Frequency quality analysis

2016

FINGRID

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Chapter 1. Introduction

This report presents results of frequency quality study of the Nordic synchronous system for the year 2016. 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 10 000 minutes. 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 several PMUs at different locations. For every hour, measurements from PMU with the most amount of available data was used. It is assumed that these measurement values represent 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 2016 is presented in Table 2.1. Availability of data per year for years 2011 to 2016 can be seen in Table 2.2 [2,3,4,5,6]. In 2016 there were valid measurement data for 99.37 % of the time. Some of the data is missing due to telecommunication errors. There were two gaps in the measurement data caused by these errors, which lasted more than half an hour. Both of them took place in June, 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 2016

Month	Available data
January	99.90 %
February	99.89 %
March	99.84 %
April	99.98 %
May	99.96 %
June	93.31 %
July	99.96 %
August	99.97 %
September	99.99 %
October	99.86 %
November	99.90 %
December	99.84 %

Table 2.2. The amount of valid measurement data available for years 2011-2016

Year	**Available data**
2011	95.36 %
2012	99.78 %
2013	92.14 %
2014	99.89 %
2015	99.91 %
2016	99.37 %

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.

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) and 131(b) (i) (1 and 2).

3.1.1 Average frequency

The following figures show the average frequency for the year 2016. 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 month in March, the average has been less than 1 mHz from 50 Hz.

Figure 3.1**. **Average frequency for each month in 2016

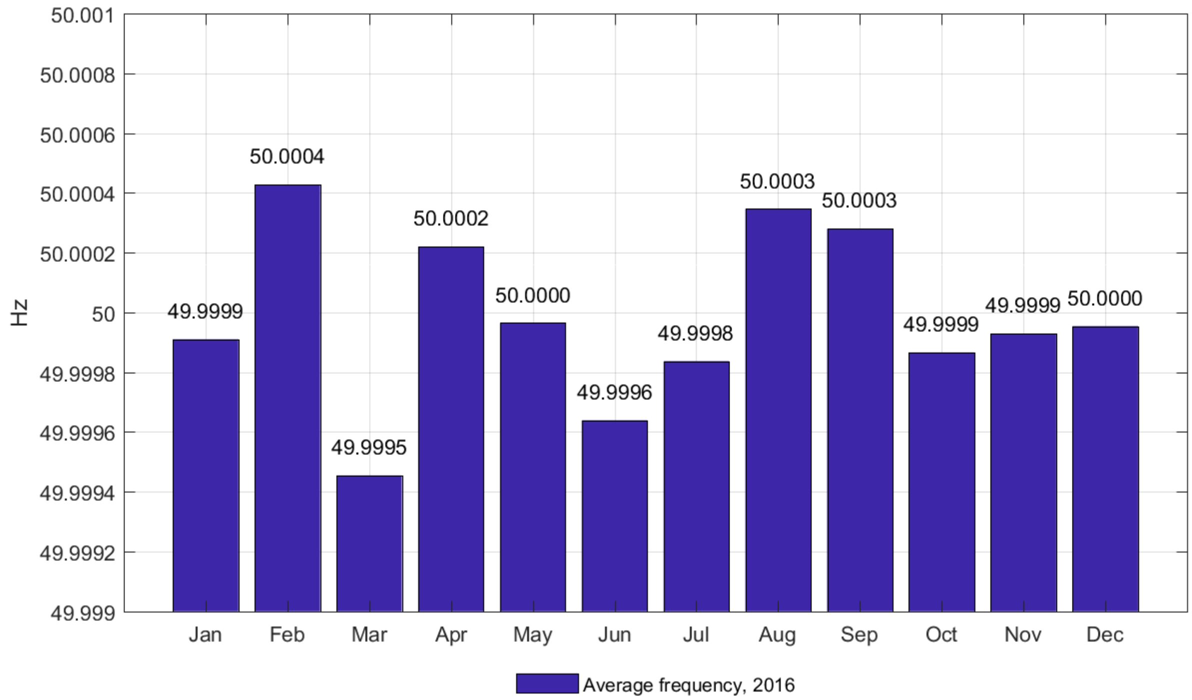


Figure 3.2 represents the average frequencies for every day of the week. On average, the frequency has been lower on the weekends and the highest on Mondays.

Figure 3.2*. *Average frequency for each day of the week in 2016

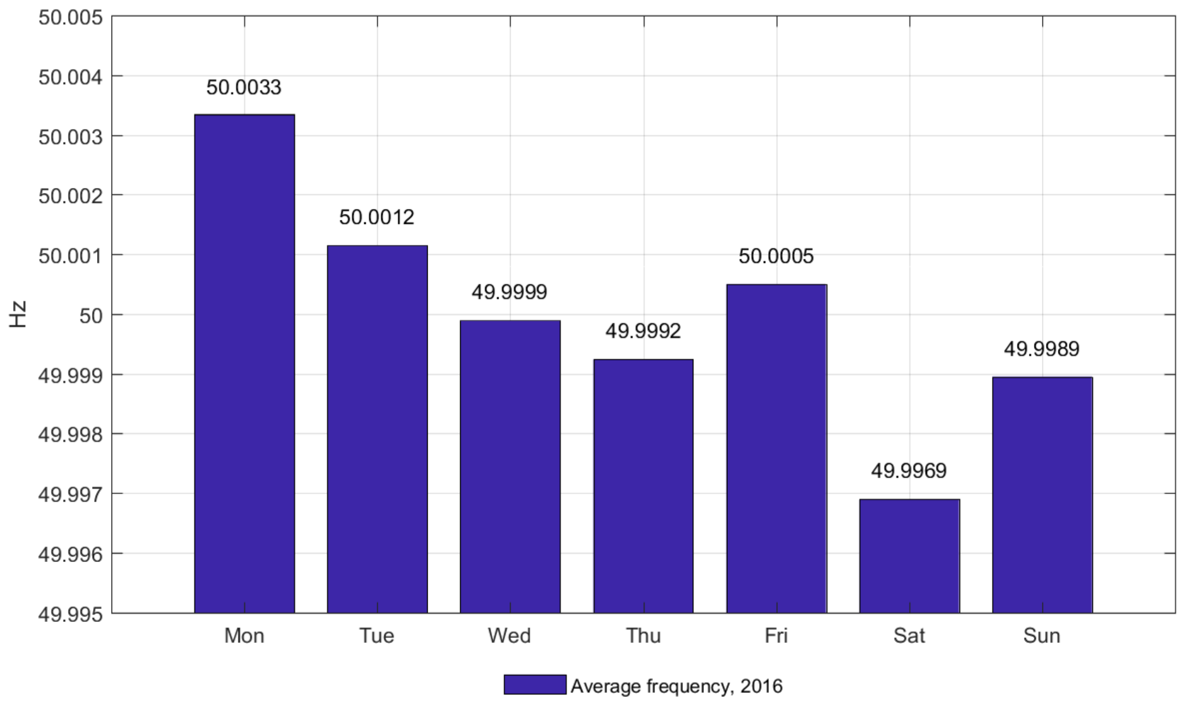


Figure 3.3 shows the average frequencies during each hour of the day. Frequency is generally lower during the night in hours from 2 a.m. to 5 a.m. The frequency is at its highest during the evenings and around midnight.

Figure 3.3**. **Average frequency for each hour of the day in 2016

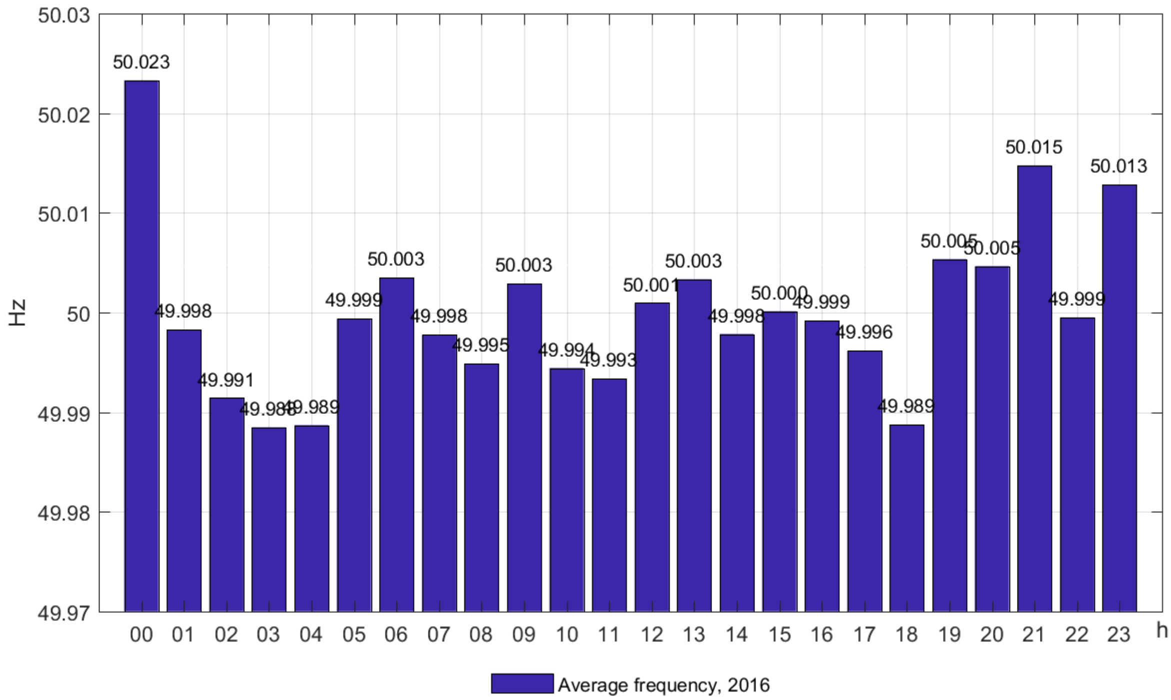
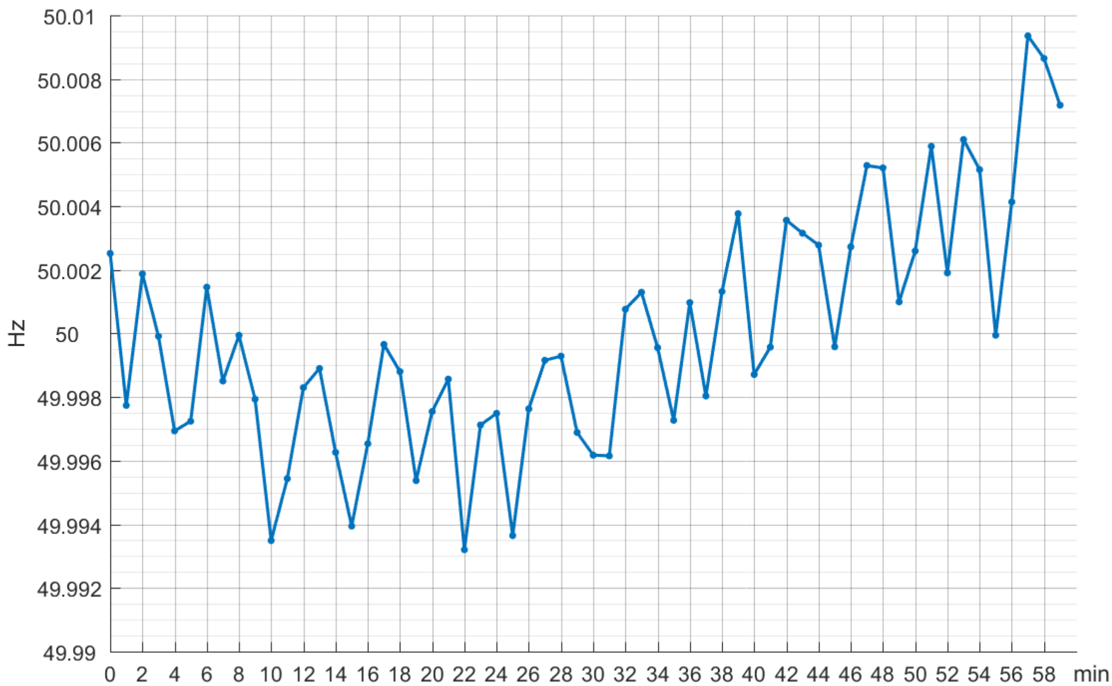


Figure 3.4 shows the average frequency inside the hour. In general the frequency is higher in the latter part of the hour. The difference between consecutive minutes is mostly between 2-4 mHz

Figure 3.4**. **Average frequency for each minute of the hour in 2016



3.1.2 Standard deviation

This section includes the figures representing the standard deviation of frequency during the year 2016. 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 2016. The lower standard deviation in November and December indicates that the 1 second values were in average closer to 50 Hz during those months. In April and May the standard deviation was slightly higher than during other months.

***Figure 3.5**. Standard deviation of the frequency for every month in 2016*

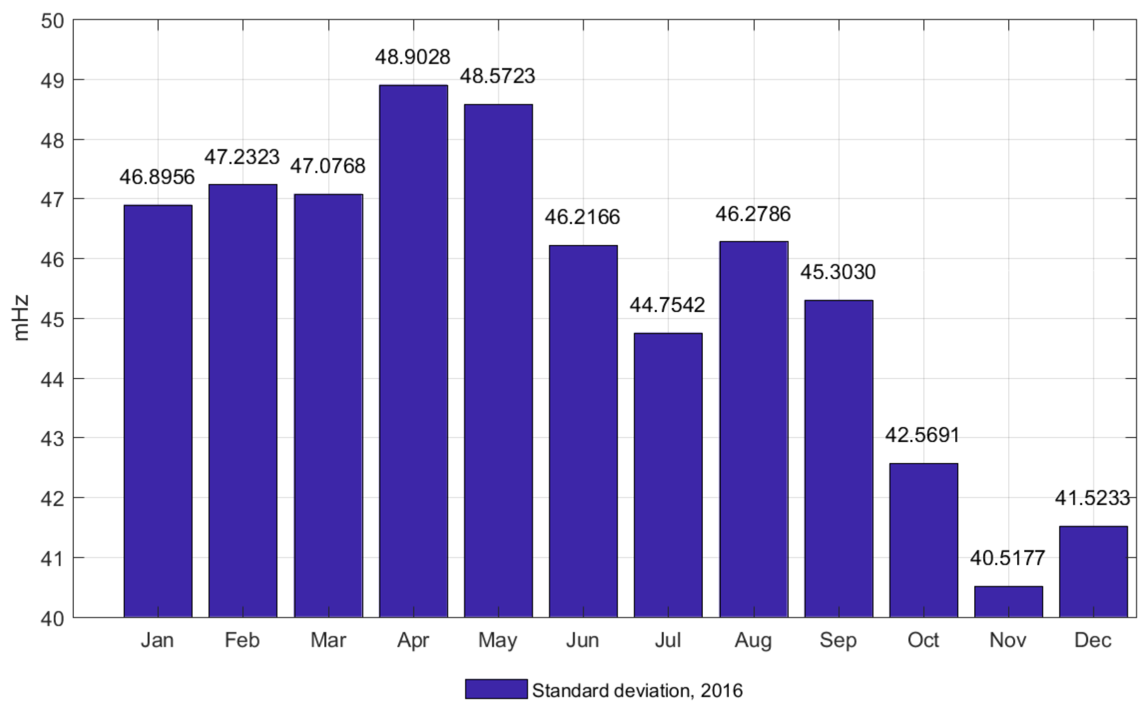


Figure 3.6 represents the standard deviation for every day of the week. Based on standard deviation, the quality of the frequency improves slightly each day from the start of the week to the end except for Wednesdays when the standard deviation is at its highest.

***Figure 3.6**. Standard deviation of the frequency for every day of the week in 2016*

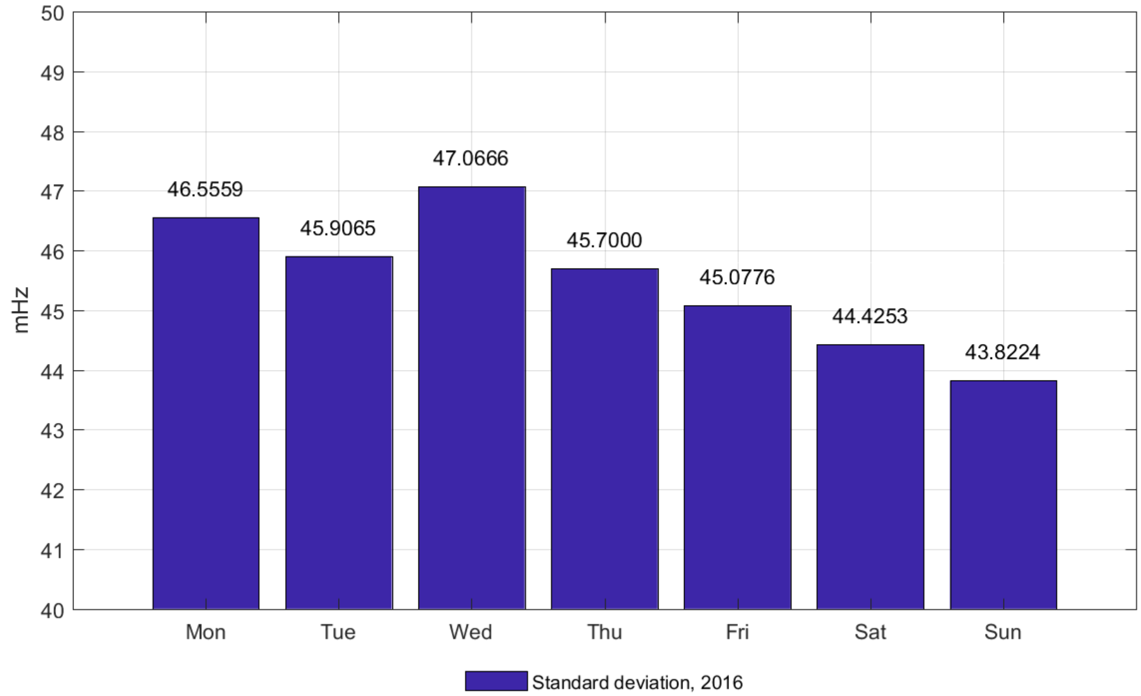


Figure 3.7 shows the standard deviation during a day. The standard deviation can vary over 10 mHz from the lowest values during night to the highest points around midnight and in the morning.

***Figure 3.7**. Standard deviation of the frequency for every hour of the day in 2016*

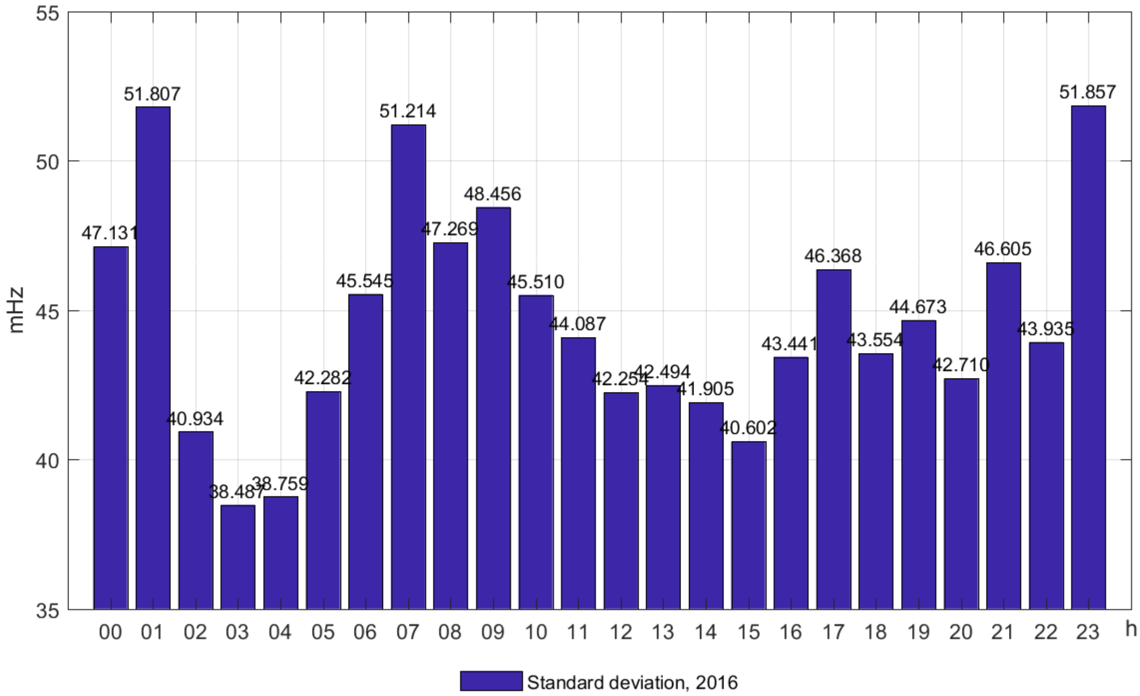
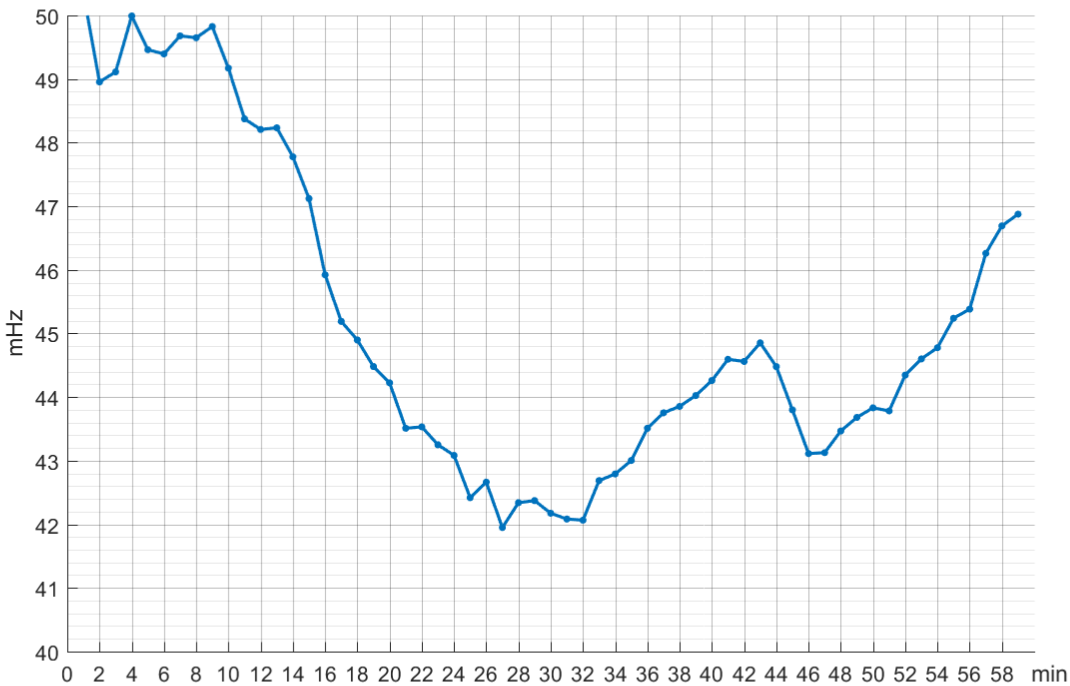


Figure 3.8 represents the standard deviation inside one hour. The standard deviation is at its highest in the beginning of the hour. From the 10th minute the standard deviation starts to drop until the half hour mark from where it starts to climb up again.

