Frequency quality analysis

2017

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 2017. 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 2017 is presented in Table 2.1. Availability of data per year for years 2012 to 2017 can be seen in Table 2.2 [2,3,4,5,6,7]. In 2017 there were valid measurement data for 97.24 % of the time. Some of the data is missing due to telecommunication errors. There were multiple gaps in the measurement data caused by these errors, which lasted more than half an hour. Majority of them took place in August, which was clearly the worst month when it comes to the availability of the data. There was also a gap lasting 4 days in October, which explains the lower availability for that month.

***Table 2.1**. The amount of valid measurement data available per month in 2017*

Month	Available data
January	99.93 %
February	99.88 %
March	99.84 %
April	99.90 %
May	99.87 %
June	99.89 %
July	99.90 %
August	81.37 %
September	99.88 %
October	86.60 %
November	99.93 %
December	99.87 %

***Table 2.2**. The amount of valid measurement data available for years 2012-2017*

Year	Available data
2012	99.76 %
2013	92.14 %
2014	99.89 %
2015	99.90 %
2016	99.37 %
2017	97.19 %

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 [8]. 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 2017. 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 0.5 mHz from 50 Hz.

***Figure 3.1**. Average frequency for each month in 2017*

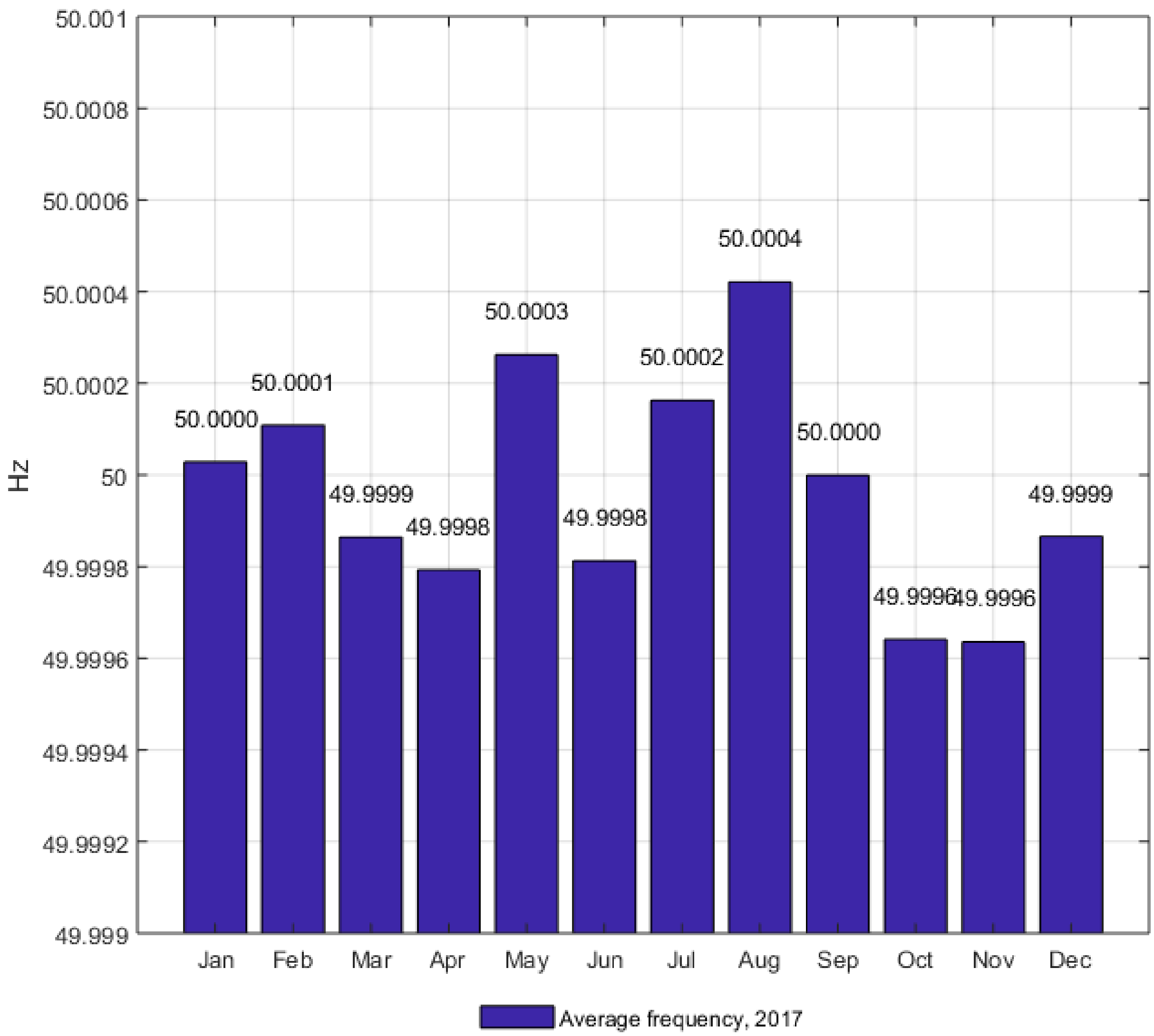


Figure 3.2 represents the average frequencies for every day of the week. On average, the frequency has been lower on the weekends and the highest on Mondays.

***Figure 3.2**. Average frequency for each day of the week in 2017*

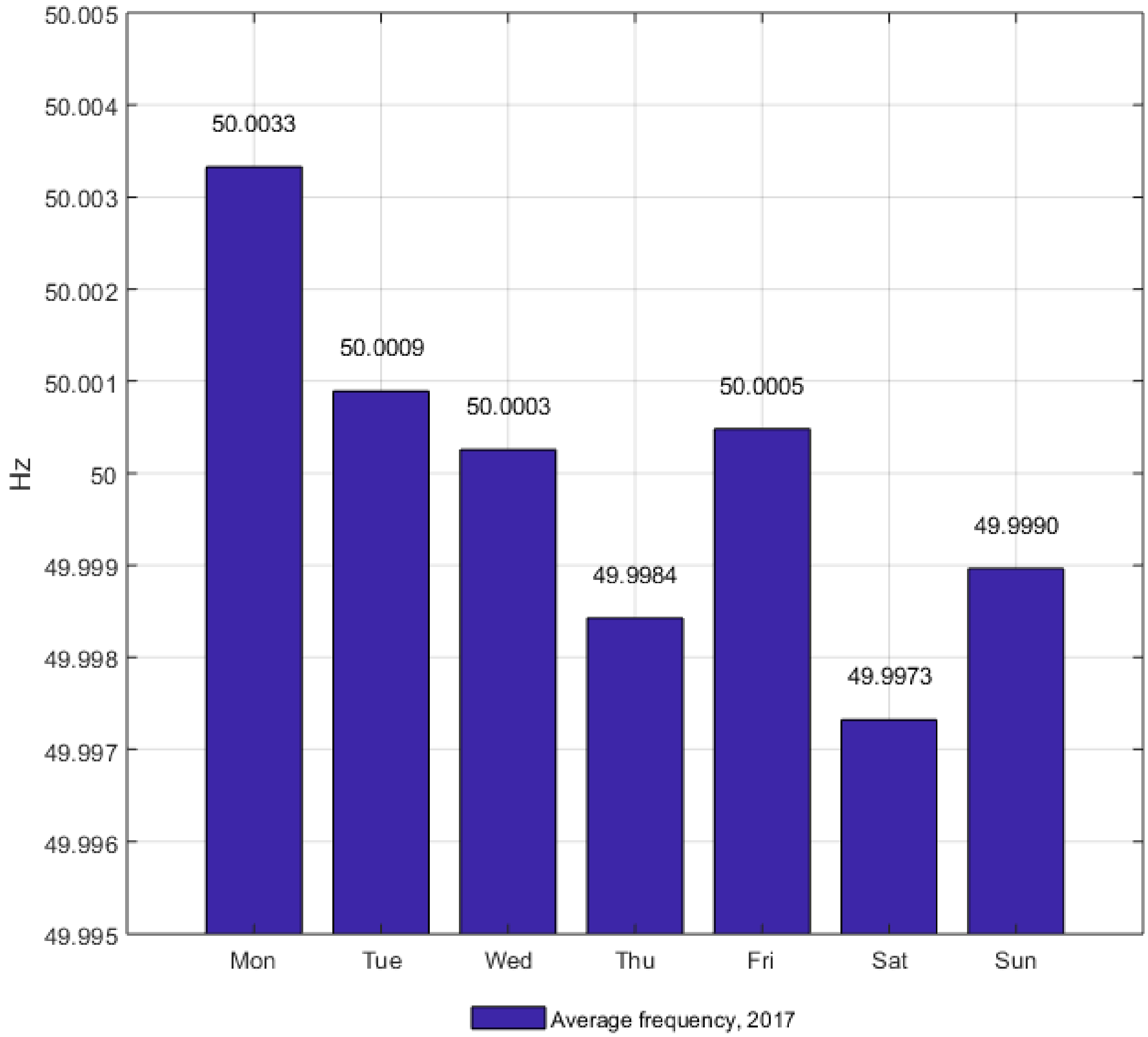


Figure 3.3 shows the average frequencies during each hour of the day. Frequency is generally lower during the night in hours from 1 a.m. to 4 a.m. The frequency is at its highest during the evenings and around midnight.

***Figure 3.3**. Average frequency for each hour of the day in 2017*

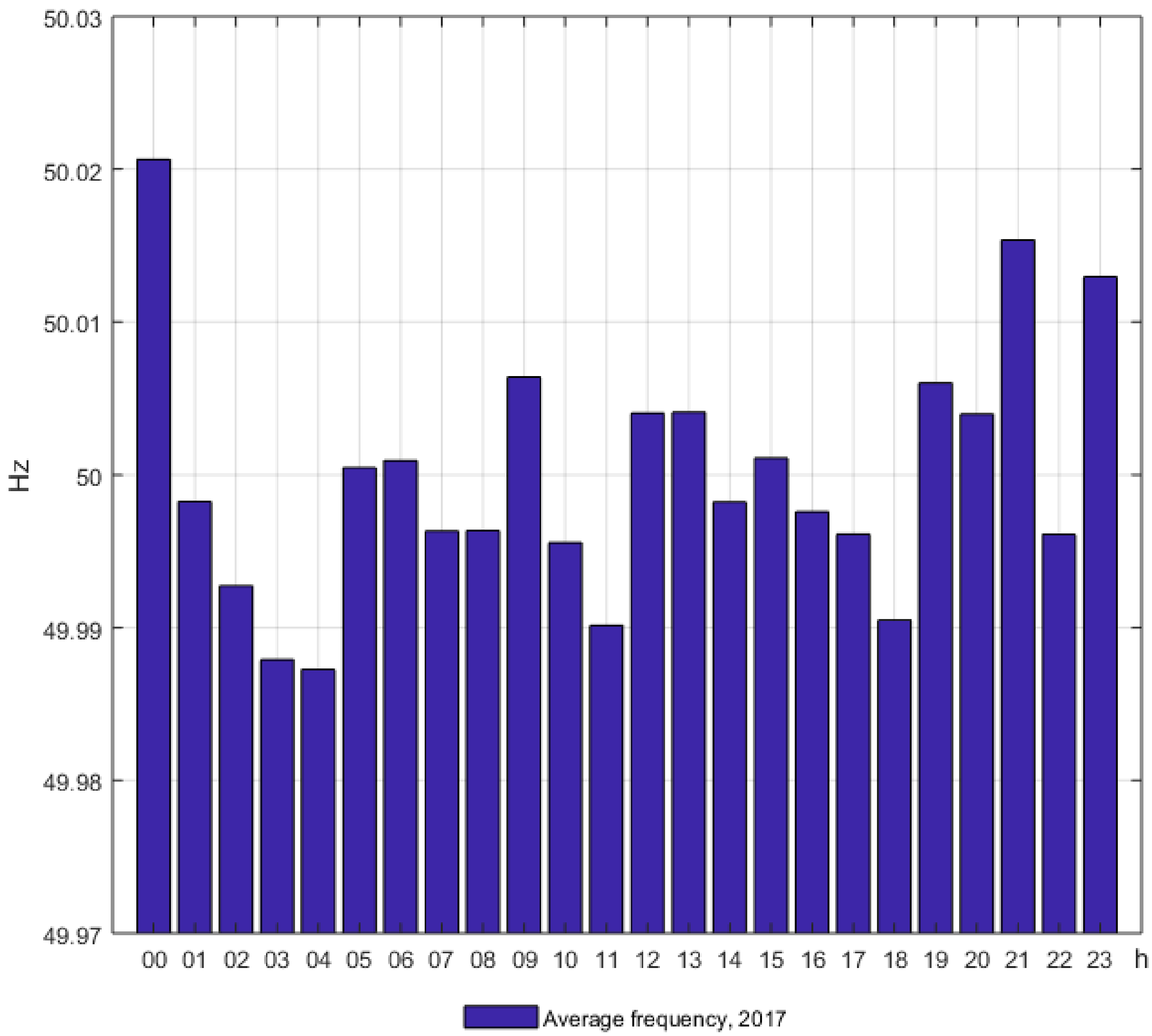
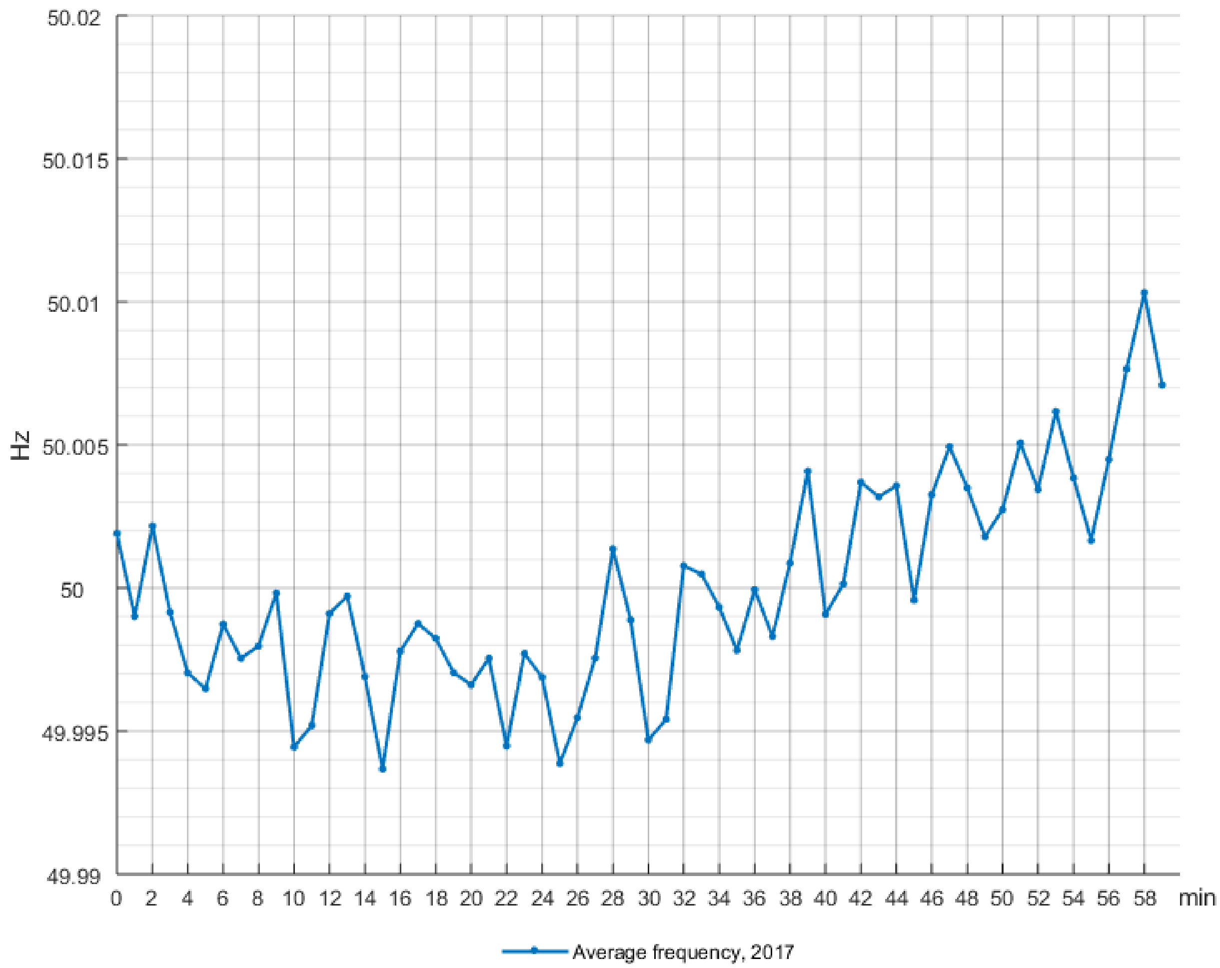


Figure 3.4 shows the average frequency inside the hour. In general the frequency is higher in the latter part of the hour. The difference between consecutive minutes is mostly between 2-4 mHz.

***Figure 3.4**. Average frequency for each minute of the hour in 2017*



3.1.2 Standard deviation

This section includes the figures representing the standard deviation of frequency during the year 2017. 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 2017. The lower standard deviation in January, February and December indicates that the 1 second values were in average closer to 50 Hz during those months. In March and October the standard deviation was slightly higher than during other months.

Figure 3.5. Standard deviation of the frequency for every month in 2017

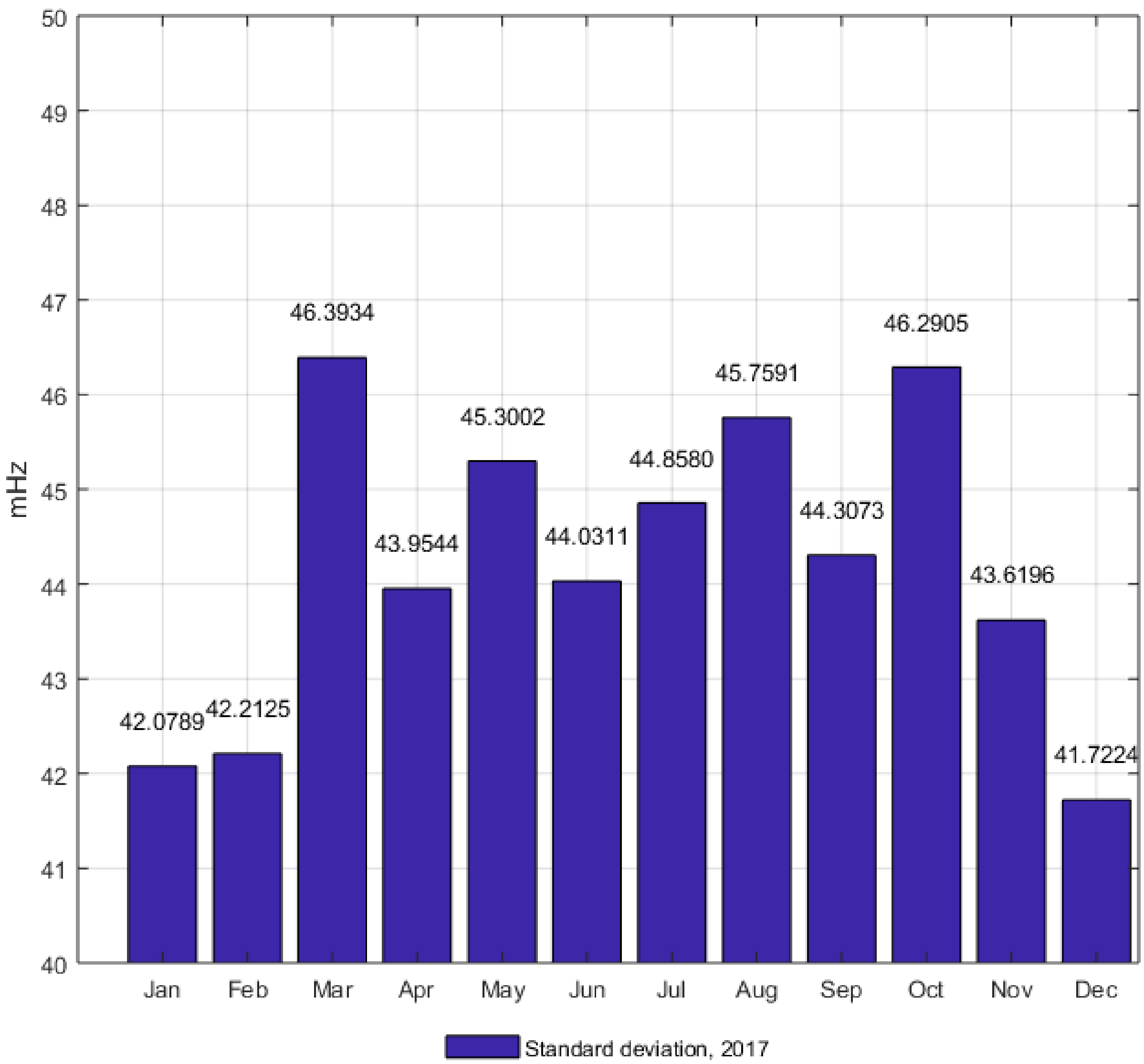


Figure 3.6 represents the standard deviation for every day of the week. Based on standard deviation, the quality of the frequency improves slightly each day from the start of the week to the end except for Fridays when the standard deviation is at its lowest. It is noteworthy that all the values are nearly within 1 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 2017*

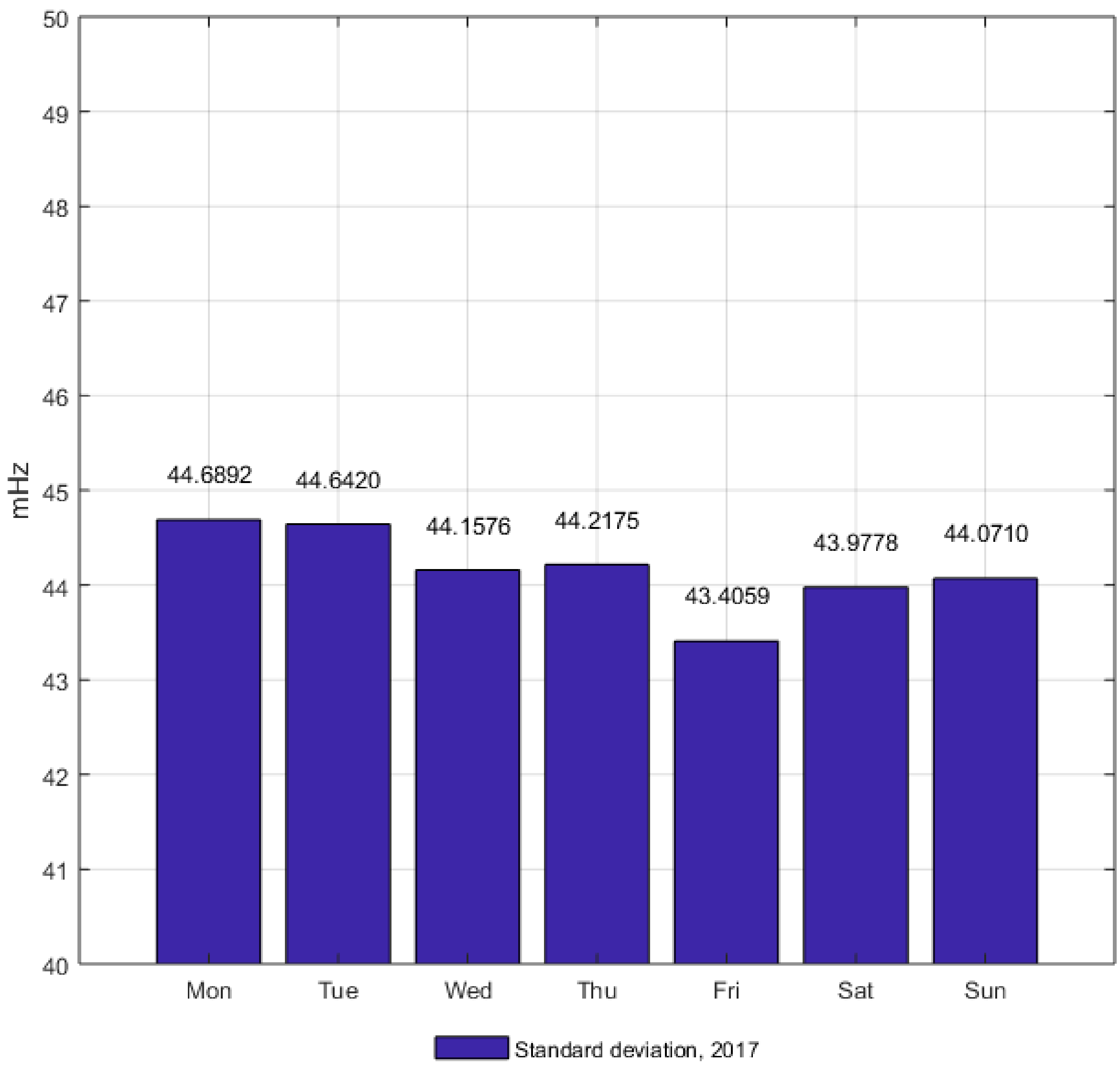


Figure 3.7 shows the standard deviation during a day. The standard deviation can vary over 10 mHz from the lowest values during night to the highest points around midnight and in the morning.

***Figure 3.7**. Standard deviation of the frequency for every hour of the day in 2017*

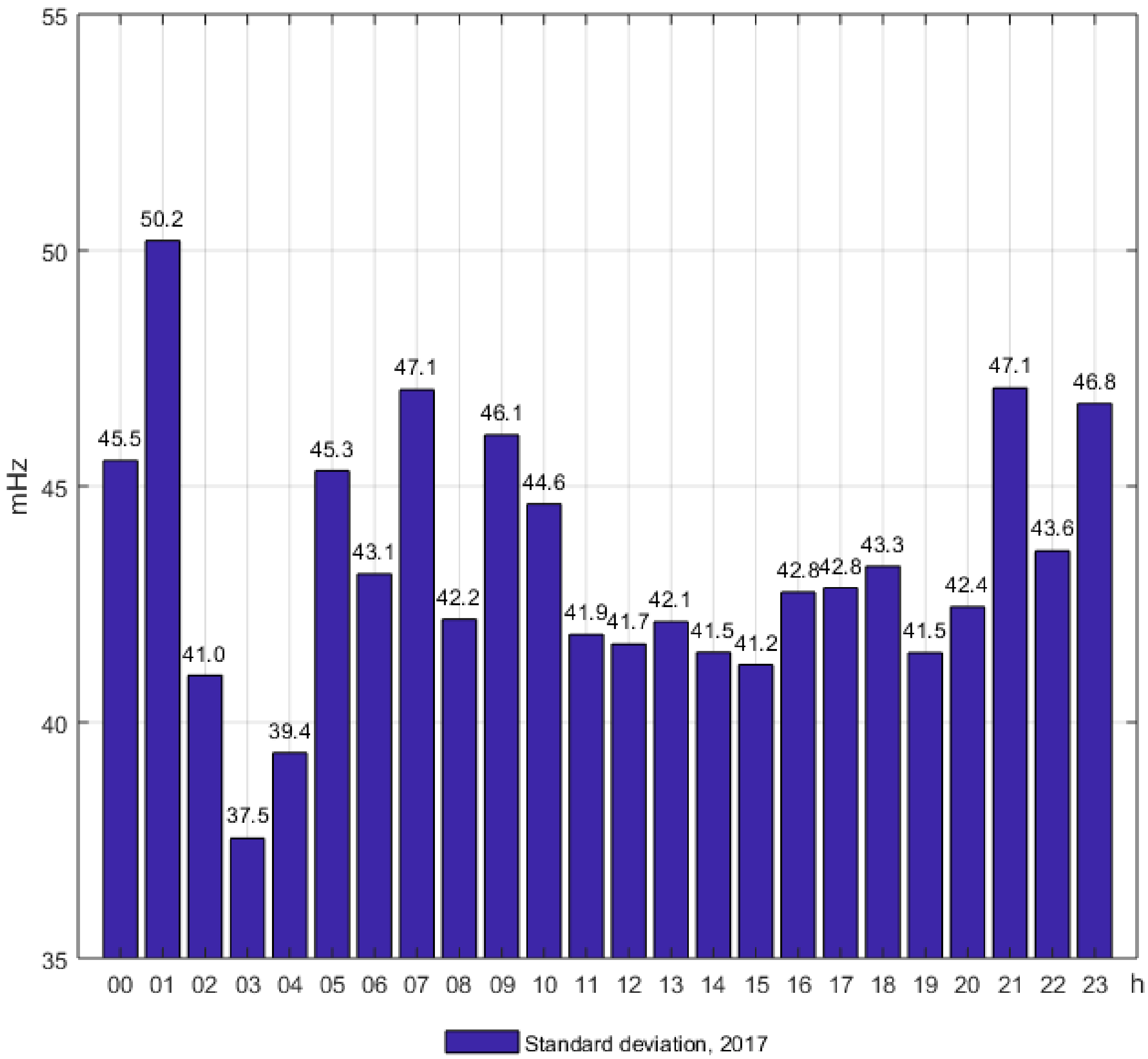
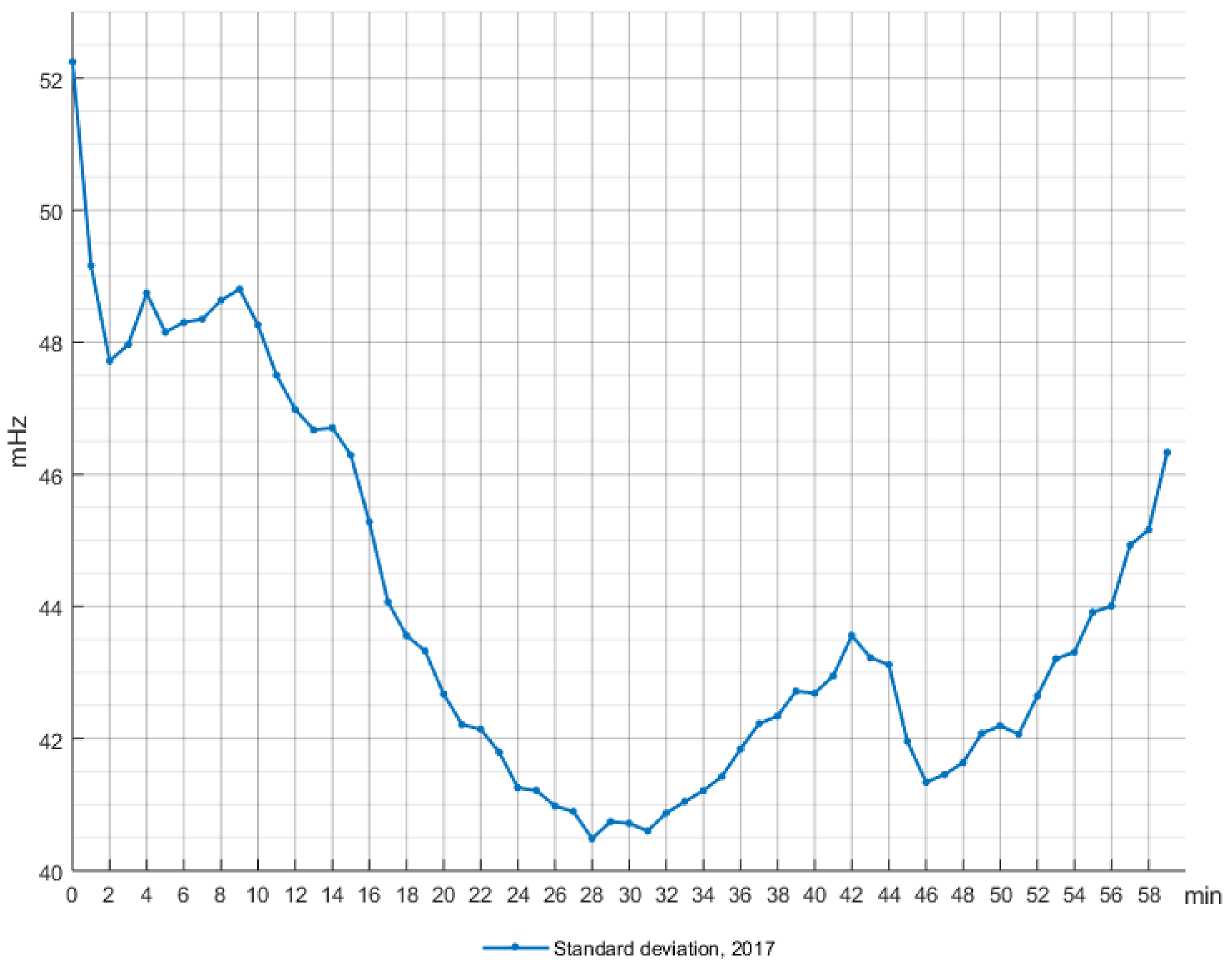


Figure 3.8 represents the standard deviation inside one hour. The standard deviation is at its highest in the beginning of the hour. From the 10th minute the standard deviation starts to drop until the half hour mark from where it starts to increase again. There is also a slight drop in the standard deviation at 45th minute.

Figure 3.8*. *Standard deviation of the frequency for every minute of the hour in 2017



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 2012 to 2017 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.

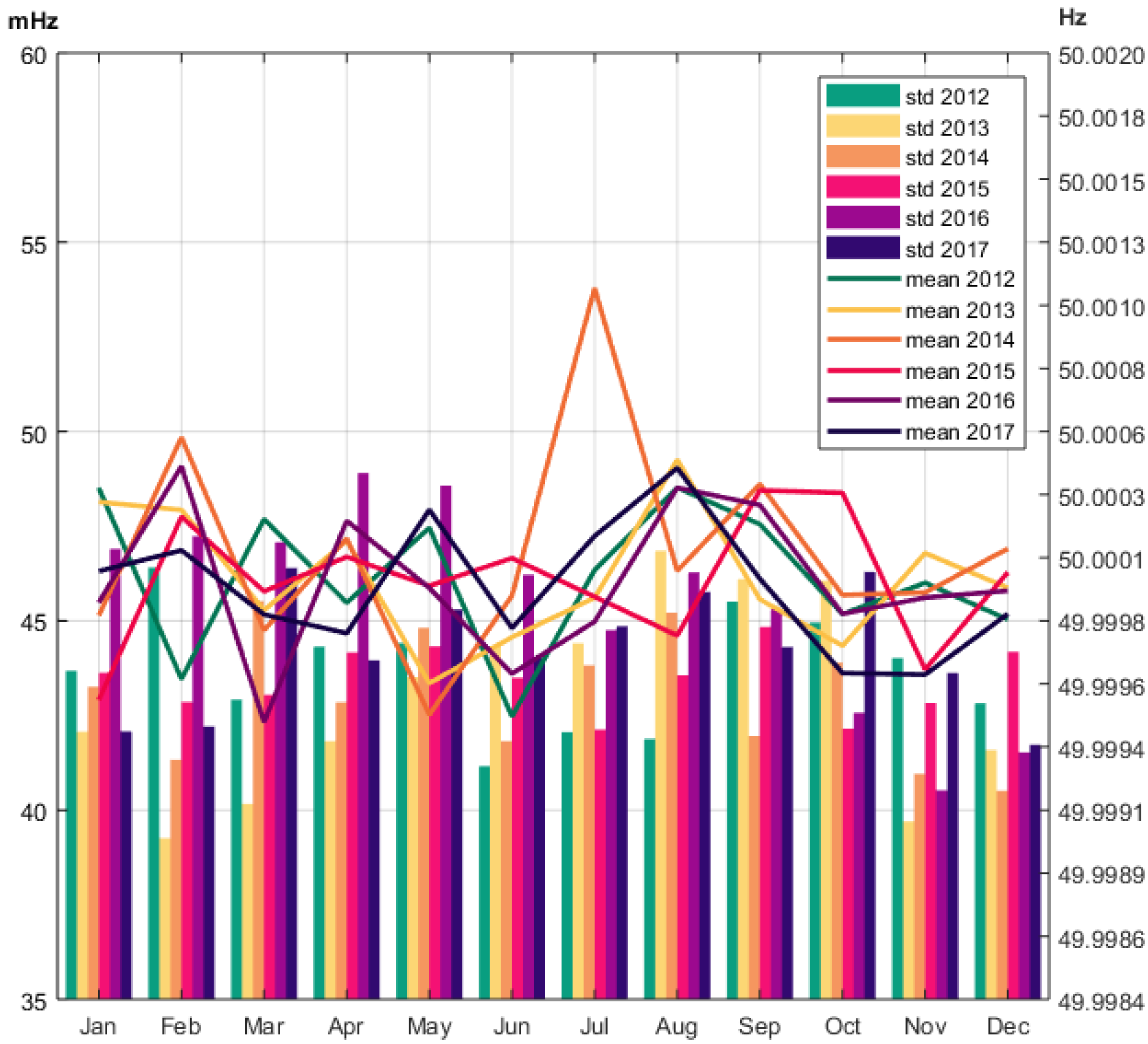
Table 3.1. Mean values and standard deviations for years 2012-2014

	2012		**2013**		**2014**	
Month	**Mean value (Hz)**	**Standard deviation (mHz)**	**Mean value (Hz)**	**Standard deviation (mHz)**	**Mean value (Hz)**	**Standard deviation (mHz)**
January	50.0003	43.7	50.0003	42.1	49.9999	43.3
February	49.9996	46.4	50.0003	39.3	50.0005	41.3
March	50.0002	42.9	49.9999	40.2	49.9998	45.5
April	49.9999	44.3	50.0001	41.8	50.0002	42.8
May	50.0002	44.4	49.9996	43.5	49.9995	44.8
June	49.9995	41.2	49.9998	44.3	49.9999	41.8
July	50.0000	42.1	49.9999	44.4	50.0011	43.8
August	50.0003	41.9	50.0005	46.8	50.0000	45.2
September	50.0002	45.5	49.9999	46.1	50.0004	42.0
October	49.9999	45.0	49.9997	46.1	49.9999	43.9
November	50.0000	44.0	50.0001	39.7	49.9999	41.0
December	49.9998	42.8	50.0000	41.6	50.0001	40.5
Entire year	**50.0000**	**43.7**	**50.0000**	**43.2**	**50.0001**	**43.1**

Table 3.2. Mean values and standard deviations for years 2015-2017

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

***Figure 3.9**. Mean values and standard deviations for years 2012-2017*

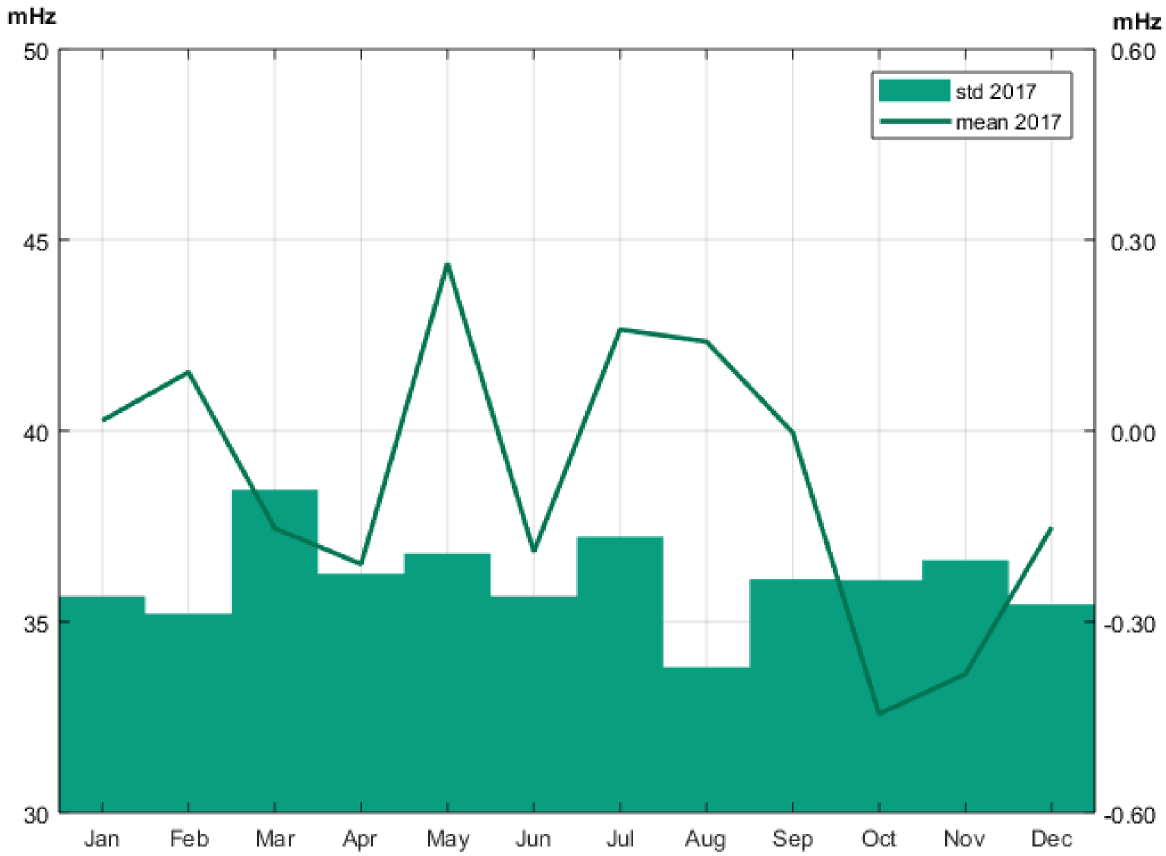


Mean values and standard deviations for frequency deviations as per Article 131(b) (i) for year 2017 can be found in Table 3.3. Results show how much frequency has deviated from nominal 50 Hz value. Visual representation can be found in Figure 3.10. The resolution of the frequency data used in the following table and figure was 15 minutes.

