Frequency quality analysis

2018

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 2018. 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 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 2018 is presented in Table 2.1. Availability of data per year for years 2013 to 2018 can be seen in Table 2.2 [2,3,4,5,6]. In 2018 there were valid measurement data for 98.91 % 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 2018

Month	Available data
January	99.90 %
February	99.88 %
March	99.89 %
April	99.89 %
May	88.20 %
June	99.91 %
July	99.89 %
August	99.94 %
September	99.91 %
October	99.78 %
November	99.88 %
December	99.90 %

Table 2.2. The amount of valid measurement data available for years 2013-2018

Year	**Available data**
2013	92.14 %
2014	99.89 %
2015	99.90 %
2016	99.37 %
2017	97.19 %
2018	98.91 %

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 2018. 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, the average has been less than 0.7 mHz from 50 Hz. In 2017 average frequency was better than in 2018 because the maximum average frequency deviation was less than 0,5 mHz from 50 Hz.

Figure 3.1**. **Average frequency for each month in 2018

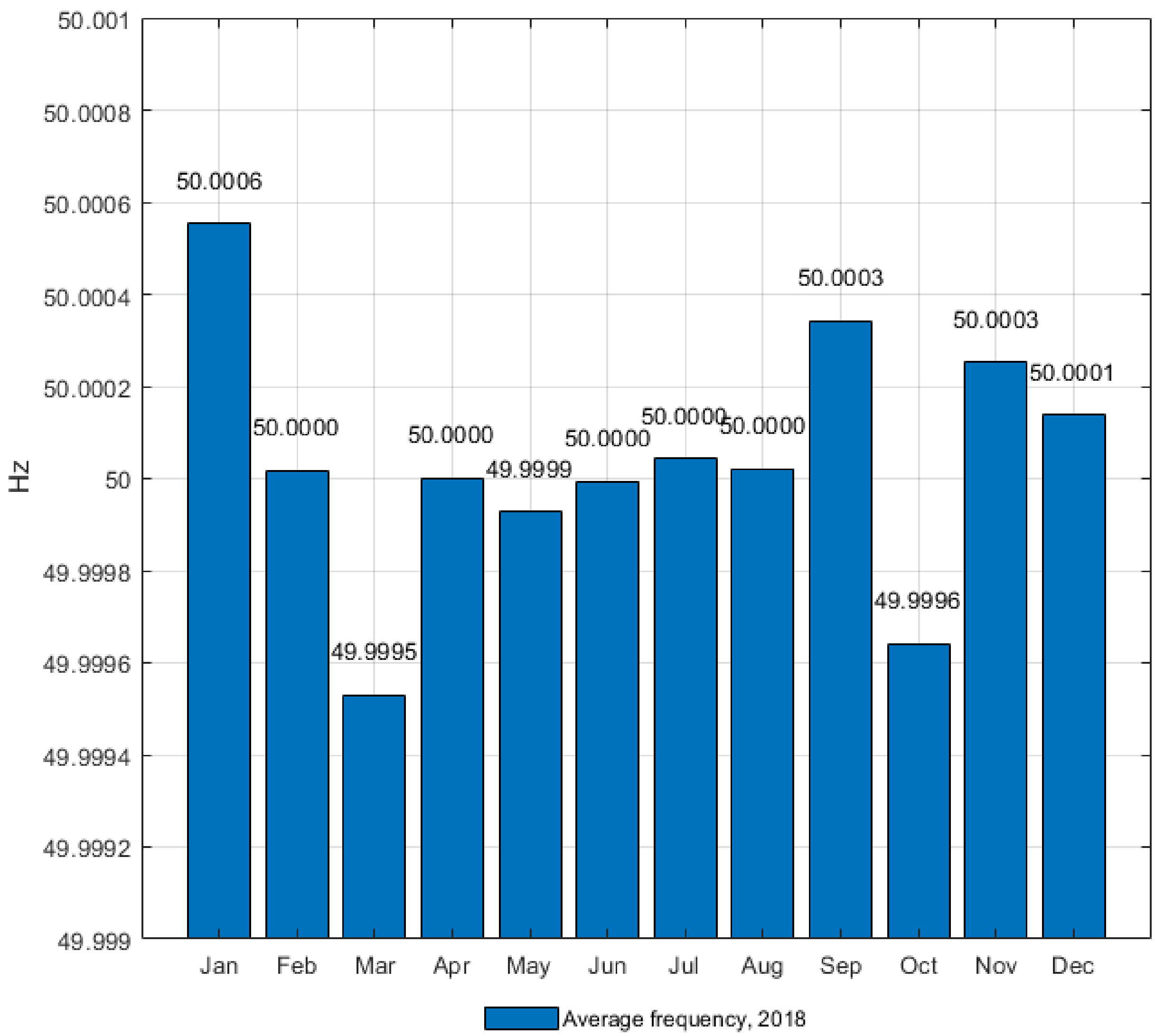


Figure 3.2 represents the average frequencies for every day of the week. On average, the frequency has been lower on the Saturdays and the highest on Mondays.

***Figure 3.2**. Average frequency for each day of the week in 2018*

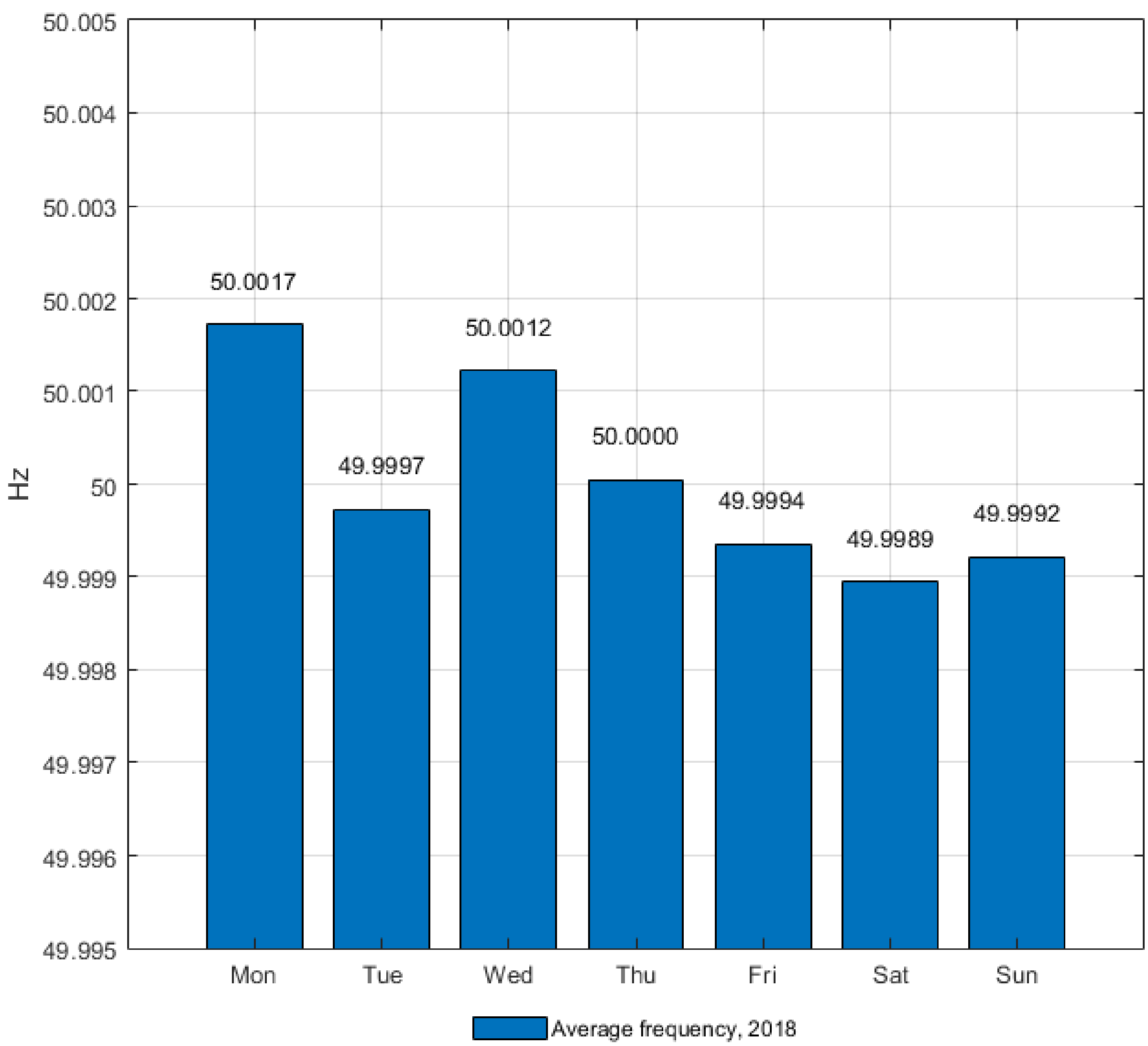


Figure 3.3 shows the average frequencies during each hour of the day. Frequency is generally lower during the night hours from 1 a.m. to 4 a.m. The frequency is at its highest during the evenings and around midnight.

Figure 3.3*. *Average frequency for each hour of the day in 2018

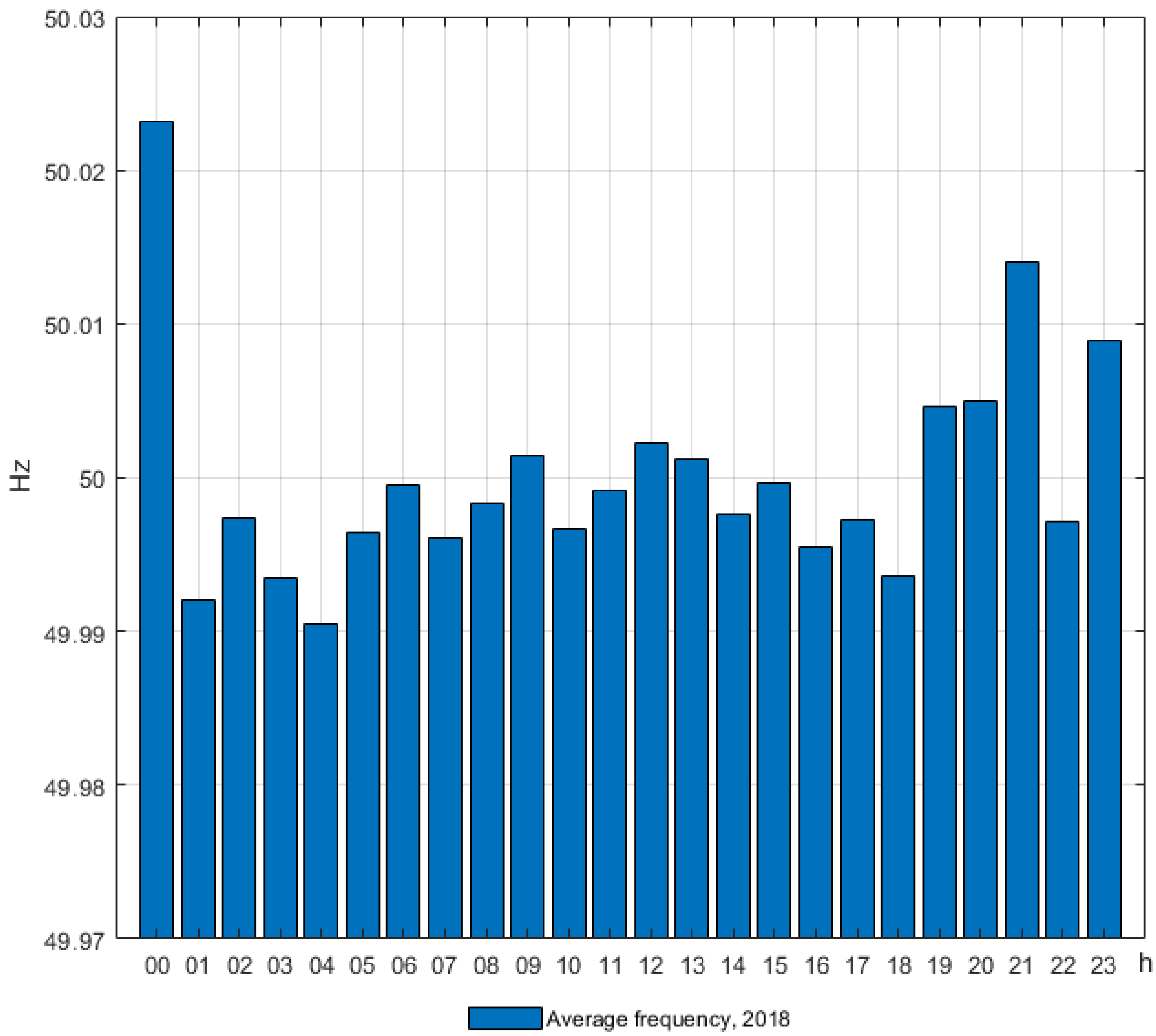
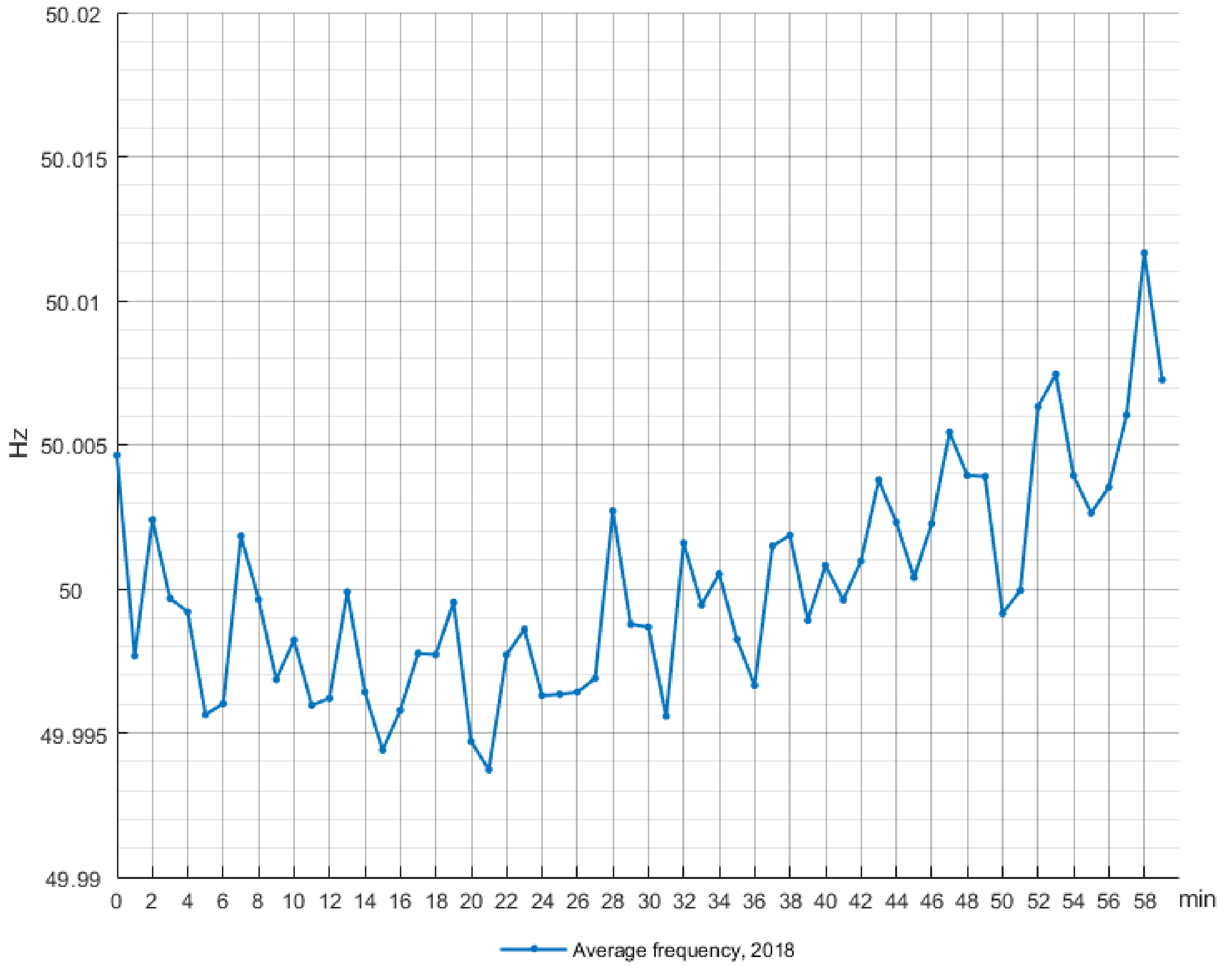


Figure 3.4 shows the average frequency inside the hour. In general the frequency is higher in the latter part of the hour. The difference between consecutive minutes is mostly between 2-4 mHz.

***Figure 3.4**. Average frequency for each minute of the hour in 2018*



3.1.2 **Standard deviation**

This section includes the figures representing the standard deviation of frequency during the year 2018. 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 2018. The lower standard deviation in January, February, March and July indicates that in these months the 1 second values were clustered closer to 50 Hz than during the rest of the year. In May, September and October the standard deviation was slightly higher than during other months.

Figure 3.5*. *Standard deviation of the frequency for every month in 2018

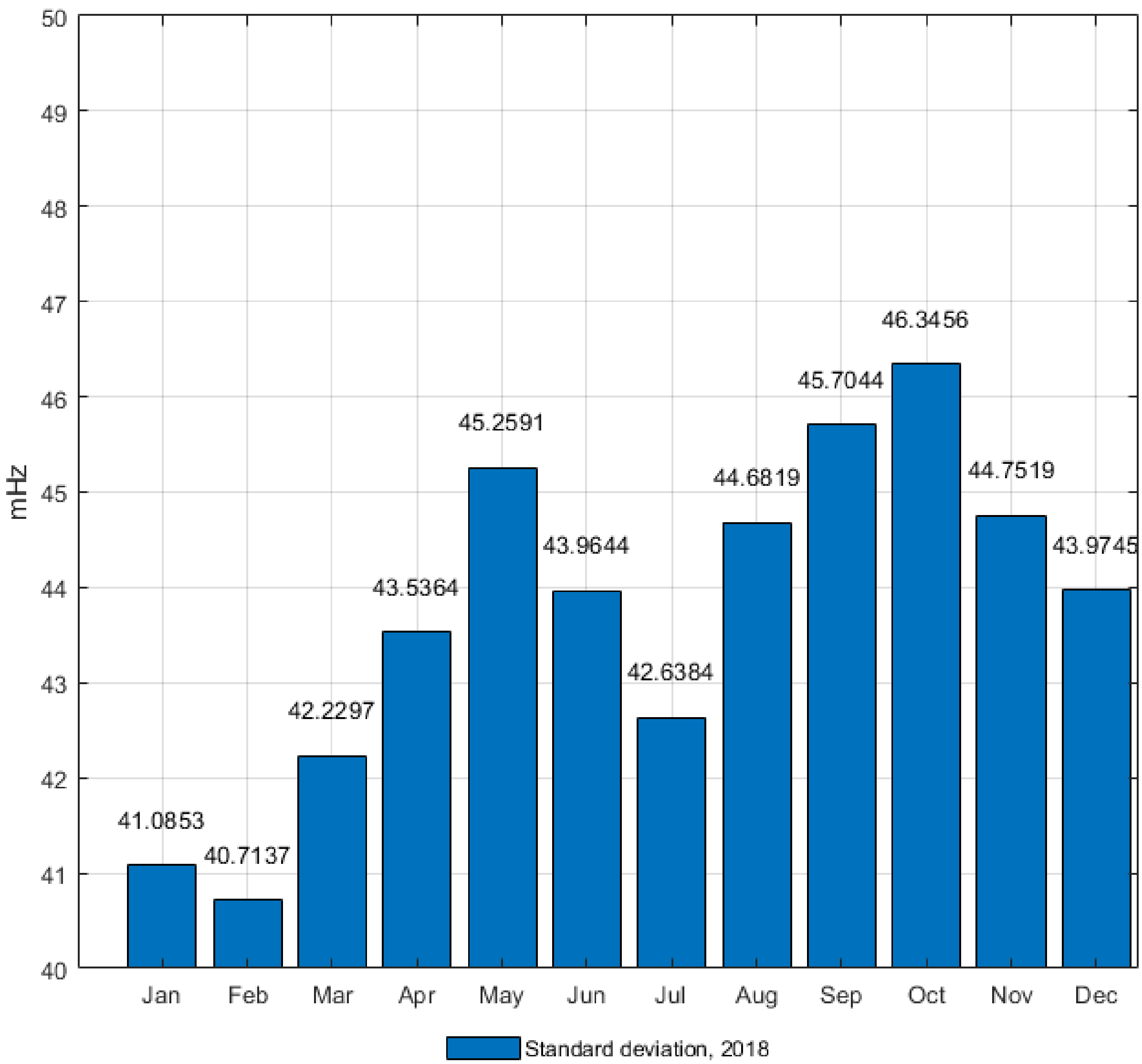


Figure 3.6 represents the standard deviation for every day of the week. Based on standard deviation, the quality of the frequency stays relatively same or gets slightly worst each day from the start of the week to the end except for Wednesdays when the standard deviation is at its highest. It is noteworthy that all the values are within 2 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 2018*

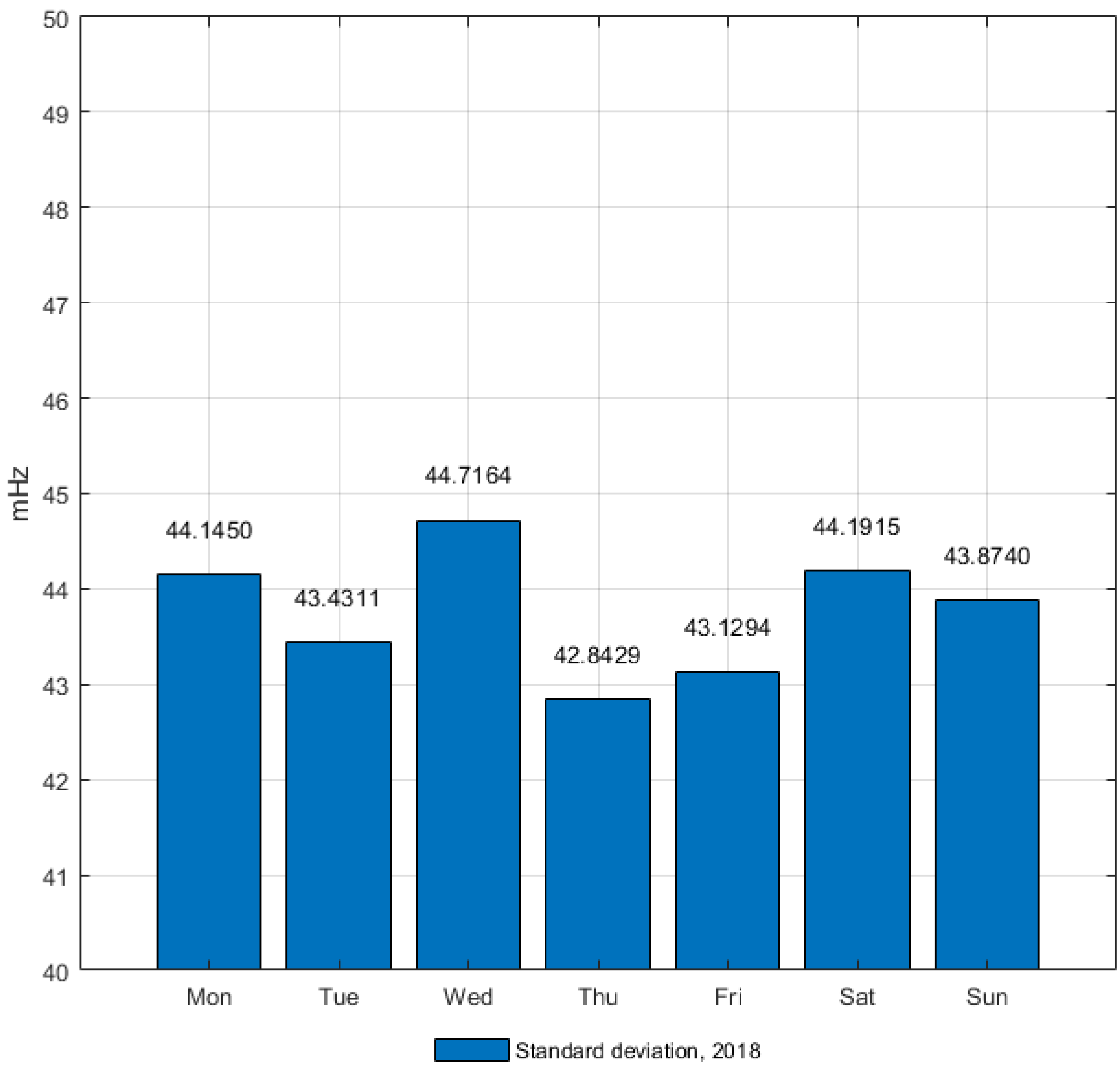


Figure 3.7 shows the standard deviation during a day. The standard deviation can vary close to 17 mHz from the lowest values during night to the highest points around midnight and in the morning.

***Figure 3.7**. Standard deviation of the frequency for every hour of the day in 2018*

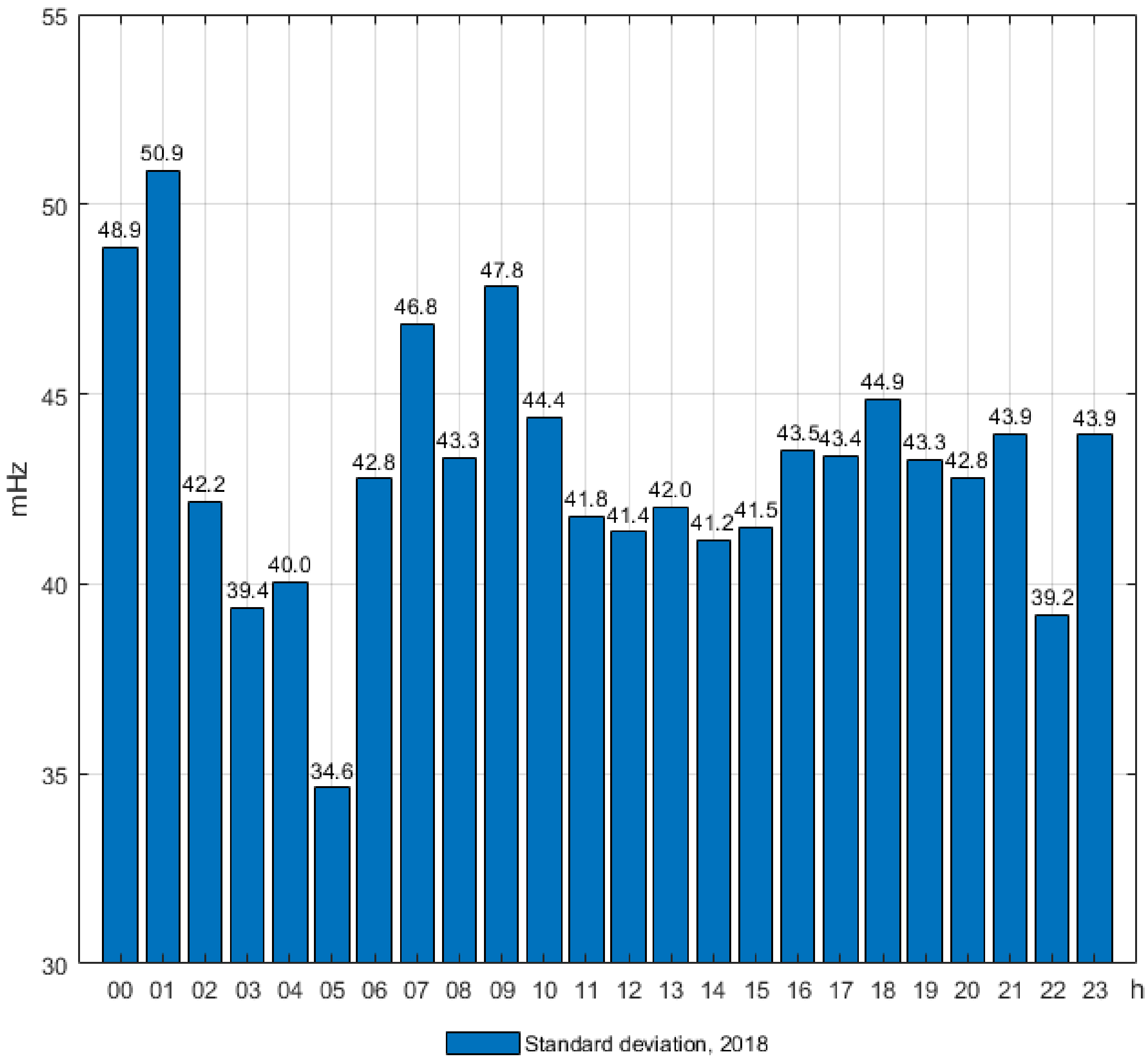
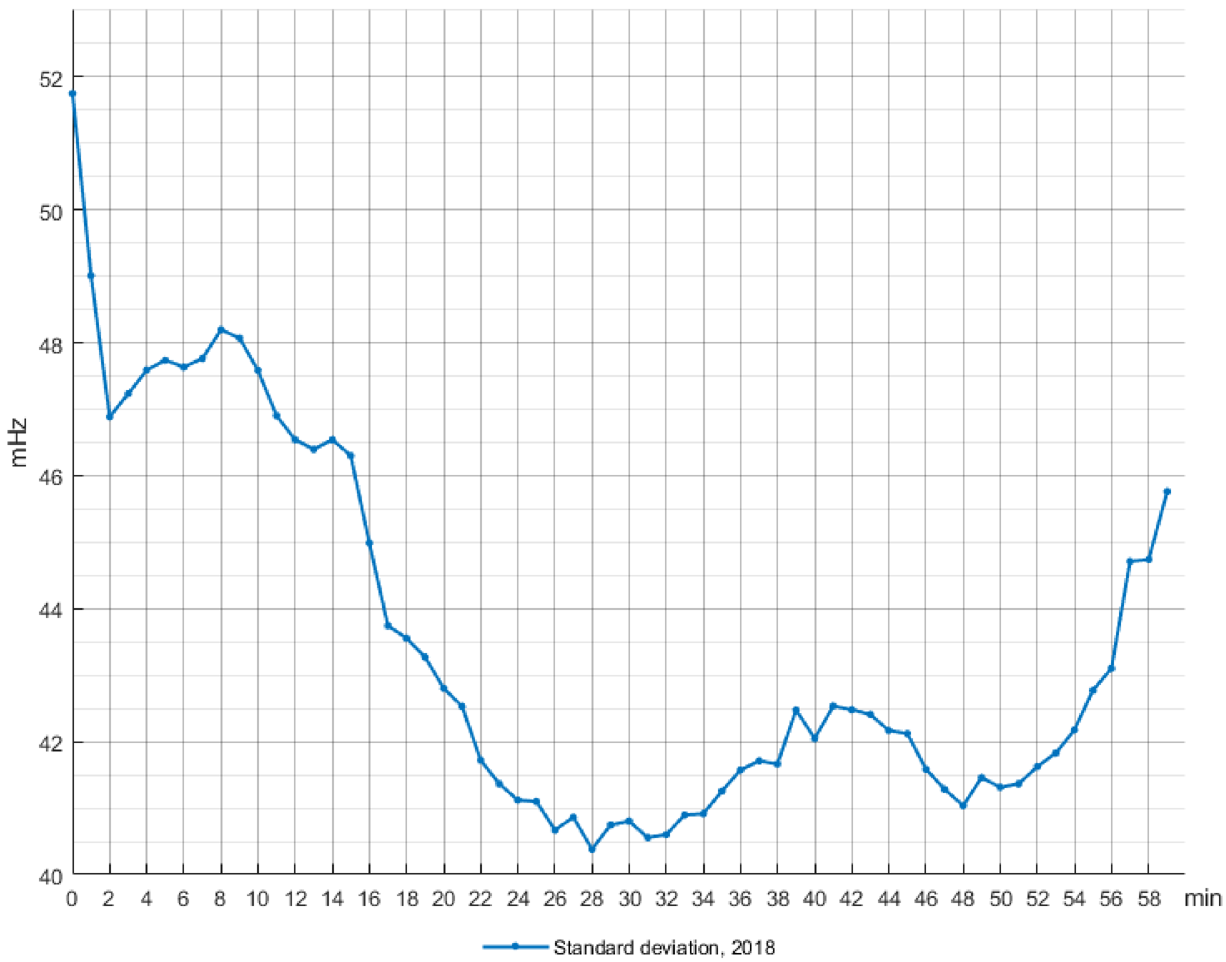


Figure 3.8 represents the standard deviation inside one hour. The standard deviation is at its highest in the beginning of the hour. For the first 30 minutes the standard deviation decreases until the half hour mark from where it starts to increase again.

Figure 3.8. Standard deviation of the frequency for every minute of the hour in 2018



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 2013 to 2018 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.

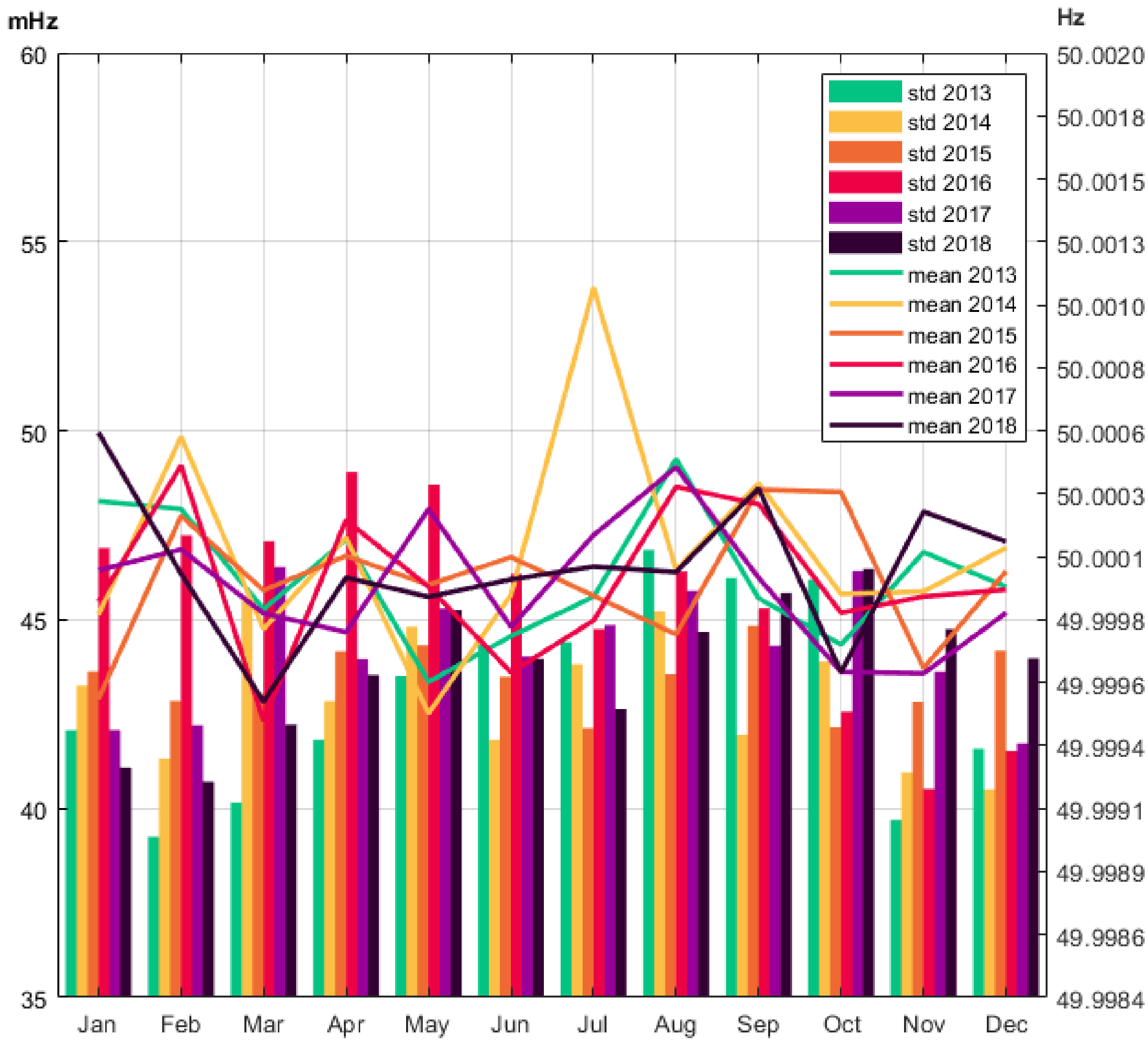
***Table 3.1**. Mean values and standard deviations for years 2013-2015*

	2013		2014		2015	
Month	**Mean value (Hz)**	**Standard deviation (mHz)**	**Mean value (Hz)**	**Standard deviation (mHz)**	**Mean value (Hz)**	**Standard deviation (mHz)**
January	50.0003	42.1	49.9999	43.3	49.9995	43.6
February	50.0003	39.3	50.0005	41.3	50.0002	42.9
March	49.9999	40.2	49.9998	45.5	50.0000	43.0
April	50.0001	41.8	50.0002	42.8	50.0001	44.2
May	49.9996	43.5	49.9995	44.8	50.0000	44.3
June	49.9998	44.3	49.9999	41.8	50.0001	43.5
July	49.9999	44.4	50.0011	43.8	49.9999	42.1
August	50.0005	46.8	50.0000	45.2	49.9998	43.6
September	49.9999	46.1	50.0004	42.0	50.0003	44.8
October	49.9997	46.1	49.9999	43.9	50.0003	42.2
November	50.0001	39.7	49.9999	41.0	49.9997	42.8
December	50.0000	41.6	50.0001	40.5	50.0000	44.2
Entire year	**50.0000**	**43.2**	**50.0001**	**43.1**	**50.0000**	**43.4**

Table 3.2. Mean values and standard deviations for years 2016-2018

	2016		**2017**		**2018**	
Month	**Mean value (Hz)**	**Standard deviation (mHz)**	**Mean value (Hz)**	**Standard deviation (mHz)**	**Mean value (Hz)**	**Standard deviation (mHz)**
January	49.9999	46.9	50.0000	42.1	50.0006	41.1
February	50.0004	47.2	50.0001	42.2	50.0000	40.7
March	49.9995	47.1	49.9999	46.4	49.9995	42.2
April	50.0002	48.9	49.9998	44.0	50.0000	43.5
May	50.0000	48.6	50.0003	45.3	49.9999	45.3
June	49.9996	46.2	49.9998	44.0	50.0000	44.0
July	49.9998	44.8	50.0002	44.9	50.0000	42.6
August	50.0003	46.3	50.0004	45.8	50.0000	44.7
September	50.0003	45.3	50.0000	44.3	50.0003	45.7
October	49.9999	42.6	49.9996	46.3	49.9996	46.3
November	49.9999	40.5	49.9996	43.6	50.0003	44.8
December	50.0000	41.5	49.9999	41.7	50.0001	44.0
Entire year	**50.0000**	**45.5**	**50.0000**	**44.2**	**50.0000**	**43.8**

***Figure 3.9**. Mean values and standard deviations for years 2013-2018*

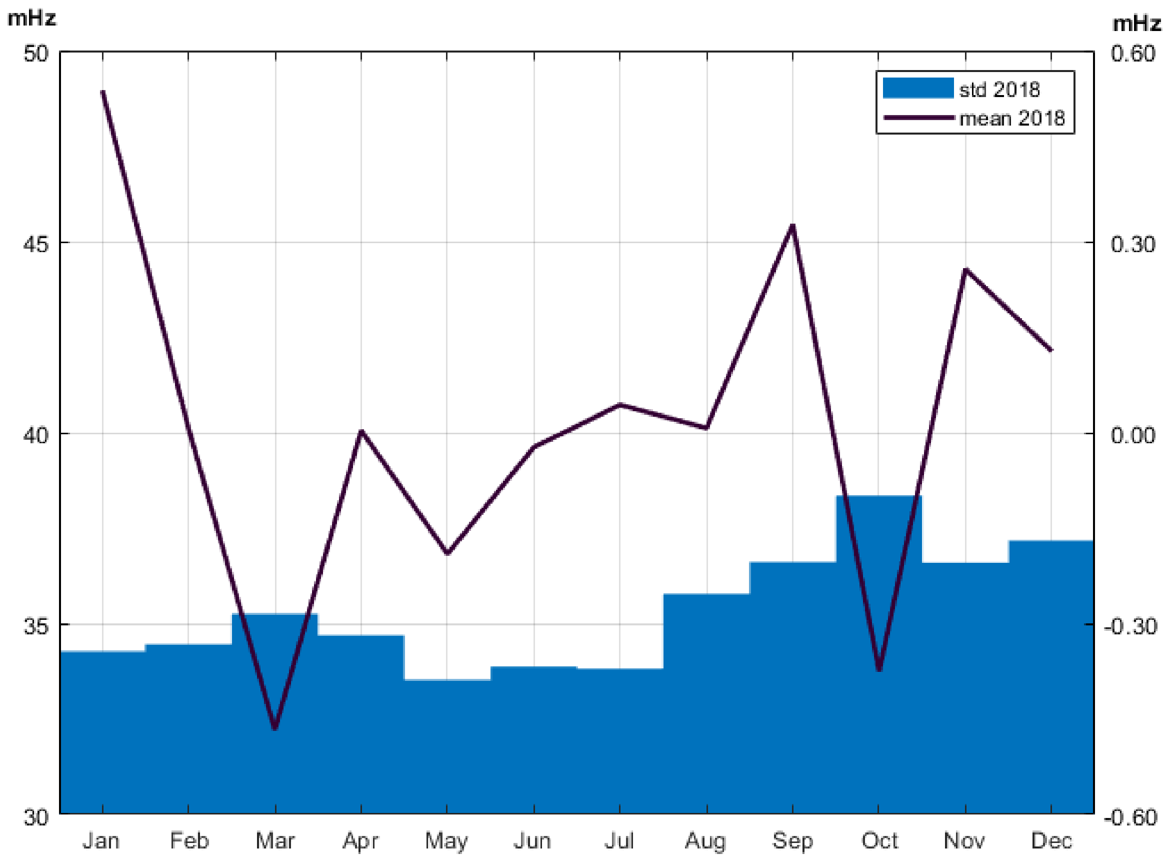


Mean values and standard deviations for frequency deviations as per Article 131(b) (i) for year 2018 can be found in Table 3.3. Results show how much frequency has deviated from nominal 50 Hz value. Visual representation can be found in Figure 3.10. The resolution of the frequency data used in the following table and figure was 15 minutes.