Figure 3.8**. **Standard deviation of the frequency for every minute of the hour in 2016



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 2011 to 2016 can be found in Table 3.1 and Table 3.2. Same results are also presented in Figure 3.9.

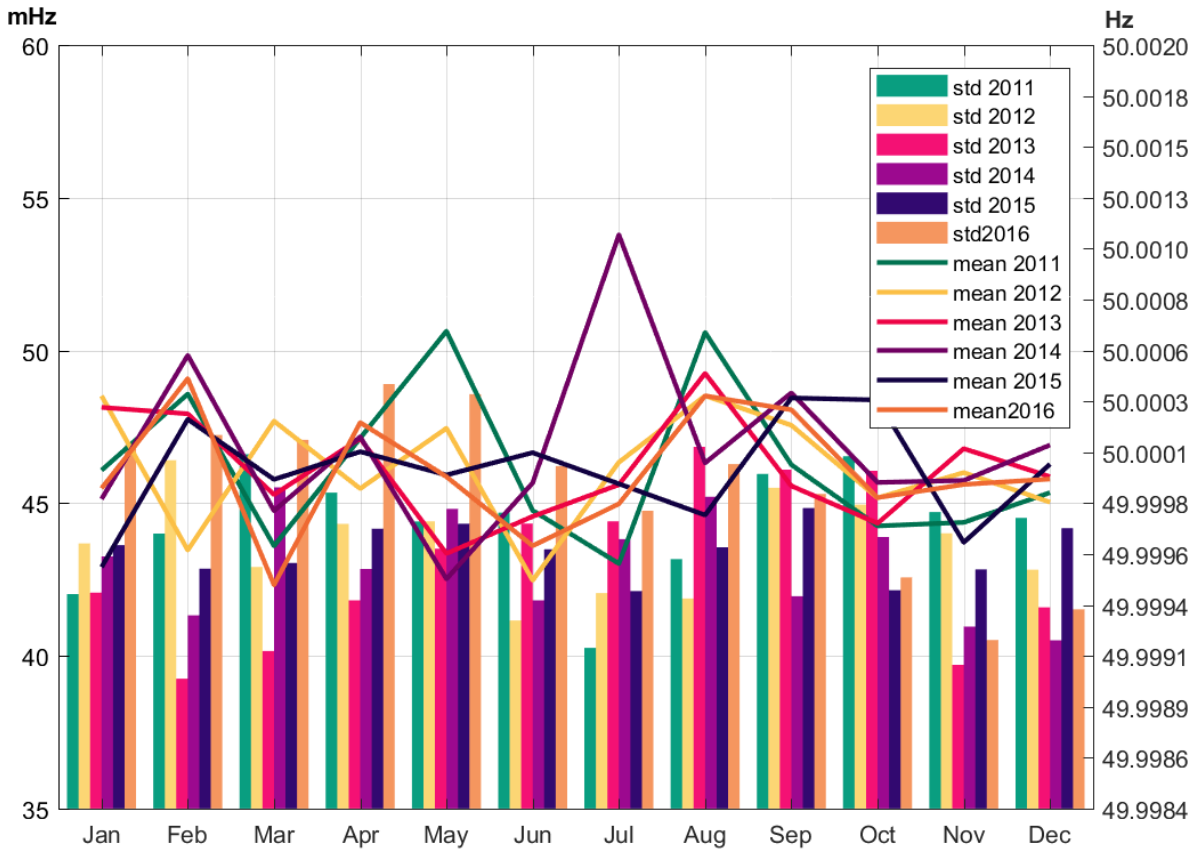
Table 3.1. Mean values and standard deviations for years 2011-2013

	2011		**2012**		**2013**	
Month	**Mean value (Hz)**	**Standard deviation (mHz)**	**Mean value (Hz)**	**Standard deviation (mHz)**	**Mean value (Hz)**	**Standard deviation (mHz)**
January	50.0000	42.0	50.0003	43.7	50.0003	42.1
February	50.0004	44.0	49.9996	46.4	50.0003	39.3
March	49.9996	46.6	50.0002	42.9	49.9999	40.2
April	50.0001	45.3	49.9999	44.3	50.0001	41.8
May	50.0007	44.4	50.0002	44.4	49.9996	43.5
June	49.9998	44.7	49.9995	41.2	49.9998	44.3
July	49.9996	40.3	50.0000	42.1	49.9999	44.4
August	50.0006	43.2	50.0003	41.9	50.0005	46.8
September	50.0000	46.0	50.0002	45.5	49.9999	46.1
October	49.9997	46.5	49.9999	45.0	49.9997	46.1
November	49.9997	44.7	50.0000	44.0	50.0001	39.7
December	49.9999	44.5	49.9998	42.8	50.0000	41.6
Entire year	**50.0000**	**44.4**	**50.0000**	**43.7**	**50.0000**	**43.2**

Table 3.2. Mean values and standard deviations for years 2014-2016

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

Figure 3.9. ***Mean values and standard deviations for years 2011-2016***

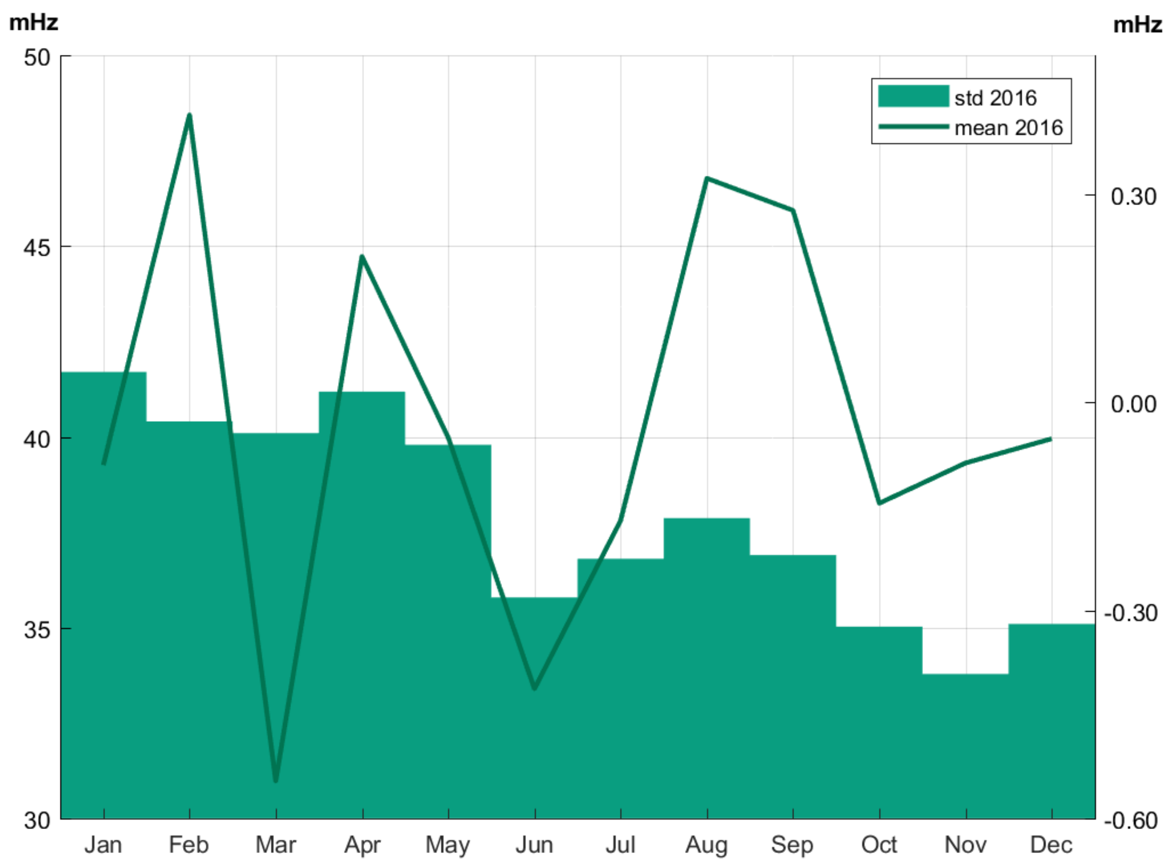


Mean values and standard deviations for frequency deviations as per Article 131(b) (i) for year 2016 can be found in Table 3.3. Results show how much frequency has deviated from nominal 50 Hz value. Visual representation can be found in Figure 3.10.

Table 3.3. Mean values and standard deviations for year 2016

	2016	
Month	**Mean value (mHz)**	**Standard deviation (mHz)**
January	-0.091	41.7
February	0.414	40.4
March	-0.546	40.1
April	0.210	41.2
May	-0.051	39.8
June	-0.413	35.8
July	-0.171	36.8
August	0.323	37.9
September	0.276	36.9
October	-0.146	35.0
November	-0.088	33.8
December	-0.053	35.1
Entire year	**-0.028**	**37.9**

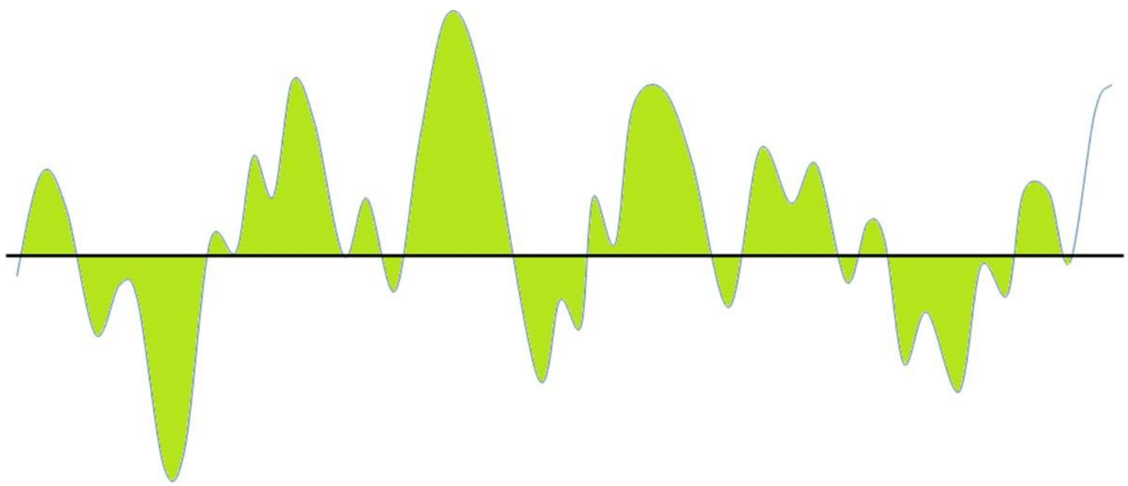
***Figure 3.10**. Mean values and standard deviations for year 2016*



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.

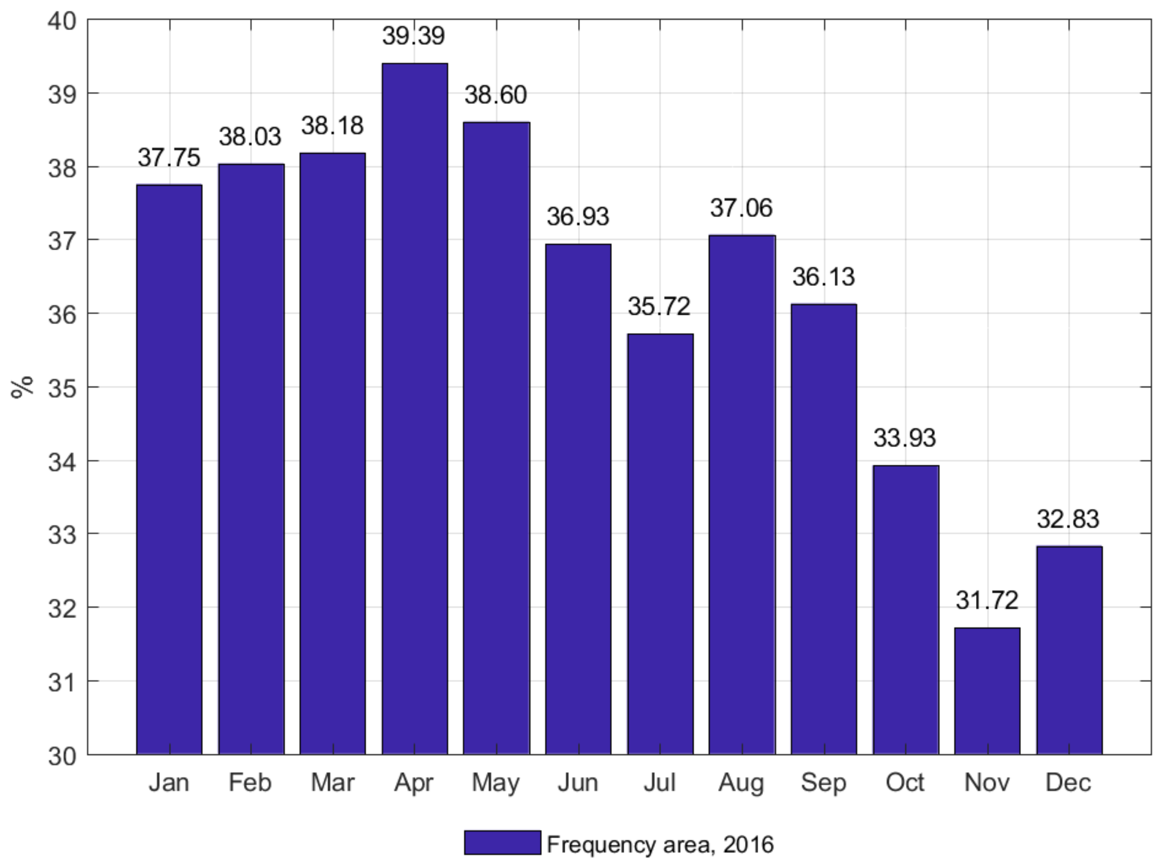
Figure 3.11*. *Frequency quality index: Frequency area [7]



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

Figure 3.12 represents the average frequency area for every month in 2016. The percentage of the area was considerably smaller later 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 2016



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 weekends.

Figure 3.13. The average frequency area for every day of the week in 2016

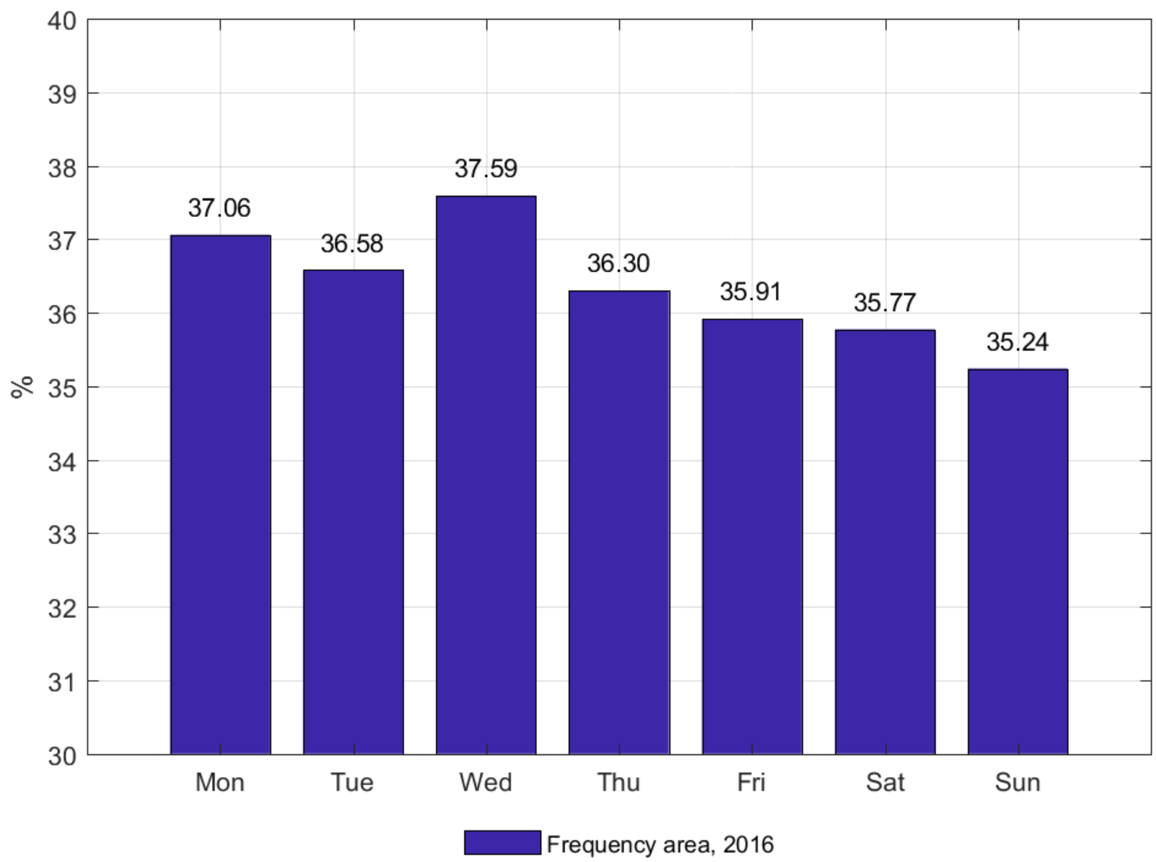


Figure 3.14 has the frequency area for every hour during the day. The figure shows that the deviation of the frequency from 50.0 Hz was smaller in the middle of the night and after noon. The area was at its highest in the first and last hour of the day.