Table 3.3. Mean values and standard deviations of frequency deviations for year 2017

	2017	
Month	**Mean value (mHz)**	**Standard deviation (mHz)**
January	0.016	35.7
February	0.092	35.2
March	-0.153	38.5
April	-0.210	36.3
May	0.263	36.8
June	-0.190	35.7
July	0.159	37.2
August	0.140	33.8
September	-0.003	36.1
October	-0.445	36.1
November	-0.382	36.6
December	-0.151	35.5
Entire year	**-0.072**	**36.1**

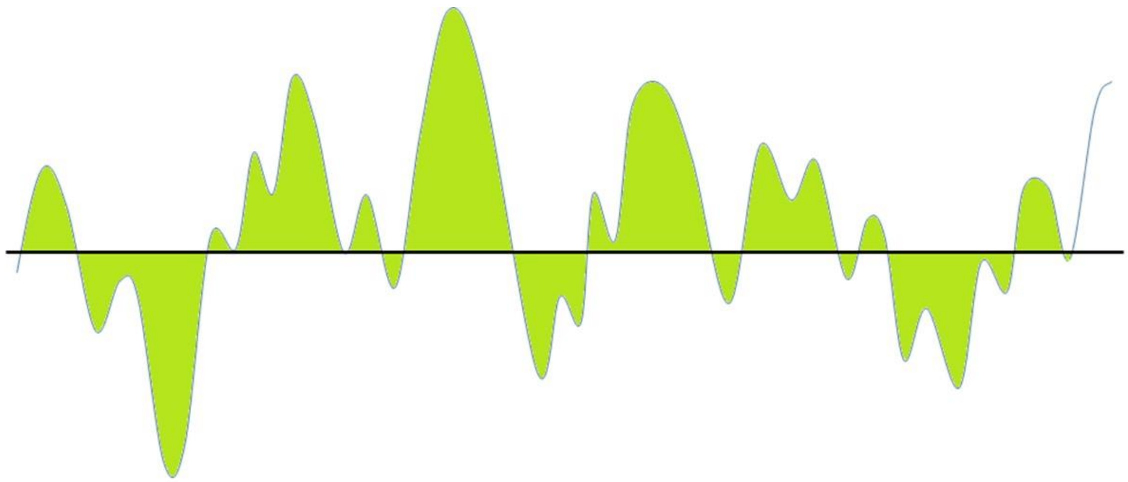
***Figure 3.10**. Mean values and standard deviations of frequency deviations for year 2017*



3.2 Frequency area

The frequency area is an indicator of how much the frequency is off 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.

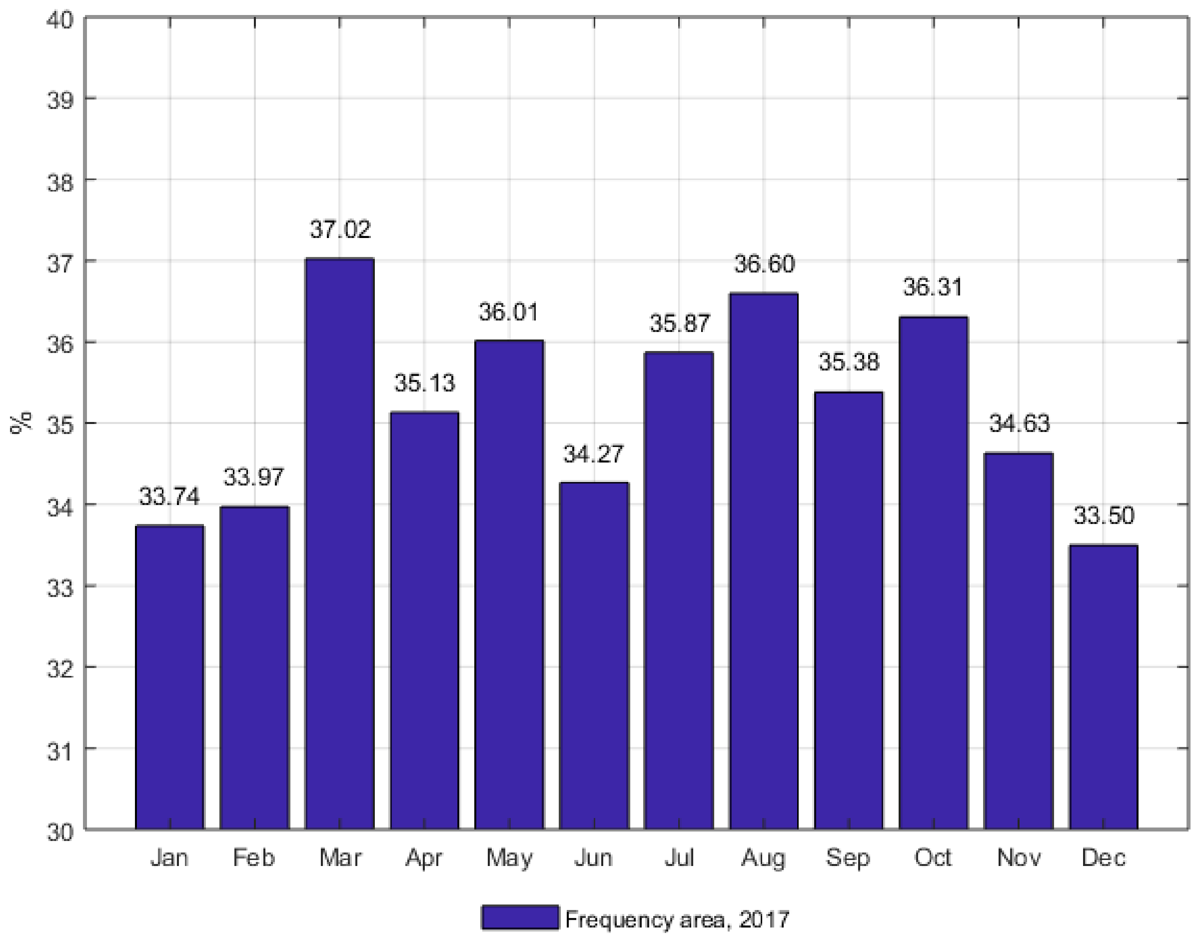
Figure 3.11. Frequency quality index: Frequency area [8]



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

Figure 3.12 represents the average frequency area for every month in 2017. The percentage of the area was considerably smaller early and late in the year, which indicates that there was less deviation from 50 Hz during those months.

***Figure 3.12**. The average frequency area for every month in 2017*



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 Fridays.

Figure 3.13**. **The average frequency area for every day of the week in 2017

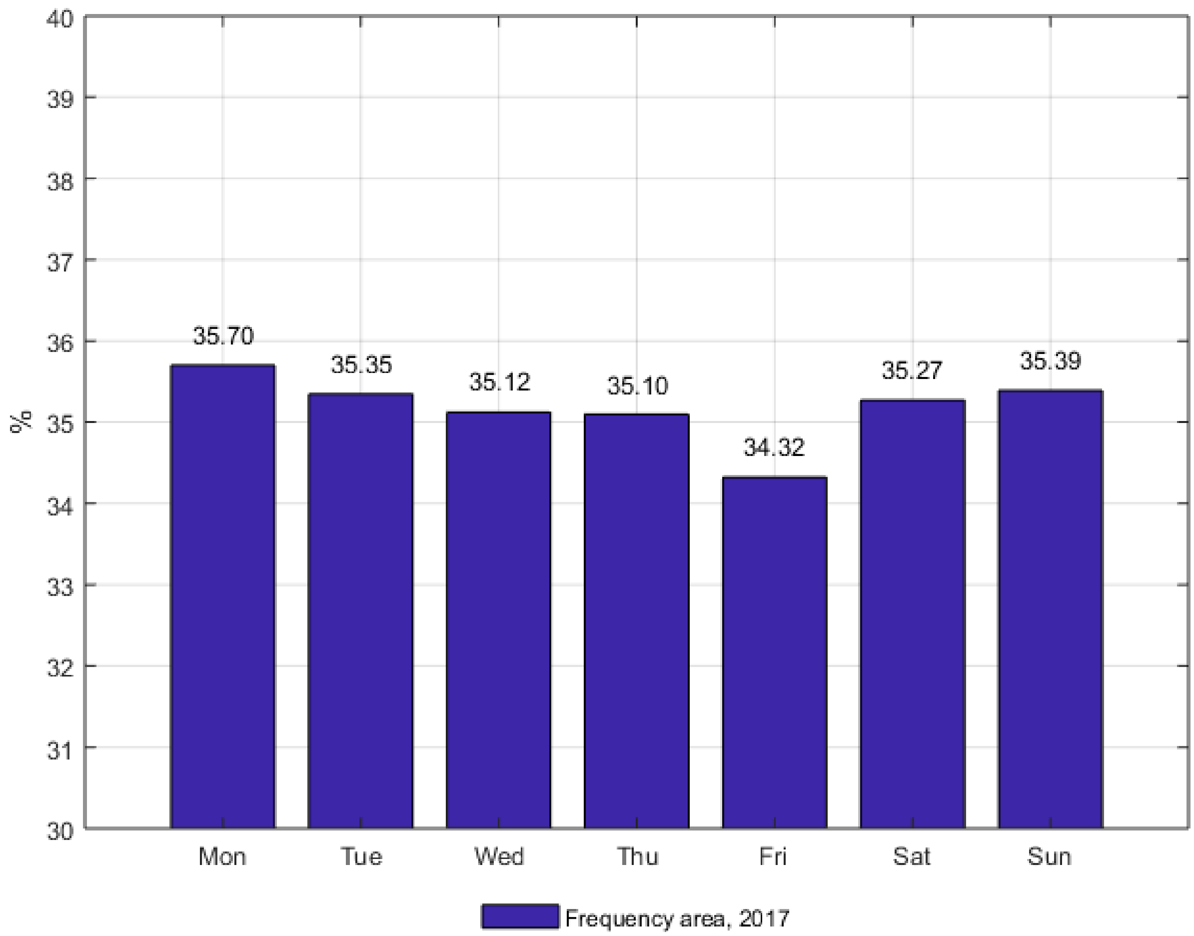


Figure 3.14 has the frequency area for every hour during the day. The figure shows that the deviation of the frequency from 50.0 Hz was smaller in the middle of the night and after noon. The area was at its highest in the first and last hours of the day.

***Figure 3.14**. The average frequency area for every hour inside the day in 2017*

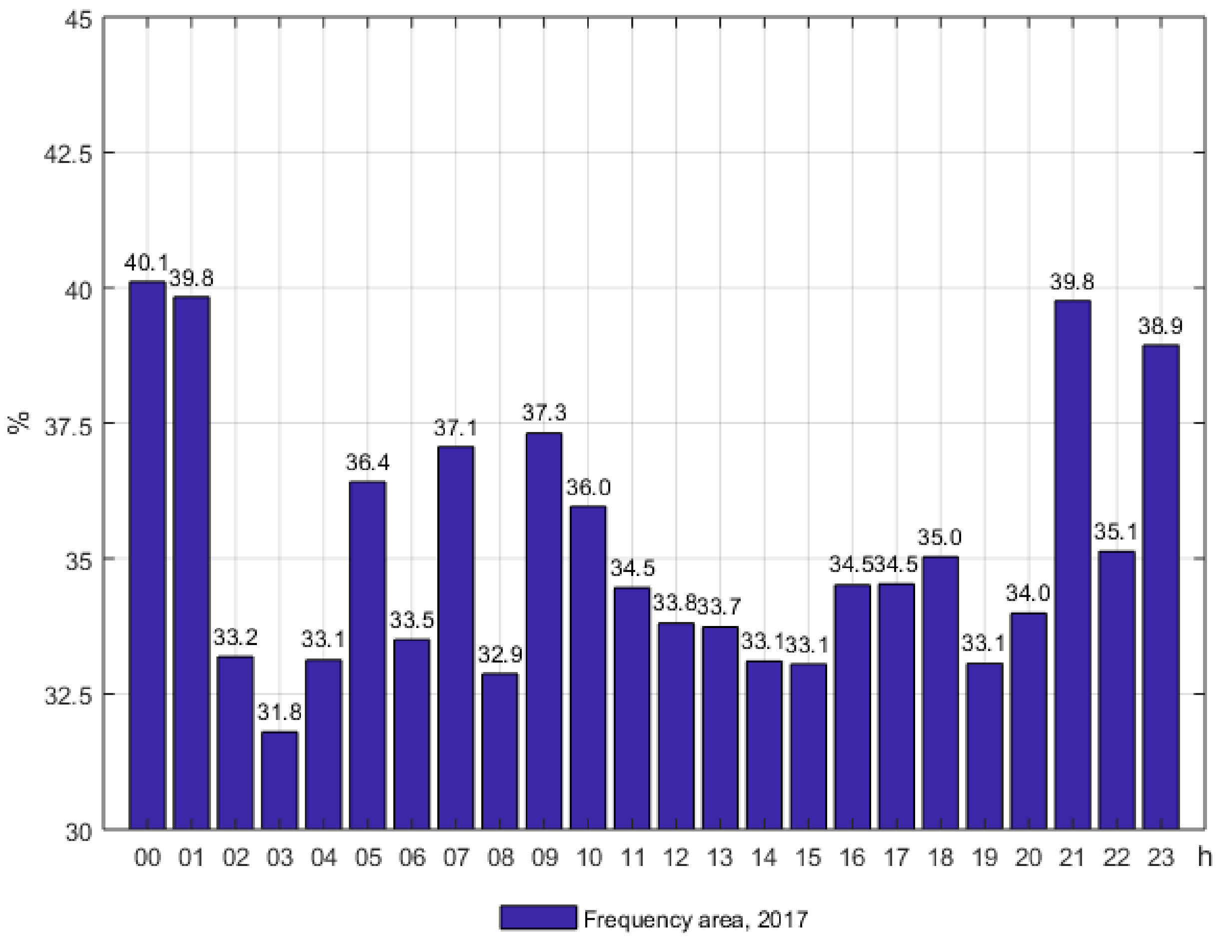
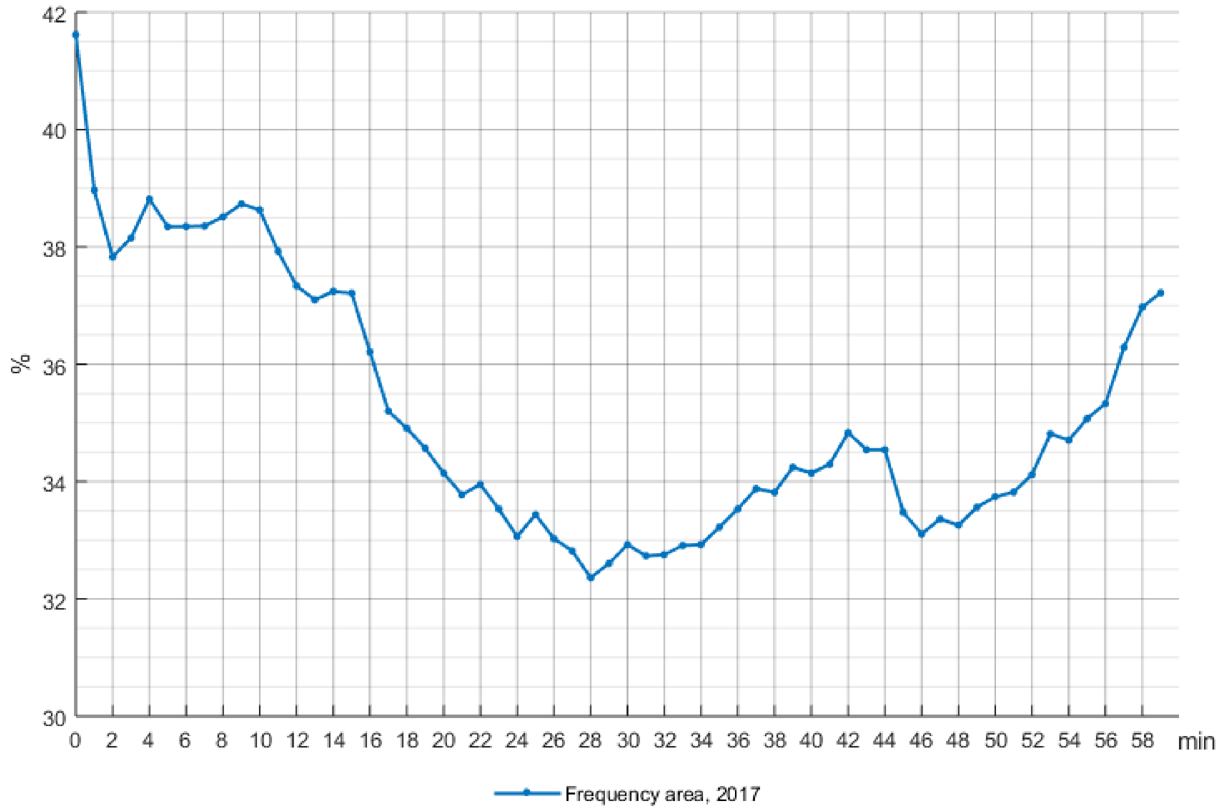


Figure 3.15 represents the frequency area within the hour. The percentage of the frequency area was smaller in the middle of the hour while more deviation occured closer the hour shift.

***Figure 3.15**. The average frequency area for every minute within the hour in 2017*



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 2012 to 2017. All results are summed up in Figure 3.16.

***Table 3.4**. The 1st, 5th, 10th, 90th, 95th and 99th percentiles for year 2012*

	2012					
Month	**1st (Hz)**	**5th (Hz)**	**10th (Hz)**	**90th (Hz)**	**95th (Hz)**	**99th (Hz)**
Jan	49.904	49.931	49.945	50.058	50.074	50.103
Feb	49.899	49.927	49.942	50.061	50.079	50.111
Mar	49.901	49.930	49.945	50.055	50.071	50.102
Apr	49.902	49.929	49.944	50.057	50.074	50.109
May	49.895	49.928	49.944	50.057	50.073	50.105
Jun	49.904	49.933	49.948	50.052	50.067	50.099
Jul	49.905	49.931	49.946	50.054	50.069	50.099
Aug	49.904	49.933	49.948	50.054	50.070	50.101
Sep	49.897	49.928	49.943	50.059	50.077	50.113
Oct	49.899	49.929	49.943	50.058	50.075	50.108
Nov	49.896	49.927	49.943	50.056	50.073	50.102
Dec	49.906	49.932	49.946	50.054	50.072	50.109
Entire year	**49.901**	**49.930**	**49.945**	**50.056**	**50.073**	**50.105**

Table 3.5. 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	49.935	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 3.6. 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 3.7. 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**

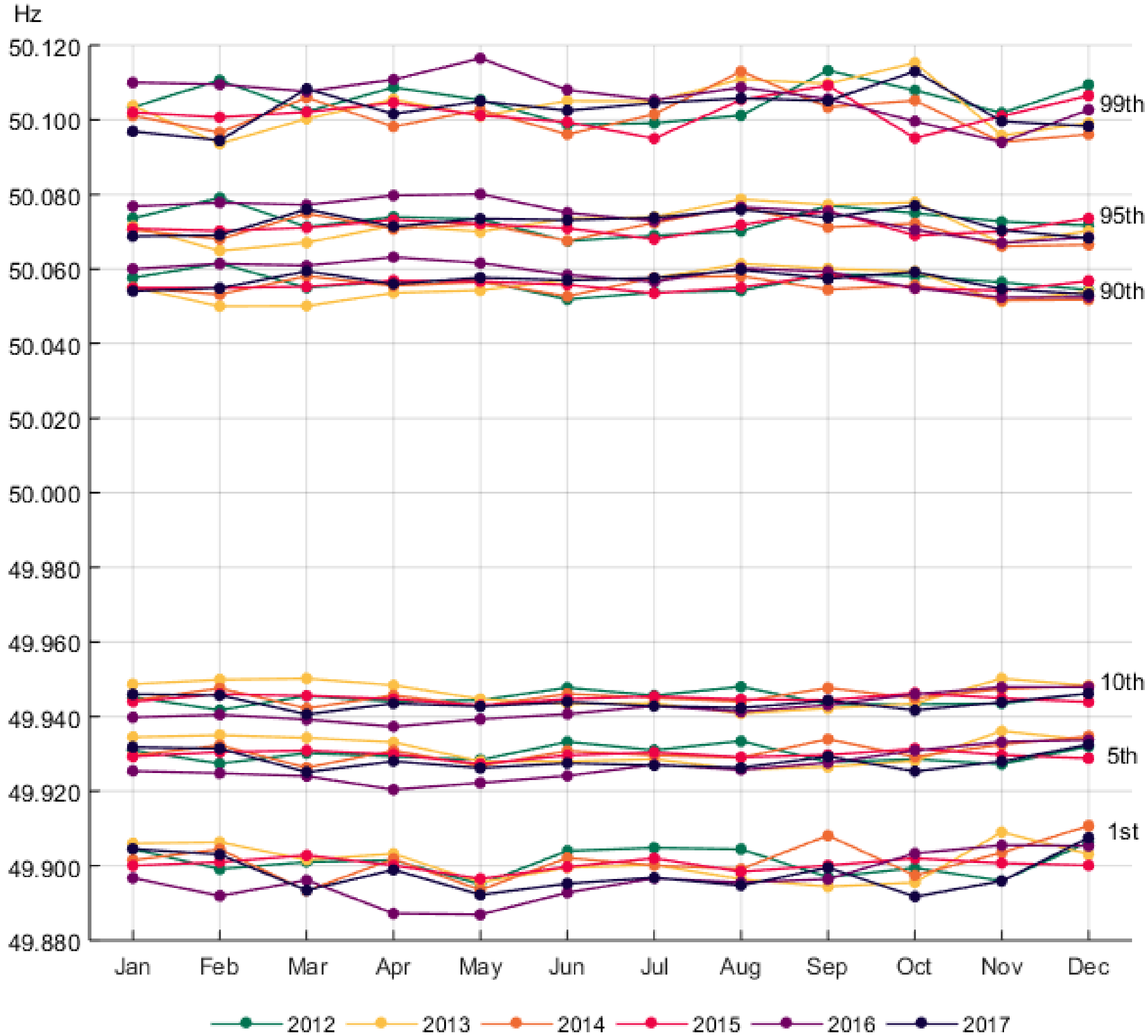
Table 3.8. The 1st, 5th, 10th, 90th, 95th and 99th percentiles for year 2016

	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 3.9. 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**

***Figure 3.16**. The 1st, 5th, 10th, 90th, 95th and 99th percentiles for years 2012-2017*



More detailed results for the percentiles of 2017 are shown in the next figures. Figure 3.17 is a visual representation of the given percentiles for each month in 2017. The percentiles in March and October were further from 50 Hz, which indicates that there were more deviations during those months.

***Figure 3.17**. The 1st, 5th, 10th, 90th, 95th and 99th percentile of the frequency for every month in 2017*

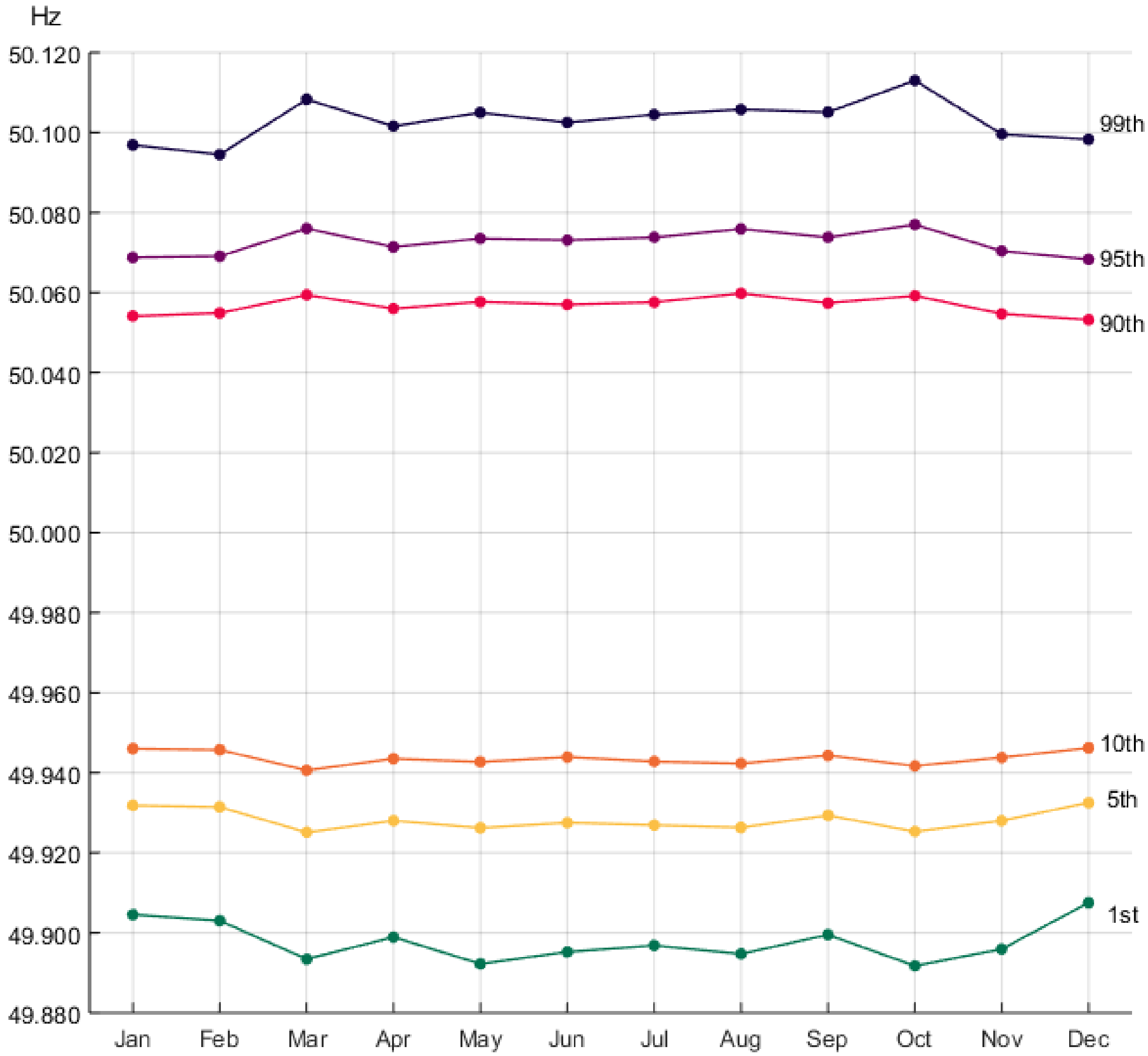


Figure 3.18 shows the percentiles for every day during the week. The 90th, 95th and 99th percentile were all slighly lower during weekends, which indicates that there were less over frequencies during that time. The 1st, 5th and 10th percentile have stayed fairly constant throughout the week.

***Figure 3.18**. The 1st, 5th, 10th, 90th, 95th and 99th percentile of the frequency for every day of the week in 2017*

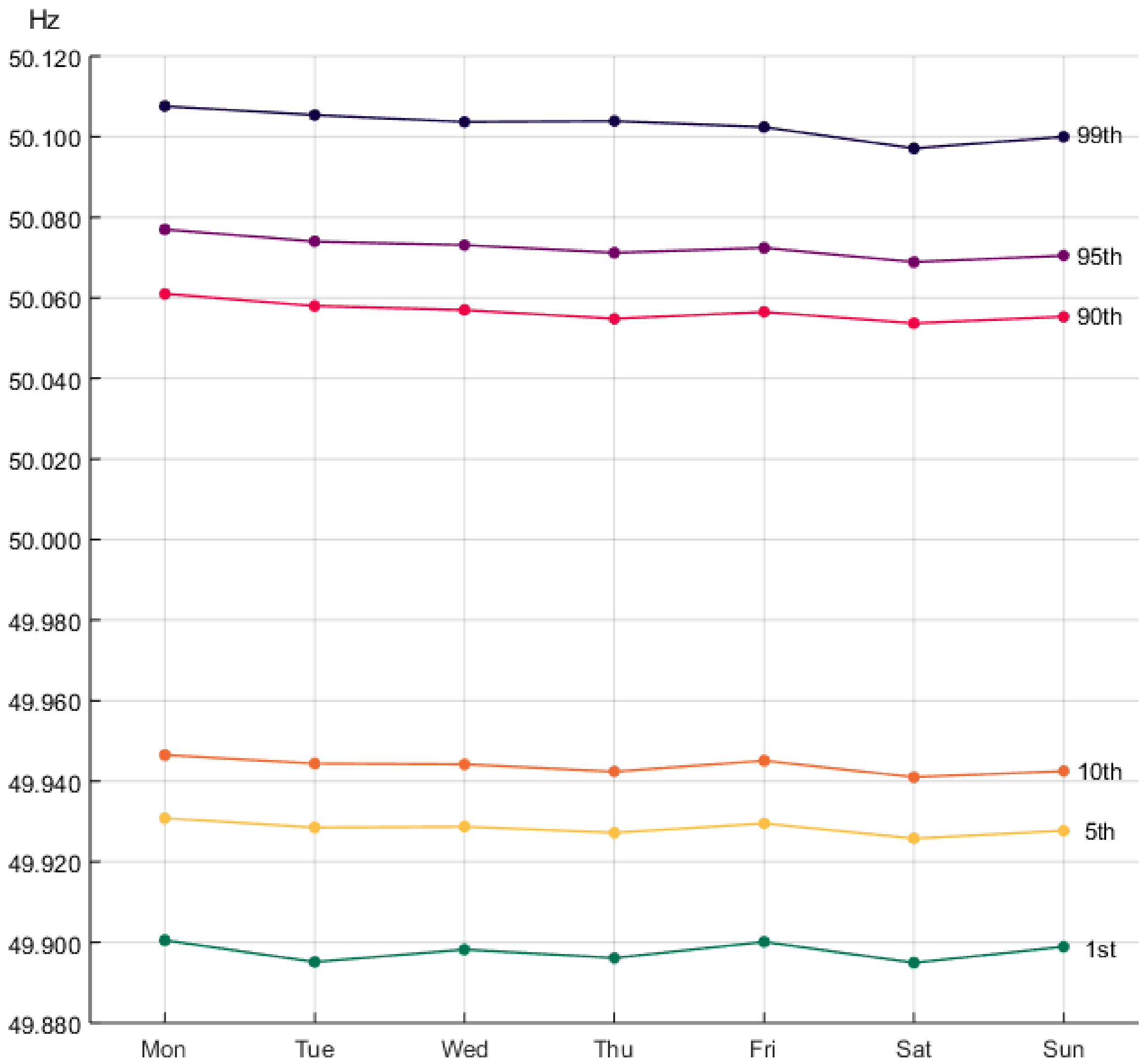
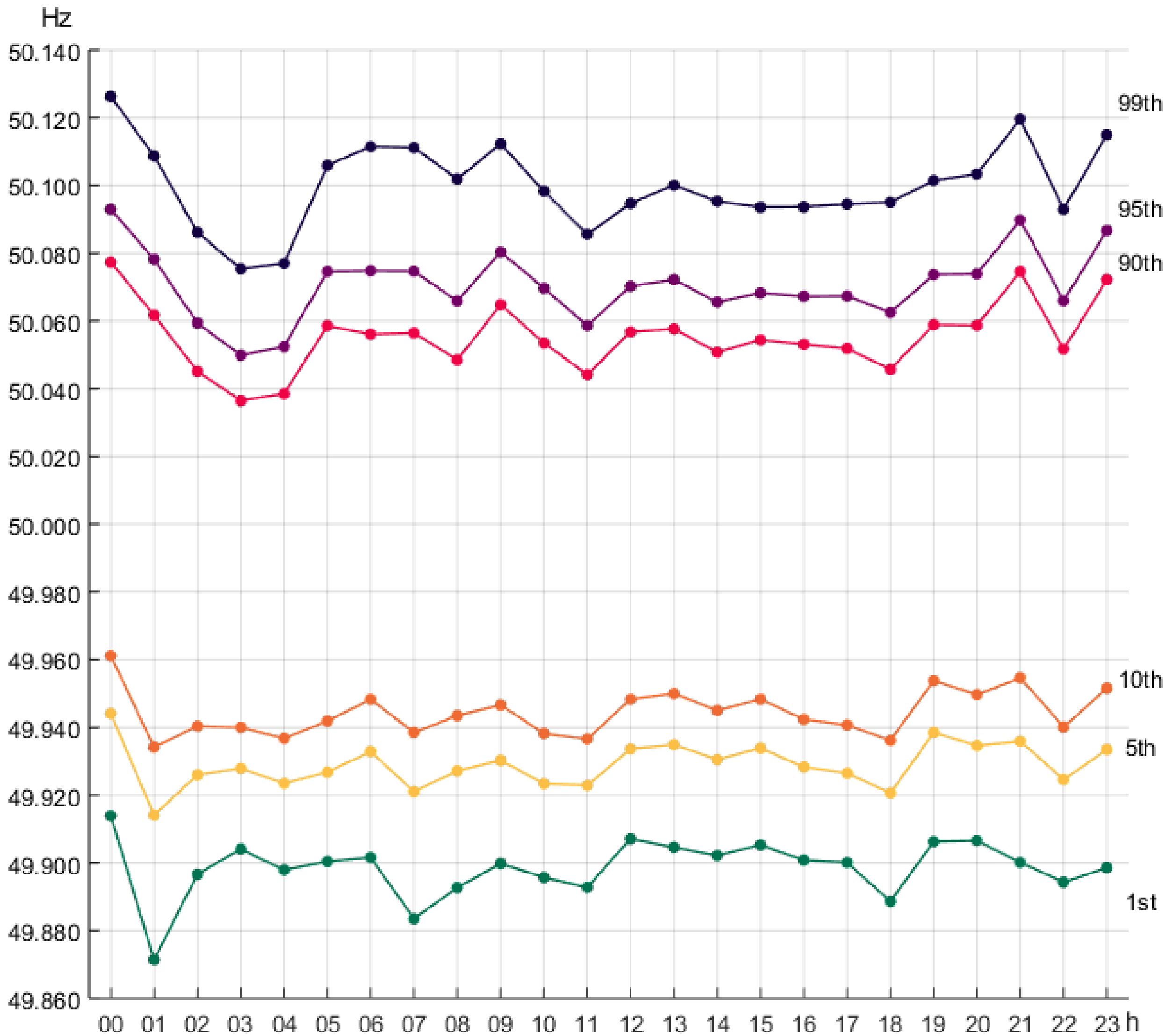


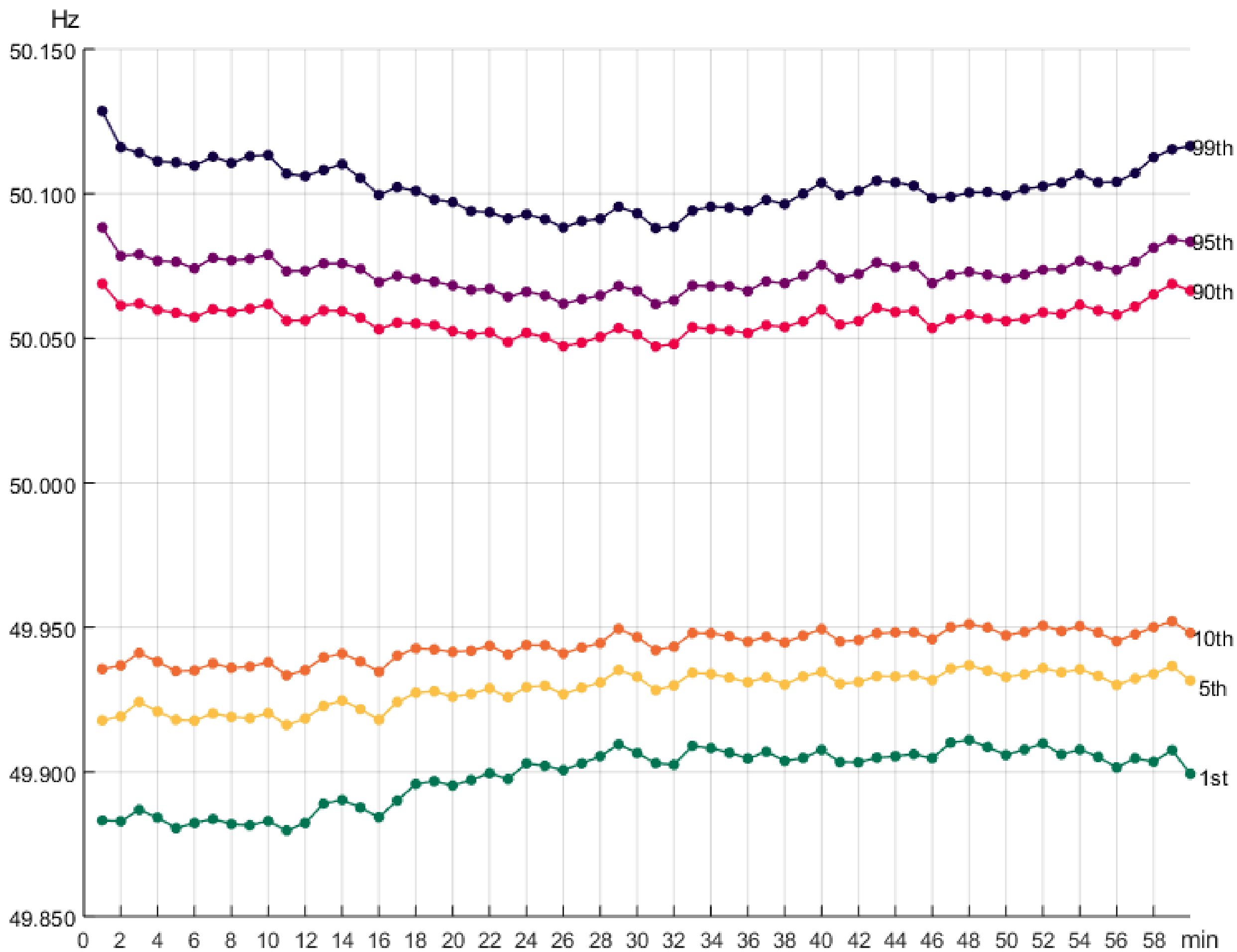
Figure 3.19 represents the percentiles inside the day. In terms of the 1st, 5th and 10th percentile, the frequencies are lowest between 01-02. For the 90th, 95th and 99th percentile, night hours have values closest to 50 Hz.