Table 3.3. Mean values and standard deviations of frequency deviations for year 2018

	2018	
Month	**Mean value (mHz)**	**Standard deviation (mHz)**
January	0.538	34.3
February	0.006	34.5
March	-0.467	35.3
April	0.003	34.7
May	-0.191	33.5
June	-0.023	33.9
July	0.044	33.8
August	0.007	35.8
September	0.327	36.6
October	-0.375	38.4
November	0.257	36.6
December	0.128	37.2
Entire year	**0.021**	**35.4**

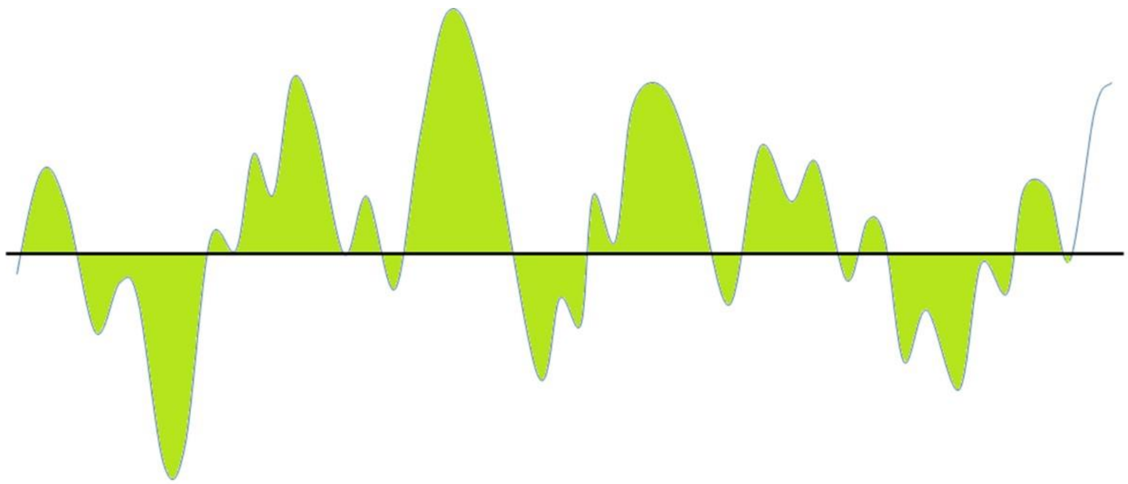
***Figure 3.10**. Mean values and standard deviations of frequency deviations for year 2018. The left y-axis represents the values of the standard deviation while the right y-axis represents the values of the mean value*



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 determining the frequency area.

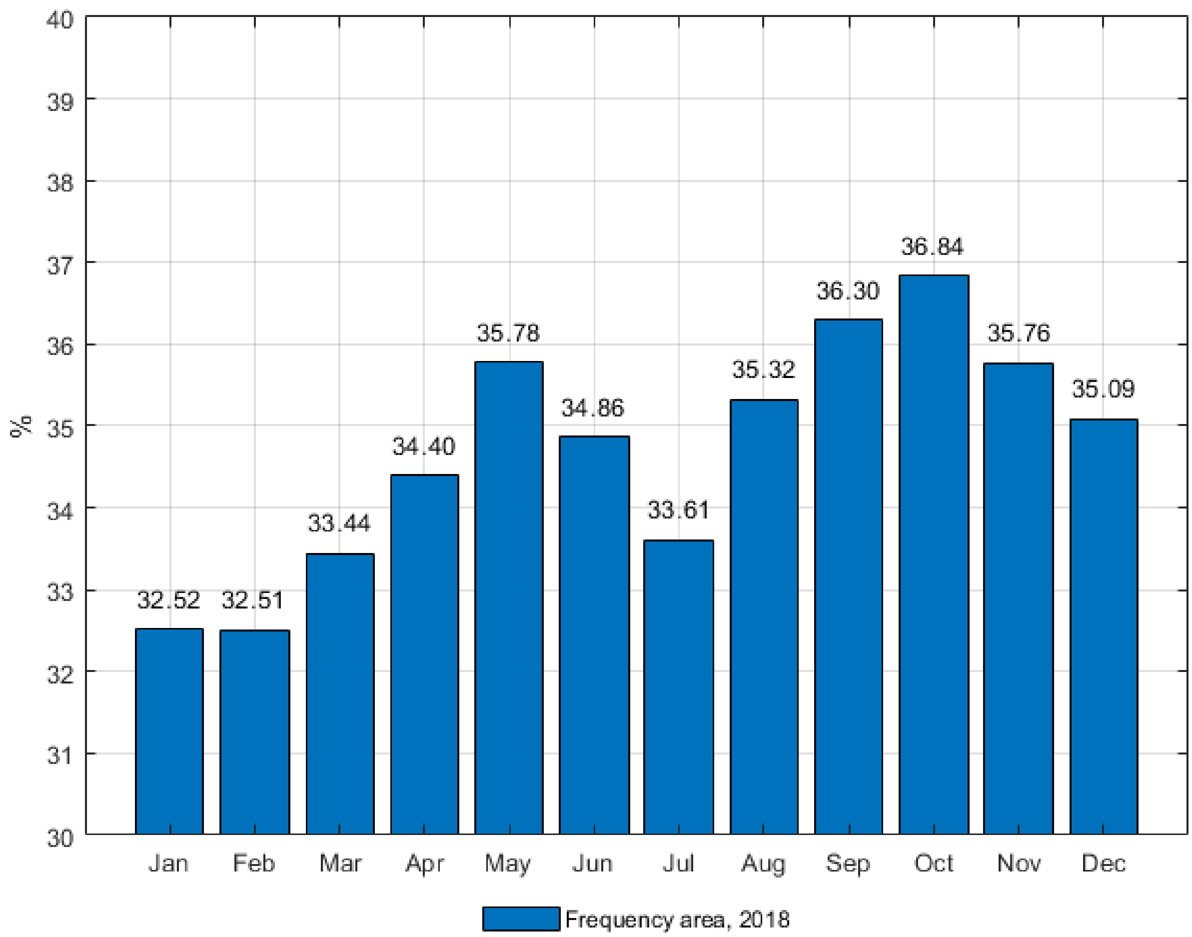
Figure 3.11**. **Frequency quality index: Frequency area [7]



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

Figure 3.12 represents the average frequency area for every month in 2018. The percentage of the area was considerably smaller early in the year, except for May, which indicates that there was less deviation from 50 Hz during those months.

Figure 3.12. The average frequency area for every month in 2018



The frequency area during each day of the week can be seen in Figure 3.13. The percentage was fairly even between the days with the average area being a little bit smaller during Tuesdays, Thursdays and Fridays.

Figure 3.13. The average frequency area for every day of the week in 2018

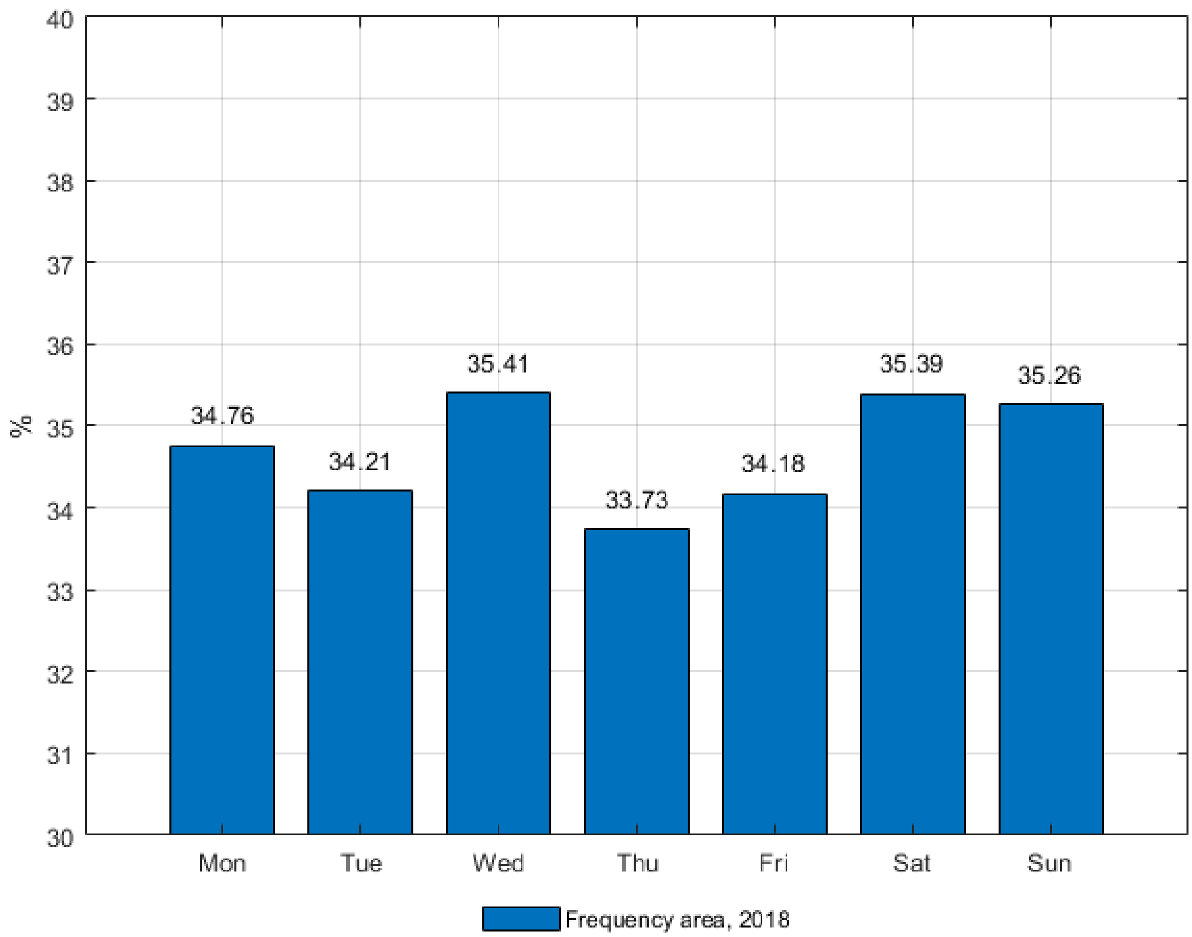


Figure 3.14 has the frequency area for every hour during the day. The figure shows that the deviation of the frequency from 50.0 Hz was smaller in the middle of the night and after noon. The area was at its highest in the first hours of the day. The average frequency area was considerably lower during hour 05.

***Figure 3.14**. The average frequency area for every hour inside the day in 2018*

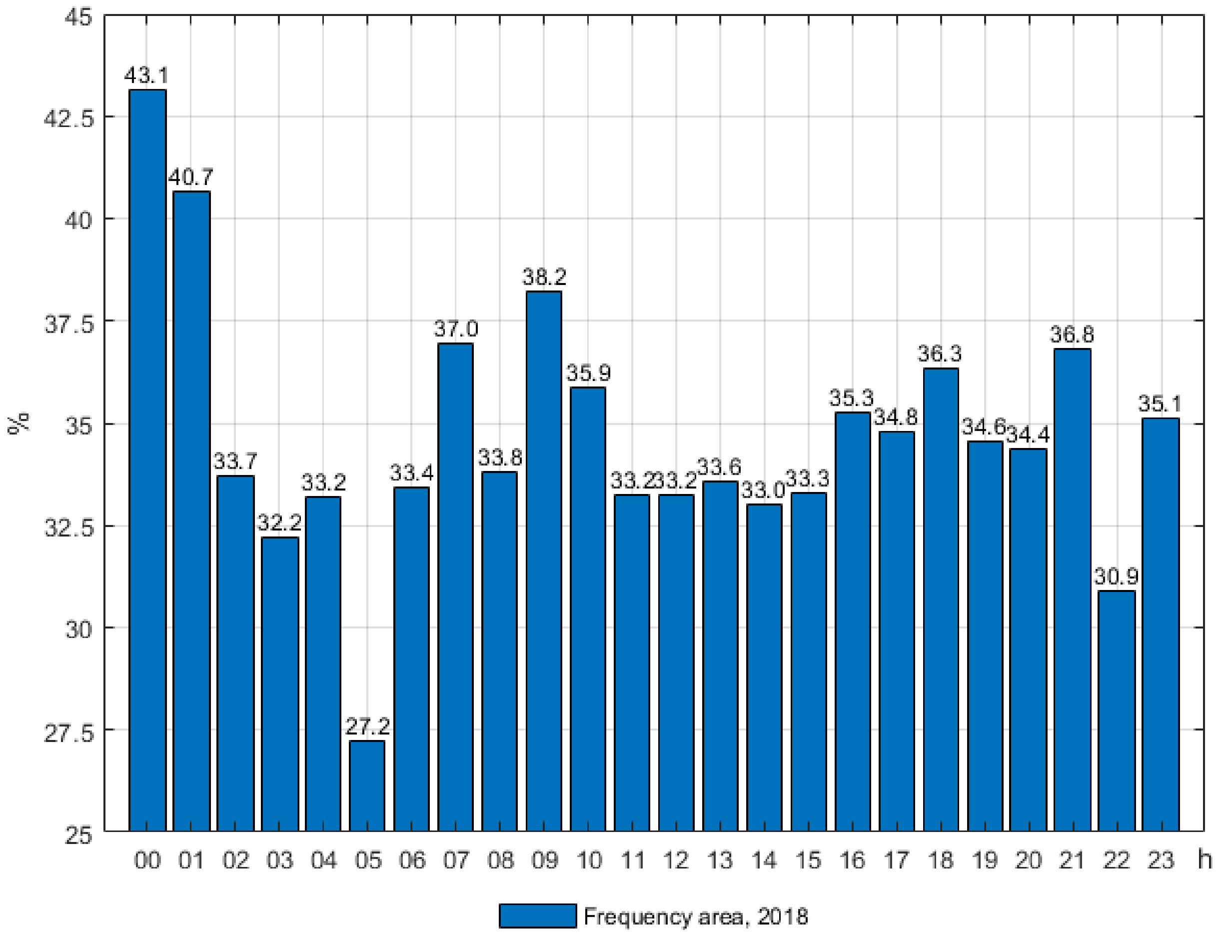
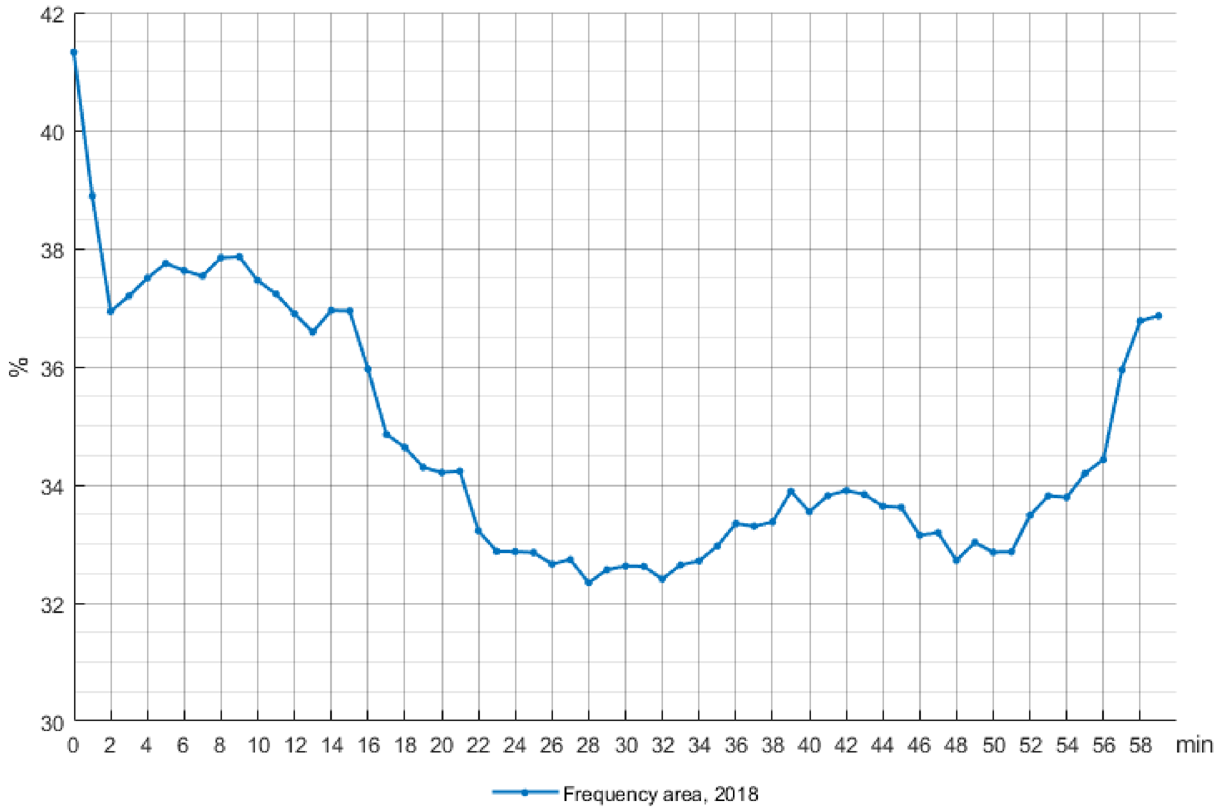


Figure 3.15 represents the frequency area within the hour. The percentage of the frequency area was smaller in the middle of the hour while more deviation occured closer to the hour shift.

***Figure 3.15**. The average frequency area for every minute within the hour in 2018*



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(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 2013 to 2018. All results are summed up in Figure 3.16.

***Table 3.4**. The 1st, 5th, 10th, 90th, 95th and 99th percentiles for year 2013*

	2013					
Month	**1st (Hz)**	**5th (Hz)**	**10th (Hz)**	**90th (Hz)**	**95th (Hz)**	**99th (Hz)**
Jan	49.906	49.934	49.949	50.055	50.071	50.104
Feb	49.906	49.935	49.950	50.050	50.065	50.094
Mar	49.902	49.934	49.950	50.050	50.067	50.100
Apr	49.903	49.933	49.948	50.054	50.072	50.105
May	49.896	49.928	49.945	50.054	50.070	50.101
Jun	49.900	49.928	49.943	50.057	50.074	50.105
Jul	49.900	49.929	49.944	50.058	50.074	50.105
Aug	49.896	49.926	49.941	50.061	50.079	50.111
Sep	49.894	49.927	49.942	50.060	50.077	50.110
Oct	49.895	49.928	49.944	50.059	50.078	50.115
Nov	49.909	49.936	49.950	50.051	50.067	50.096
Dec	49.903	49.934	49.948	50.054	50.070	50.099
Entire year	**49.900**	**49.931**	**49.946**	**50.056**	**50.072**	**50.105**

Table 3.5. 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 3.6. 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 3.7. 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**

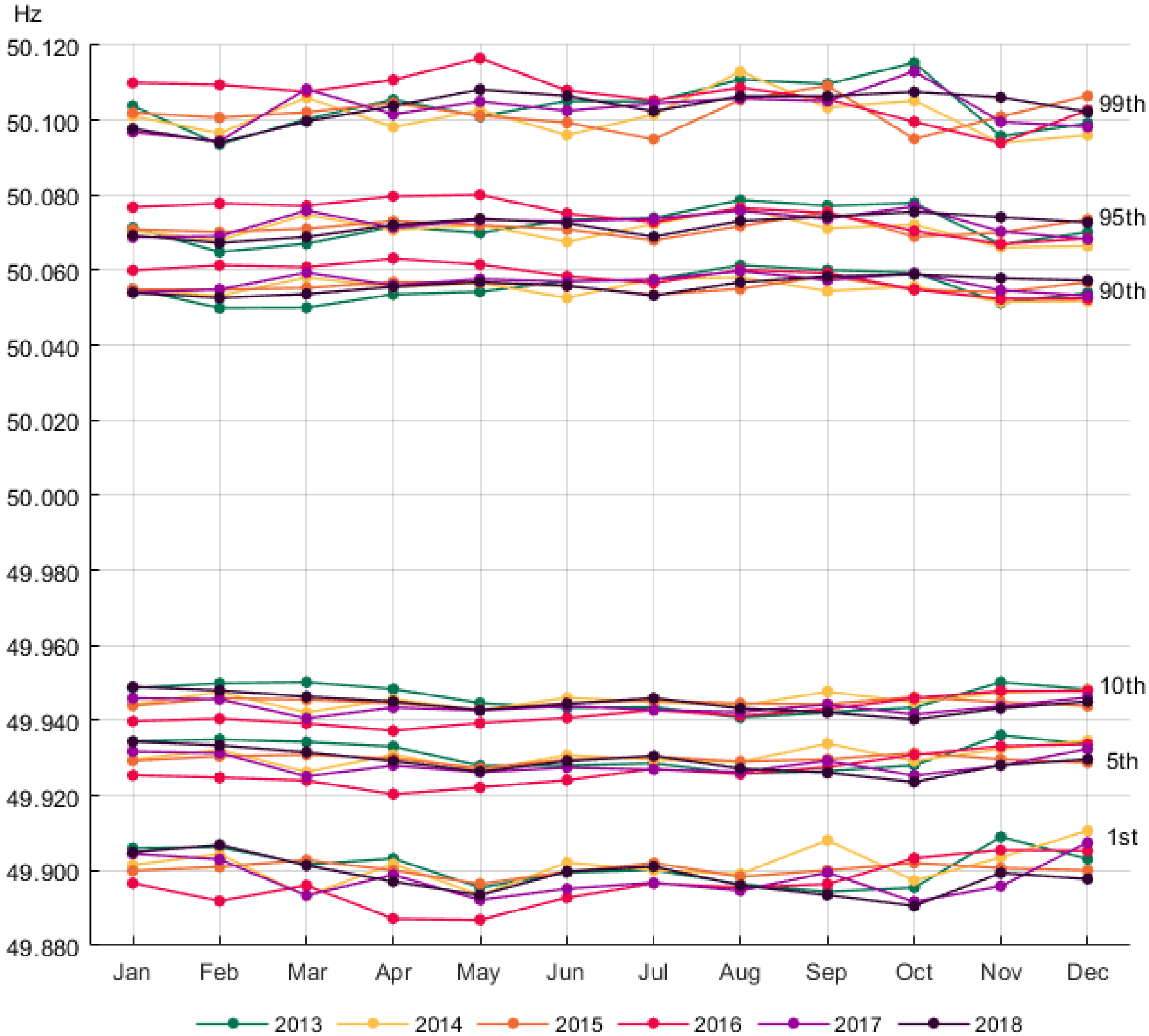
Table 3.8. The 1st, 5th, 10th, 90th, 95th and 99th percentiles for year 2017

	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 3.9. 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**

***Figure 3.16**. The 1st, 5th, 10th, 90th, 95th and 99th percentiles for years 2013-2018*



More detailed results for the percentiles of 2018 are shown in the next figures. Figure 3.17 is a visual representation of the given percentiles for each month in 2018. The percentiles in May were further from 50 Hz, which indicates that there were more deviations during that month.

***Figure 3.17**. The 1st, 5th, 10th, 90th, 95th and 99th percentile of the frequency for every month in 2018*

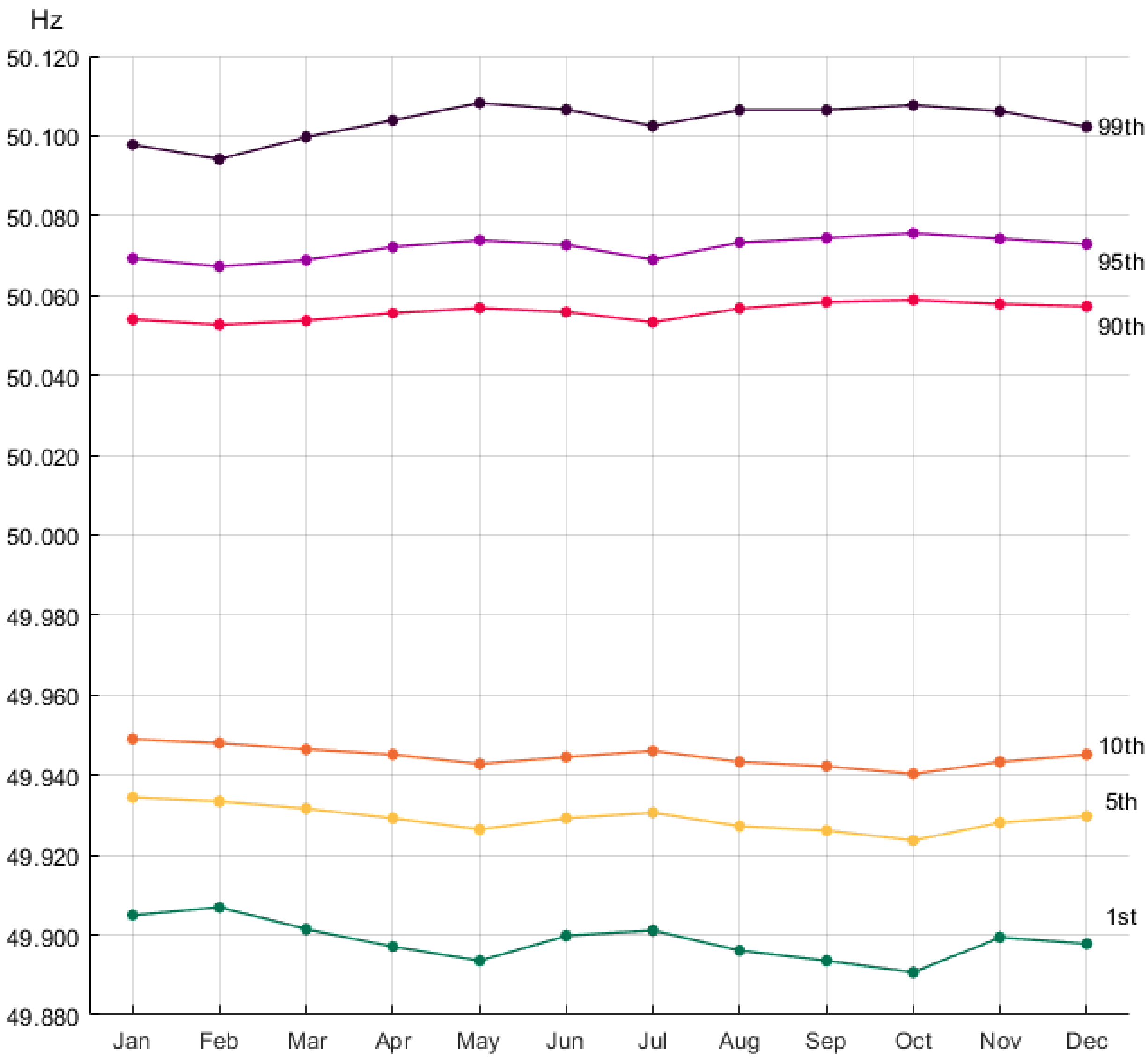


Figure 3.18 shows the percentiles for every day during the week. The 90th, 95th and 99th percentile were all slighly higher during Sundays, which indicates that there were more over frequencies during that time. The 1st, 5th and 10th percentile have stayed fairly constant throughout the week.

Figure 3.18*. *The 1st, 5th, 10th, 90th, 95th and 99th percentile of the frequency for every day of the week in 2018

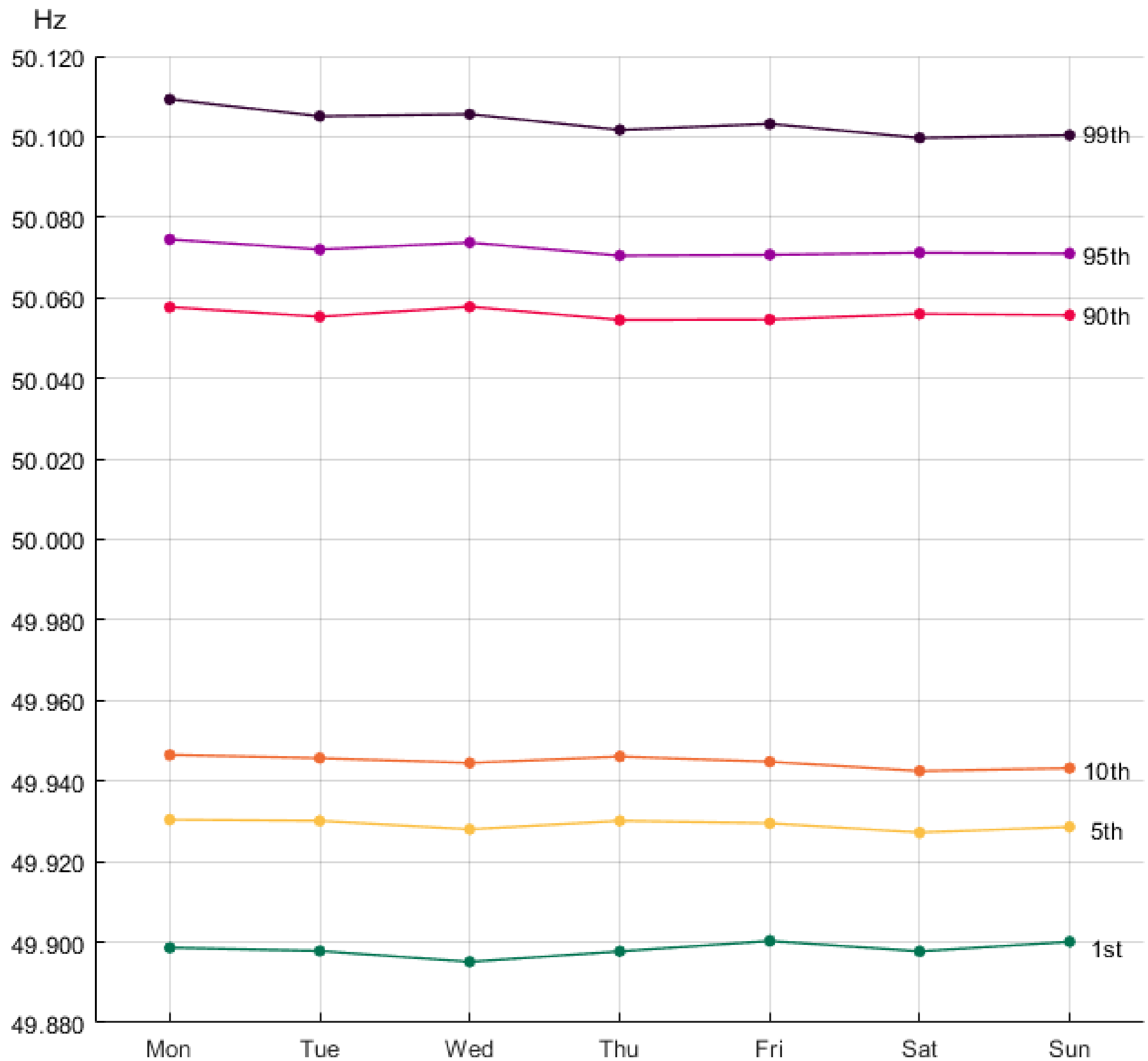
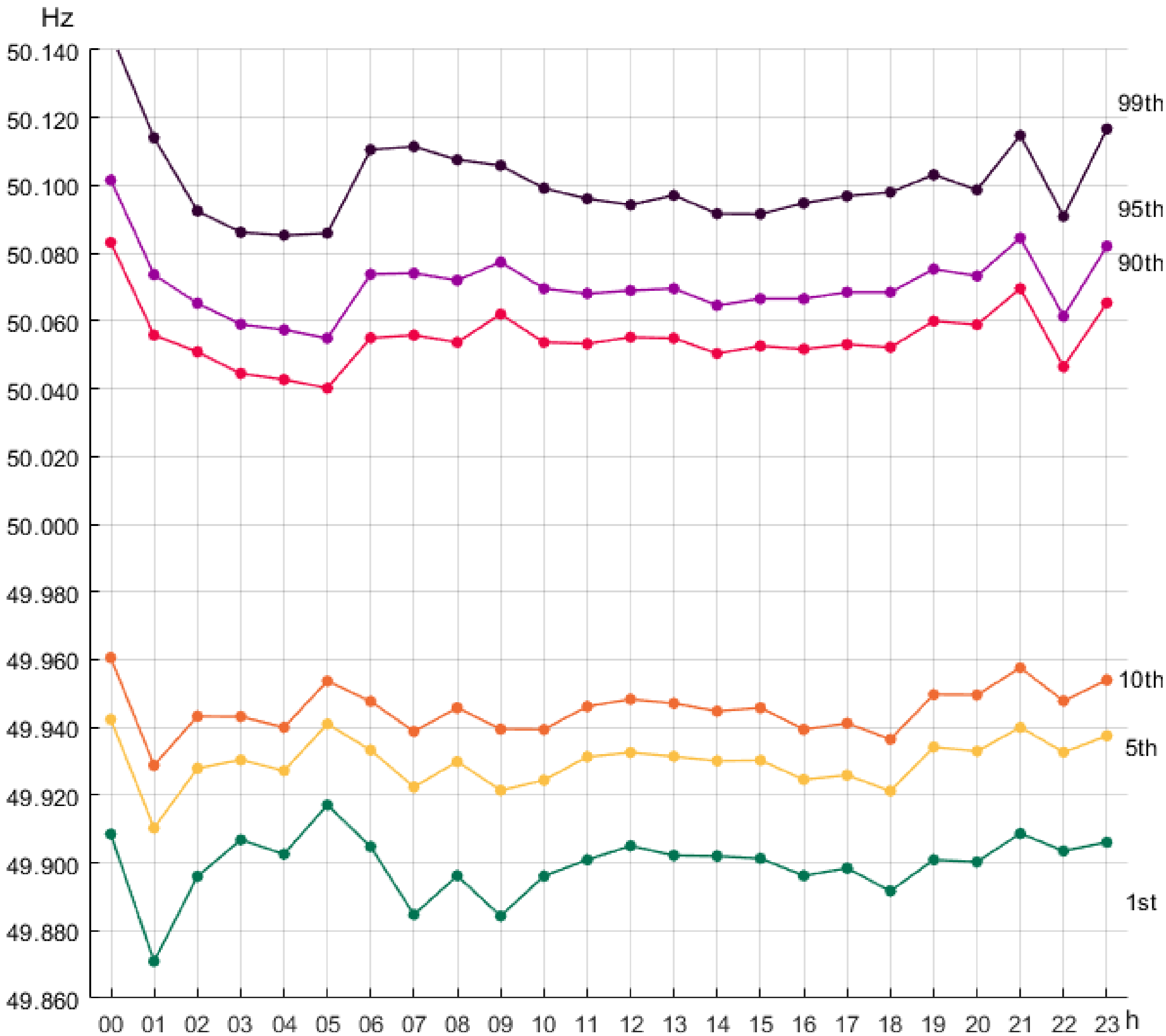


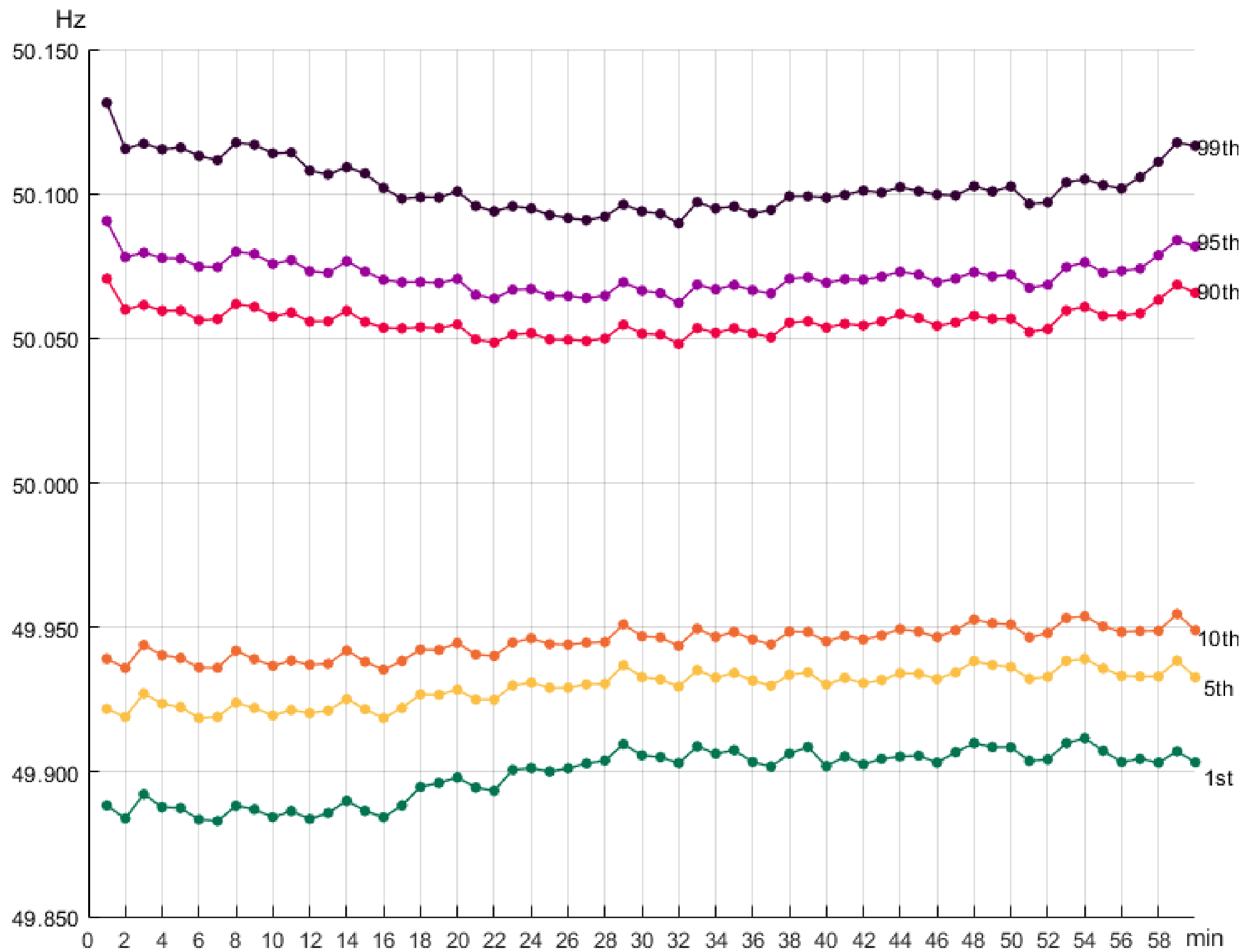
Figure 3.19 represents the percentiles inside the day. In terms of the 1st, 5th and 10th percentile, the frequencies are lowest between 01-02. For the 90th, 95th and 99th percentile, night hours have values closest to 50 Hz.

***Figure 3.19**. The 1st, 5th, 10th, 90th, 95th and 99th percentile of the frequency for every hour of the day in 2018*



Inside the hour the variation of the percentiles was fairly low. For the 1st, 5th and 10th percentile, the frequency was lower in the first minutes of the hour. For the other percentiles, the minutes around the hour shift were slighly higher than the ones in the middle of the hour.

