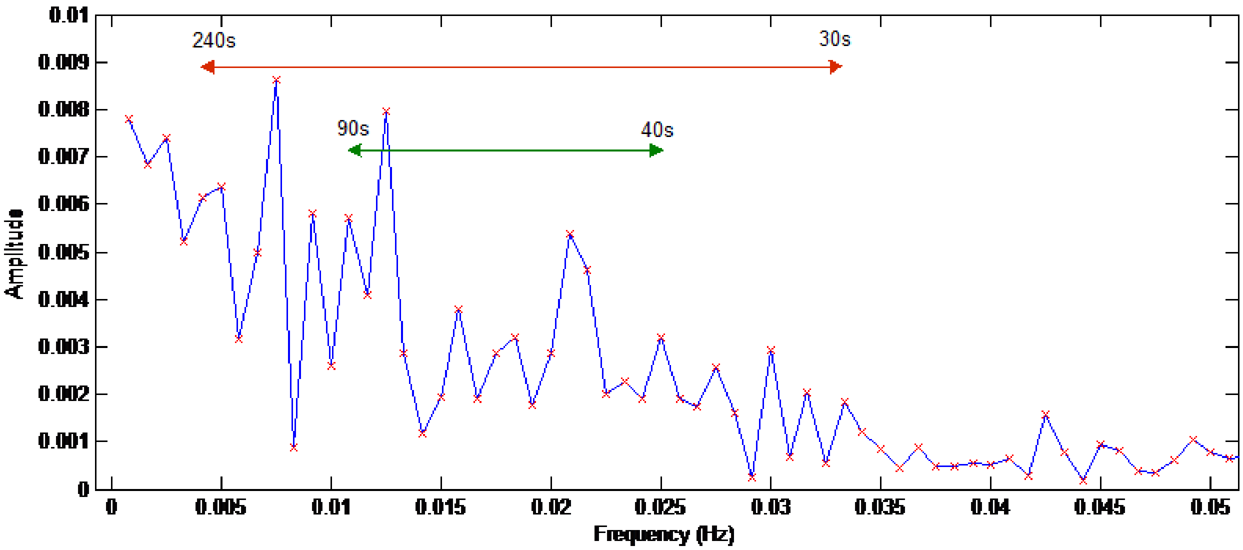
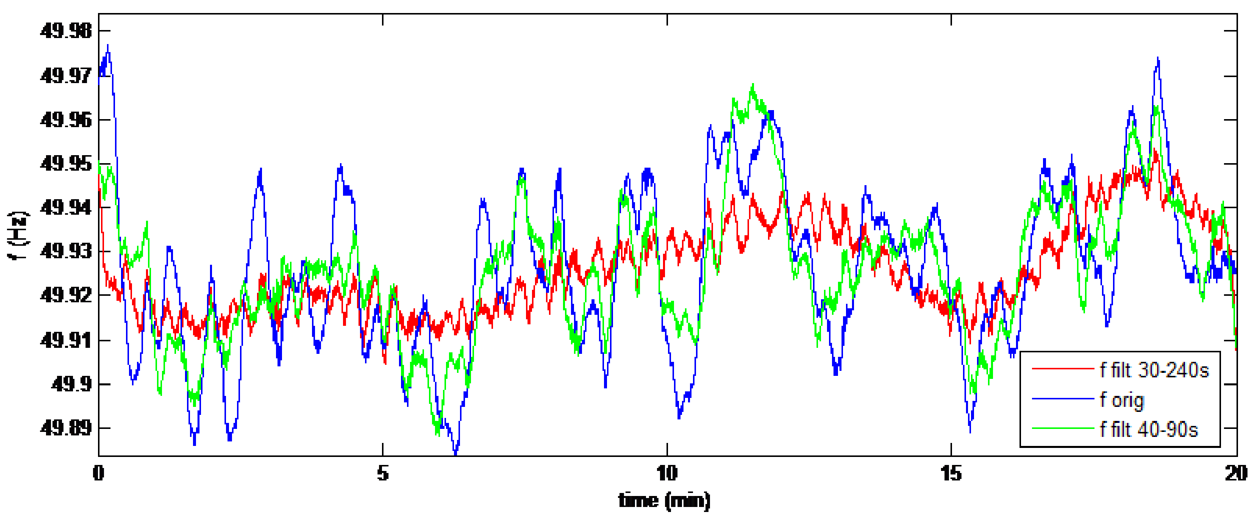


Figure 3.59. Original frequency (blue), frequency with 40-90 s band filtered (green) and frequency with 30-240 s band filtered (red). First 20 minutes of December 2012 are shown (UTC+2) [8]



3.8.2 Amount of oscillation

Figure 3.60 shows hourly values and 24 hour moving averages for the amount of oscillation in 2019. 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 is at its highest in the summer and autumn. January, February and December had the least amount of oscillation in 2019.

Figures 3.61 and 3.62 contain the previously mentioned 24 hour moving averages for years 2014-2016 and 2017-2019, respectively. In the calculations for years 2013-2015 it was required that there had to be enough eligible data for at least 22 hours in the frame of 24 hours. For 2016-2019, 12 hours of eligible data was required.