***Figure 3.19**. The 1st, 5th, 10th, 90th, 95th and 99th percentile of the frequency for every hour of the day in 2017*



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 2017*

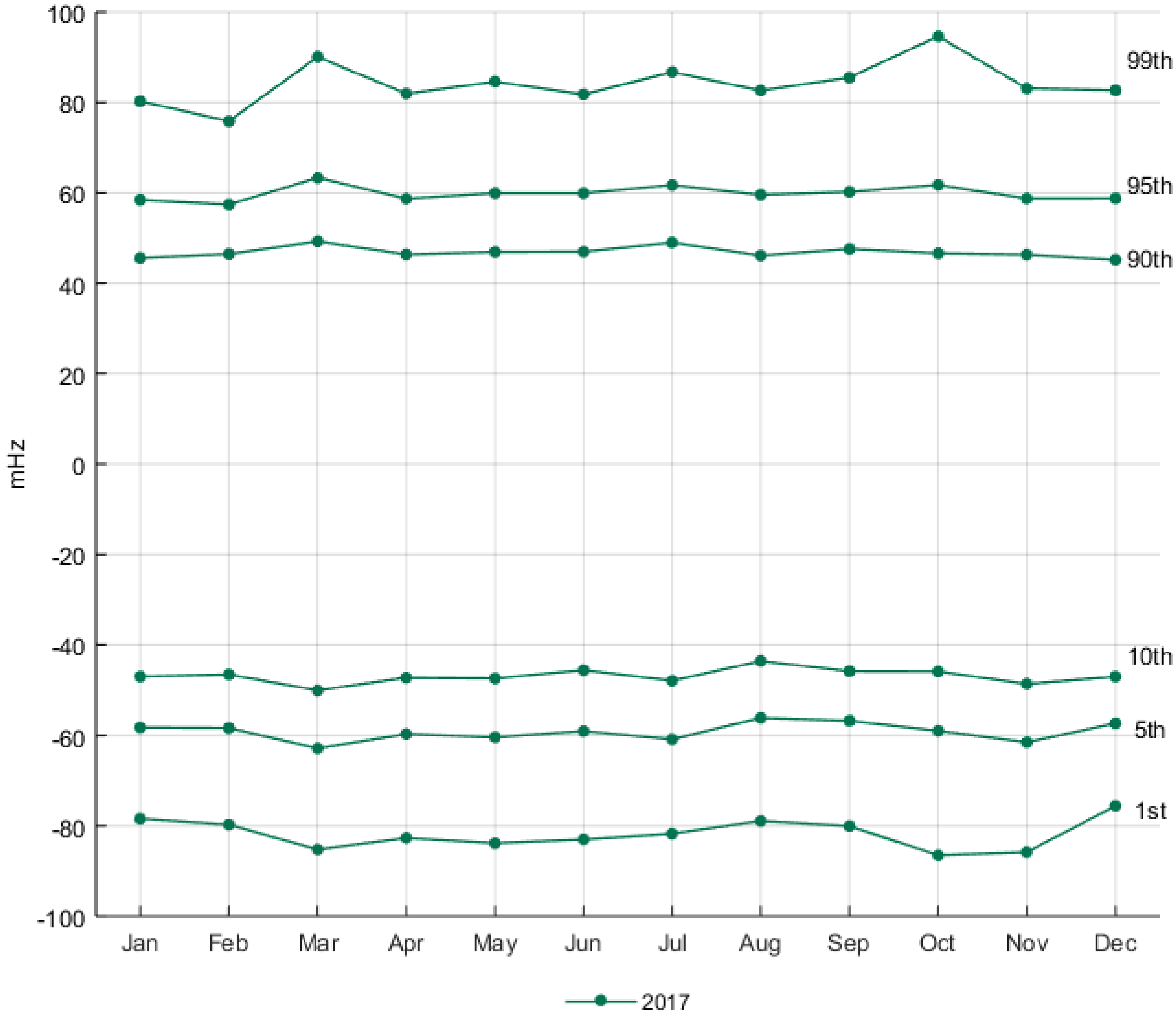


The 1st, 5th, 10th, 90th, 95th and 99th percentiles according to SO GL Article 131(b) i(3) are presented in Table 3.10. Figure 3.21 below the table shows results in graphical form. Results are deviations from nominal 50 Hz value and a frequency data with a resolution of 15 minutes was used.

Table 3.10. The 1st, 5th, 10th, 90th, 95th and 99th percentiles for year 2017

	2017					
Month	**1st (mHz)**	**5th (mHz)**	**10th (mHz)**	**90th (mHz)**	**95th (mHz)**	**99th (mHz)**
Jan	-78.4	-58.2	-47.0	45.6	58.4	80.2
Feb	-79.7	-58.3	-46.5	46.5	57.4	75.8
Mar	-85.2	-62.8	-50.0	49.3	63.3	90.0
Apr	-82.7	-59.7	-47.2	46.4	58.7	81.9
May	-83.8	-60.4	-47.4	46.9	59.9	84.6
Jun	-83.0	-59.0	-45.5	47.0	60.0	81.8
Jul	-81.7	-60.8	-47.9	49.0	61.7	86.7
Aug	-78.9	-56.1	-43.5	46.1	59.6	82.6
Sep	-80.0	-56.7	-45.8	47.6	60.2	85.5
Oct	-86.5	-59.0	-45.8	46.6	61.7	94.6
Nov	-85.8	-61.5	-48.6	46.3	58.8	83.1
Dec	-75.6	-57.3	-47.0	45.2	58.8	82.7
Entire year	**-81.8**	**-59.2**	**-46.9**	**46.9**	**59.9**	**84.1**

***Figure 3.21**. The 1st, 5th, 10th, 90th, 95th and 99th percentiles for year 2017*



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 2017. The curves are fairly linear throughout the year, though the growth is slightly more restrained during winter months. The frequency has been outside the standard range just under 12 000 minutes, close to 6 000 min over 50.1 Hz and slightly under 6 000 min under 49.9 Hz.

Figure 3.22. Cumulative minutes outside the standard frequency range in 2017

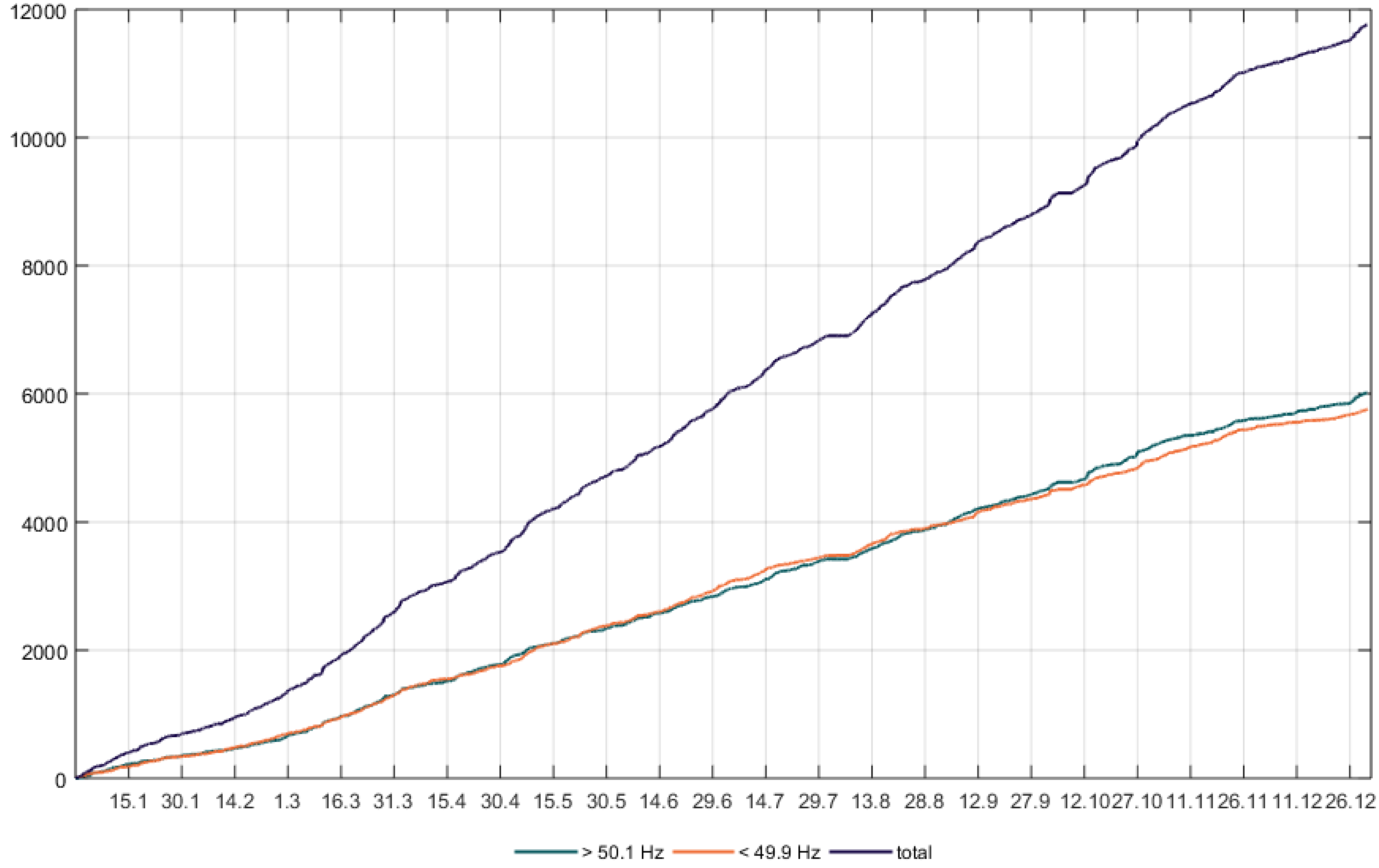
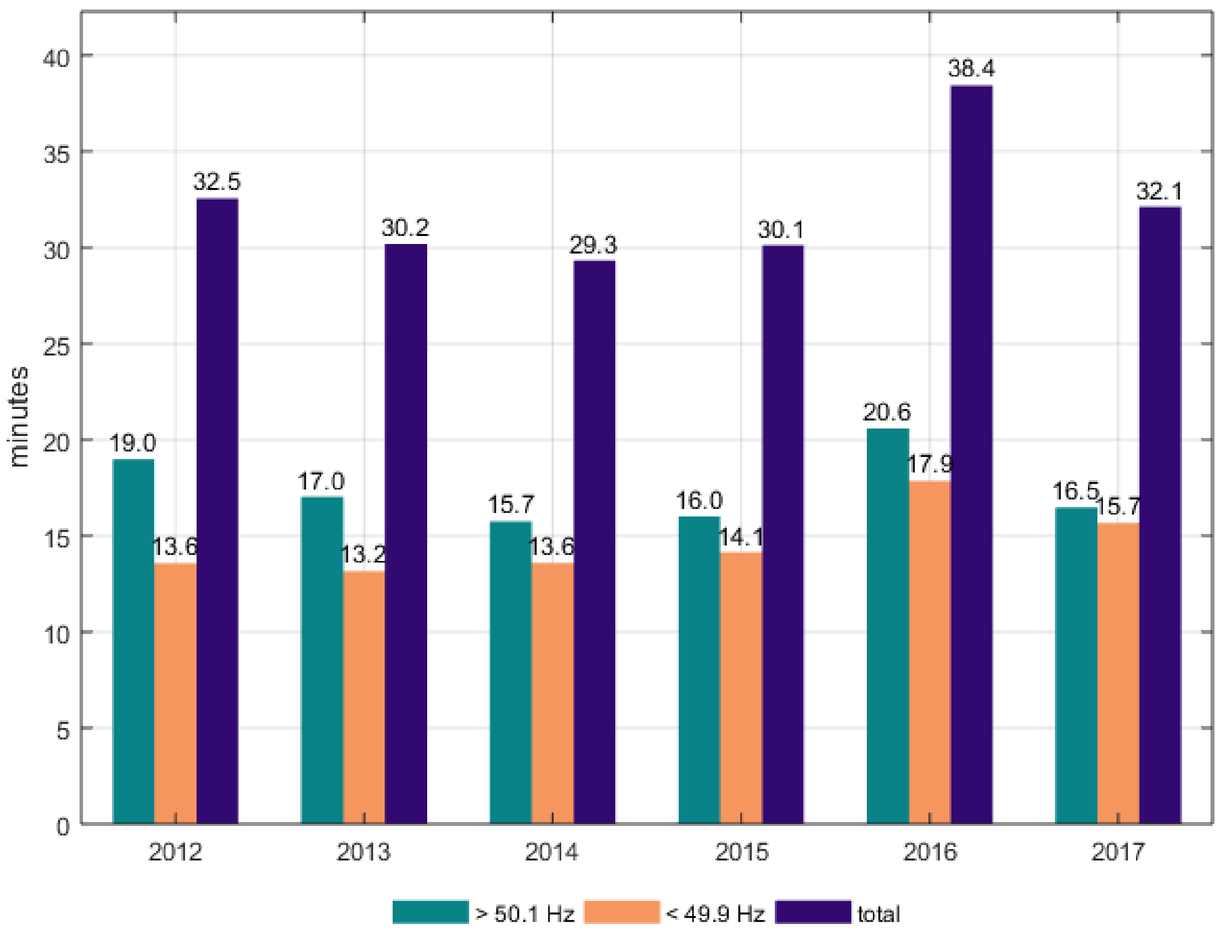


Figure 3.23 represents the daily average number of minutes per year that the frequency was outside the standard frequency range. The amount of minutes has stayed around 30 each year except for 2016 when the average was over 38 minutes. Every year there has been more over frequencies than under frequencies.

***Figure 3.23**. Daily average number of minutes per year that the frequency was outside the standard frequency range in 2012-2017*



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
2012	1.32 %	0.94 %	97.73 %
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 %

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)
2012	6965	4977	11941
2013	6750	5212	11963
2014	5755	4959	10714
2015	5844	5166	11010
2016	7586	6574	14160
2017	6185	5884	12069

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 2012 to 2017. 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 2012-2014*

	2012		**2013**		**2014**	
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	542	339	522	311	474	409
February	737	438	123	132	324	309
March	507	420	453	411	629	616
April	652	394	532	334	387	391
May	593	561	474	576	517	608
June	400	348	384	302	340	383
July	418	315	599	442	487	444
August	477	345	810	547	830	471
September	784	508	723	573	516	247
October	668	462	851	541	583	506
November	484	536	326	250	303	353
December	686	300	422	383	359	218
Entire year	**6948**	**4965**	**6220**	**4803**	**5749**	**4954**

Table 3.14. Total time in which the frequency was outside the 49.9-50.1 Hz band in years 2015-2017

	2015		**2016**		**2017**	
Month	**> 50.1 Hz (min)**	**< 49.9 Hz (min)**	**> 50.1 Hz (min)**	**< 49.9 Hz (min)**	**> 50.1 Hz (min)**	**< 49.9 Hz (min)**
January	498	444	723	526	362	345
February	420	379	687	612	272	338
March	506	376	679	566	669	611
April	544	428	779	809	471	460
May	478	535	962	820	577	642
June	414	438	607	594	501	549
July	323	397	587	537	569	530
August	579	485	704	572	504	476
September	678	428	584	523	564	442
October	314	398	434	362	703	573
November	454	414	288	310	420	522
December	629	443	504	325	399	266
Entire year	**5838**	**5165**	**7539**	**6555**	**6011**	**5756**

***Figure 3.24**. Total time in which the frequency was outside the 49.9-50.1 band in years 2012-2017*

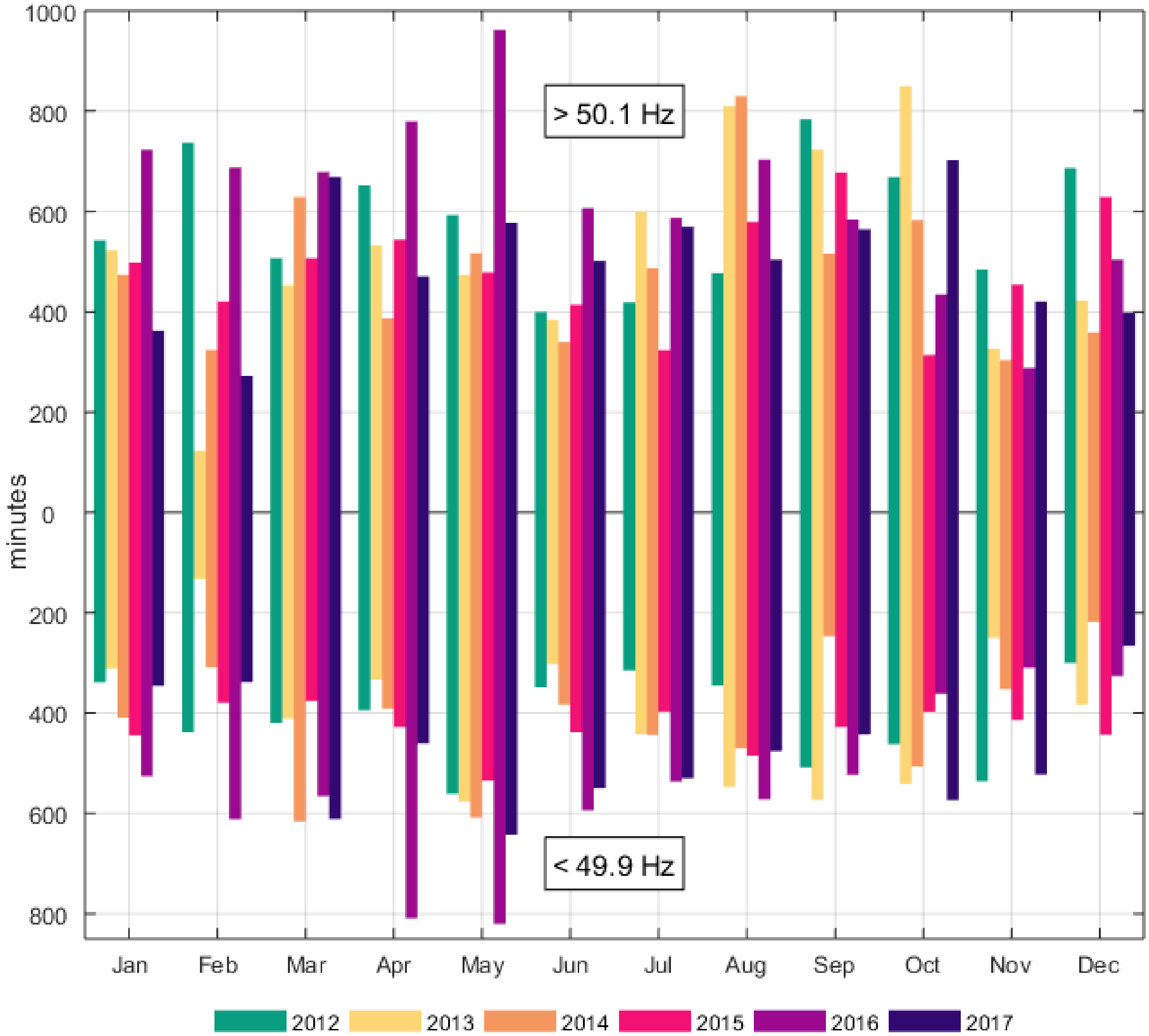


Figure 3.25 shows the daily average in minutes month by month when frequency was outside the standard frequency range in years 2012-2017. In 2017, March, May and October were the months with the longest time outside the standard frequency range. January, February and December had the best frequency in this comparison.

***Figure 3.25**. Daily average time that the frequency was outside the standard frequency range month by month for years 2012-2017*

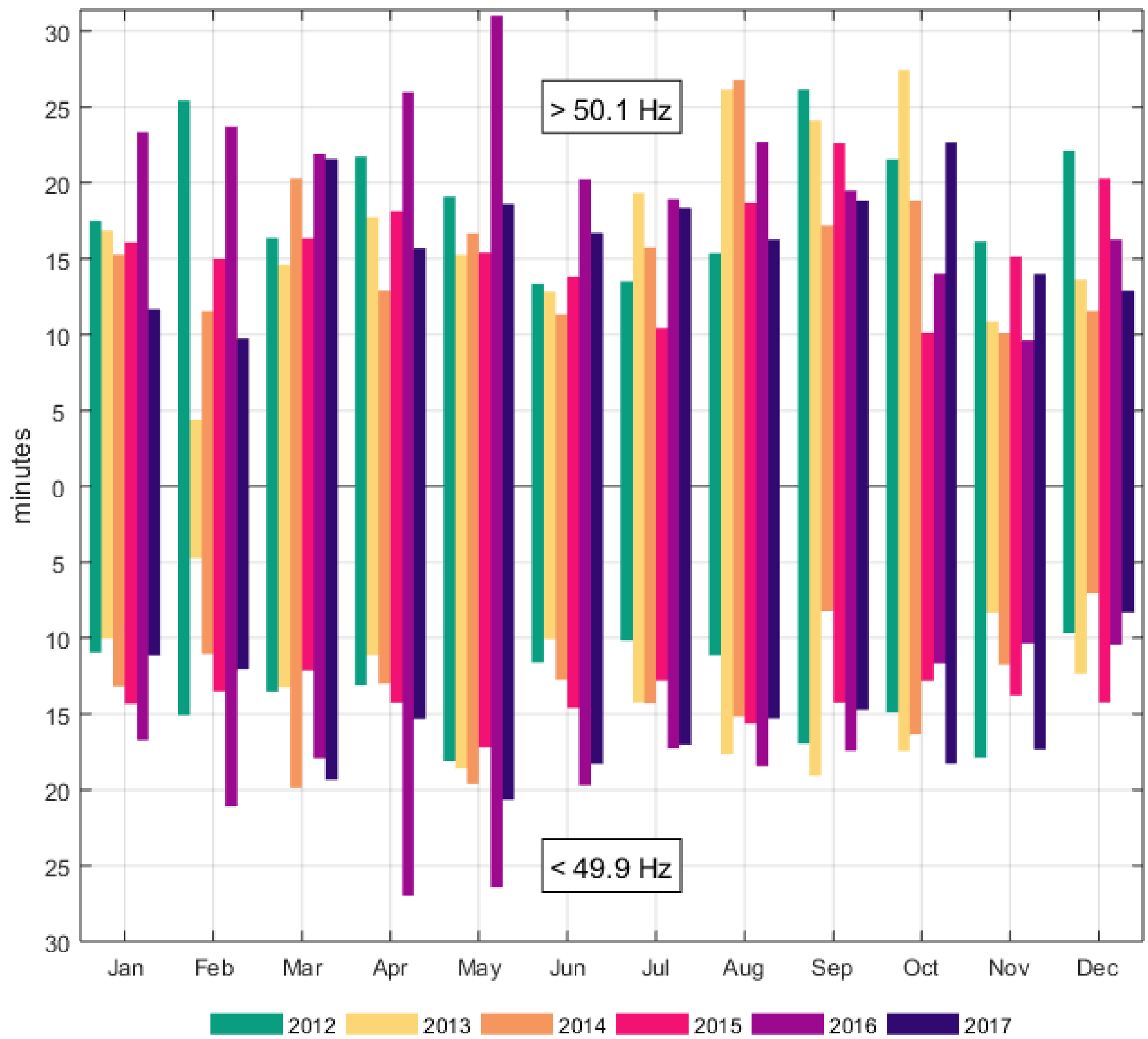


Figure 3.26 represents the daily averge time that the frequency was outside the standard frequency range during each day of the week. Every year has had a similar pattern, where the frequency has been outside the standard frequency range more often during weekdays than weekends.

***Figure 3.26**. Daily average time that the frequency was outside the standard frequency range during each day of the week for years 2012-2017*

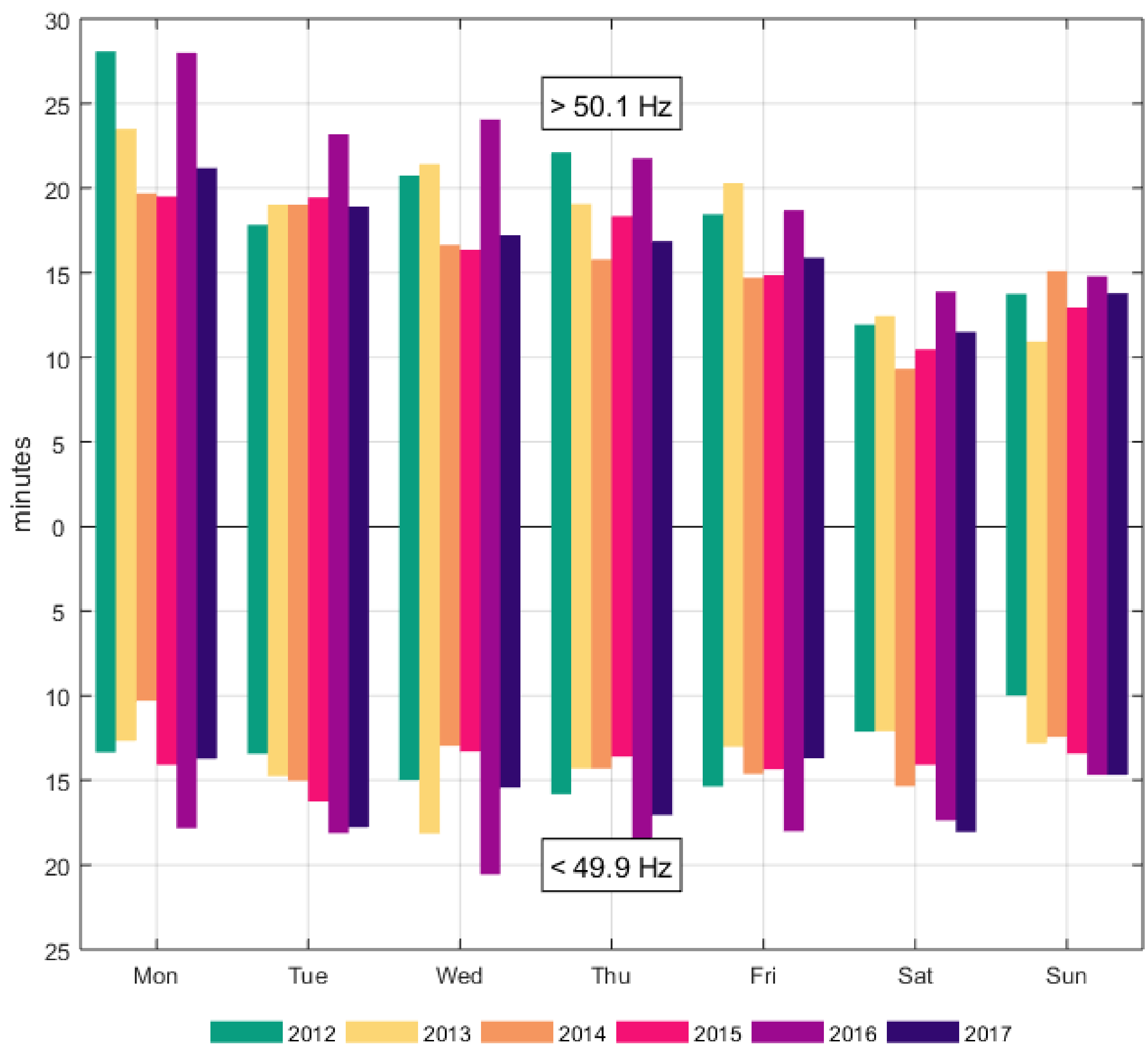


Figure 3.27 represents the daily average time that the frequency was outside the standard frequency range for each hour in the day. The hours are according to the Finnish time (UTC+2 / UTC+3 in the summer). In 2017, the frequency has been over 50.1 Hz the most at the hours 21 and 0 and under 49.9 Hz at 1 and 7. In previous years, the frequency has also been outside the standard frequency range more frequently at the morning hours as well as in the evening and midnight. Frequency has stayed best inside the standard frequency range at 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 2012-2017**

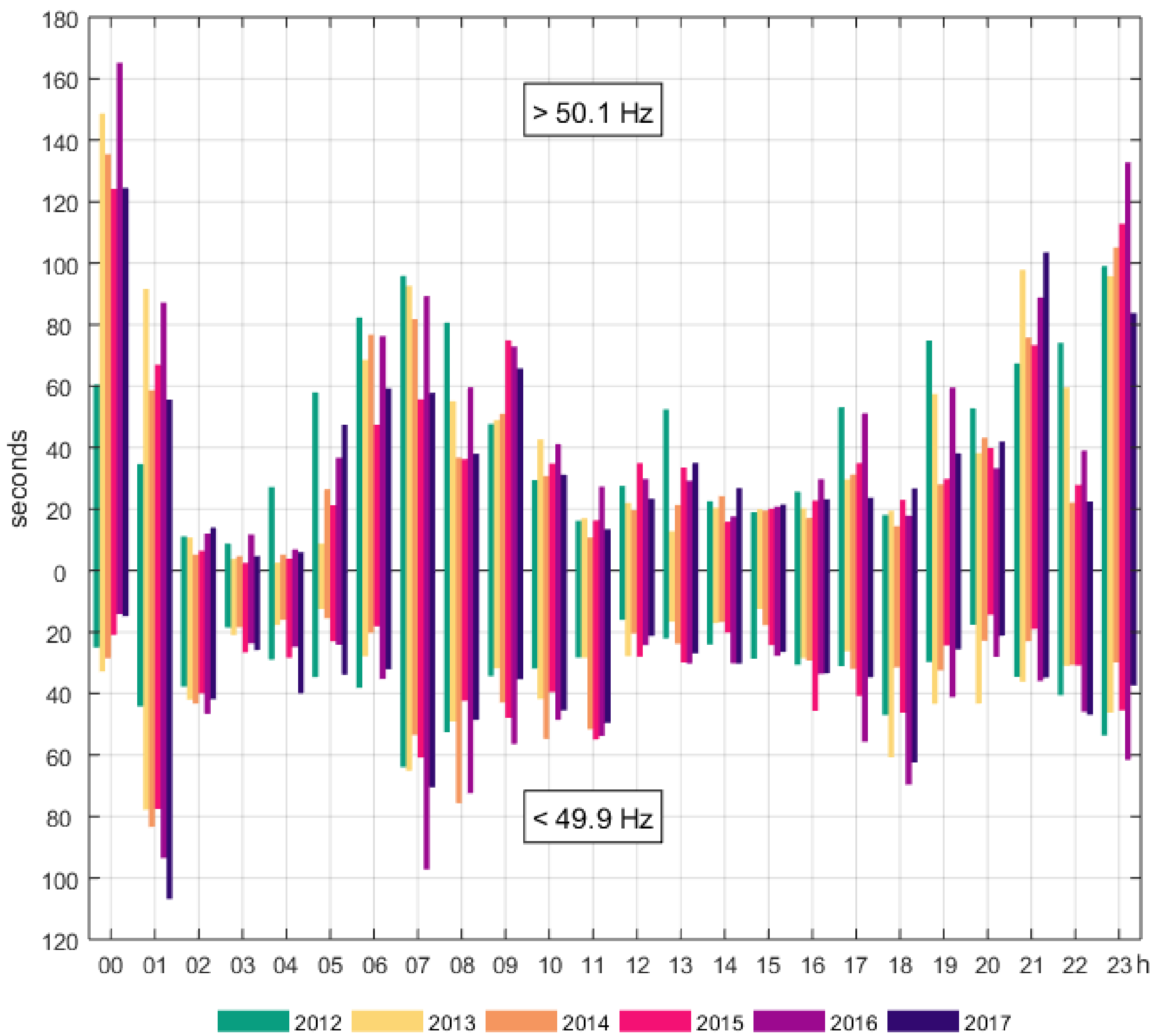


Figure 3.28 shows the daily average time outside the standard frequency range per hour and absolute value of Nordic consumption and production difference. Also transmission difference of HVDC links connecting the Nordic power system to Continental Europe and Russia is presented.

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 over 3 500 MWh while the consumption difference curve peaks close to 3 000 MWh. Near midnight the peaks for production and consumption differences are around 2000-2500 MWh. Highest values of frequency deviations are also found during these hours. Differences in HVDC transmission do not peak as high but the curve still follows the same pattern as production and consumption difference. Results for year 2016 were very similar to the year 2017 [7].

***Figure 3.28**. Seconds per hour outside the standard frequency range and the absolute values of Nordic consumption, production and HVDC transmission differences in 2017*

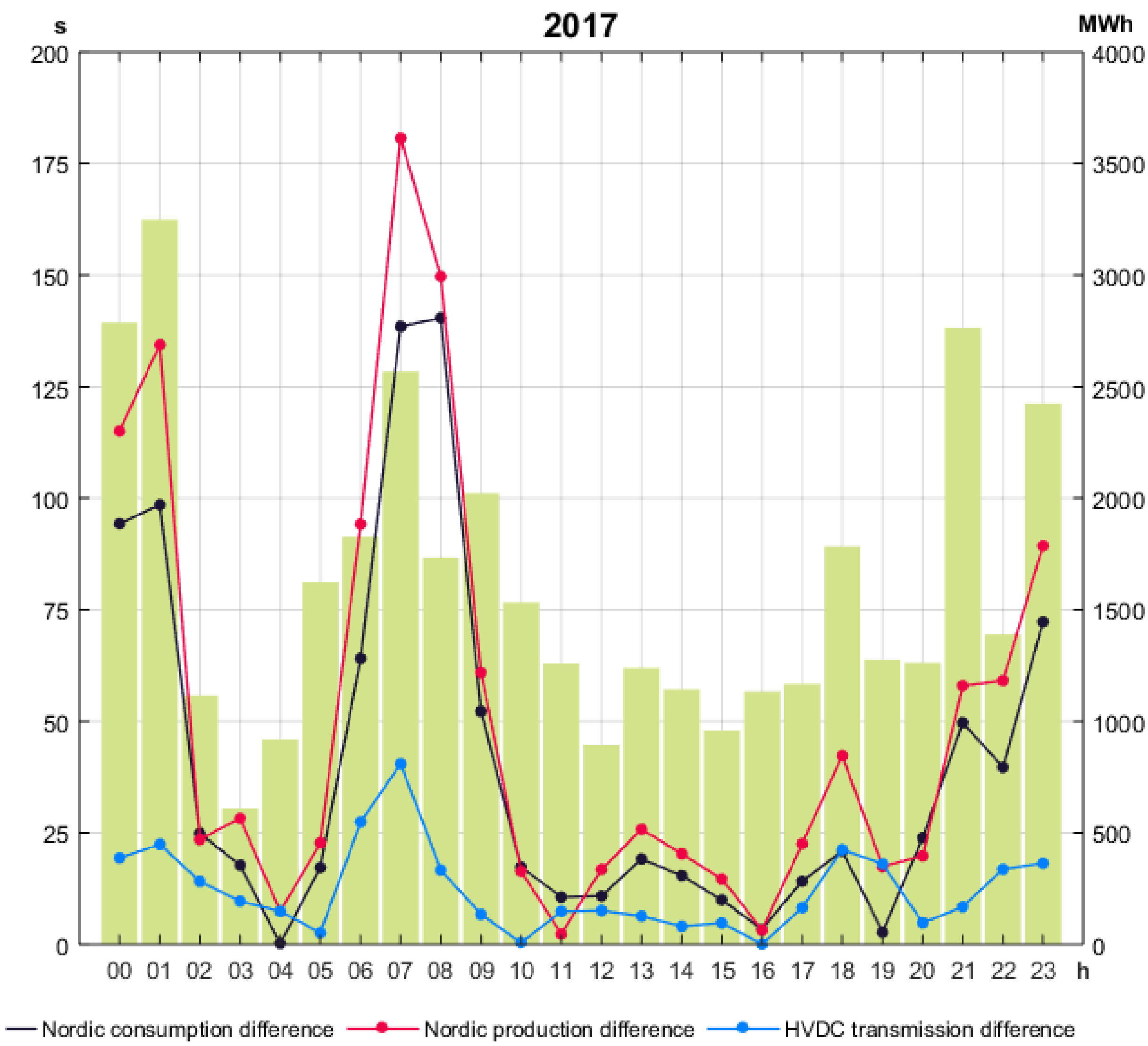


Figure 3.29 illustrates an average hour divided to 60 minutes. For each minute of the average hour there is a value in seconds per hour that frequency has been over or below the standard frequency range. In years 2012-2017 frequency has been outside the standard frequency range more often during the 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 2012-2017 for each minute of an average hour*

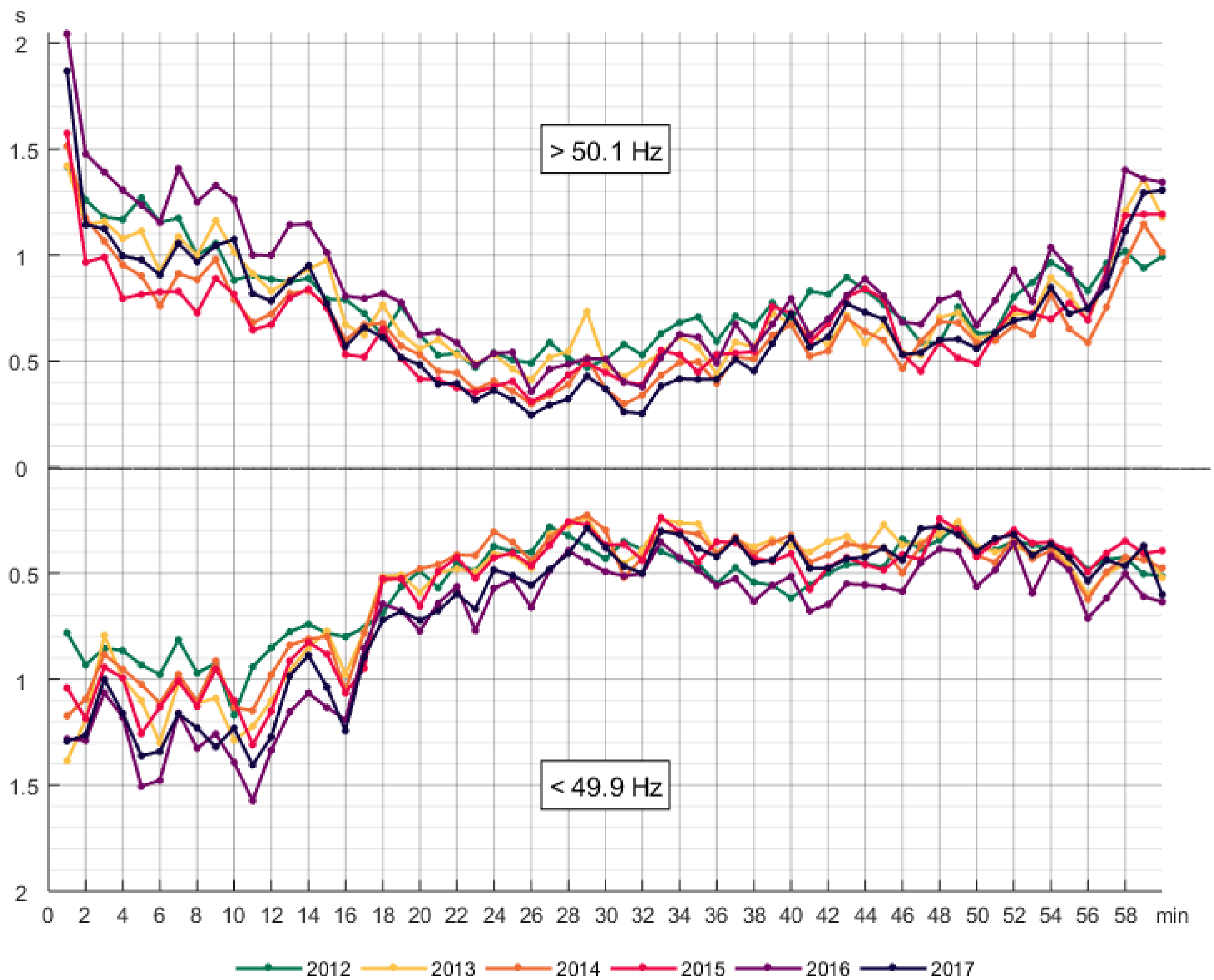
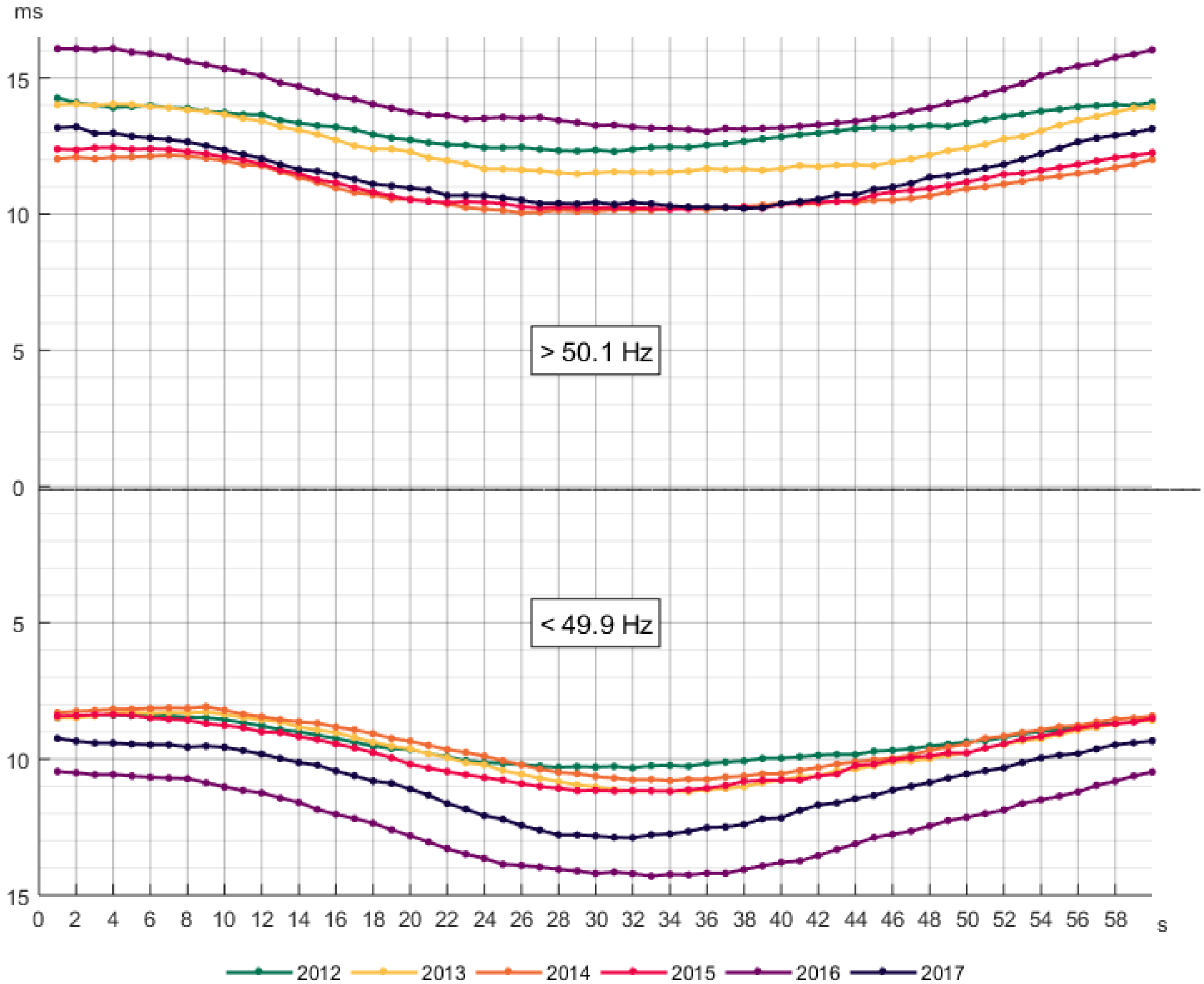


Figure 3.30 illustrates an average minute divided to 60 seconds. For each second of the average minute there is a value in milliseconds per minute that frequency has been over or below the standard frequency range. Overall the shape of the curve has been fairly smooth, but there have been slightly more over frequencies at the beginning and at the end of minutes. Under frequencies have occurred more in the middle of minutes. The 2017 curve has followed the same pattern as in previous years.