***Figure 3.20**. The 1st, 5th, 10th, 90th, 95th and 99th percentile of the frequency for every minute inside the hour in 2018*

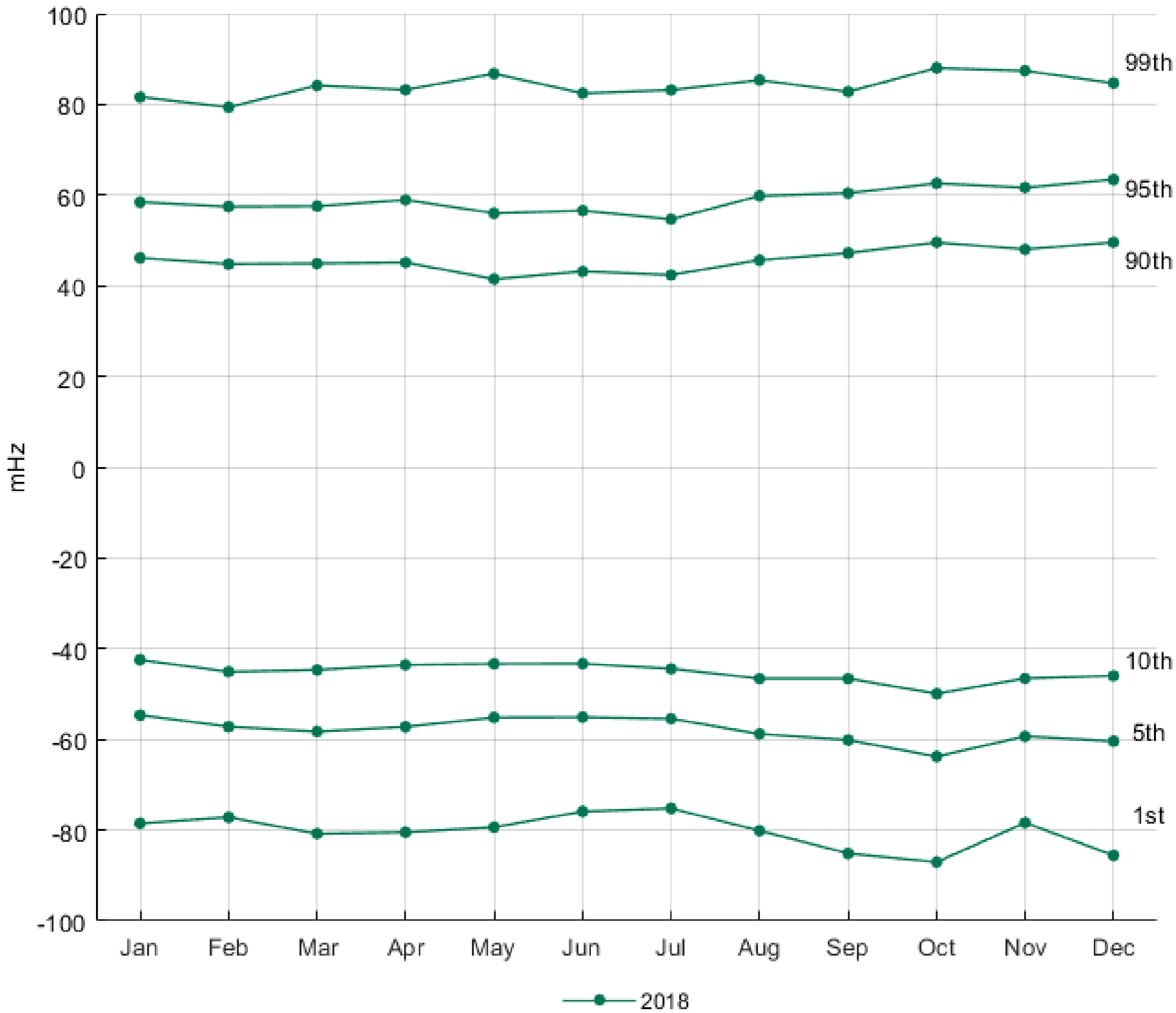


The 1st, 5th, 10th, 90th, 95th and 99th percentiles according to SO GL Article 131(b) i(3) are presented in Table 3.10. Figure 3.21 below the table shows results in graphical form. Results are deviations from nominal 50 Hz value and a frequency data with a resolution of 15 minutes was used.

***Table 3.10**. The 1st, 5th, 10th, 90th, 95th and 99th percentiles of frequency deviations for year 2018*

	2018					
Month	**1st (mHz)**	**5th (mHz)**	**10th (mHz)**	**90th (mHz)**	**95th (mHz)**	**99th (mHz)**
Jan	-78.5	-54.6	-42.5	46.2	58.4	81.6
Feb	-77.2	-57.2	-45.1	44.8	57.4	79.4
Mar	-80.8	-58.2	-44.7	44.9	57.6	84.2
Apr	-80.5	-57.2	-43.6	45.1	58.9	83.2
May	-79.3	-55.2	-43.3	41.5	56.0	86.8
Jun	-75.9	-55.1	-43.3	43.2	56.6	82.5
Jul	-75.2	-55.4	-44.4	42.4	54.7	83.2
Aug	-80.1	-58.8	-46.6	45.7	59.8	85.4
Sep	-85.1	-60.1	-46.6	47.2	60.4	82.8
Oct	-87.0	-63.8	-49.9	49.5	62.6	88.0
Nov	-78.4	-59.3	-46.5	48.1	61.7	87.4
Dec	-85.6	-60.4	-46.0	49.6	63.4	84.7
Entire year	**-80.3**	**-57.9**	**-45.2**	**45.7**	**59.0**	**84.1**

***Figure 3.21**. The 1st, 5th, 10th, 90th, 95th and 99th percentiles for year 2018*



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 2018. The curves are fairly linear throughout the year, though the growth is slightly more rapid during May. The frequency has been outside the standard range just under 12 000 minutes, close to 6 200 min over 50.1 Hz and slightly under 6 000 min 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 2018

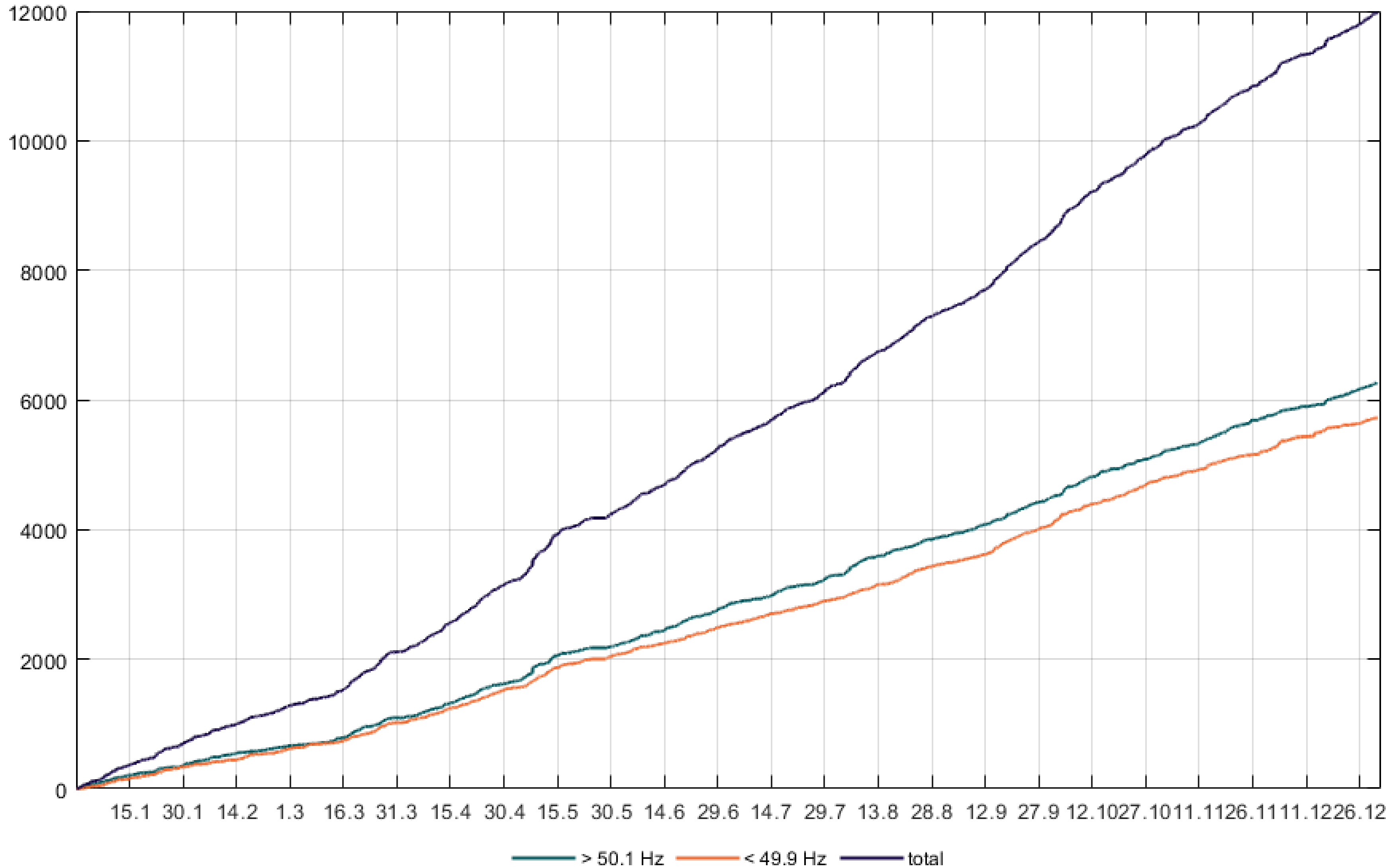
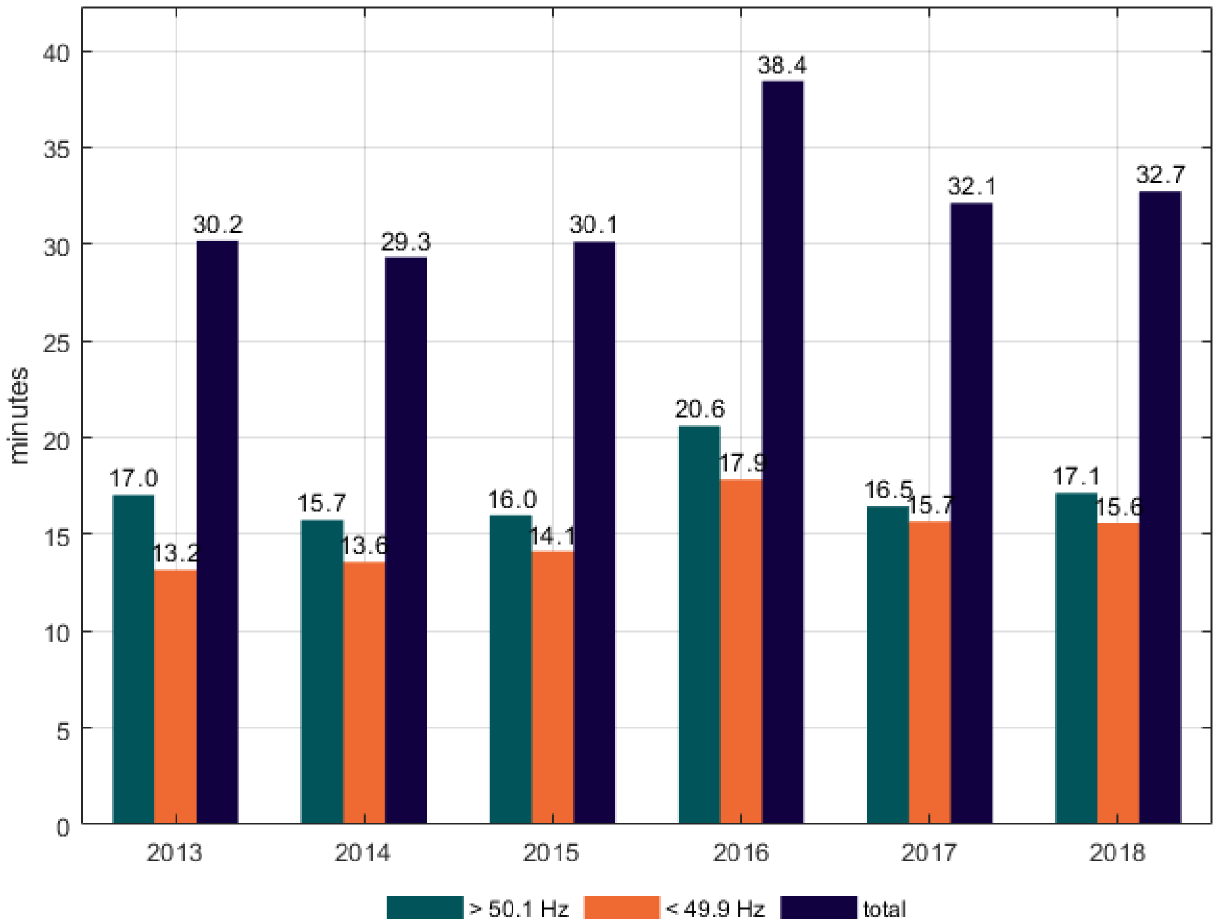


Figure 3.23 represents the daily average number of minutes per year that the frequency was outside the standard frequency range. The amount of minutes has stayed around 30 each year except for 2016 when the average was over 38 minutes. Every year there has been more over frequencies than under frequencies.

Figure 3.23*. *Daily average number of minutes per year that the frequency was outside the standard frequency range in 2013-2018



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
2013	1.28 %	0.99 %	97.72 %
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 %

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)
2013	6750	5212	11963
2014	5755	4959	10714
2015	5844	5166	11010
2016	7586	6574	14160
2017	6185	5884	12069
2018	6328	5755	12083

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 2013 to 2018. These results are based on the evaluation criteria defined in SO GL Article 131(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 3.24.

***Table 3.13**. Total time in which the frequency was outside the 49.9-50.1 Hz band in years 2013-2015*

	2013		**2014**		**2015**	
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	522	311	474	409	498	444
February	123	132	324	309	420	379
March	453	411	629	616	506	376
April	532	334	387	391	544	428
May	474	576	517	608	478	535
June	384	302	340	383	414	438
July	599	442	487	444	323	397
August	810	547	830	471	579	485
September	723	573	516	247	678	428
October	851	541	583	506	314	398
November	326	250	303	353	454	414
December	422	383	359	218	629	443
Entire year	**6220**	**4803**	**5749**	**4954**	**5838**	**5165**

Table 3.14. Total time in which the frequency was outside the 49.9-50.1 Hz band in years 2016-2018

	2016		**2017**		**2018**	
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	723	526	362	345	386	340
February	687	612	272	338	272	266
March	679	566	669	611	436	415
April	779	809	471	460	529	501
May	962	820	577	642	582	547
June	607	594	501	549	588	436
July	587	537	569	530	495	419
August	704	572	504	476	608	549
September	584	523	564	442	598	590
October	434	362	703	573	662	708
November	288	310	420	522	596	447
December	504	325	399	266	508	497
Entire year	**7539**	**6555**	**6011**	**5756**	**6259**	**5715**

***Figure 3.24**. Total time in which the frequency was outside the 49.9-50.1 band in years 2013-2018*

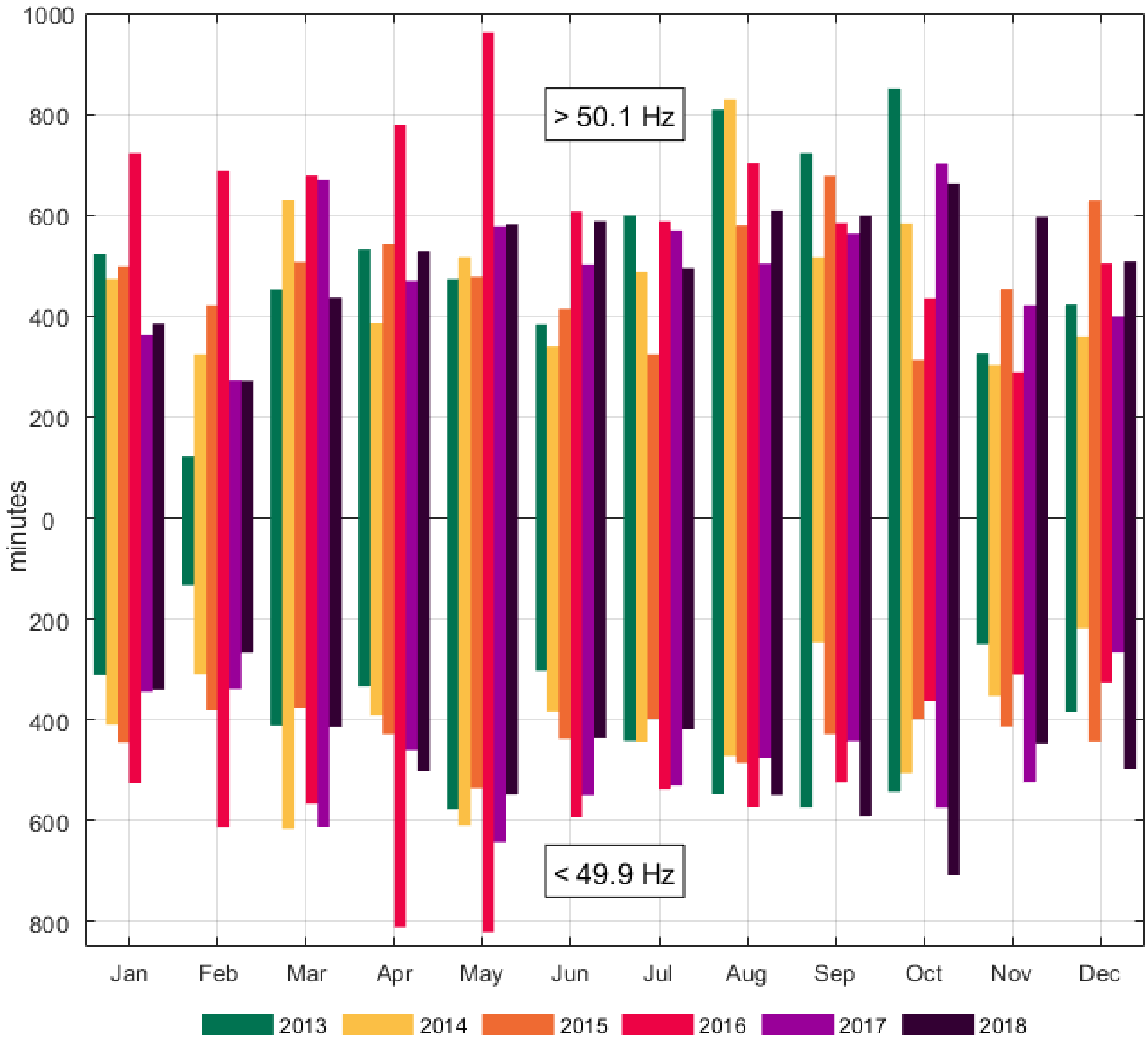


Figure 3.25 shows the daily average in minutes month by month when frequency was outside the standard frequency range in years 2013-2018. In 2018, May and October were the months with the longest time outside the standard frequency range. January and February had the best frequency in this comparison.

***Figure 3.25**. Daily average time that the frequency was outside the standard frequency range month by month for years 2013-2018*

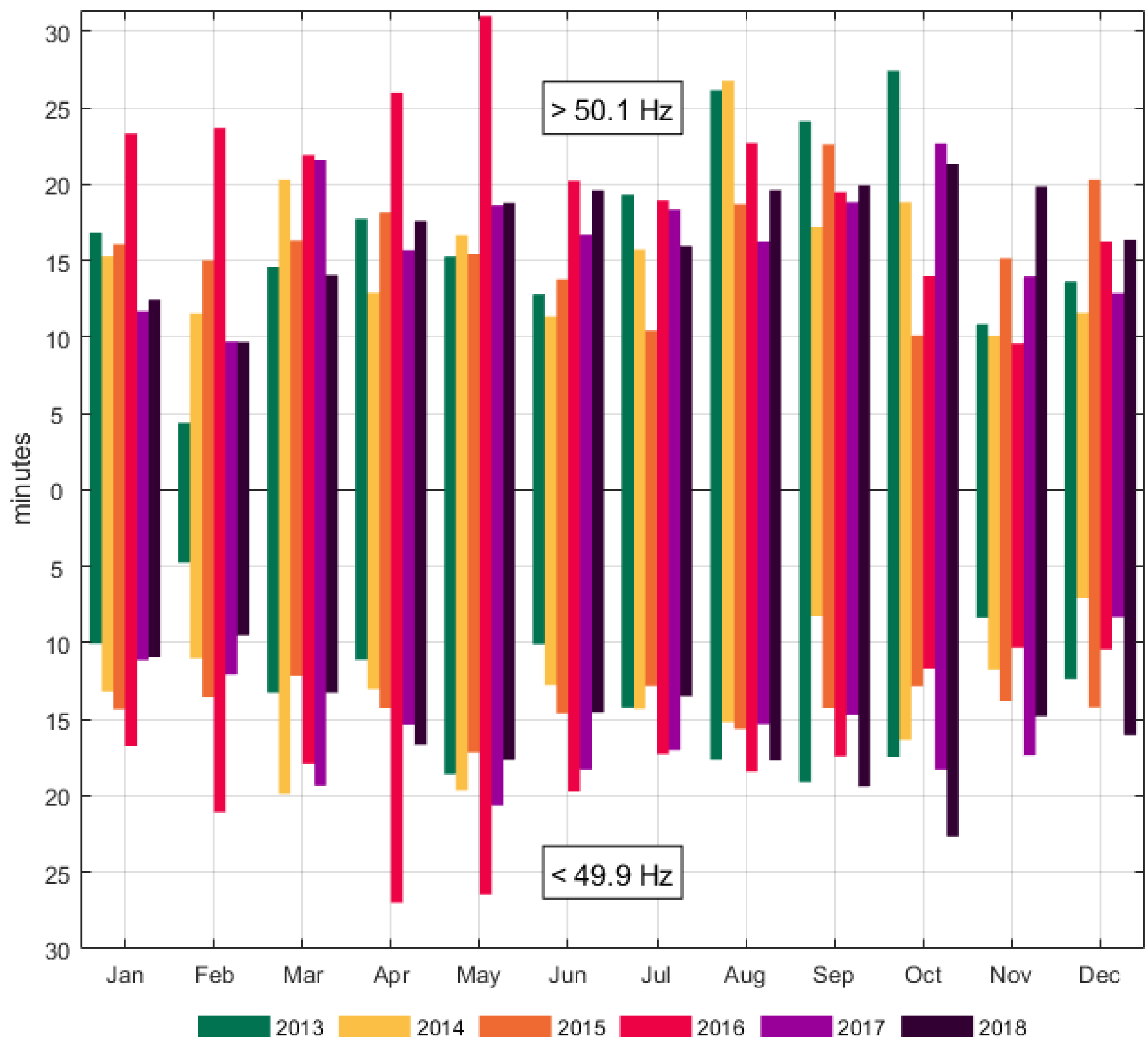


Figure 3.26 represents the daily averge time that the frequency was outside the standard frequency range during each day of the week. Every year has had a similar pattern, where the frequency has been outside the standard frequency range more often during weekdays than weekends.

***Figure 3.26**. Daily average time that the frequency was outside the standard frequency range during each day of the week for years 2013-2018*

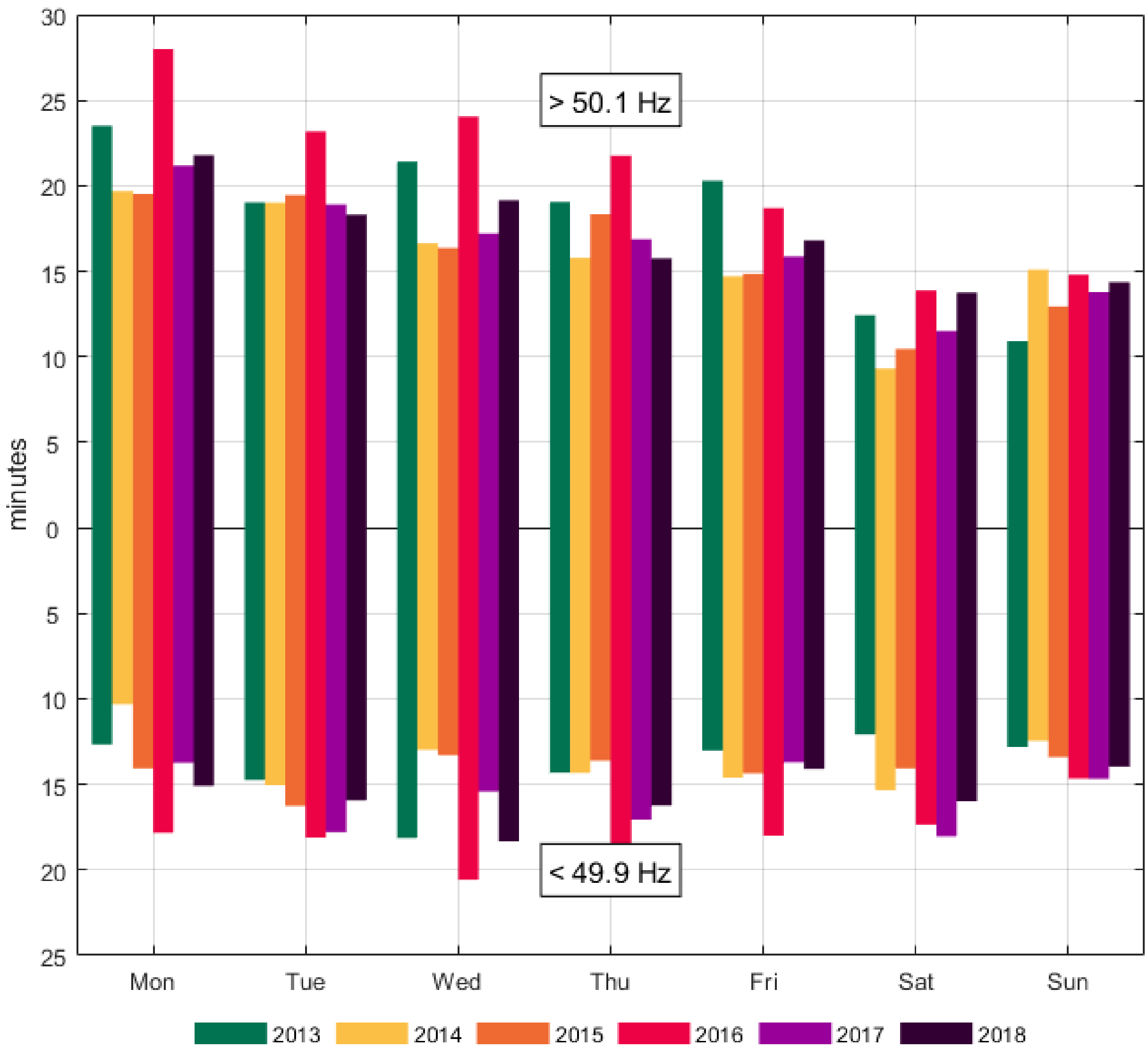


Figure 3.27 represents the daily average time that the frequency was outside the standard frequency range for each hour in the day. The hours are according to the Finnish time (UTC+2 / UTC+3 in the summer). In 2018, the frequency has been over 50.1 Hz the most at the hours 21, 23 and 0 and under 49.9 Hz at 1. In previous years, the frequency has also been outside the standard frequency range more frequently in the morning hours as well as in the evening and midnight. Frequency has stayed inside the standard frequency range the best during hours from 3 to 5. Hours right after noon have also been good in terms of time outside 49.9-50.1 Hz.

***Figure 3.27**. Daily average time that the frequency was outside the standard frequency range during each hour of the day for years 2013-2018*

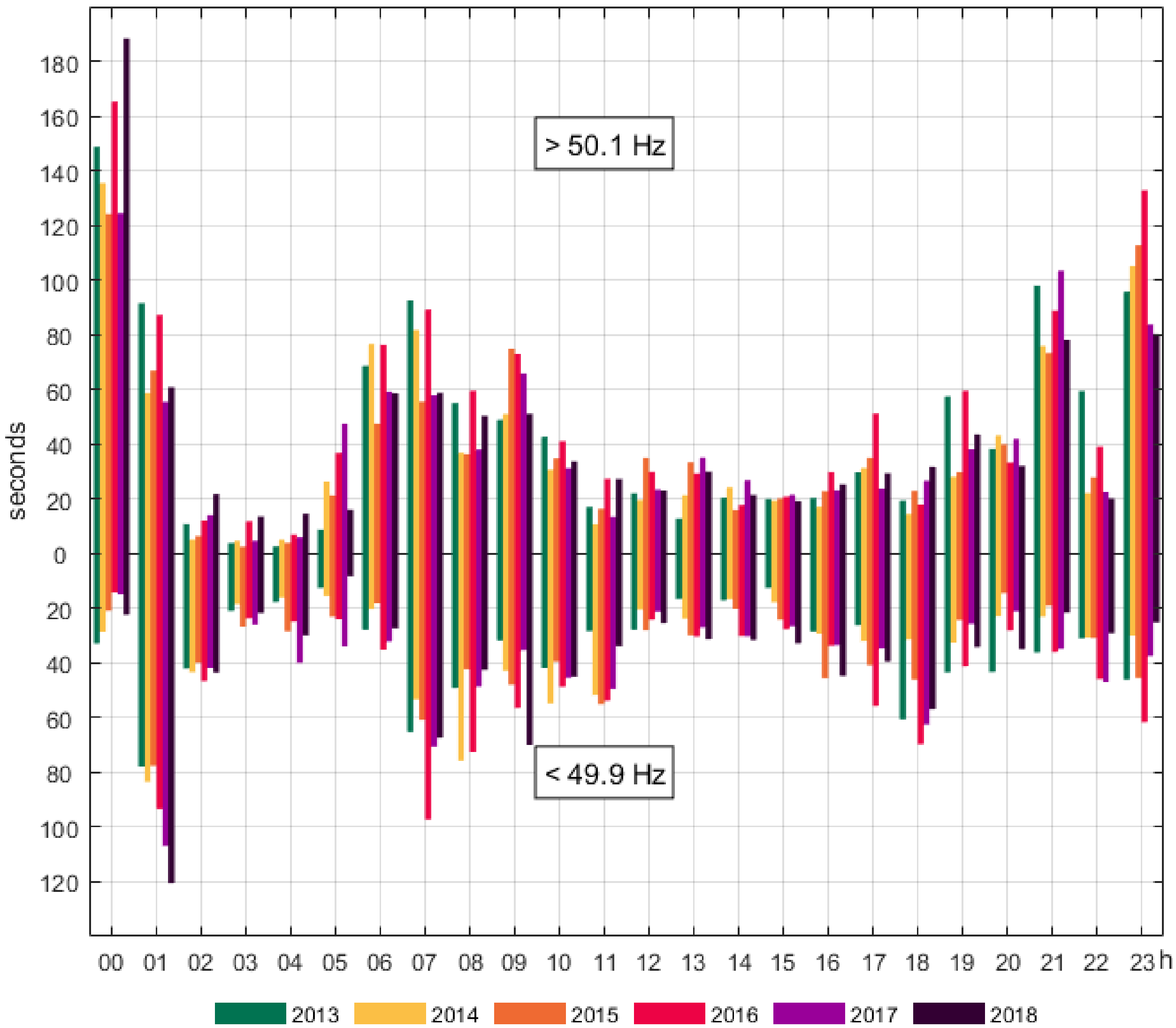


Figure 3.28 shows the daily average time outside the standard frequency range per hour and absolute value of Nordic consumption and production difference. Also transmission difference of HVDC links connecting the Nordic power system to Continental Europe and Russia is presented.

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).

The Nordic production difference curve peaks at 4 000 MWh while the consumption difference curve peaks close to 2 700 MWh. Near midnight the peaks for production and consumption differences are around 2000-2800 MWh. Highest values of frequency deviations are also found during these hours. Differences in HVDC transmission do not peak as high and the curve does not follow the same pattern as production and consumption difference as well as in previous years. Results for year 2017 were very similar to the year 2018 [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 2018

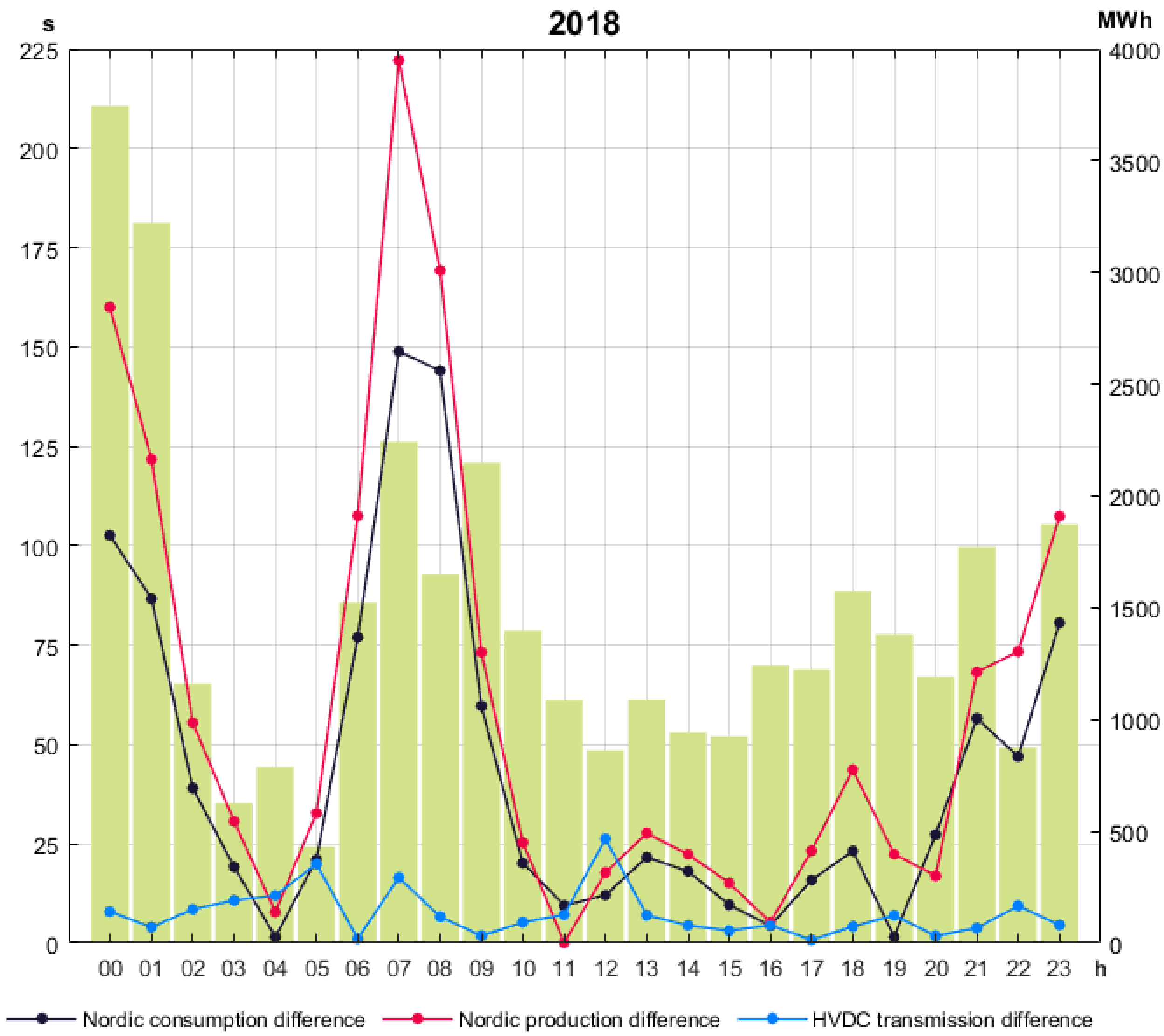


Figure 3.29 illustrates an average hour divided to 60 minutes. For each minute of the average hour there is a value in seconds per hour that frequency has been over or below the standard frequency range. In years 2013-2018 frequency has been outside the standard frequency range more often during the beginning of hours. Frequency has stayed best inside the standard frequency range in the middle of hours. The time above the standard frequency range has increased again towards the end of hours.

***Figure 3.29**. Number of seconds per hour outside the standard frequency range in 2013-2018 for each minute of an average hour*

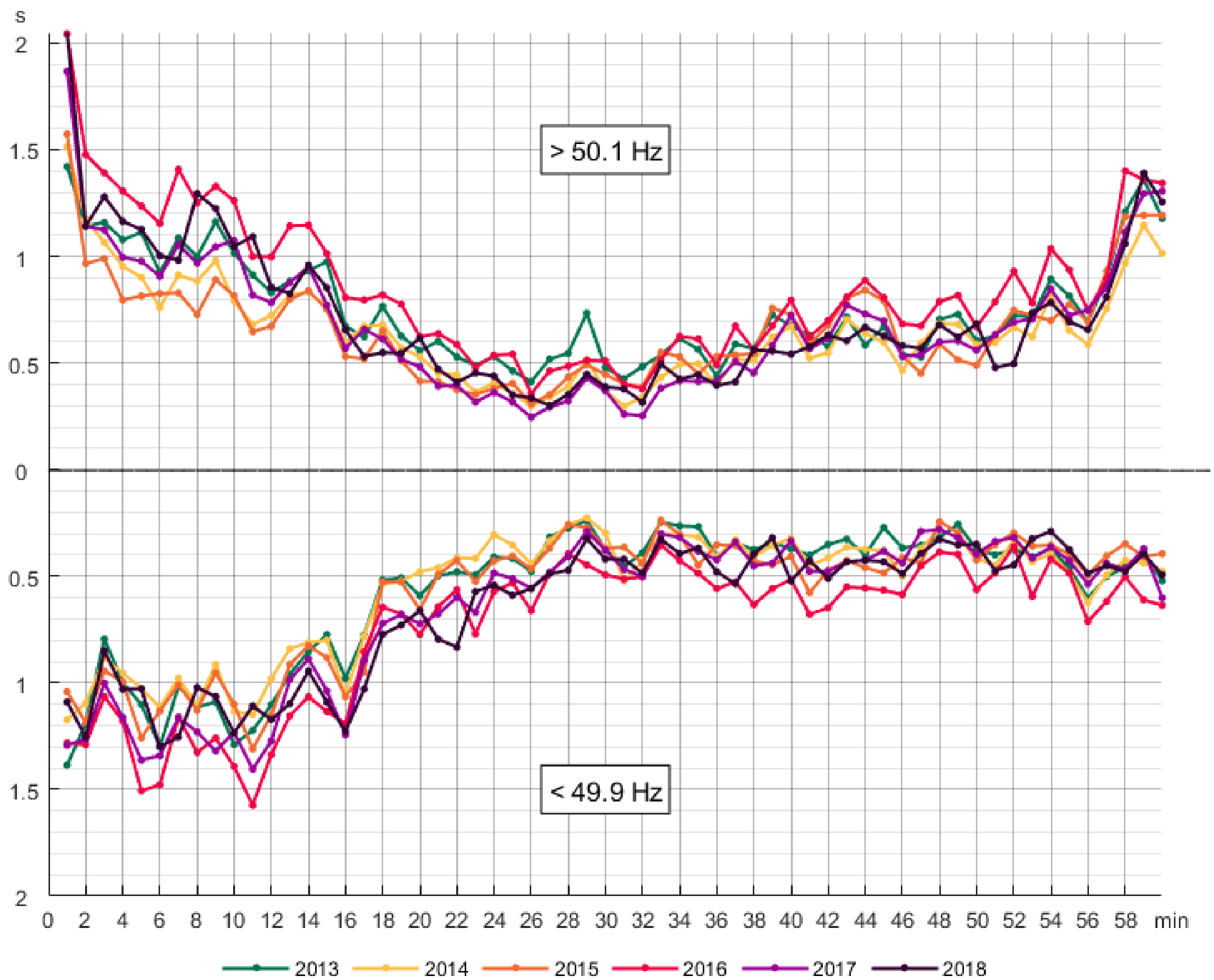
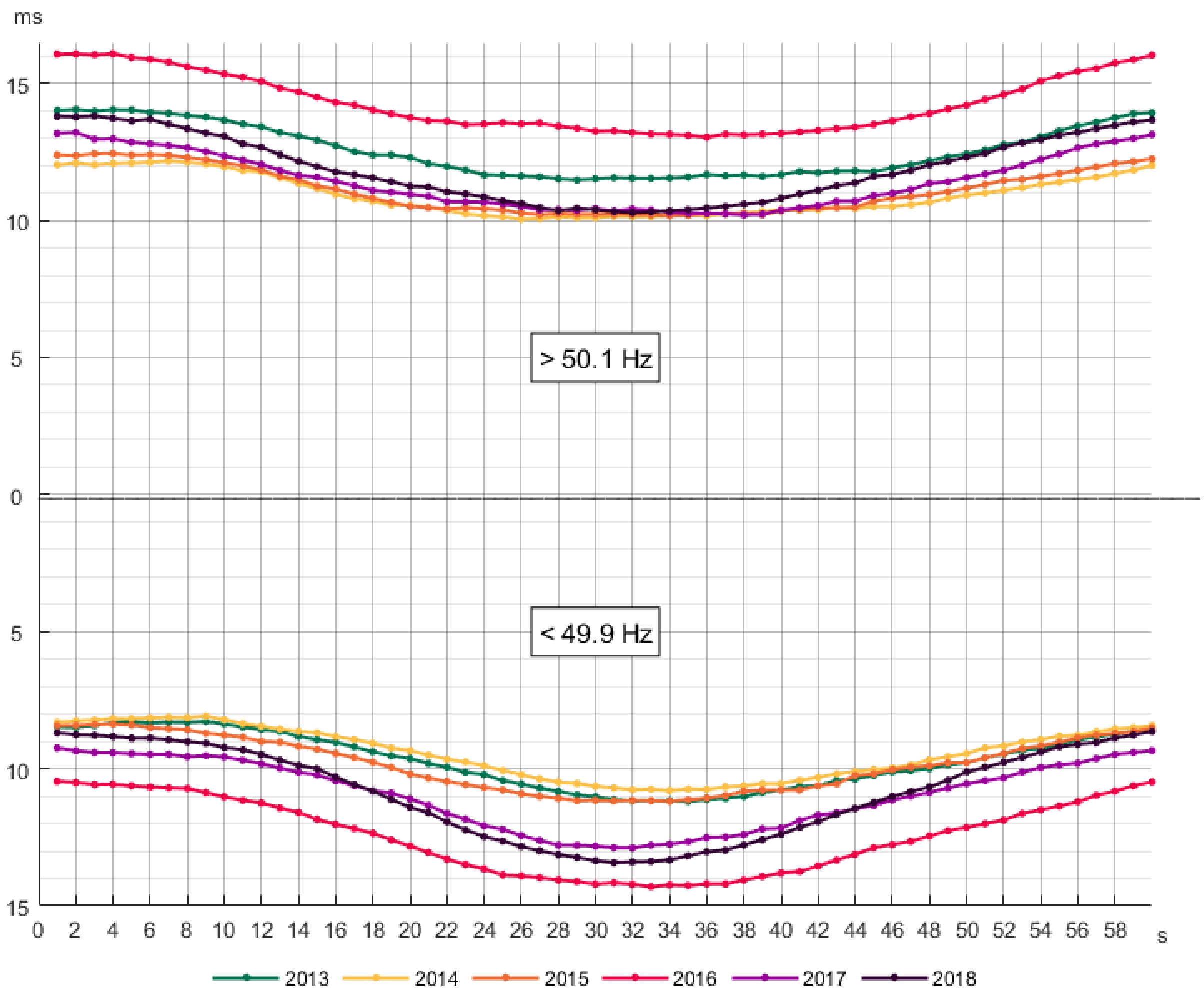


Figure 3.30 illustrates an average minute divided to 60 seconds. For each second of the average minute there is a value in milliseconds per minute that frequency has been over or below the standard frequency range. Overall the shape of the curve has been fairly smooth, but there have been slightly more over frequencies at the beginning and at the end of minutes. Under frequencies have occurred more frequently in the middle of minutes. The 2018 curve has followed the same pattern as in previous years.