Figure 3.60. Amount of oscillation in 2019

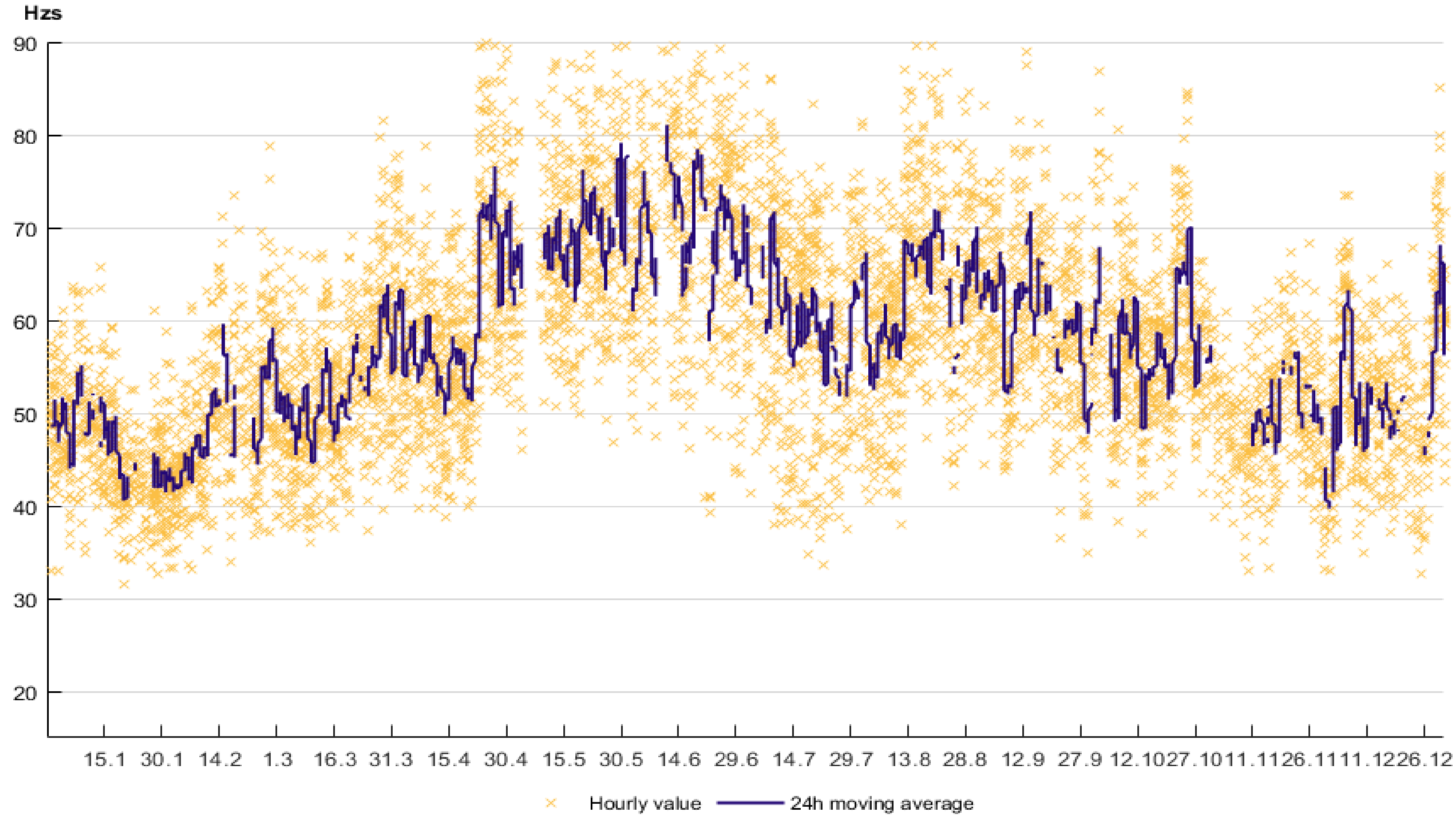


Figure 3.61. Amount of oscillation in 2014-2016

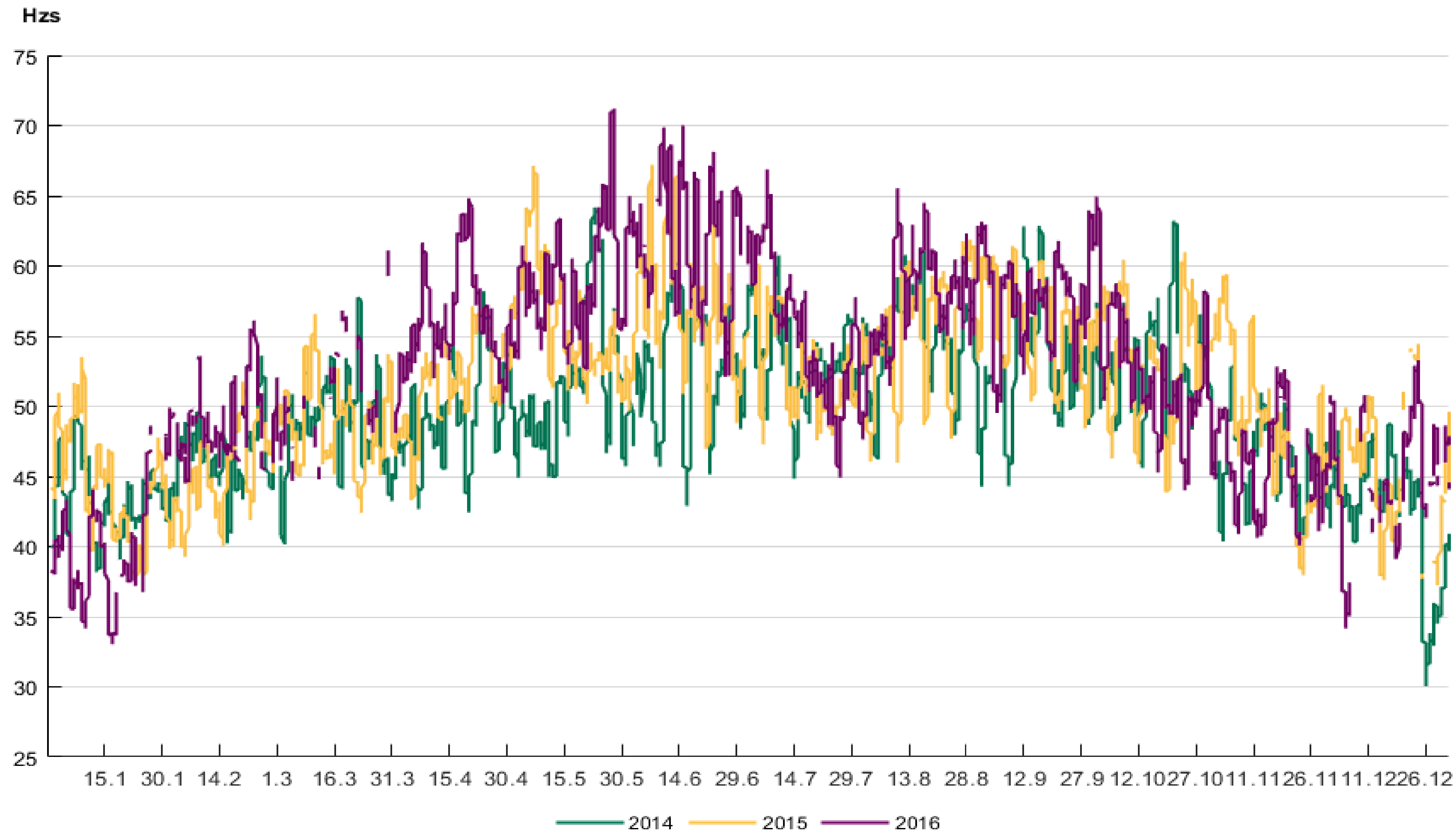
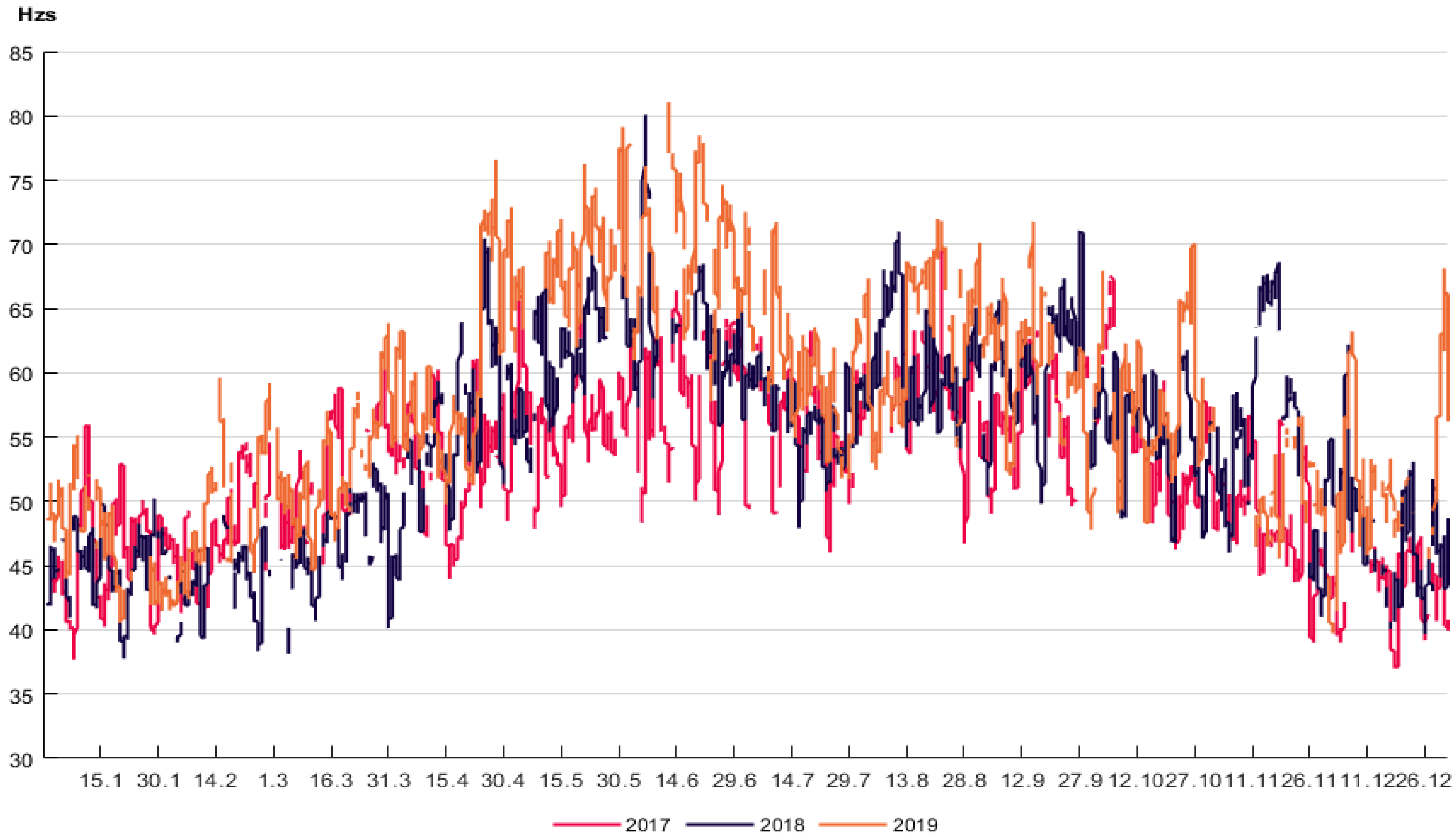


Figure 3.62. Amount of oscillation in 2017-2019



Mean value and standard deviation of the oscillation for each month from 2014 to 2019 are shown in Table 3.24 and 3.25. Figure 3.63 represents the same information in a visual form. The frequency has oscillated the most between May and September. Frequency oscillated significantly more in 2019 when compared to the previous years. The last two years have been among the worst years in terms of oscillation.

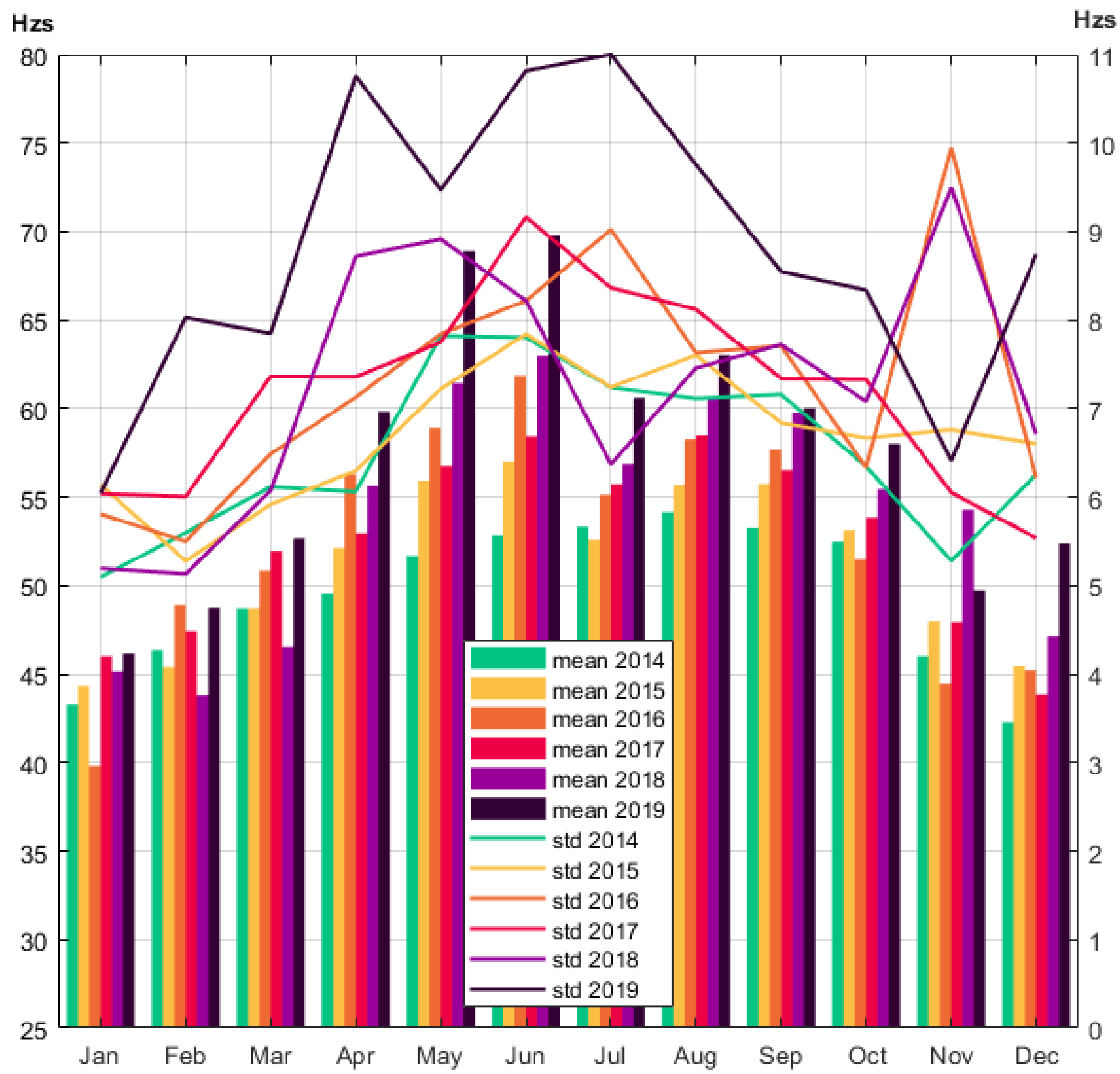
***Table 3.24**. Mean values and standard deviations for oscillation in years 2014-2016*

	Mean value (Hzs)			**Standard deviation (Hzs)**		
Month	**2014**	**2015**	**2016**	**2014**	**2015**	**2016**
January	43.3	44.3	39.8	5.1	6.1	5.8
February	46.4	45.4	48.9	5.6	5.3	5.5
March	48.7	48.7	50.8	6.1	5.9	6.5
April	49.5	52.1	56.3	6.1	6.3	7.1
May	51.7	55.9	58.9	7.8	7.2	7.8
June	52.8	57.0	61.9	7.8	7.8	8.2
July	53.3	52.6	55.1	7.2	7.2	9.0
August	54.2	55.7	58.3	7.1	7.6	7.6
September	53.3	55.8	57.7	7.2	6.8	7.7
October	52.5	53.1	51.5	6.3	6.7	6.3
November	46.0	48.0	44.5	5.3	6.8	9.9
December	42.3	45.4	45.2	6.3	6.6	6.2
Entire year	**49.5**	**51.2**	**52.4**	**6.5**	**6.7**	**7.3**

Table 3.25. Mean values and standard deviations for oscillation in years 2017-2019