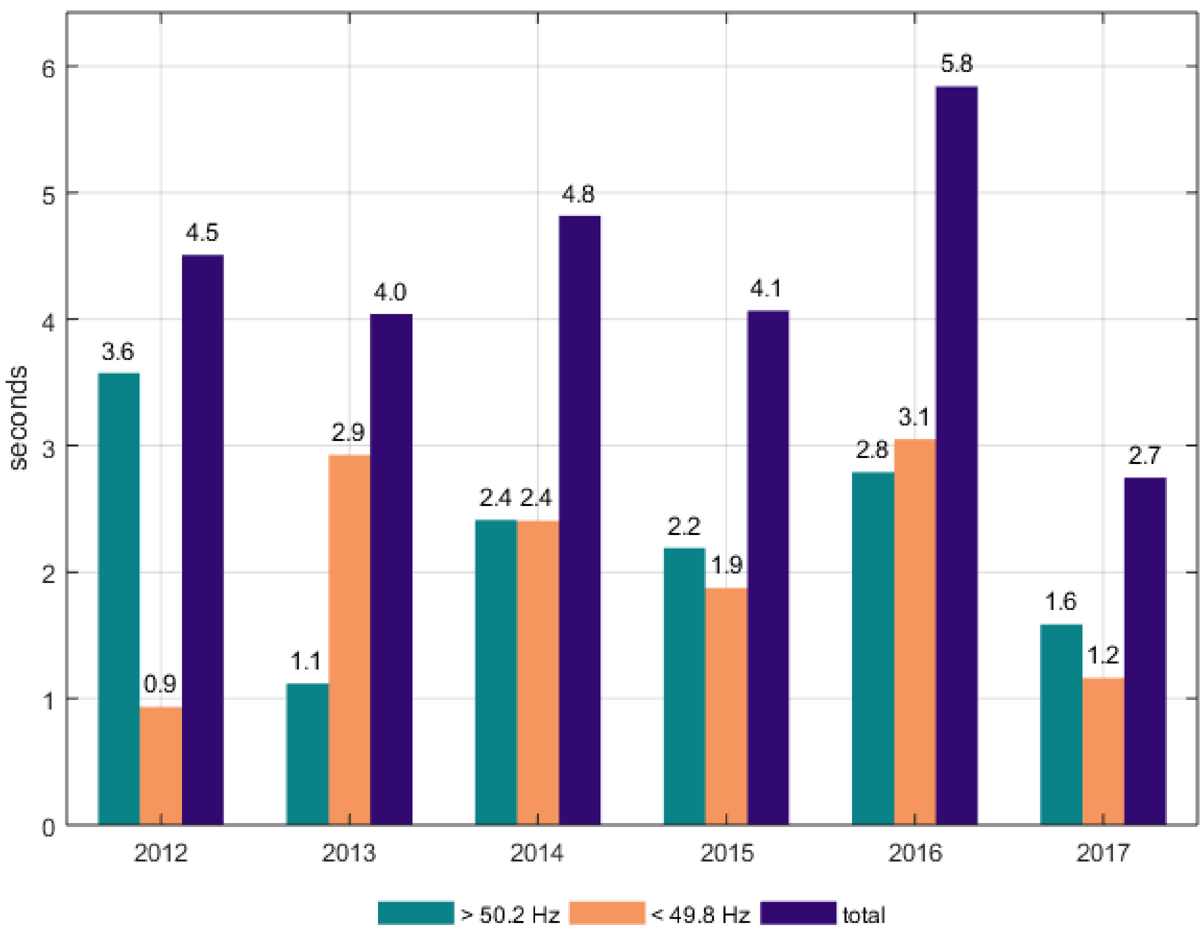
***Figure 3.30*. Number of milliseconds per minute outside the standard frequency range in 2012-2017 for each second of an average minute**



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 lower in 2017 than during any of the previous five years. In 2012, average number of seconds over 50.2 Hz was considerably higher than under 49.8 Hz while in 2013, it was the other way around. For the last four years, there has been only slight difference between over and under frequencies.

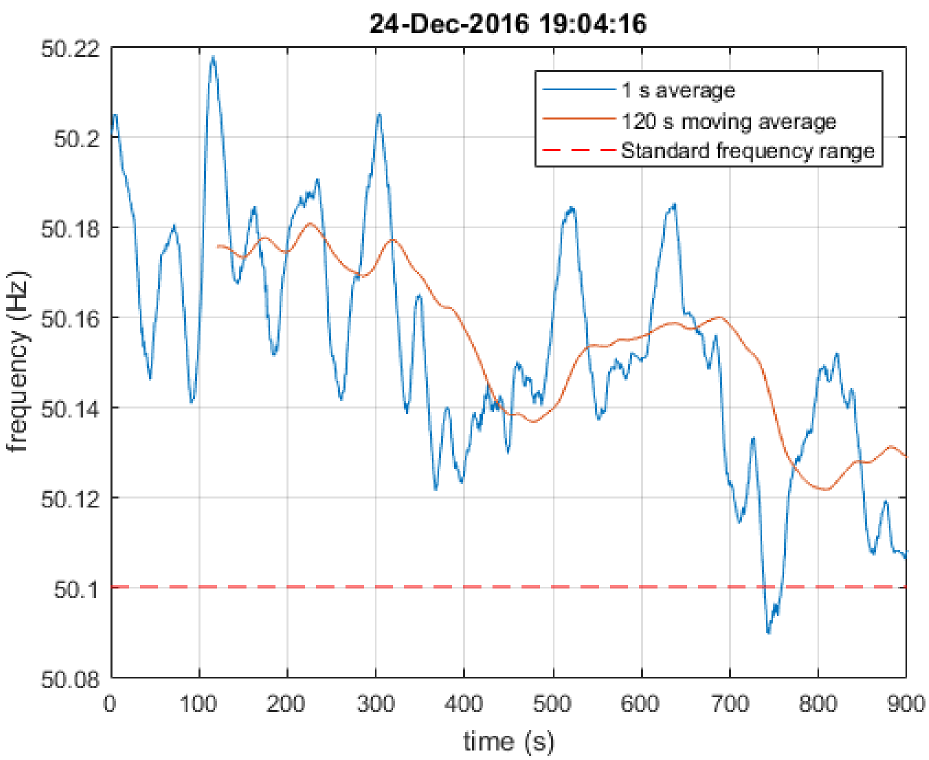
***Figure 3.31**. Average number of seconds per day that the frequency was outside the 49.8-50.2 Hz band for years 2012-2017*



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 2012-2014 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.

	2012		**2013**		**2014**		**2015**		**2016**		**2017**	
Month	**> 50.2 Hz**	**< 49.8 Hz**	**> 50.2 Hz**	**< 49.8 Hz**	**> 50.2 Hz**	**< 49.8 Hz**	**> 50.2 Hz**	**< 49.8 Hz**	**> 50.2 Hz**	**< 49.8 Hz**	**> 50.2 Hz**	**< 49.8 Hz**
January	0	0	0	0	0	0	0	0	1	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	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	0	0	0
October	0	0	0	0	0	0	0	0	0	0	0	0
November	0	0	0	0	0	0	0	0	0	0	0	0
December	0	0	0	0	0	0	0	0	0	0	0	0
Entire year	0	0	0	0	0	0	0	0	1	0	**0**	**0**

Table 3.16 shows the number of events in 2015-2017 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.

	2012		**2013**		**2014**		**2015**		**2016**		**2017**	
Month	**> 50.2 Hz**	**< 49.8 Hz**	**> 50.2 Hz**	**< 49.8 Hz**	**> 50.2 Hz**	**< 49.8 Hz**	**> 50.2 Hz**	**< 49.8 Hz**	**> 50.2 Hz**	**< 49.8 Hz**	**> 50.2 Hz**	**< 49.8 Hz**
January	1	0	2	1	0	0	1	0	3	0	0	0
February	2	0	0	0	0	0	2	0	0	1	0	0
March	1	0	0	0	0	0	0	0	0	0	0	0
April	1	0	0	0	0	0	4	0	1	0	1	0
May	0	0	0	0	0	0	0	0	0	0	1	0
June	1	1	0	0	0	0	0	0	0	0	1	0
July	0	0	0	0	0	0	0	0	1	0	0	0
August	1	0	0	0	0	0	2	0	0	0	0	0
September	2	0	0	0	1	0	1	0	1	0	0	0
October	0	0	3	1	0	1	0	0	2	0	0	0
November	0	0	0	0	0	0	0	0	0	0	0	0
December	0	0	0	0	1	0	0	0	1	0	0	0
Entire year	9	1	5	2	2	1	10	0	9	1	**3**	**0**
Sum	**10**		**7**		**3**		**10**		**10**		**3**	

3.4.3 Time outside 49.0-51.0 Hz

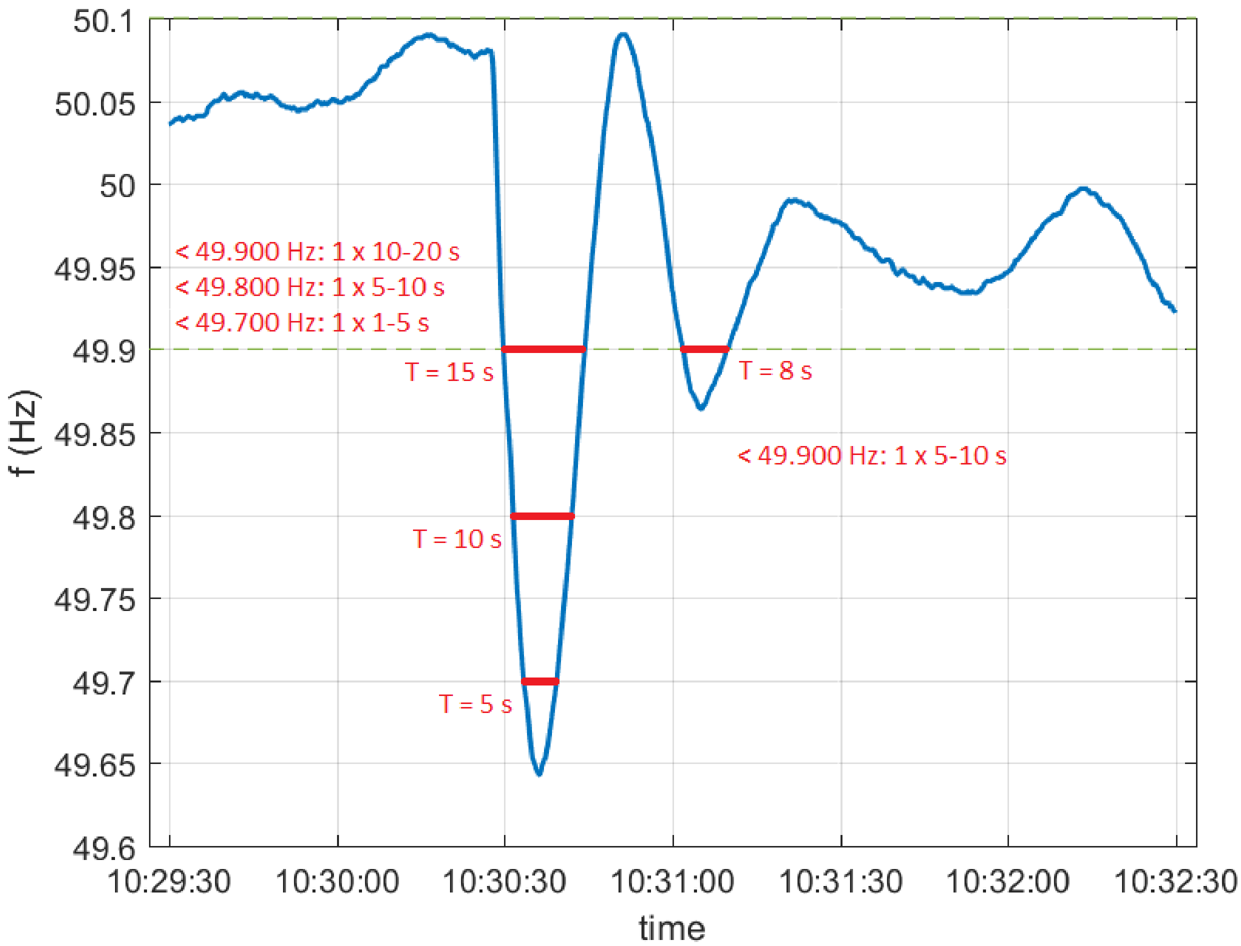
Time outside 49.0 Hz and 51.0 Hz is calculated by counting the number of samples that are below 49.0 Hz or above 51.0 Hz and multiplying the number by the time duration of the sample. The criteria are also defined in SO GL Article 131(a) (v). The resolution of the data used was 1 second.

There were no instances in 2012-2017 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 [6]*



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 2012 to 2017. 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 2012

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	28716	5208	3658	5428	3750	887	768	174	48589	1669.90	8.47
> 50.2	124	27	27	29	12	1	2	0	222	119.20	5.85
> 50.3	0	1	0	0	0	0	0	0	1	2.00	2.00
< 49.9	22393	4405	2905	4358	3034	708	569	77	38449	931.10	7.65
< 49.8	11	11	9	11	2	1	0	0	45	42.50	7.46
< 49.7	0	1	5	1	0	0	0	0	7	11.30	7.09
< 49.6	0	2	1	0	0	0	0	0	3	6.40	5.23
< 49.5	0	0	0	0	0	0	0	0	0	0.00	0.00

Table 3.18. 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 3.19. 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 3.20. 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 3.21. 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 3.22. 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

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.

Figure 3.34. Daily average number of frequency deviations per duration

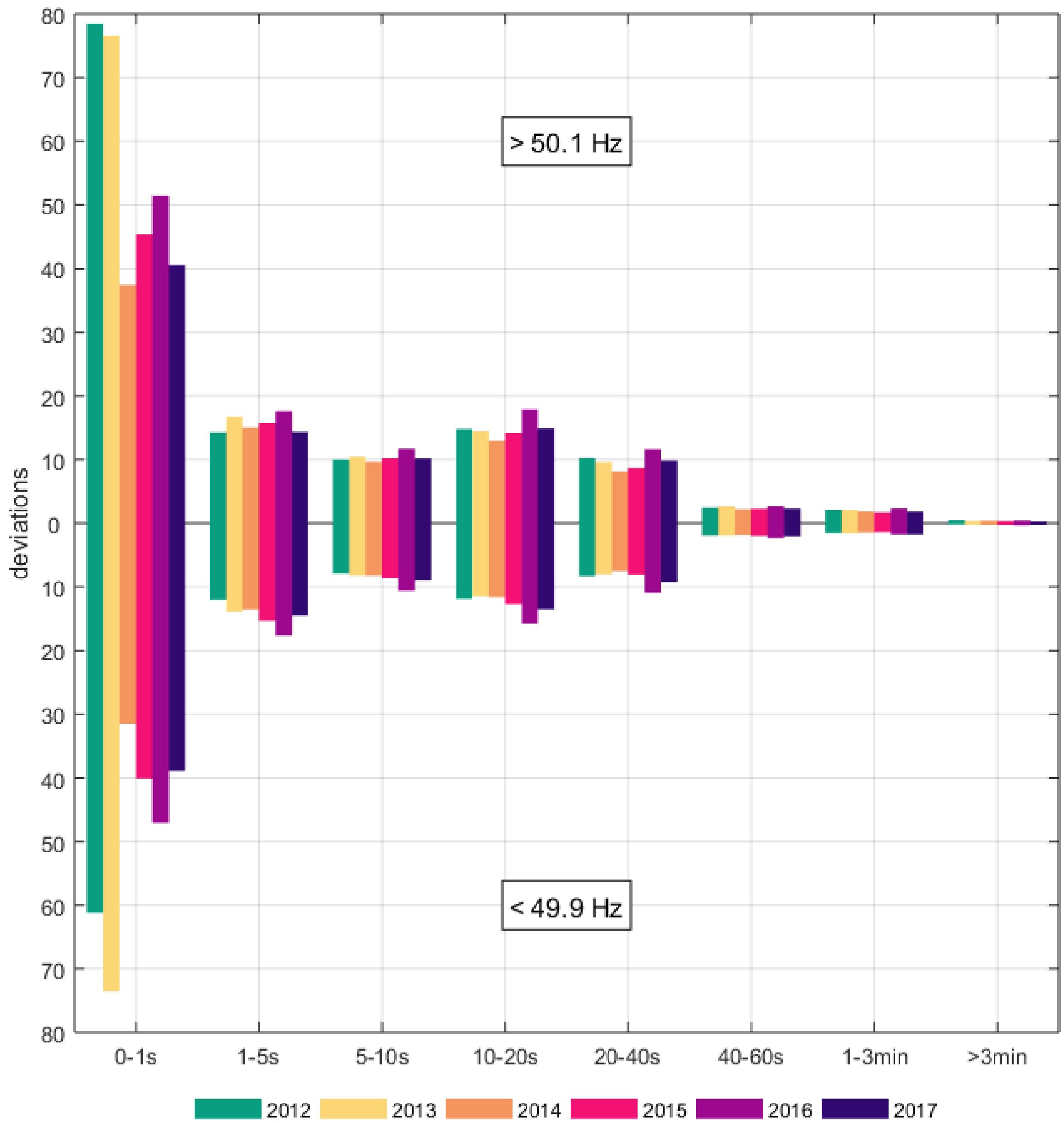
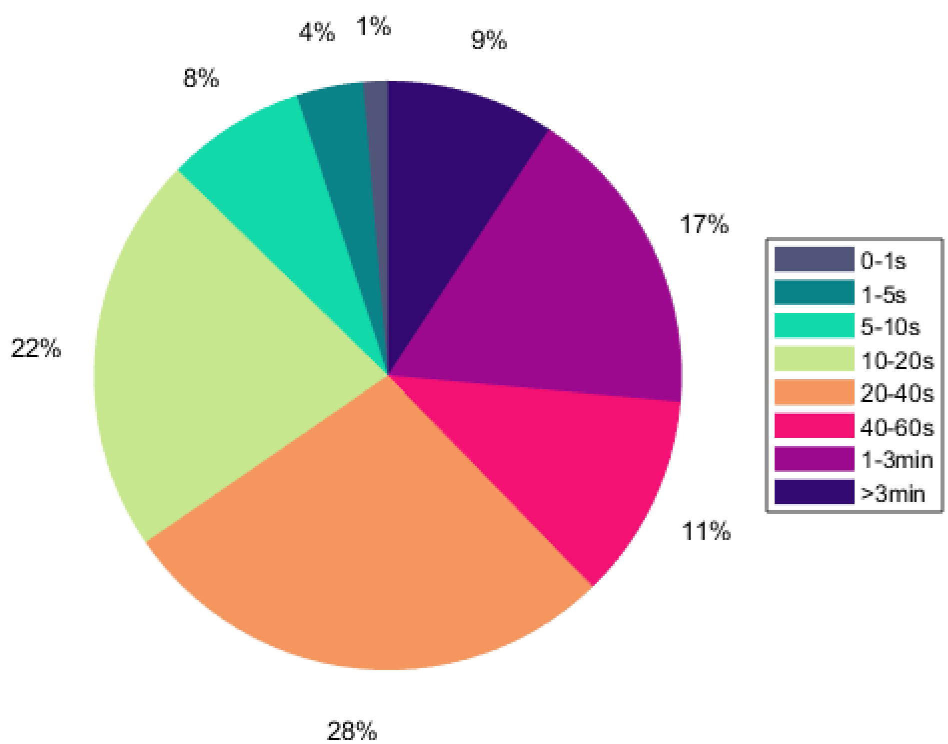


Table 3.23 shows how deviations of different duration affected to the total time outside the standard frequency range in 2017. Times are given in minutes. Pie chart in Figure 3.35 shows in percentages how the total time outside the standard frequency range was divided between deviations of different duration. Deviations with duration of 10-20 s and 20-40 s lasted almost half of the total time outside the standard frequency range.

***Table 3.23**. Total minutes in 2017 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	78	213	467	1308	1640	681	976	504	5867
< 49.9 Hz	75	208	411	1198	1533	612	992	554	5583
total	154	421	879	2506	3173	1293	1968	1058	11450

***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 2017. Figure 3.36 represents the total number of deviations per duration for each month in 2017. Most of the deviations lasted only between 0-1 seconds. Months from June to October had generally the most frequency deviations across all durations. The least amount of deviations occurred in the first and last months of the year.

***Figure 3.36**. Total number of frequency deviations per duration for each month in 2017*

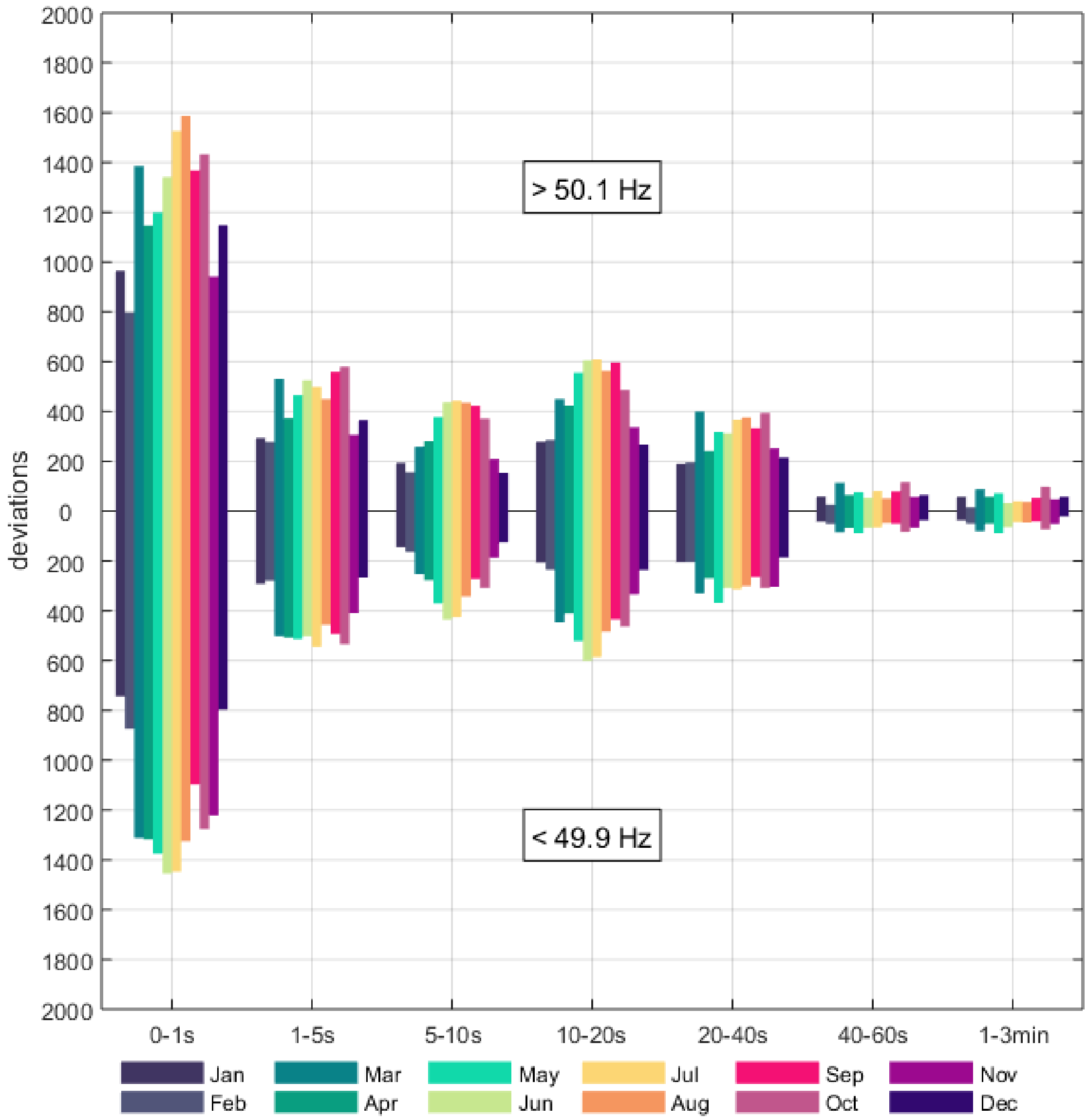
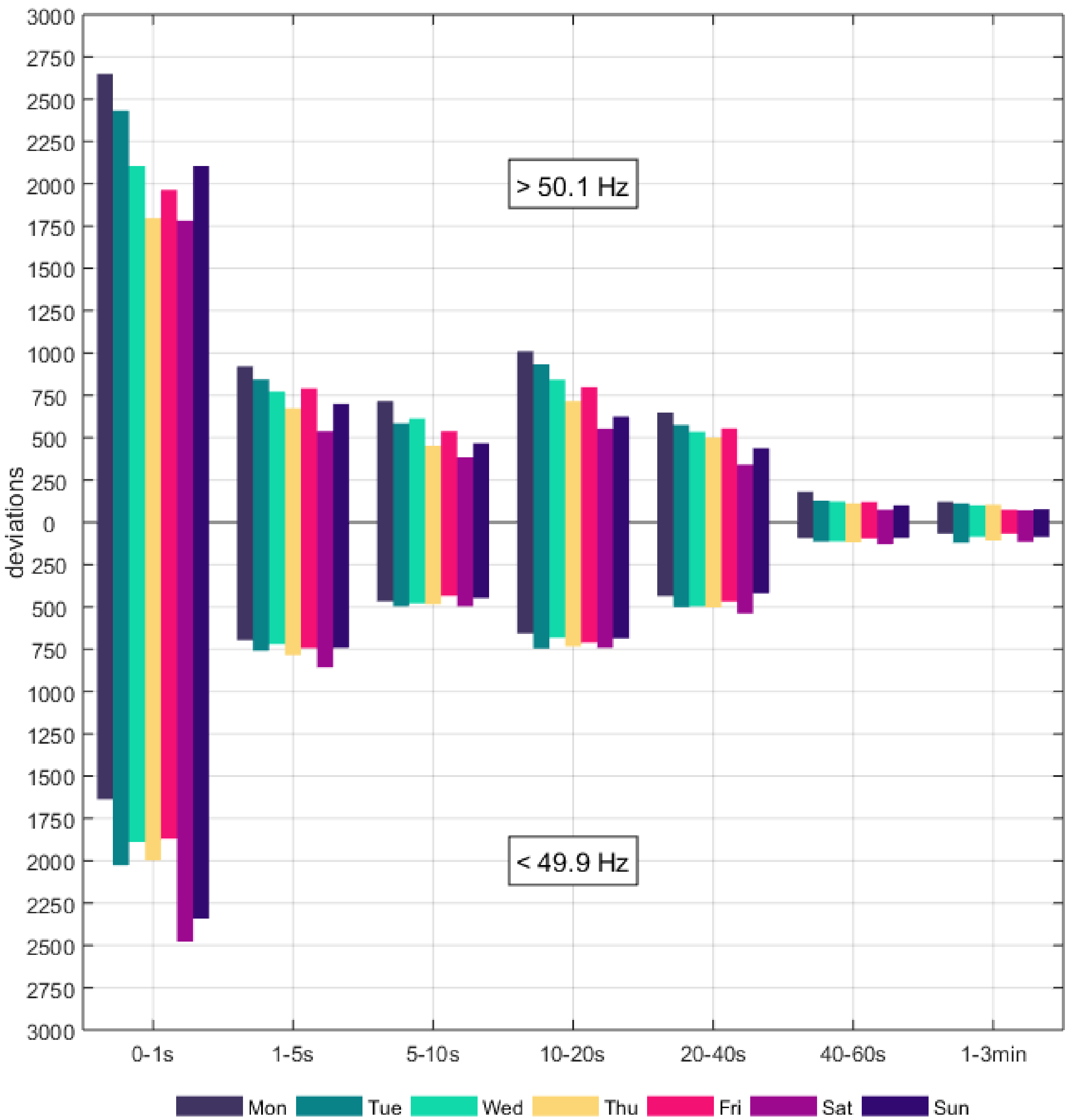


Figure 3.37 shows the number of deviations for every day of the week. Short-lasting deviations under 49.9 Hz were more common on weekends but for longer durations, the deviations under 49.9 Hz were pretty even throughout the week. Over 50.1 Hz deviations took place more often in the beginning of the week on Monday and Tuesday across all durations.

Figure 3.37. Total number of frequency deviations per duration for each day of the week in 2017



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 2017*

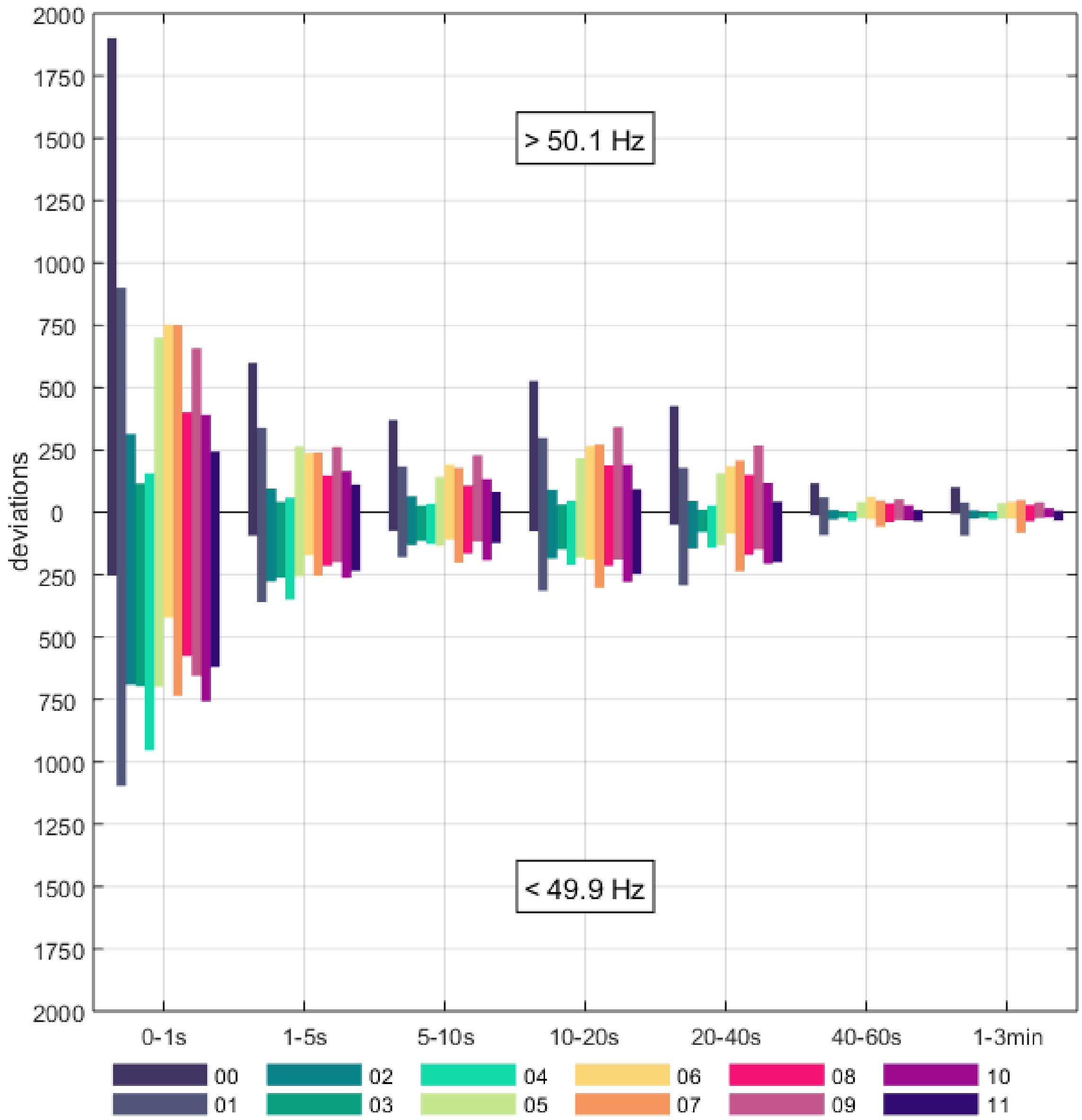


***Figure 3.39**. Total number of frequency deviations per duration for hours 12-23 in 2017*

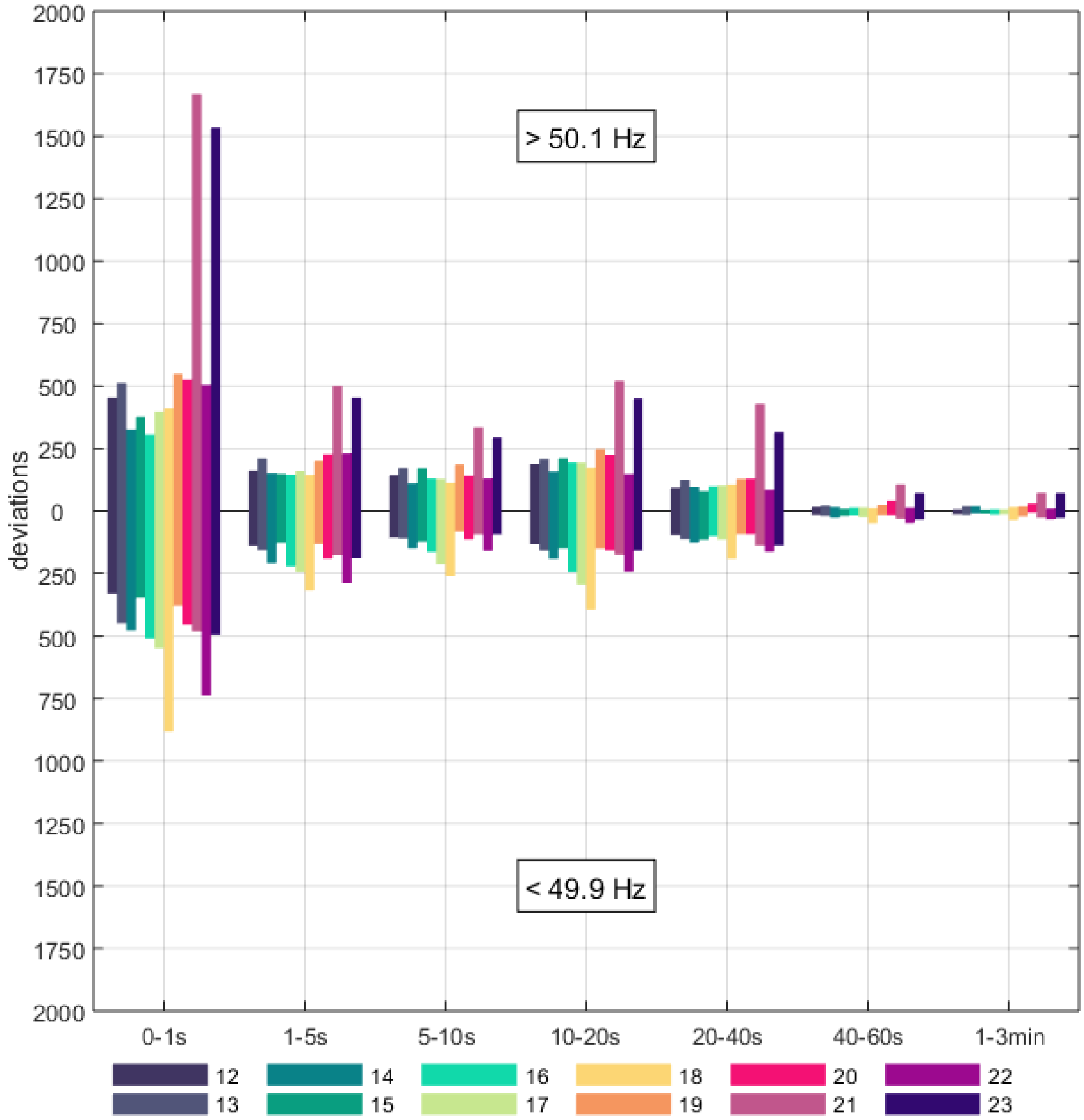
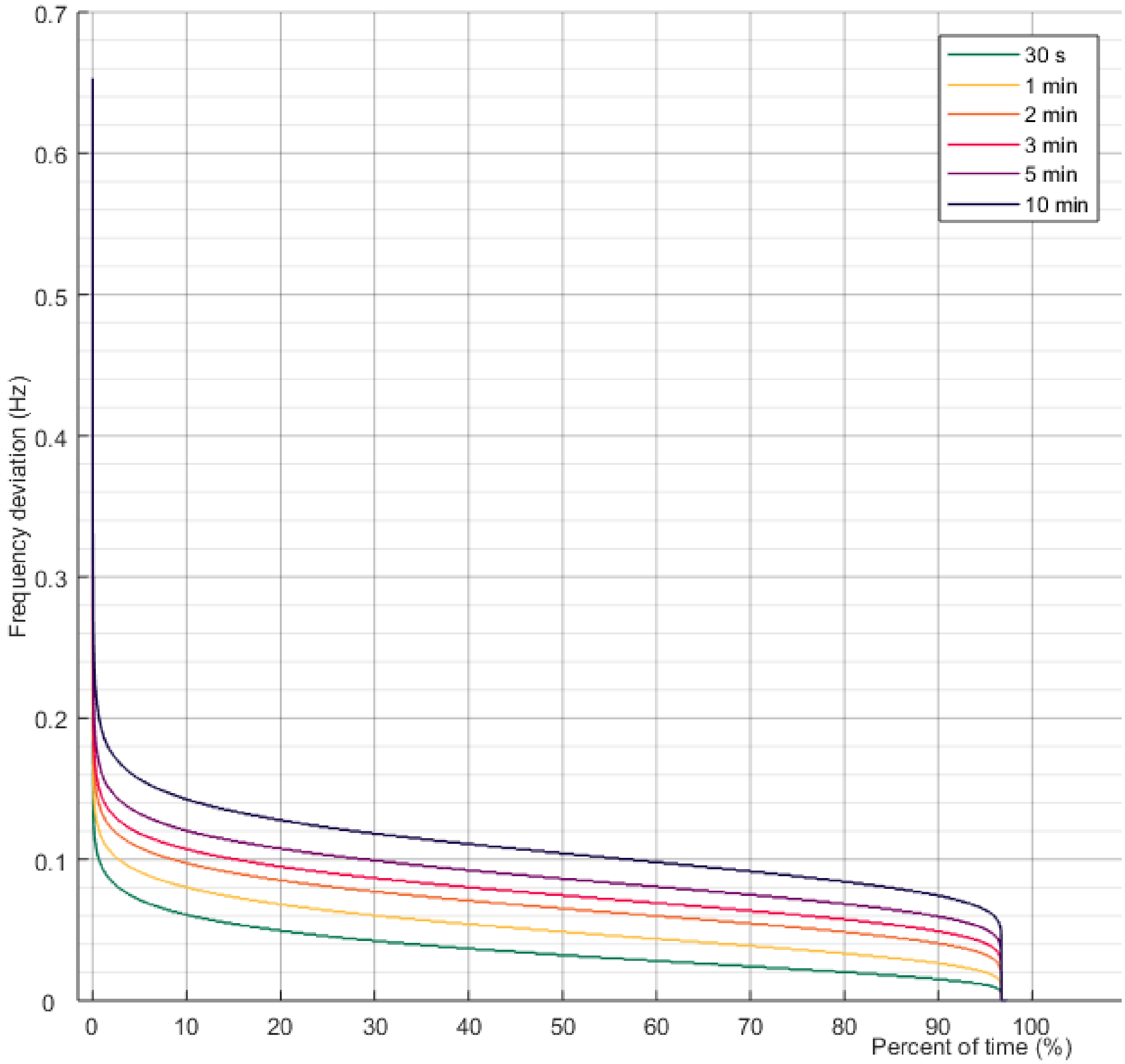


Figure 3.40 represents the duration curve of maximum frequency deviation inside different time windows in year 2017. The time window was slid through the year with a time interval of one second. Studied time windows can be found from legend of the Figure 3.40. Chapter 4 shows in detail frequency disturbances 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 2017



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 2012-2017. The number of deviations has decreased 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 2012-2017*

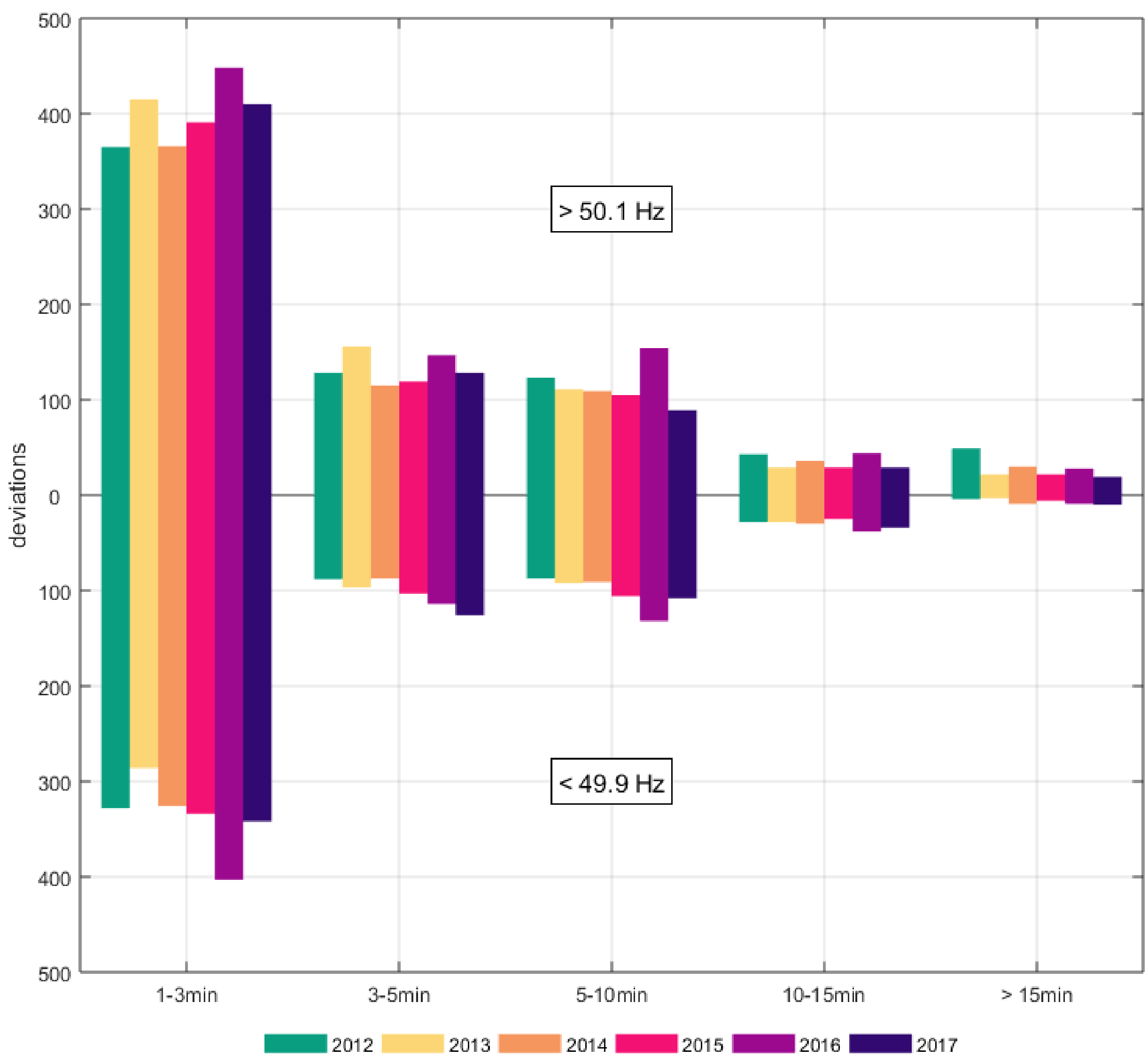


Figure 3.42 shows the total number of longer deviations for each month in 2017. Months of March and October had the most deviations lasting between 1-3 minutes.