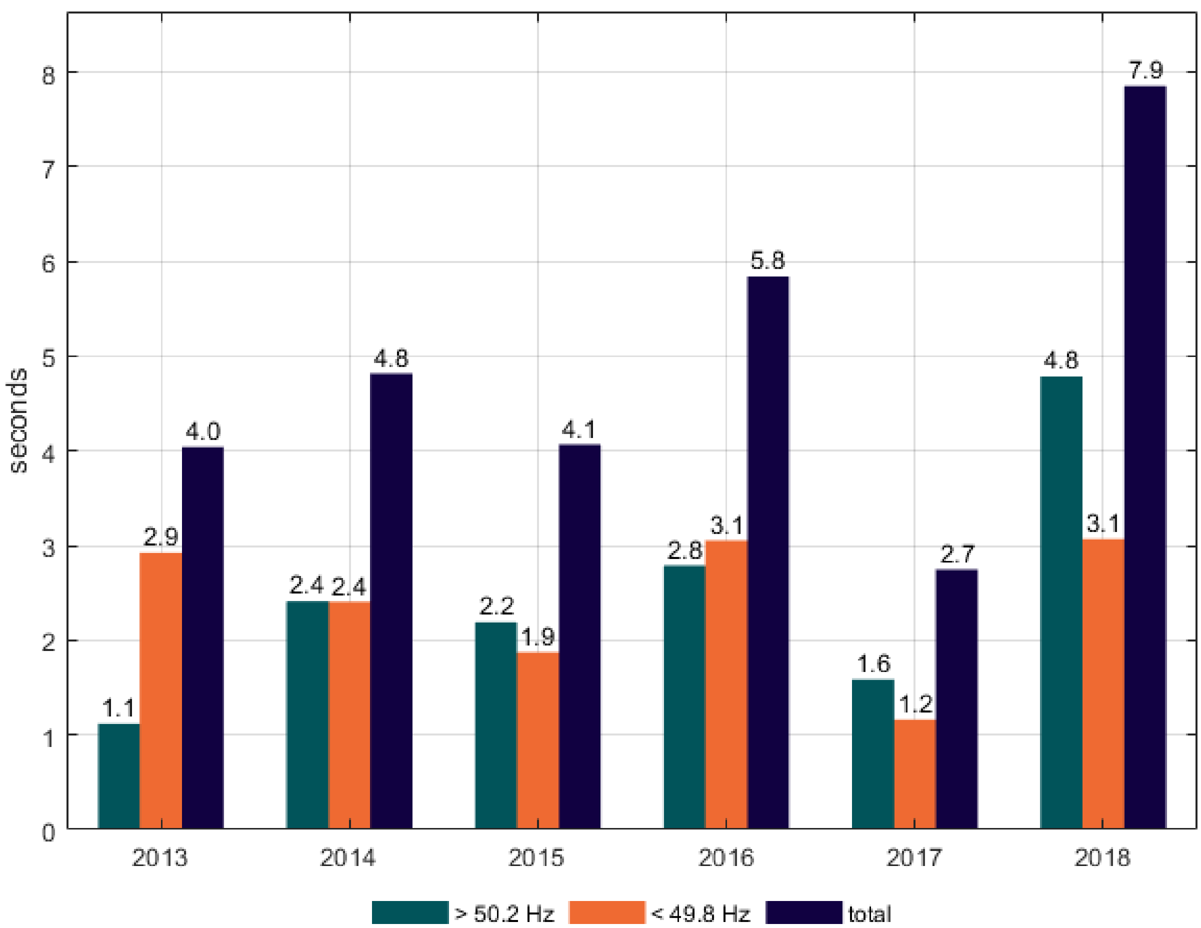
***Figure 3.30**. Number of milliseconds per minute outside the standard frequency range in 2013-2018 for each second of an average minute*



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 value was higher in 2018 than during any of the previous five years. For the last four years, there has been only slight difference between over and under frequencies except for 2018 when over frequencies were notably more common.

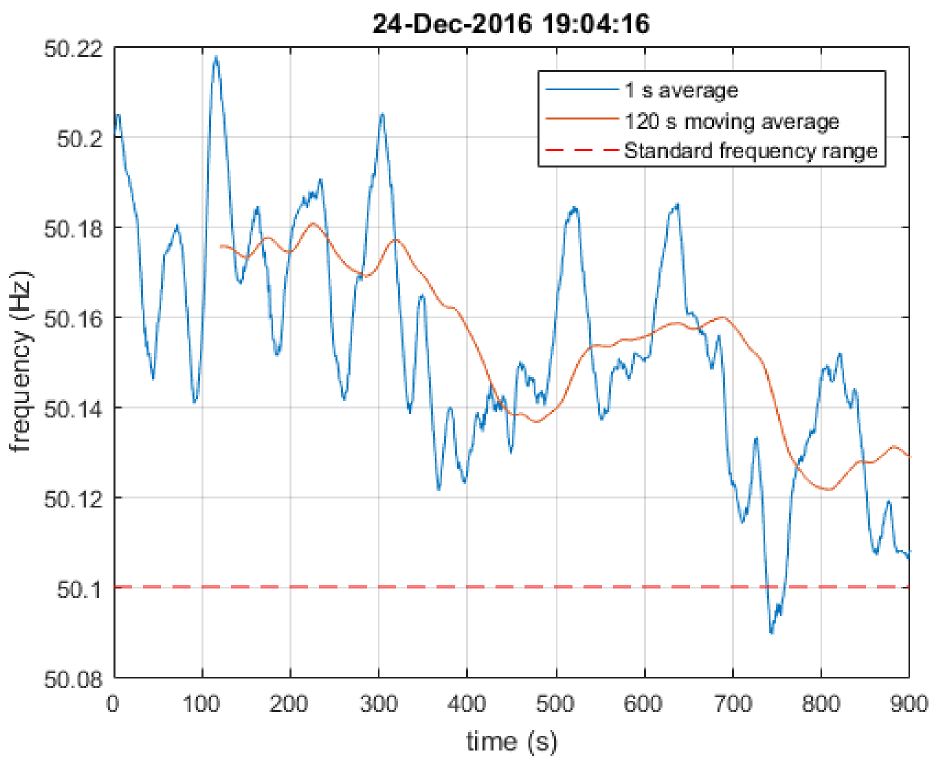
Figure 3.31**. **Average number of seconds per day that the frequency was outside the 49.8-50.2 Hz band for years 2013-2018



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 2013-2018 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.*

	2013		**2014**		**2015**		**2016**		**2017**		**2018**	
Month	**> 50.2 Hz**	**< 49.8 Hz**	**> 50.2 Hz**	**< 49.8 Hz**	**> 50.2 Hz**	**< 49.8 Hz**	**> 50.2 Hz**	**< 49.8 Hz**	**> 50.2 Hz**	**< 49.8 Hz**	**> 50.2 Hz**	**< 49.8 Hz**
January	0	0	0	0	0	0	1	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	0	0	1	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	0	0	1
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	0	0	1	0	0	0	**1**	**1**

Table 3.16 shows the number of events in 2013-2018 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.*

	2013		**2014**		**2015**		**2016**		**2017**		**2018**	
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	2	1	0	0	1	0	3	0	0	0	0	0
February	0	0	0	0	2	0	0	1	0	0	0	0
March	0	0	0	0	0	0	0	0	0	0	0	0
April	0	0	0	0	4	0	1	0	1	0	0	0
May	0	0	0	0	0	0	0	0	1	0	2	0
June	0	0	0	0	0	0	0	0	1	0	2	0
July	0	0	0	0	0	0	1	0	0	0	1	0
August	0	0	0	0	2	0	0	0	0	0	0	0
September	0	0	1	0	1	0	1	0	0	0	0	1
October	3	1	0	1	0	0	2	0	0	0	0	0
November	0	0	0	0	0	0	0	0	0	0	1	0
December	0	0	1	0	0	0	1	0	0	0	0	1
Entire year	5	2	2	1	10	0	9	1	3	0	**6**	**2**
Sum	**7**		**3**		**10**		**10**		**3**		**8**	

3.4.3 **Time outside 49.0-51.0 Hz**

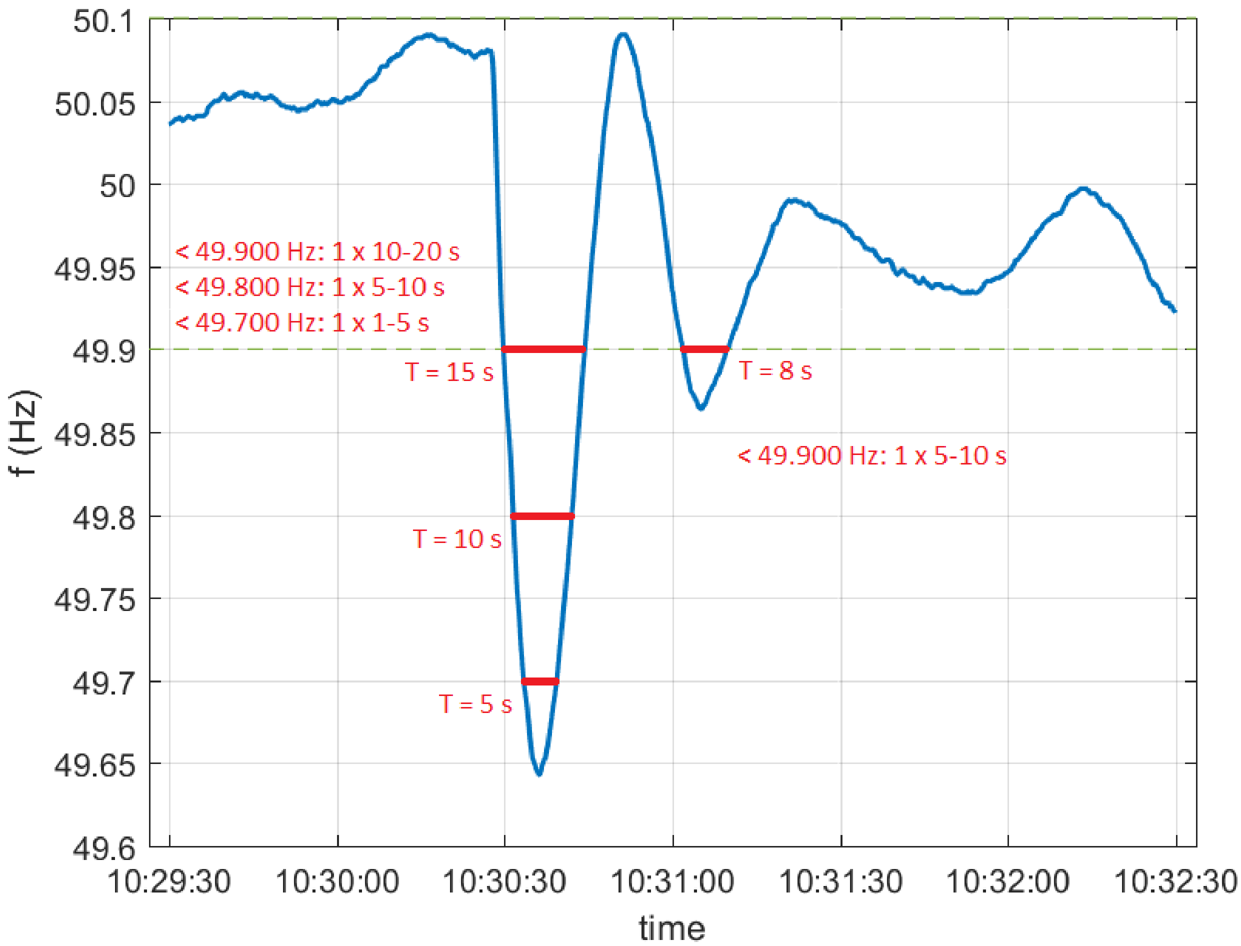
Time outside 49.0 Hz and 51.0 Hz is calculated by counting the number of samples that are below 49.0 Hz or above 51.0 Hz and multiplying the number by the time duration of the sample. The criteria are also defined in SO GL Article 131(a) (v). The resolution of the data used was 1 second.

There were no instances in 2013-2018 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 2013 to 2018. 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 2013

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	26346	5765	3602	4965	3299	906	725	119	45727	1370.20	7.95
> 50.2	118	14	15	10	2	1	0	0	160	54.80	2.59
> 50.3	0	1	0	0	0	0	0	0	1	3.00	3.00
< 49.9	25286	4797	2828	3954	2774	666	542	81	40928	948.40	6.86
< 49.8	103	16	25	22	3	1	4	0	174	81.30	6.01
< 49.7	13	8	5	3	0	0	0	0	29	14.00	3.68
< 49.6	13	0	4	0	0	0	0	0	17	10.00	2.04
< 49.5	0	4	0	0	0	0	0	0	4	4.70	3.60

Table 3.18. 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 3.19. 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 3.20. 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 3.21**. 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 3.22**. 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

Figure 3.34 is a visual representation of the data in Tables 3.17-3.22. Number of deviations are now given as a daily average instead of total amount per year. There was a remarkable fall in the number of short-lasting frequency deviations from year 2013 to 2014. The amount of short-lasting deviations rose from 2014 to 2016 and decreased again in 2017. Year 2018 has been very similar to 2017 but slightly worse.

Figure 3.34. Daily average number of frequency deviations per duration

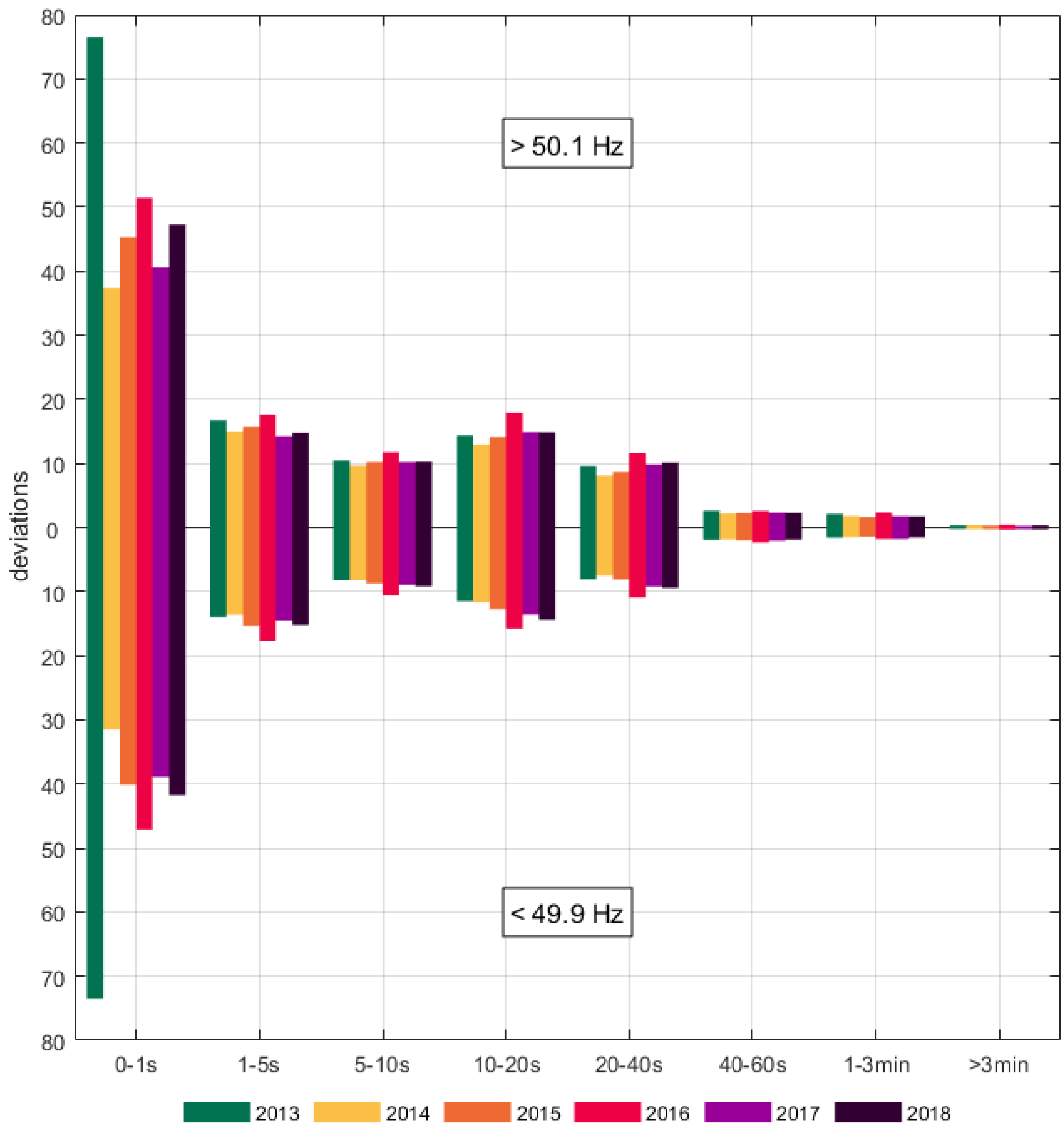
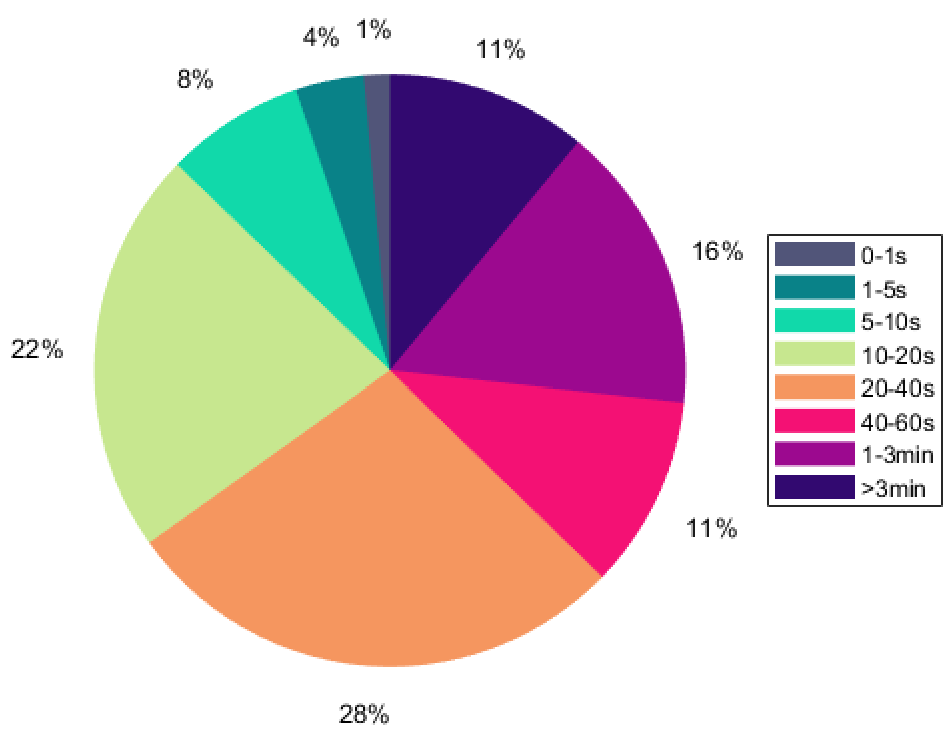


Table 3.23 shows how deviations of different duration affected to the total time outside the standard frequency range in 2018. Times are given in minutes. Pie chart in Figure 3.35 shows in percentages how the total time outside the standard frequency range was divided between deviations of different duration. Deviations with duration of 10-20 s and 20-40 s lasted half of the total time outside the standard frequency range.

Table 3.23*. *Total minutes in 2018 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	216	469	1309	1686	670	991	687	6115
< 49.9 Hz	79	219	420	1265	1564	556	844	592	5540
total	166	434	889	2574	3250	1227	1836	1279	11655

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 2018. Figure 3.36 represents the total number of deviations per duration for each month in 2018. Most of the deviations lasted only between 0-1 seconds. Months from June to October and also January had generally the most frequency deviations across all durations. The least amount of deviations occurred in the second and last months of the year.

Figure 3.36. Total number of frequency deviations per duration for each month in 2018

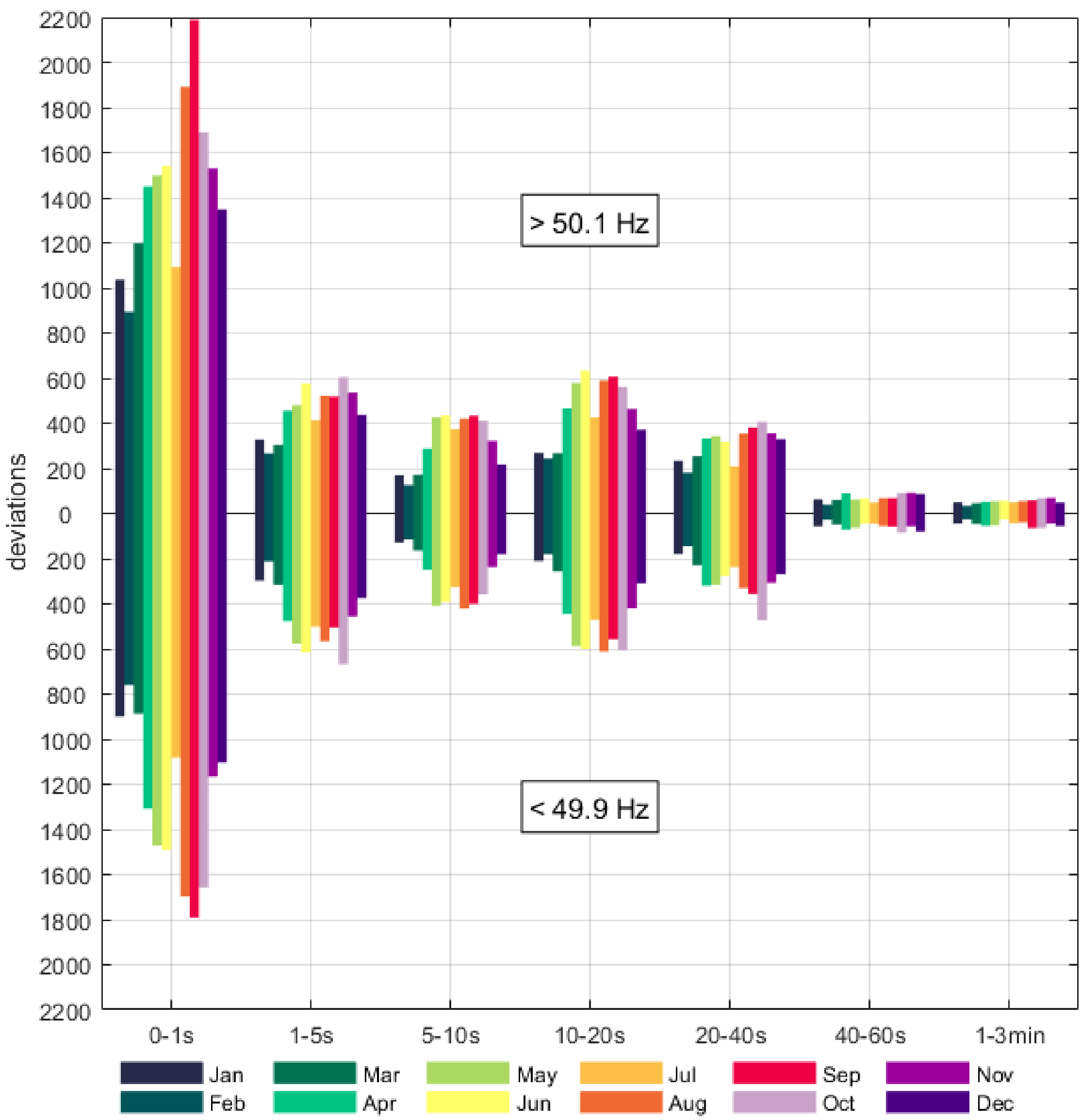
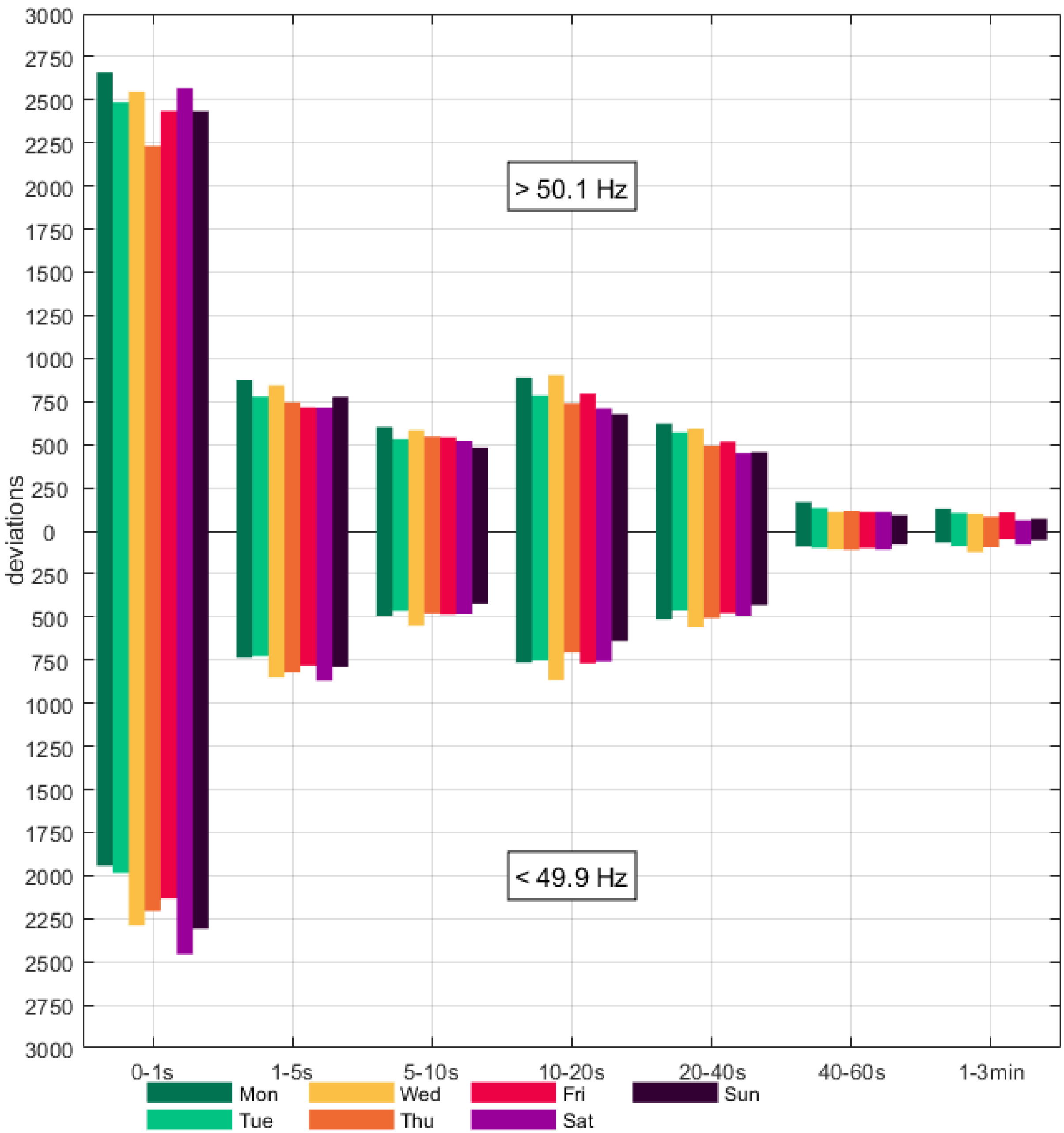


Figure 3.37 shows the number of deviations for every day of the week. Short-lasting deviations over 50.1 Hz were more common on weekends but for longer durations, the deviations over 50.1 Hz were pretty even throughout the week. Short under 49.9 Hz deviations took place more often in the end of the week on Friday and Saturday. Longer deviations under 49,9 Hz took place more often in the beginning of the week simlar to over frequencies.

***Figure 3.37**. Total number of frequency deviations per duration for each day of the week in 2018*



Figures 3.38 and 3.39 illustrate the number of deviations per duration inside the day with Figure 3.38 including hours from 0-11 and Figure 3.39 the hours from 12-23. By far most of the deviations over the standard frequency range occurred around midnight in the first and last hours of the day.

***Figure 3.38**. Total number of frequency deviations per duration for hours 0-11 in 2018*

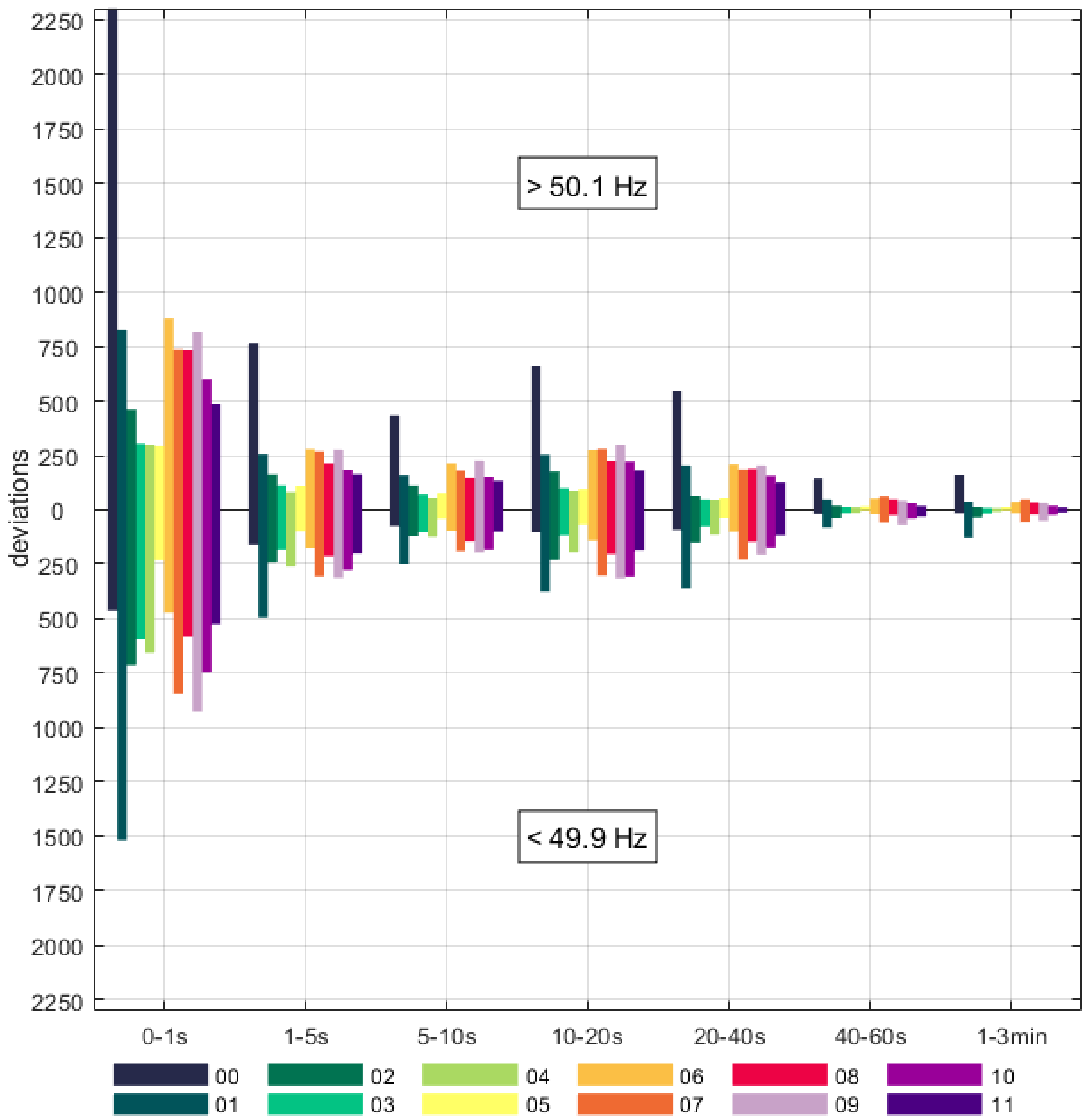


***Figure 3.39**. Total number of frequency deviations per duration for hours 12-23 in 2018*

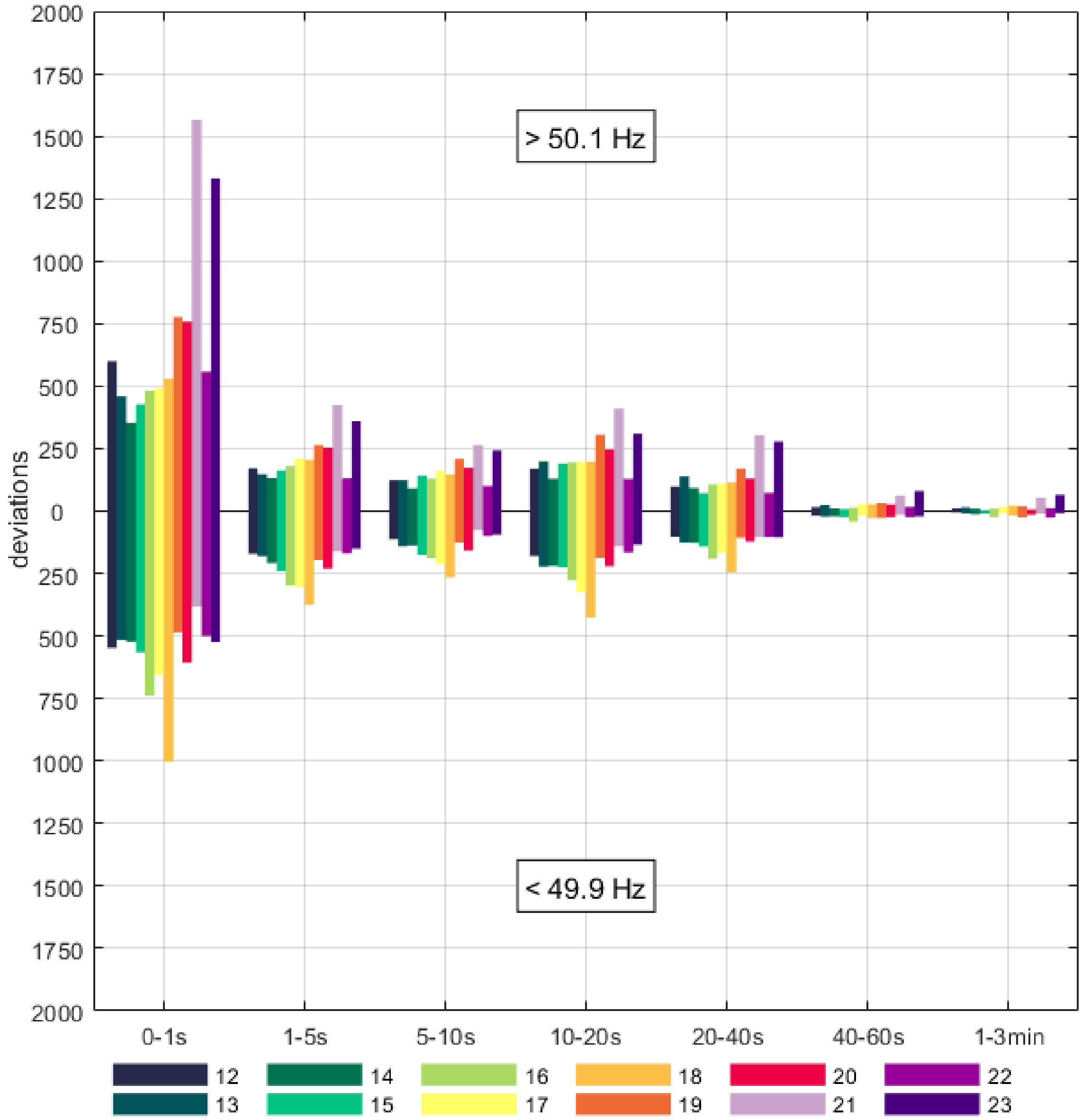
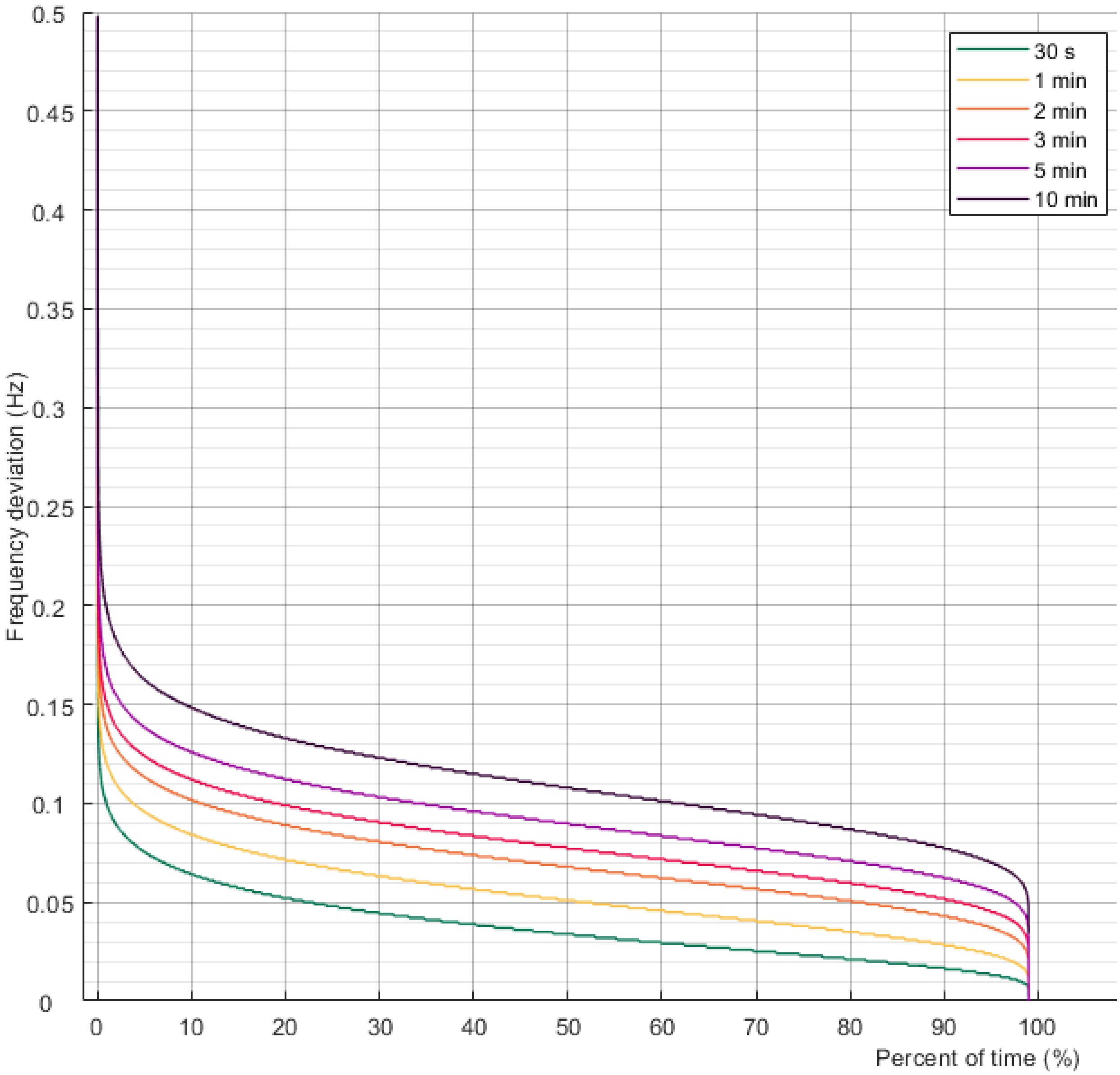


Figure 3.40 represents the duration curve of maximum frequency deviation inside different time windows in year 2018. The time window was slid through the year with a time interval of one second. Studied time windows can be found from legend of the Figure 3.40. Chapter 4 shows in detail frequency disturbances 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 2018**



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 3.41 shows the total number of deviations for years between 2013-2018. The number of deviations has increased from previous year, but it is fairly even with the other years in the figure.