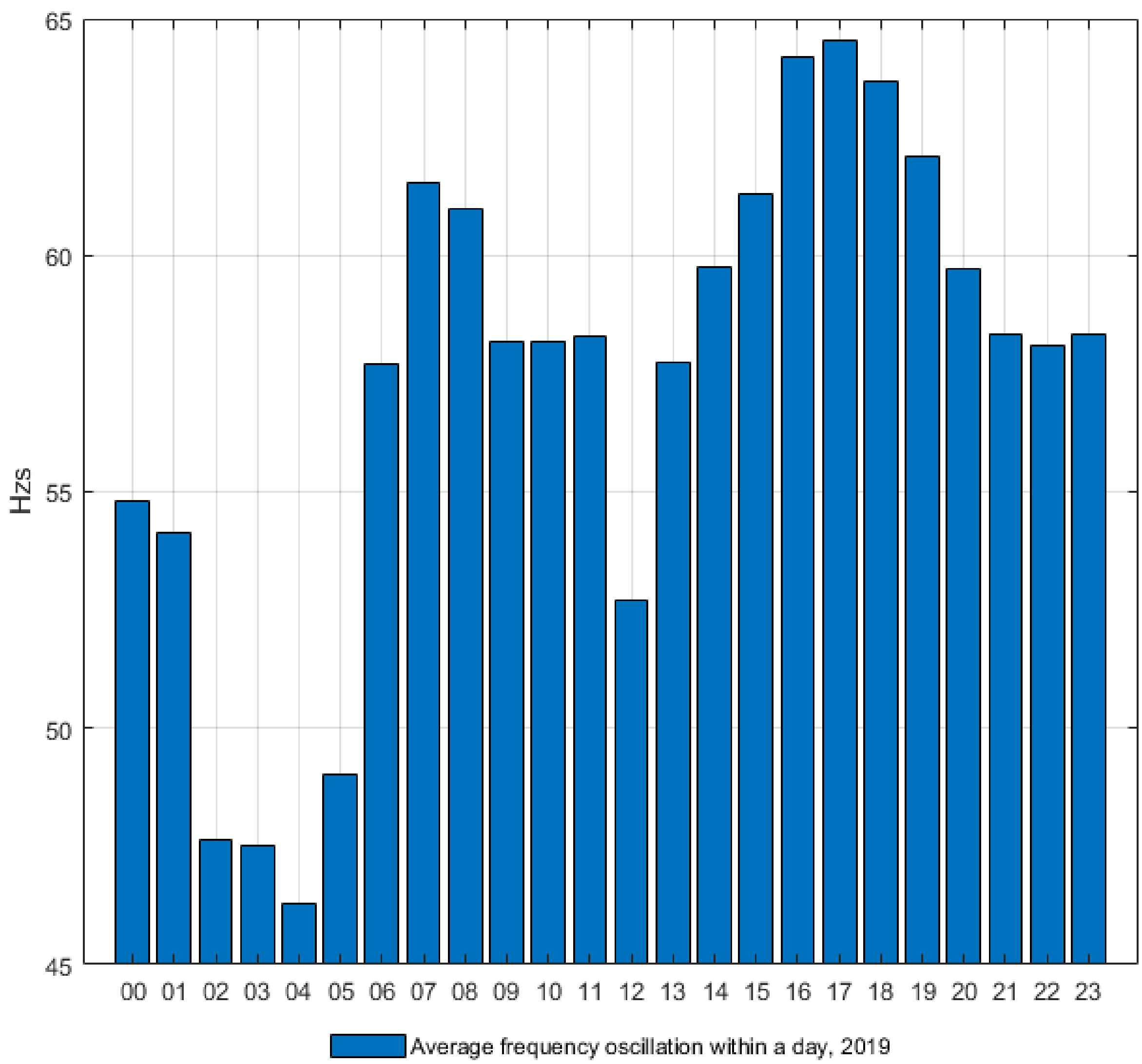
	Mean value (Hzs)			**Standard deviation (Hzs)**		
Month	**2017**	**2018**	**2019**	**2017**	**2018**	**2019**
January	46.0	45.1	46.2	6.0	5.2	6.0
February	47.4	43.8	48.7	6.0	5.1	8.0
March	52.0	46.5	52.7	7.4	6.1	7.8
April	52.9	55.6	59.8	7.4	8.7	10.8
May	56.8	61.4	68.9	7.7	8.9	9.5
June	58.4	63.0	69.8	9.2	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**

***Figure 3.63**. Mean values (left y-axis) and standard deviations (right y-axis) for oscillation in years 2014-2019*



Average oscillation within a day divided into 24 hours can be seen in fig 3.64. Peaks in the oscillation occur during hours 0, 7, and 17. The amount of oscillation in 2019 is clearly much greater compared to previous years.

Figure 3.64. Average frequency oscillation within a day in 2019

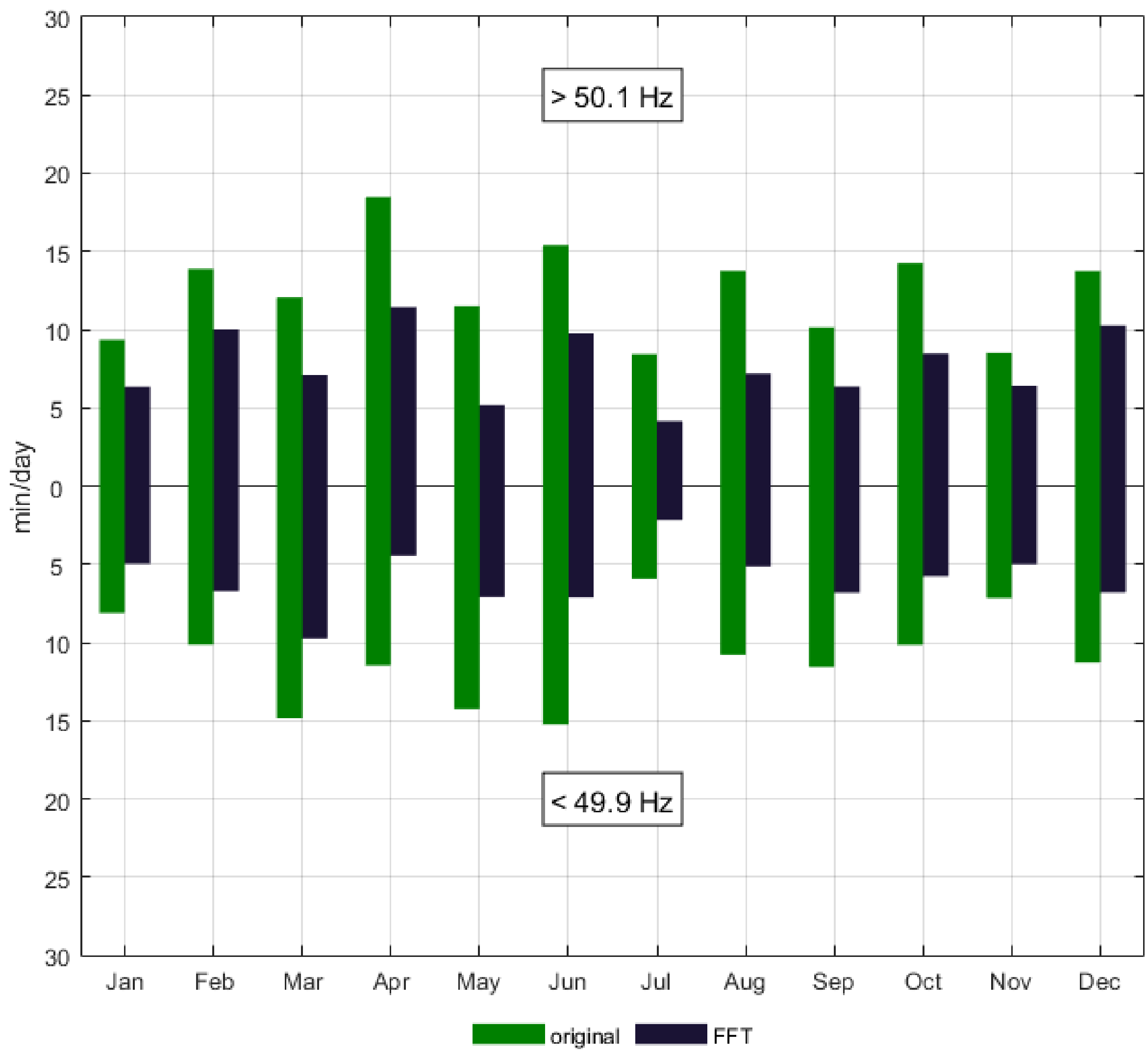


3.8.3 Influence of oscillation on frequency variations

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

Figure 3.65 shows the average minutes per day outside the standard frequency range in 2019 without filtering and after applying FFT-filtering. Figure 3.65 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 3.65**. Average time per day outside the standard frequency range in 2019*



In Figure 3.66, 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 under frequencies in April and July the reduction of time otside the standard frequency range is more than 60 % and for over frequencies in May and July more than 50 %.

***Figure 3.66**. Reduction in time per month outside the standard frequency range after filtering in 2019*

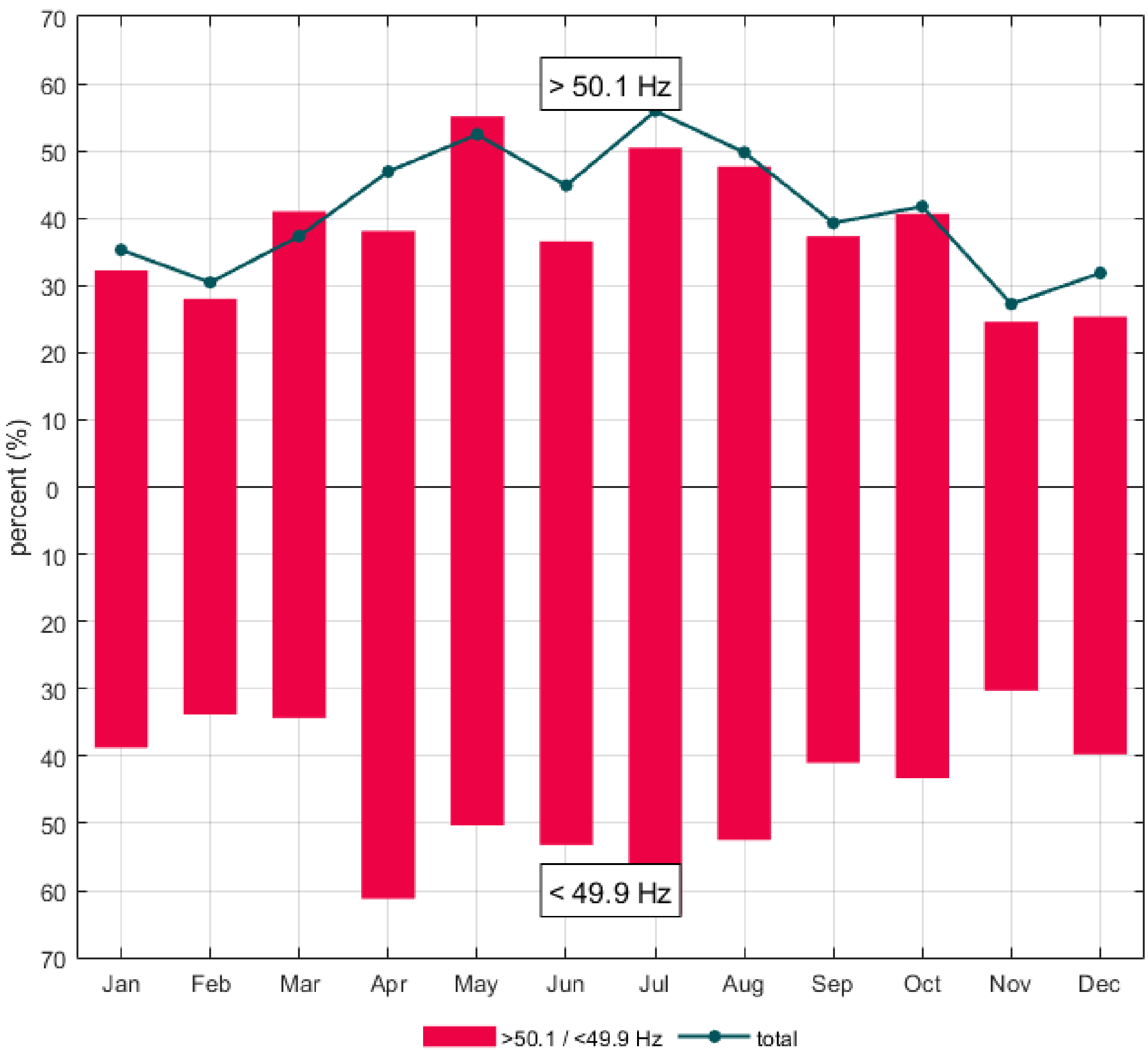
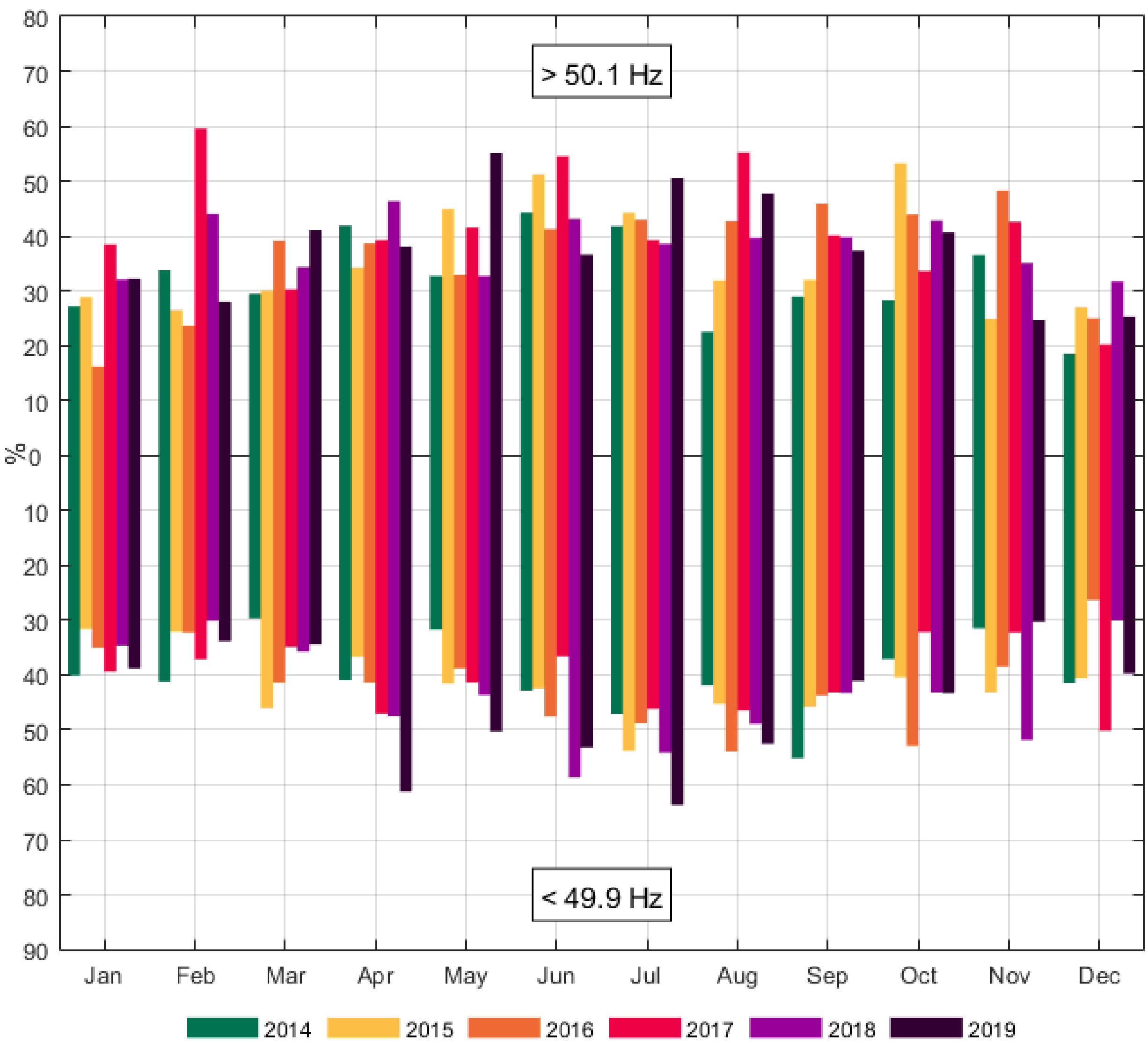