***Figure 3.42**. Total number of longer frequency deviations per duration for each month in 2017*

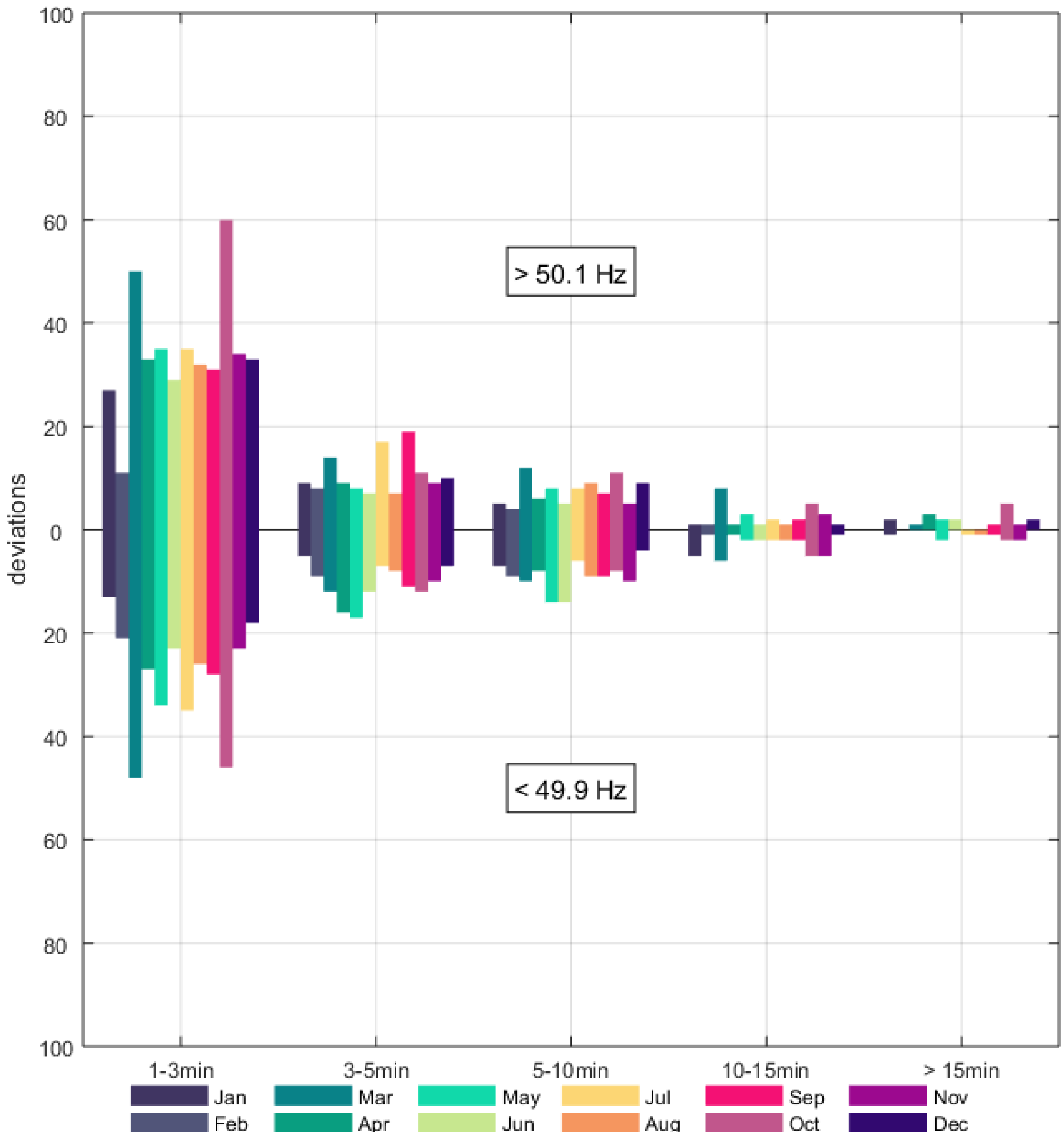
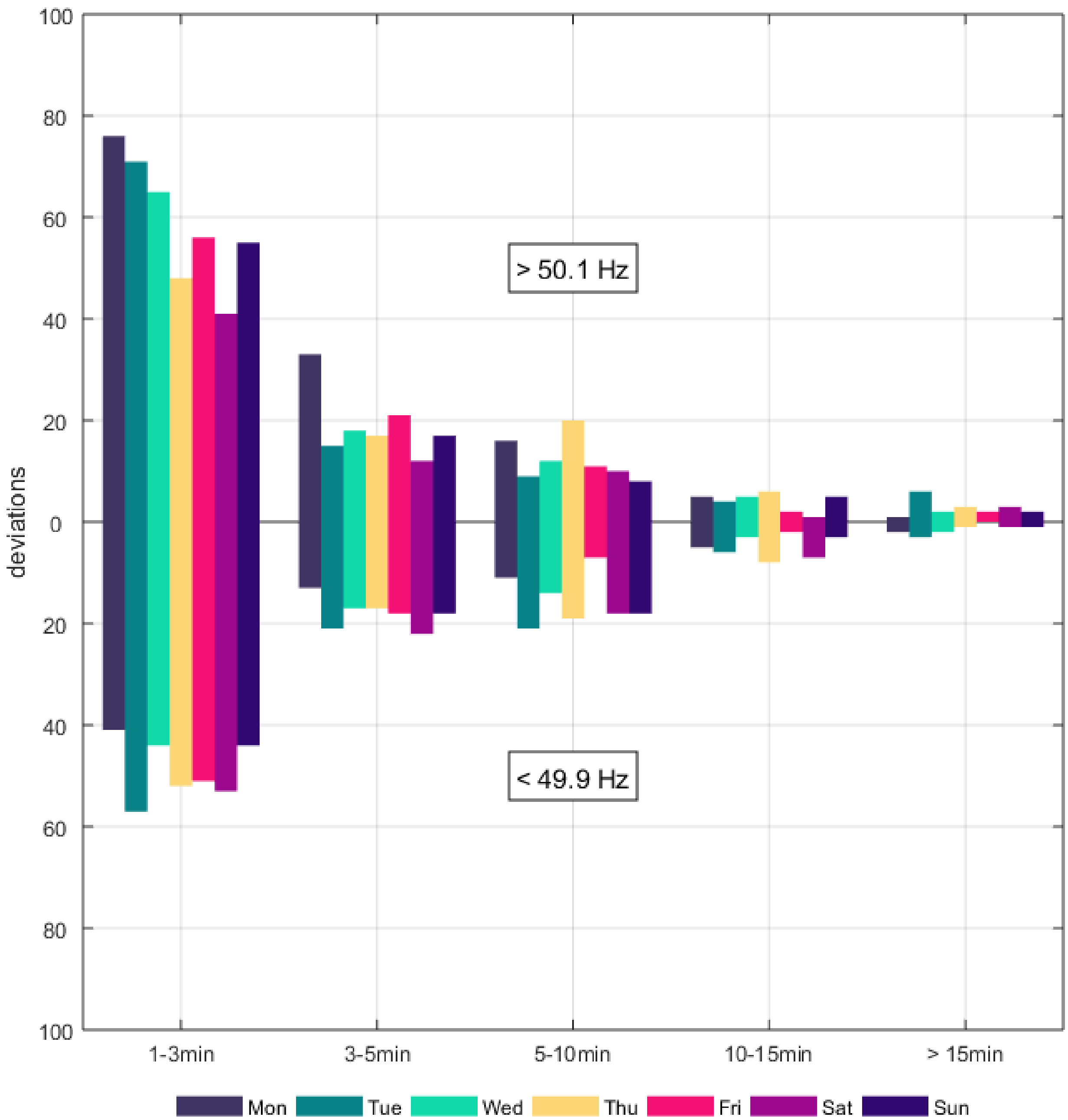


Figure 3.43 represents the number of deviations with different durations during every day of the week in 2017. Beginning of the week had more over frequencies while under frequencies are distributed fairly evenly throughout the week.

***Figure 3.43**. Total number of longer frequency deviations per duration for each day of the week in 2017*



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 2017*

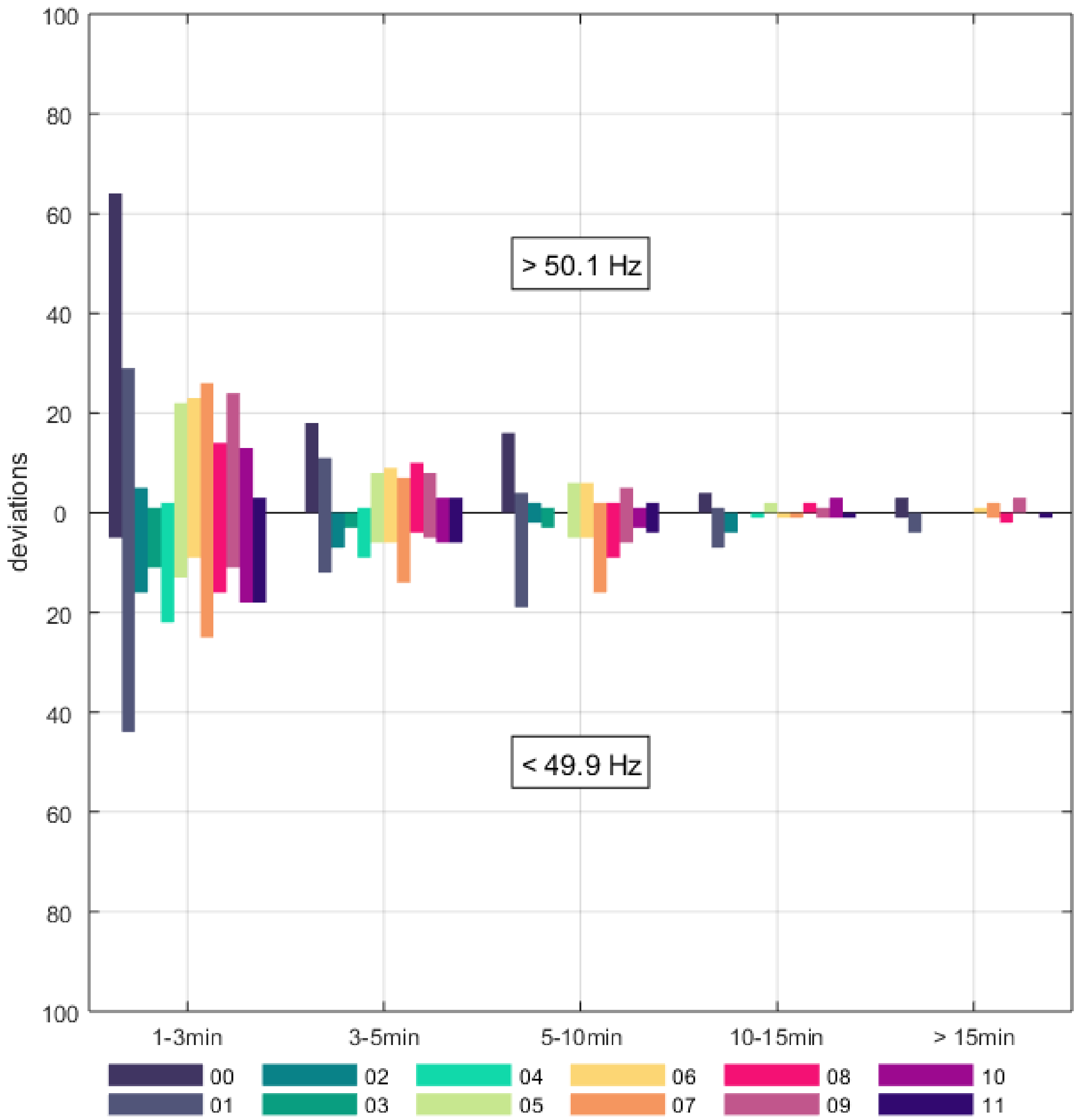
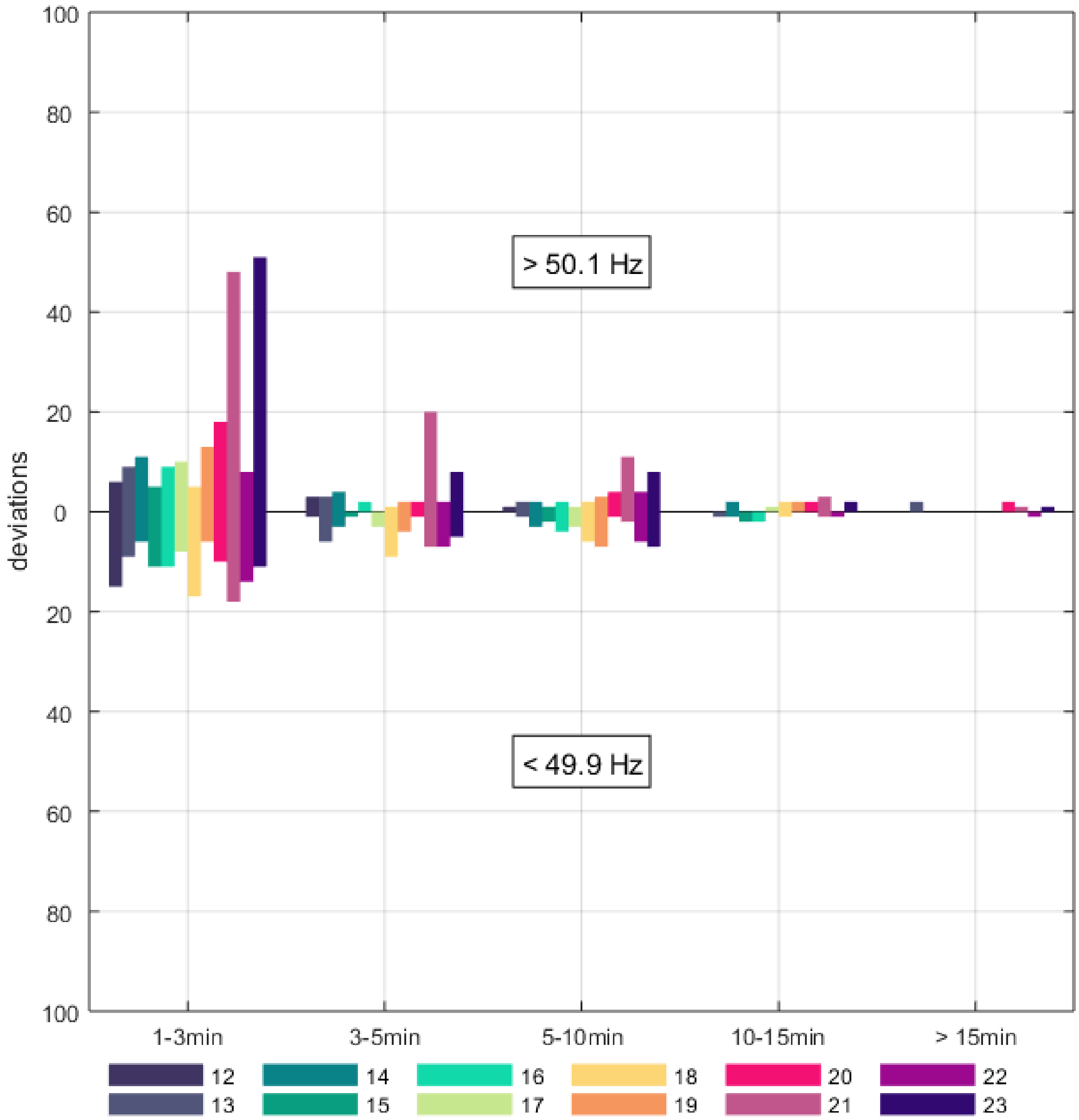


Figure 3.45*. *Total number of longer frequency deviations per duration for hours 12-23 in 2017



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 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 2012 to 2017. 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 2012-2017

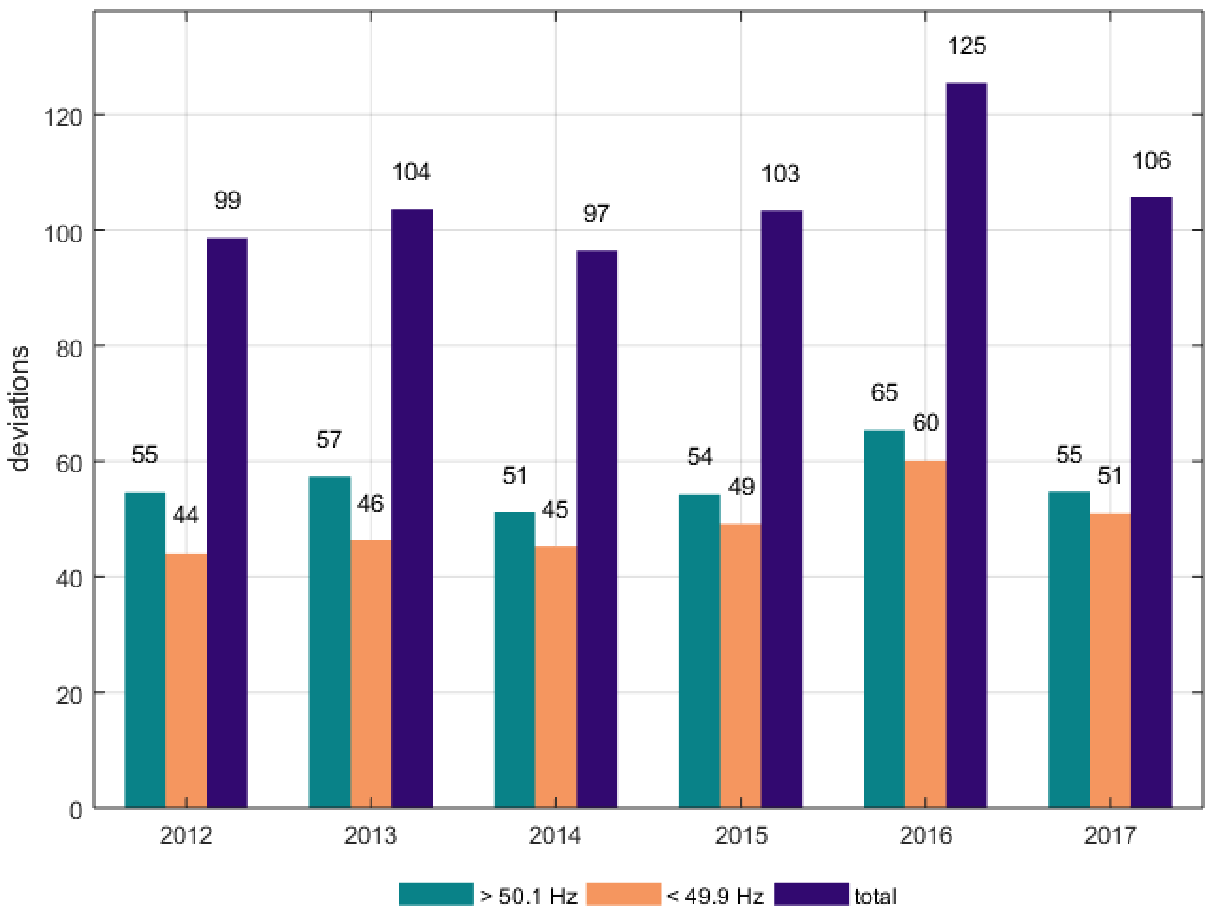


Figure 3.47 represents the daily average number of threshold crossings for each month in 2017. There has been slightly more crossings over 50.1 Hz than crossings under 49.9 Hz. In total, the frequency crossed the threshold more often between March and October.

Figure 3.47. Daily average number of threshold crossings for every month in 2017

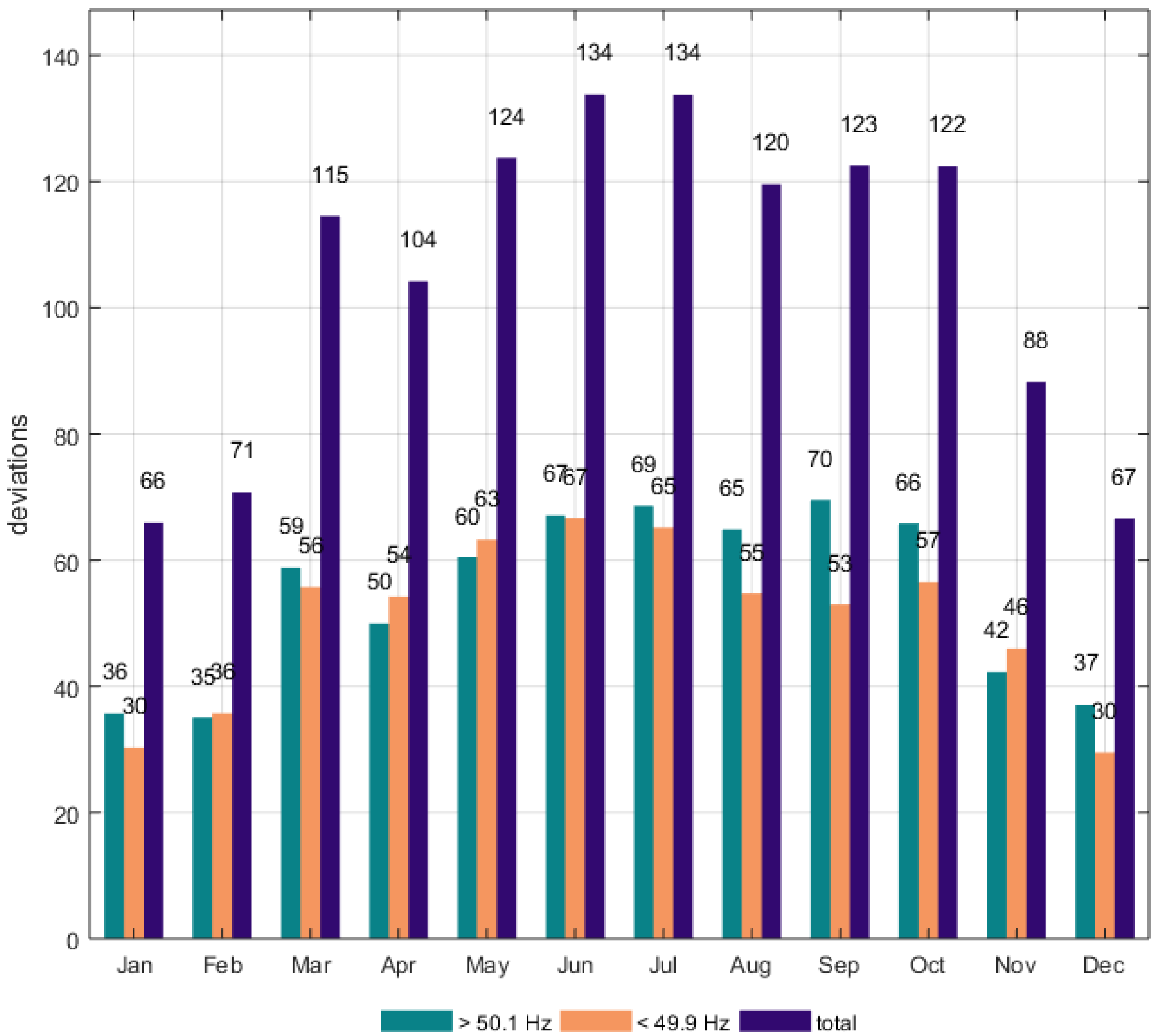
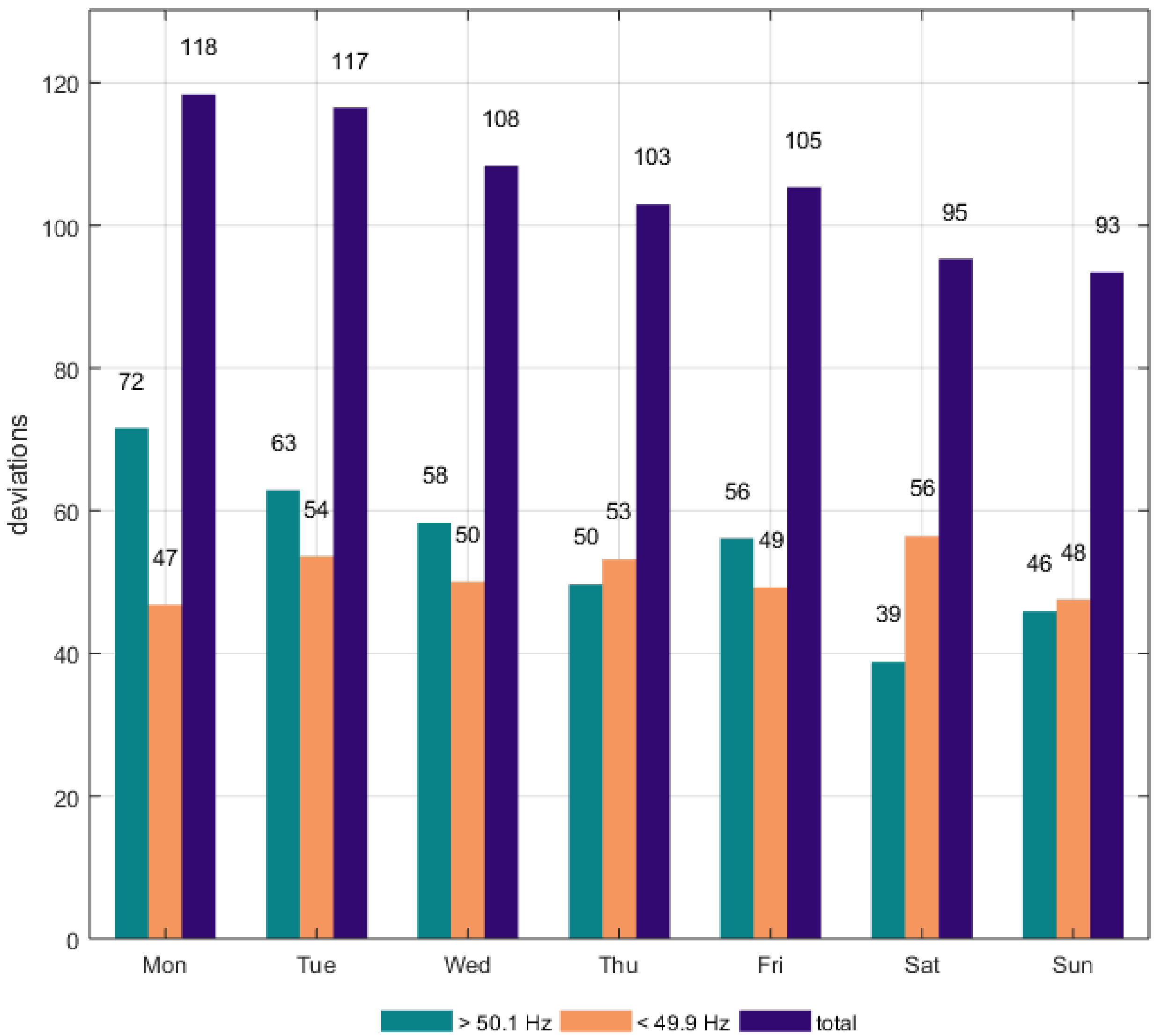


Figure 3.48 shows the number of threshold crossings for each day of the week in 2017. During the weekends, the number was smaller and more crossings were under 49.9 Hz than over 50.1 Hz.

***Figure 3.48**. Daily average number of threshold crossings for every day of the week in 2017*



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 2 to 4 and afternoon from 11 to 16. Close to midnight and in the morning around 7 the frequency crossed the threshold more often.

***Figure 3.49*. Average number of threshold crossings for every hour of the day in 2017**

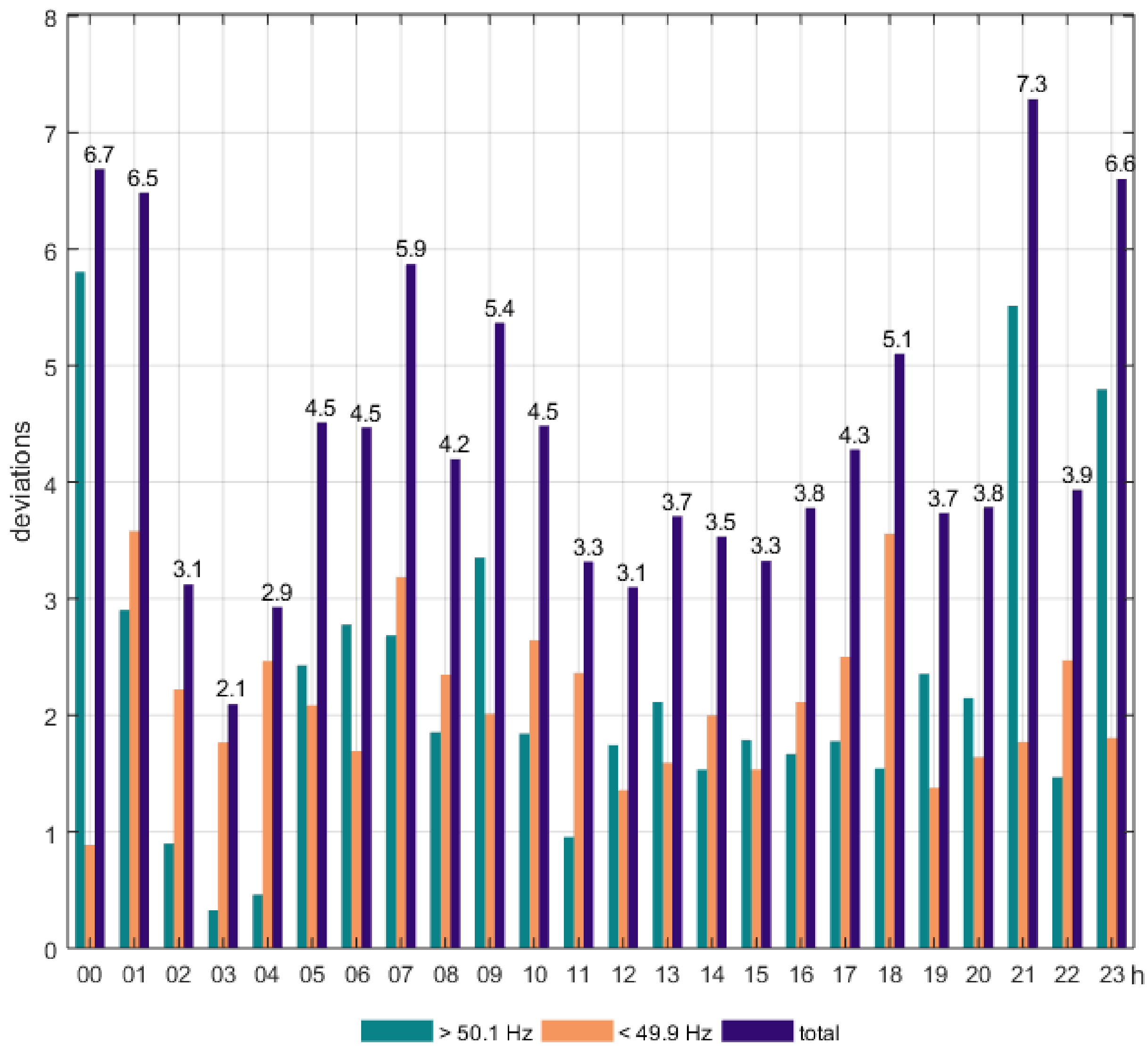
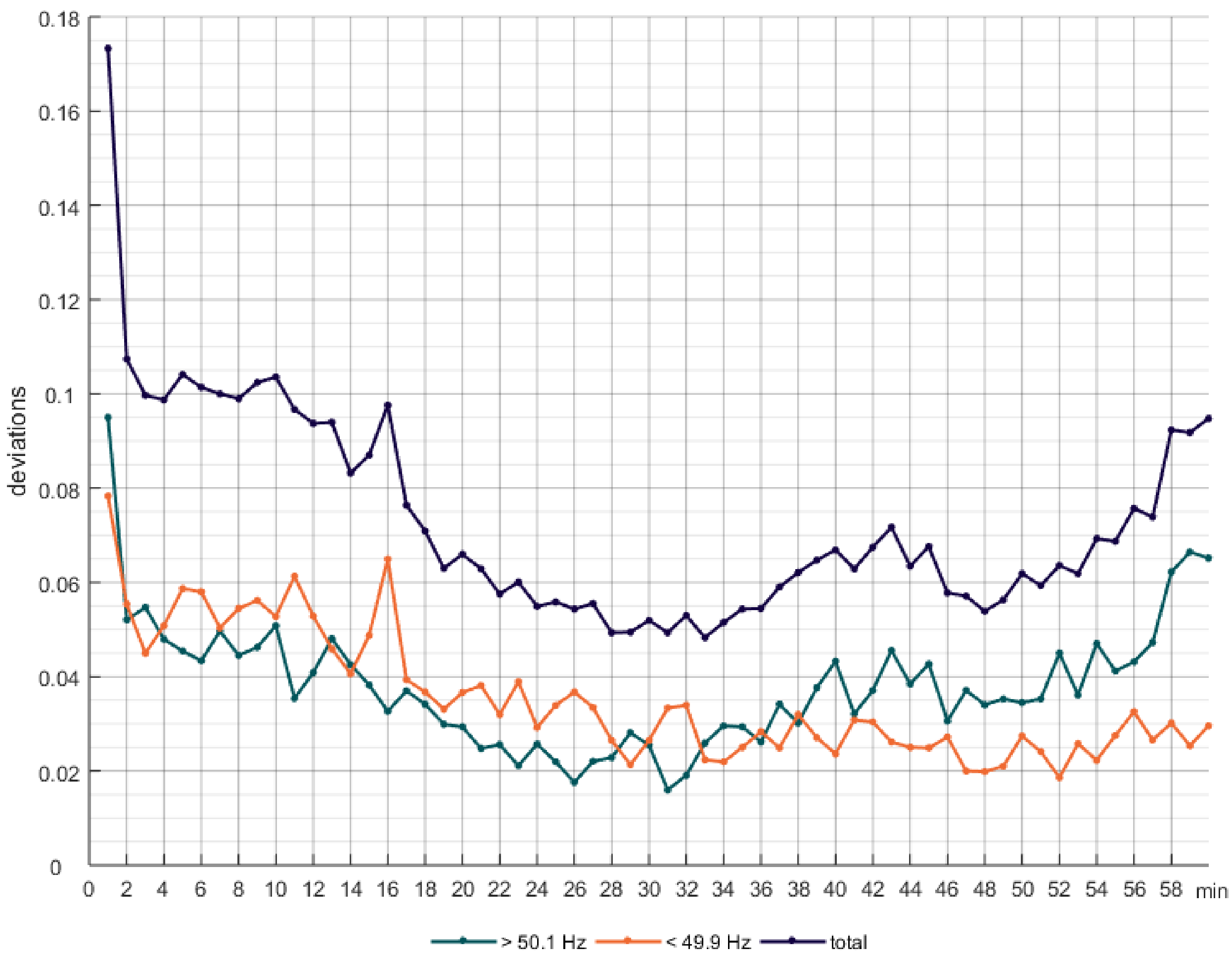


Figure 3.50 represents the average number of threshold crossings for every minute inside the hour. Most crossings take place within the first minutes of the hour. During the first 30 minutes of the hour, the frequency crosses 49.9 Hz more often, while more crossings of 50.1 Hz take place in the latter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

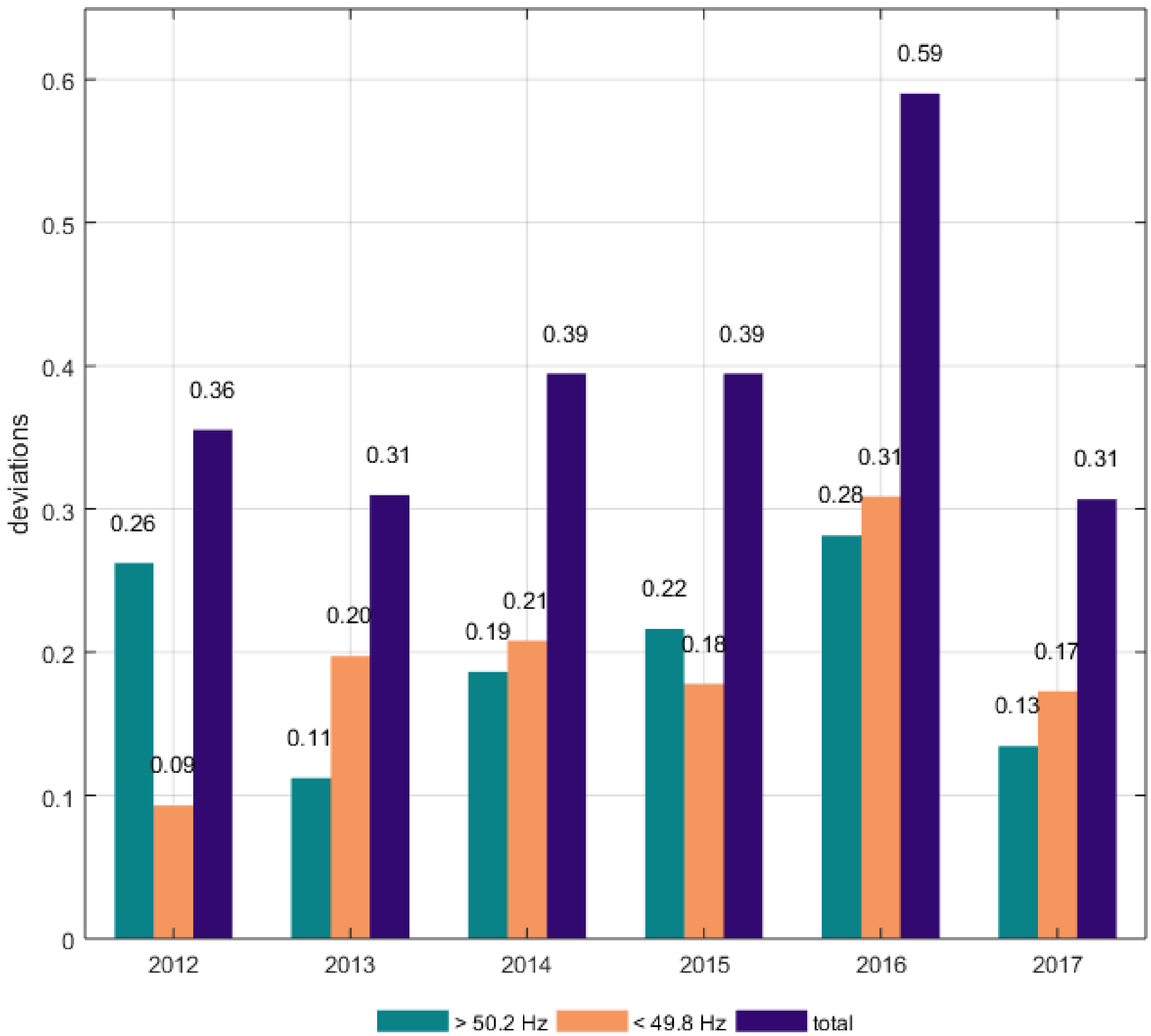
***Figure 3.50**. Average number of threshold crossings for every minute of the hour in 2017*



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 but otherwise it has been fairly constant. 2017 is still one of the best years in this comparison.