***Figure 3.14**. The average frequency area for every hour inside the day in 2016*

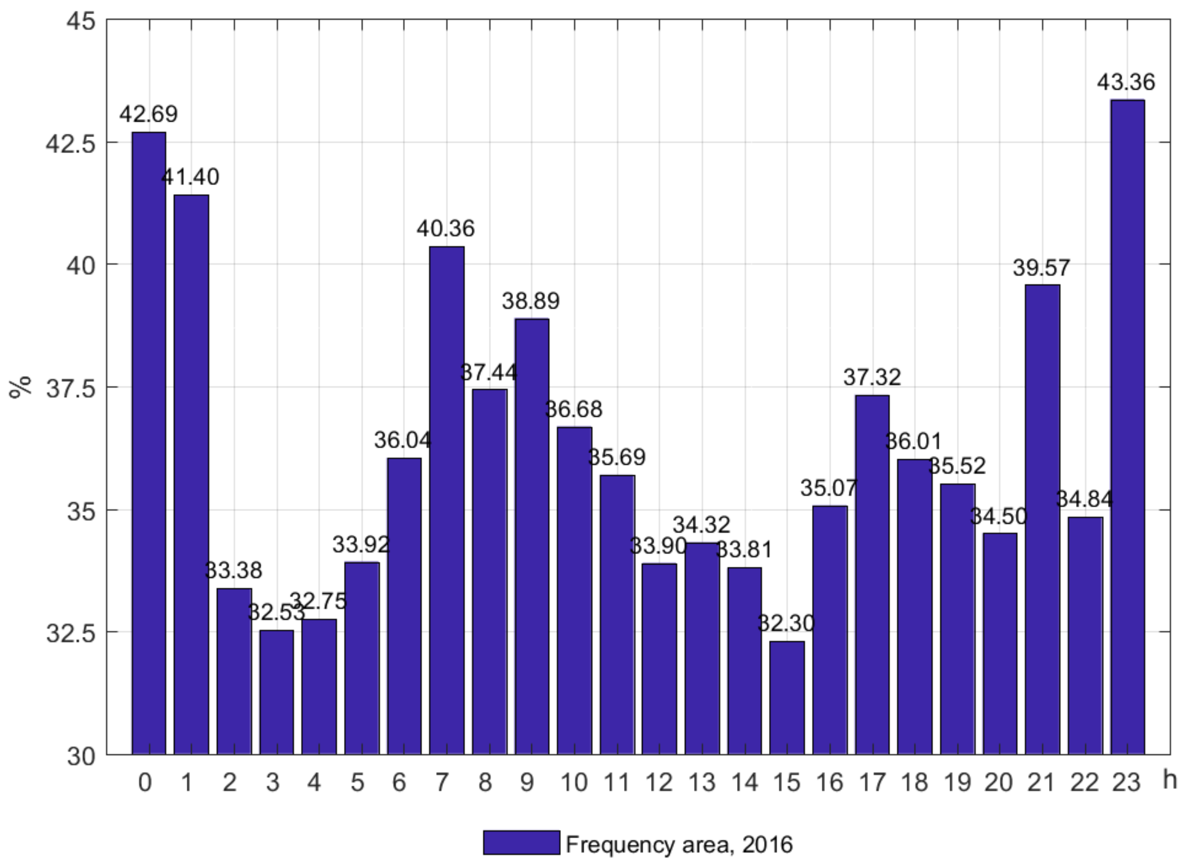
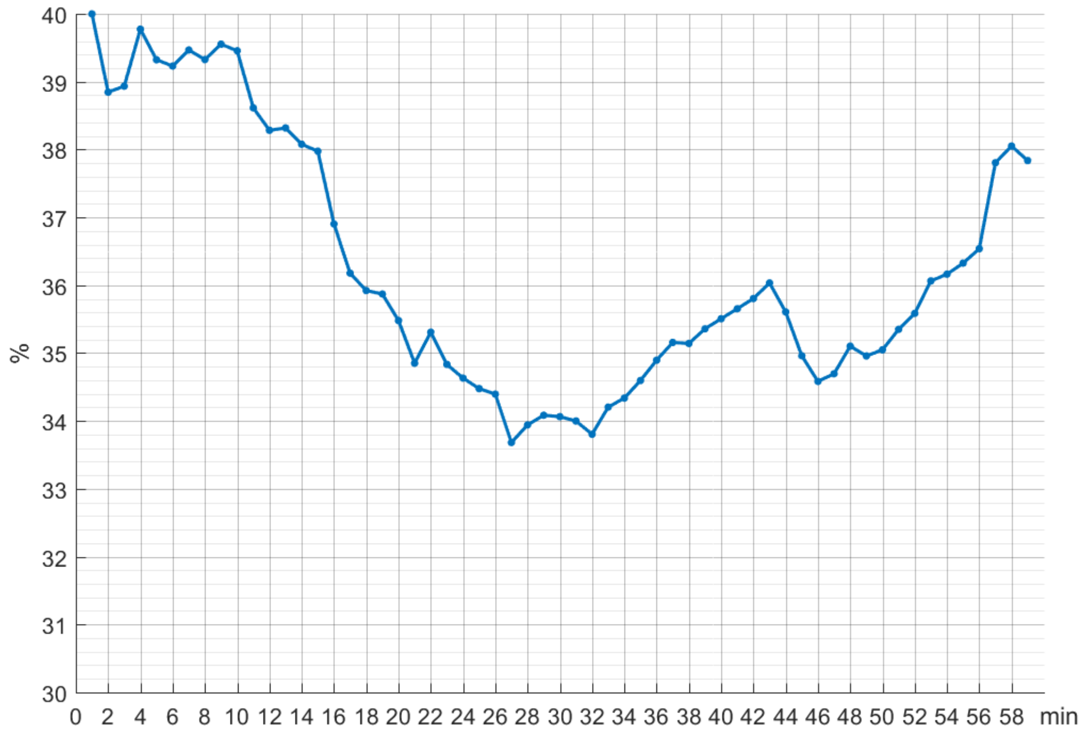


Figure 3.15 represents the frequency area within the hour. The percentage of the frequency area was smaller in the middle of the hour while more deviation occured closer the hour shift.

***Figure 3.15**. The average frequency area for every minute within the hour in 2016*



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 2011 to 2016. All results are summed up in Figure 3.16.

***Table 3.4**. The 1st, 5th, 10th, 90th, 95th and 99th percentiles for year 2011*

	2011					
Month	**1st (Hz)**	**5th (Hz)**	**10th (Hz)**	**90th (Hz)**	**95th (Hz)**	**99th (Hz)**
January	49.906	49.934	49.948	50.055	50.070	50.101
February	49.902	49.931	49.945	50.058	50.074	50.104
March	49.896	49.927	49.942	50.060	50.079	50.114
April	49.895	49.927	49.943	50.058	50.077	50.115
May	49.899	49.929	49.945	50.058	50.075	50.108
June	49.894	49.927	49.943	50.057	50.073	50.102
July	49.907	49.933	49.948	50.051	50.065	50.094
August	49.904	49.932	49.946	50.057	50.073	50.105
September	49.896	49.927	49.943	50.060	50.079	50.110
October	49.892	49.925	49.941	50.060	50.078	50.111
November	49.898	49.928	49.943	50.058	50.074	50.104
December	49.899	49.929	49.943	50.057	50.074	50.104
Entire year	**49.899**	**49.929**	**49.944**	**50.057**	**50.074**	**50.106**

Table 3.5. 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)**
January	49.904	49.931	49.945	50.058	50.074	50.103
February	49.899	49.927	49.942	50.061	50.079	50.111
March	49.901	49.930	49.945	50.055	50.071	50.102
April	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
June	49.904	49.933	49.948	50.052	50.067	50.099
July	49.905	49.931	49.946	50.054	50.069	50.099
August	49.904	49.933	49.948	50.054	50.070	50.101
September	49.897	49.928	49.943	50.059	50.077	50.113
October	49.899	49.929	49.943	50.058	50.075	50.108
November	49.896	49.927	49.943	50.056	50.073	50.102
December	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 3.6. 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)**
January	49.906	49.935	49.949	50.055	50.071	50.104
February	49.906	49.935	49.950	50.050	50.065	50.094
March	49.902	49.934	49.950	50.050	50.067	50.100
April	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
June	49.900	49.928	49.943	50.057	50.074	50.105
July	49.900	49.929	49.944	50.058	50.074	50.105
August	49.896	49.926	49.941	50.061	50.079	50.111
September	49.894	49.927	49.942	50.060	50.077	50.110
October	49.895	49.928	49.944	50.059	50.078	50.115
November	49.909	49.936	49.950	50.051	50.067	50.096
December	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 3.7. 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)**
January	49.902	49.930	49.944	50.055	50.071	50.101
February	49.904	49.932	49.948	50.053	50.068	50.097
March	49.893	49.926	49.942	50.058	50.075	50.106
April	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
June	49.902	49.931	49.946	50.053	50.068	50.096
July	49.900	49.930	49.945	50.058	50.072	50.102
August	49.899	49.929	49.944	50.058	50.077	50.113
September	49.908	49.934	49.948	50.055	50.071	50.103
October	49.897	49.929	49.945	50.056	50.072	50.105
November	49.903	49.932	49.947	50.052	50.066	50.094
December	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**

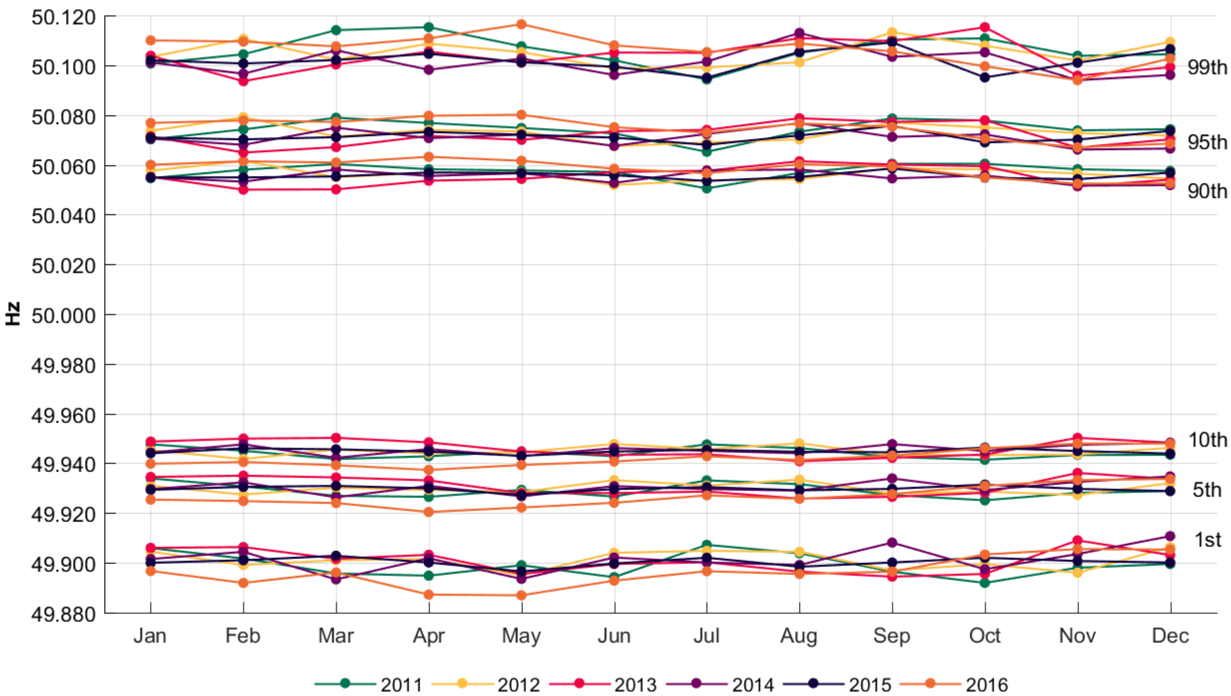
Table 3.8. The 1st, 5th, 10th, 90th, 95th and 99th percentiles for year 2015

	2015					
Month	**1st (Hz)**	**5th (Hz)**	**10th (Hz)**	**90th (Hz)**	**95th (Hz)**	**99th (Hz)**
January	49.900	49.929	49.944	50.055	50.071	50.102
February	49.901	49.931	49.946	50.055	50.070	50.101
March	49.903	49.931	49.946	50.055	50.071	50.102
April	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
June	49.900	49.930	49.945	50.056	50.071	50.099
July	49.902	49.930	49.945	50.054	50.068	50.095
August	49.898	49.929	49.945	50.055	50.072	50.105
September	49.900	49.930	49.944	50.058	50.076	50.109
October	49.902	49.931	49.946	50.055	50.069	50.095
November	49.901	49.930	49.945	50.054	50.070	50.101
December	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 3.9. 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)**
January	49.897	49.925	49.940	50.060	50.077	50.110
February	49.892	49.925	49.941	50.061	50.078	50.110
March	49.896	49.924	49.939	50.061	50.077	50.108
April	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
June	49.893	49.924	49.941	50.058	50.075	50.108
July	49.897	49.927	49.943	50.057	50.073	50.105
August	49.896	49.926	49.941	50.060	50.077	50.109
September	49.896	49.928	49.943	50.059	50.075	50.106
October	49.903	49.931	49.946	50.055	50.070	50.100
November	49.905	49.933	49.948	50.052	50.067	50.094
December	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**

***Figure 3.16**. The 1st, 5th, 10th, 90th, 95th and 99th percentiles for years 2011-2016*



More detailed results for the percentiles of 2016 are shown in the next figures. Figure 3.17 is a visual representation of the given percentiles for each month in 2016. There was more deviation in April and May, as the gap between the lower and higher percentiles was wider in those months.

Figure 3.17. The 1st, 5th, 10th, 90th, 95th and 99th percentile of the frequency for every month in 2016

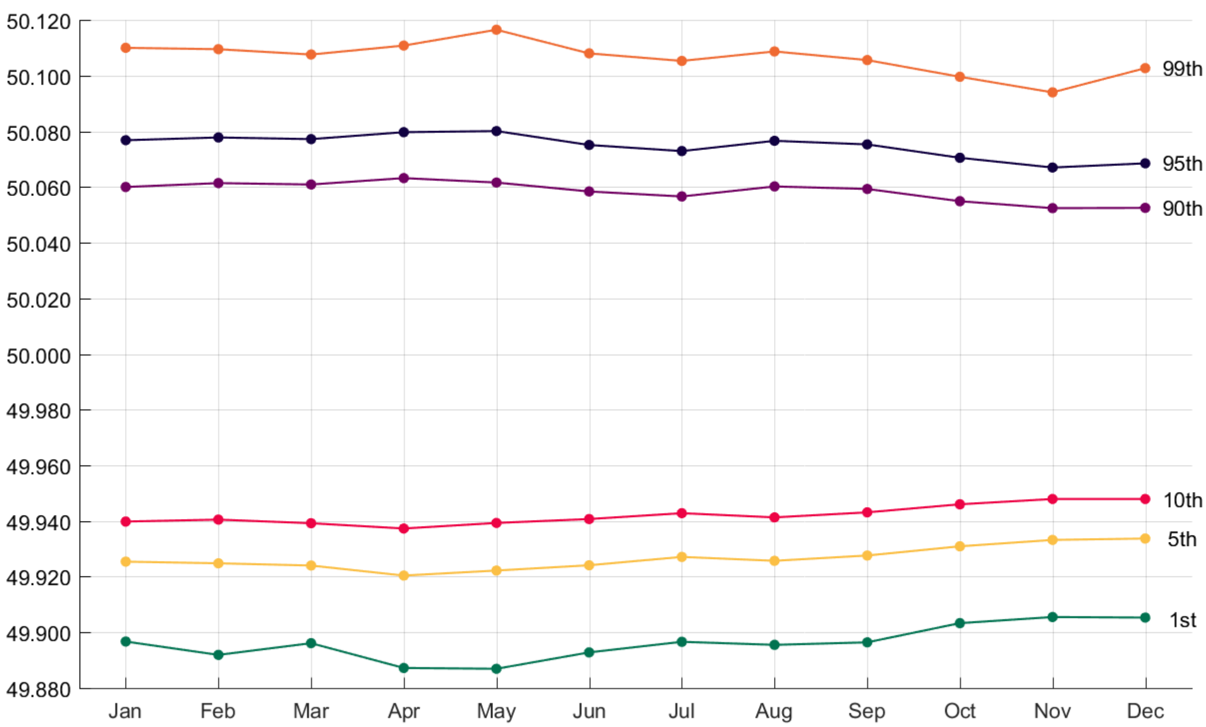


Figure 3.18 shows the percentiles for every day during the week. Percentiles above 50 were slighly lower during weekends while percentiles below 50 were higher, which indicates that the frequency was closer to 50.0 Hz during the weekends.

Figure 3.18. The 1st, 5th, 10th, 90th, 95th and 99th percentile of the frequency for every day of the week in 2016

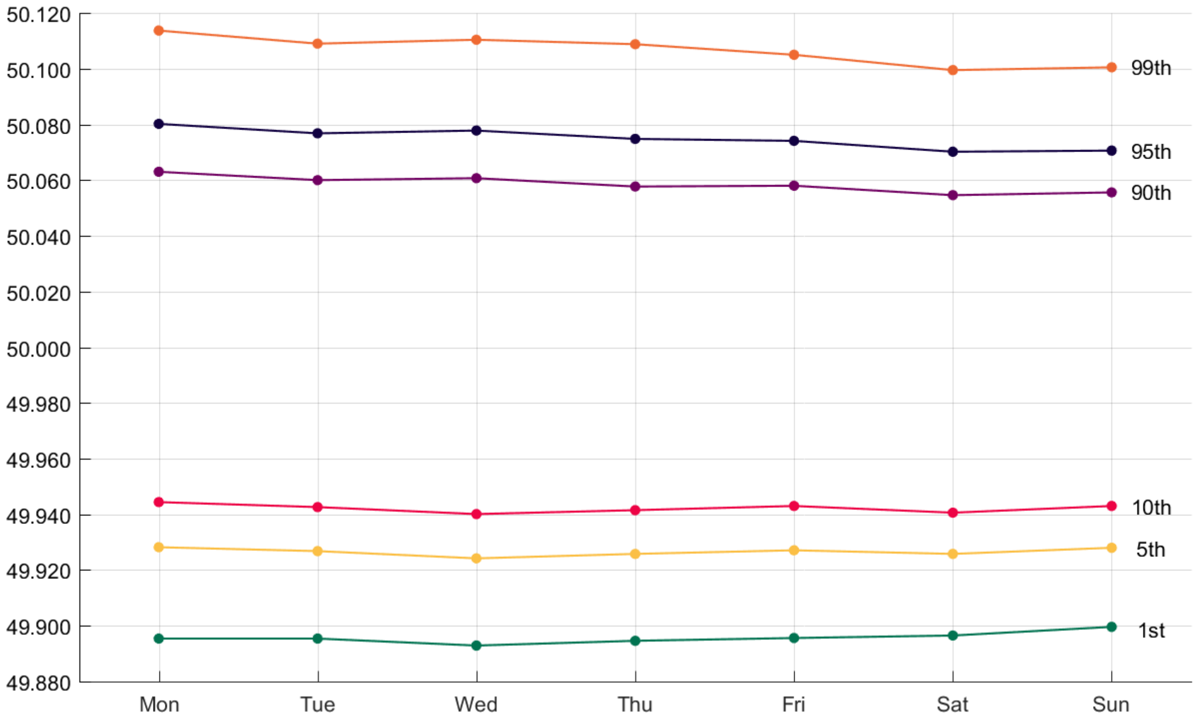
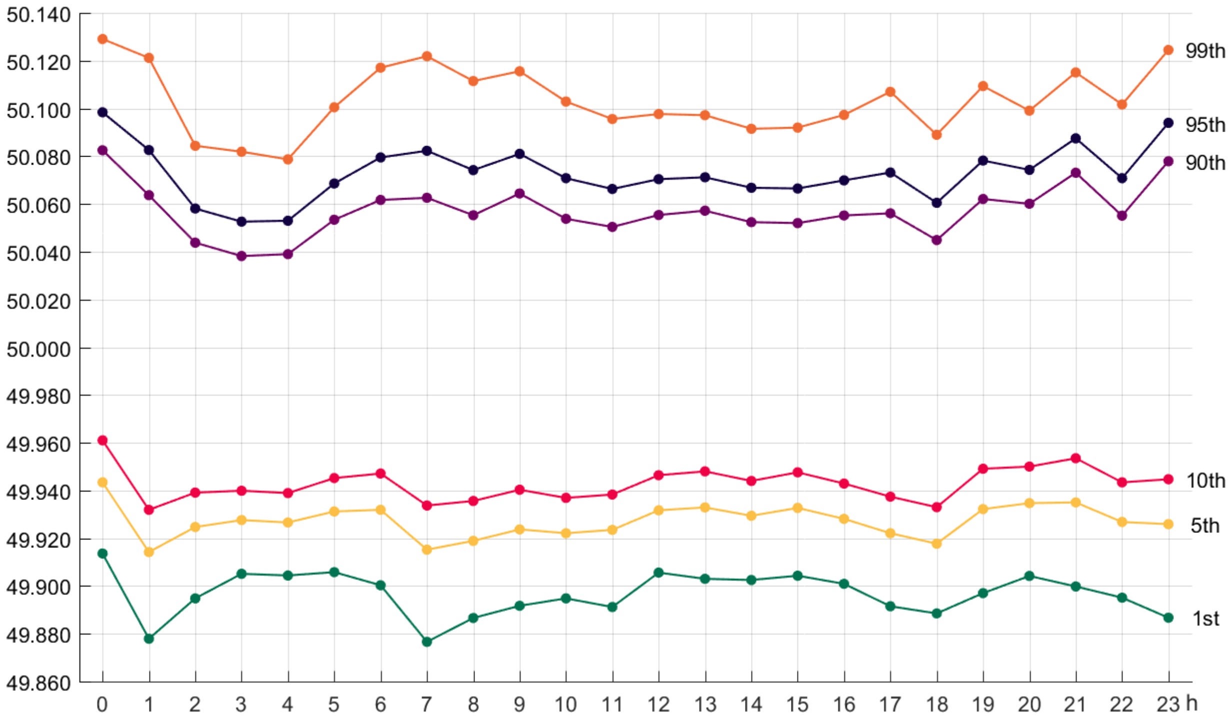


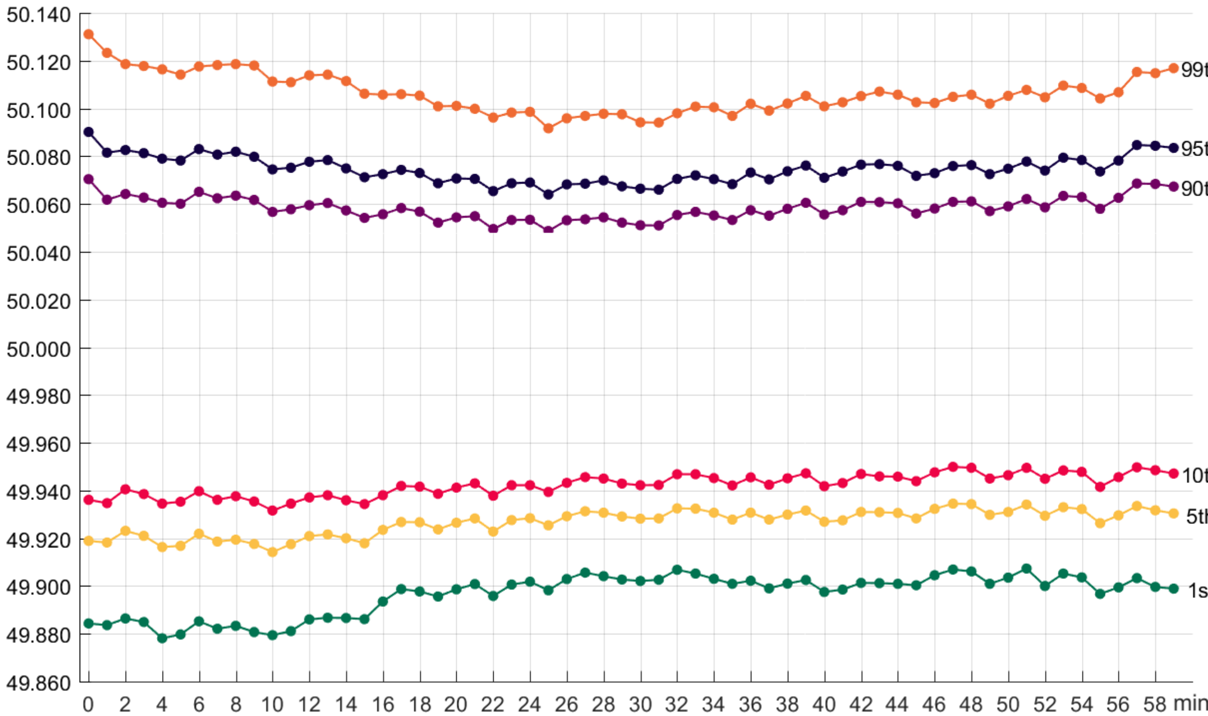
Figure 3.19 represents the percentiles inside the day. In terms of the 1st, 5th and 10th percentile, the frequencies were lower in the morning from 7 to 10 and afternoon from 16 to 18. For the 90th, 95th and 99th percentile, those hours had the highest frequencies.