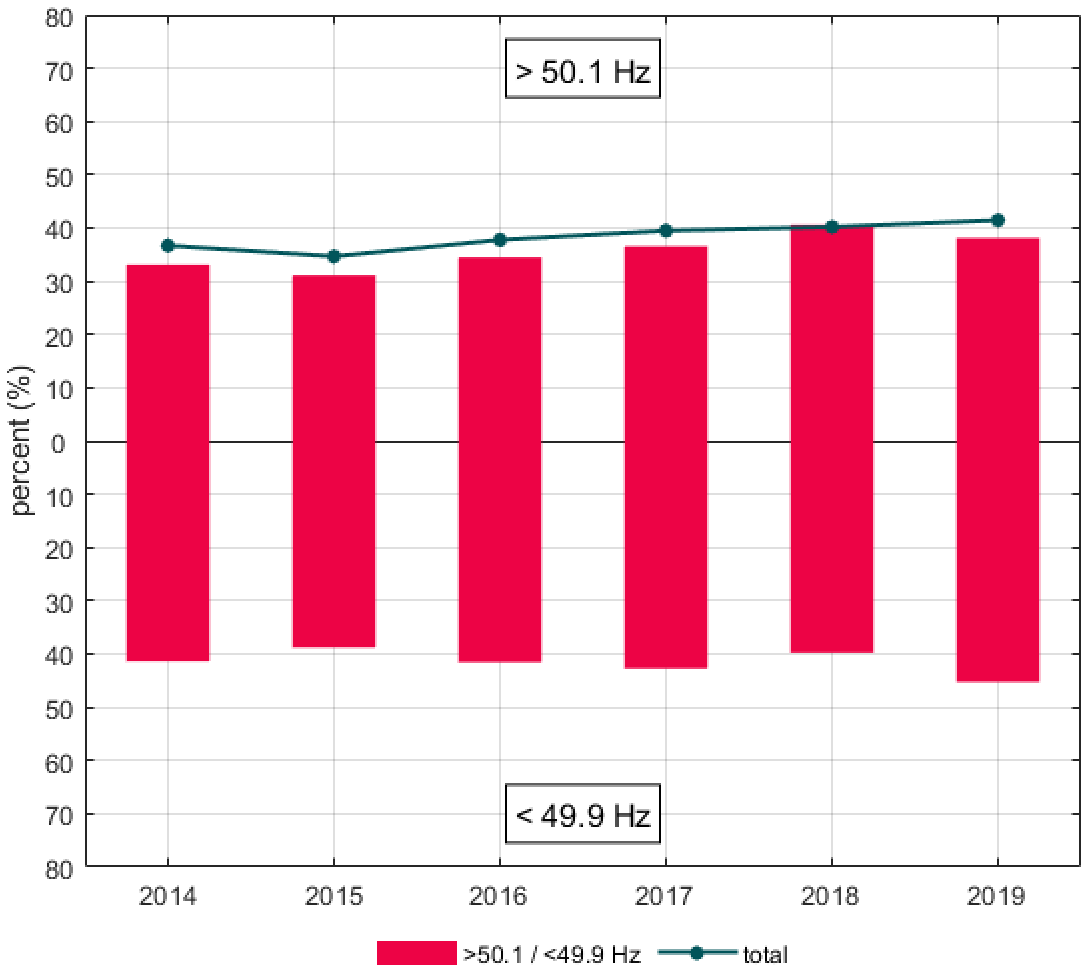
Figure 3.67 represents the reduction in time outside the standard frequency range in percentages month by month for years 2014 to 2019.

***Figure 3.67**. Reduction in time per month outside the standard frequency range after filtering in years 2014-2019*



In addition to the monthly values presented in the previous figure, results for the entire year in 2014-2019 are shown below in Figure 3.68. Filtering the oscillation reduces duration of frequency deviations around 35-42 %. Slight yearly growth in reduction can bee seen from 2015 onwards. The reduction is about 10% more for under frequency deviations.

Figure 3.68. Reduction in time outside the standard frequency range after filtering for years 2014-2019



3.9 Quarters outside FRCE target level 1 and level 2

3.9.1 FRCE Ranges

The FRCE Ranges have been calculated according to the SO GL Article 128, which is presented below.

> *System Operation Guideline, Article 128:*
>
> "3. All TSOs of the CE and Nordic synchronous areas shall endeavour to comply with the following FRCE target parameters for each LFC block of the synchronous area:
>
> (a) the number of time intervals per year outside the Level 1 FRCE range within a time interval equal to the time to restore frequency shall be less than 30 % of the time intervals of the year; and
>
> (b) the number of time intervals per year outside the Level 2 FRCE range within a time interval equal to the time to restore frequency shall be less than 5 % of the time intervals of the year."

FRCE Ranges were calculated by calculating mean values of 15-minute moving averages. This method was used as it is thought to result in descriptive results. Time intervals with corrupted measurements were disregarded. The frequency data that was used in the calculation has a time interval of 100 ms between two consecutive samples.

Table 3.26 and 3.27 show the FRCE Ranges for years 2014-2019. The same results are presented in a graphical form in Figure 3.69.

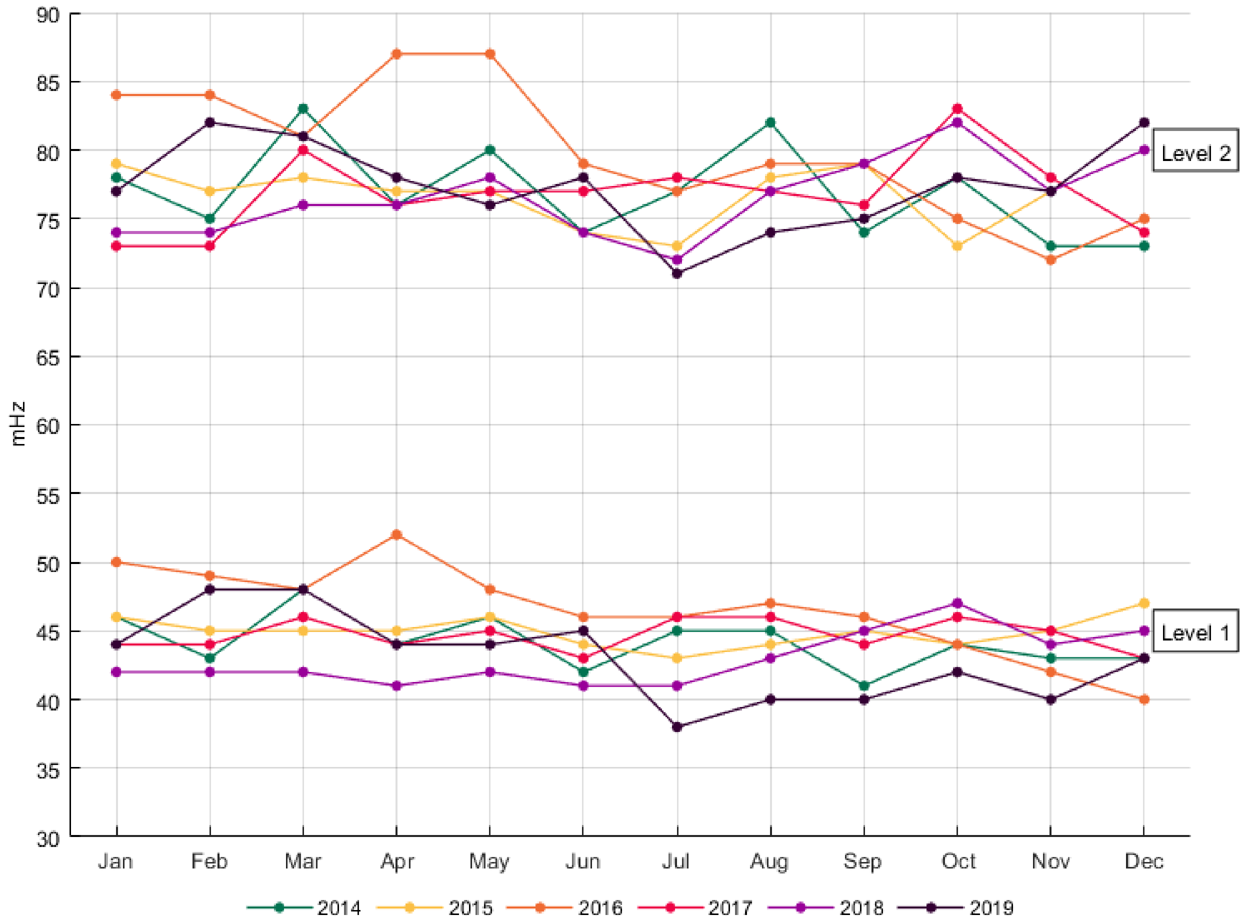
Table 3.26. FRCE Ranges for NE, calculated with 15 min moving averages, years 2014-2016