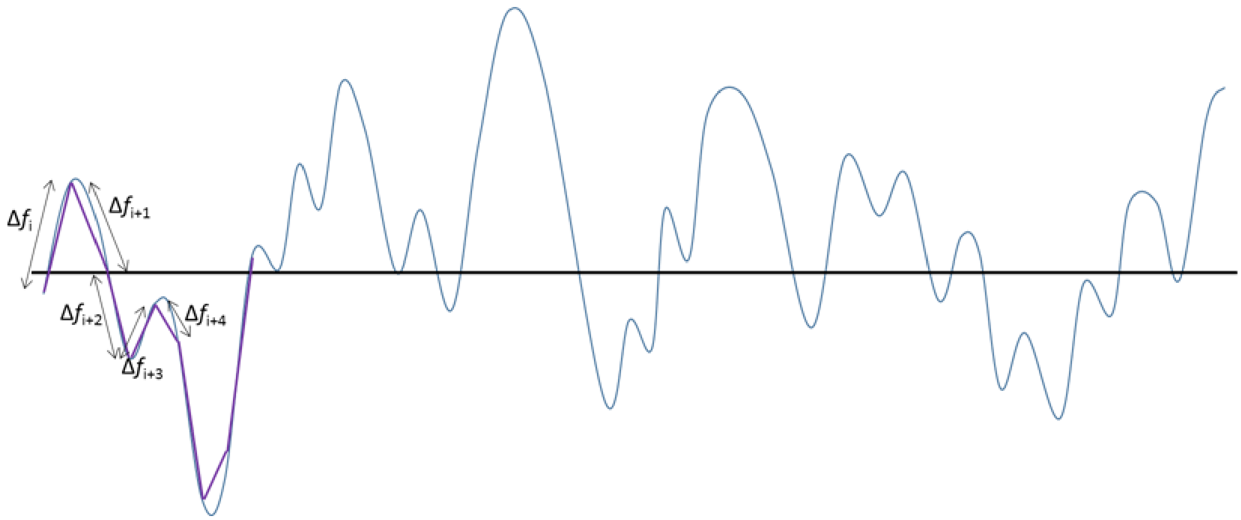
Figure 3.51. Daily average number of frequency deviations larger than ±200 mHz for years 2012-2017



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).

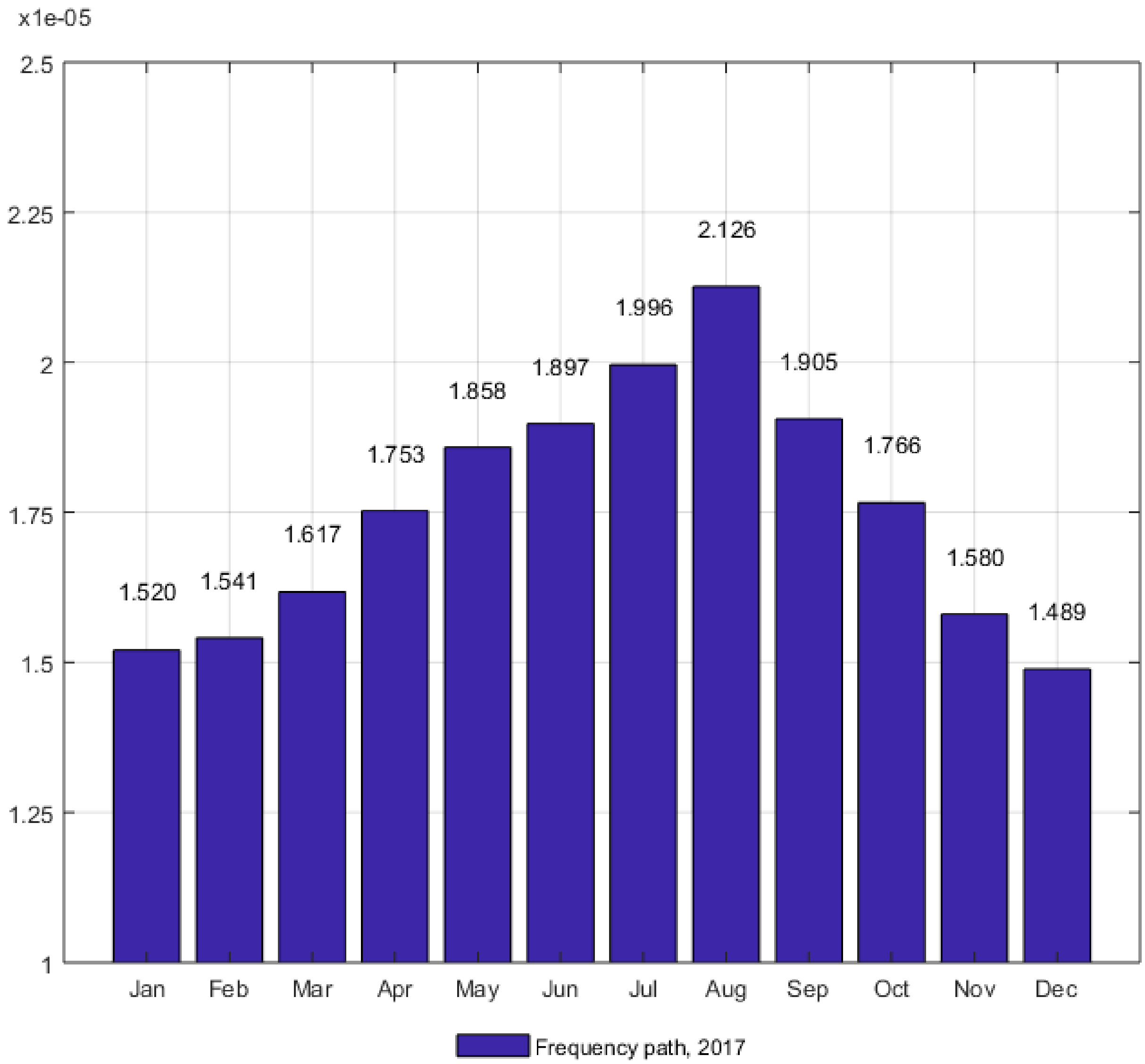
Figure 3.52*. *Frequency quality index: Length of the frequency path [8]



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

Figure 3.53 represents the frequency path for each month in 2017. Tthe path was increasing steadily until it peaked in August from where it started to decrease to the end of the year.

***Figure 3.53**. Length of the frequency path month by month in 2017*



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. Thursdays have had slighly shorter frequency path on average.

***Figure 3.54**. Length of the frequency path for every day of the week in 2017*

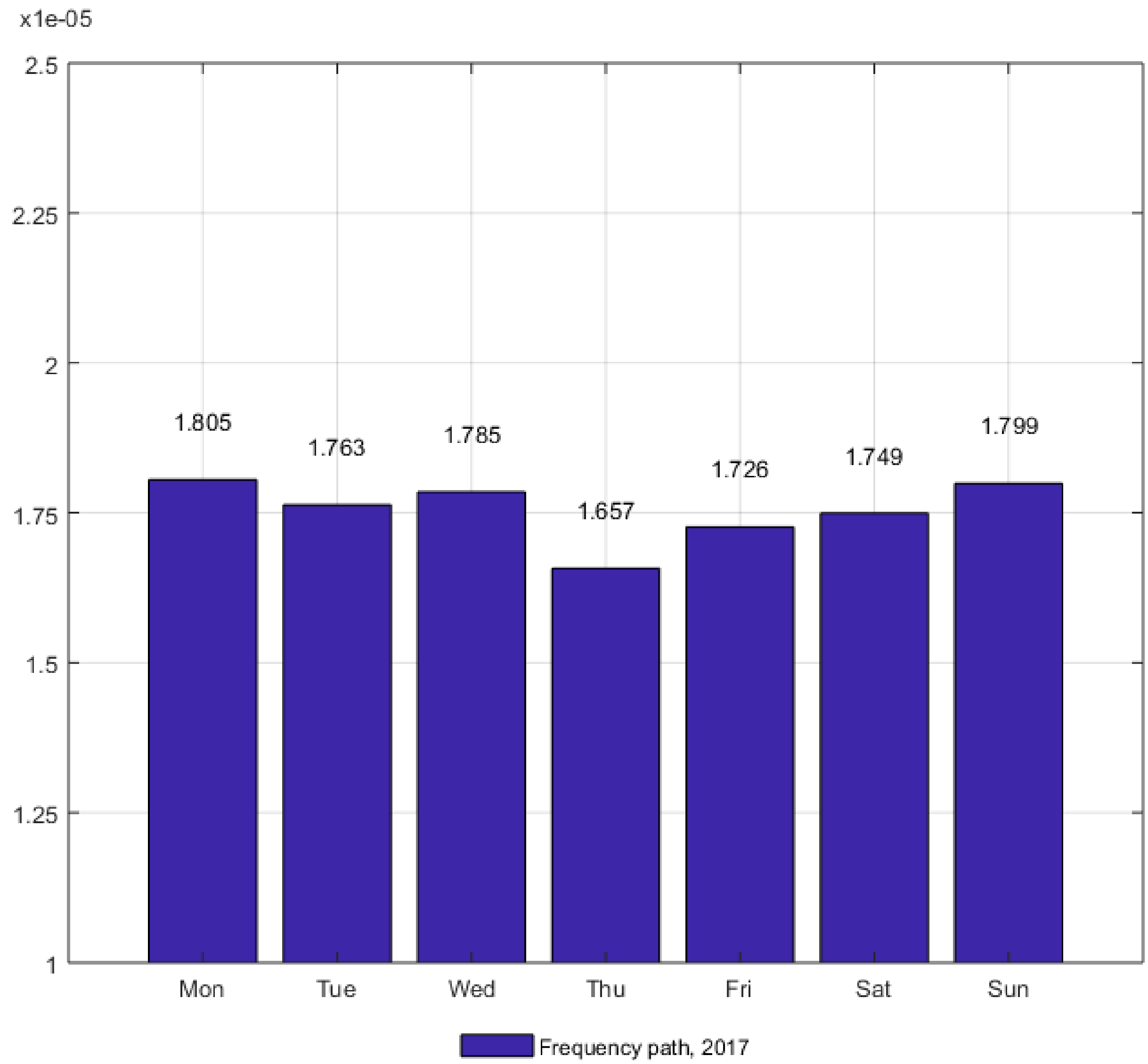


Figure 3.55 shows the frequency path during the day. The path is longer closer to the shift of the day and shorter around noon.

***Figure 3.55**. Length of the frequency path for every hour of the day in 2017*

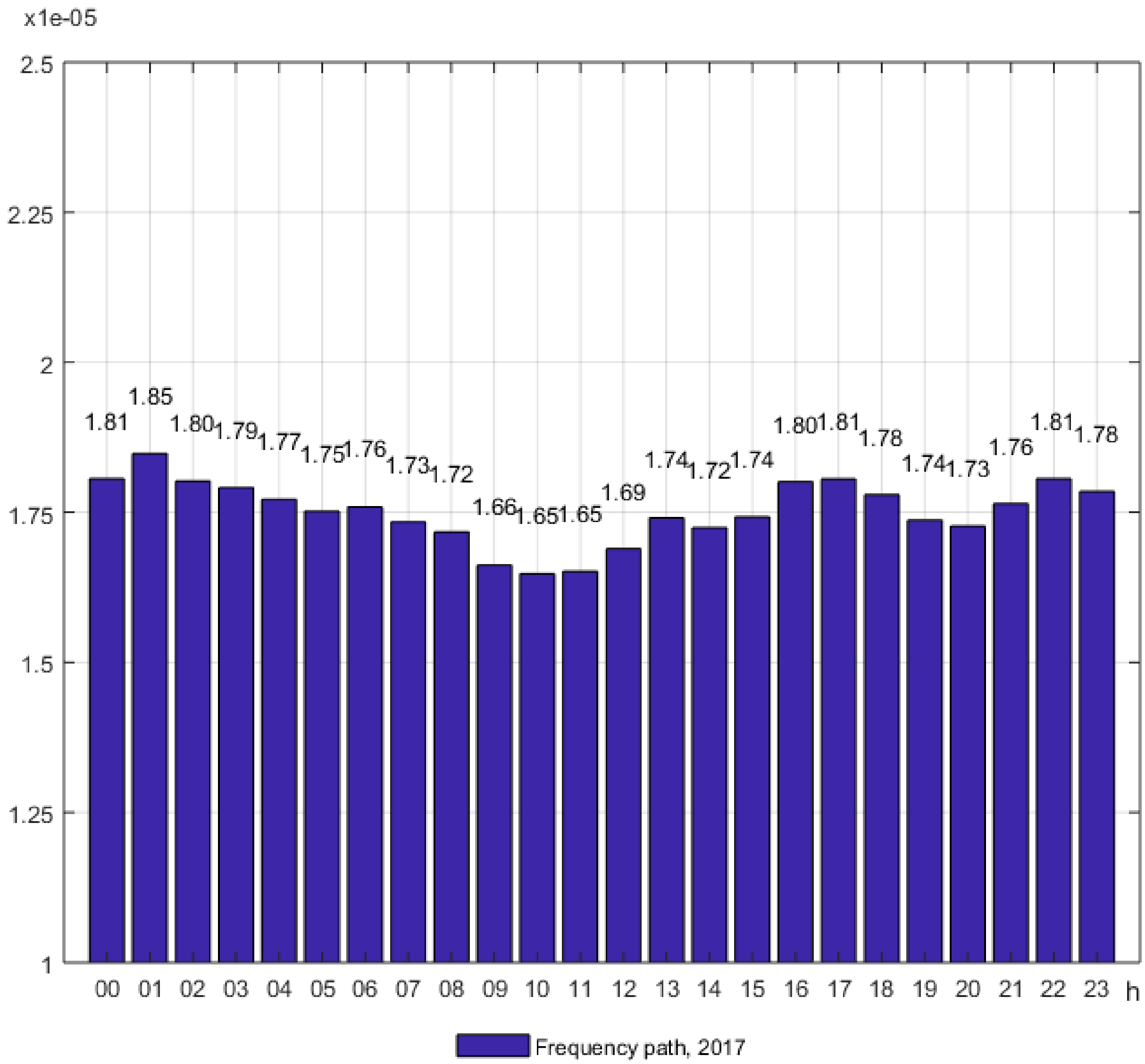
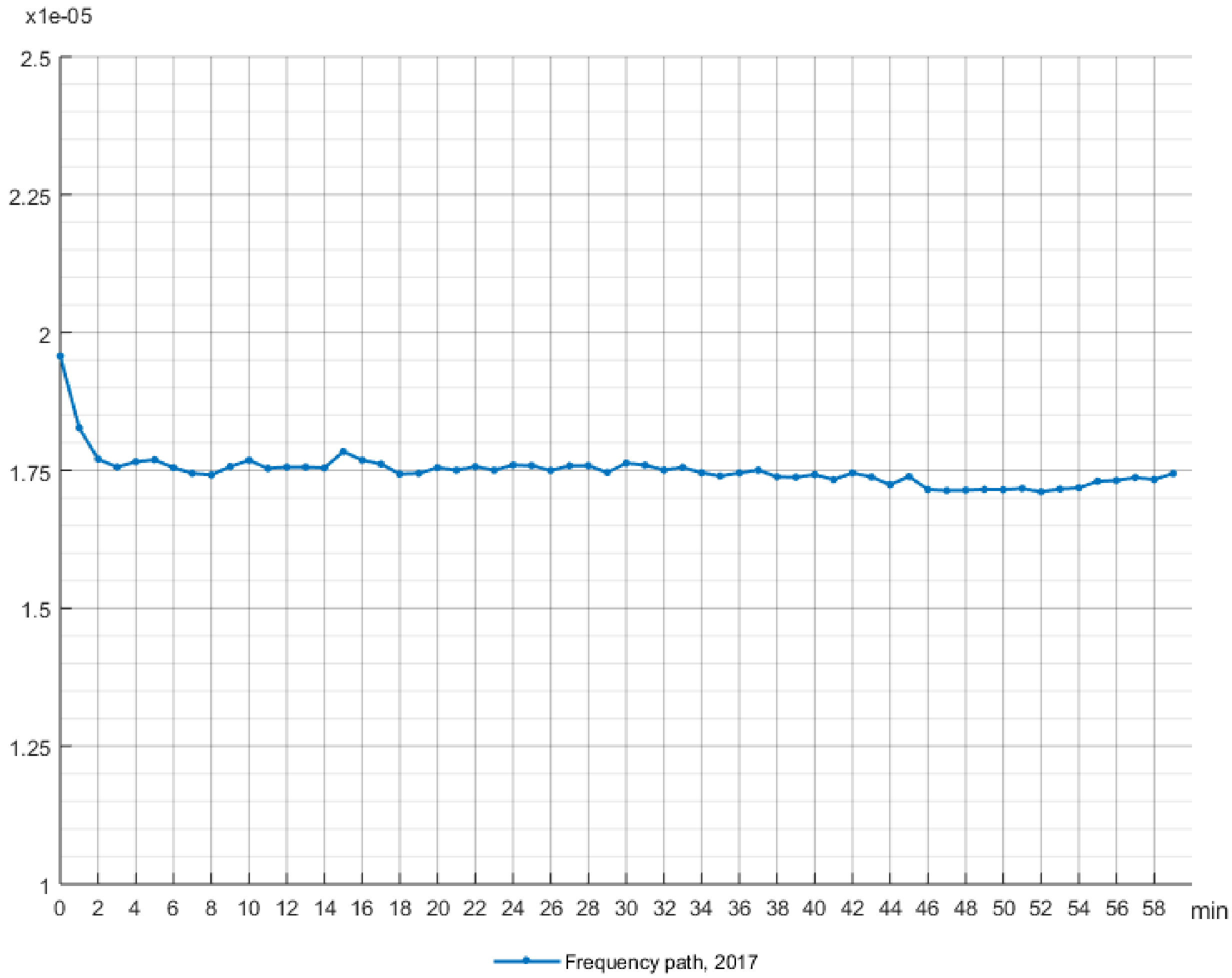


Figure 3.56 represents the average frequency path for every minute inside the hour. The path is longer during the first minutes of the hour, but otherwise it stays pretty even throughout the hour.

Figure 3.56. Length of the frequency path for every minute of the hour in 2017



3.8 Amount of frequency oscillation

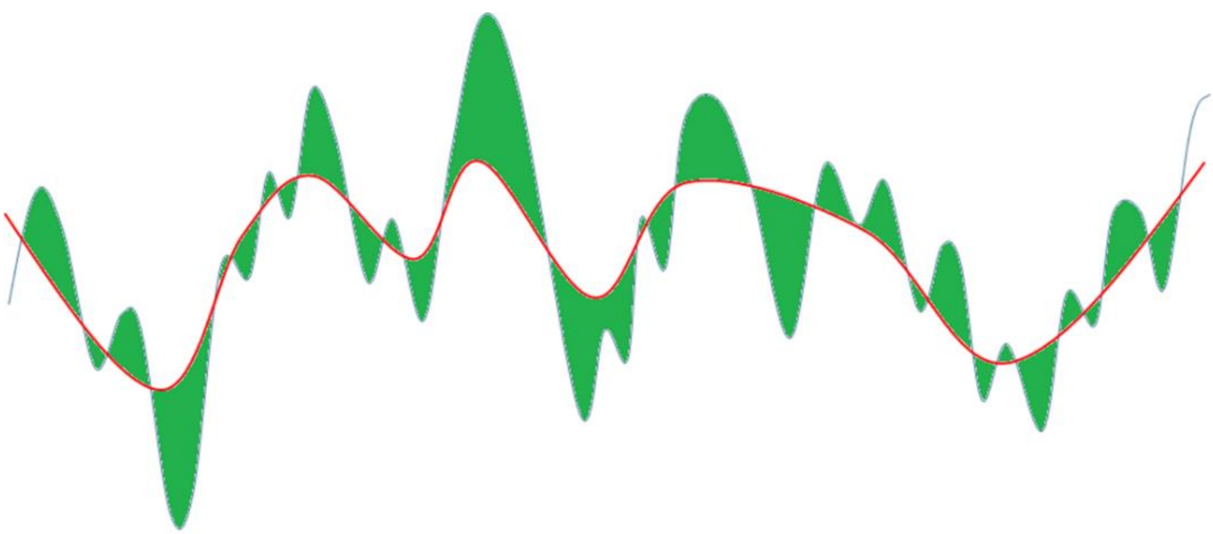
Frequency of the Nordic synchronous system oscillates constantly. Time period of the oscillation is approximately 40 to 90 seconds. This behavior is a natural characteristic of the system but it can be influenced through adequate settings of system reserves. Oscillation has an increasing effect on the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

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 [6,7,9,10], 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 [8].

Figure 3.57**. **Frequency quality index: Amount of frequency oscillation [8]



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 [9] . 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 [9]

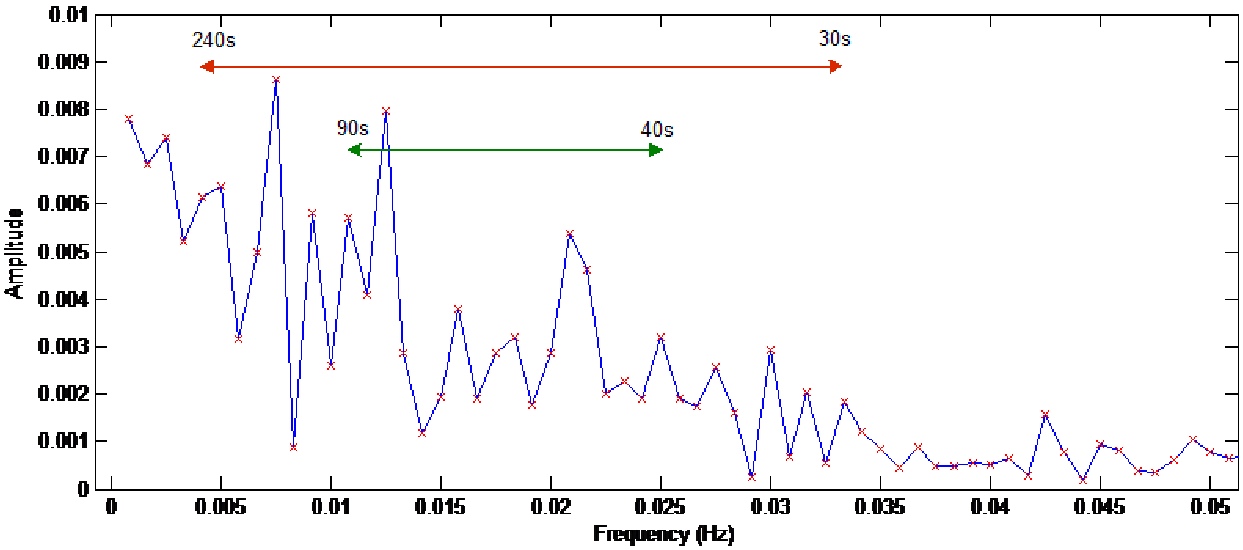
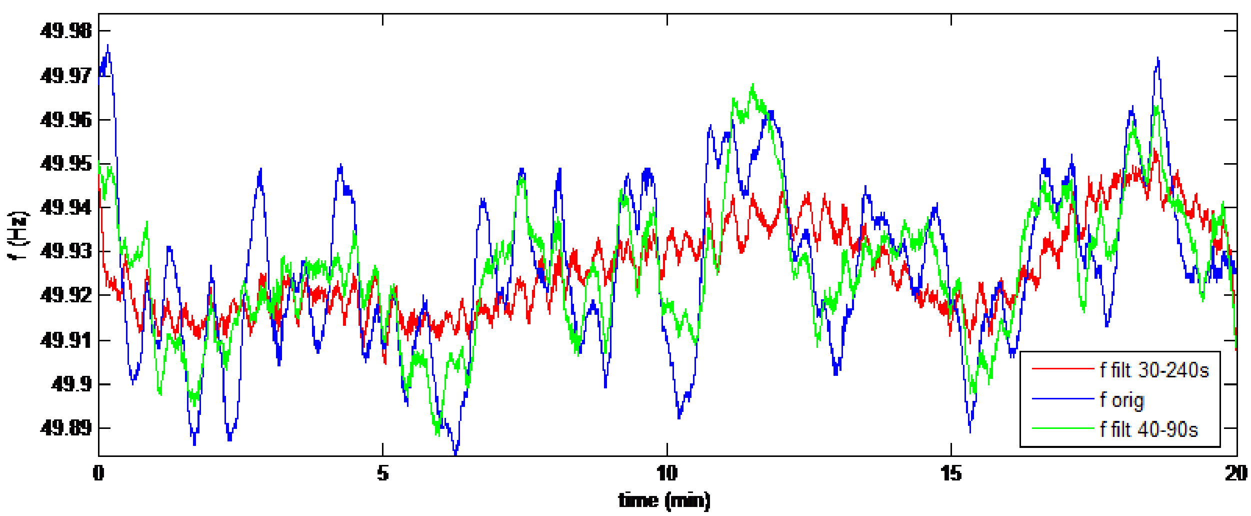


Figure 3.59. Original frequency (blue), frequency with 40-90 s band filtered (green) and frequency with 30-240 s band filtered (red). First 20 minutes of December 2012 are shown (UTC+2) [9]



3.8.2 Amount of oscillation

Figure 3.60 shows hourly values and 24 hour moving averages for the amount of oscillation in 2017. 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 and December had the least amount of oscillation in 2017.

Figures 3.61 and 3.62 contain the previously mentioned 24 hour moving averages for years 2012-2014 and 2015-2017, respectively. In the calculations for years 2011-2015 it was required that there had to be enough eligible data for at least 22 hours in the frame of 24 hours. For 2016 and 2017, 12 hours of eligible data was required.

Figure 3.60. Amount of oscillation in 2017

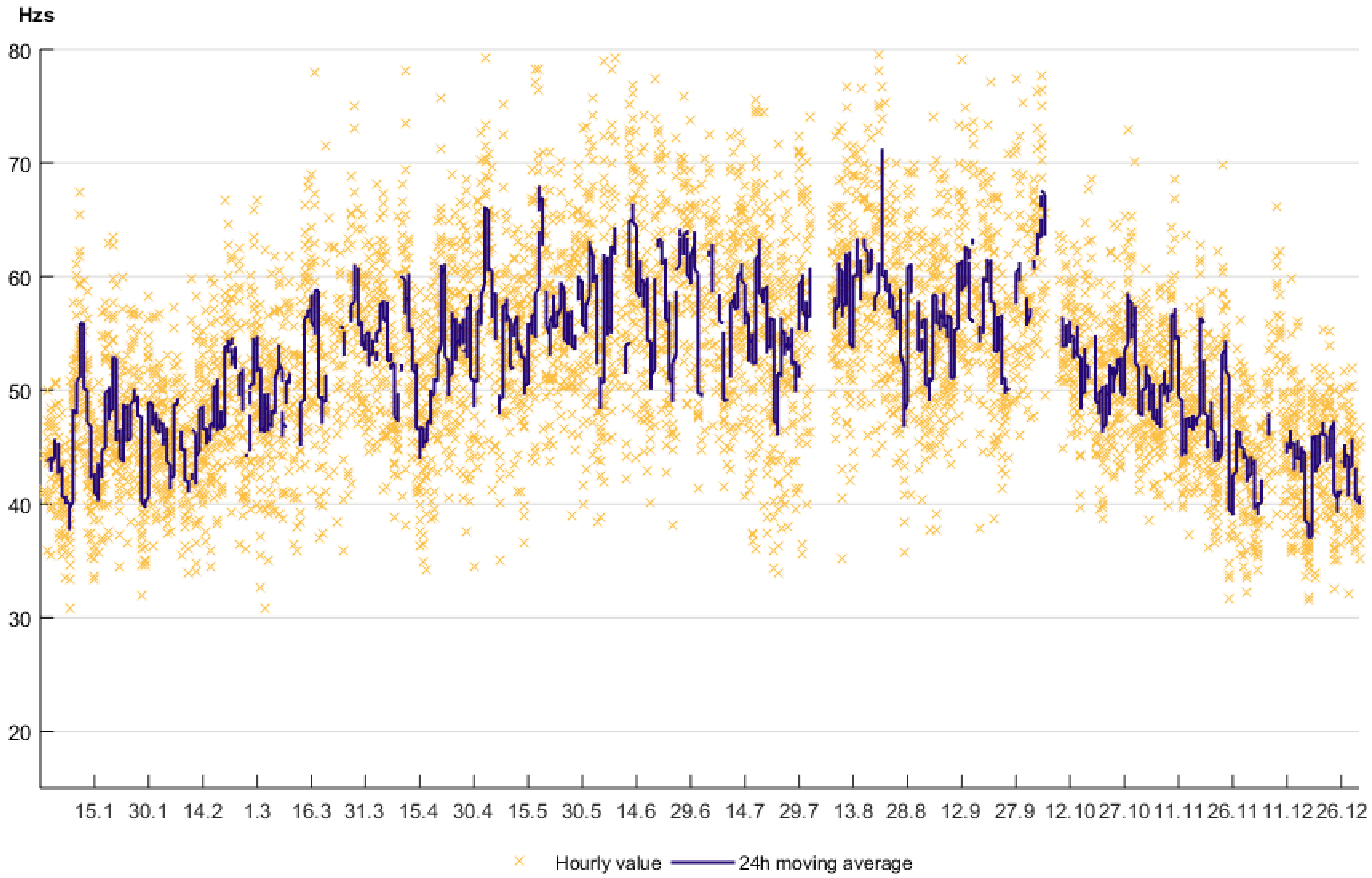


Figure 3.61. Amount of oscillation in 2012-2014

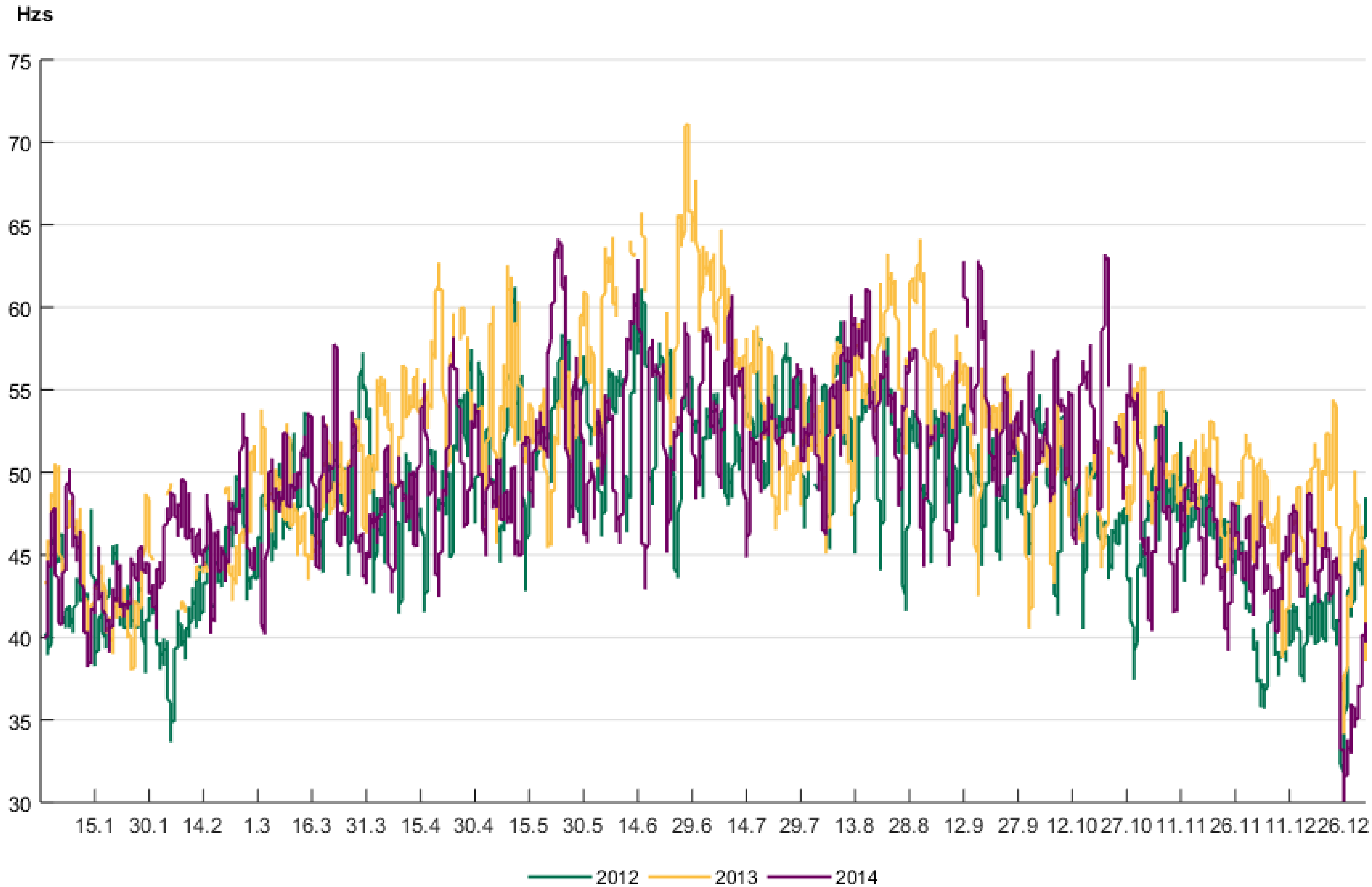
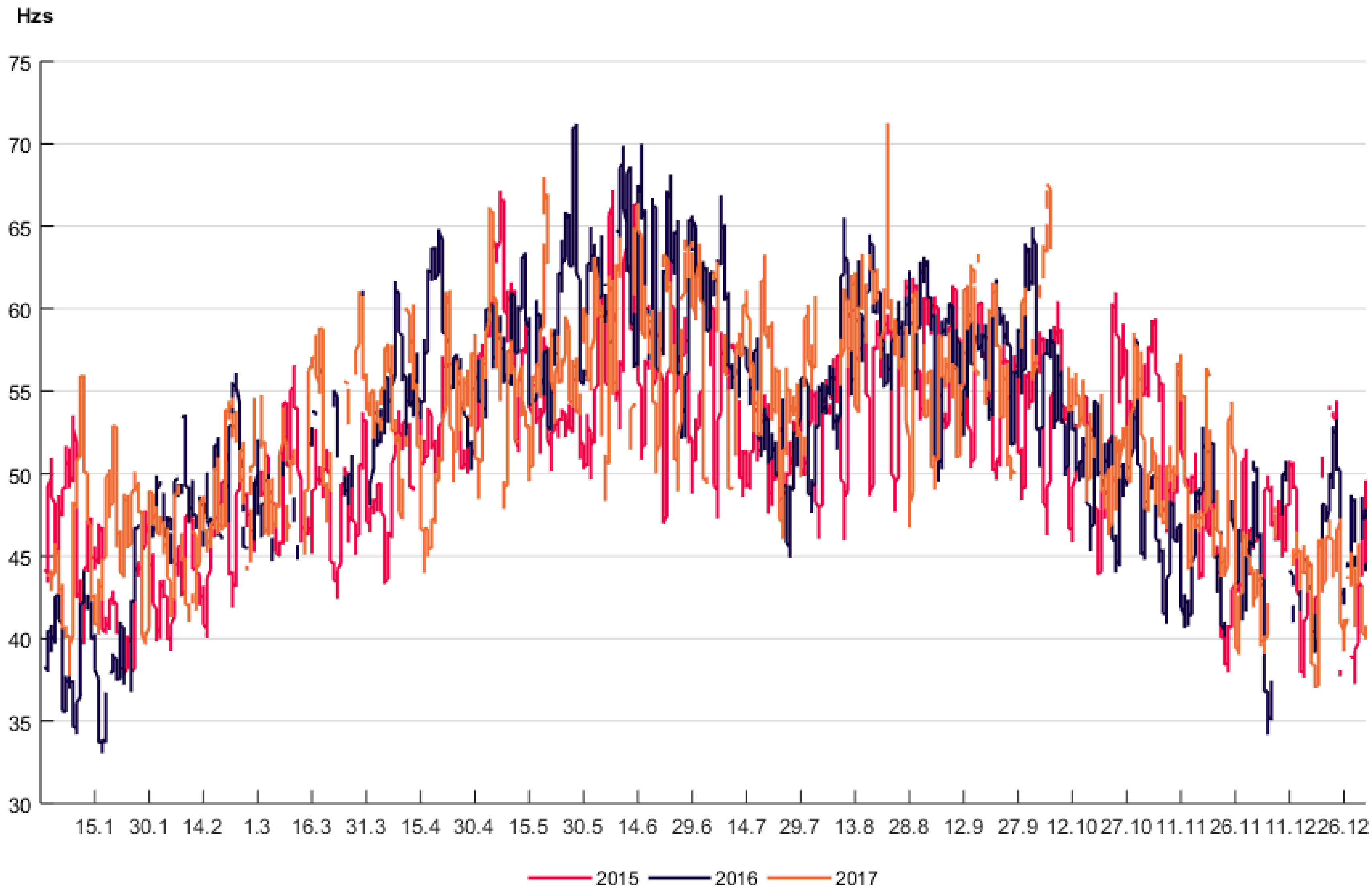


***Figure 3.62**. Amount of oscillation in 2015-2017*



Mean value of the oscillation and standard deviation for each month from 2012 to 2017 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 around the same amount in 2017 as in previous year 2016. The last two years have been among the worst years in terms of oscillation.