Figure 3.19*. *The 1st, 5th, 10th, 90th, 95th and 99th percentile of the frequency for every hour of the day in 2016



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 2016*

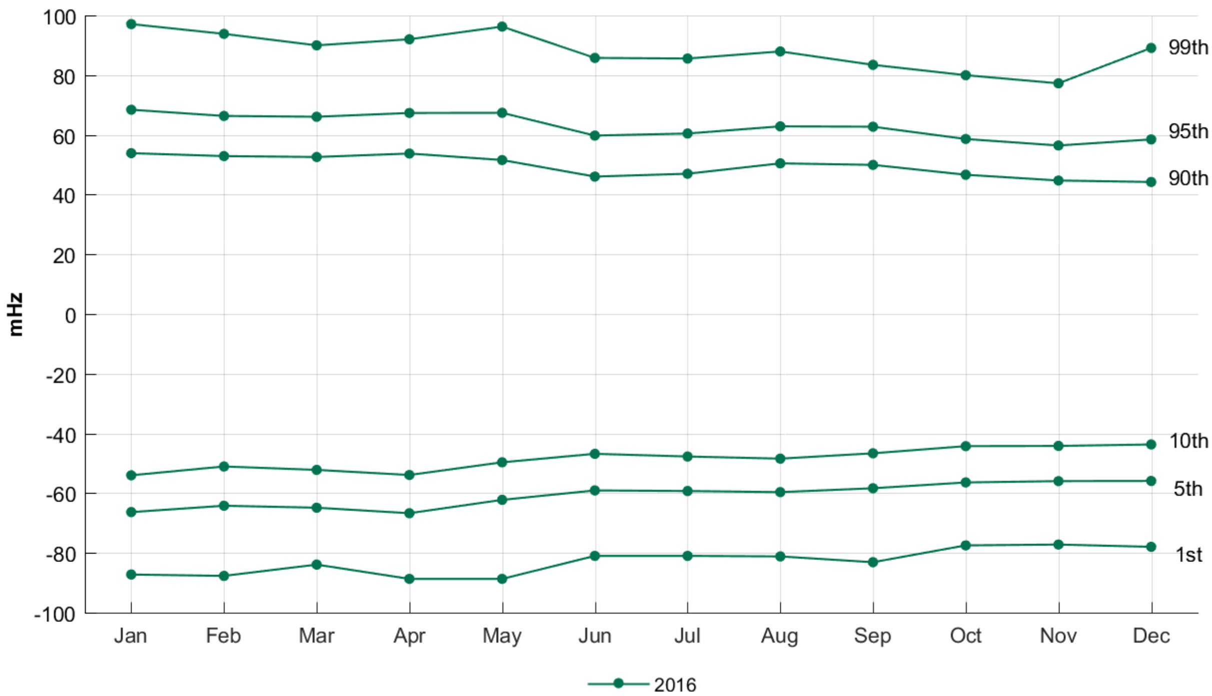


The 1st, 5th, 10th, 90th, 95th and 99th percentiles according to SO GL Article 131(b) i(3) are presented in Table 3.10. Figure 3.21 below the table shows results in graphical form. Results are deviations from nominal 50 Hz value.

***Table 3.10**. The 1st, 5th, 10th, 90th, 95th and 99th percentiles for year 2016*

	2016					
Month	**1st (mHz)**	**5th (mHz)**	**10th (mHz)**	**90th (mHz)**	**95th (mHz)**	**99th (mHz)**
January	-87.3	-66.4	-54.0	53.9	68.4	97.1
February	-87.7	-64.2	-51.1	52.9	66.4	93.8
March	-84.0	-64.9	-52.2	52.6	66.1	90.0
April	-88.7	-66.7	-53.9	53.8	67.3	92.0
May	-88.7	-62.3	-49.7	51.6	67.4	96.3
June	-81.0	-59.1	-46.9	46.0	59.8	85.8
July	-81.0	-59.3	-47.7	47.0	60.5	85.6
August	-81.2	-59.7	-48.5	50.5	62.9	88.0
September	-83.2	-58.4	-46.7	50.0	62.7	83.5
October	-77.5	-56.4	-44.3	46.7	58.6	80.0
November	-77.2	-56.0	-44.2	44.7	56.5	77.3
December	-78.0	-55.9	-43.7	44.2	58.5	89.1
Entire year	**-83.0**	**-60.8**	**-48.6**	**49.5**	**62.9**	**88.2**

***Figure 3.21**. The 1st, 5th, 10th, 90th, 95th and 99th percentiles for year 2016*



3.4 Time outside different ranges

Time outside 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 2016. The curves are fairly linear throughout the year. The frequency has been outside the standard range just over 14000 minutes, 7500 min over 50.1 Hz and 6500 min under 49.9 Hz.

Figure 3.22. Cumulative minutes outside the standard frequency range in 2016

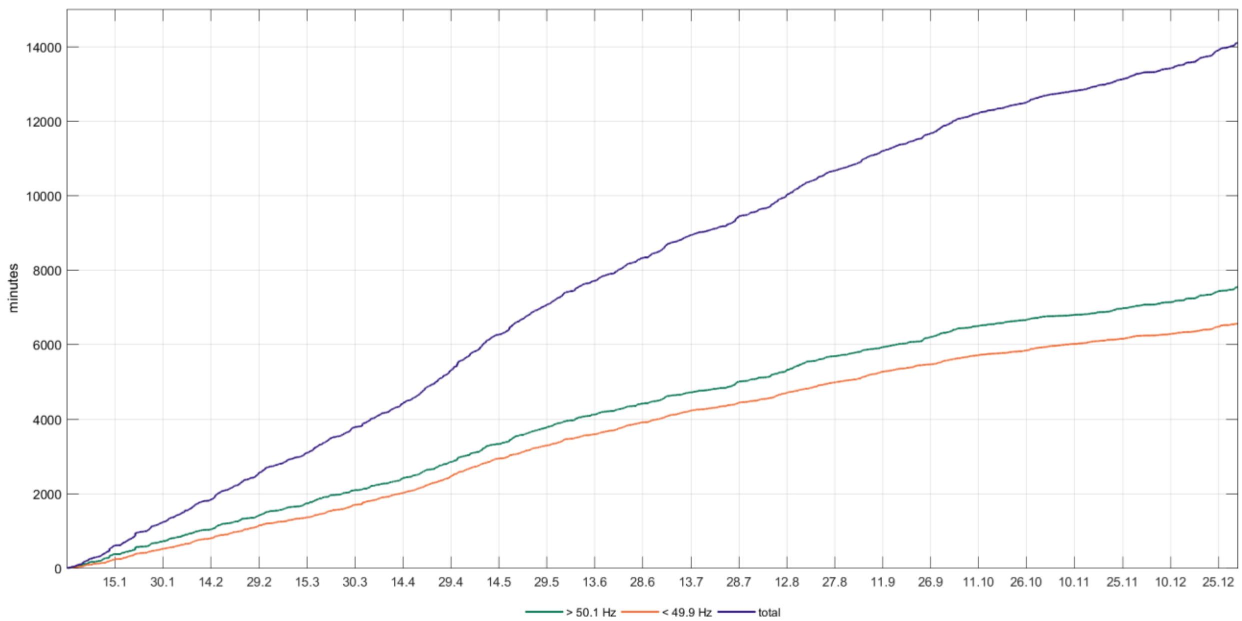
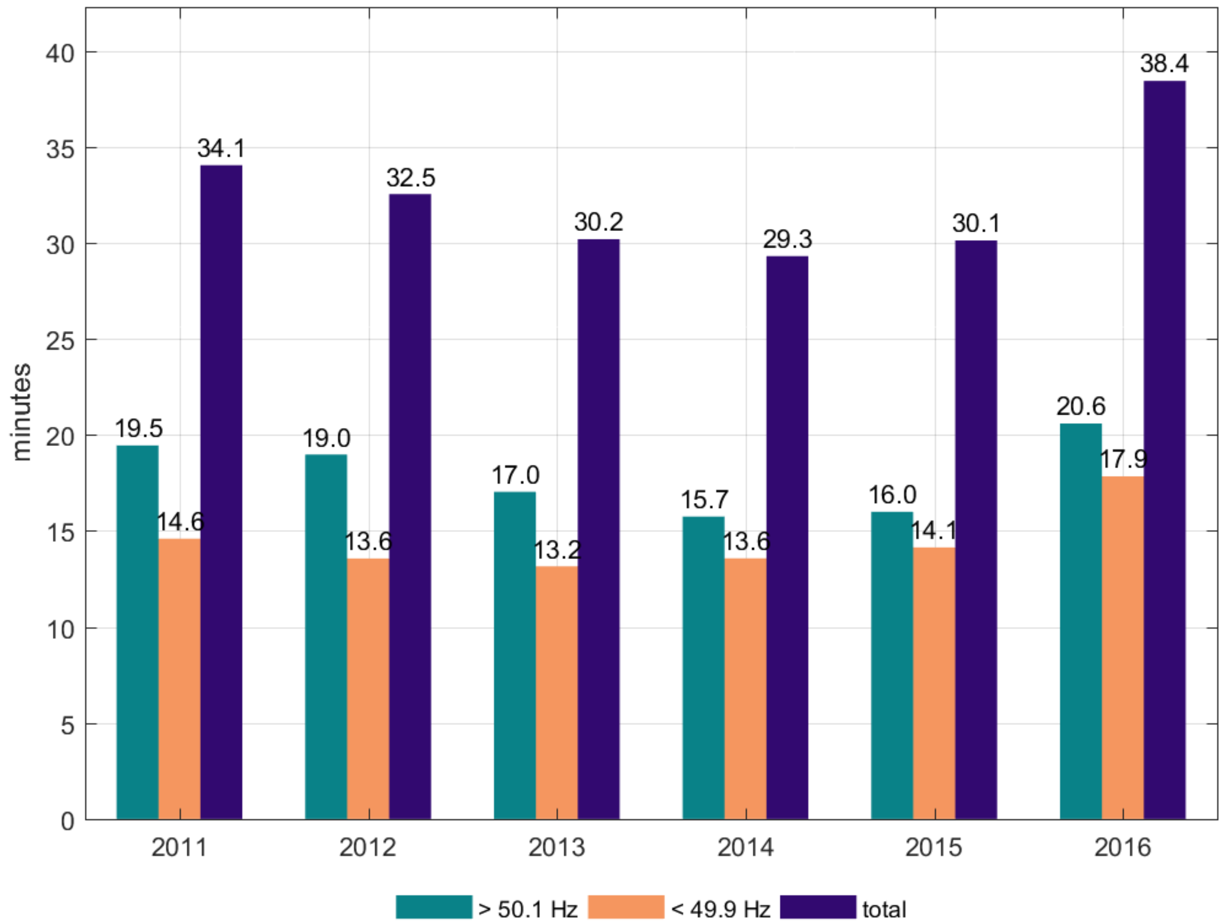


Figure 3.23 represents the daily average number of minutes per year that the frequency was outside the standard frequency range. After a decreasing trend after 2011, the duration that the frequency was outside the standard frequency range peaked in 2016.

Figure 3.23*. *Daily average number of minutes per year that the frequency was outside the standard frequency range in 2011-2016



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
2011	1.38 %	1.04 %	97.58 %
2012	1.30 %	0.93 %	97.76 %
2013	1.25 %	0.97 %	97.78 %
2014	1.07 %	0.92 %	98.01 %
2015	1.09 %	0.96 %	97.96 %
2016	1.44 %	1.25 %	97.31 %

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)
2011	7258	5448	12706
2012	6874	4916	11790
2013	6576	5081	11657
2014	5608	4835	10443
2015	5704	5049	10753
2016	7491	6492	13984

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 2011 to 2016. 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 2011-2013*

	2011		**2012**		**2013**	
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	466	323	542	339	522	311
February	524	371	737	438	123	132
March	892	553	507	420	453	411
April	698	466	652	394	532	334
May	616	430	593	561	474	576
June	487	575	400	348	384	302
July	317	263	418	315	599	442
August	583	349	477	345	810	547
September	788	526	784	508	723	573
October	757	658	668	462	851	541
November	391	354	484	536	326	250
December	581	460	686	300	422	383
Entire year	**7101**	**5328**	**6948**	**4965**	**6220**	**4803**

***Table 3.14**. Total time in which the frequency was outside the 49.9-50.1 Hz band in years 2014-2016*

	2014		**2015**		**2016**	
Month	**> 50.1 Hz (min)**	**< 49.9 Hz (min)**	**> 50.1 Hz (min)**	**< 49.9 Hz (min)**	**> 50.1 Hz (min)**	**< 49.9 Hz (min)**
January	474	409	498	444	723	526
February	324	309	420	379	687	612
March	629	616	506	376	679	566
April	387	391	544	428	779	809
May	517	608	478	535	962	820
June	340	383	414	438	607	594
July	487	444	323	397	587	537
August	830	471	579	485	704	572
September	516	247	678	428	584	523
October	583	506	314	398	434	362
November	303	353	454	414	288	310
December	359	218	629	443	504	325
Entire year	**5749**	**4954**	**5838**	**5165**	**7539**	**6555**

***Figure 3.24**. Total time in which the frequency was outside the 49.9-50.1 band in years 2011-2016*

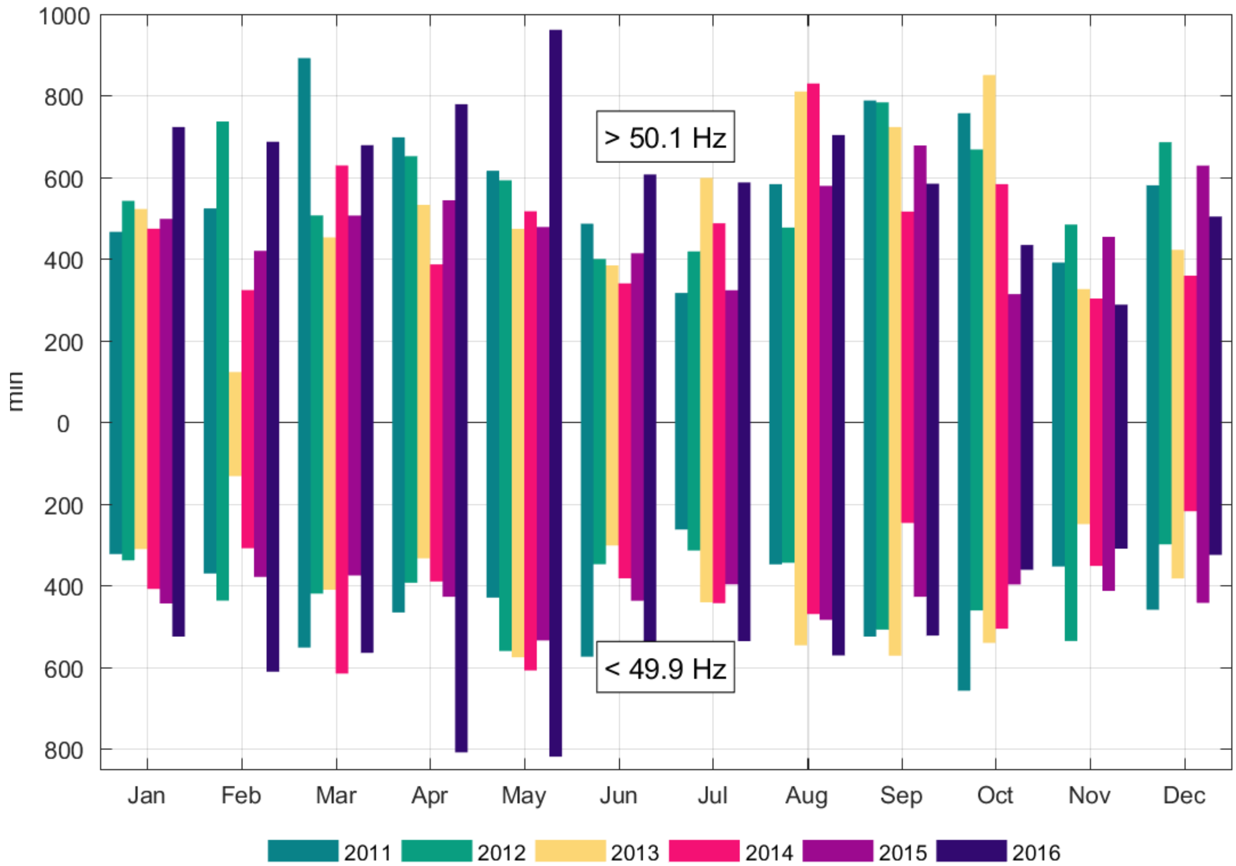


Figure 3.25 shows the daily average in minutes month by month when frequency was outside the standard frequency range in years 2011-2016. In 2016, April and May were the months with the longest time outside the standard frequency range. October and November had the best frequency in this comparison.