	2014		**2015**		**2016**	
Month	**Level 1 (mHz)**	**Level 2 (mHz)**	**Level 1 (mHz)**	**Level 2 (mHz)**	**Level 1 (mHz)**	**Level 2 (mHz)**
January	±46	±78	±46	±79	±50	±84
February	±43	±75	±45	±77	±49	±84
March	±48	±83	±45	±78	±48	±81
April	±44	±76	±45	±77	±52	±87
May	±46	±80	±46	±77	±48	±87
June	±42	±74	±44	±74	±46	±79
July	±45	±77	±43	±73	±46	±77
August	±45	±82	±44	±78	±47	±79
September	±41	±74	±45	±79	±46	±79
October	±44	±78	±44	±73	±44	±75
November	±43	±73	±45	±77	±42	±72
December	±43	±73	±47	±82	±40	±75
Entire year	**±44**	**±77**	**±45**	**±77**	**±47**	**±80**

Table 3.27. FRCE Ranges for NE, calculated with 15 min moving averages, years 2017-2019

	2017		**2018**		**2019**	
Month	**Level 1 (mHz)**	**Level 2 (mHz)**	**Level 1 (mHz)**	**Level 2 (mHz)**	**Level 1 (mHz)**	**Level 2 (mHz)**
January	±44	±73	±42	±74	±44	±77
February	±44	±73	±42	±74	±48	±82
March	±46	±80	±42	±76	±48	±81
April	±44	±76	±41	±76	±44	±78
May	±45	±77	±42	±78	±44	±76
June	±43	±77	±41	±74	±45	±78
July	±46	±78	±41	±72	±38	±71
August	±46	±77	±43	±77	±40	±74
September	±44	±76	±45	±79	±40	±75
October	±46	±83	±47	±82	±42	±78
November	±45	±78	±44	±77	±40	±77
December	±43	±74	±45	±80	±43	±82
Entire year	**±45**	**±77**	**±43**	**±77**	**±43**	**±77**

***Figure 3.69**. FRCE Ranges for years 2014-2019 calculated with 15 min moving averages*



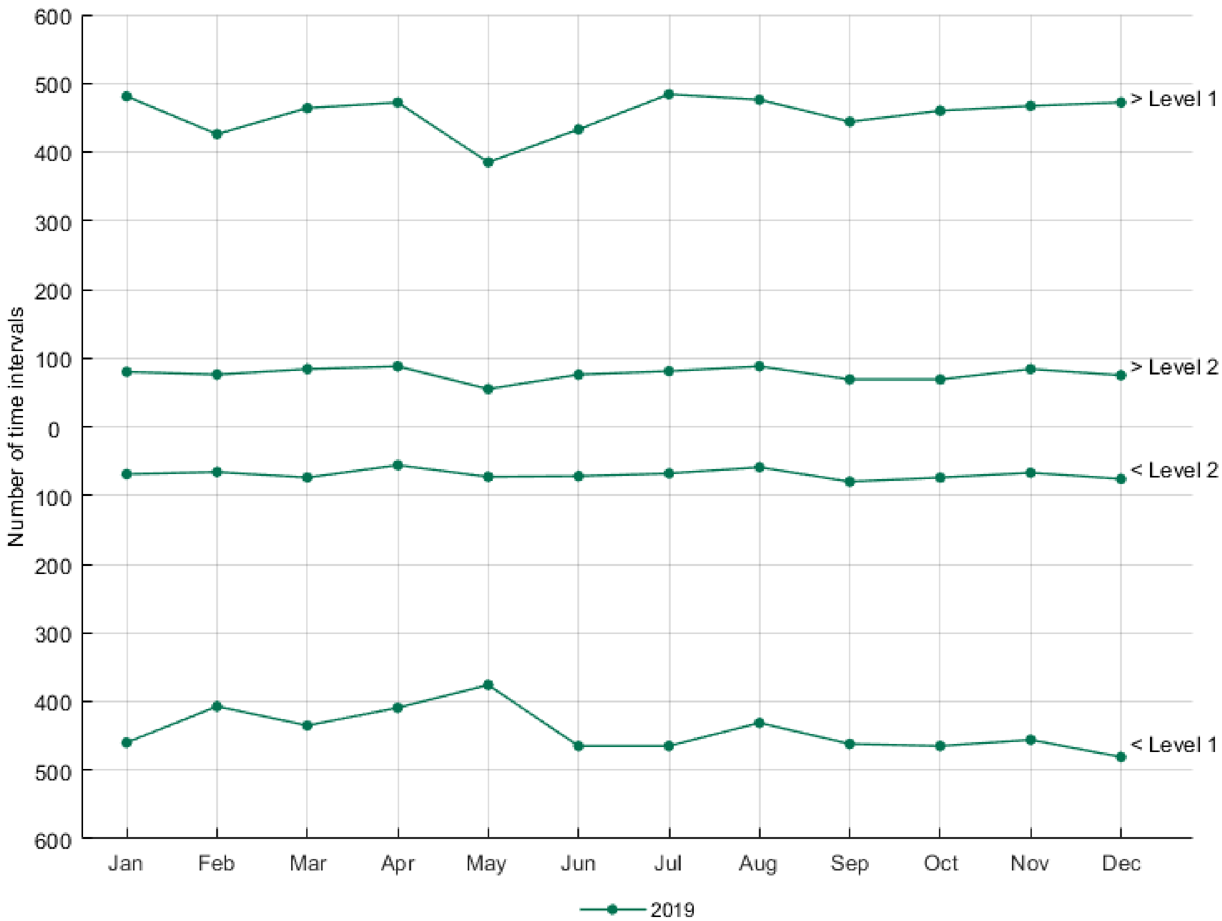
3.9.2 Number of time intervals outside Level 1 and Level 2 FRCE Range

Table 3.28 shows the number of 15 minute time intervals outside Level 1 and Level 2 FRCE Ranges in year 2019. This evaluation criteria is defined in Article 131(b) i(4 and 5). Because the ranges were calculated by sliding the 15 minute interval through the whole year the same principle was used here also. To keep the amount of 15 minute time intervals the same as if they were searched categorically from the beginning of the year (as SO GL might suggest), the already found crossing and the next 15 minutes from it were removed from the next calculations. Figure 3.70 gives a visual representation of the results in Table 3.28.

***Table 3.28**. The number of 15-minute time intervals over positive and under negative Level 1 and Level 2 FRCE Ranges month by month in 2019*

	2019			
Month	**> Level 1 (+)**	**< Level 1 (-)**	**> Level 2 (+)**	**< Level 2 (-)**
January	481	460	80	69
February	426	407	76	66
March	464	435	84	74
April	472	409	88	56
May	385	376	55	73
June	433	465	76	72
July	484	465	81	68
August	476	431	88	59
September	444	462	69	80
October	460	465	69	74
November	467	456	84	67
December	472	481	75	76
Entire year	**5464**	**5312**	**925**	**834**

***Figure 3.70**. The number of time intervals over positive and under negative FRCE Level 1 and Level 2 Ranges for year 2019*



3.10 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 2019. Of the total samples in a period, the 1st, 5th, 10th, 50th, 90th, 95th and 99th percentile are determined. Figure 3.71 shows the definition of deterministic frequency deviation. The resolution of the frequency data was 1 second.

***Figure 3.71**. Definition of deterministic frequency deviation [7]*

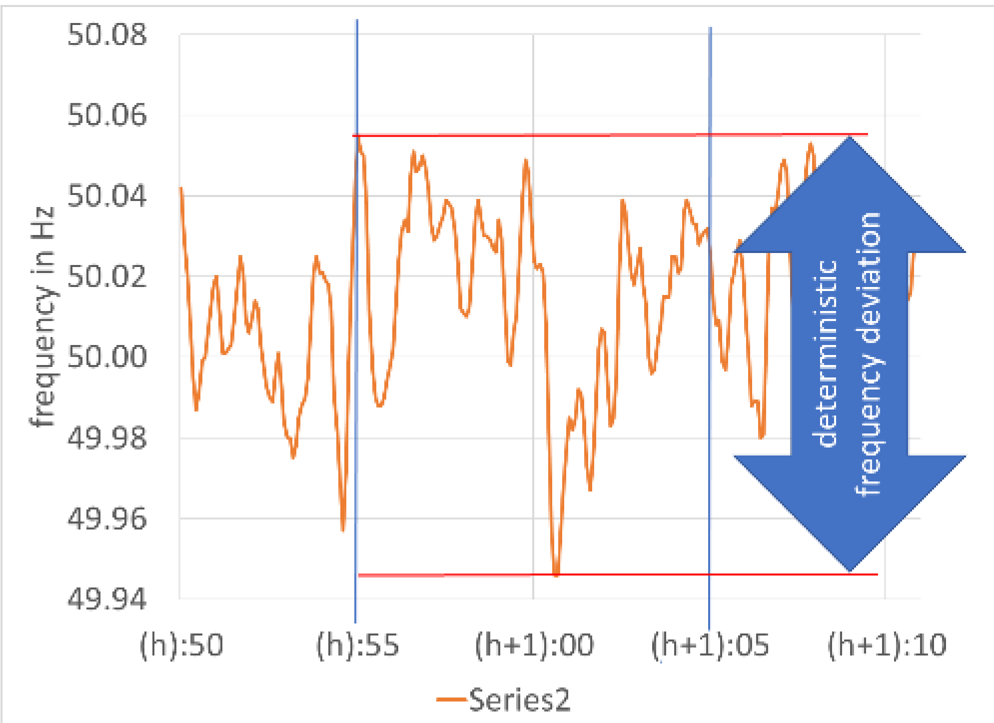


Figure 3.72 represents the deterministic frequency deviation per month in 2019. The 50th percentile stays below zero for the entire year, which indicates that the highest frequency took place before the lowest in more than half of the hour shifts.