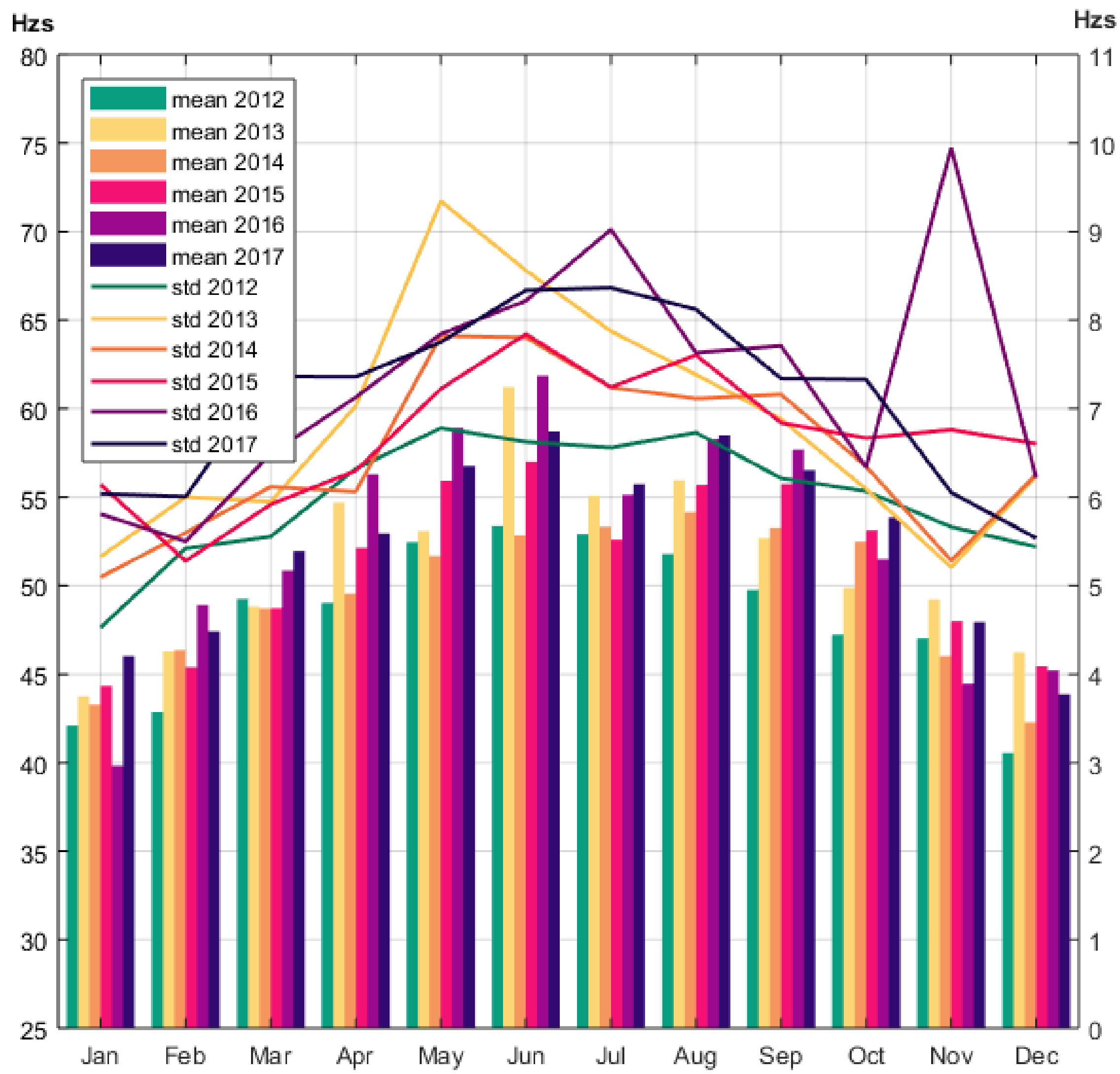
Table 3.24. Mean values and standard deviations for oscillation in years 2012-2014

	Mean value (Hzs)			**Standard deviation (Hzs)**		
Month	**2012**	**2013**	**2014**	**2012**	**2013**	**2014**
January	42.1	43.8	43.3	4.5	5.3	5.1
February	42.9	46.3	46.4	5.4	6.0	5.6
March	49.2	48.8	48.7	5.6	5.9	6.1
April	49.0	54.7	49.5	6.3	7.0	6.1
May	52.5	53.1	51.7	6.8	9.3	7.8
June	53.4	61.2	52.8	6.6	8.6	7.8
July	52.9	55.1	53.3	6.6	7.9	7.2
August	51.8	56.0	54.2	6.7	7.4	7.1
September	49.8	52.7	53.3	6.2	6.9	7.2
October	47.2	49.9	52.5	6.1	6.1	6.3
November	47.0	49.2	46.0	5.7	5.2	5.3
December	40.5	46.2	42.3	5.4	6.2	6.3
Entire year	**48.2**	**51.4**	**49.5**	**6.0**	**6.8**	**6.5**

Table 3.25. Mean values and standard deviations for oscillation in years 2015-2017

	Mean value (Hzs)			**Standard deviation (Hzs)**		
Month	**2015**	**2016**	**2017**	**2015**	**2016**	**2017**
January	44.3	39.8	46.0	6.1	5.8	6.0
February	45.4	48.9	47.4	5.3	5.5	6.0
March	48.7	50.8	52.0	5.9	6.5	7.4
April	52.1	56.3	52.9	6.3	7.1	7.4
May	55.9	58.9	56.8	7.2	7.8	7.7
June	57.0	61.9	58.7	7.8	8.2	8.3
July	52.6	55.1	55.7	7.2	9.0	8.4
August	55.7	58.3	58.5	7.6	7.6	8.1
September	55.8	57.7	56.5	6.8	7.7	7.3
October	53.1	51.5	53.8	6.7	6.3	7.3
November	48.0	44.5	47.9	6.8	9.9	6.1
December	45.4	45.2	43.9	6.6	6.2	5.5
Entire year	**51.2**	**52.4**	**52.5**	**6.7**	**7.3**	**7.1**

***Figure 3.63**. Mean values (left y-axis) and standard deviations (right y-axis) for oscillation in years 2012-2017*

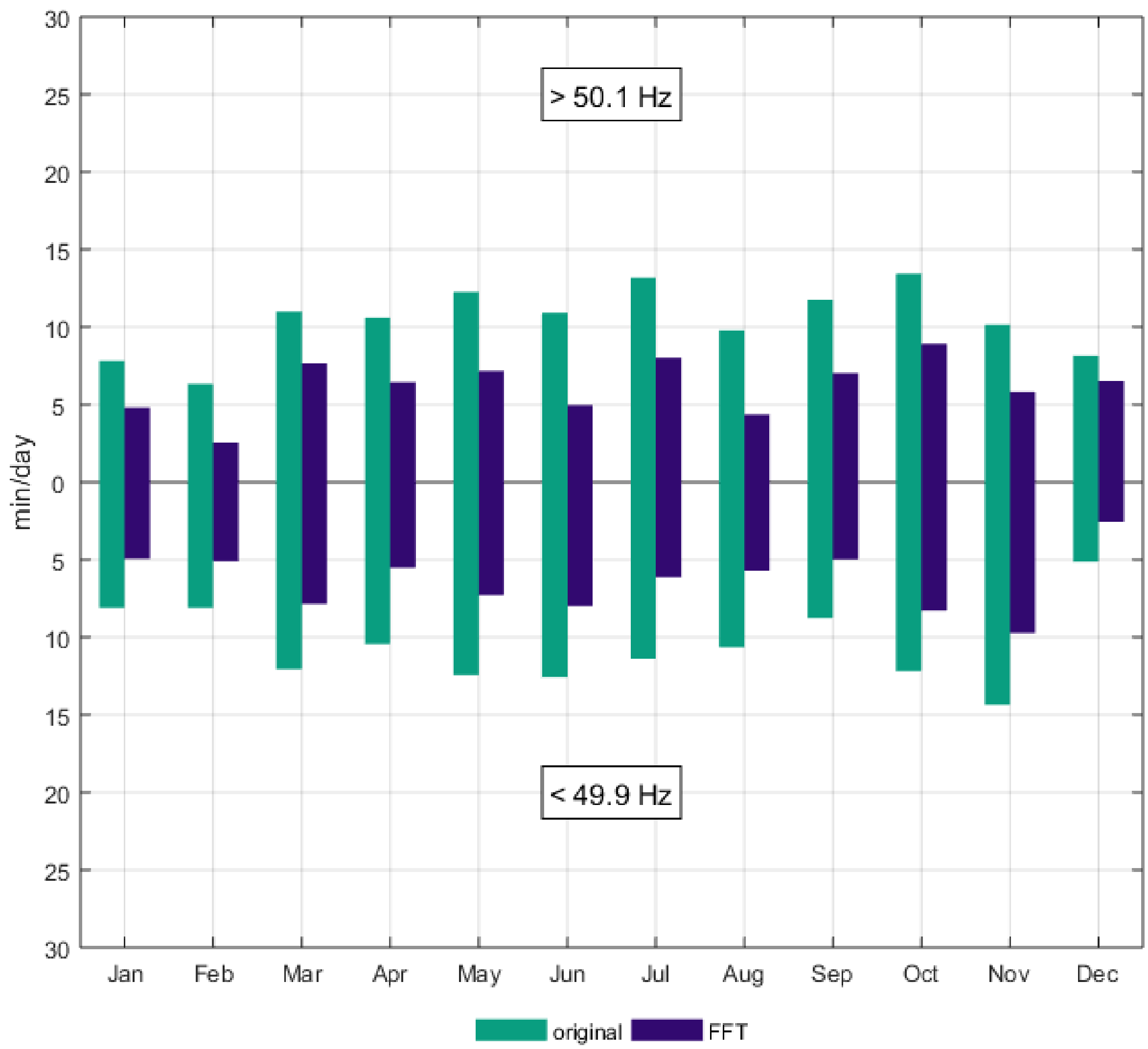


3.8.3 Influence of oscillation on frequency variations

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 3.64 shows the average minutes per day outside the standard frequency range in 2017 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 3.64**. Average time per day outside the standard frequency range in 2017*



In Figure 3.65, 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 3.65**. Reduction in time per month outside the standard frequency range after filtering in 2017*

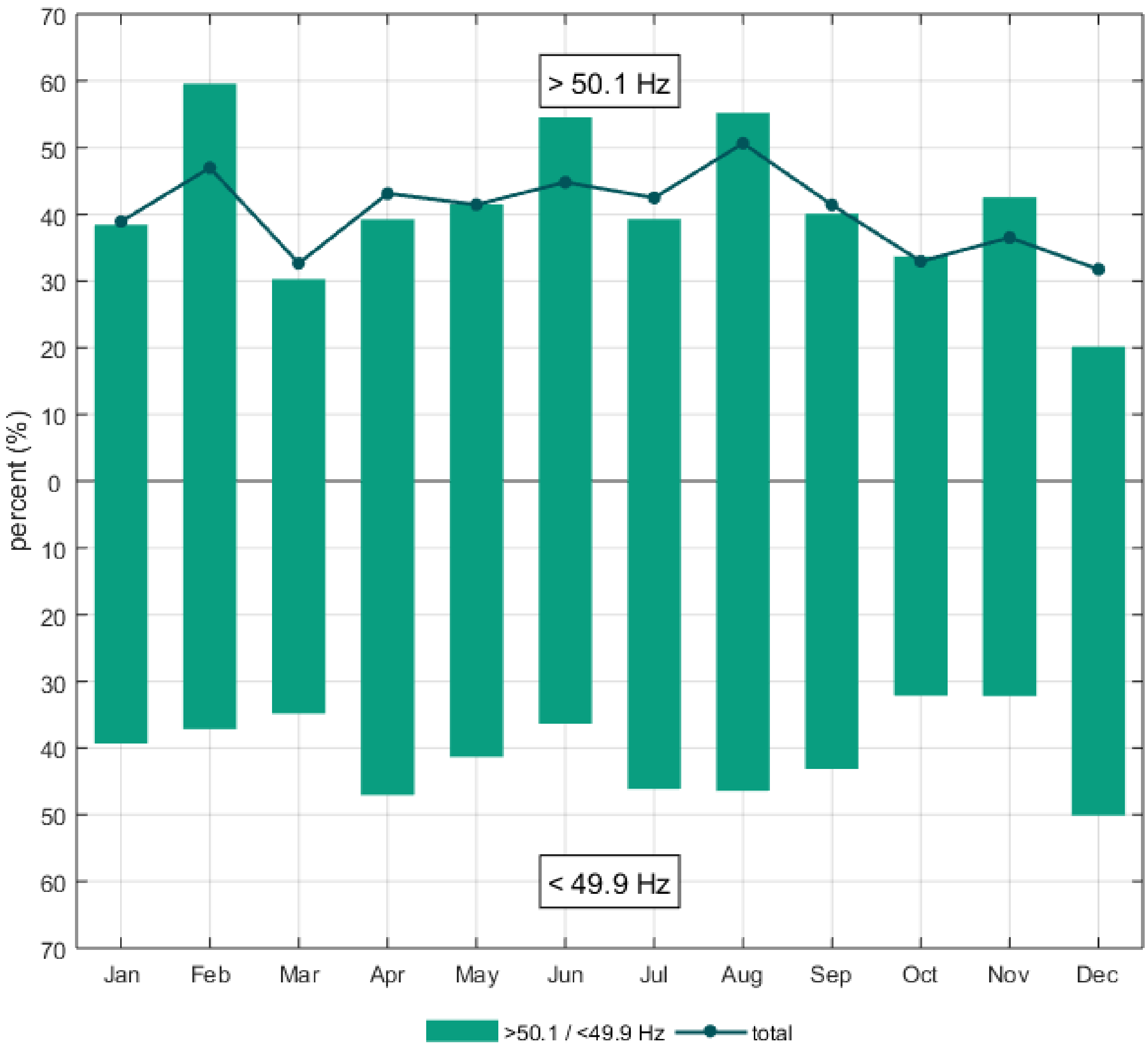
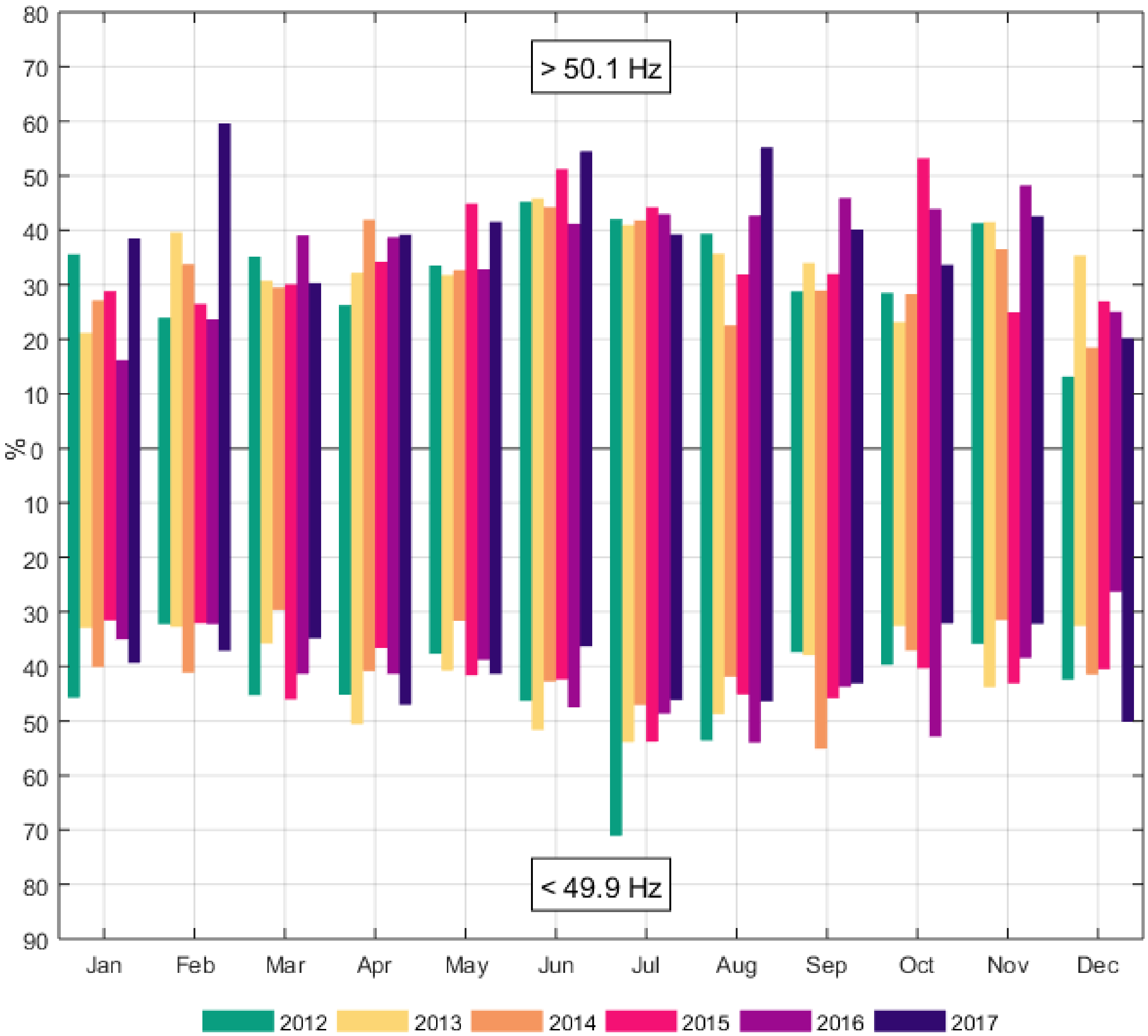


Figure 3.66 represents the reduction in time outside the standard frequency range in percentages month by month for years 2012 to 2017.

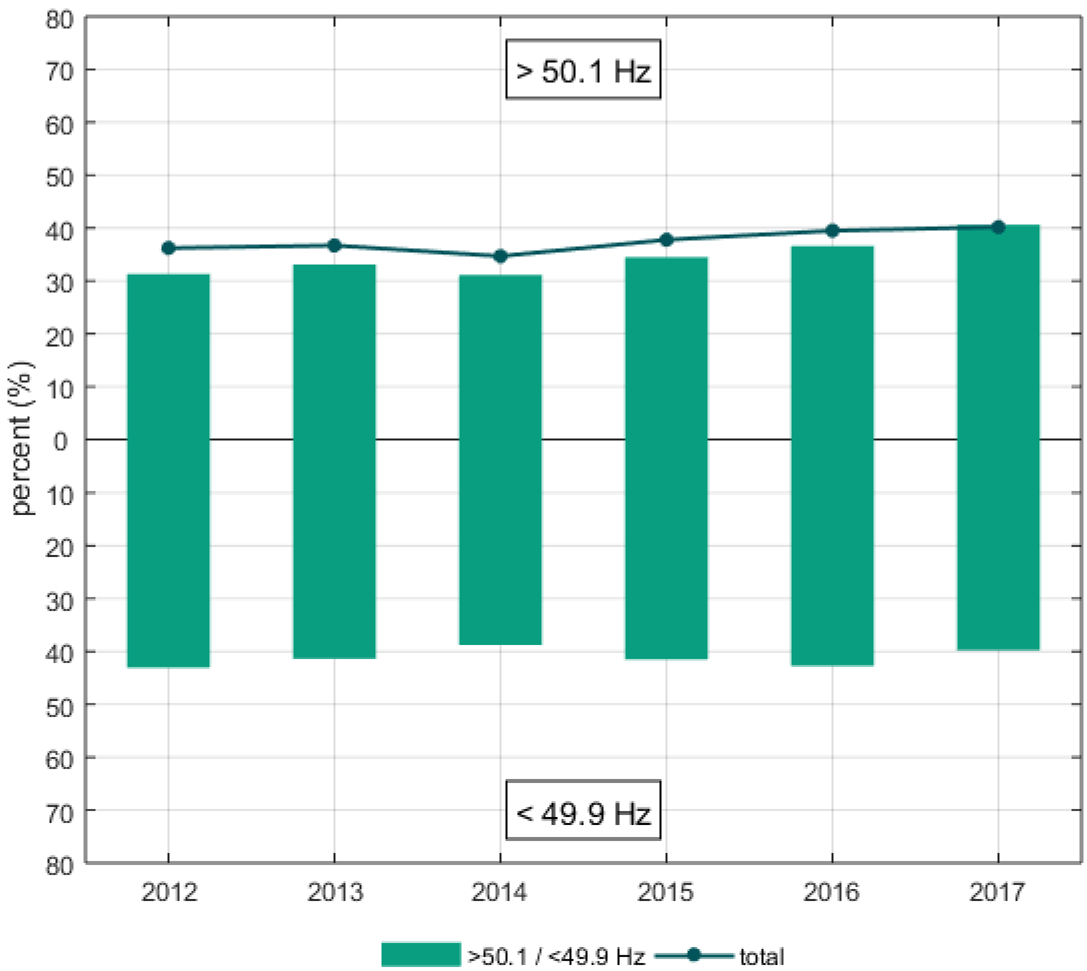
***Figure 3.66**. Reduction in time per month outside the standard frequency range after filtering in years 2012-2017*



In addition to the monthly values presented in the previous figure, results for the entire year in 2012-2017 are shown below in Figure 3.67.

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 3.67. Reduction in time outside the standard frequency range after filtering for years 2012-2017



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 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 2012-2017. The same results are presented in a graphical form in Figure 3.68.

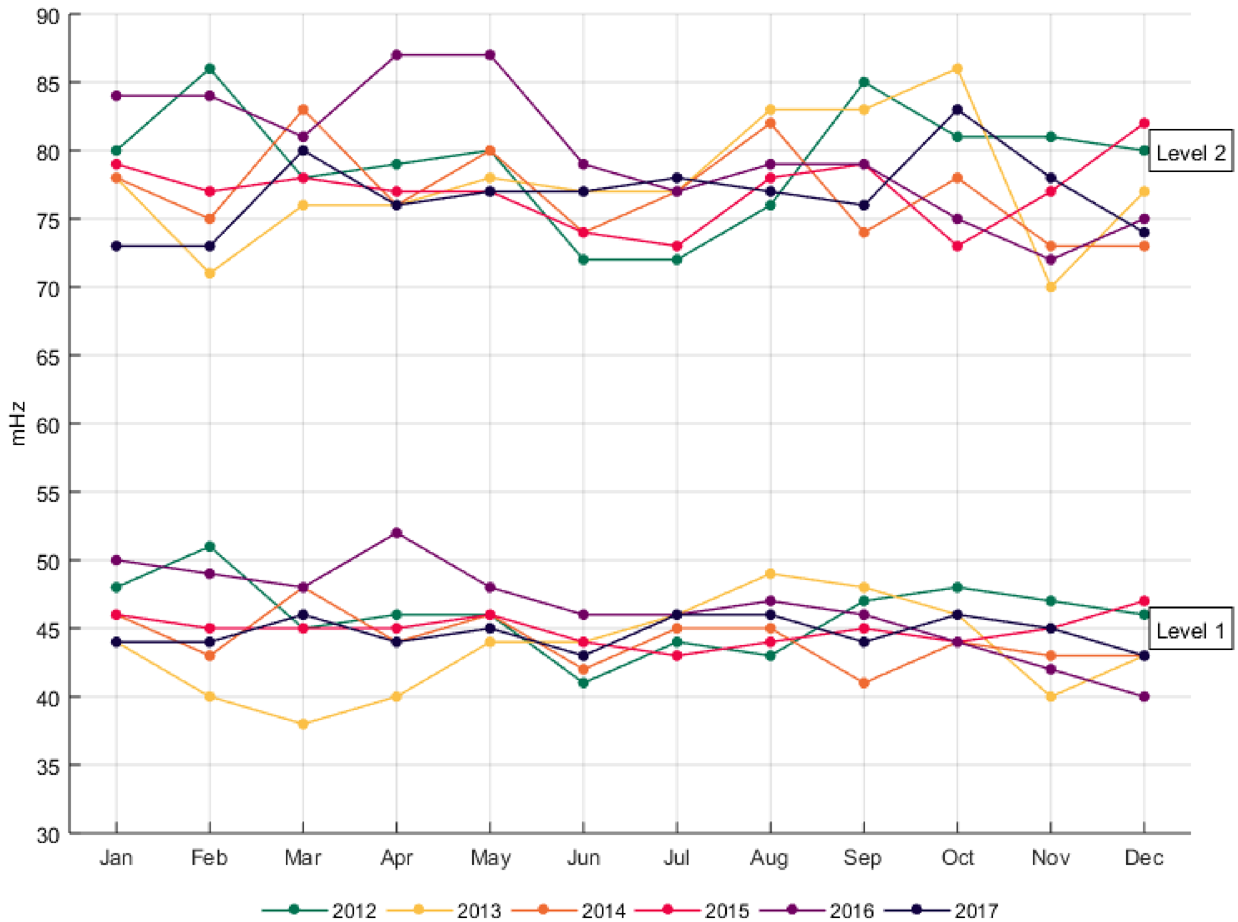
Table 3.26. FRCE Ranges for NE, calculated with 15 min moving averages, years 2012-2014

	2012		**2013**		**2014**	
Month	**Level 1 (mHz)**	**Level 2 (mHz)**	**Level 1 (mHz)**	**Level 2 (mHz)**	**Level 1 (mHz)**	**Level 2 (mHz)**
January	±48	±80	±44	±78	±46	±78
February	±51	±86	±40	±71	±43	±75
March	±45	±78	±38	±76	±48	±83
April	±46	±79	±40	±76	±44	±76
May	±46	±80	±44	±78	±46	±80
June	±41	±72	±44	±77	±42	±74
July	±44	±72	±46	±77	±45	±77
August	±43	±76	±49	±83	±45	±82
September	±47	±85	±48	±83	±41	±74
October	±48	±81	±46	±86	±44	±78
November	±47	±81	±40	±70	±43	±73
December	±46	±80	±43	±77	±43	±73
Entire year	**±46**	**±79**	**±44**	**±78**	**±44**	**±77**

Table 3.27. FRCE Ranges for NE, calculated with 15 min moving averages, years 2015-2017

	2015		**2016**		**2017**	
Month	**Level 1 (mHz)**	**Level 2 (mHz)**	**Level 1 (mHz)**	**Level 2 (mHz)**	**Level 1 (mHz)**	**Level 2 (mHz)**
January	±46	±79	±50	±84	±44	±73
February	±45	±77	±49	±84	±44	±73
March	±45	±78	±48	±81	±46	±80
April	±45	±77	±52	±87	±44	±76
May	±46	±77	±48	±87	±45	±77
June	±44	±74	±46	±79	±43	±77
July	±43	±73	±46	±77	±46	±78
August	±44	±78	±47	±79	±46	±77
September	±45	±79	±46	±79	±44	±76
October	±44	±73	±44	±75	±46	±83
November	±45	±77	±42	±72	±45	±78
December	±47	±82	±40	±75	±43	±74
Entire year	**±45**	**±77**	**±47**	**±80**	**±45**	**±77**

Figure 3.68. FRCE Ranges for years 2012-2017 calculated with 15 min moving averages



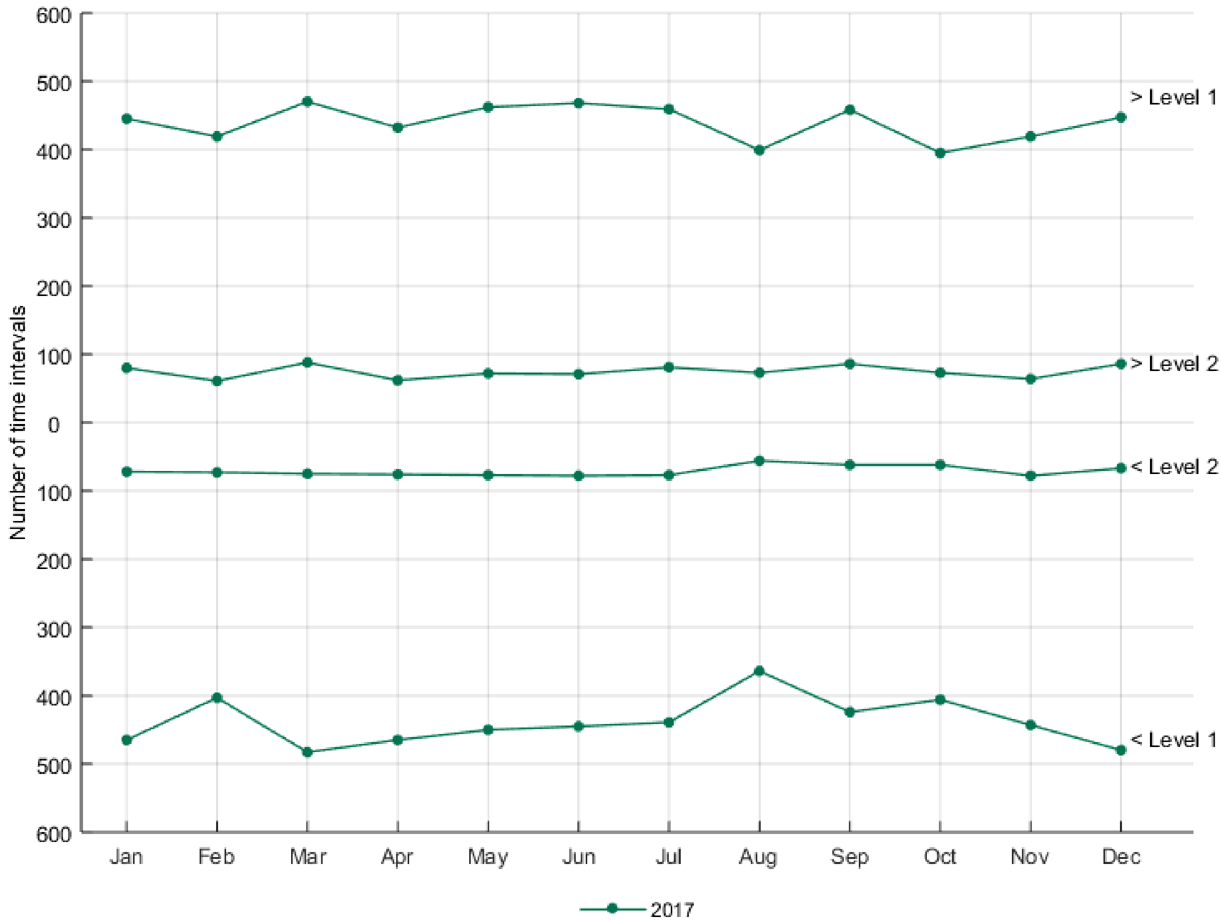
3.9.2 Number of time intervals outside Level 1 and Level 2 FRCE Range

Table 3.28 shows the number of 15 minute time intervals outside Level 1 and Level 2 FRCE Ranges in year 2017. 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 3.69 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 2017

	2017			
Month	**> Level 1 (+)**	**< Level 1 (-)**	**> Level 2 (+)**	**< Level 2 (-)**
January	445	465	80	72
February	419	403	61	73
March	470	483	88	75
April	432	465	62	76
May	462	450	72	77
June	468	445	71	78
July	459	439	81	77
August	399	364	73	56
September	458	424	86	62
October	395	406	73	62
November	419	443	64	78
December	447	480	86	67
Entire year	**5273**	**5267**	**897**	**853**

***Figure 3.69**. The number of time intervals over positive and under negative FRCE Level 1 and Level 2 Ranges for year 2017*



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 2017. Of the total samples in a period, the 1st, 5th, 10th, 50th, 90th, 95th and 99th percentile are determined. Figure 3.70 shows the definition of deterministic frequency deviation. The resolution of the frequency data was 1 second.

***Figure 3.70**. Definition of deterministic frequency deviation [8]*

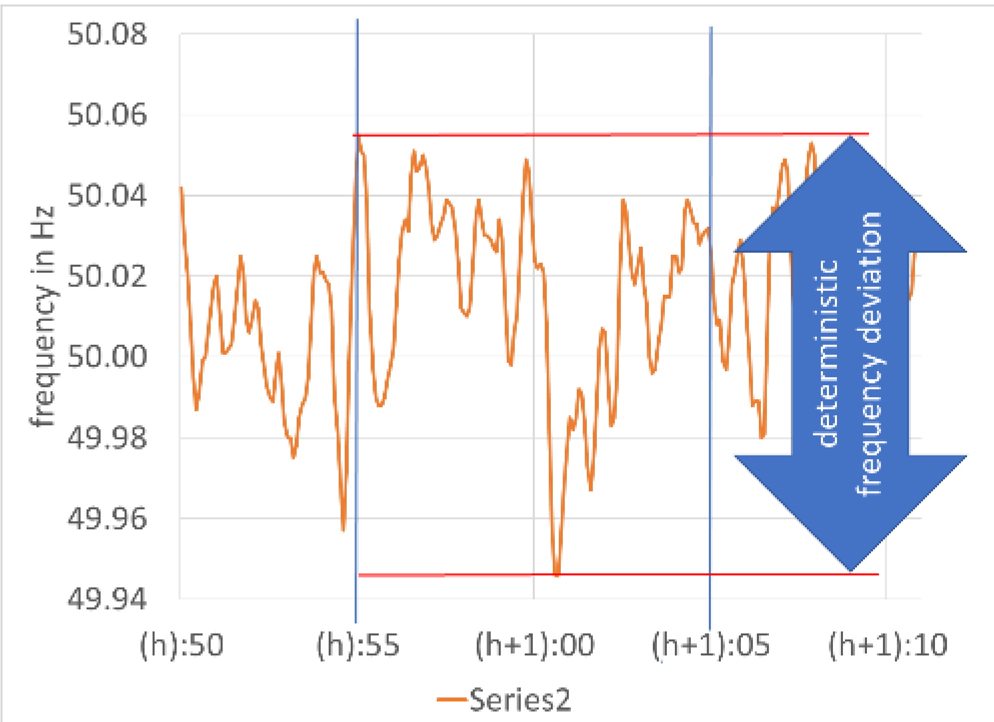


Figure 3.71 represents the deterministic frequency deviation per month in 2017. The 50th percentile stays below zero for the entire year, which indicates that the highest frequency took place before the lowest in more than half of the hour shifts.

***Figure 3.71**. The 1st, 5th, 10th, 50th, 90th, 95th, and 99th percentile of deterministic frequency deviation for every month in 2017*

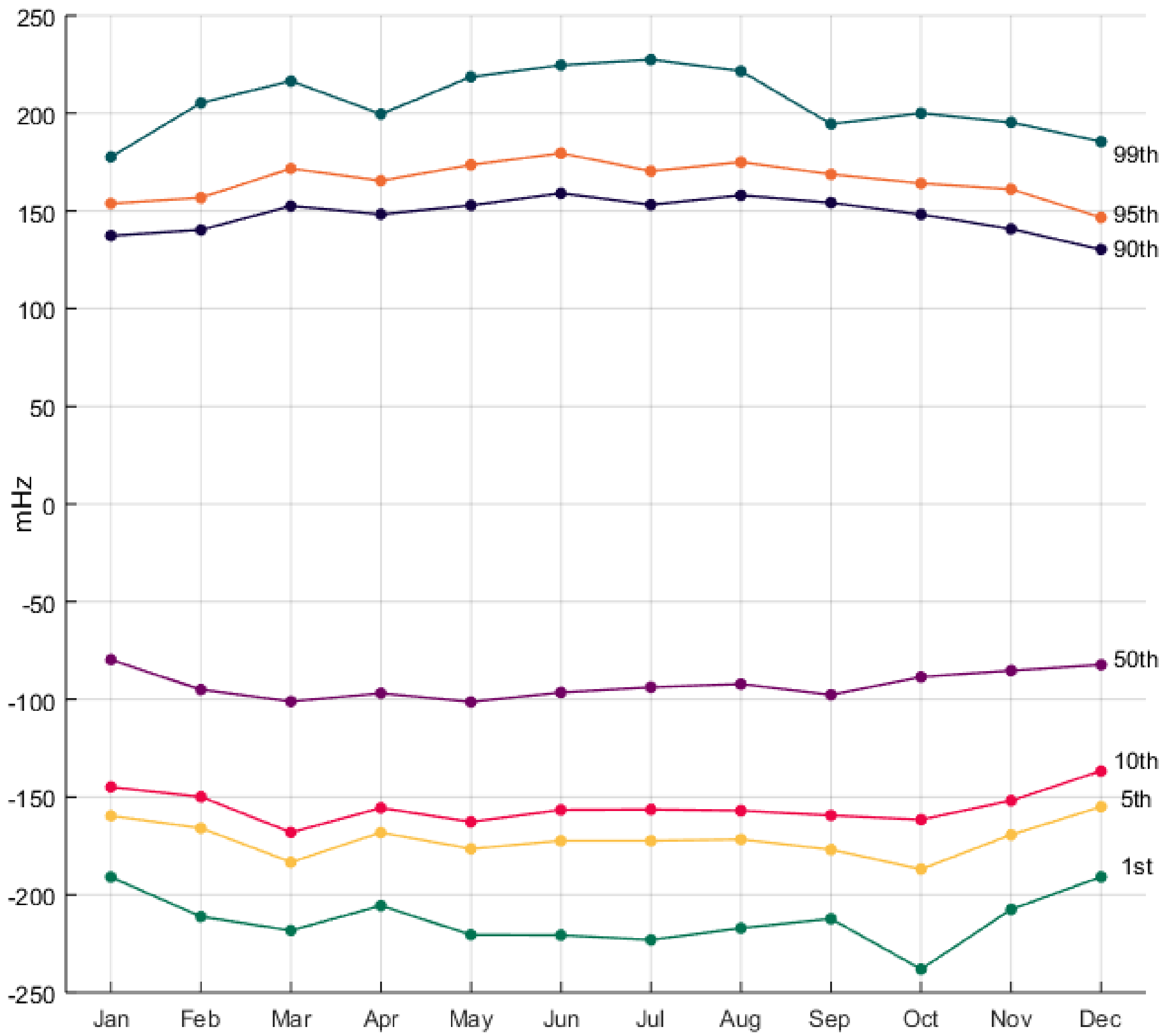
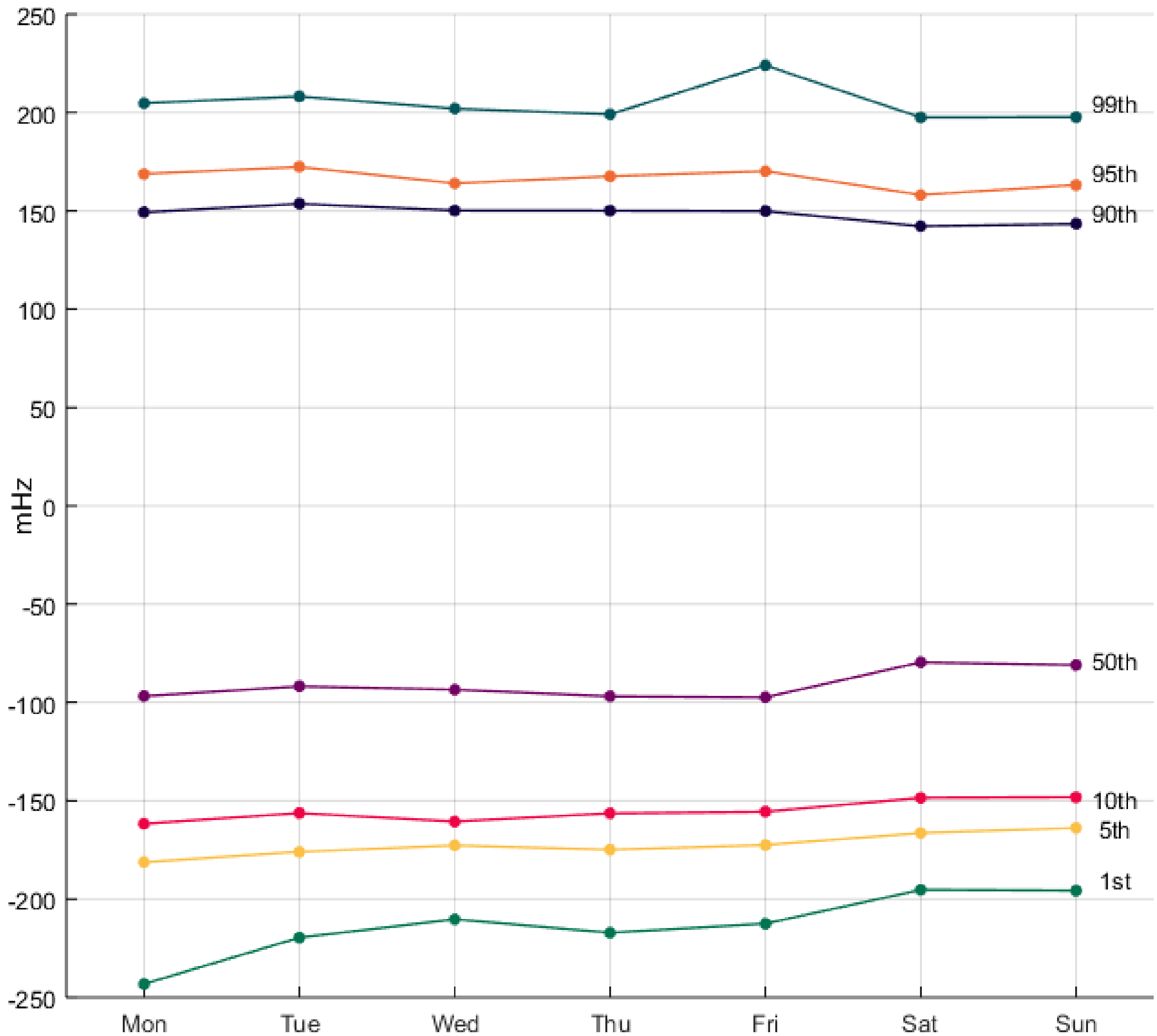


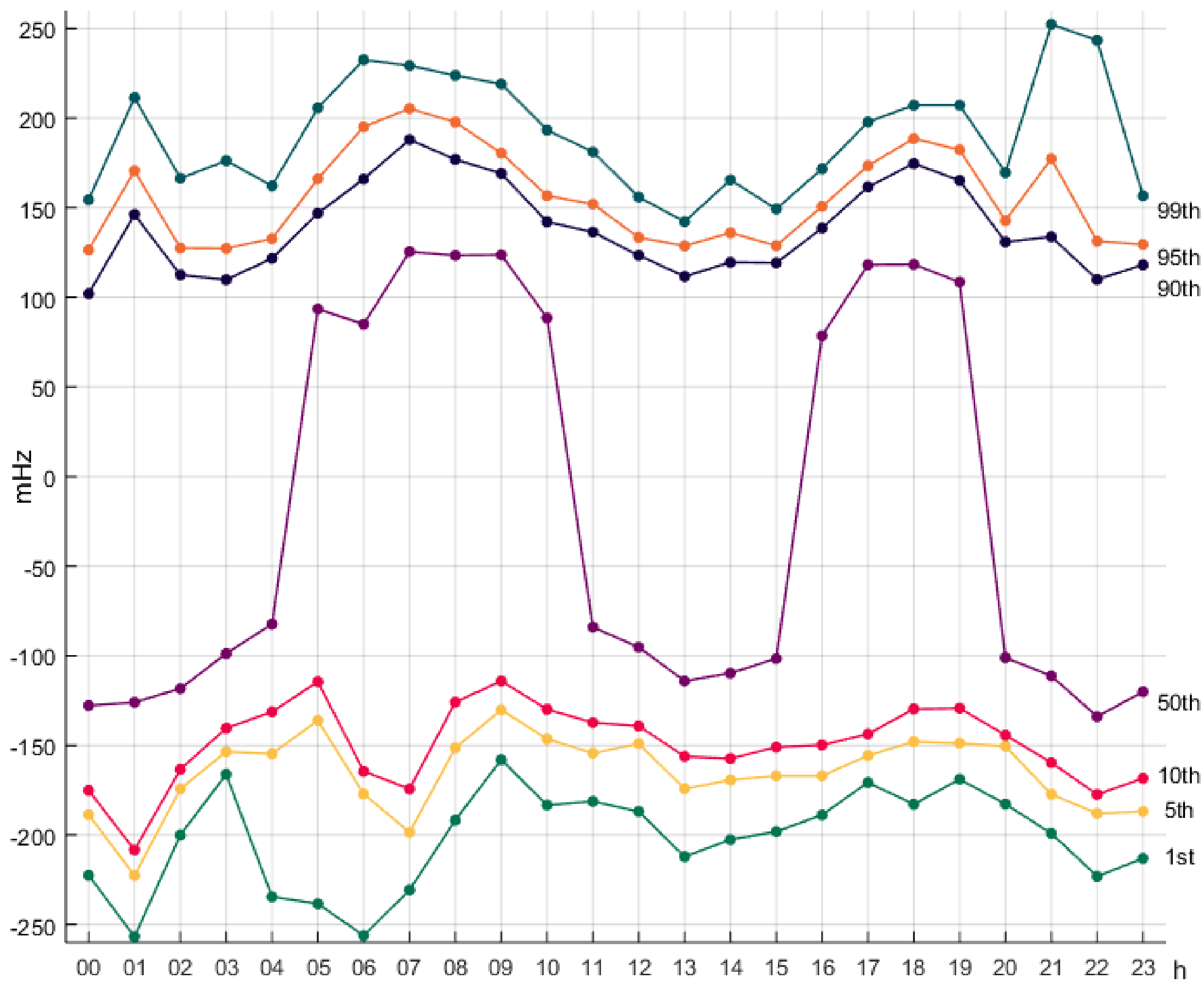
Figure 3.72 shows the percentiles around the hour shift for every day of the week in 2017. The 1st, 5th, 10th and 50th percentile are all slightly higher during the weekends.