Figure 3.25*. *Daily average time that the frequency was outside the standard frequency range month by month for years 2011-2016

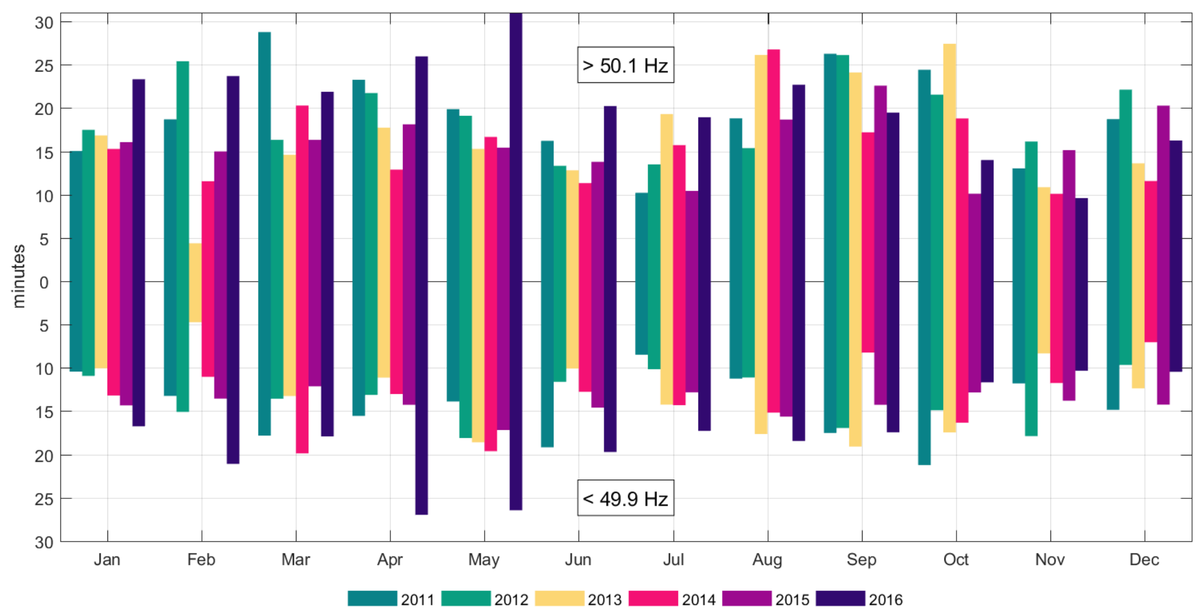


Figure 3.26 represents the daily averge time that the frequency was outside the standard frequency range during each day of the week. Year 2016 was one of the worst years in this relation. Every year has had a similar pattern, where the frequency has been outside the standard frequency range more often 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 2011-2016*

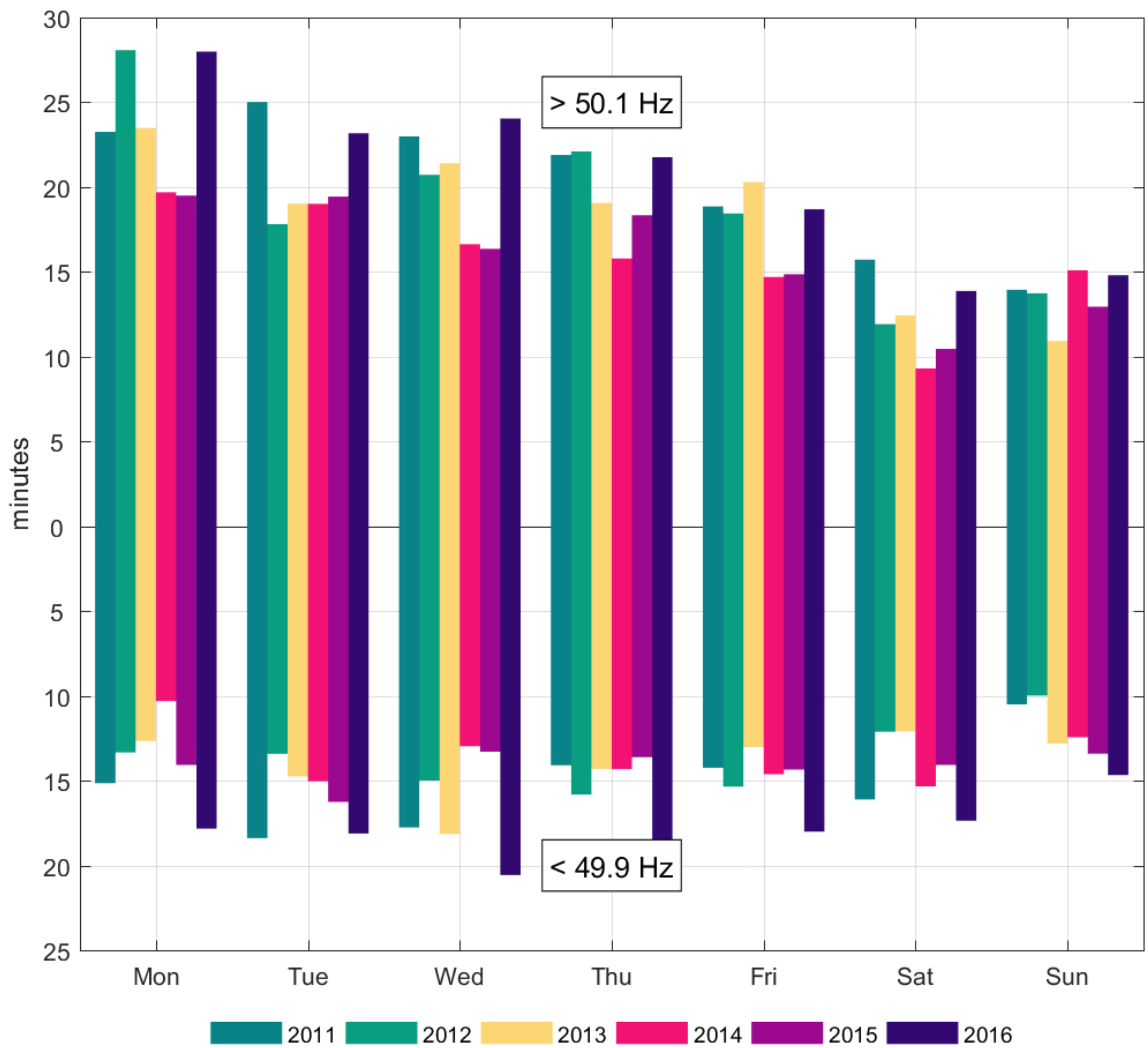


Figure 3.27 represents the daily average time that the frequency was outside the standard frequency range for each hour in the day. The hours are according to the Finnish time (UTC+2 / UTC+3 in the summer). The highest over frequency deviations in 2016 were at the hours 23 and 0 and under frequency deviations at 1 and 7. The worst frequencies in previous years in this case have also been at the morning hours and in the evening and midnight. Frequency has stayed inside the standard frequency range for the most at the hours from 3 to 5. Hours from 12 to 15 have also been rather good.

Figure 3.27*. *Daily average time that the frequency was outside the standard frequency range during each hour of the day for years 2011-2016

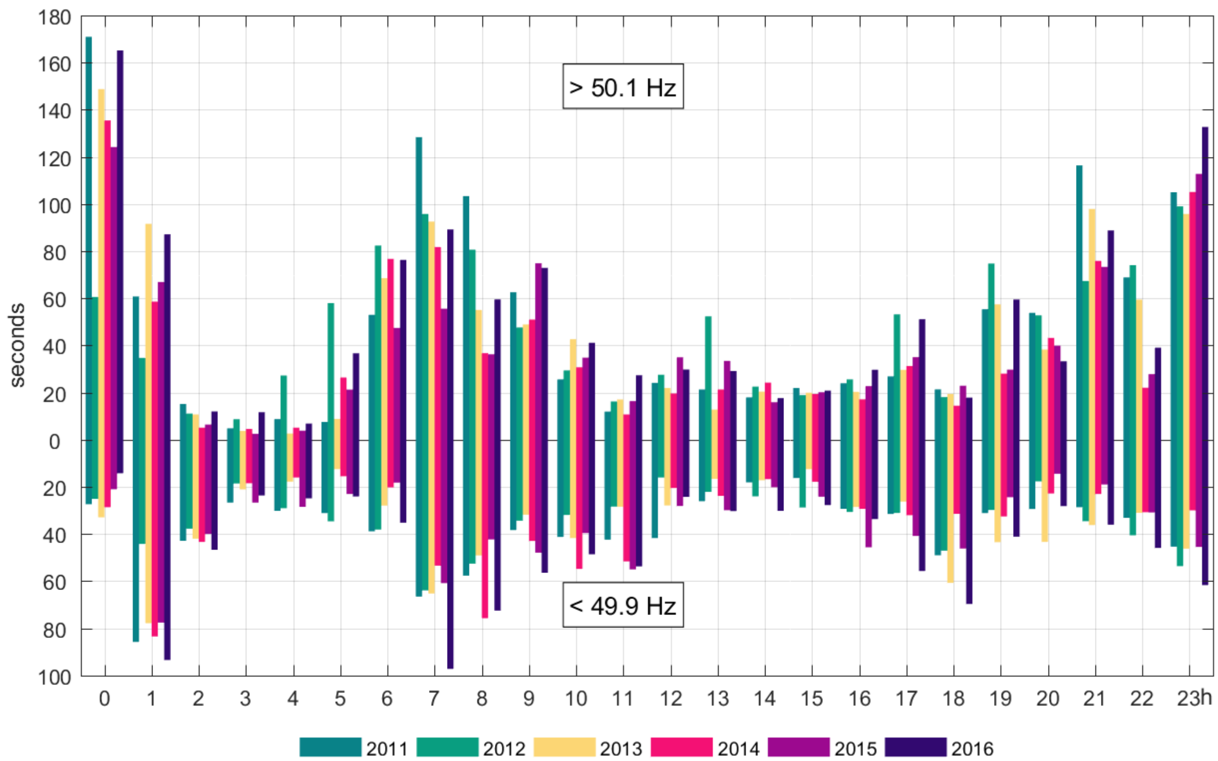


Figure 3.28 shows the daily average time outside the standard frequency range per hour and absolute value of Nordic consumption and production difference. Also transmission difference of HVDC links connecting Nordic power system to Continental Europe and Russia is presented.

The differences were calculated by subtracting average power of the previous hour from the corresponding value of the current hour. Consumption and production data was retrieved from the Nord Pool website and the 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 nearly 4000 MWh while the consumption difference curve peaks close to 2500 MWh in the morning hours 7 and 8. Near midnight the peaks are around 2000-2500 MWh. Highest values of frequency deviations are also found during these hours. Differences in HVDC transmission does not peak as high but the curve still follows the same pattern as production and consumption difference. Results for year 2015 were very similar to the year 2016 [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 2016**

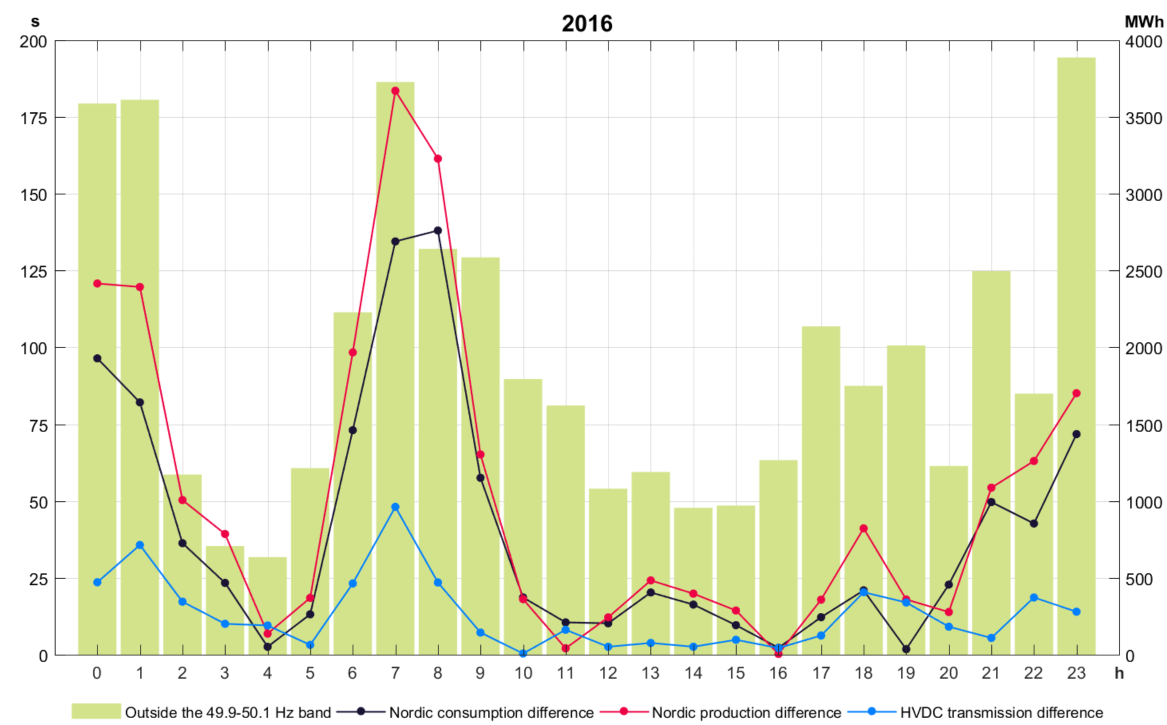


Figure 3.29 illustrates an average hour divided to 60 minutes. For each minute of the average hour there is a value in seconds per hour that frequency has been over or below the standard frequency range. In years 2011-2016 frequency has been outside the standard frequency range more often during beginning of hours. Frequency has stayed best inside the standard frequency range in the middle of hours. The amount of over frequency deviations have increased again towards the end of hours.

Figure 3.29*. *Number of seconds per hour outside the standard frequency range in 2011-2016 for each minute of an average hour

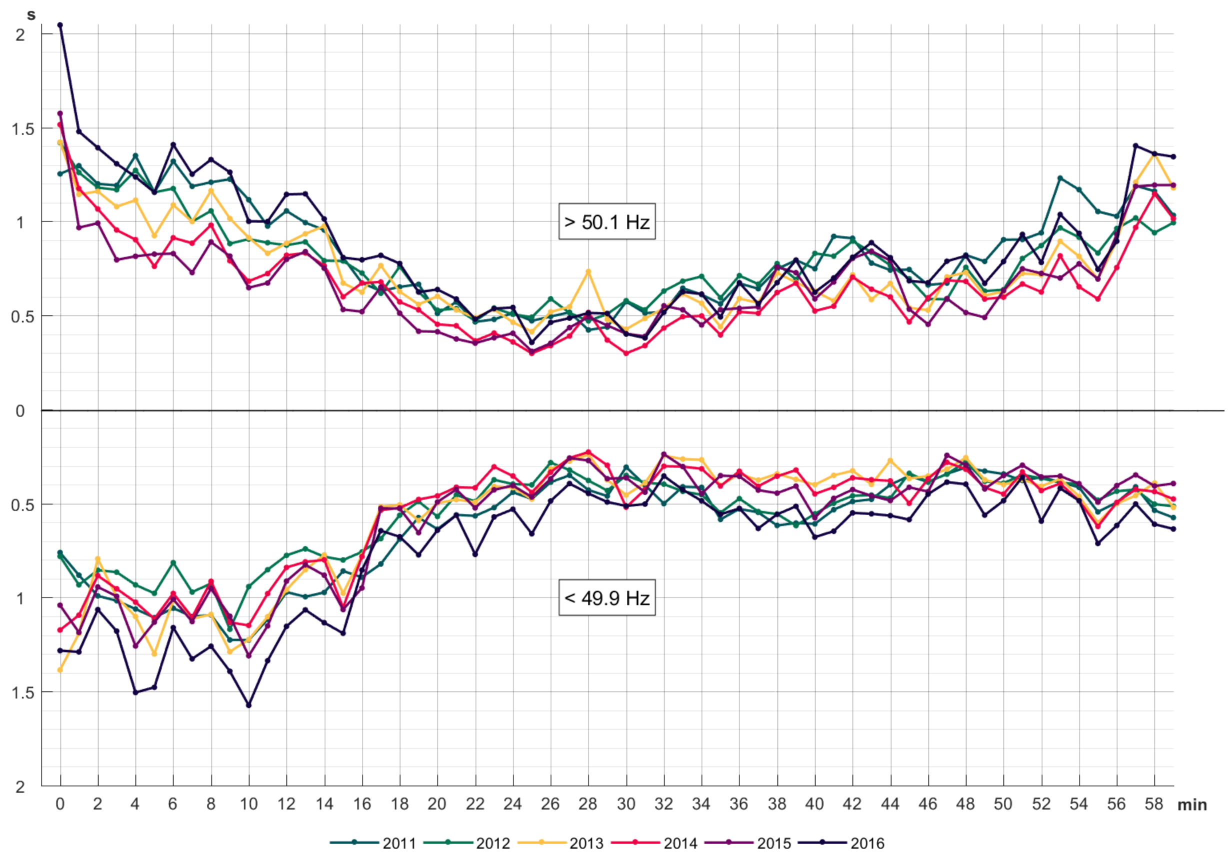
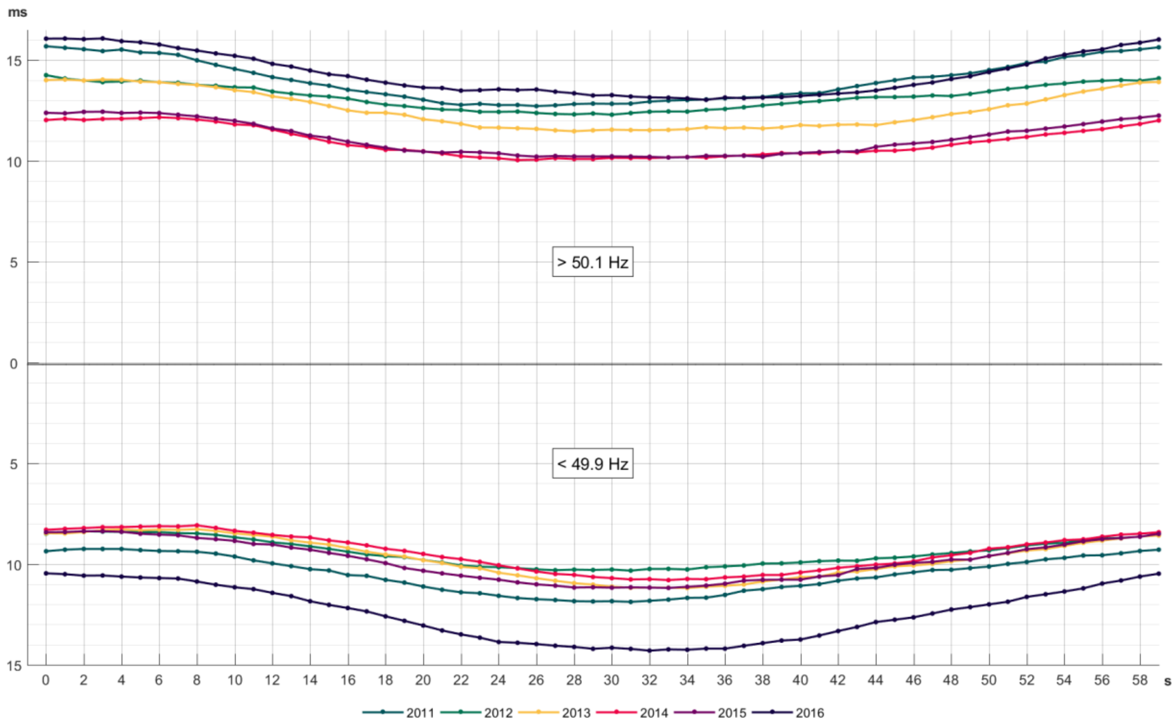


Figure 3.30 illustrates an average minute divided to 60 seconds. For each second of the average minute there is a value in milliseconds per minute that frequency has been over or below the standard frequency range. Shape of the curve is fairly smooth so there hasn't been large deviations inside one minute. There have been slightly more over frequencies at the beginning and at the end of minutes. Under frequencies have occurred more at the middle of minutes. In 2016 the number of milliseconds per minute under the standard frequency range has been considerably higher than in previous years.

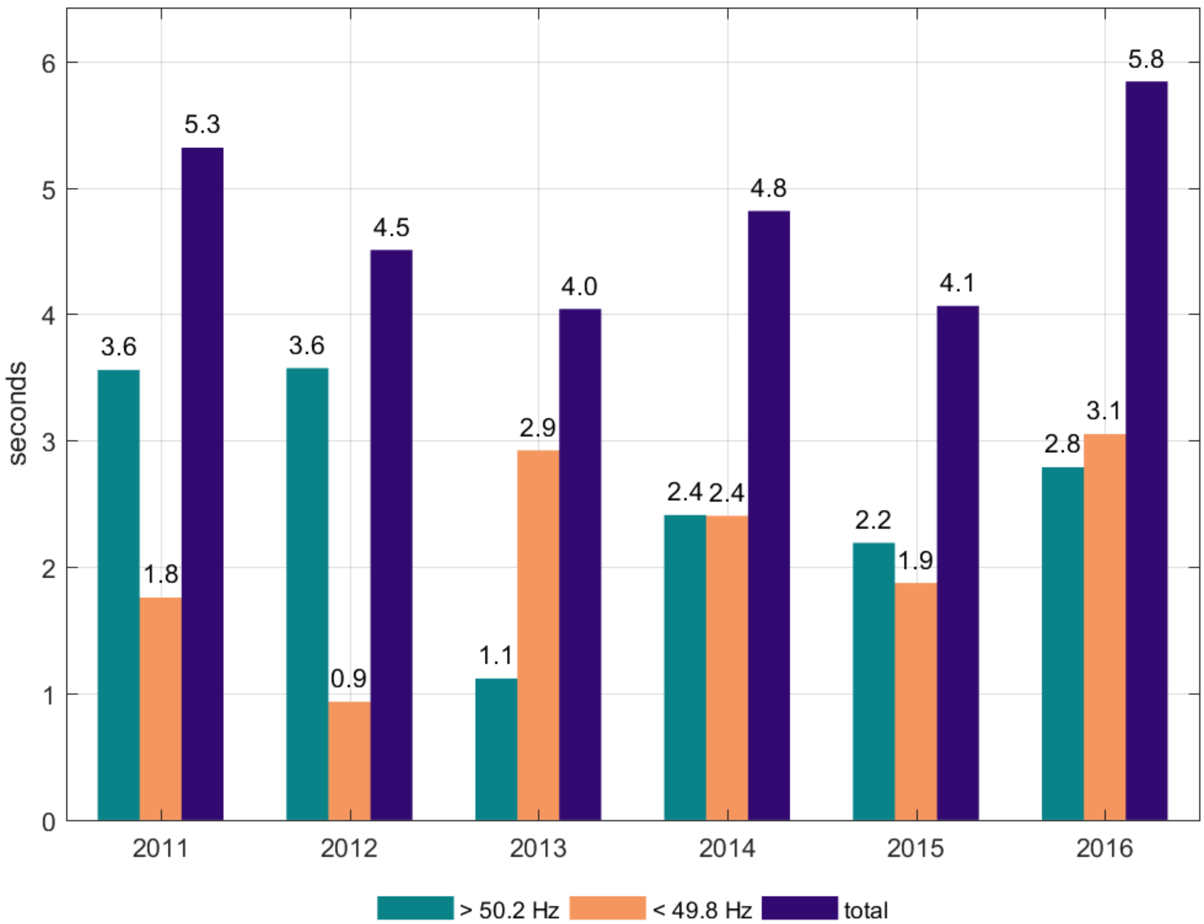
***Figure 3.30*. Number of milliseconds per minute outside the standard frequency range in 2011-2016 for each second of an average minute**



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 amount of these deviations was higher in 2016 than during any previous years. In 2011 and 2012, average number of seconds over 50.2 Hz was considerably more than under 49.8 Hz while in 2013, it was the other way around. For the last three years, there has been only slight difference between over and under frequencies.