***Figure 3.72**. The 1st, 5th, 10th, 50th, 90th, 95th, and 99th percentile of deterministic frequency deviation for every month in 2019*

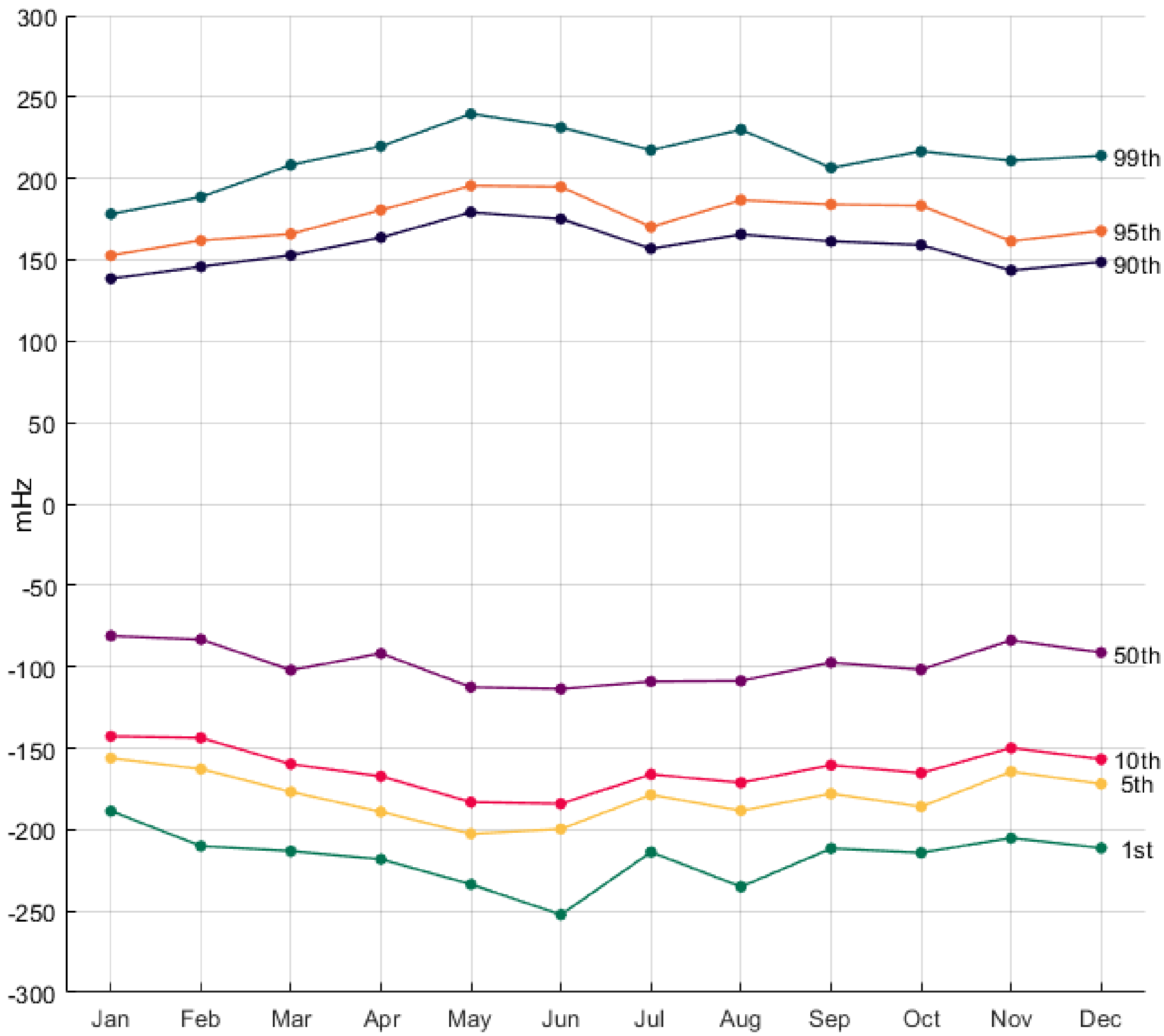
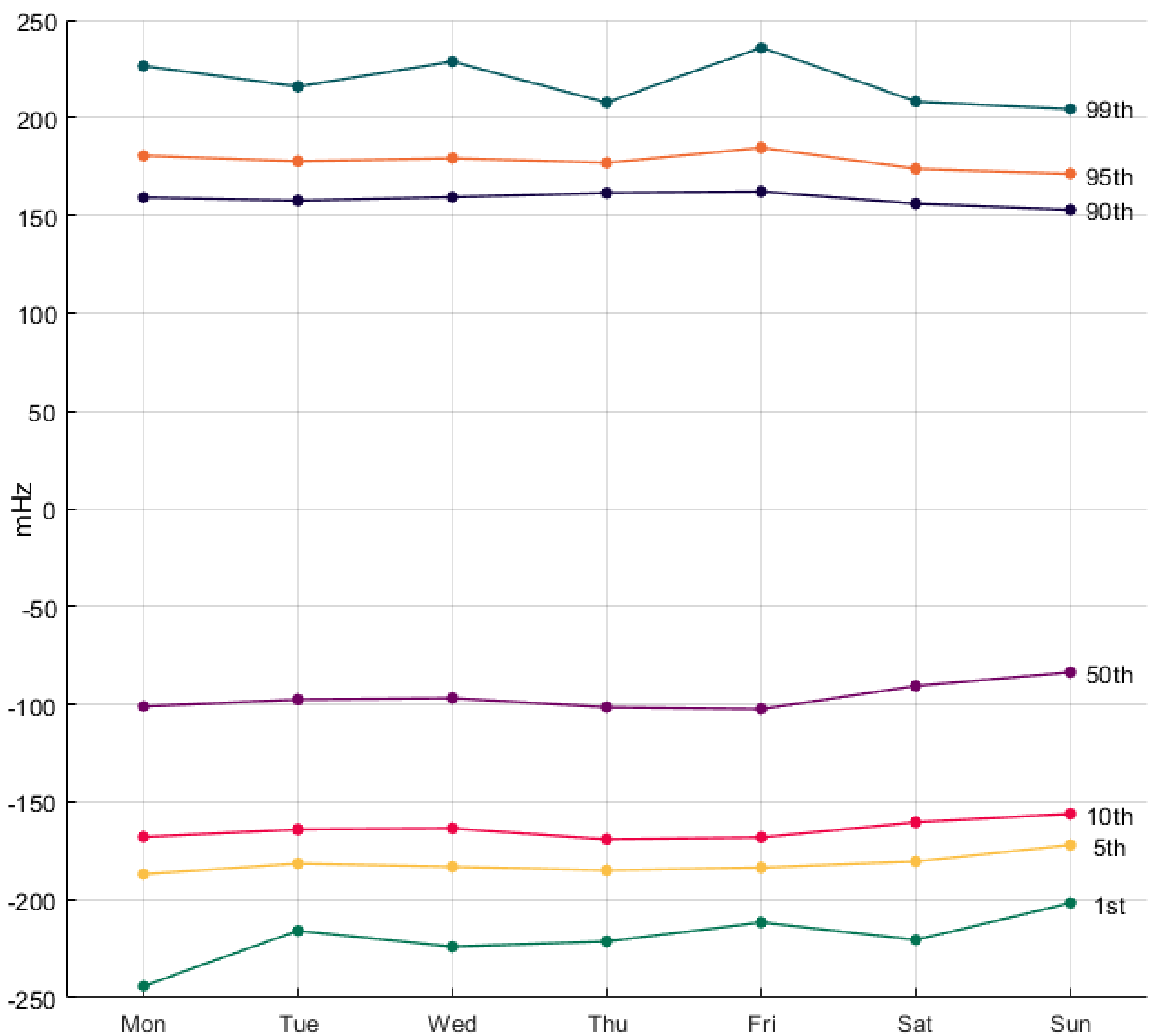


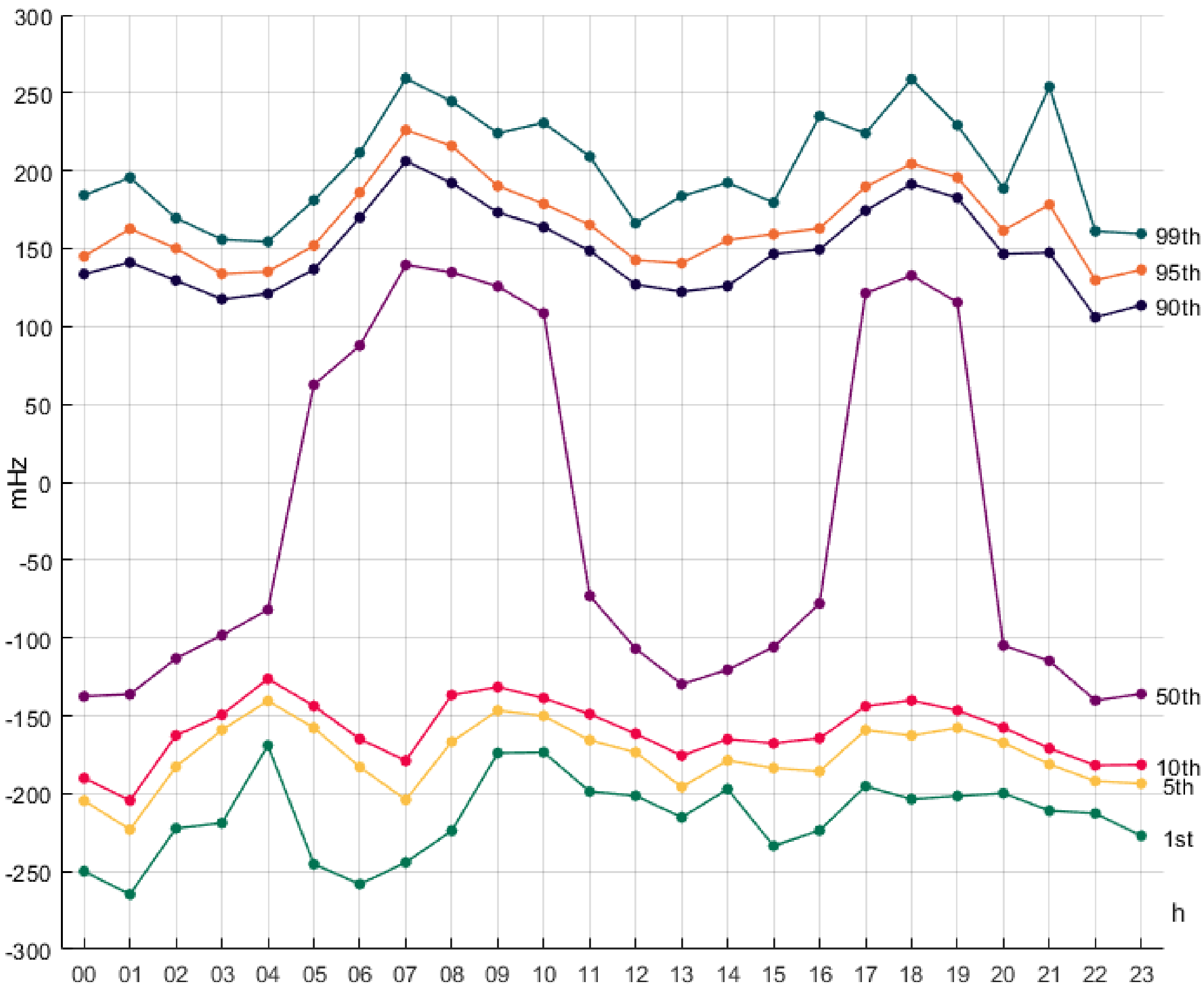
Figure 3.73 shows the percentiles around the hour shift for every day of the week in 2019. The 5th, 10th and 50th percentile are slightly higher during the weekends. The 99th percentile is clearly higher during Fridays.

***Figure 3.73**. The 1st, 5th, 10th, 50th, 90th, 95th, and 99th percentile of deterministic frequency deviation for every day of the week in 2019*



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 3.74. During morning hours from 5 to 10 and in the evening from 17 to 19, the value for the 50th percentile was positive, which means the lowest frequency took place before the highest in more than half of the hour shifts during those hours.

***Figure 3.74**. The 1st, 5th, 10th, 50th, 90th, 95th, and 99th percentile of deterministic frequency deviation for every hour of the day in 2019*



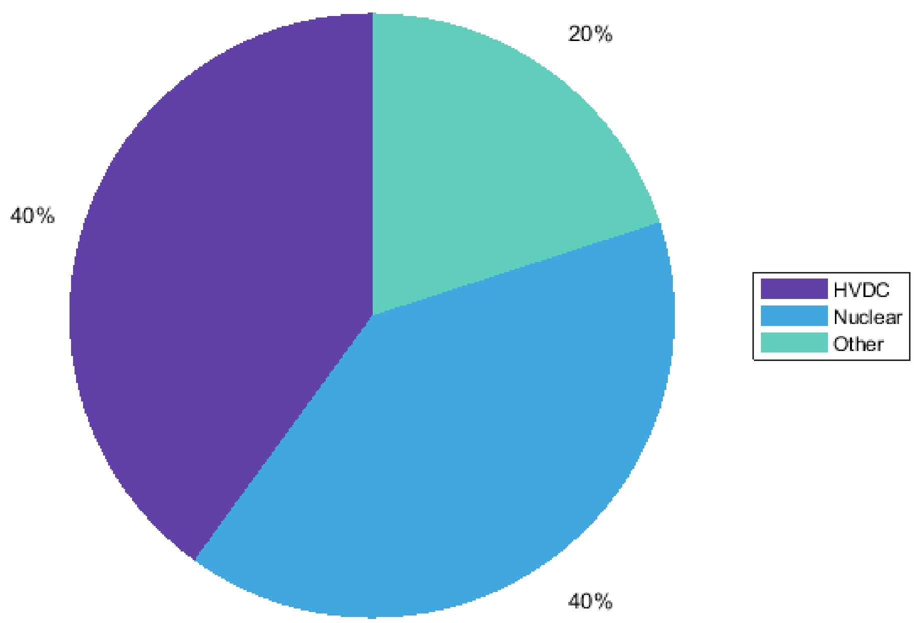
Chapter 4. Frequency disturbances exceeding 300 mHz frequency deviation

This chapter offers information of the major frequency disturbances in the Nordic synchronous system in the year 2019. Over 300 mHz frequency deviations are included.