Figure 3.41**. **Total number of longer frequency deviations per duration between 2013-2018

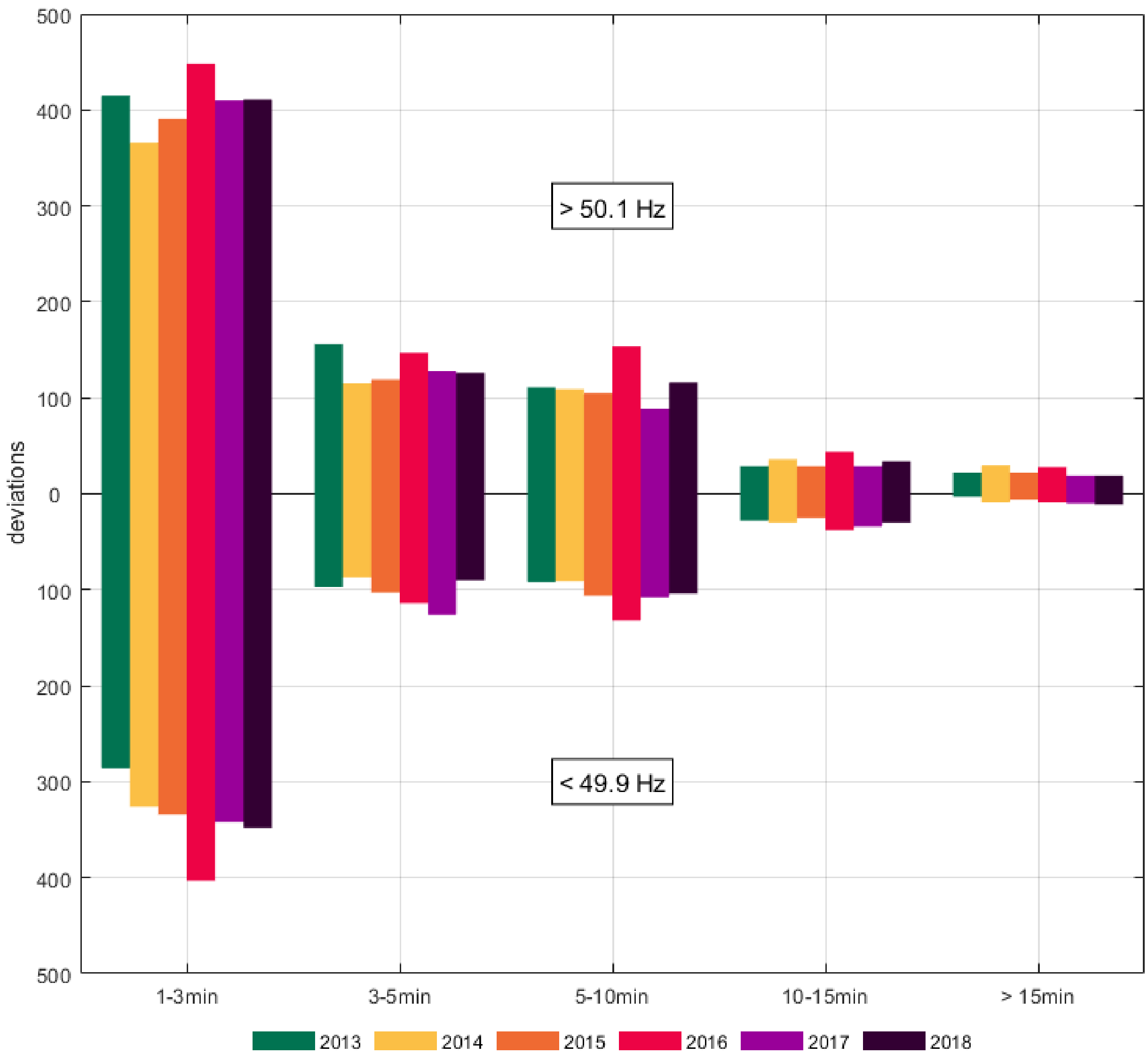


Figure 3.42 shows the total number of longer deviations for each month in 2018. September had the most deviations lasting between 1-3 minutes.

***Figure 3.42**. Total number of longer frequency deviations per duration for each month in 2018*

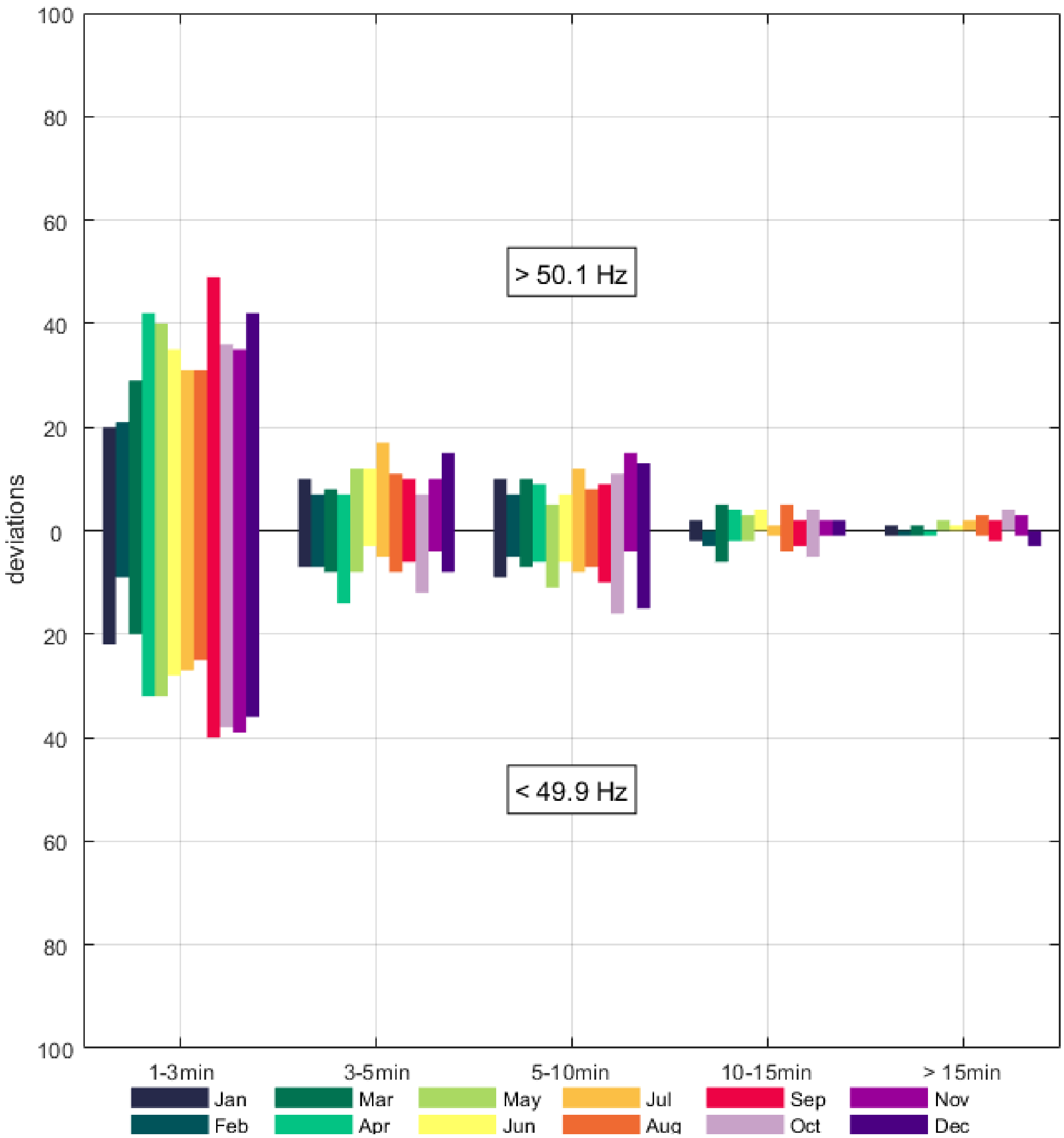
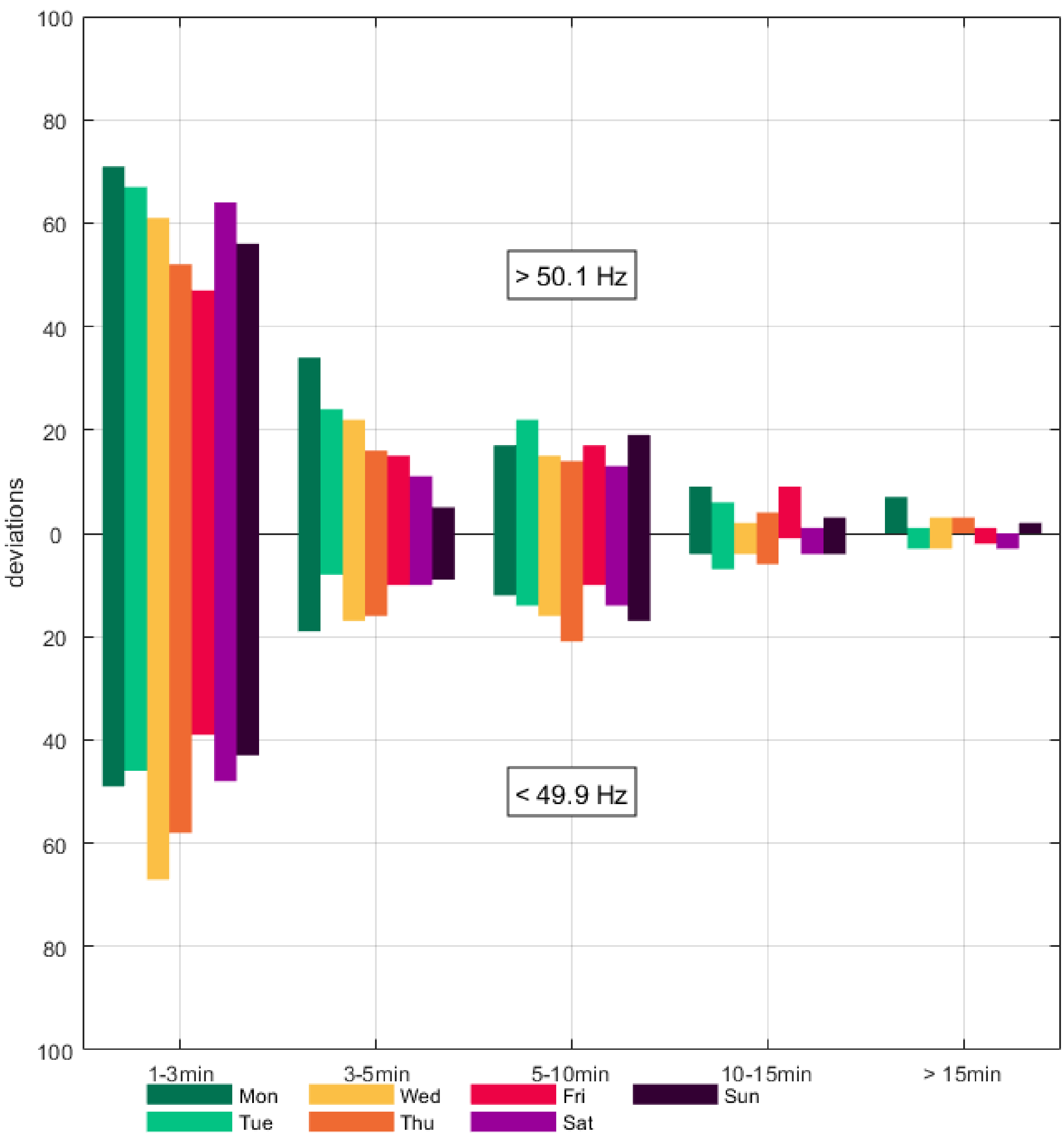


Figure 3.43 represents the number of deviations with different durations during every day of the week in 2018. Beginning of the week had more over frequencies while under frequencies are distributed fairly evenly throughout the week.

***Figure 3.43**. Total number of longer frequency deviations per duration for each day of the week in 2018*



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 2018*

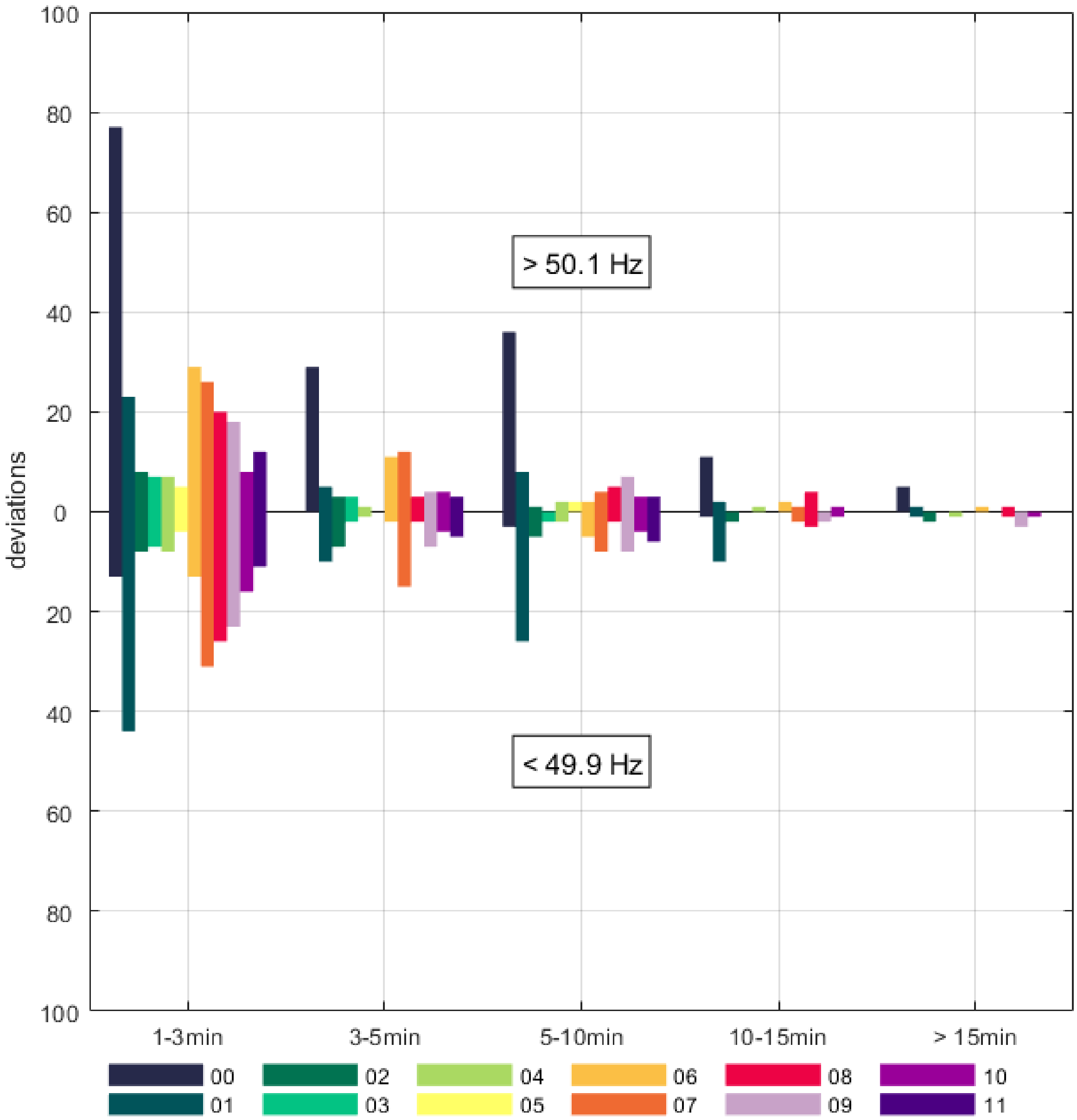
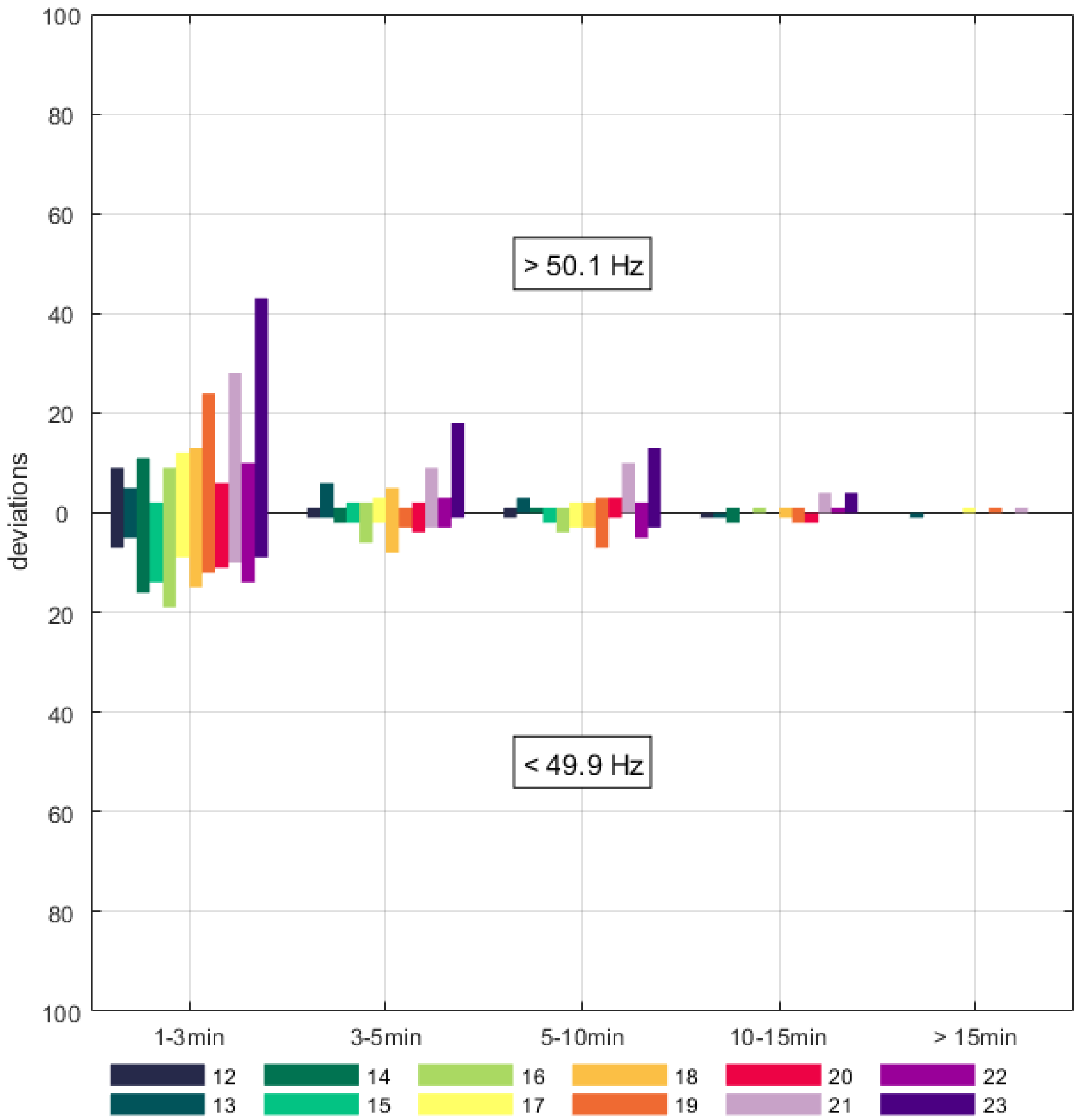


***Figure 3.45**. Total number of longer frequency deviations per duration for hours 12-23 in 2018*



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 2013 to 2018. The amount has remained fairly even throughout except for 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 2013-2018

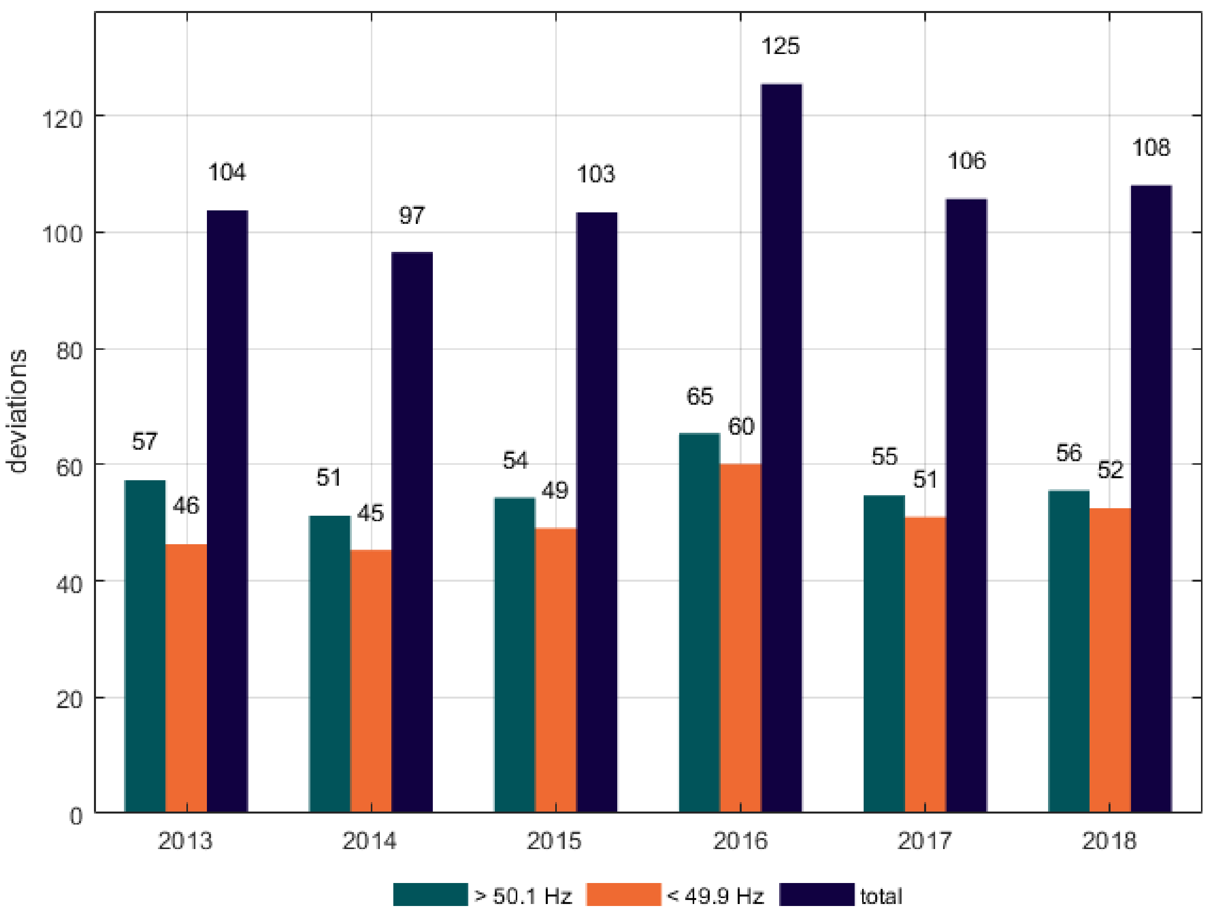


Figure 3.47 represents the daily average number of threshold crossings for each month in 2018. There has been slightly more crossings over 50.1 Hz than crossings under 49.9 Hz. In total, the frequency crossed the threshold more often between April and June and also between August and October.

***Figure 3.47**. Daily average number of threshold crossings for every month in 2018*

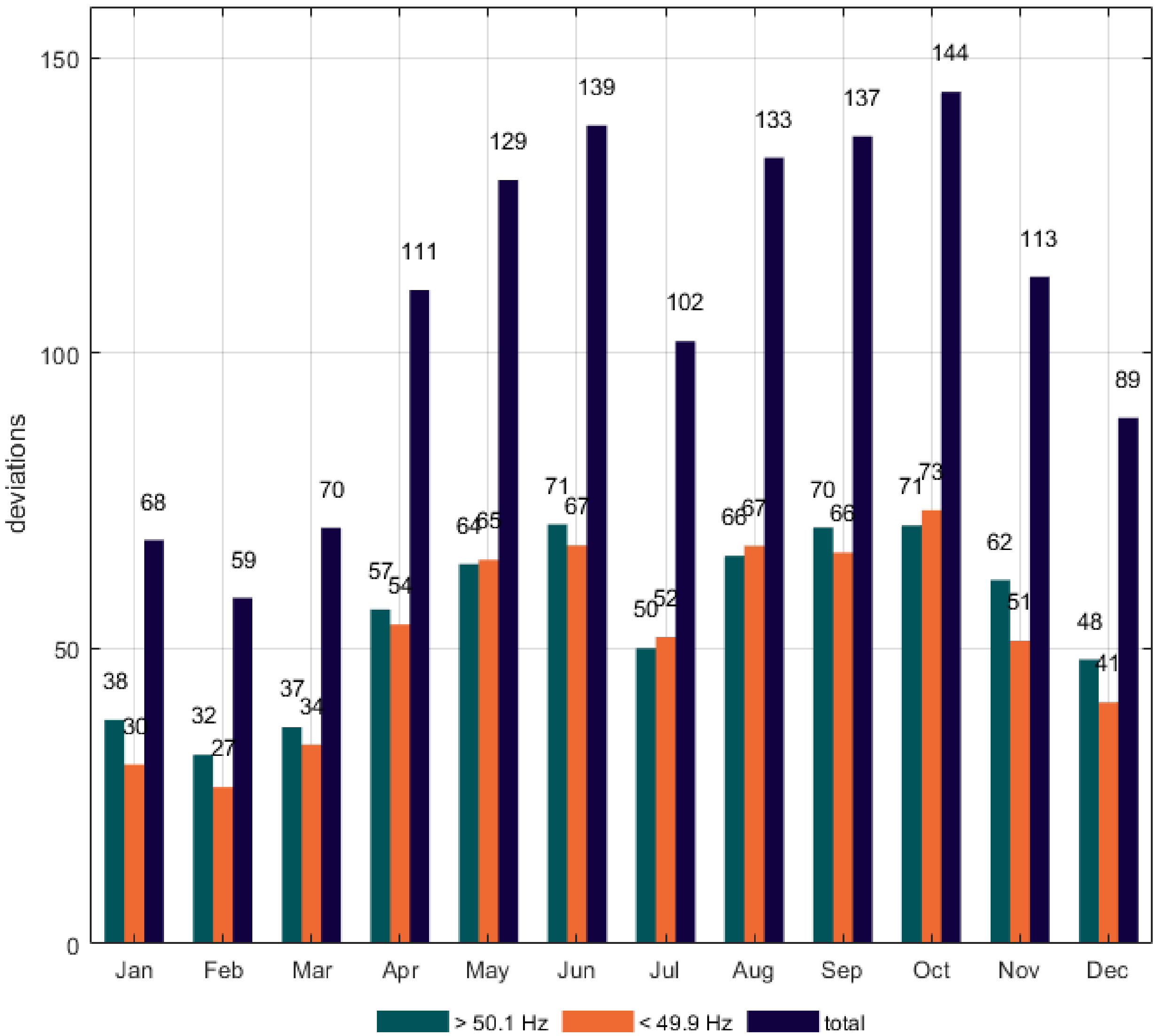
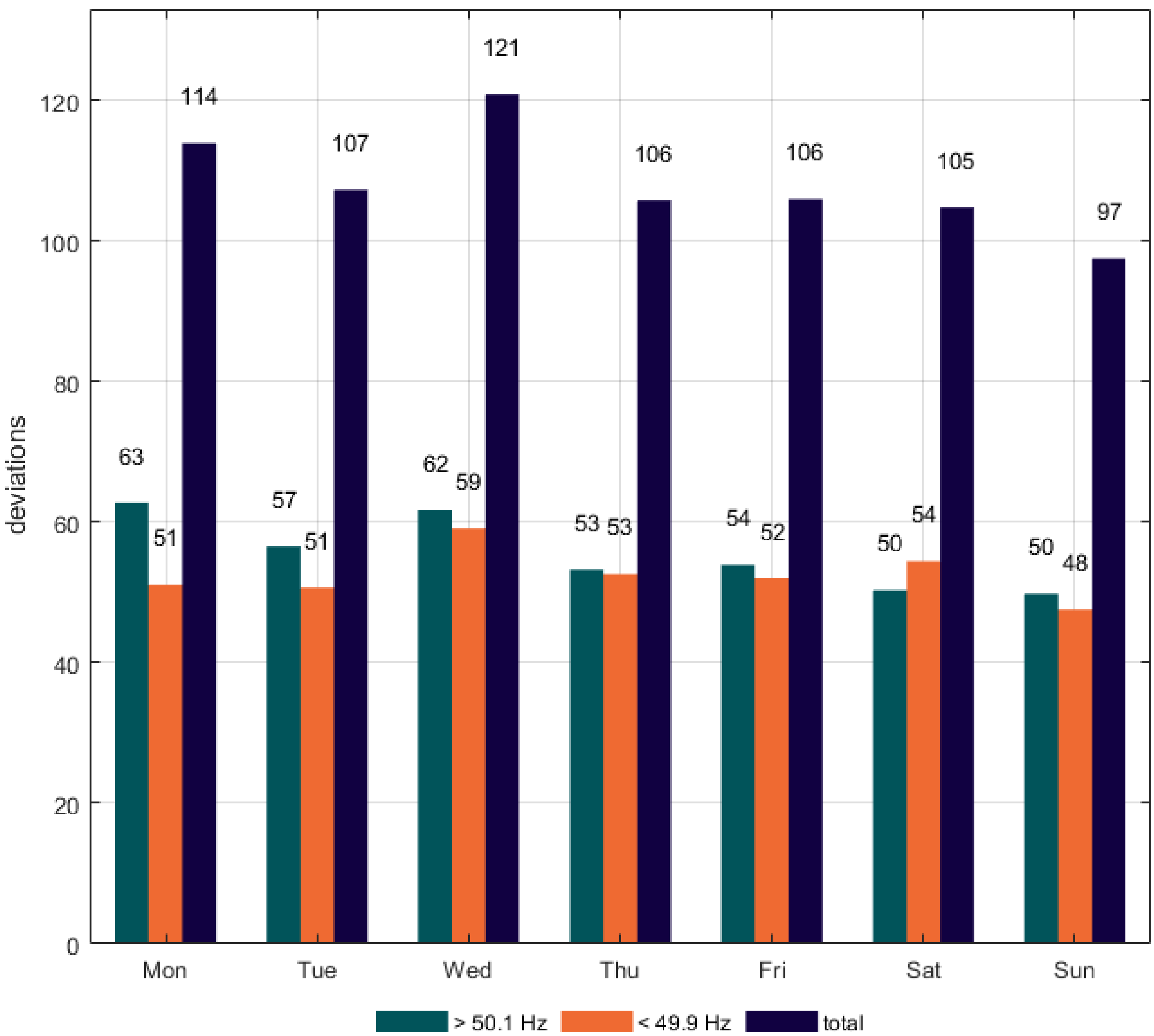


Figure 3.48 shows the number of threshold crossings for each day of the week in 2018. During the weekends, the number was smaller.

***Figure 3.48**. Daily average number of threshold crossings for every day of the week in 2018*



The number of threshold crossings inside the day on average is in Figure 3.49. The least amount of threshold crossings occur in the night from 3 to 5, afternoon from 11 to 15 and from 22 to 23. Close to midnight and in the morning around 7-9 the frequency crossed the threshold more often.

***Figure 3.49**. Average number of threshold crossings for every hour of the day in 2018*

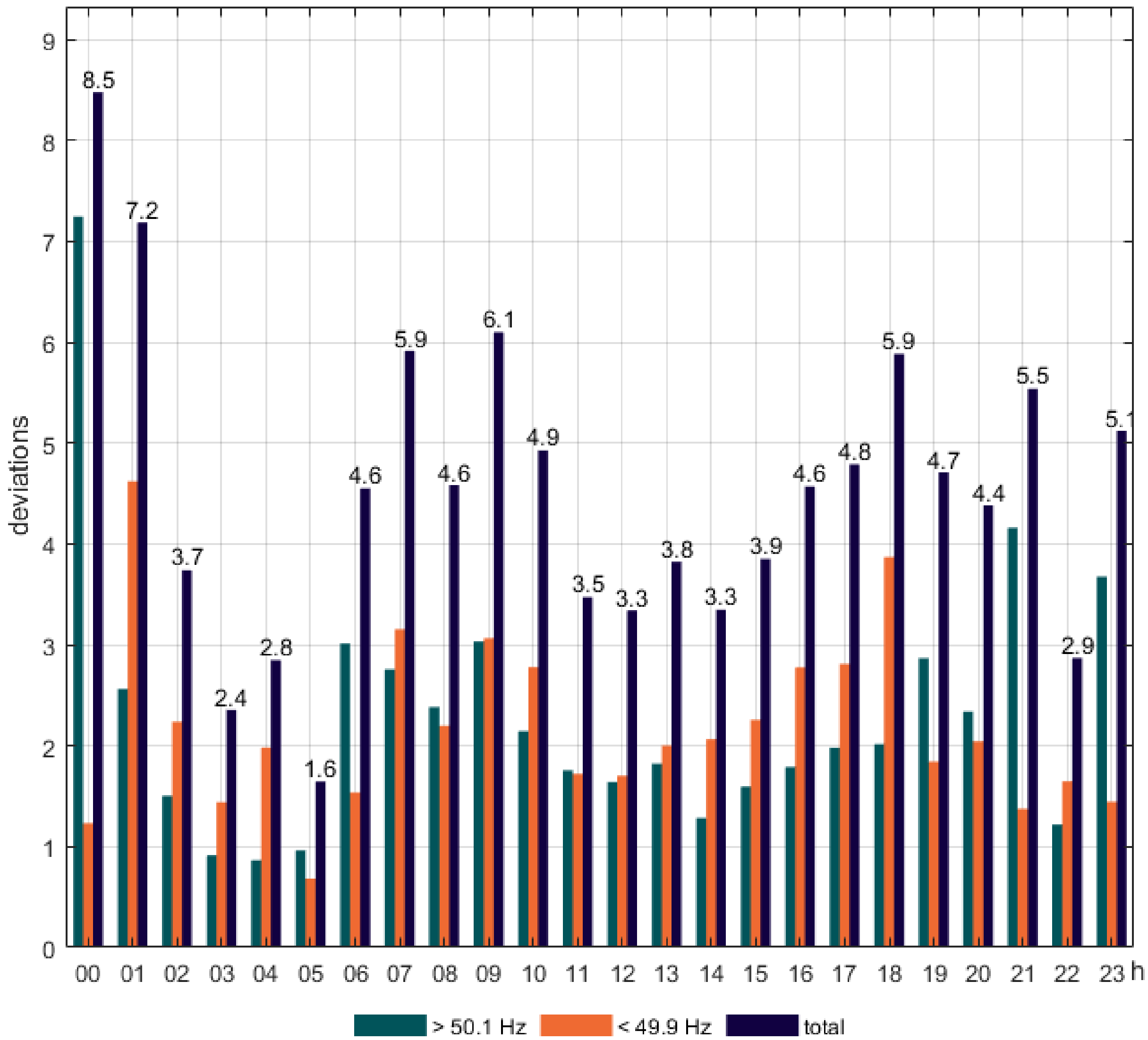
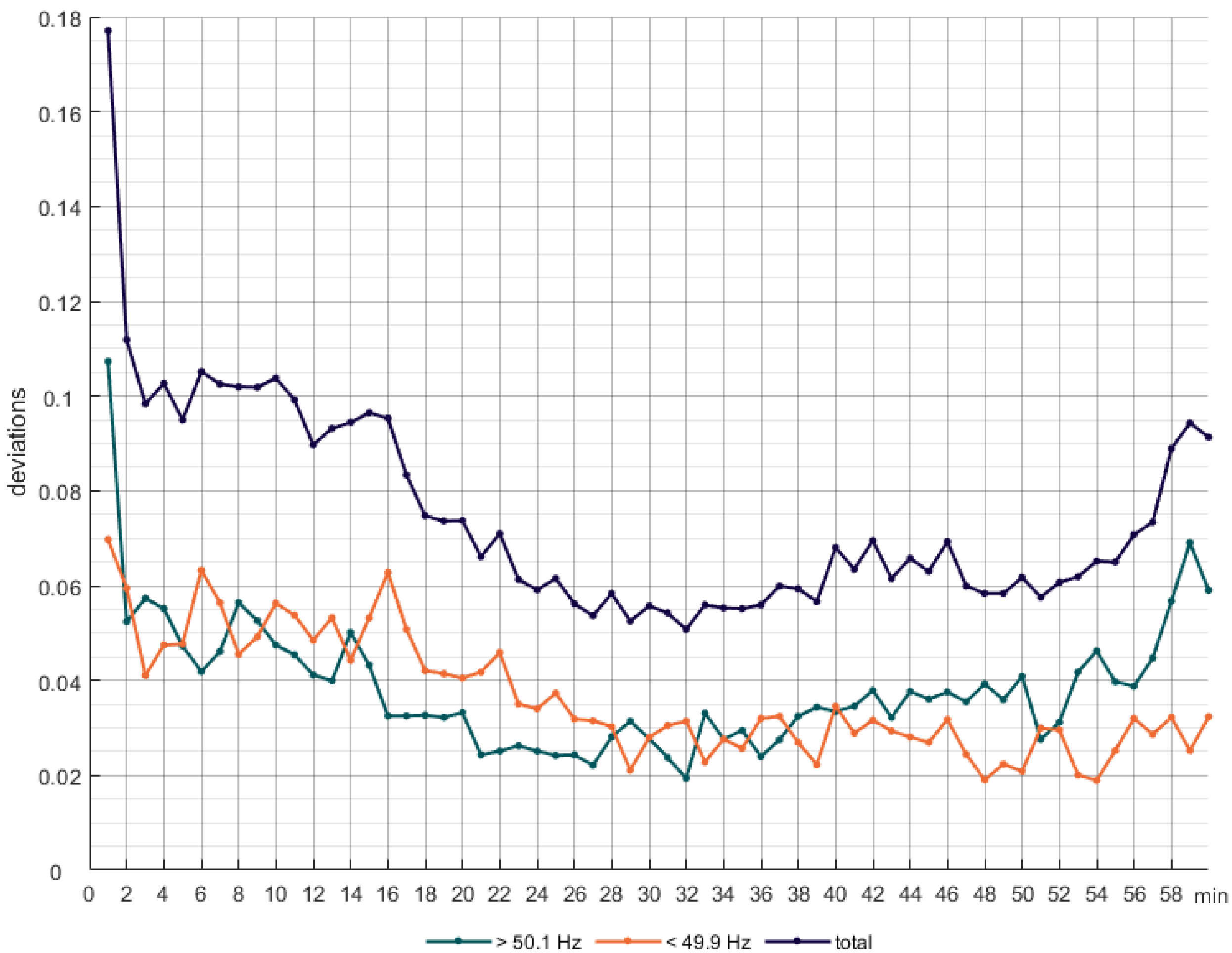


Figure 3.50 represents the average number of threshold crossings for every minute inside the hour. Most crossings take place within the first minutes of the hour. During the first 30 minutes of the hour, the frequency crosses 49.9 Hz more often, while more crossings of 50.1 Hz take place in the latter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

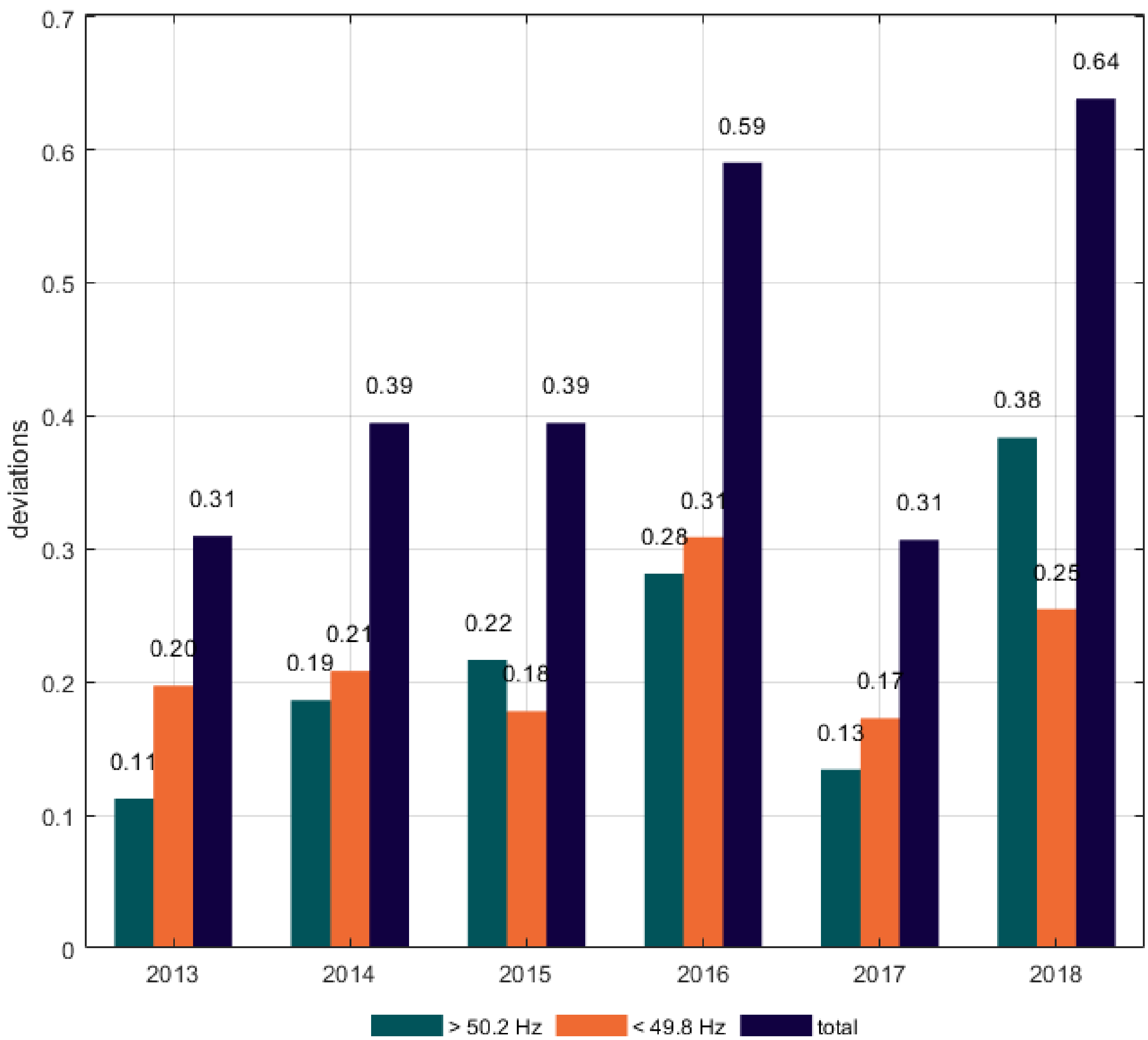
***Figure 3.50**. Average number of threshold crossings for every minute of the hour in 2018*



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. The number was significantly higher in 2016 and 2018 but otherwise it has been fairly constant. 2017 is one of the best years in this comparison.