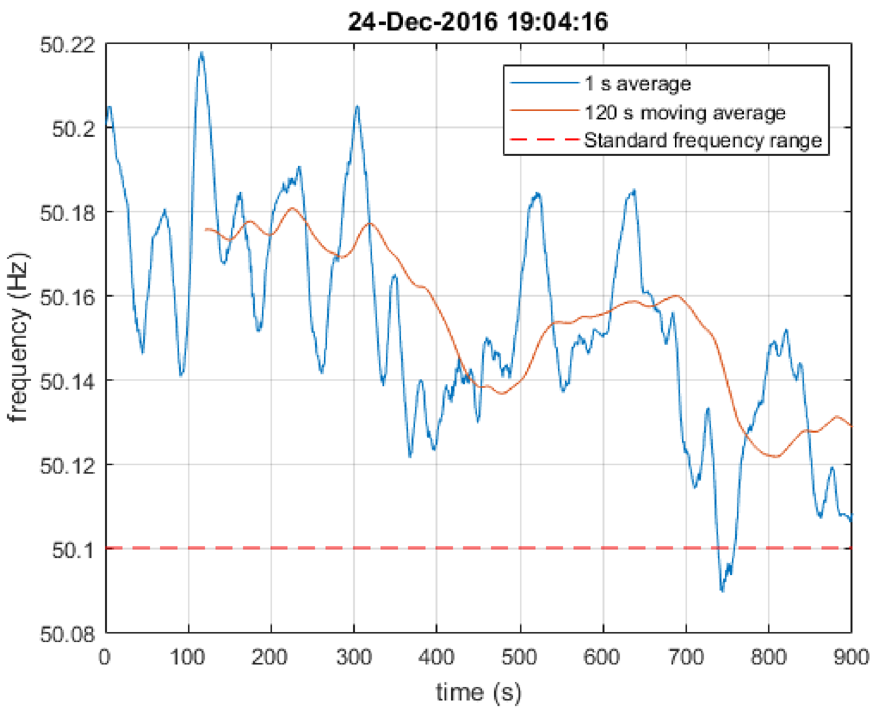
***Figure 3.31**. Average number of seconds per day that the frequency was outside the 49.8-50.2 Hz band for years 2011-2016*



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.

Figure 3.32 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 2011-2016 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.

	2011		**2012**		**2013**		**2014**		**2015**		**2016**	
Month	**> 50.2 Hz**	**< 49.8 Hz**	**> 50.2 Hz**	**< 49.8 Hz**	**> 50.2 Hz**	**< 49.8 Hz**	**> 50.2 Hz**	**< 49.8 Hz**	**> 50.2 Hz**	**< 49.8 Hz**	**> 50.2 Hz**	**< 49.8 Hz**
January	0	0	0	0	0	0	0	0	0	0	1	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**	**0**	**0**	**1**	**0**

Table 3.16 shows the number of events in 2011-2016 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.

	2011		**2012**		**2013**		**2014**		**2015**		**2016**	
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	1	1	0	2	1	0	0	1	0	3	0
February	0	0	2	0	0	0	0	0	2	0	0	1
March	0	0	1	0	0	0	0	0	0	0	0	0
April	2	0	1	0	0	0	0	0	4	0	1	0
May	1	0	0	0	0	0	0	0	0	0	0	0
June	0	0	1	1	0	0	0	0	0	0	0	0
July	0	0	0	0	0	0	0	0	0	0	1	0
August	0	0	1	0	0	0	0	0	2	0	0	0
September	0	0	2	0	0	0	1	0	1	0	1	0
October	2	0	0	0	3	1	0	1	0	0	2	0
November	0	0	0	0	0	0	0	0	0	0	0	0
December	0	0	0	0	0	0	1	0	0	0	1	0
Entire year	5	1	9	1	5	2	2	1	10	0	**9**	**1**
Sum	**6**		**10**		**7**		**3**		**10**		**10**	

3.4.3 Time outside 49.0-51.0 Hz

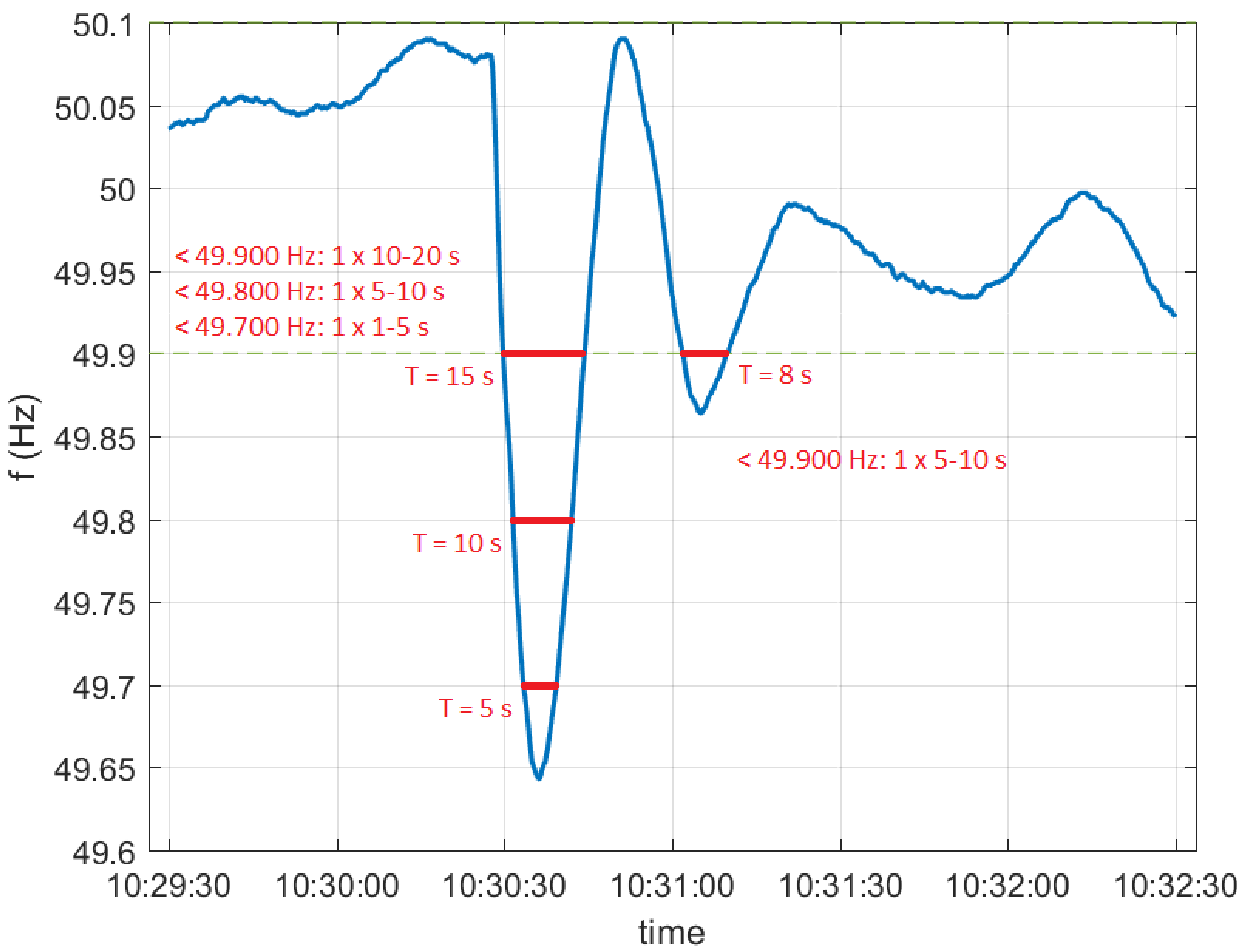
Time outside 49.0 Hz and 51.0 Hz is calculated by counting the number of samples that are below 49.0 Hz or above 51.0 Hz and multiplying the number by the time duration of the sample. The criteria are also defined in SO GL Article 131(a) (v). The resolution of the data used was 1 second.

There were no instances in 2011-2016 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, this time 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 2011 to 2016. 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 2011

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	28047	7917	3741	5773	3772	999	855	129	51233	2302.60	8.09
> 50.2	91	39	26	19	10	7	1	0	193	61.90	6.60
> 50.3	0	0	1	0	0	0	0	0	1	7.70	7.70
< 49.9	20818	6683	2848	4482	3139	730	576	92	39368	1216.70	7.91
< 49.8	62	22	15	17	4	1	1	0	122	71.50	5.15
< 49.7	2	2	4	1	1	0	0	0	10	20.10	6.70
< 49.6	0	1	1	1	0	0	0	0	3	13.50	7.40
< 49.5	0	0	1	0	0	0	0	0	1	7.60	7.60

Table 3.18. 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 3.19. 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 3.20. 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 3.21. 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 3.22. 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	849.50	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

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 once again from 2014 to 2016.

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

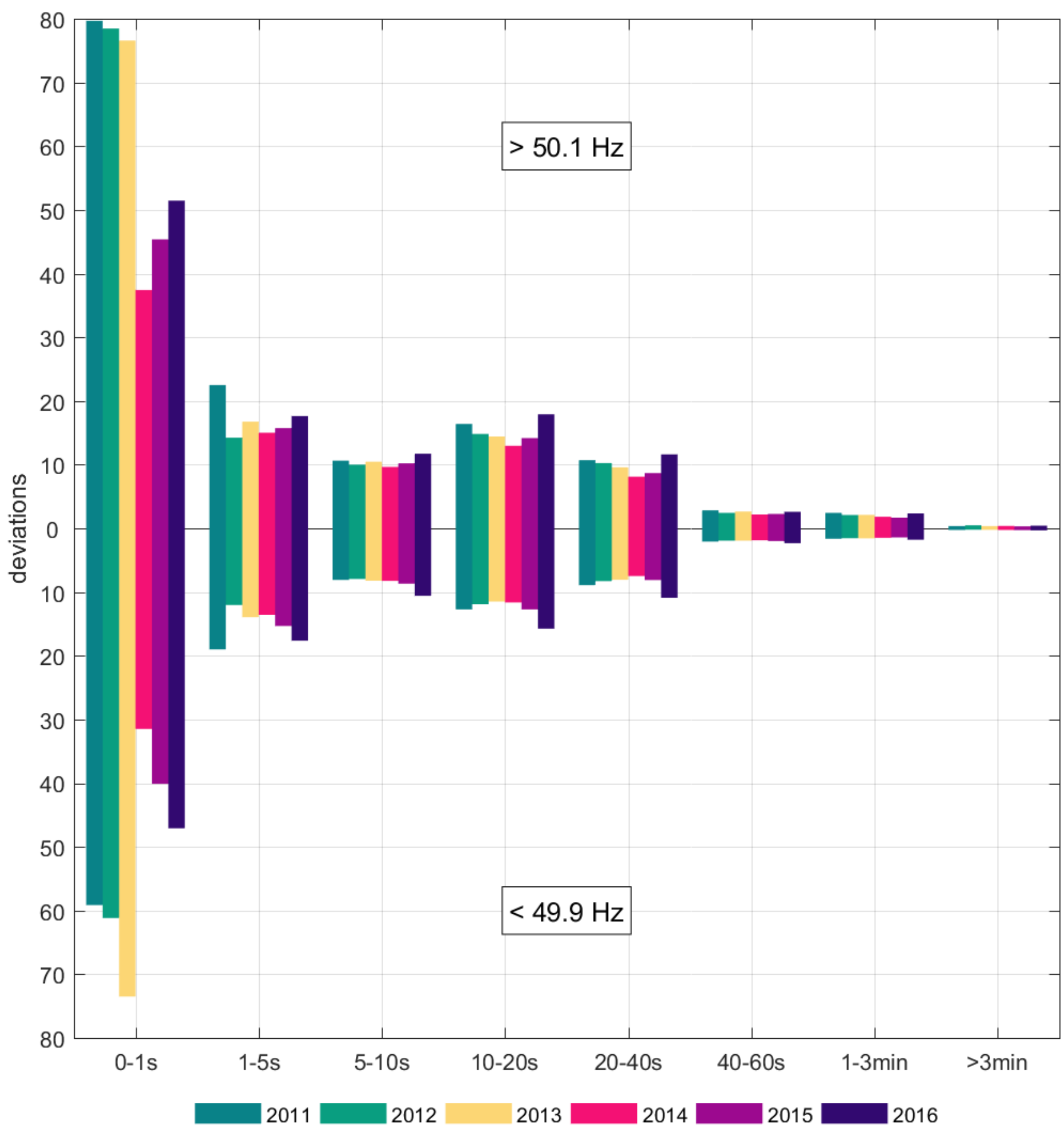
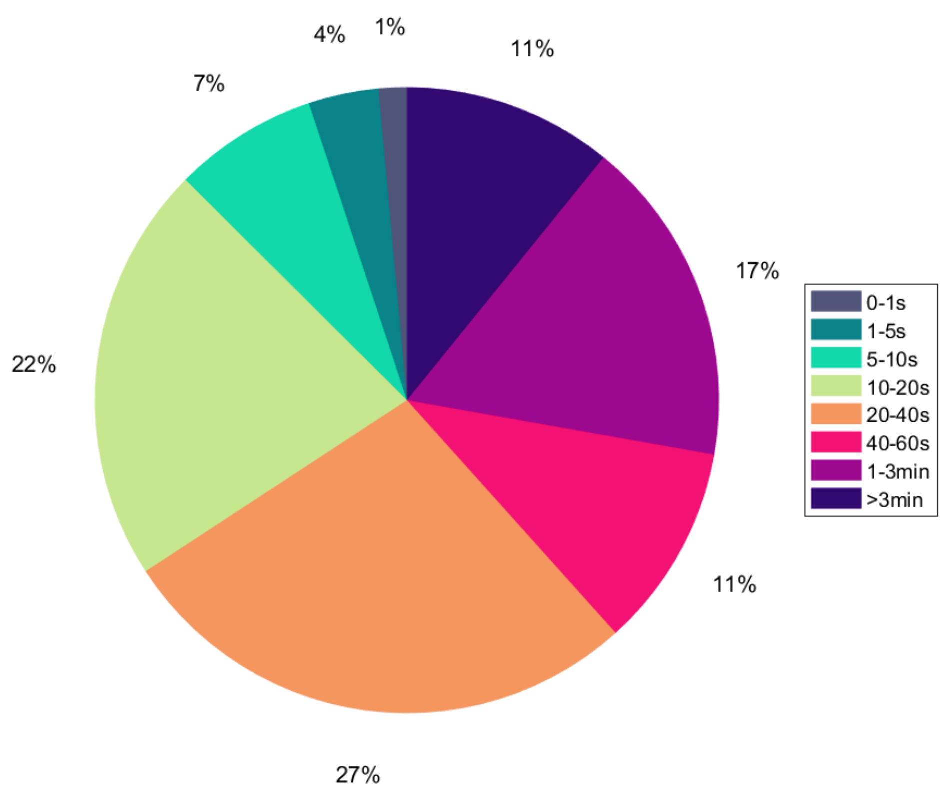


Table 3.23 shows how deviations of different duration affected to the total time outside the standard frequency range in 2016. Times are given in minutes. Pie chart in Figure 3.35 shows in percentages how the total time outside the standard frequency range was divided between deviations of different 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 2016 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	104	252	540	1574	1953	767	1327	854	7369
< 49.9 Hz	97	247	486	1400	1819	684	999	638	6371
total	201	499	1026	2974	3772	1451	2326	1492	13740

***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 2016. Figure 3.36 represents the total number of devations per duration for each mont in 2016. Most of the deviations lasted only 0-1 seconds. April and May had the most frequency deviations across all durations. The least amount of devitions occurred in November and December.

***Figure 3.36**. Total number of frequency deviations per duration for each month in 2016*

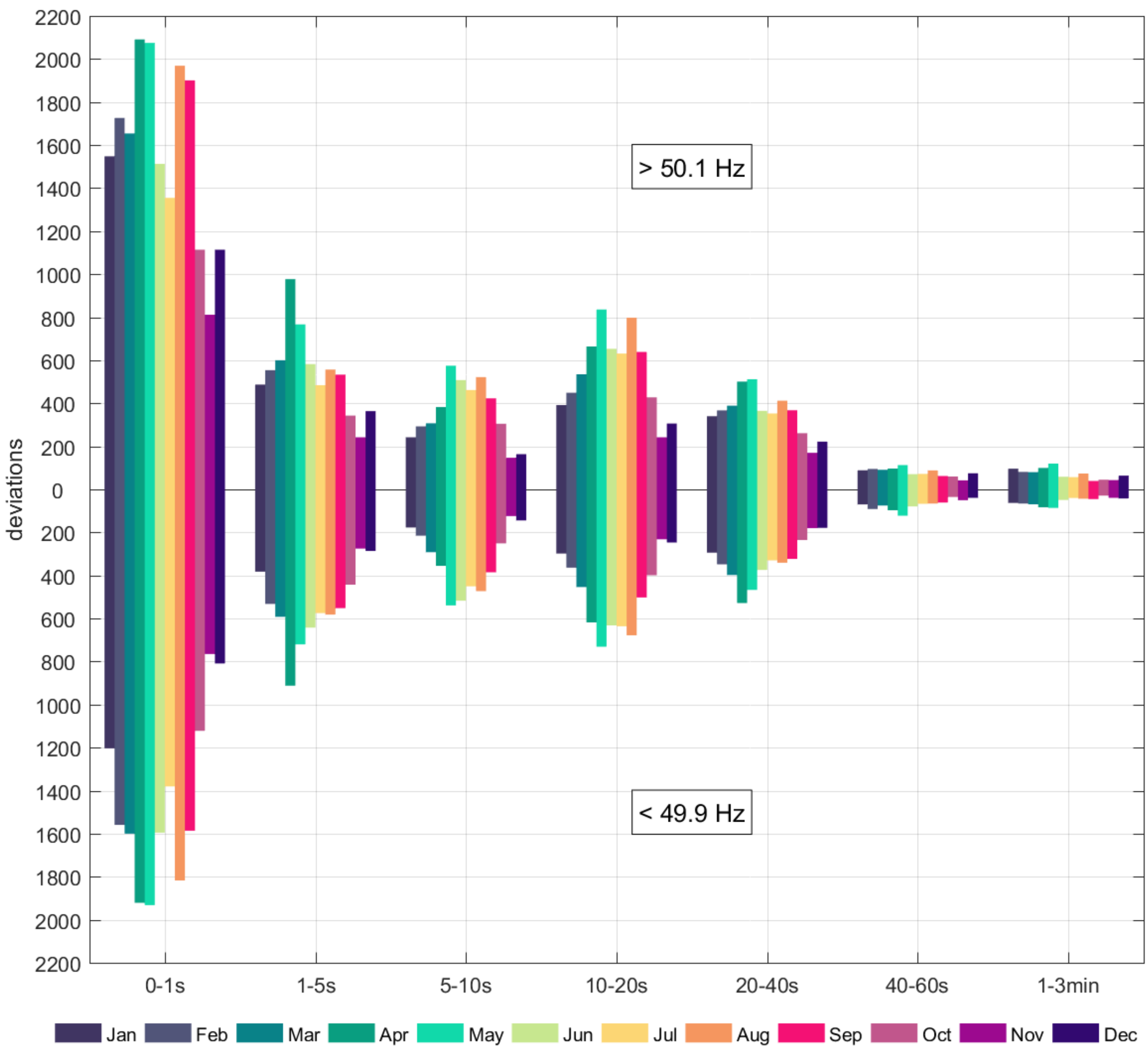
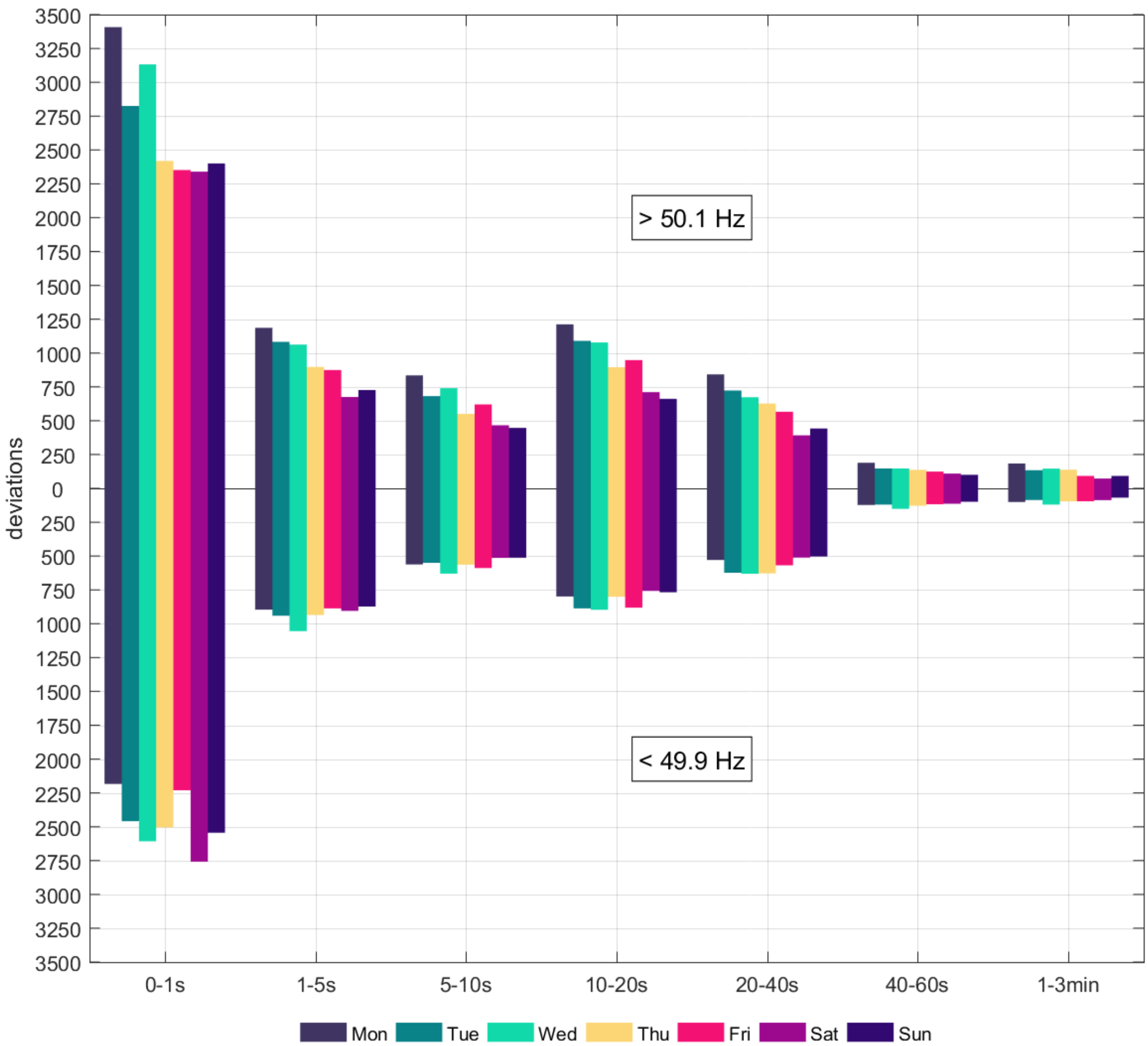