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

There were five over ±300 mHz disturbances in 2019. Two of the disturbances were caused by tripping of HVDC connections, two were caused by failures in nuclear power production and one was caused by other reasons. Figure 4.1. represents the share of factors causing over 300 mHz deviations. In 2019 there were two over ±300 mHz disturbances less compared to 2018. In 2018 the most of the disturbances were caused by grid faults in nuclear connections or by failures in nuclear power production.

***Figure 4.1**. Shares of factors causing over 300 mHz disturbances in the Nordic synchronous system in 2019*



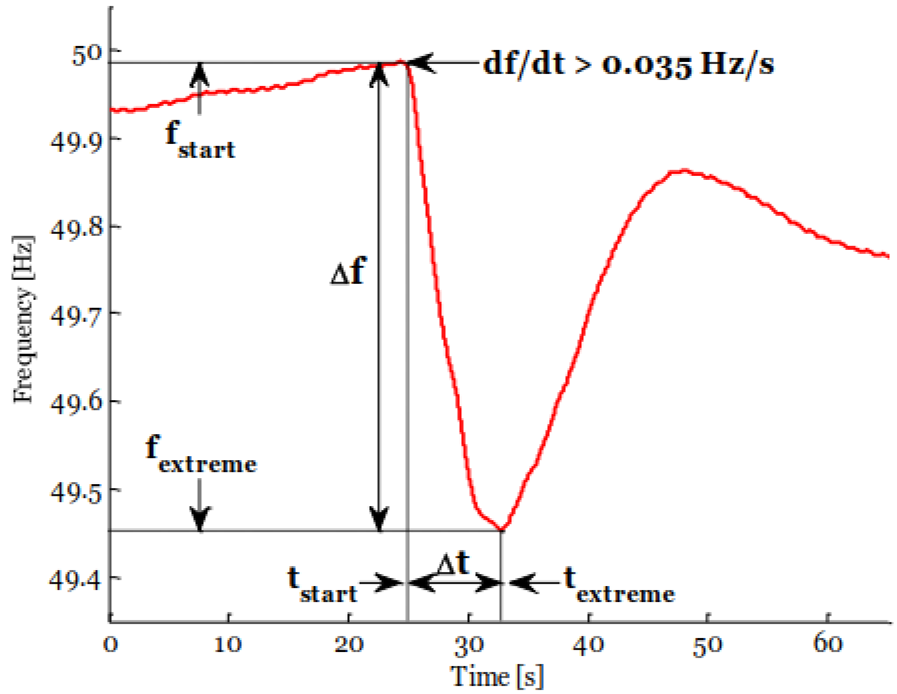
The largest maximum frequency deviation with Δf-value of -0.41 Hz was caused by a tripping nuclear plant on the 4th of March. This also caused the lowest instantaneous frequency value of 49.59 Hz. The highest reported instantaneous frequency value was 50.33 Hz on 4th of June after tripping of an HVDC link.

The following part of the chapter will go into more detail on every disturbance that took place in 2019. 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 [10]



Occasionally included disturbances can have Δf-values below 300 mHz. Δf is defined to be the absolute value between f_{start} and $f_{extreme}$ 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 2019 there were no such cases. [11]

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 2019 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 (E_k) 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. [11]

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 2019*

Event date	Δf (Hz)	ΔP (MW)	Δt (s)	E_k (GWs)	Cause	Page
04-Mar-2019 14:05:17	-0.408	1249	8.6	227	Nuclear	115
04-Jun-2019 13:51:20	0.320	666	8.5	201	HVDC	116
29-Jul-2019 16:00:48	0.337	681	7.7	190	HVDC	117
24-Sep-2019 23:10:04	-0.310	769	8.3	198	Nuclear	118
06-Nov-2019 13:23:43	-0.373	904	8.2	239	Other	119

Figure 4.3. Disturbance 04-Mar-2019 14:05:17

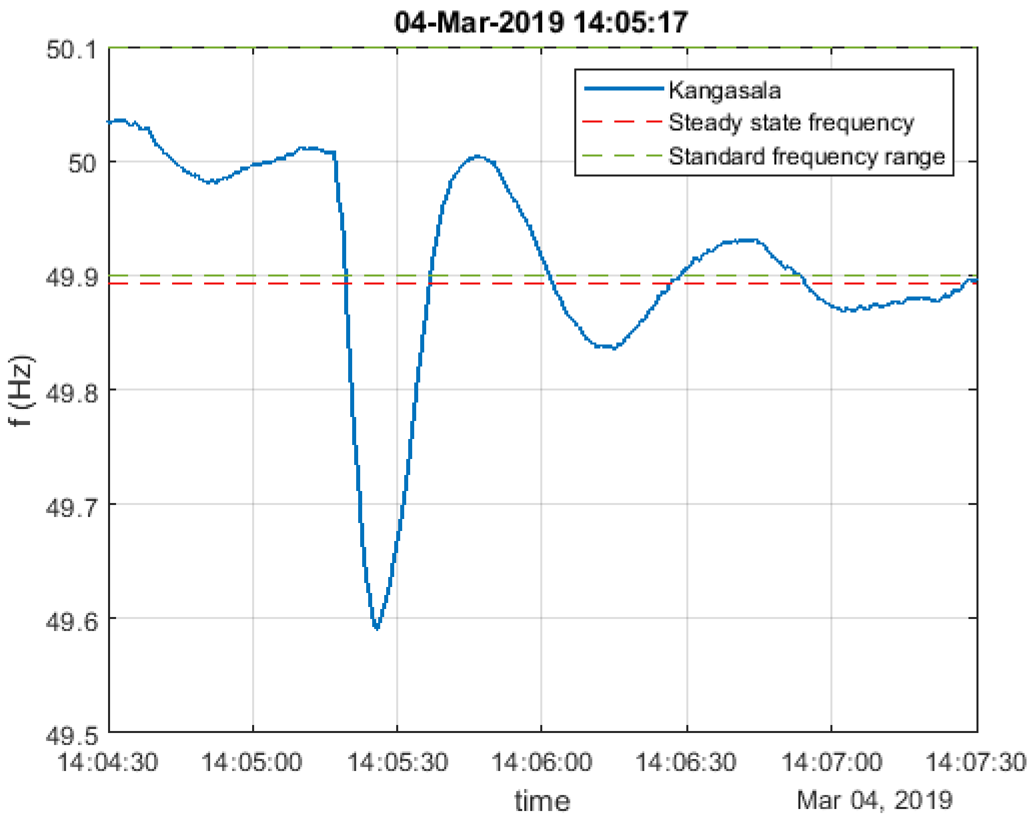


Table 4.2. Disturbance 04-Mar-2019 14:05:17

Date		**04-Mar-2019 14:05:17**	
f_{start}	49.999 Hz	$f_{steady\ state}$	49.893 Hz
$f_{extreme}$	49.591 Hz	$\Delta f_{steady\ state}$	0.106 Hz
Δf	-0.408 Hz	$f_{extreme2}$	50.004 Hz
Δt	8.6 s	$f_{extreme3}$	49.836 Hz
ΔP	1249 MW	damping	40.63 %
E_k	227 GWs	FBF	11767 MW/Hz
cause		Nuclear	

Figure 4.4. Disturbance 04-Jun-2019 13:51:20

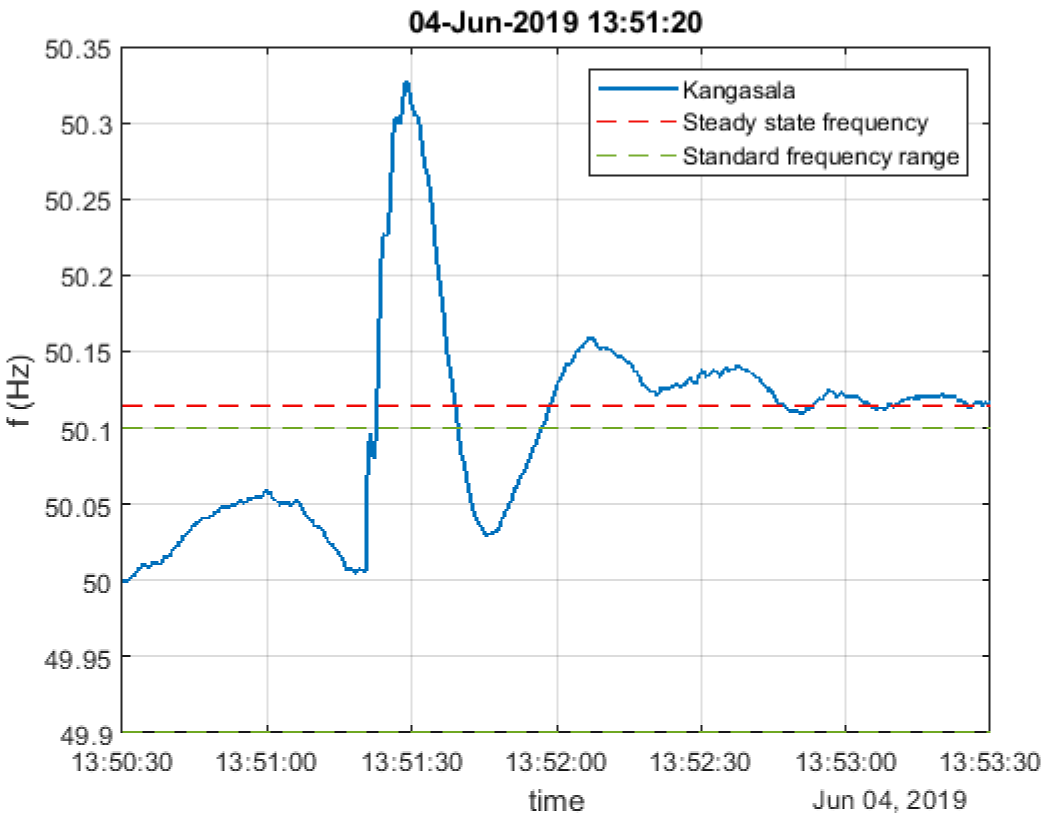


Table 4.3. Disturbance 04-Jun-2019 13:51:20

Date		**04-Jun-2019 13:51:20**	
f_{start}	50.008 Hz	$f_{steady\ state}$	50.114 Hz
$f_{extreme}$	50.328 Hz	$\Delta f_{steady\ state}$	0.107 Hz
Δf	0.320 Hz	$f_{extreme2}$	50.030 Hz
Δt	8.5 s	$f_{extreme3}$	50.159 Hz
ΔP	666 MW	damping	43.20 %
E_k	201 GWs	FBF	6252 MW/Hz
cause		HVDC	