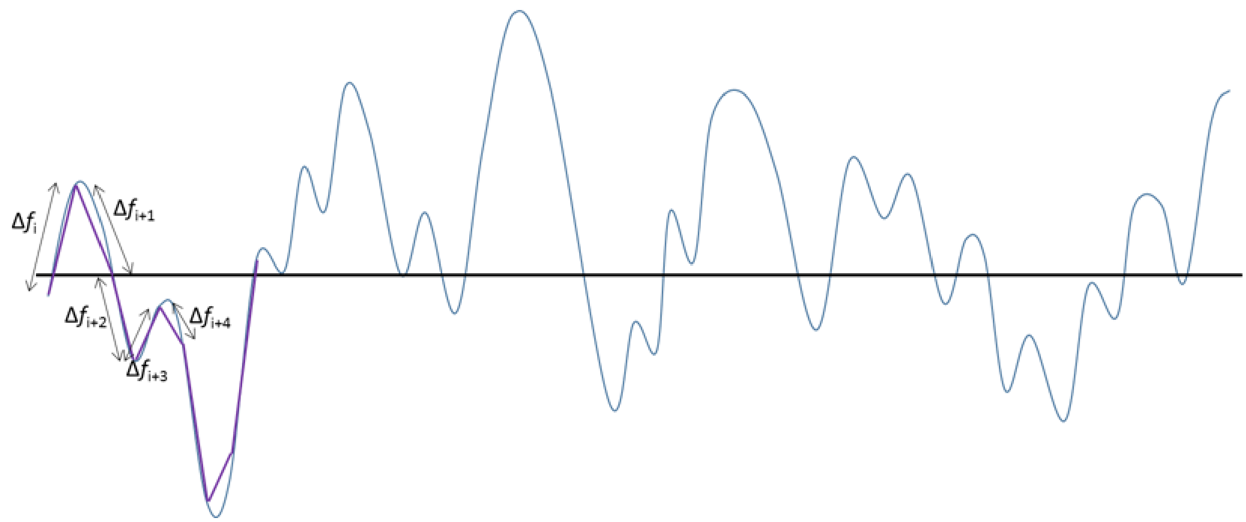
***Figure 3.51**. Daily average number of frequency deviations larger than ±200 mHz for years 2013-2018*



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 3.52. 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 frequency path, where Δt is the length of the time step (in this case 0.1 s).

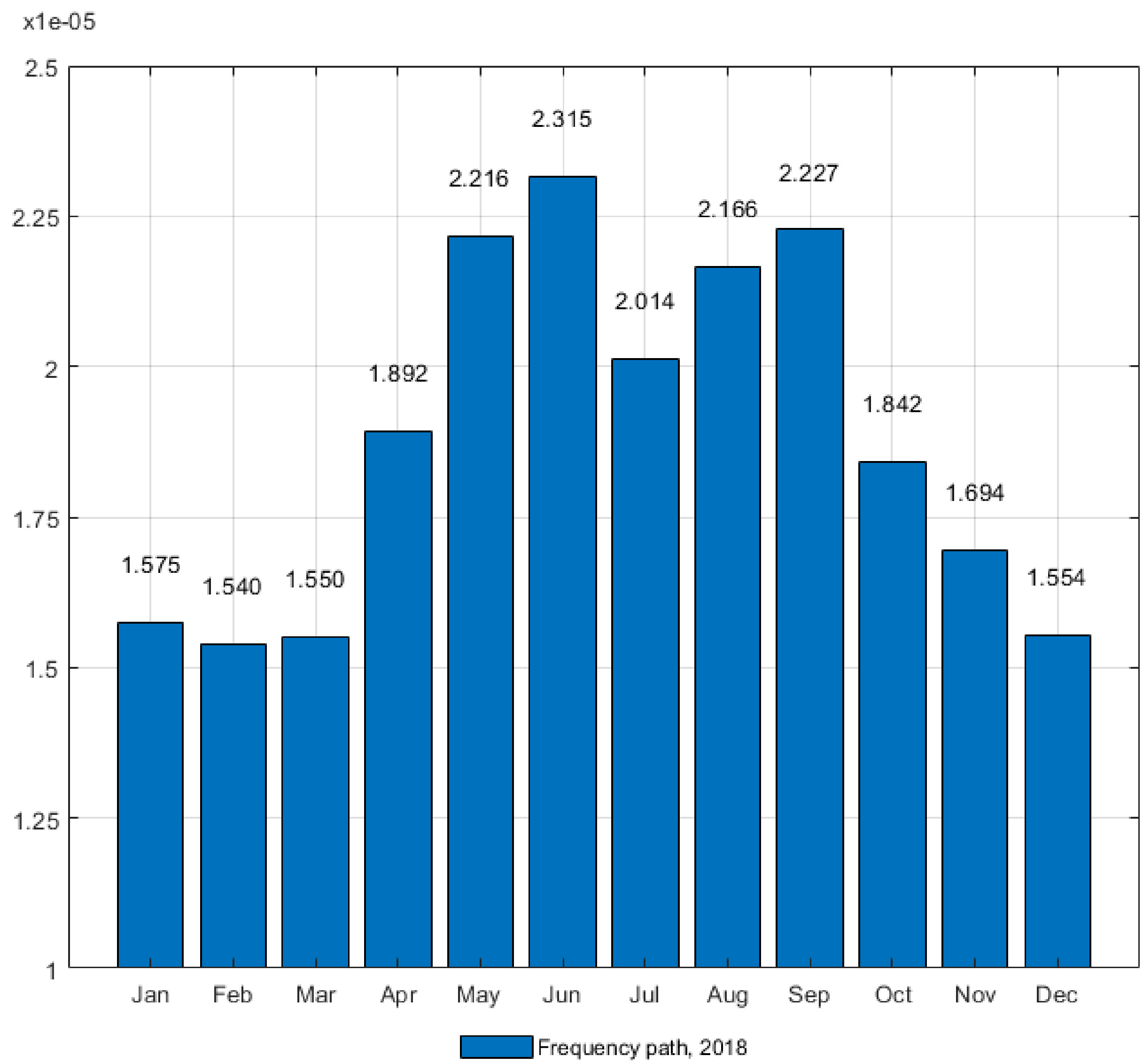
Figure 3.52. Frequency quality index: Length of the frequency path [7]



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

Figure 3.53 represents the frequency path for each month in 2018. June has a conciderably longer frequency path in 2018 when compared to the January of 2017. The path stayed realitively smooth from January to March. After March the length of the frequency path started to increase. The length of the frequency path peaked first in June and second time in September after which the frequency path started to decrease steadily. The length of the frequency path per month in 2018 is longer than the corresponding value in 2017 except for February and March.

***Figure 3.53**. Length of the frequency path month by month in 2018*



The frequency path for every day of the week shows in Figure 3.54. There has been very little variation in the frequency path between the days.

***Figure 3.54**. Length of the frequency path for every day of the week in 2018*

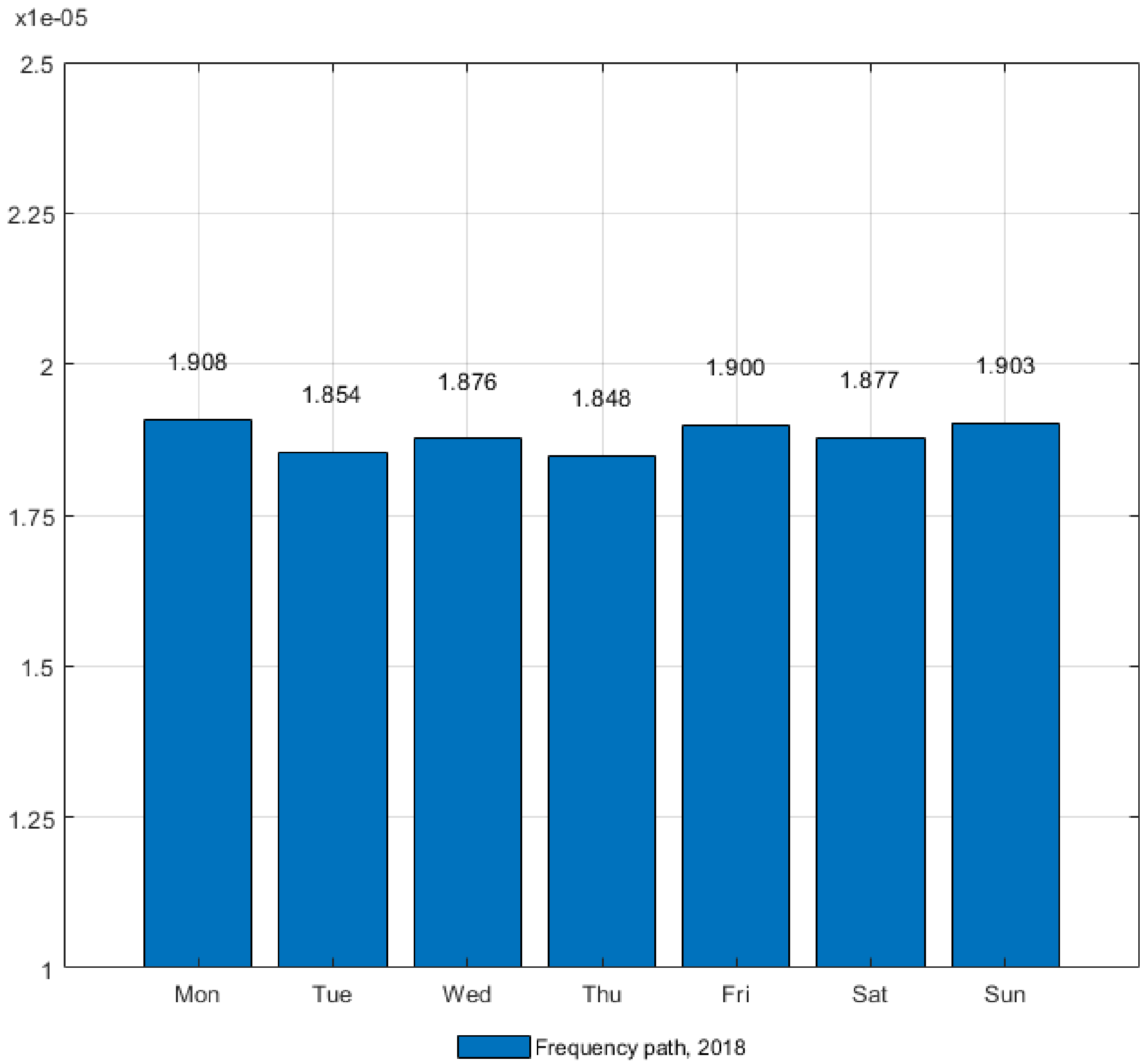


Figure 3.55 shows the frequency path during the day. The path is longer closer to the shift of the day and shorter around noon.

***Figure 3.55**. Length of the frequency path for every hour of the day in 2018*

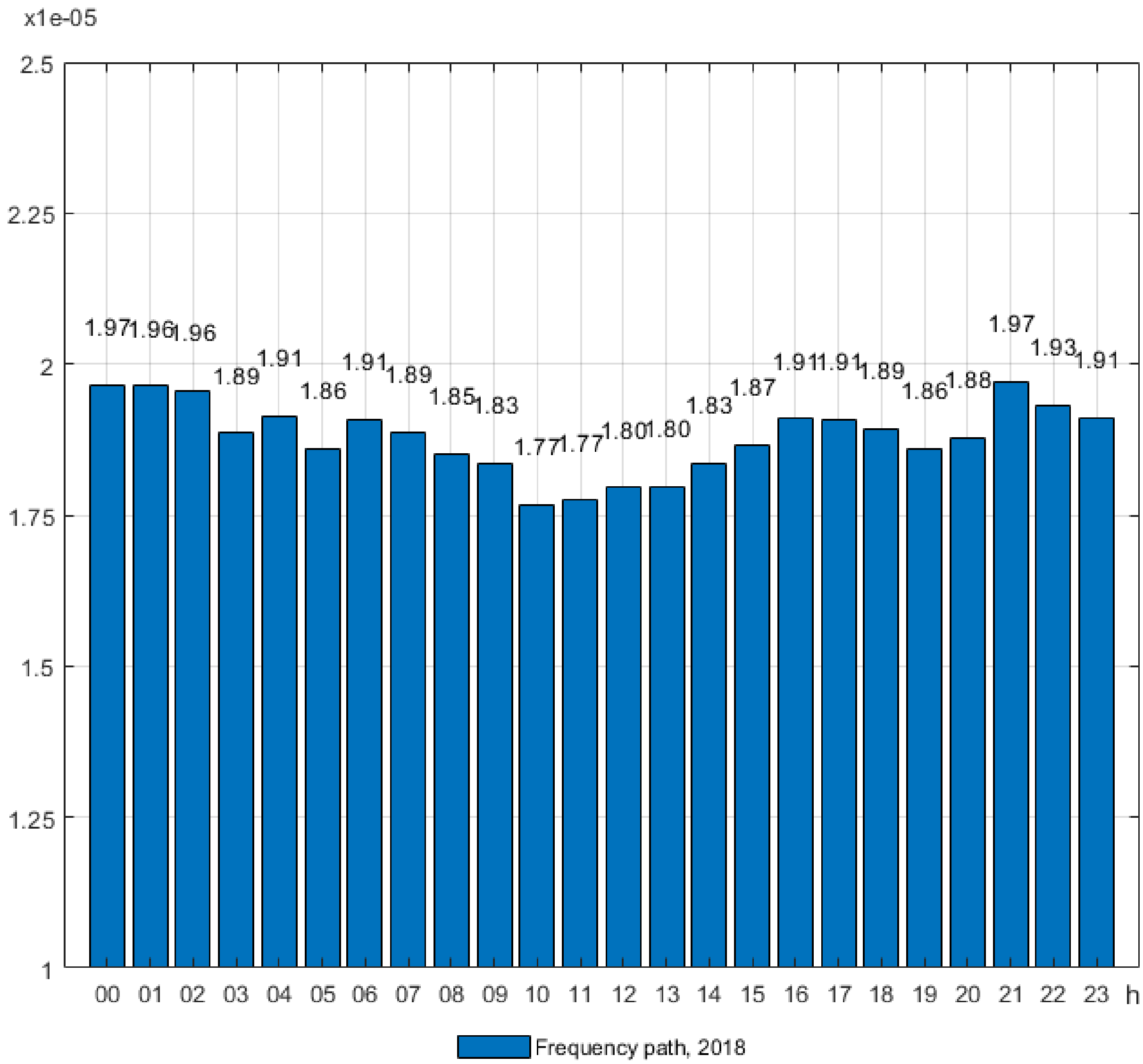
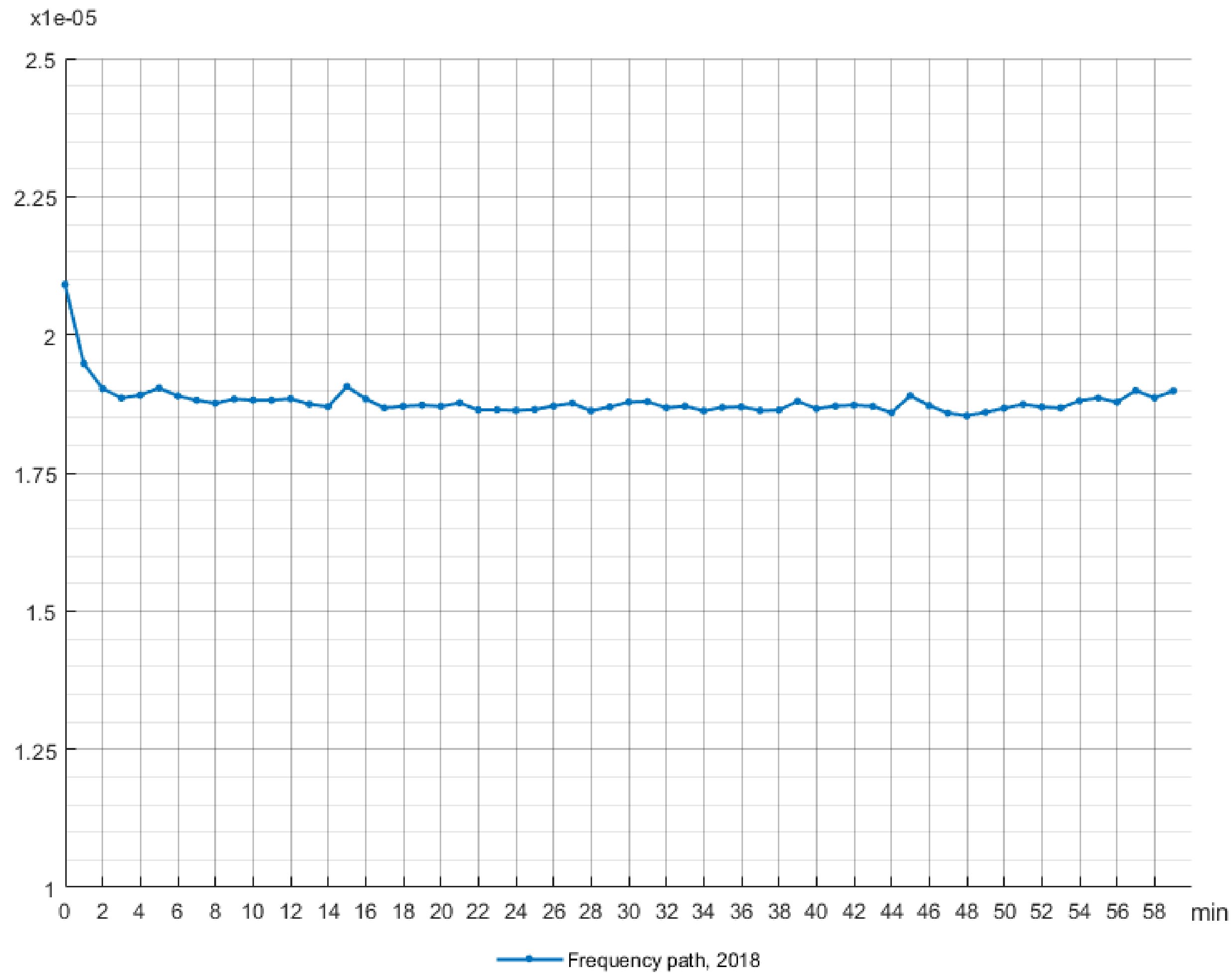


Figure 3.56 represents the average frequency path for every minute inside the hour. The path is longer during the first minutes of the hour, but otherwise it stays pretty even throughout the hour.

***Figure 3.56**. Length of the frequency path for every minute of the hour in 2018*



3.8 **Amount of frequency oscillation**

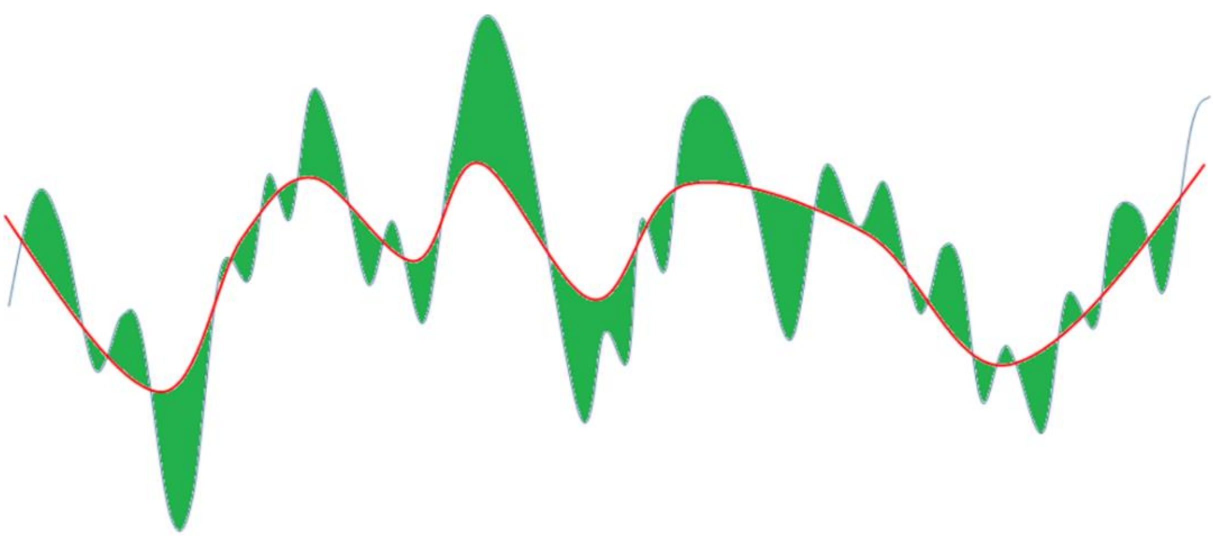
Frequency of the Nordic synchronous system oscillates constantly. Time period of the oscillation is approximately 40 to 90 seconds. This behavior is a natural characteristic of the system but it can be influenced through adequate settings of system reserves. Oscillation has an increasing effect on the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

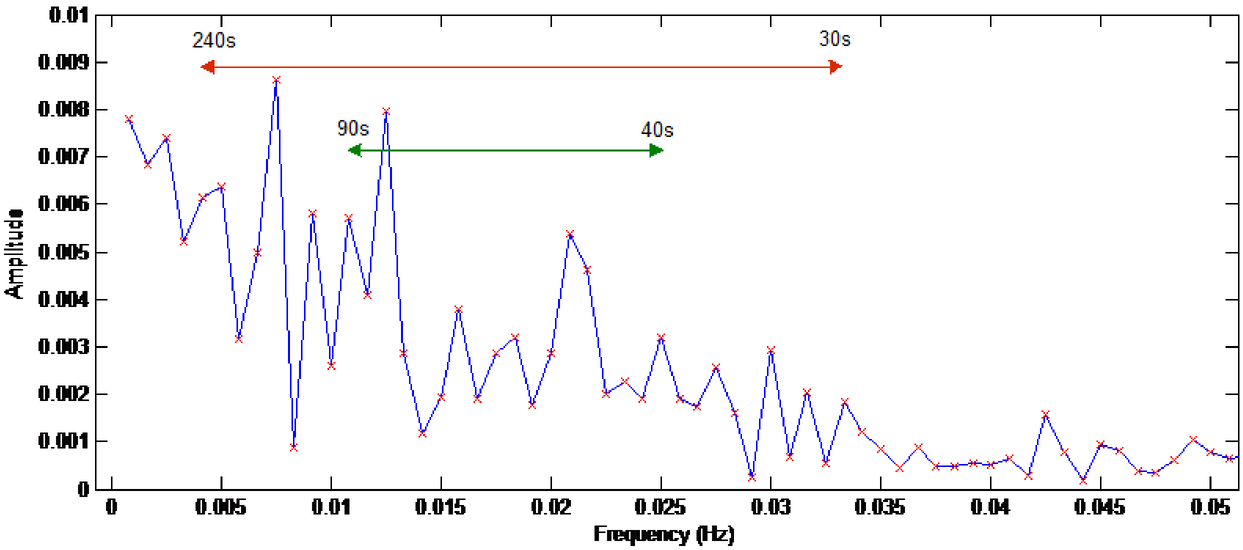
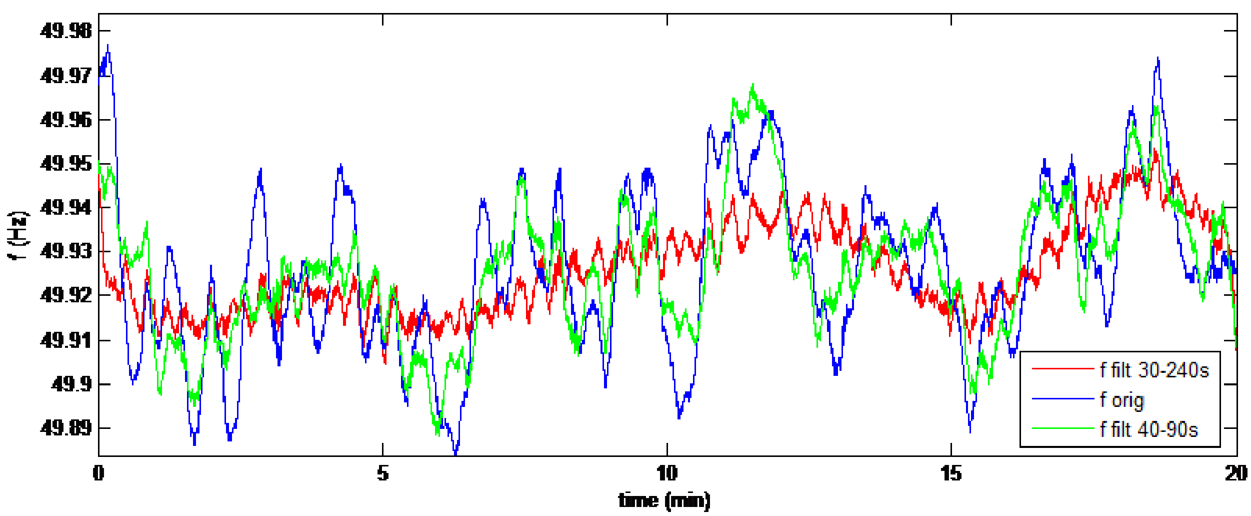


Figure 3.59. Original frequency (blue), frequency with 40-90 s band filtered (green) and frequency with 30-240 s band filtered (red). First 20 minutes of December 2012 are shown (UTC+2) [8]



3.8.2 **Amount of oscillation**

Figure 3.60 shows hourly values and 24 hour moving averages for the amount of oscillation in 2018. 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 2018.

Figures 3.61 and 3.62 contain the previously mentioned 24 hour moving averages for years 2013-2015 and 2016-2018, 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 2016-2018, 12 hours of eligible data was required.

Figure 3.60. Amount of oscillation in 2018

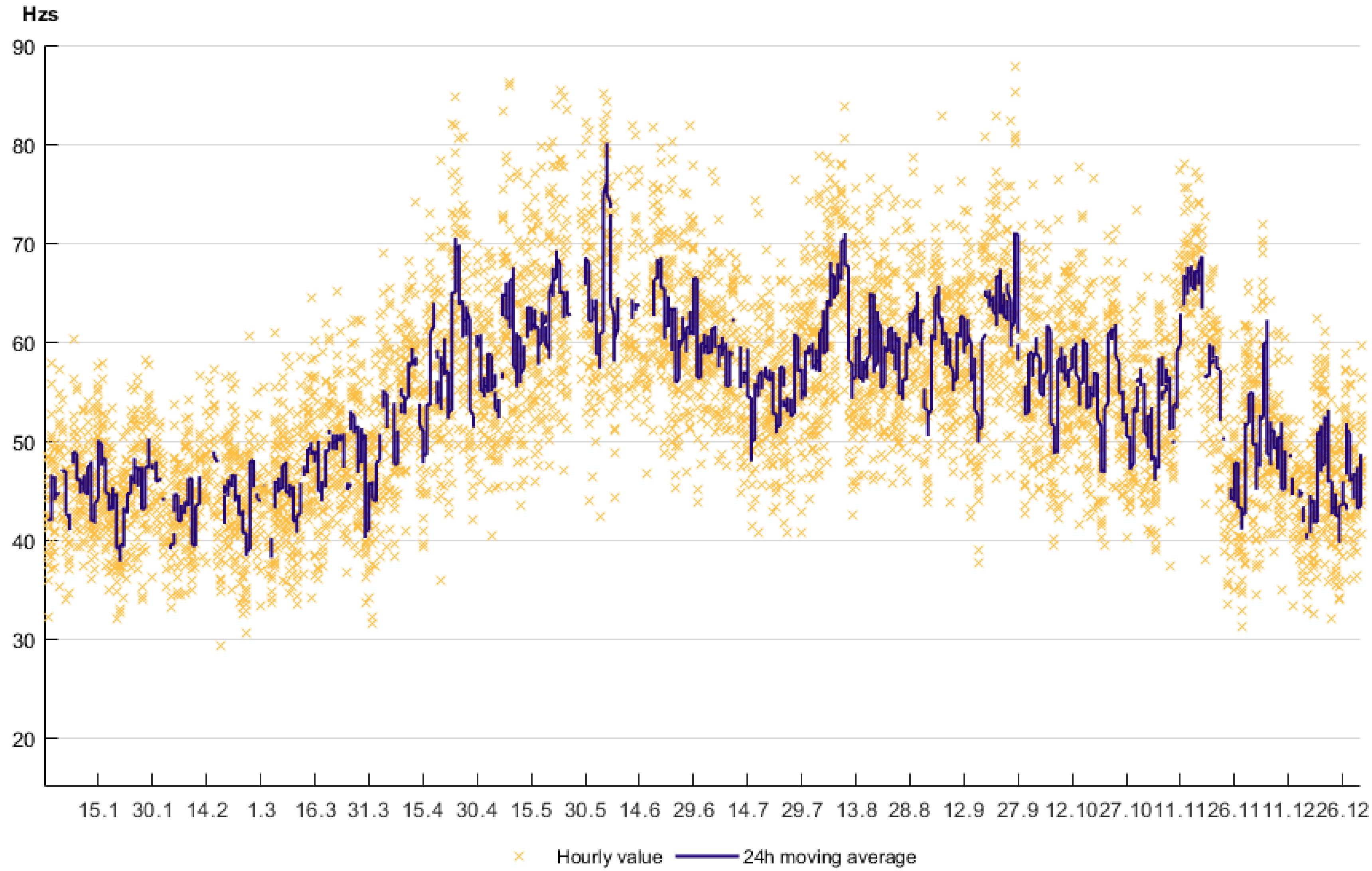


***Figure 3.61**. Amount of oscillation in 2013-2015*

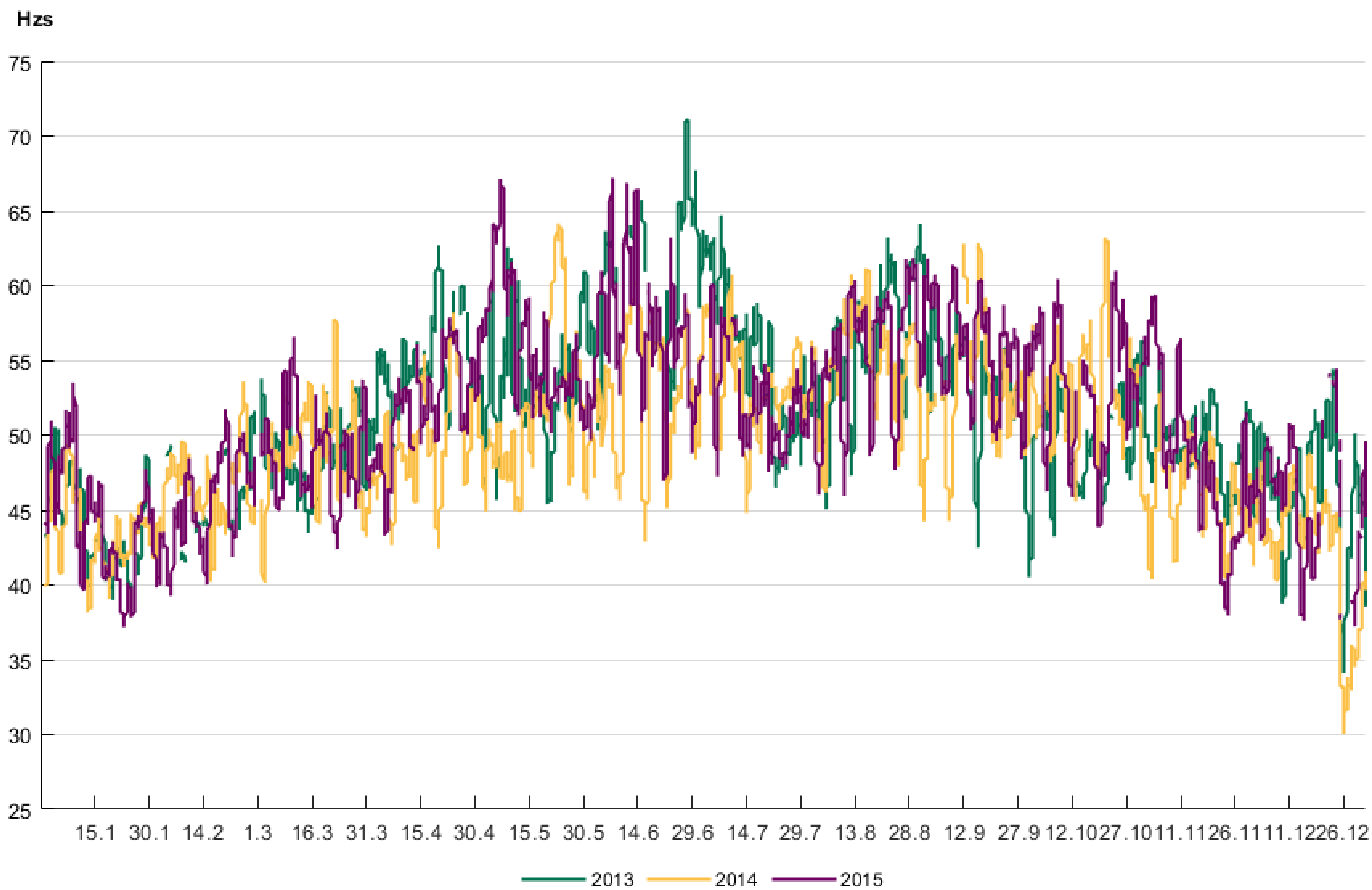
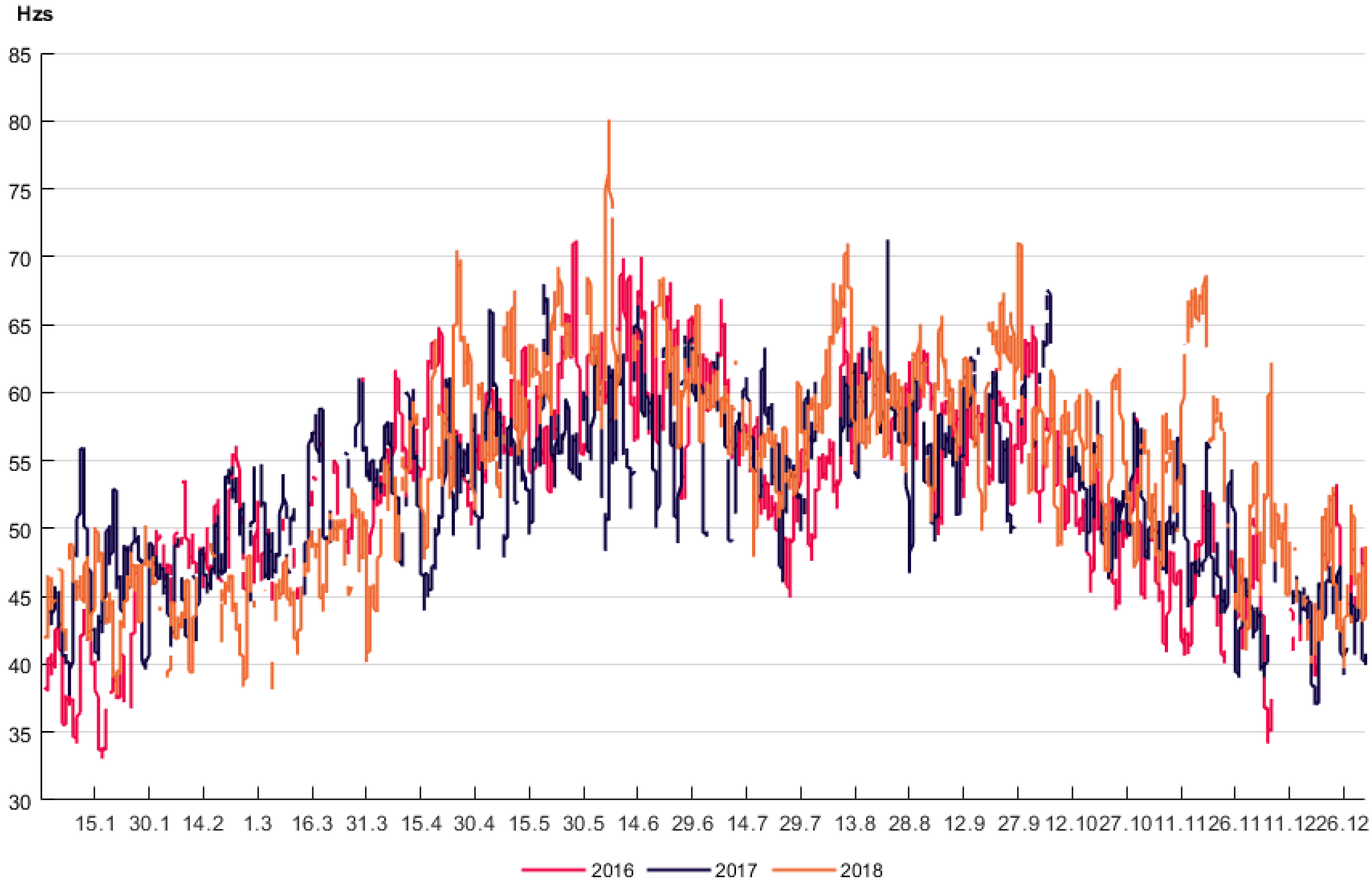


***Figure 3.62**. Amount of oscillation in 2016-2018*



Mean value of the oscillation and standard deviation for each month from 2013 to 2018 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 2018 when compared to the previous year 2017. The last two years have been among the worst years in terms of oscillation.