Figure 3.37 shows the number of deviations for every day of the week. Deviations under 49.9 Hz were all quite even across all days but most of the deviations over 50.1 Hz took place in the beginning of the week on Monday, Tuesday and Wednesday.

***Figure 3.37**. Total number of frequency deviations per duration for each day of the week in 2016*



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 were around midnight on the first and last hours of the day.

***Figure 3.38**. Total number of frequency deviations per duration for hours 0-11 in 2016*

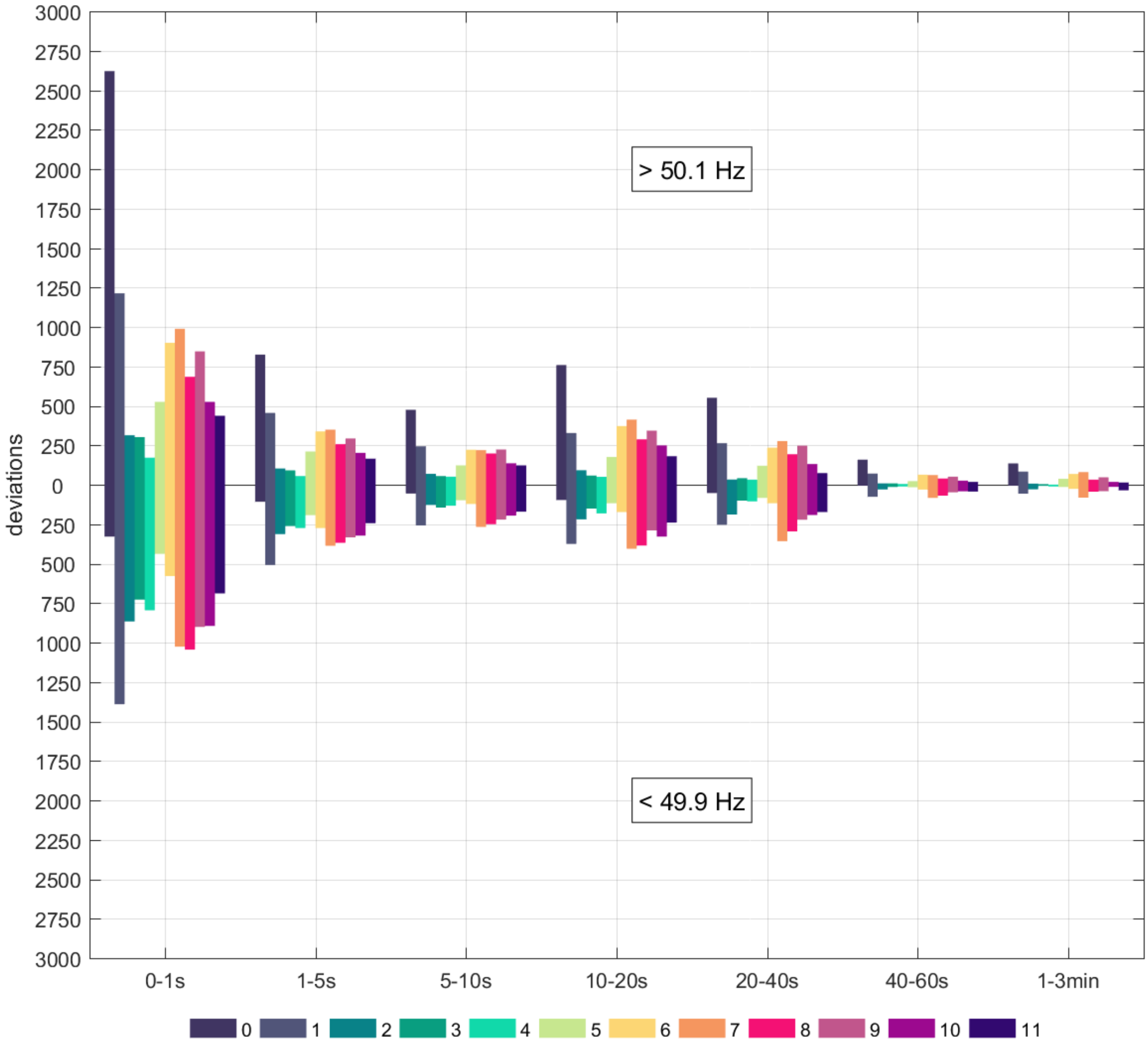


***Figure 3.39**. Total number of frequency deviations per duration for hours 12-23 in 2016*

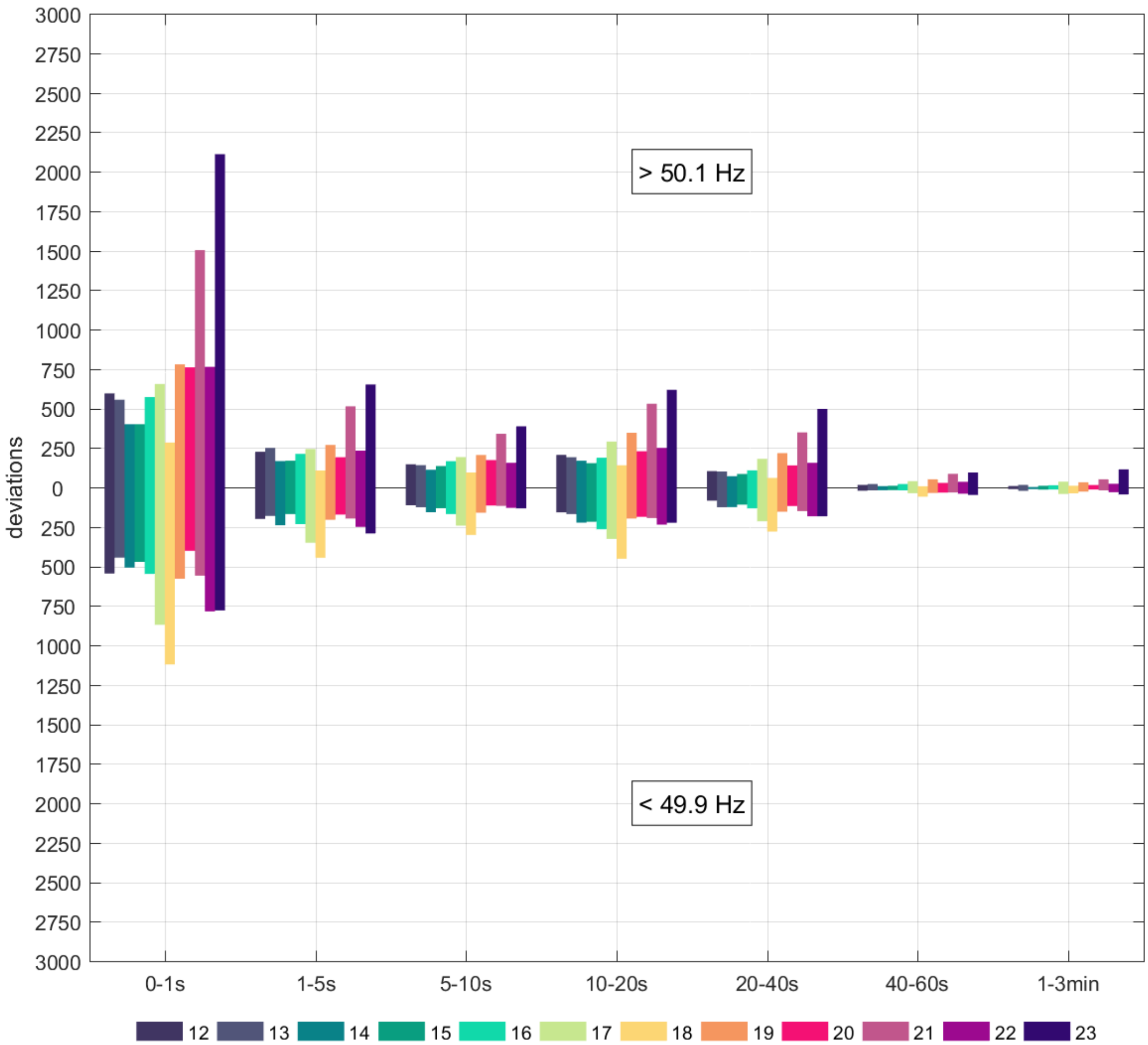
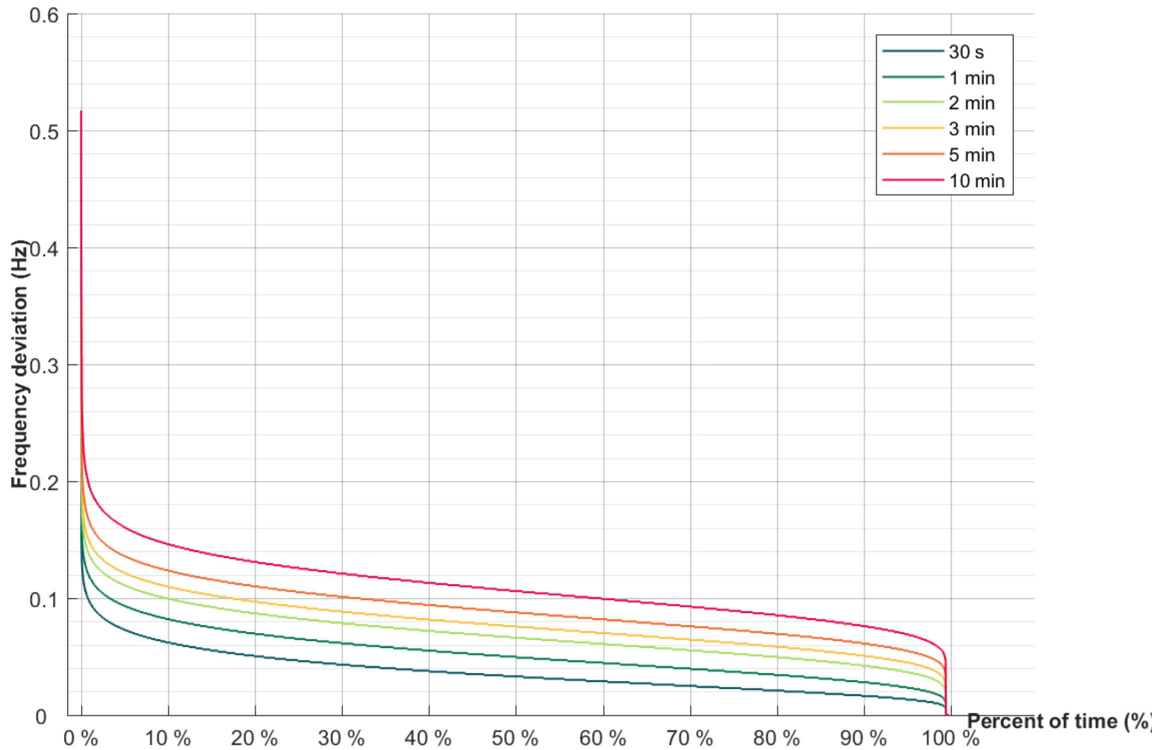


Figure 3.40 represents duration curve of maximum frequency deviation inside different time windows in year 2016. The time window was slid through the year with a time interval of one second. Studied time windows can be found from legend of the Figure 3.40. Chapter 4 shows in detail frequency disturbances 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 2016*



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 and only results for 2016 are presented. Figure 3.41 shows the total number of deviations for each month in 2016. The first half of the year had generally more longer lasting durations than the latter part of the year.

***Figure 3.41**. Total number of longer frequency deviations per duration for each month in 2016*

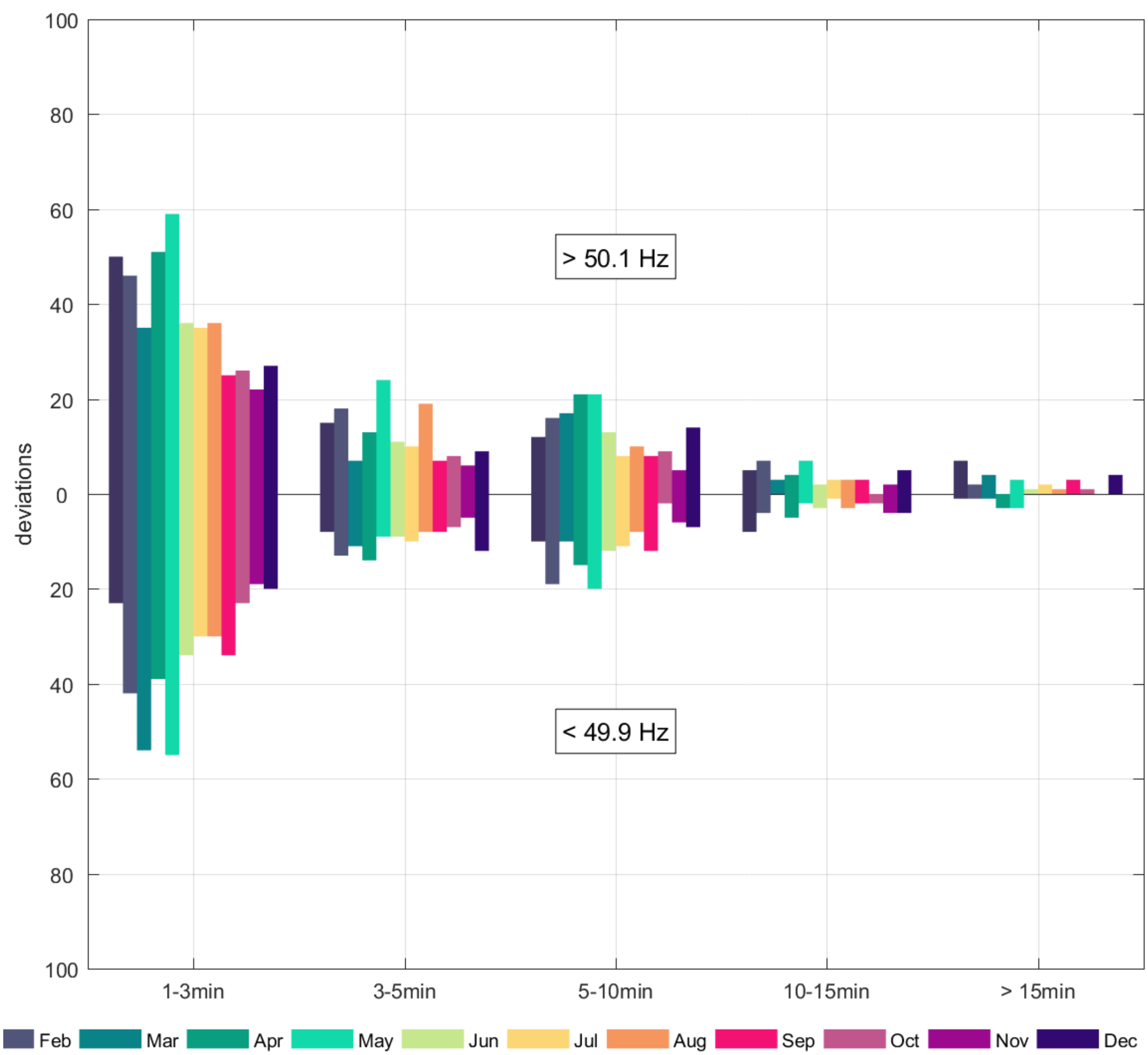
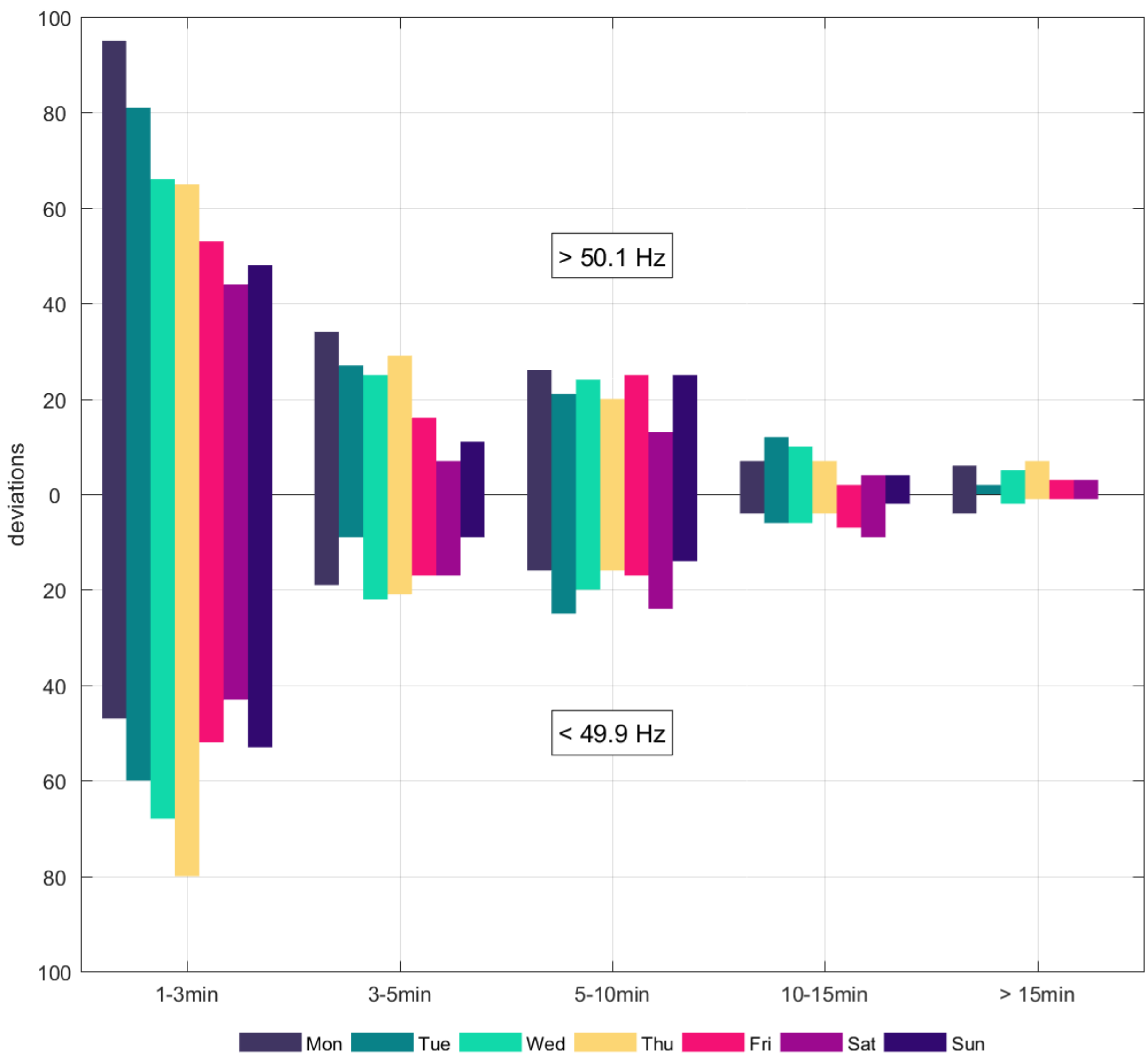


Figure 3.42 represents the number of deviations with different durations during every day of the week in 2016. From Monday to Thursday with 1-3 min durations, the total number of deviations is fairly even. During Monday and Tuesday, most of the deviations were over 50.1 Hz and for Wednesday and Thursday, the deviations were more often under 49.9 Hz. Especially during the weekends, there were less deviations.