***Figure 4.5**. Disturbance 29-Jul-2019 16:00:48*

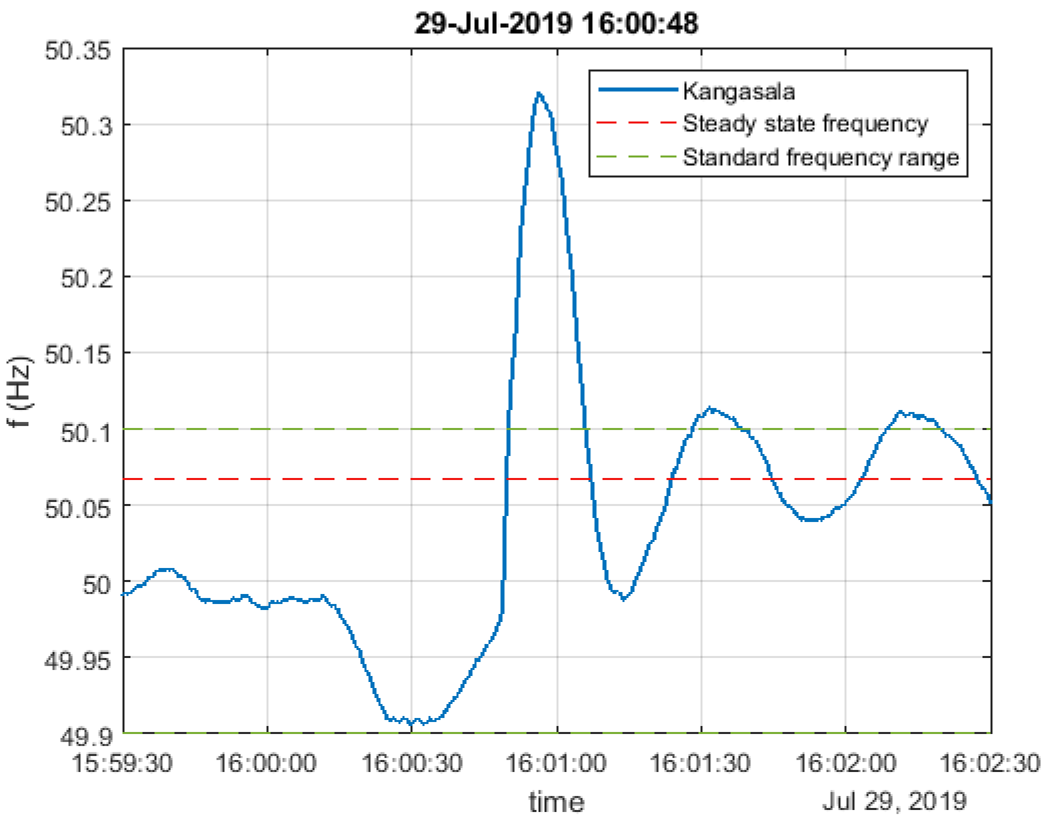


***Table 4.4**. Disturbance 29-Jul-2019 16:00:48*

Date		**29-Jul-2019 16:00:48**	
f_{start}	49.983 Hz	$f_{steady\ state}$	50.067 Hz
$f_{extreme}$	50.320 Hz	$\Delta f_{steady\ state}$	0.084 Hz
Δf	0.337 Hz	$f_{extreme2}$	49.988 Hz
Δt	7.7 s	$f_{extreme3}$	50.114 Hz
ΔP	681 MW	damping	37.90 %
E_k	190 GWs	FBF	8071 MW/Hz
cause		HVDC	

***Figure 4.6**. Disturbance 24-Sep-2019 23:10:04*

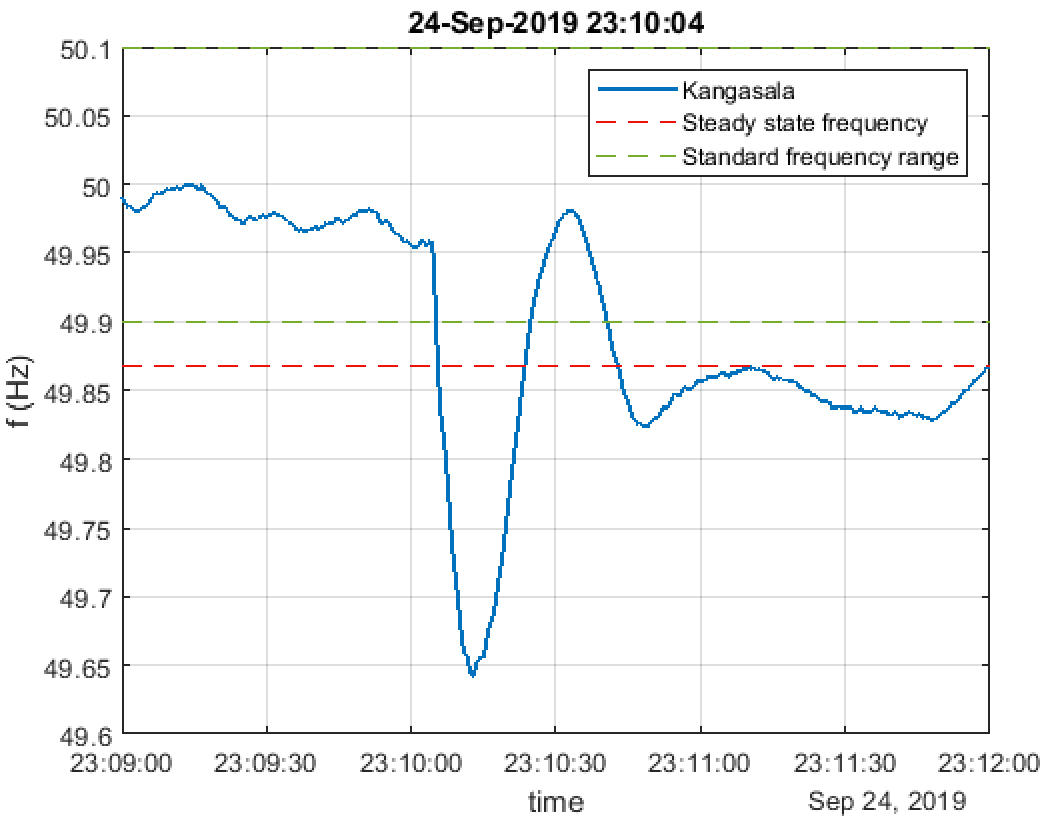


***Table 4.5**. Disturbance 24-Sep-2019 23:10:04*

Date		**24-Sep-2019 23:10:04**	
f_{start}	49.952 Hz	$f_{steady\ state}$	49.868 Hz
$f_{extreme}$	49.642 Hz	$\Delta f_{steady\ state}$	0.084 Hz
Δf	-0.310 Hz	$f_{extreme2}$	49.981 Hz
Δt	8.3 s	$f_{extreme3}$	49.824 Hz
ΔP	769 MW	damping	46.24 %
E_k	198 GWs	FBF	9168 MW/Hz
cause		Nuclear	

***Figure 4.7**. Disturbance 06-Nov-2019 13:23:43*

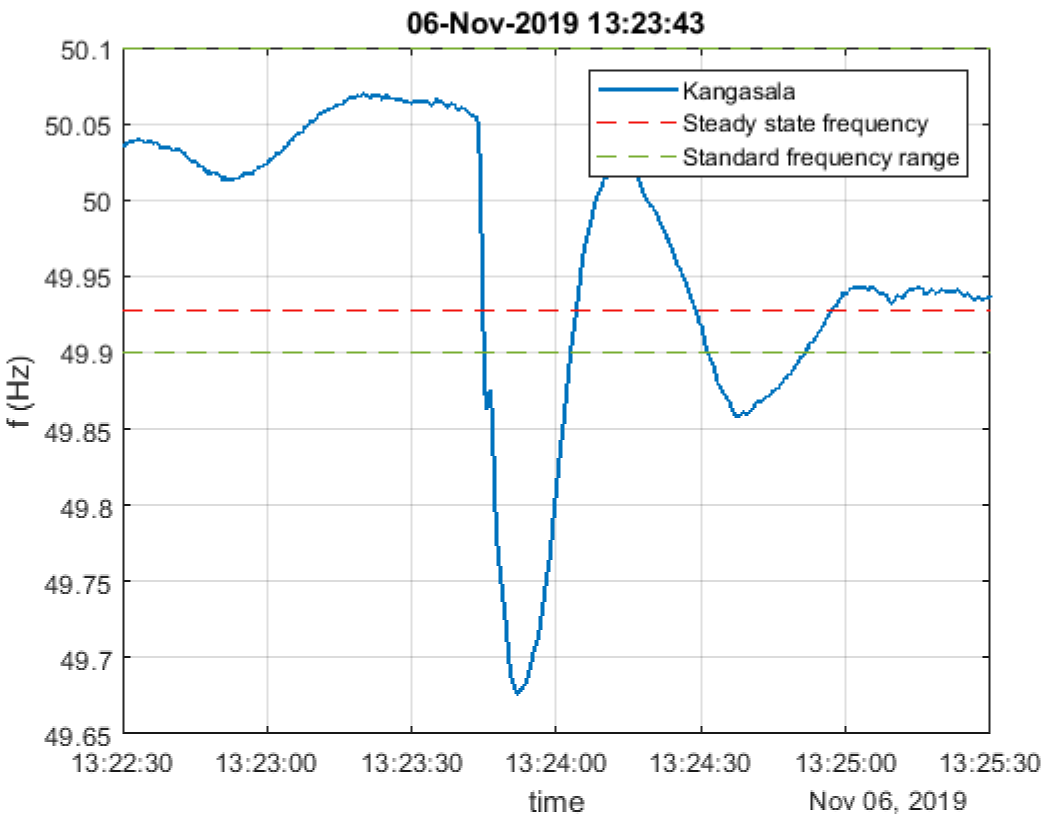


***Table 4.6**. Disturbance 06-Nov-2019 13:23:43*

Date		**06-Nov-2019 13:23:43**	
f_{start}	50.049 Hz	$f_{steady\ state}$	49.927 Hz
$f_{extreme}$	49.676 Hz	$\Delta f_{steady\ state}$	0.122 Hz
Δf	-0.373 Hz	$f_{extreme2}$	50.025 Hz
Δt	8.2 s	$f_{extreme3}$	49.859 Hz
ΔP	904 MW	damping	47.59 %
E_k	239 GWs	FBF	7409 MW/Hz
cause		Other	

Chapter 5. Summary

The aim of this report is to analyze frequency quality in the Nordic synchronous system in 2019. Various indices were used to assess frequency quality, and the results were compared to the previous years. The overall quality of the frequency was worse in 2019 than in 2018. By many criteria, the frequency quality was also worse compared to all the previous five years except 2016.

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 increased from 2018. June was the worst month in terms of frequency quality. The frequency quality in December was also worse in 2019 compared to the previous years. More frequency deviations occurred during the weekend in 2019 than in the previous years, especially on Saturday.

In the hourly analysis, there was a clear increase in the number of deviations and time outside the standard frequency range from hours 10 to 18. On the other hand, deviations around midnight decreased in comparison to the previous years. The highest number of threshold crossings occurred in hour 17. 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 2018. 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. Year 2019 was not an exception in this case. On an average day, the largest amount of oscillation occurred in the morning and afternoon hours. Removal of the oscillation by filtering the frequency data clearly reduced frequency deviations. The reduction was around 40 % with the FFT-filtering method. The reduction was generally higher for under frequency deviations.

Time outside 49.8-50.2 Hz decreased from the previous year. The number of larger 200 mHz and 300 mHz frequency deviations also decreased. There were five frequency disturbances exceeding 300 mHz in 2019. Most of the disturbances were caused by tripping HVDC connections or failures in the nuclear power production. The number of frequency deviations exceeding 300 mHz was reduced by two when compared to 2018.

Chapter 6. Sources

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

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

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[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

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