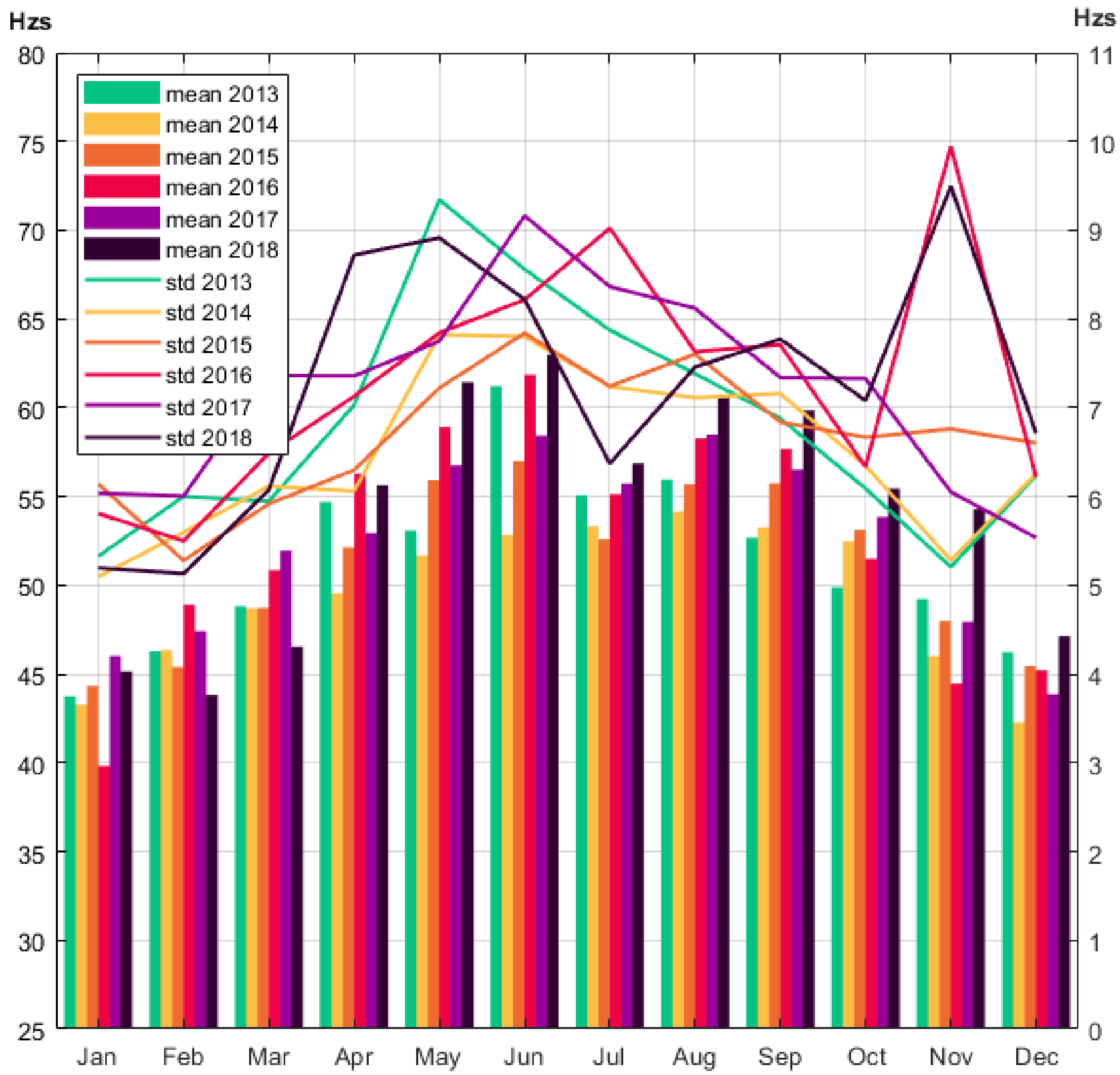
Table 3.24. Mean values and standard deviations for oscillation in years 2013-2015

	Mean value (Hzs)			**Standard deviation (Hzs)**		
Month	**2013**	**2014**	**2015**	**2013**	**2014**	**2015**
January	43.8	43.3	44.3	5.3	5.1	6.1
February	46.3	46.4	45.4	6.0	5.6	5.3
March	48.8	48.7	48.7	5.9	6.1	5.9
April	54.7	49.5	52.1	7.0	6.1	6.3
May	53.1	51.7	55.9	9.3	7.8	7.2
June	61.2	52.8	57.0	8.6	7.8	7.8
July	55.1	53.3	52.6	7.9	7.2	7.2
August	56.0	54.2	55.7	7.4	7.1	7.6
September	52.7	53.3	55.8	6.9	7.2	6.8
October	49.9	52.5	53.1	6.1	6.3	6.7
November	49.2	46.0	48.0	5.2	5.3	6.8
December	46.2	42.3	45.4	6.2	6.3	6.6
Entire year	**51.4**	**49.5**	**51.2**	**6.8**	**6.5**	**6.7**

Table 3.25. Mean values and standard deviations for oscillation in years 2016-2018

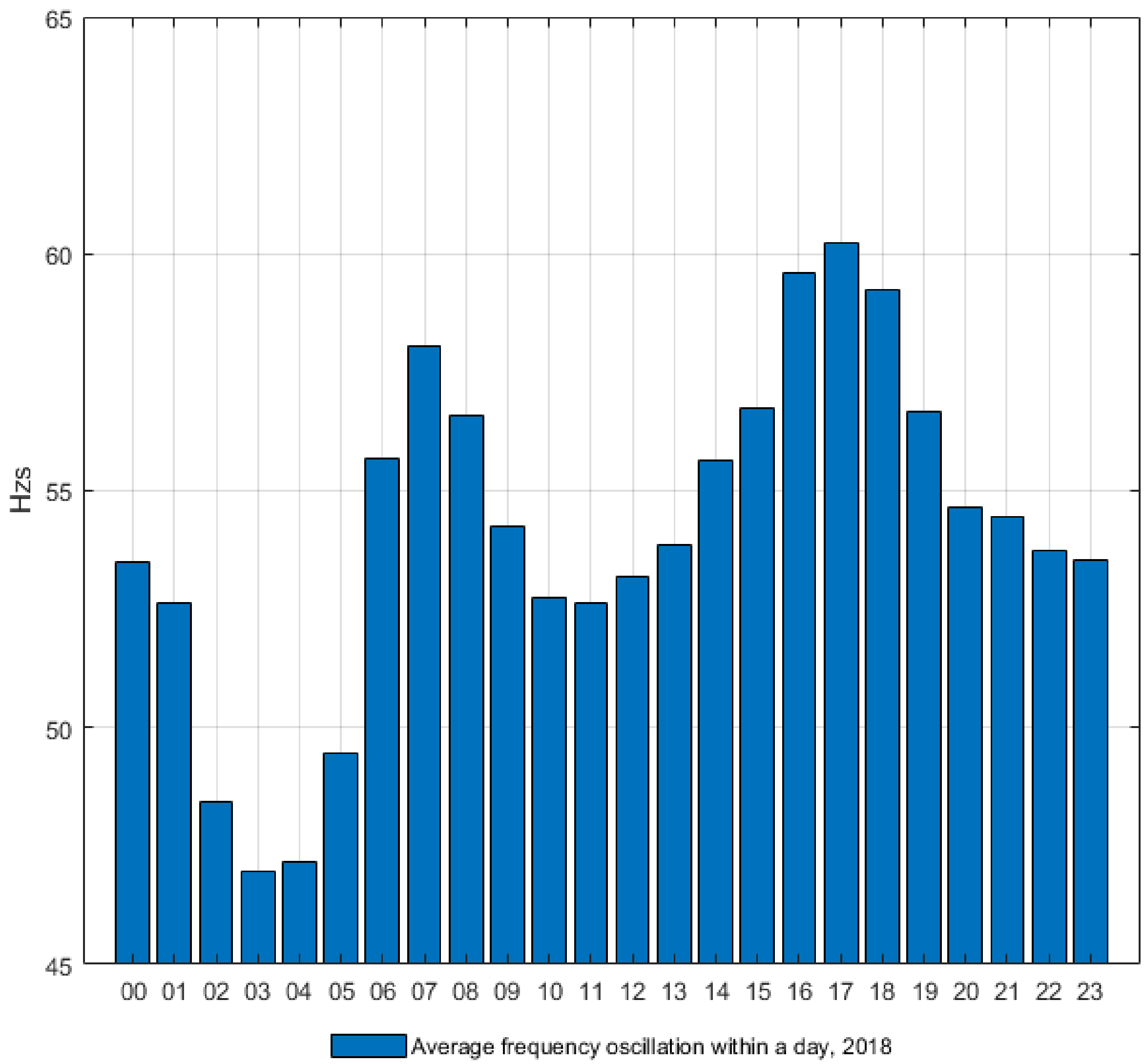
	Mean value (Hzs)			Standard deviation (Hzs)		
Month	**2016**	**2017**	**2018**	**2016**	**2017**	**2018**
January	39.8	46.0	45.1	5.8	6.0	5.2
February	48.9	47.4	43.8	5.5	6.0	5.1
March	50.8	52.0	46.5	6.5	7.4	6.1
April	56.3	52.9	55.6	7.1	7.4	8.7
May	58.9	56.8	61.4	7.8	7.7	8.9
June	61.9	58.4	63.0	8.2	9.2	8.2
July	55.1	55.7	56.9	9.0	8.4	6.4
August	58.3	58.5	60.6	7.6	8.1	7.5
September	57.7	56.5	59.9	7.7	7.3	7.8
October	51.5	53.8	55.4	6.3	7.3	7.1
November	44.5	47.9	54.3	9.9	6.1	9.5
December	45.2	43.9	47.1	6.2	5.5	6.7
Entire year	**52.4**	**52.5**	**54.1**	**7.3**	**7.2**	**7.3**

***Figure 3.63**. Mean values (left y-axis) and standard deviations (right y-axis) for oscillation in years 2013-2018*



Average oscillation within a day divided into 24 hours can be seen in fig 3.64. Oscillation within a day in 2018 doesn't follow a clear pattern but there are peaks during hours 0, 7, and 17. The average hourly oscillation is 54.14 Hzs and standard deviation 3.5 Hzs.

Figure 3.64**. **Average frequency oscillation within a day in 2018

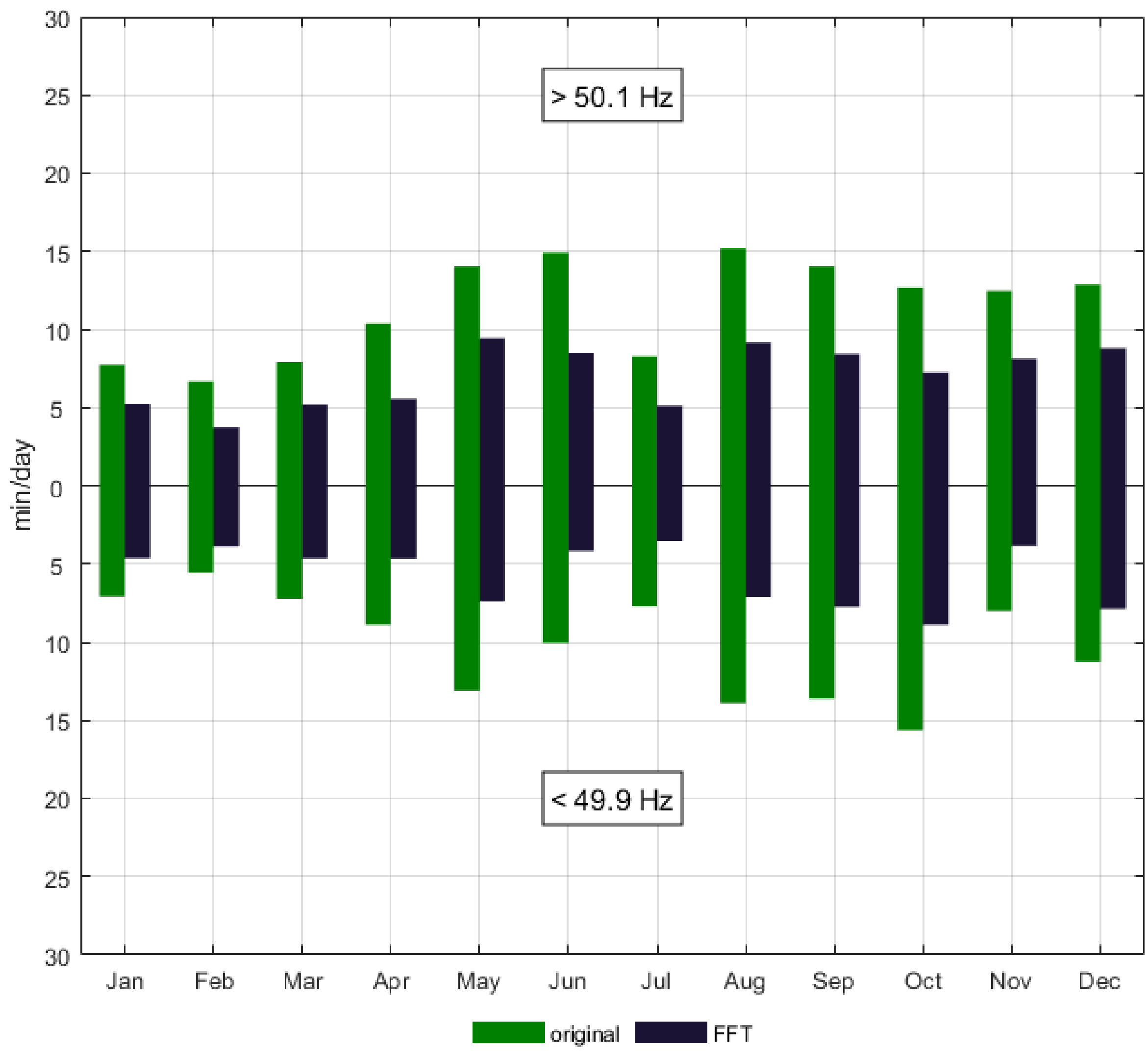


3.8.3 **Influence of oscillation on frequency variations**

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 3.65 shows the average minutes per day outside the standard frequency range in 2018 without filtering and after applying FFT-filtering. Figure 3.64 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 2018*



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.

***Figure 3.66**. Reduction in time per month outside the standard frequency range after filtering in 2018*

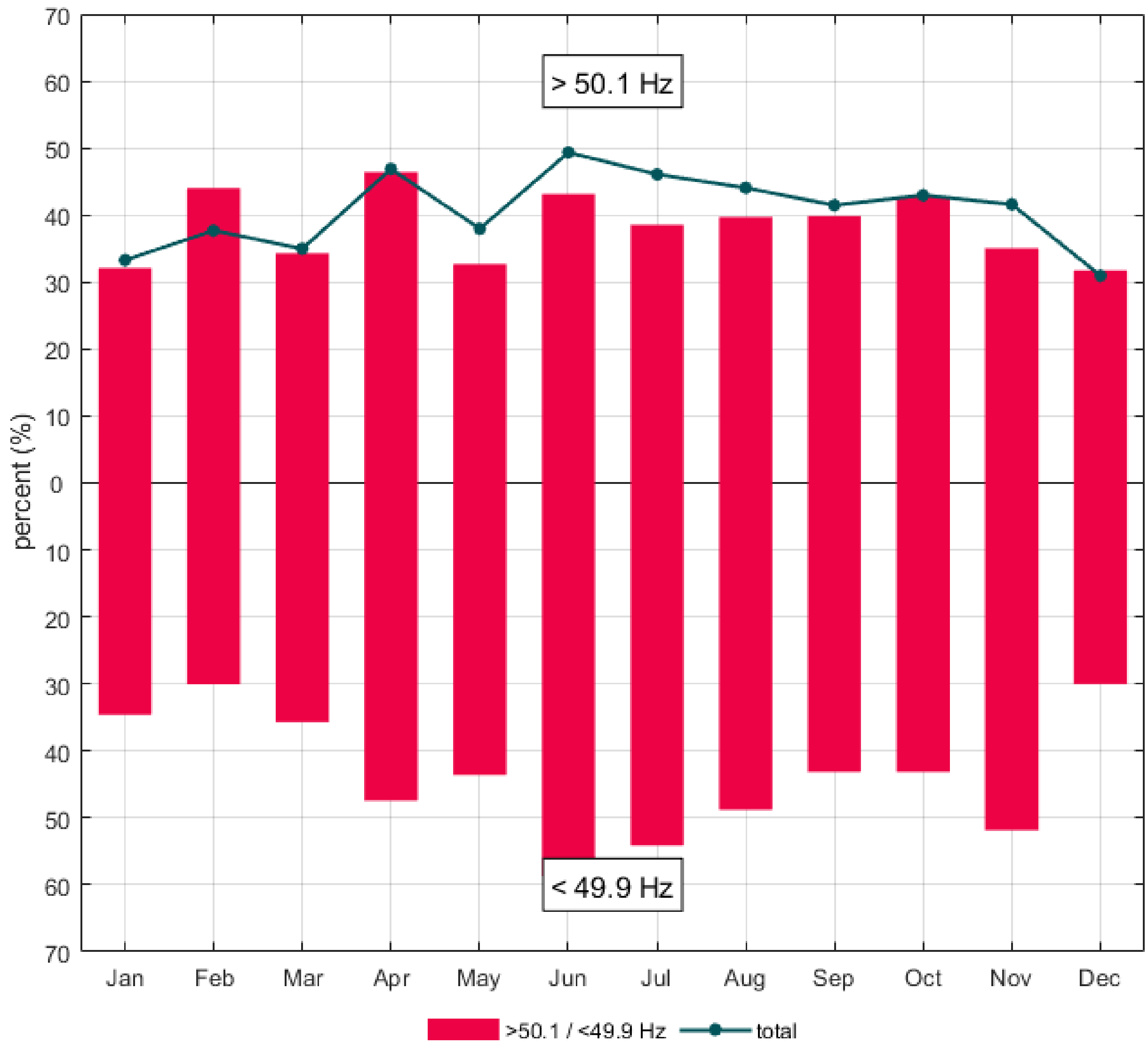
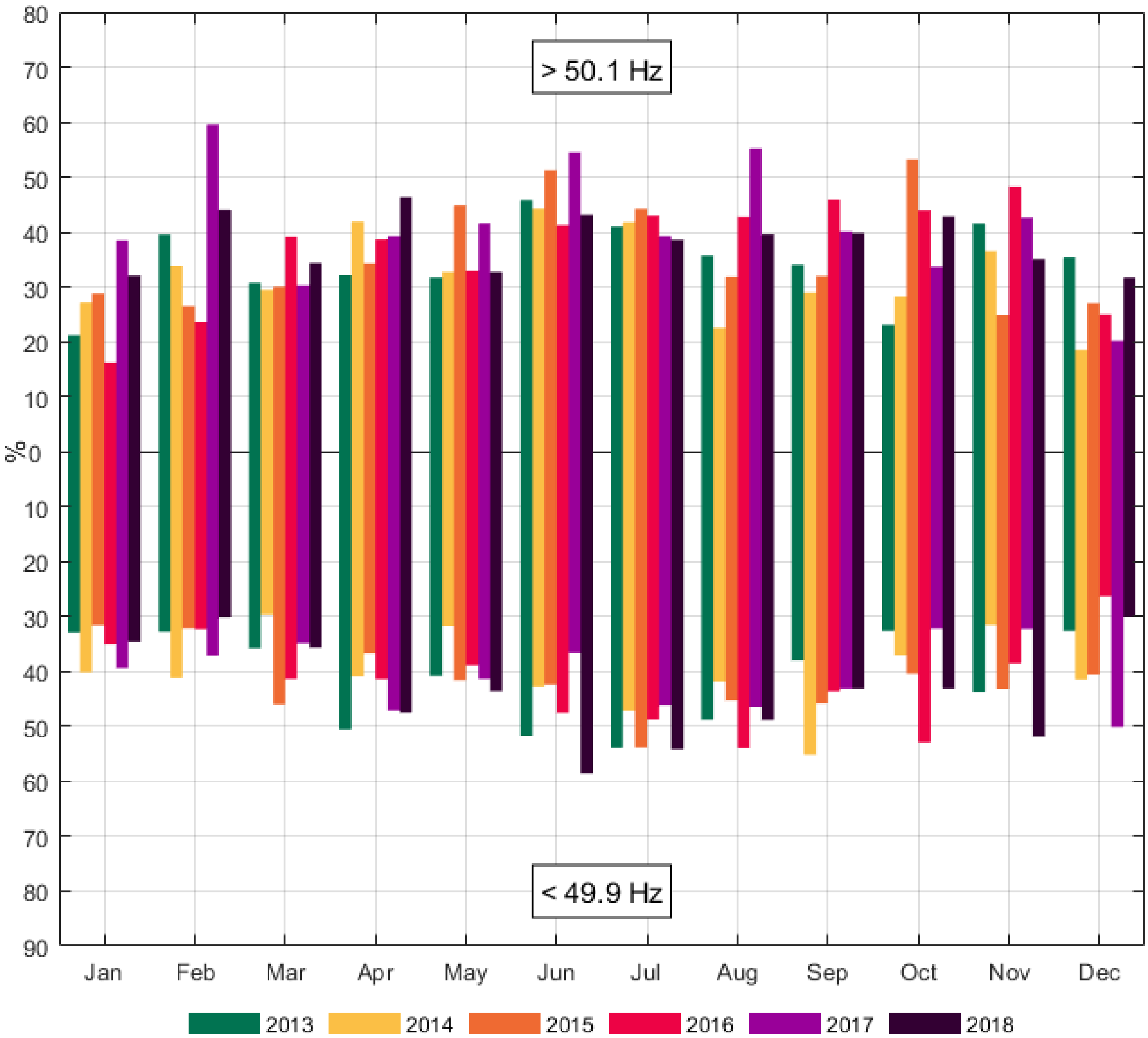


Figure 3.67 represents the reduction in time outside the standard frequency range in percentages month by month for years 2013 to 2018.

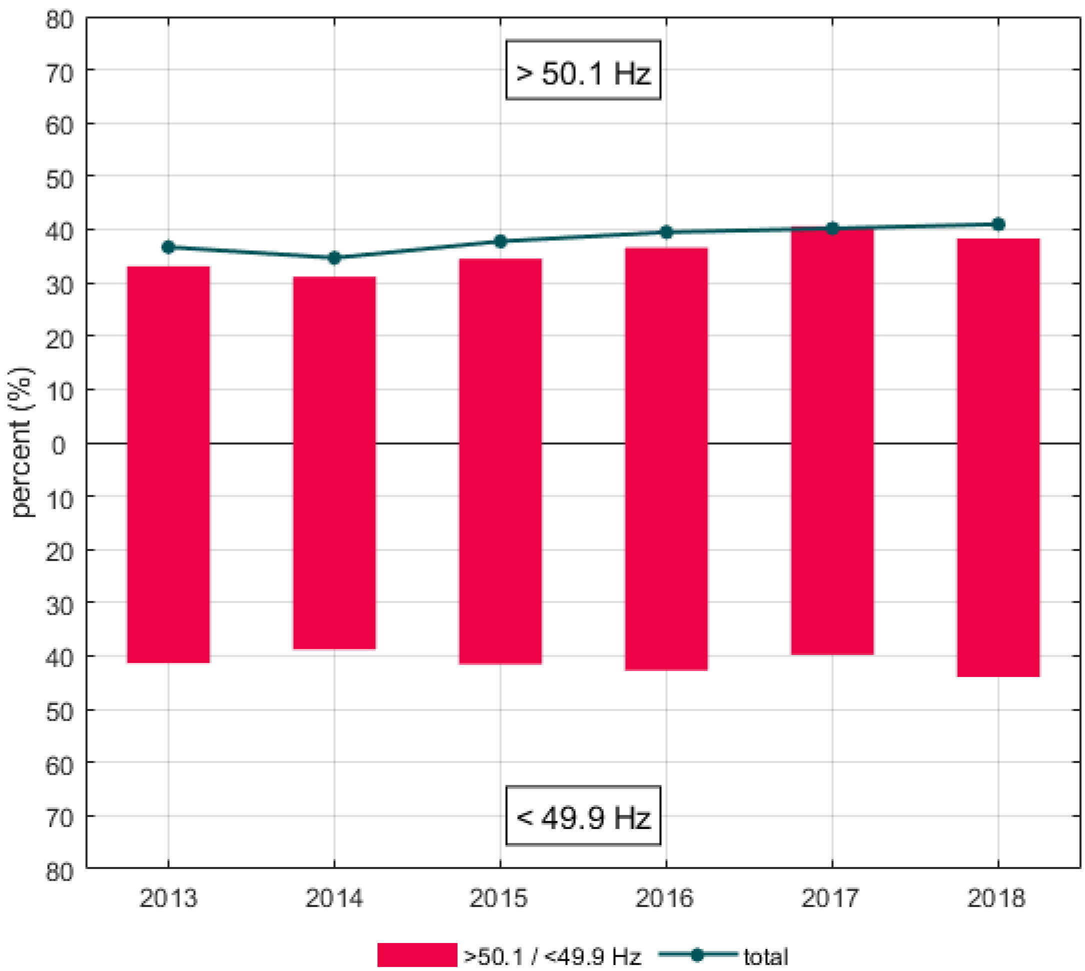
***Figure 3.67**. Reduction in time per month outside the standard frequency range after filtering in years 2013-2018*



In addition to the monthly values presented in the previous figure, results for the entire year in 2013-2018 are shown below in Figure 3.68.

Filtering the oscillation reduces duration of frequency deviations around 35-40 %. The reduction has been roughly on the same level from year to year. 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 2013-2018*



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 2013-2018. The same results are presented in a graphical form in Figure 3.69.

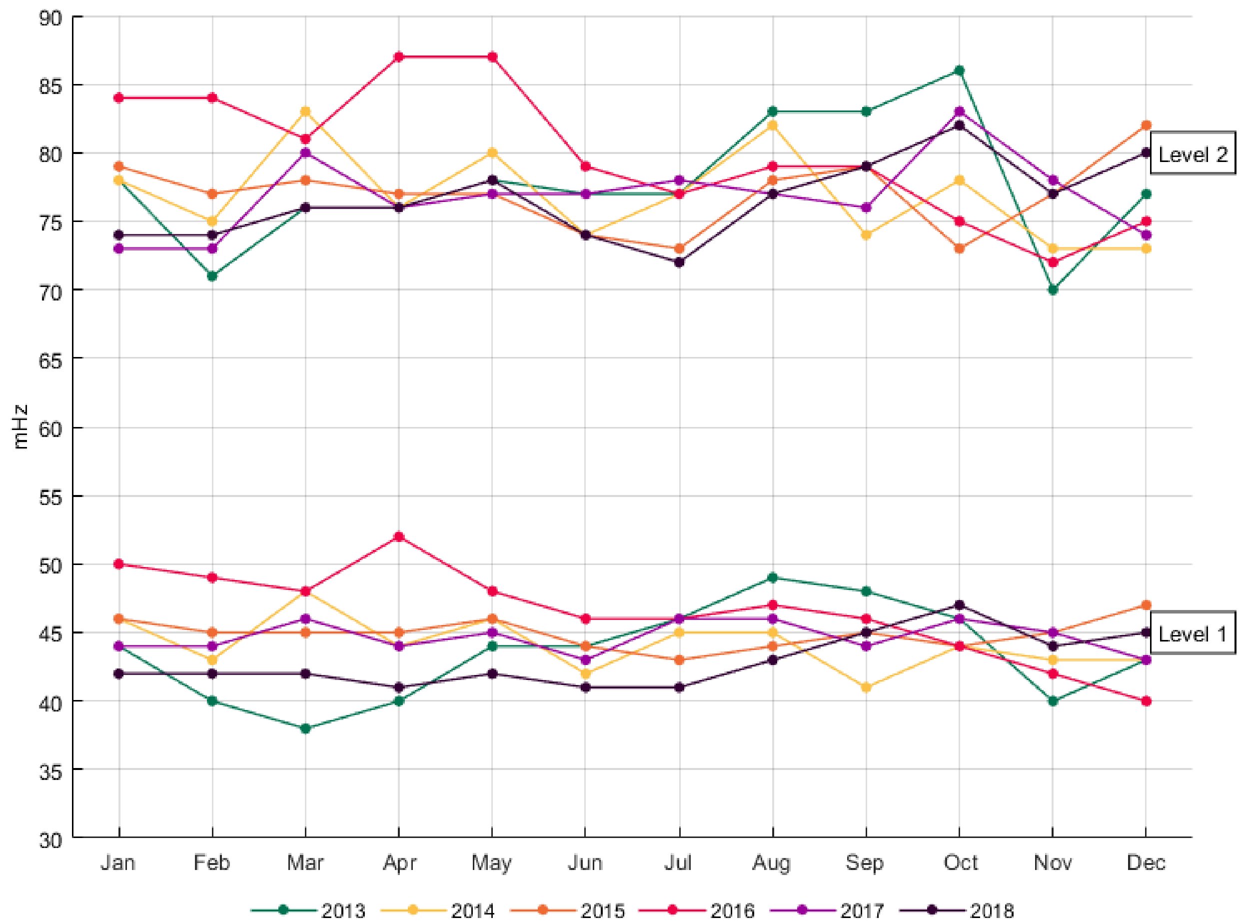
Table 3.26. FRCE Ranges for NE, calculated with 15 min moving averages, years 2013-2015

	2013		**2014**		**2015**	
Month	**Level 1 (mHz)**	**Level 2 (mHz)**	**Level 1 (mHz)**	**Level 2 (mHz)**	**Level 1 (mHz)**	**Level 2 (mHz)**
January	±44	±78	±46	±78	±46	±79
February	±40	±71	±43	±75	±45	±77
March	±38	±76	±48	±83	±45	±78
April	±40	±76	±44	±76	±45	±77
May	±44	±78	±46	±80	±46	±77
June	±44	±77	±42	±74	±44	±74
July	±46	±77	±45	±77	±43	±73
August	±49	±83	±45	±82	±44	±78
September	±48	±83	±41	±74	±45	±79
October	±46	±86	±44	±78	±44	±73
November	±40	±70	±43	±73	±45	±77
December	±43	±77	±43	±73	±47	±82
Entire year	**±44**	**±78**	**±44**	**±77**	**±45**	**±77**

Table 3.27. FRCE Ranges for NE, calculated with 15 min moving averages, years 2016-2018

	2016		**2017**		**2018**	
Month	**Level 1 (mHz)**	**Level 2 (mHz)**	**Level 1 (mHz)**	**Level 2 (mHz)**	**Level 1 (mHz)**	**Level 2 (mHz)**
January	±50	±84	±44	±73	±42	±74
February	±49	±84	±44	±73	±42	±74
March	±48	±81	±46	±80	±42	±76
April	±52	±87	±44	±76	±41	±76
May	±48	±87	±45	±77	±42	±78
June	±46	±79	±43	±77	±41	±74
July	±46	±77	±46	±78	±41	±72
August	±47	±79	±46	±77	±43	±77
September	±46	±79	±44	±76	±45	±79
October	±44	±75	±46	±83	±47	±82
November	±42	±72	±45	±78	±44	±77
December	±40	±75	±43	±74	±45	±80
Entire year	**±47**	**±80**	**±45**	**±77**	**±43**	**±77**

***Figure 3.69**. FRCE Ranges for years 2013-2018 calculated with 15 min moving averages*



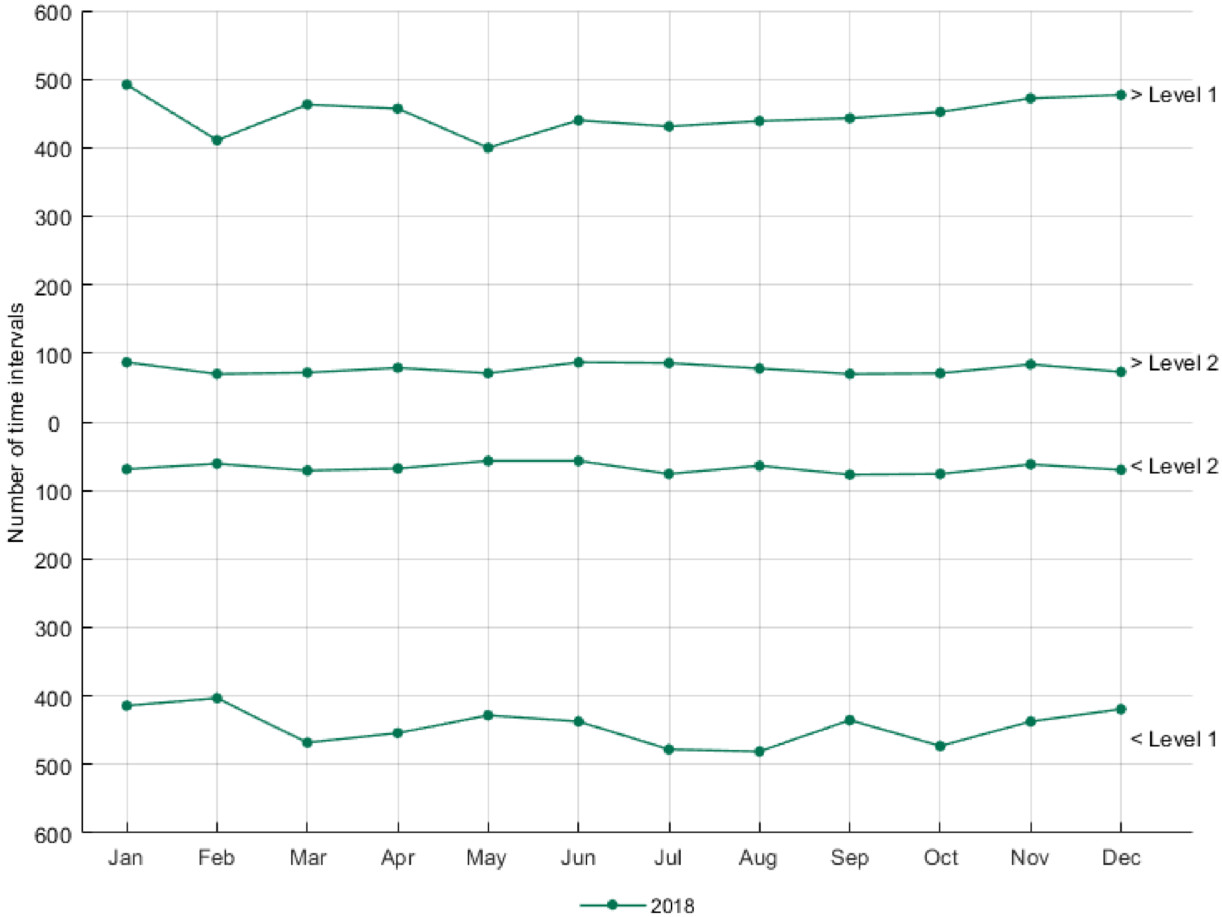
3.9.2 **Number of time intervals outside Level 1 and Level 2 FRCE Range**

Table 3.28 shows the number of 15 minute time intervals outside Level 1 and Level 2 FRCE Ranges in year 2018. 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 2018

	2018			
Month	**> Level 1 (+)**	**< Level 1 (-)**	**> Level 2 (+)**	**< Level 2 (-)**
January	492	414	87	69
February	411	403	70	61
March	463	468	72	71
April	457	454	79	68
May	400	428	71	57
June	440	437	87	57
July	431	478	86	76
August	439	481	78	64
September	443	435	70	77
October	452	473	71	76
November	472	437	84	62
December	477	419	73	70
Entire year	**5377**	**5327**	**928**	**808**

***Figure 3.70**. The number of time intervals over positive and under negative FRCE Level 1 and Level 2 Ranges for year 2018*



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 2018. 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]

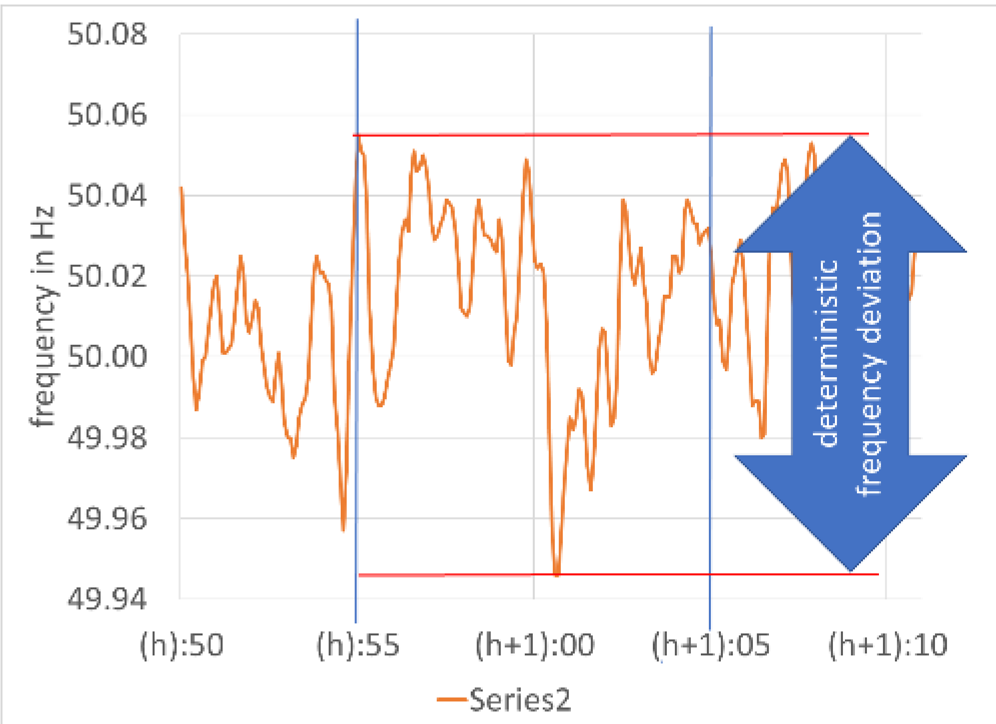


Figure 3.72 represents the deterministic frequency deviation per month in 2018. The 50th percentile stays below zero for the entire year, which indicates that the highest frequency took place before the lowest in more than half of the hour shifts.