***Figure 3.72**. The 1st, 5th, 10th, 50th, 90th, 95th, and 99th percentile of deterministic frequency deviation for every day of the week in 2017*



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 3.73. 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 3.73**. The 1st, 5th, 10th, 50th, 90th, 95th, and 99th percentile of deterministic frequency deviation for every hour of the day in 2017*



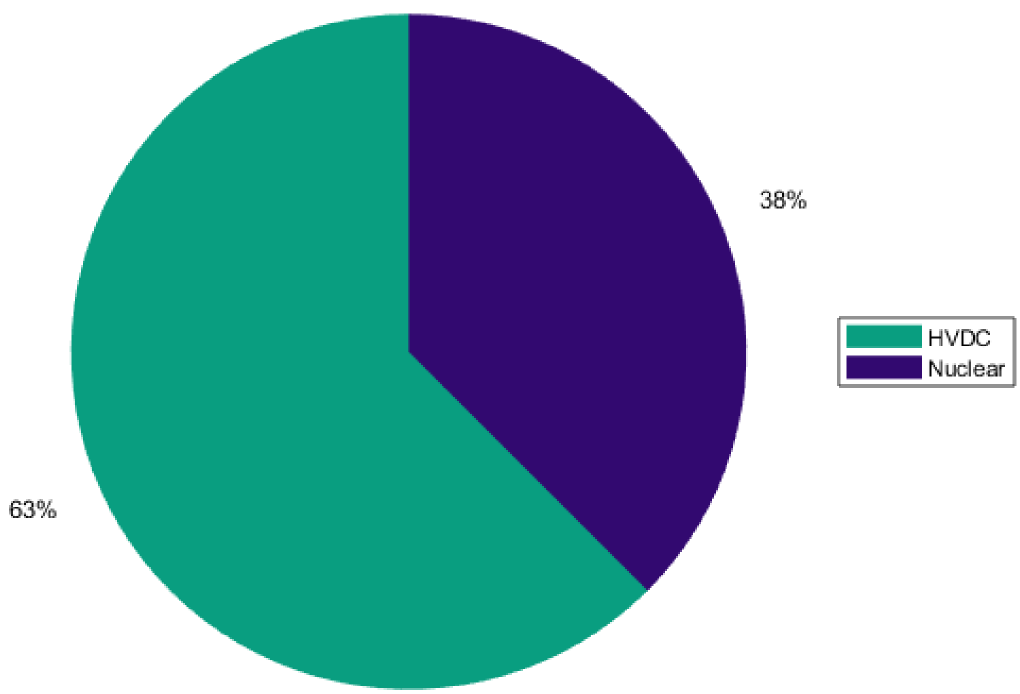
Chapter 4. Frequency disturbances exceeding 300 mHz frequency deviation

This chapter offers information of the major frequency disturbances in the Nordic synchronous system in the year 2017. 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 over ±300 mHz disturbances were caused by failures in HVDC links, which can be seen from Figure 4.1. The rest of the disturbances were caused by failures in nuclear power production.

***Figure 4.1*. Shares of factors causing over 300 mHz disturbances in the Nordic synchronous system in 2017**



Most failures in HVDC links caused over frequencies of 50.25 Hz and above. Drops of nuclear plants naturally led to under frequencies with an amplitude from 49.8 Hz to 49.6 Hz.

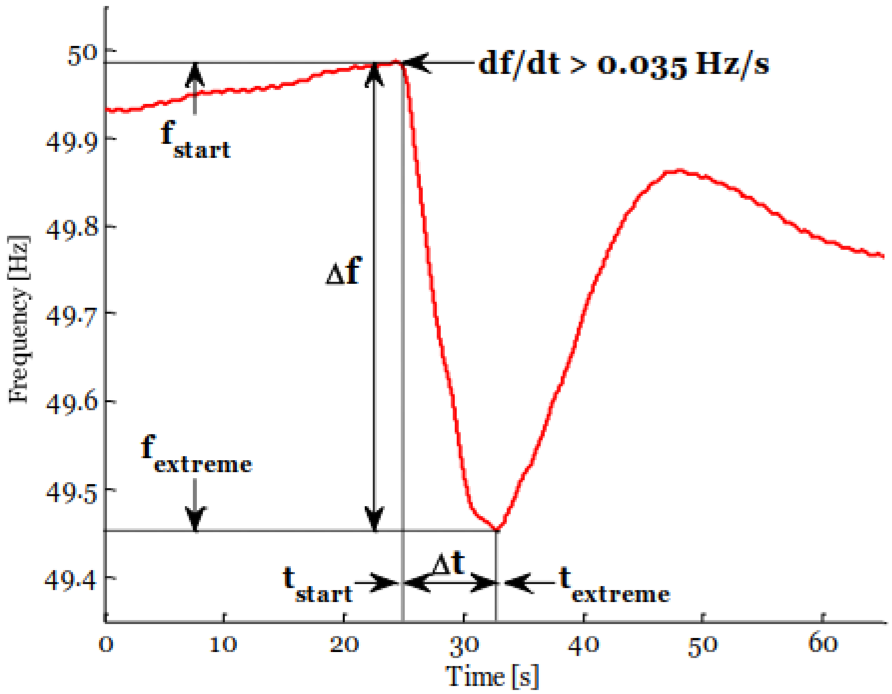
The largest maximum frequency deviation was caused by failure in HVDC link on the 13th of June with a value of 0.391 Hz. This also caused the highest instantaneous frequency of 50.360 Hz. The lowest instantaneous frequency value was 49.577 Hz caused by the tripping of nuclear plant on the 8th of November.

The following part of the chapter will go into more detail on every disturbance that took place in 2017. 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 [11]*



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 1. 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. [12]

Kinetic energy (E_k) is an estimation of the rotation energy of synchronously connected generators in the Nordic synchronous system. Values for kinetic energy are given because it affects to the system inertia which describes system's ability to oppose changes in frequency. Higher kinetic energy provides higher inertia and therefore better ability to oppose frequency deviations. [12]

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 2017

Event date	**Δf (Hz)**	**ΔP (MW)**	**Δt (s)**	**E_k (GWs)**	**Cause**	**Page**
14-May-2017 21:16:04	0.312	600	8.4	202	HVDC	114
13-Jun-2017 04:55:29	0.391	700	7.3	145	HVDC	115
27-Jun-2017 22:33:31	0.344	700	7.4	172	HVDC	116
14-Jul-2017 16:04:42	-0.281	578	8.4	185	Nuclear	117
23-Jul-2017 21:28:50	0.316	730	8.4	174	HVDC	118
24-Jul-2017 13:00:11	-0.198	600	7.0	186	Nuclear	119
02-Sep-2017 18:53:17	0.298	620	9.3	168	HVDC	120
08-Nov-2017 16:49:09	-0.342	1100	7.2	233	Nuclear	121

Figure 4.3. Disturbance 14-May-2017 21:16:04

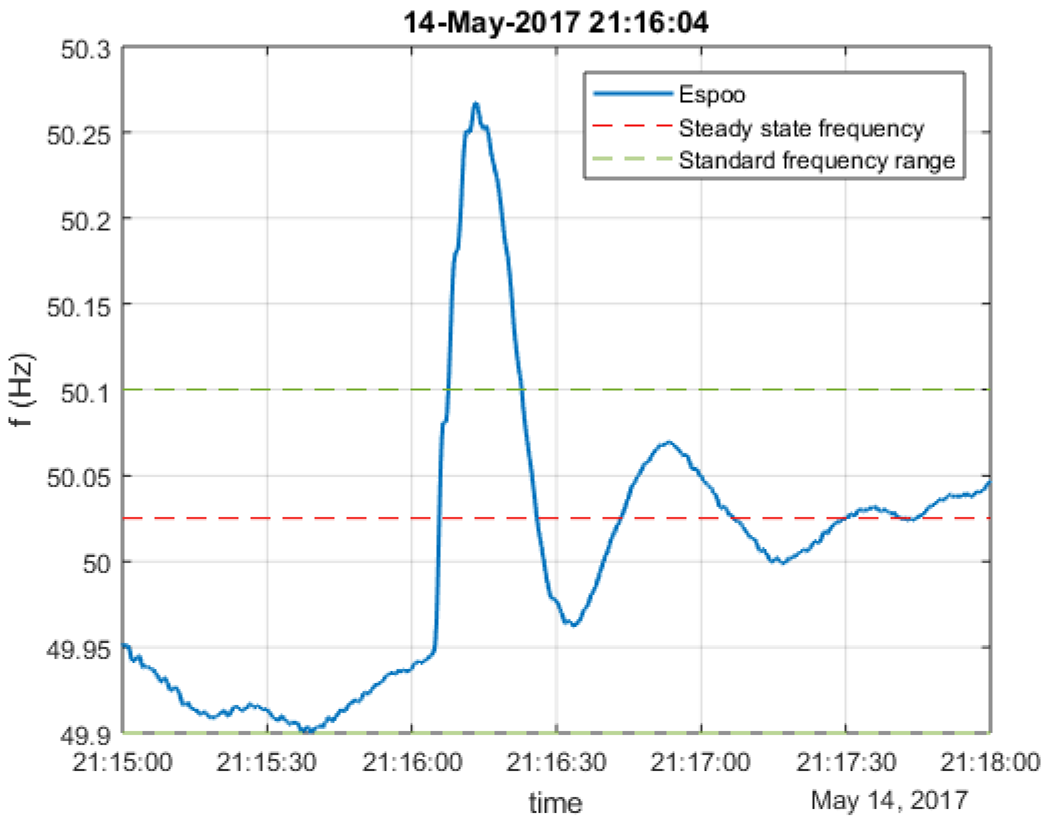


Table 4.2. Disturbance 14-May-2017 21:16:04

Date		**14-May-2017 21:16:04**	
f_{start}	49.955 Hz	$f_{steady\ state}$	50.025 Hz
$f_{extreme}$	50.267 Hz	$\Delta f_{steady\ state}$	0.070 Hz
Δf	0.312 Hz	$f_{extreme2}$	49.962 Hz
Δt	8.4 s	$f_{extreme3}$	50.070 Hz
ΔP	600 MW	damping	35.35 %
E_k	202 GWs	FBF	8541 MW/Hz
cause		HVDC	

Figure 4.4. Disturbance 13-Jun-2017 04:55:29

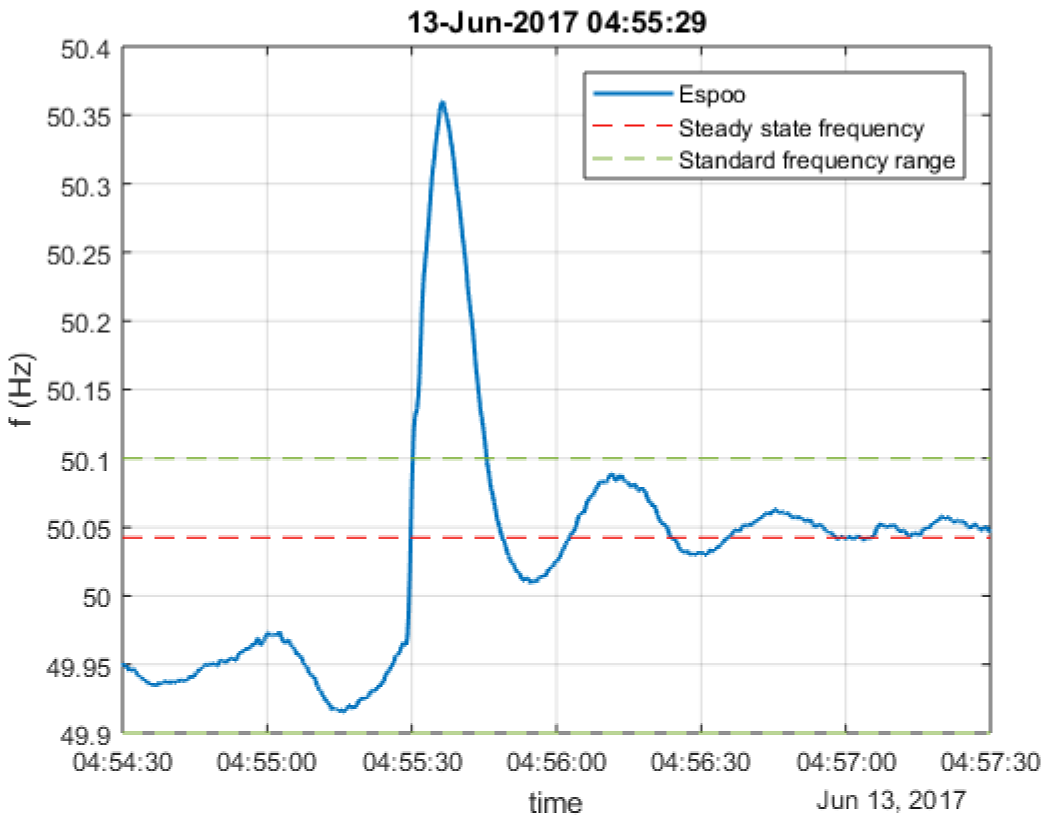


Table 4.3. Disturbance 13-Jun-2017 04:55:29

Date		**13-Jun-2017 04:55:29**	
f_{start}	49.969 Hz	$f_{steady\ state}$	50.042 Hz
$f_{extreme}$	50.360 Hz	$\Delta f_{steady\ state}$	0.074 Hz
Δf	0.391 Hz	$f_{extreme2}$	50.010 Hz
Δt	7.3 s	$f_{extreme3}$	50.089 Hz
ΔP	700 MW	damping	22.58 %
E_k	145 GWs	FBF	9506 MW/Hz
cause		HVDC	

***Figure 4.5**. Disturbance 27-Jun-2017 22:33:31*

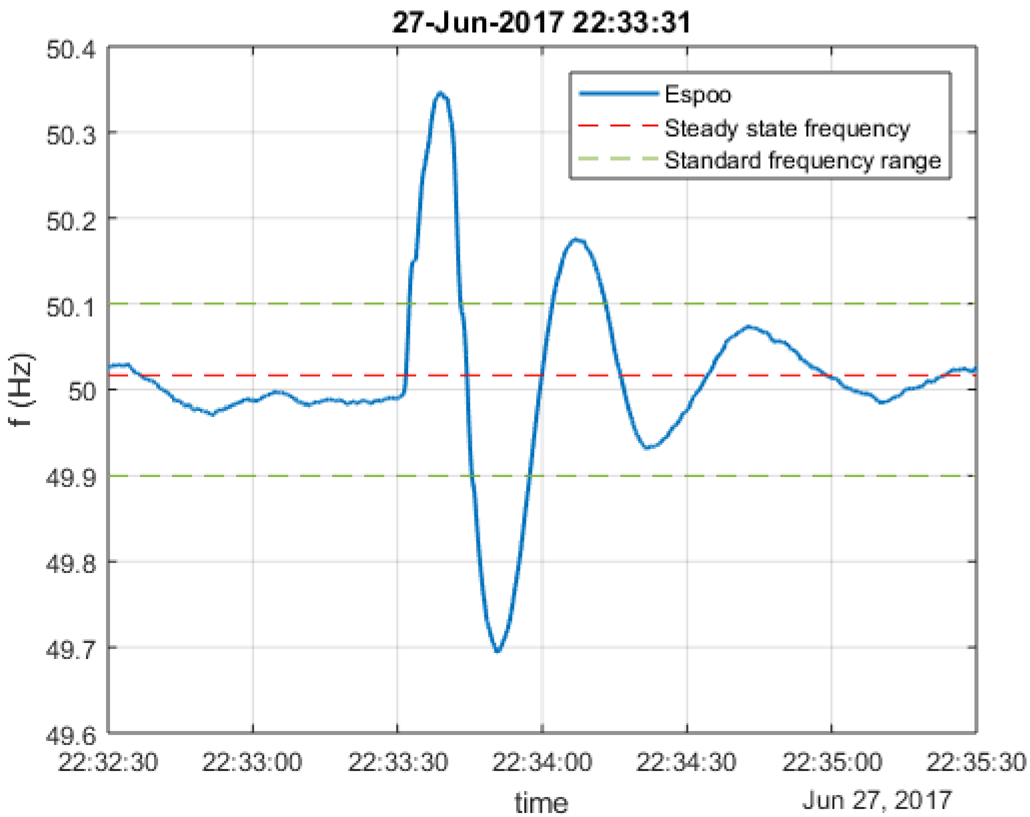


***Table 4.4**. Disturbance 27-Jun-2017 22:33:31*

Date		**27-Jun-2017 22:33:31**	
f_{start}	50.002 Hz	$f_{steady\ state}$	50.017 Hz
$f_{extreme}$	50.346 Hz	$\Delta f_{steady\ state}$	0.014 Hz
Δf	0.344 Hz	$f_{extreme2}$	49.695 Hz
Δt	7.4 s	$f_{extreme3}$	50.175 Hz
ΔP	700 MW	damping	73.71 %
E_k	172 GWs	FBF	48562 MW/Hz
cause		HVDC	

***Figure 4.6**. Disturbance 14-Jul-2017 16:04:42*

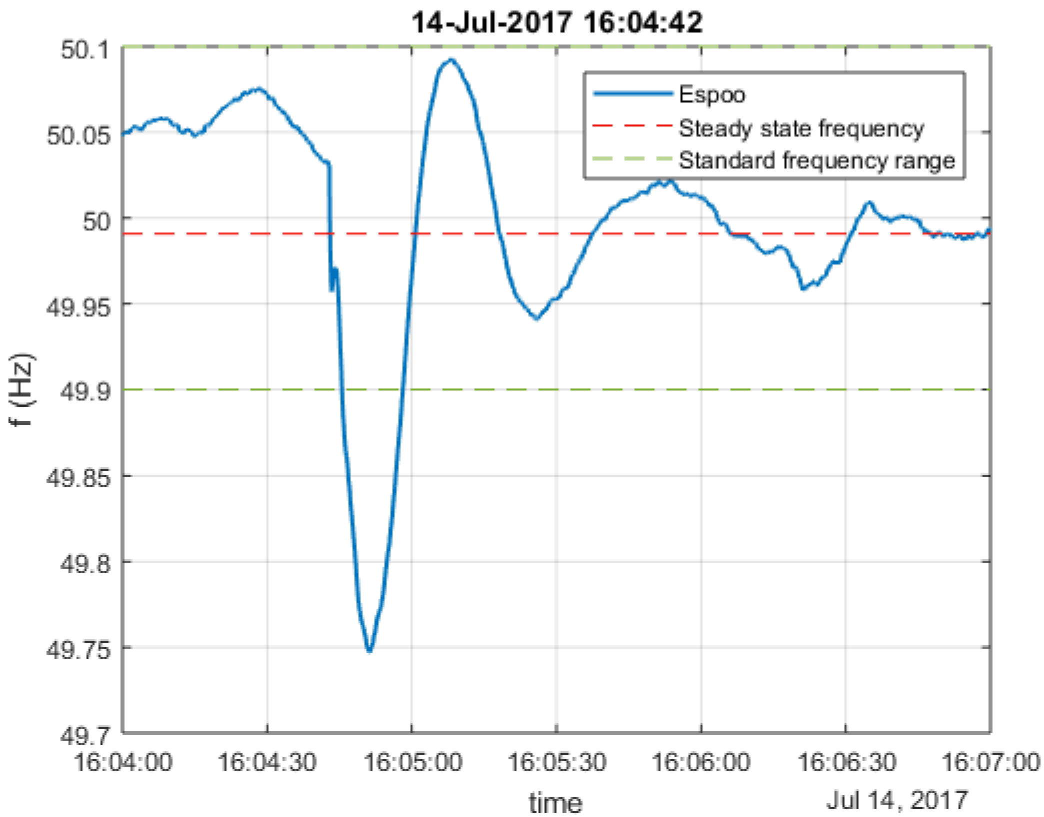


***Table 4.5**. Disturbance 14-Jul-2017 16:04:42*

Date		**14-Jul-2017 16:04:42**	
f_{start}	50.028 Hz	$f_{steady\ state}$	49.991 Hz
$f_{extreme}$	49.748 Hz	$\Delta f_{steady\ state}$	0.037 Hz
Δf	-0.281 Hz	$f_{extreme2}$	50.093 Hz
Δt	8.4 s	$f_{extreme3}$	49.941 Hz
ΔP	578 MW	damping	43.92 %
E_k	185 GWs	FBF	15466 MW/Hz
cause		Nuclear	

***Figure 4.7**. Disturbance 23-Jul-2017 21:28:50*

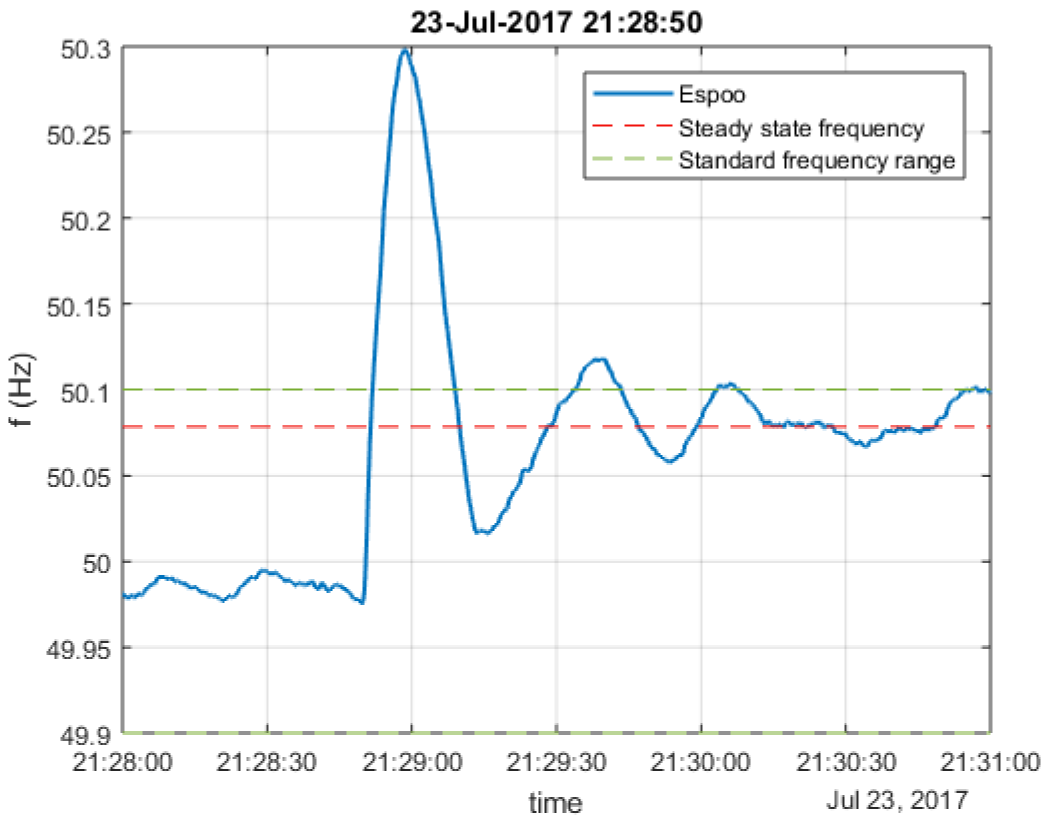


***Table 4.6**. Disturbance 23-Jul-2017 21:28:50*

Date		**23-Jul-2017 21:28:50**	
f_{start}	49.982 Hz	$f_{steady\ state}$	50.079 Hz
$f_{extreme}$	50.298 Hz	$\Delta f_{steady\ state}$	0.097 Hz
Δf	0.316 Hz	$f_{extreme2}$	50.016 Hz
Δt	8.4 s	$f_{extreme3}$	50.118 Hz
ΔP	730 MW	damping	36.07 %
E_k	174 GWs	FBF	7560 MW/Hz
cause		HVDC	

***Figure 4.8**. Disturbance 24-Jul-2017 13:00:11*

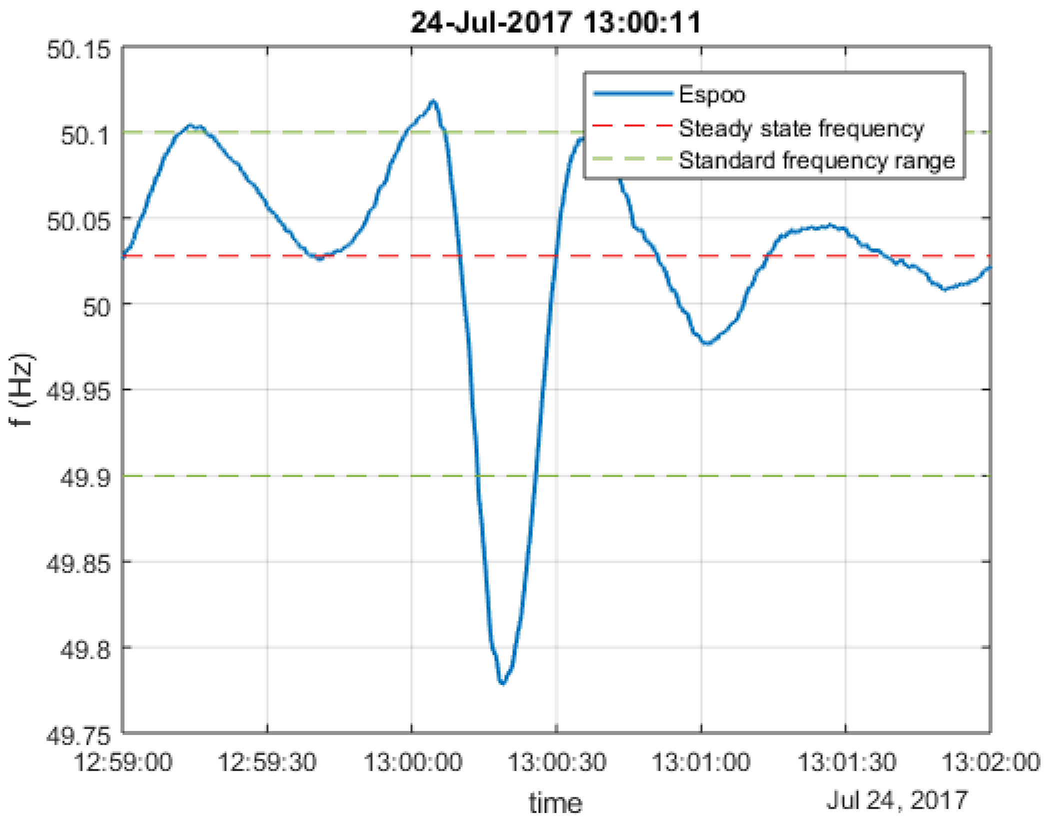


***Table 4.7**. Disturbance 24-Jul-2017 13:00:11*

Date		**24-Jul-2017 13:00:11**	
f_{start}	49.977 Hz	$f_{steady\ state}$	50.028 Hz
$f_{extreme}$	49.778 Hz	$\Delta f_{steady\ state}$	0.051 Hz
Δf	-0.198 Hz	$f_{extreme2}$	50.102 Hz
Δt	7.0 s	$f_{extreme3}$	49.976 Hz
ΔP	600 MW	damping	38.77 %
E_k	186 GWs	FBF	11766 MW/Hz
cause		Nuclear	

Figure 4.9. Disturbance 02-Sep-2017 18:53:17

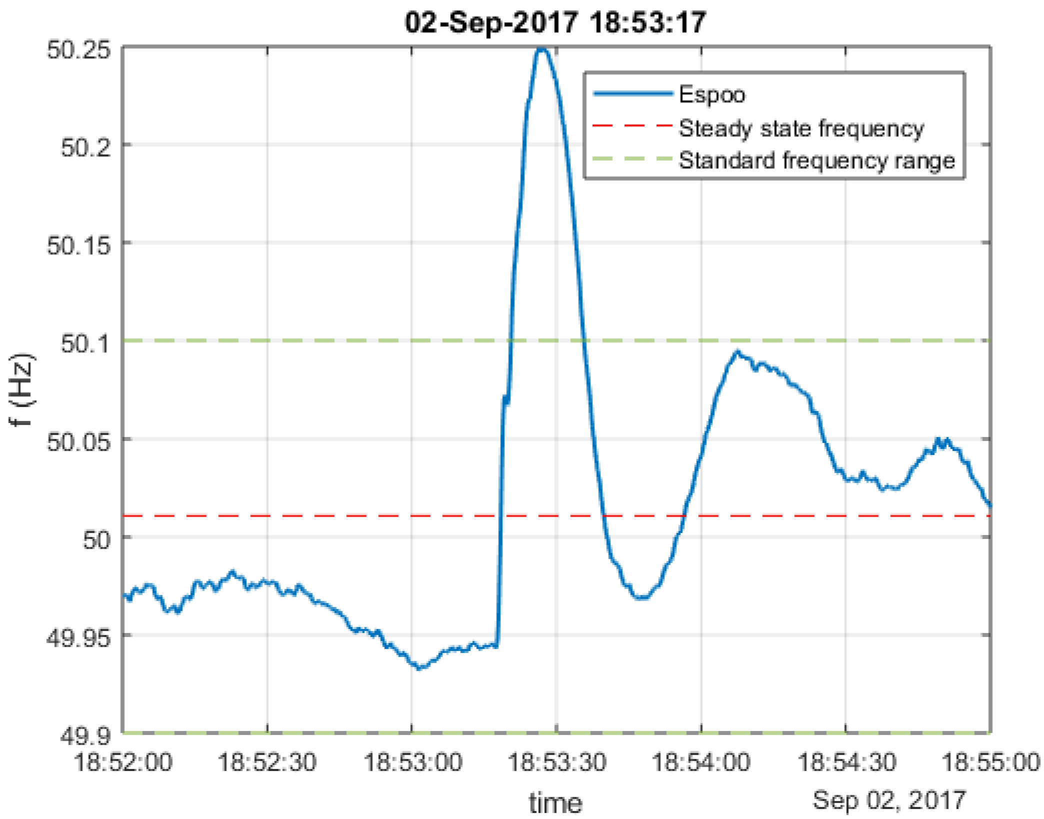


Table 4.8. Disturbance 02-Sep-2017 18:53:17

Date		02-Sep-2017 18:53:17	
f_{start}	49.950 Hz	$f_{steady\ state}$	50.011 Hz
$f_{extreme}$	50.249 Hz	$\Delta f_{steady\ state}$	0.061 Hz
Δf	0.298 Hz	$f_{extreme2}$	49.968 Hz
Δt	9.3 s	$f_{extreme3}$	50.095 Hz
ΔP	620 MW	damping	45.07 %
E_k	168 GWs	FBF	10239 MW/Hz
cause		HVDC	

***Figure 4.10**. Disturbance 08-Nov-2017 16:49:09*

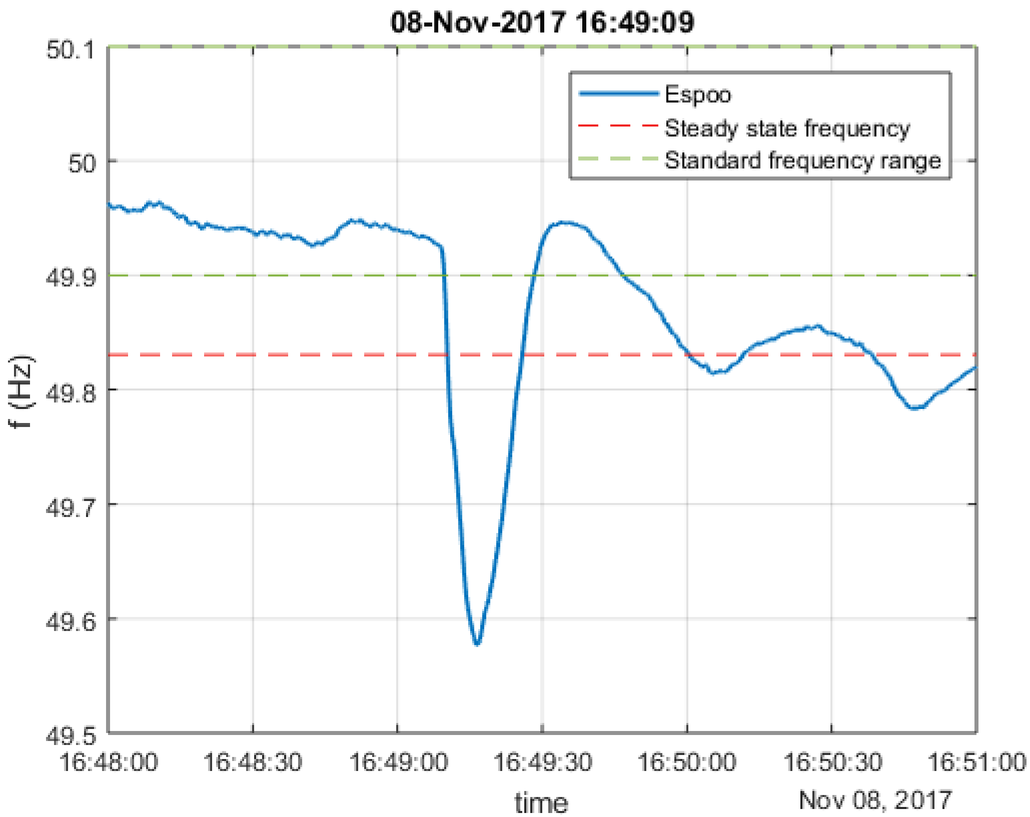


***Table 4.9**. Disturbance 08-Nov-2017 16:49:09*

Date		**08-Nov-2017 16:49:09**	
f_{start}	49.919 Hz	$f_{steady\ state}$	49.830 Hz
$f_{extreme}$	49.577 Hz	$\Delta f_{steady\ state}$	0.089 Hz
Δf	-0.342 Hz	$f_{extreme2}$	49.946 Hz
Δt	7.2 s	$f_{extreme3}$	49.814 Hz
ΔP	1100 MW	damping	35.78 %
E_k	233 GWs	FBF	12408 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 2017. The overall quality of frequency was better than in the previous year of 2016 and otherwise in line with the quality of the rest of the years examined in this report. There was a noticeable improvement on the overall time when the frequency was outside 49.8-50.2 Hz when compared to previous years.

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 2017 The frequency was outside the standard frequency range the most in March and October. February and December had the best quality of all months in 2017. Typically frequency has stayed within the standard frequency range better at weekends than during the weekdays. This was the case in 2017 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 2017 has been similar to the levels of the previous years. The mean value of oscillation was highest in June and August and the standard deviation in June and July. During the past years the frequency has oscillated less during winter and more from spring to autumn. Year 2017 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 8 frequency disturbances in 2017, where the deviation exceeded 300 mHz. All the disturbances were caused by failures in either HVDC links or nuclear power plants, with HVDC links being slightly more common cause. The amount of frequency deviations exceeding 300 mHz has decreased when compared to the two previous years when there were around 20 disturbances annually.

Chapter 6. Sources

[1] Frequency measurement data, Fingrid Oyj, available at www.fingrid.fi (Power system -> Power system management -> Maintenance of power and balance -> Frequency measurement data)

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