***Figure 3.72**. The 1st, 5th, 10th, 50th, 90th, 95th, and 99th percentile of deterministic frequency deviation for every month in 2018*

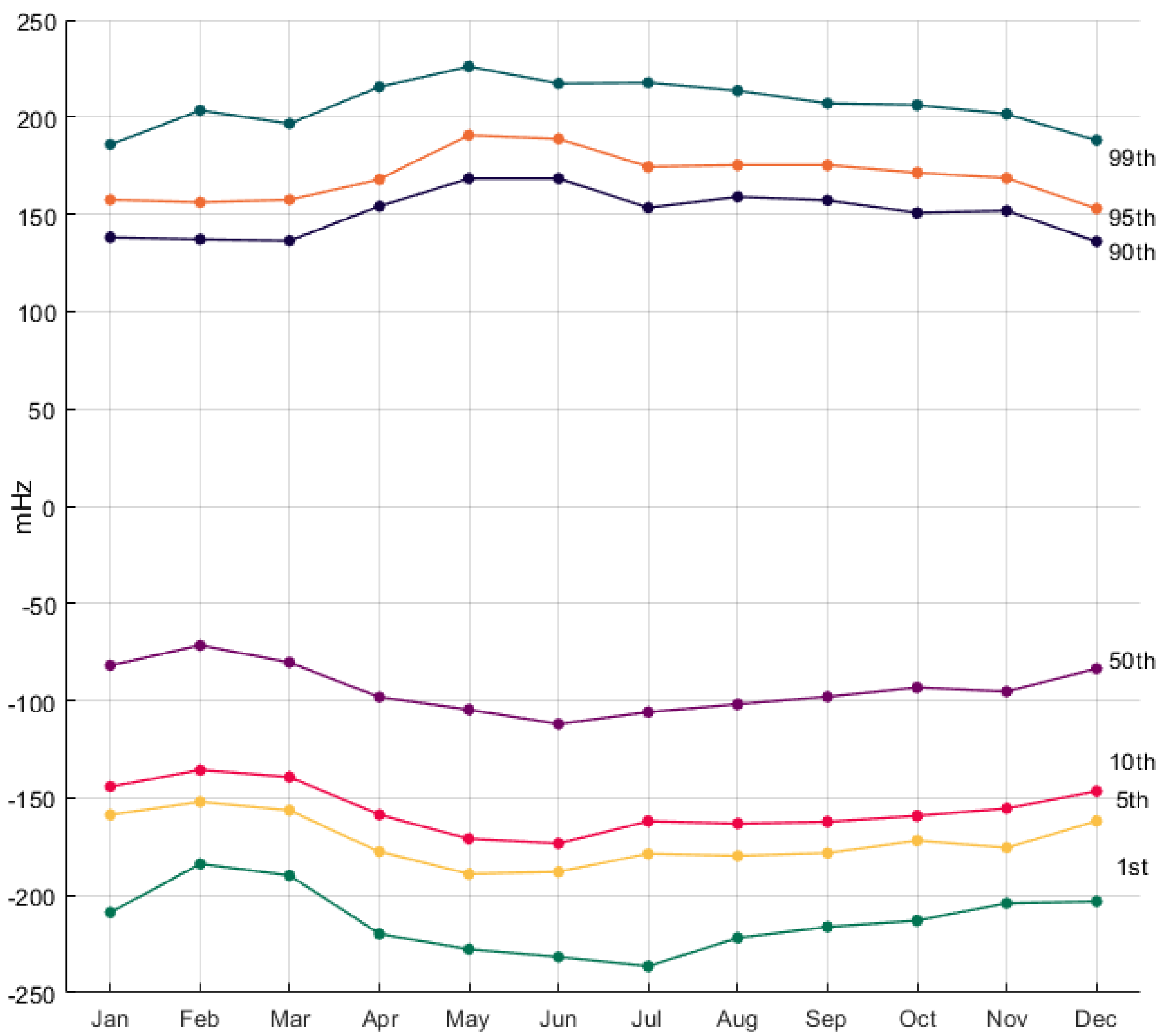
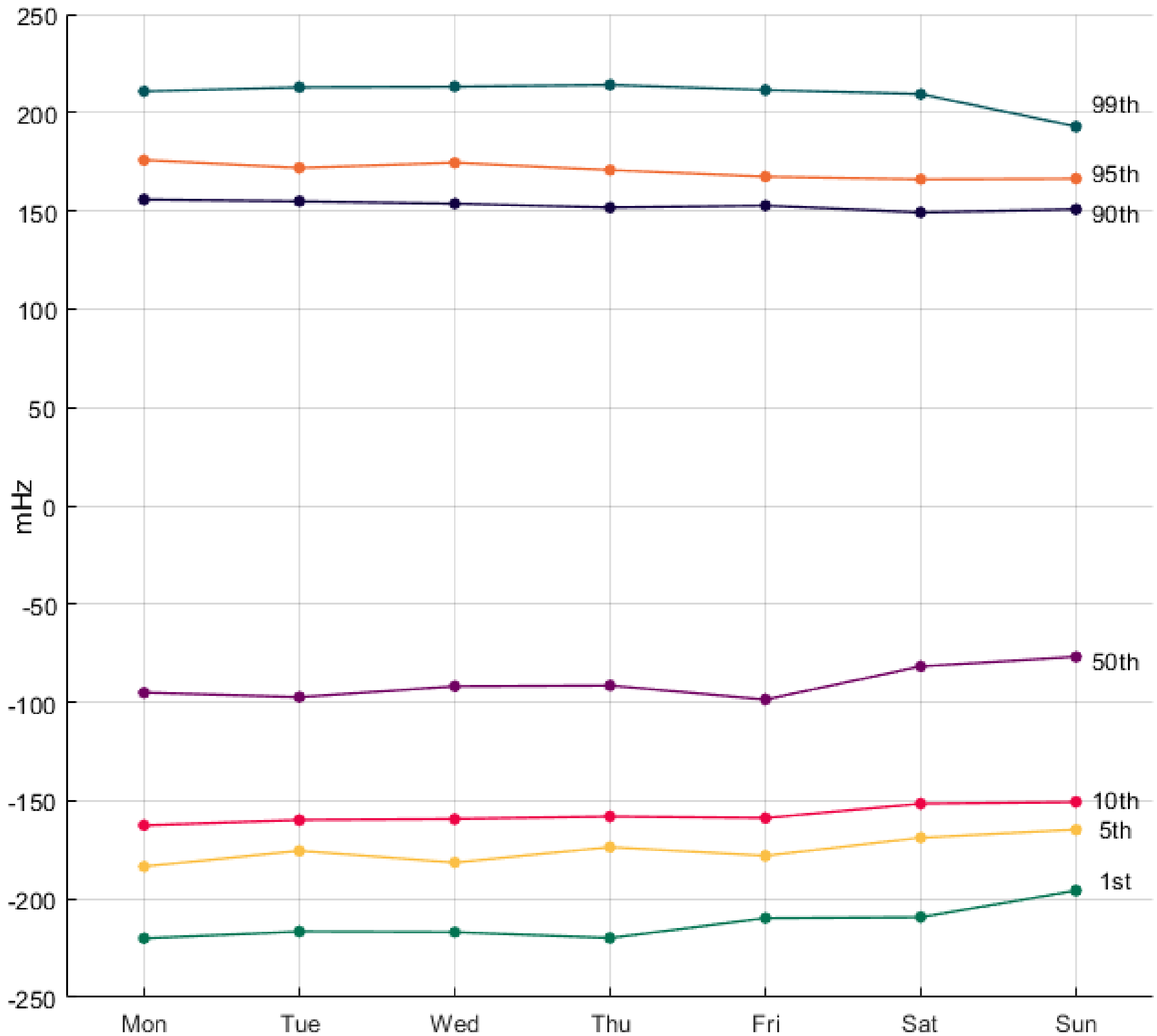


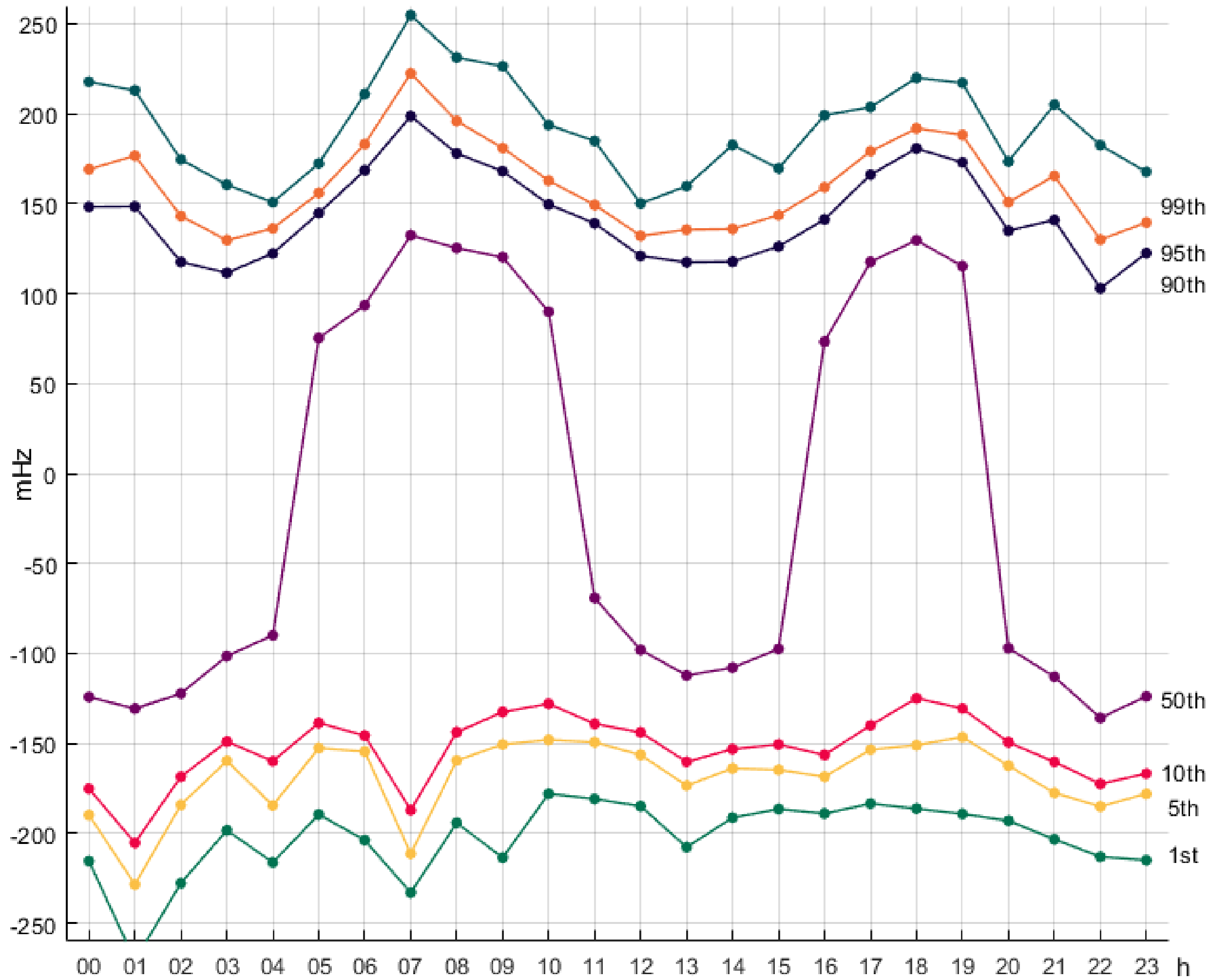
Figure 3.73 shows the percentiles around the hour shift for every day of the week in 2018. The 1st, 5th, 10th and 50th percentile are all slightly higher during the weekends.

***Figure 3.73**. The 1st, 5th, 10th, 50th, 90th, 95th, and 99th percentile of deterministic frequency deviation for every day of the week in 2018*



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 16 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 2018*



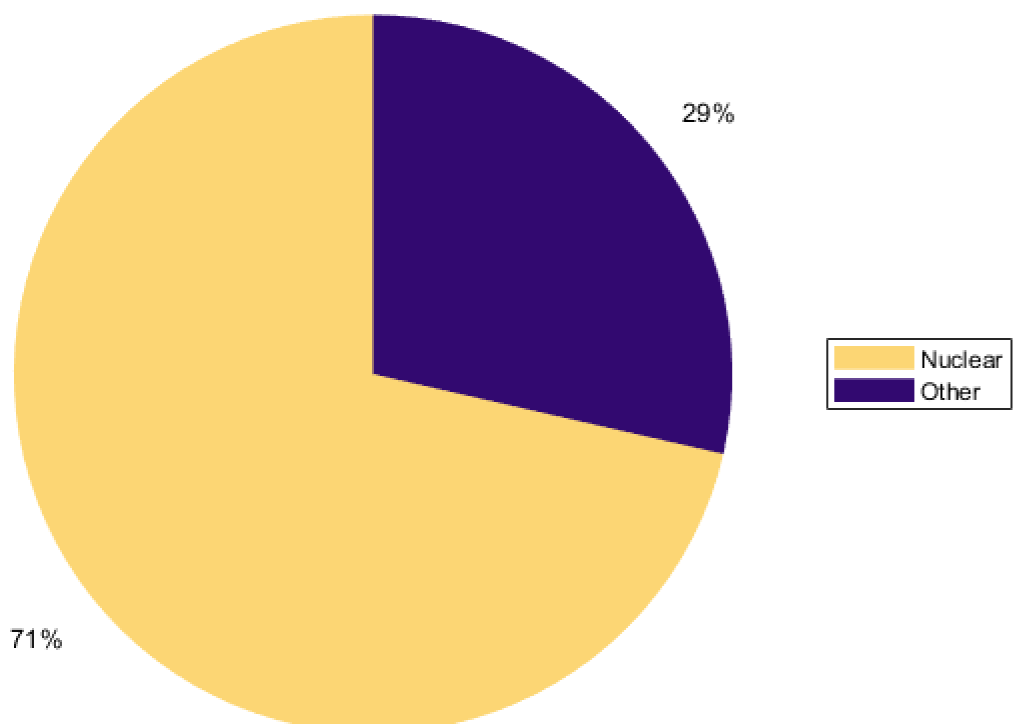
Chapter 4. Frequency disturbances exceeding 300 mHz frequency deviation

This chapter offers information of the major frequency disturbances in the Nordic synchronous system in the year 2018. Over 300 mHz frequency deviations are included.

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

Most of the over ±300 mHz disturbances in 2018 were caused by grid faults in nuclear connections or by failures in nuclear power productions while the rest were caused by other reasons, which can be seen from Figure 4.1. During 2018 there was one less over ±300 mHz disturbance when compared to 2017. In 2017 most of the severe disturbances were caused by tripping of HVDC links or nuclear plants.

***Figure 4.1**. Shares of factors causing over 300 mHz disturbances in the Nordic synchronous system in 2018*



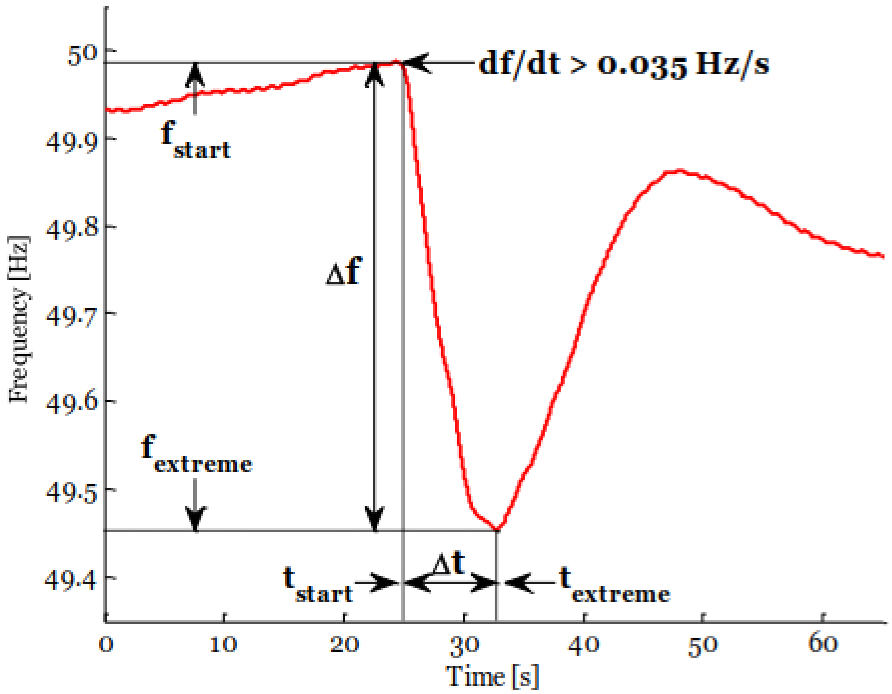
The largest maximum frequency deviation with a value of -0.432 Hz was caused by tripping nuclear plant on the 2nd of January. This also caused the lowest instantaneous frequency value of 49.532 Hz. The highest reported instantaneous frequency value out of all of the deviations over 300 mHz was 50.130 Hz during 12th of July after recovering from a severe frequency drop caused by a tripping nuclear plant.

The following part of the chapter will go into more detail on every disturbance that took place in 2018. 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]*



Some of the disturbances included 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 was a frequency deviation at a later moment that was higher than Δf and exceeded the ±300 mHz deviation. Those cases were included also. [11]

For a frequency disturbance to be reported as an over 300 mHz disturbance the ratio between a momentary change in frequency divided by the change in time has to be over 0.035 Hz/s in the beginning of the disturbance as seen in Figure 4.2. In 2018 there was one disturbance that was not calculated as an over 300 mHz disturbance for this reason even though the maximum frequency deviation was over 300 mHz.

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 4.3-4.9 and Tables 4.2-4.8.

Table 4.1. List of disturbance events in 2018

Event date	Δf (Hz)	ΔP (MW)	Δt (s)	E_k (GWs)	Cause	Page
02-Jan-2018 04:46:32	-0.432	1200	7.1	183	Nuclear	115
12-Jul-2018 09:00:14	-0.383	866	8.7	199	Nuclear	116
12-Jul-2018 16:40:06	-0.323	998	12.3	198	Other	117
12-Jul-2018 18:06:12	-0.257	783	6.7	198	Other	118
18-Jul-2018 08:57:07	-0.404	878	8.0	189	Nuclear	119
18-Jul-2018 21:39:22	-0.359	889	7.9	189	Nuclear	120
27-Dec-2018 02:49:40	-0.351	922	7.4	184	Nuclear	121

***Figure 4.3**. Disturbance 02-Jan-2018 04:46:32*

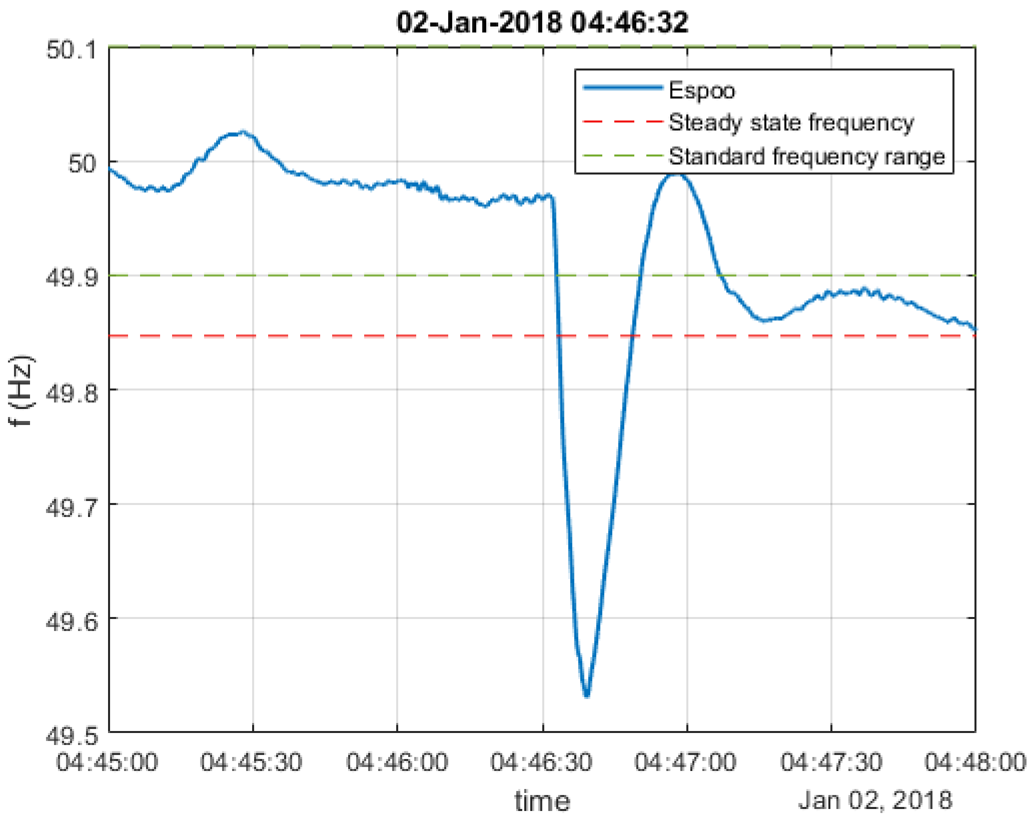


***Table 4.2**. Disturbance 02-Jan-2018 04:46:32*

Date		**02-Jan-2018 04:46:32**	
f_{start}	49.964 Hz	$f_{steady\ state}$	49.847 Hz
$f_{extreme}$	49.532 Hz	$\Delta f_{steady\ state}$	0.117 Hz
Δf	-0.432 Hz	$f_{extreme2}$	49.989 Hz
Δt	7.1 s	$f_{extreme3}$	49.857 Hz
ΔP	1200 MW	damping	28.84 %
E_k	183 GWs	FBF	10256 MW/Hz
cause		Nuclear	

***Figure 4.4**. Disturbance 12-Jul-2018 09:00:14*

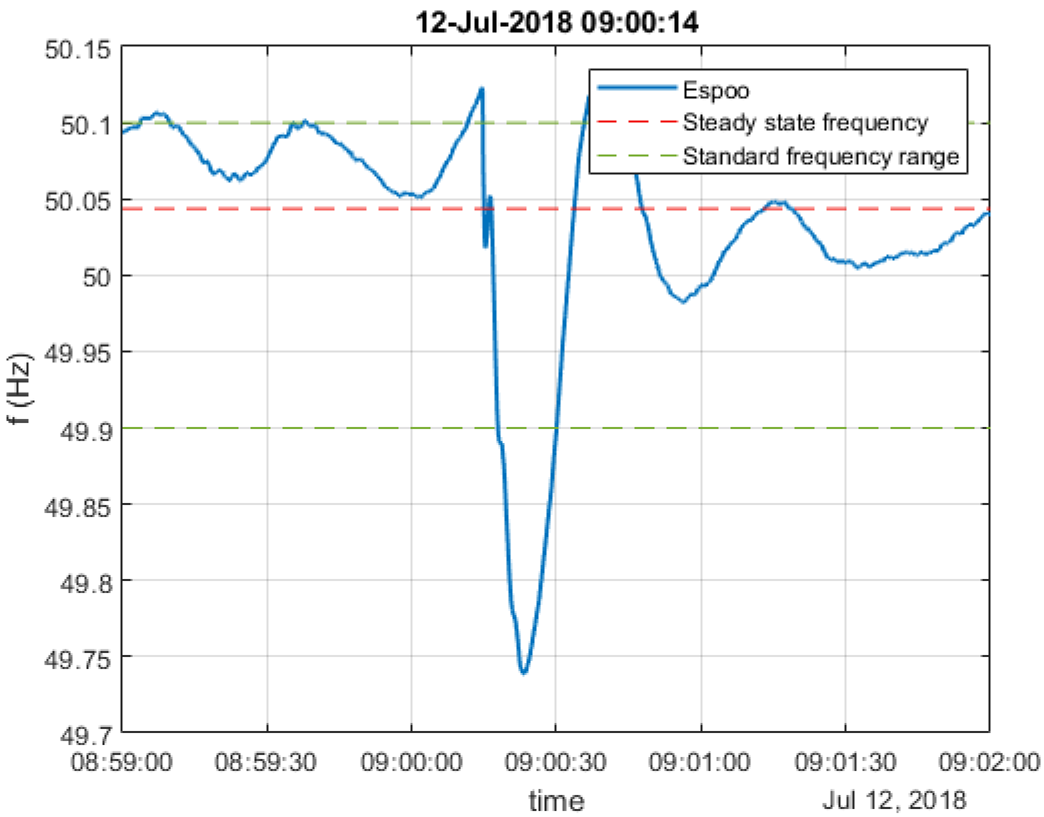


***Table 4.3**. Disturbance 12-Jul-2018 09:00:14*

Date		**12-Jul-2018 09:00:14**	
f_{start}	50.122 Hz	$f_{steady\ state}$	50.044 Hz
$f_{extreme}$	49.739 Hz	$\Delta f_{steady\ state}$	0.078 Hz
Δf	-0.383 Hz	$f_{extreme2}$	50.130 Hz
Δt	8.7 s	$f_{extreme3}$	49.982 Hz
ΔP	866 MW	damping	37.83 %
E_k	199 GWs	FBF	11103 MW/Hz
cause		Nuclear	

Figure 4.5. Disturbance 12-Jul-2018 16:40:06

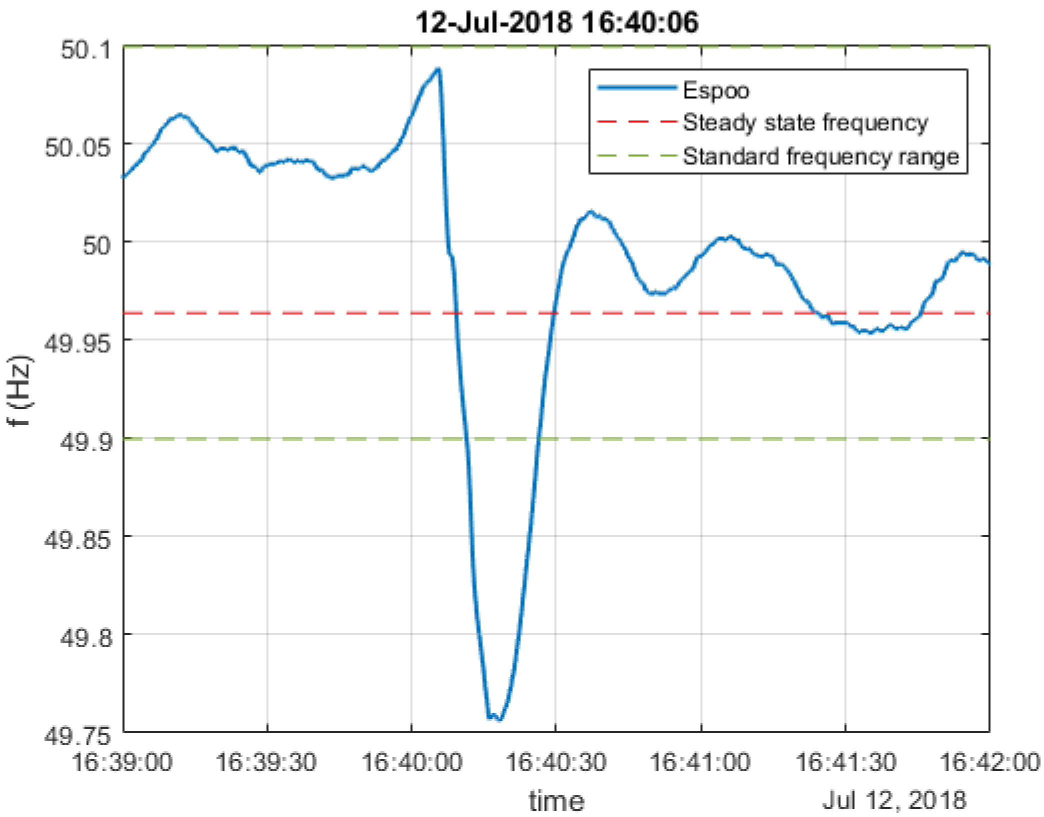


Table 4.4. Disturbance 12-Jul-2018 16:40:06

Date		**12-Jul-2018 16:40:06**	
f_{start}	50.079 Hz	$f_{steady\ state}$	49.964 Hz
$f_{extreme}$	49.756 Hz	$\Delta f_{steady\ state}$	0.115 Hz
Δf	-0.323 Hz	$f_{extreme2}$	50.016 Hz
Δt	12.3 s	$f_{extreme3}$	49.954 Hz
ΔP	998 MW	damping	23.86 %
E_k	198 GWs	FBF	8678 MW/Hz
cause		Other	

Figure 4.6. Disturbance 12-Jul-2018 18:06:12

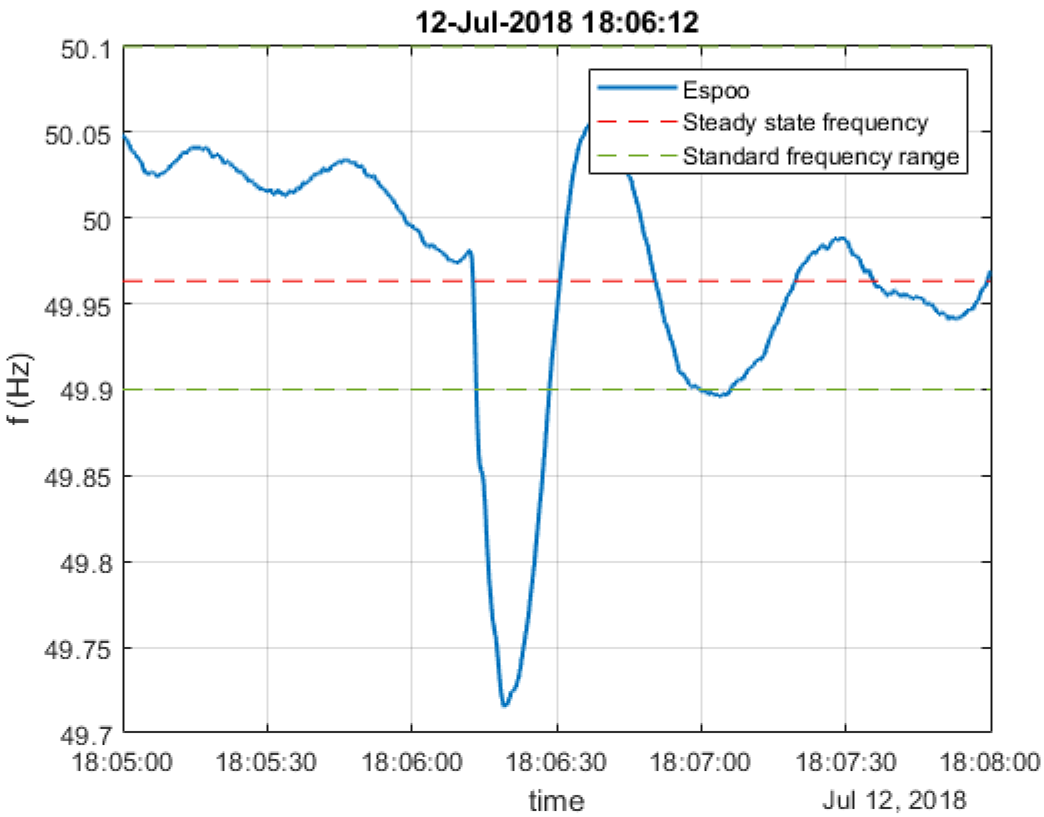


Table 4.5. Disturbance 12-Jul-2018 18:06:12

Date		**12-Jul-2018 18:06:12**	
f_{start}	49.973 Hz	$f_{steady\ state}$	49.963 Hz
$f_{extreme}$	49.716 Hz	$\Delta f_{steady\ state}$	0.010 Hz
Δf	-0.257 Hz	$f_{extreme2}$	50.059 Hz
Δt	6.7 s	$f_{extreme3}$	49.896 Hz
ΔP	783 MW	damping	47.39 %
E_k	198 GWs	FBF	78300 MW/Hz
cause		Other	

Figure 4.7. Disturbance 18-Jul-2018 08:57:07

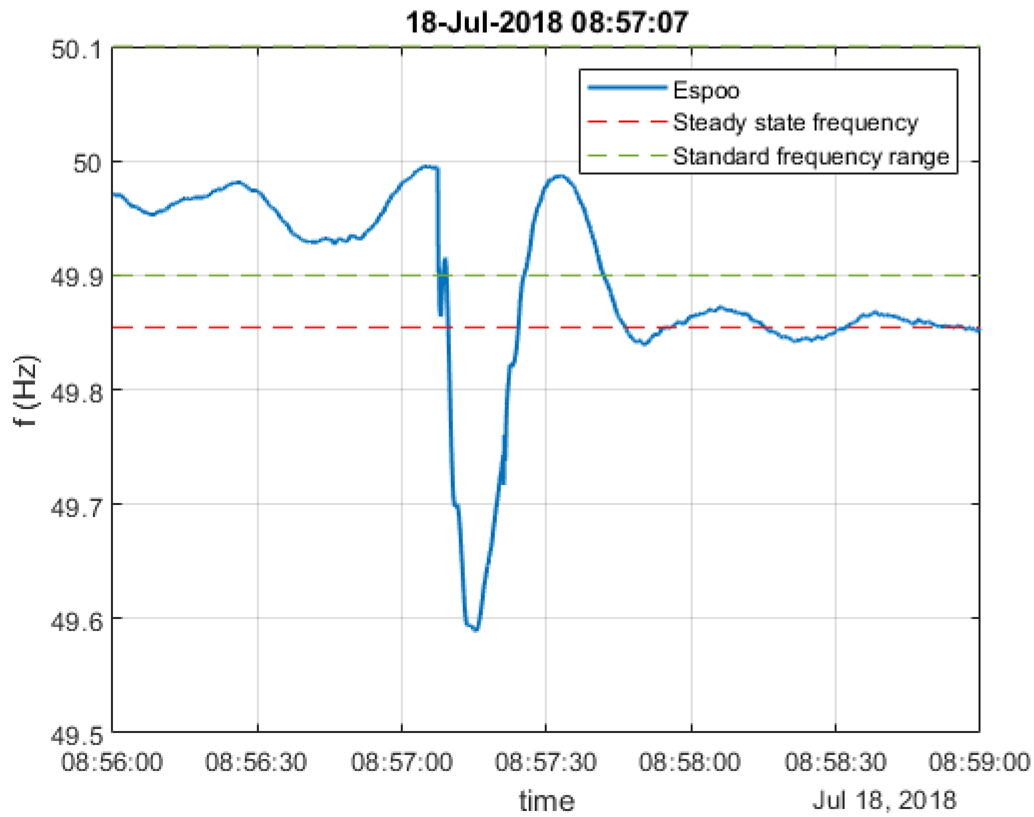


Table 4.6. Disturbance 18-Jul-2018 08:57:07

Date		**18-Jul-2018 08:57:07**	
f_{start}	49.993 Hz	$f_{steady\ state}$	49.854 Hz
$f_{extreme}$	49.589 Hz	$\Delta f_{steady\ state}$	0.138 Hz
Δf	-0.404 Hz	$f_{extreme2}$	49.987 Hz
Δt	8.0 s	$f_{extreme3}$	49.839 Hz
ΔP	878 MW	damping	37.15 %
E_k	189 GWs	FBF	6362 MW/Hz
cause		Nuclear	

Figure 4.8. Disturbance 18-Jul-2018 21:39:22

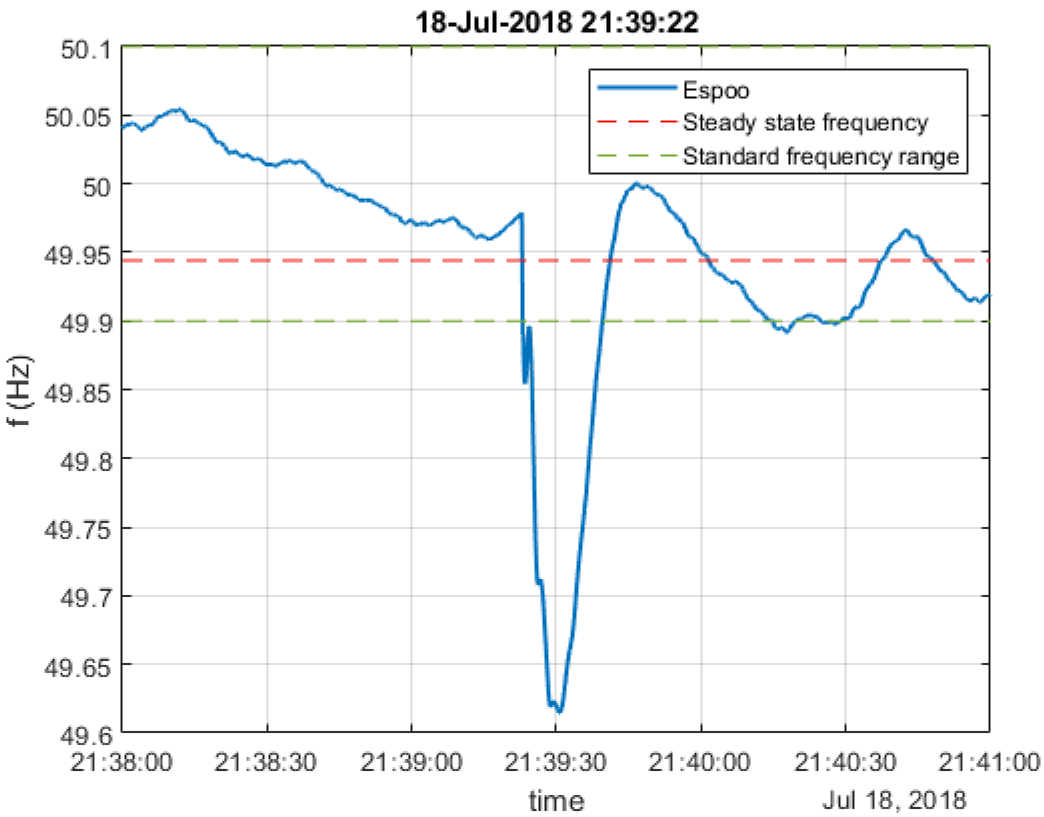


Table 4.7. Disturbance 18-Jul-2018 21:39:22

Date		**18-Jul-2018 21:39:22**	
f_{start}	49.974 Hz	$f_{steady\ state}$	49.944 Hz
$f_{extreme}$	49.615 Hz	$\Delta f_{steady\ state}$	0.030 Hz
Δf	-0.359 Hz	$f_{extreme2}$	50.000 Hz
Δt	7.9 s	$f_{extreme3}$	49.892 Hz
ΔP	889 MW	damping	28.05 %
E_k	189 GWs	FBF	29633 MW/Hz
cause		Nuclear	

Figure 4.9. Disturbance 27-Dec-2018 02:49:40

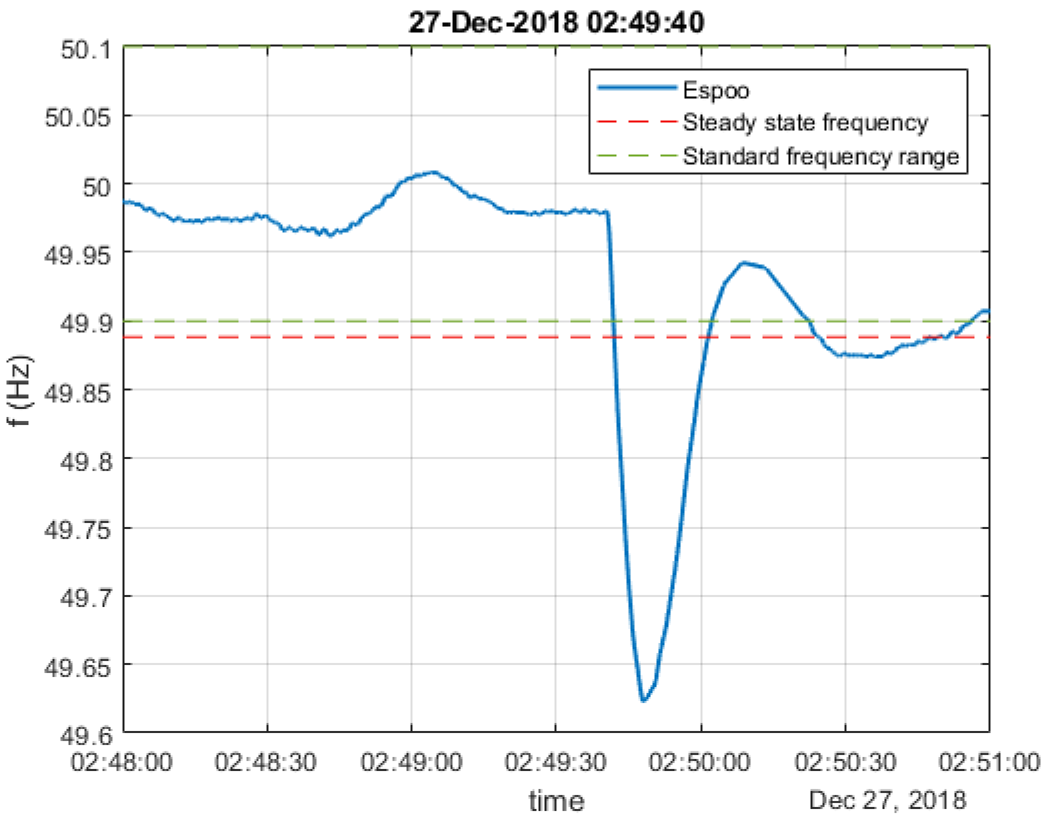


Table 4.8. Disturbance 27-Dec-2018 02:49:40

Date		**27-Dec-2018 02:49:40**	
f_{start}	49.974 Hz	$f_{steady\ state}$	49.888 Hz
$f_{extreme}$	49.623 Hz	$\Delta f_{steady\ state}$	0.086 Hz
Δf	-0.351 Hz	$f_{extreme2}$	49.942 Hz
Δt	7.4 s	$f_{extreme3}$	49.874 Hz
ΔP	922 MW	damping	21.43 %
E_k	184 GWs	FBF	10721 MW/Hz
cause		Nuclear	

Chapter 5. Summary

The aim of this report was to analyze frequency variation and oscillation in the Nordic synchronous system in 2018. The overall quality of frequency was worse than in the previous year of 2017 and otherwise in line with the quality of the rest of the years examined in this report. There was a noticeable increase in the overall time when the frequency was outside 49.8-50.2 Hz when compared to previous year.

The average duration of frequency deviations varies on monthly and daily basis. The monthly results vary from year to year but the highest values have often occurred in March to May and August to October. In 2018 the frequency was outside the standard frequency range the most in August and October. January and February had the best quality of all months in 2018. Typically frequency has stayed within the standard frequency range better during weekends than during the weekdays. This was the case in 2018 as well.

Within a day the frequency rises above 50.1 Hz most often around midnight and falls below 49.9 Hz at hours 1, 7 and 8. Generally there are more deviation in the morning and evening hours while the least amount of deviations occur in hours 2-5 and 12-16. Inside an hour the quality of the frequency is worse closer the hour shift and especially at the beginning of the hour.

The amount of oscillation in 2018 has been higher than the levels of the previous years. The mean value of oscillation was highest in May and June and the standard deviation in May and November. During the past years the frequency has oscillated less during winter and more from spring to autumn. Year 2018 was not an exception in this case.

Removal of the oscillation by filtering the frequency data clearly reduces frequency deviations. The reduction is around 40 % with the FFT-filtering method. The reduction is generally higher for under frequency deviations.

There were 7 frequency disturbances in 2018, where the deviation exceeded 300 mHz. Most of the disturbances were caused by failures in nuclear power plants and the rest by other reasons. The amount of frequency deviations exceeding 300 mHz has decreased slightly when compared to 2017 but decreased dramatically when compared to 2015-2016. In 2015-2016 there were around 20 disturbances annually.

Chapter 6. Sources

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