Figure 3.42*. *Total number of longer frequency deviations per duration for each day of the week in 2016



Figures 3.43 and 3.44 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 3.43**. Total number of longer frequency deviations per duration for hours 0-11 in 2016*

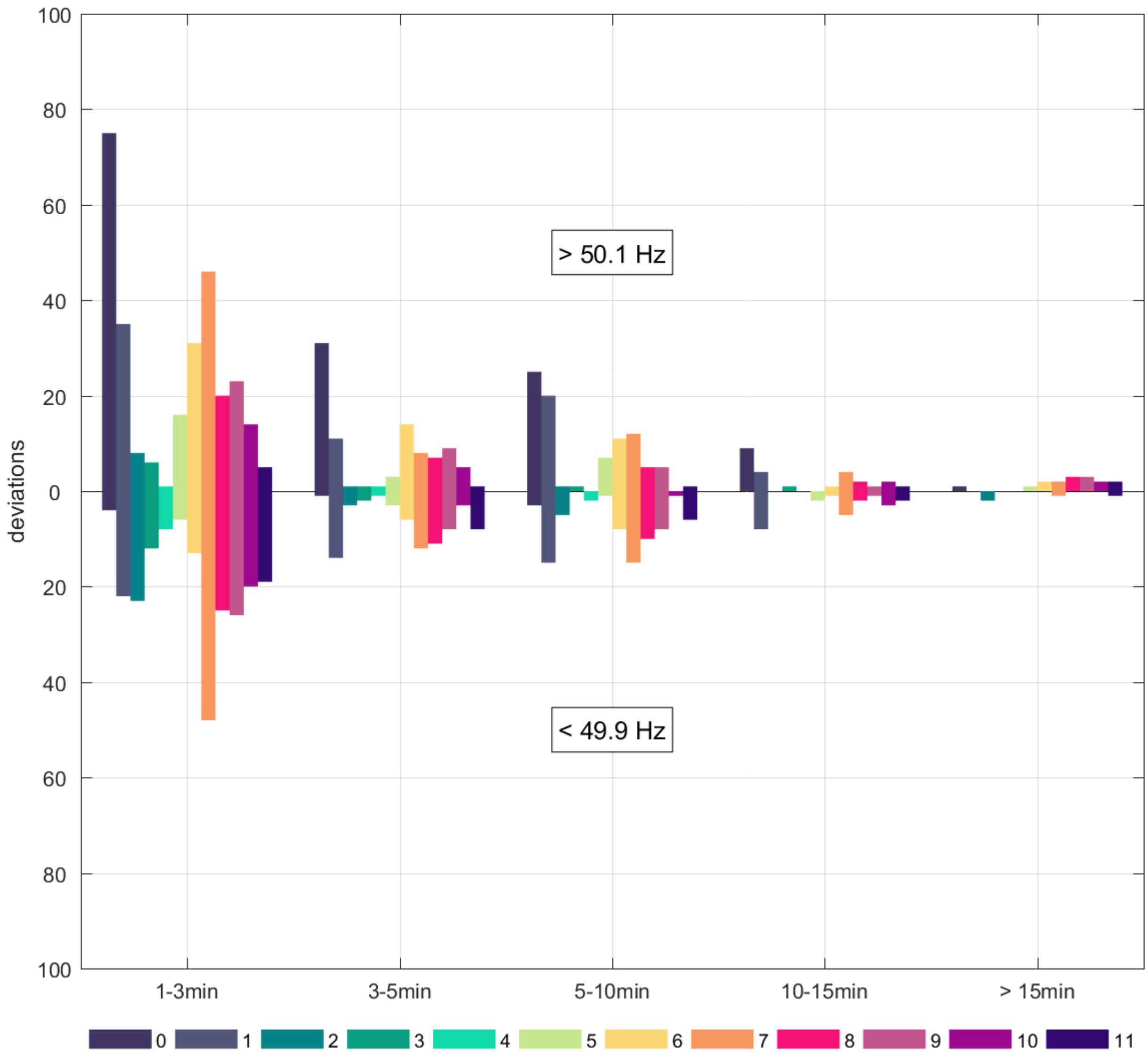
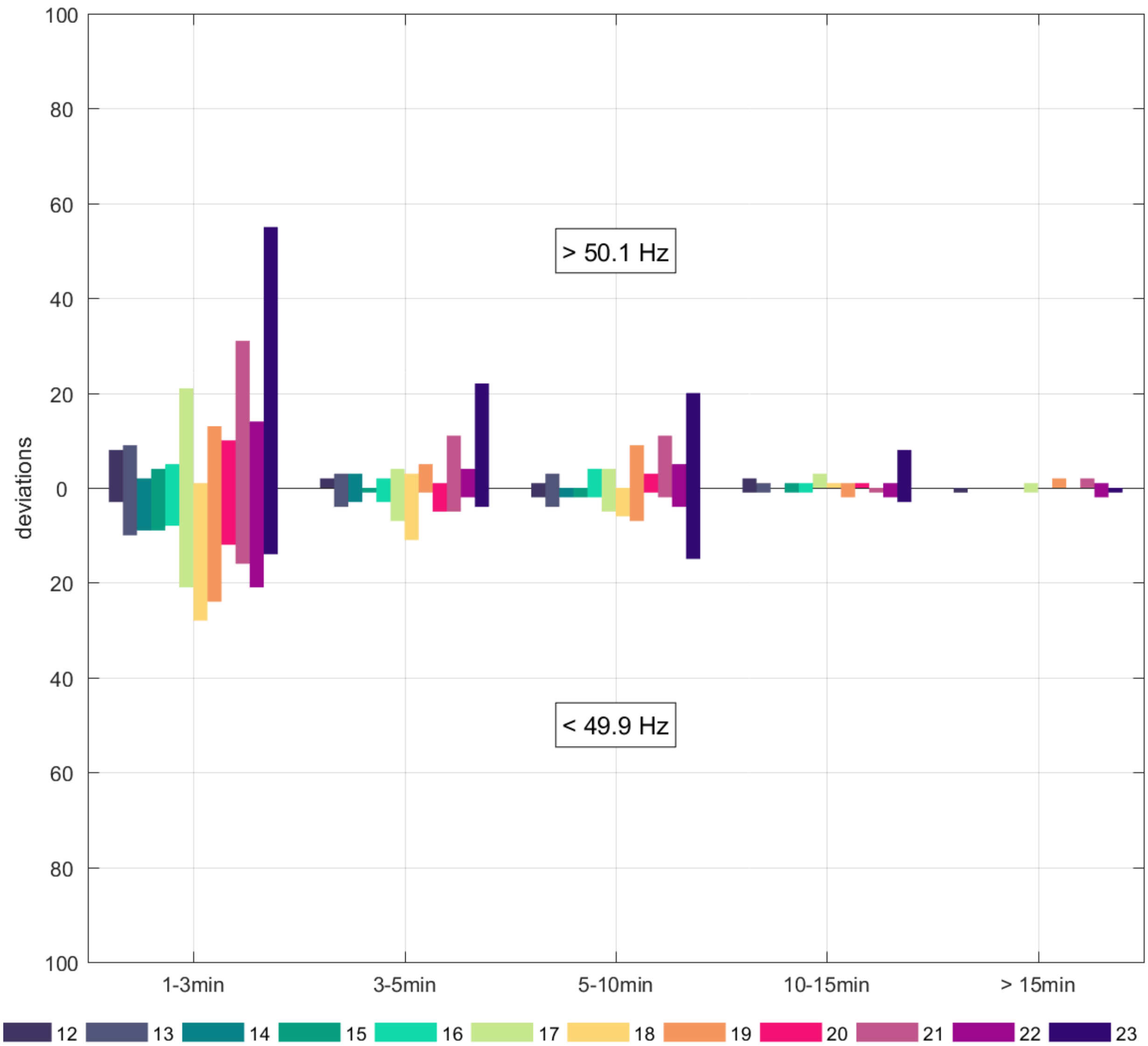


***Figure 3.44**. Total number of longer frequency deviations per duration for hours 12-23 in 2016*



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 frequneycy range. The resolution of the frequency is one second.

3.6.1 Number of 49.9-50.1 Hz crossings

Figure 3.45 shows the daily average numbers of over and under frequency deviations from 2011 to 2016. The amount has remained fairly even from 2012 to 2015, but increased in 2016. Every year there has been slightly more threshold crossings over 50.1 Hz than under 49.9 Hz.

***Figure 3.45**. Daily average number of frequency deviations for years 2011-2016*

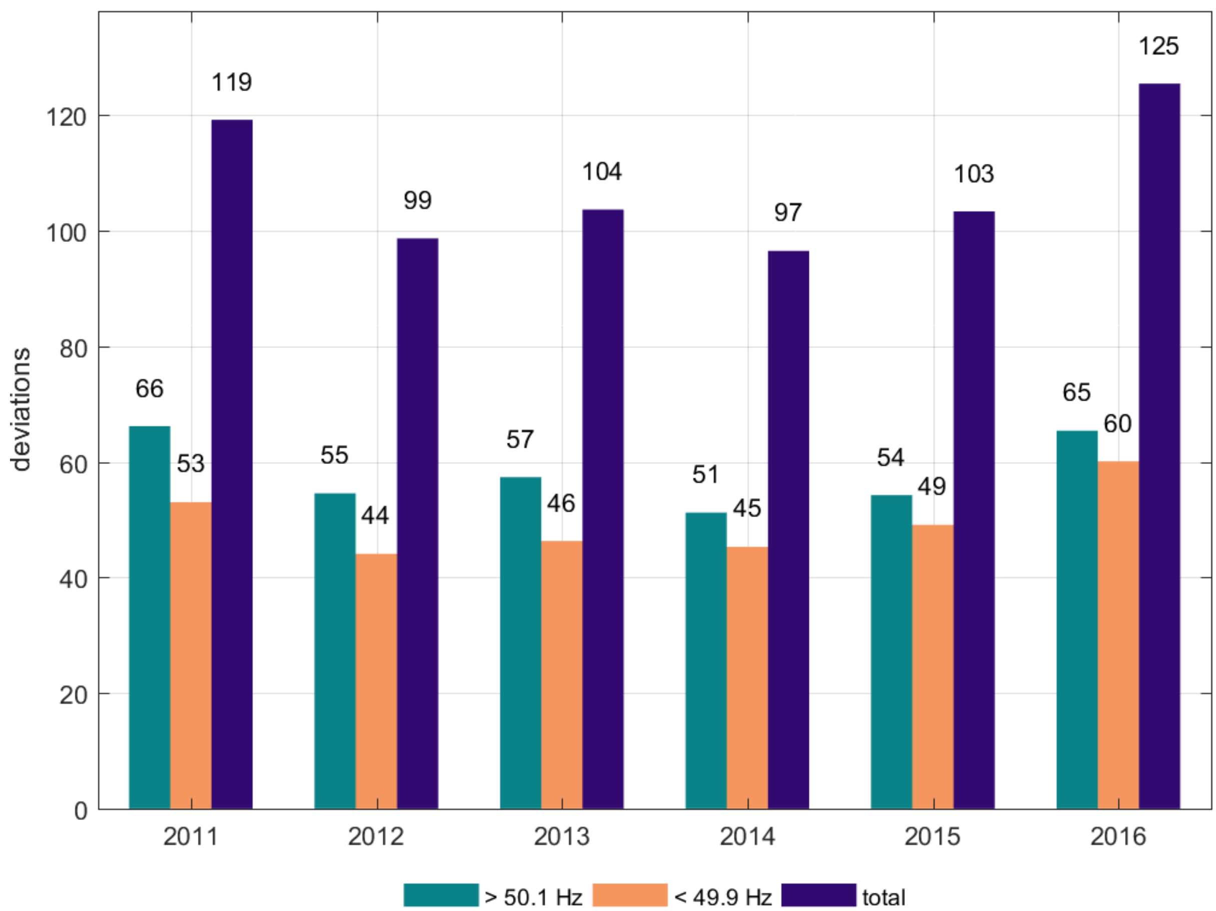


Figure 3.46 represents the daily average number of threshold crossings for each month in 2016. There has been slightly more crossings over 50.1 Hz than crossings under 49.9 Hz. In total, the frequency crossed the threshold more often during spring and summer months.

Figure 3.46*. *Daily average number of threshold crossings for every month in 2016

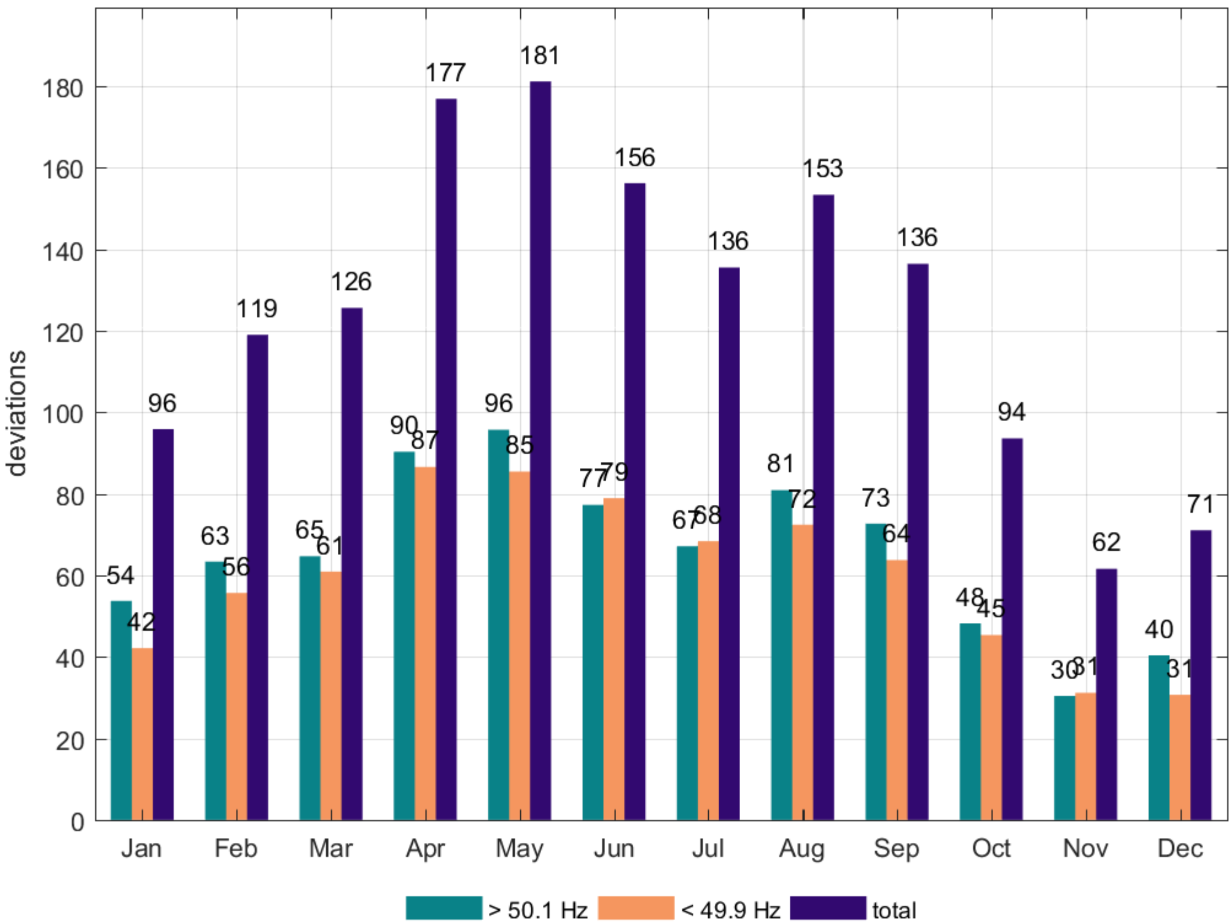
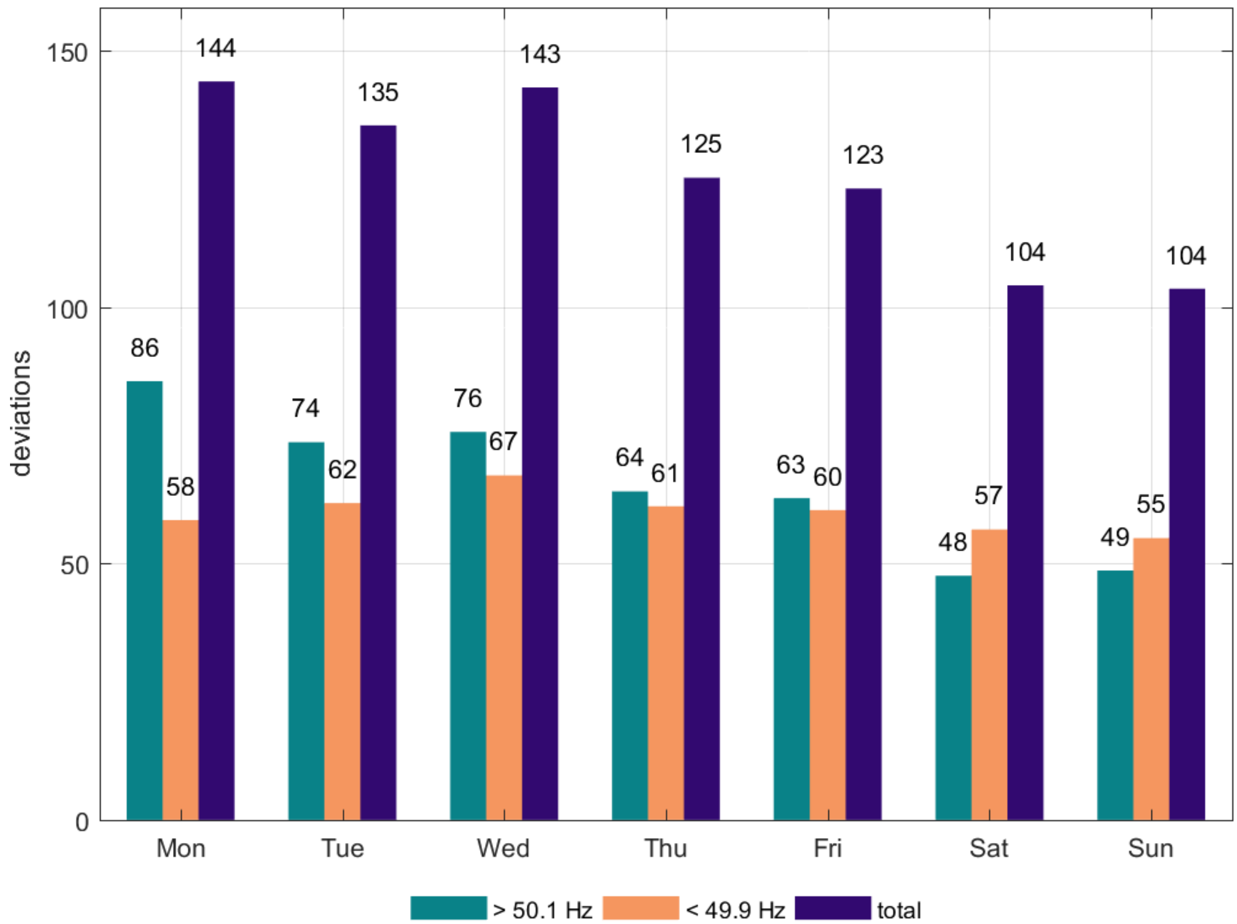


Figure 3.47 shows the number of threshold crossings for each day of the week in 2016. During the weekends, the number was smaller and more crossings were under 49.9 Hz than over 50.1 Hz.

***Figure 3.47**. Daily average number of threshold crossings for every day of the week in 2016*



The number of threshold crossings inside the day on average is in Figure 3.48. Not surprisingly, 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 is when the frequency crosses the threshold more often.

***Figure 3.48**. Average number of threshold crossings for every hour of the day in 2016*

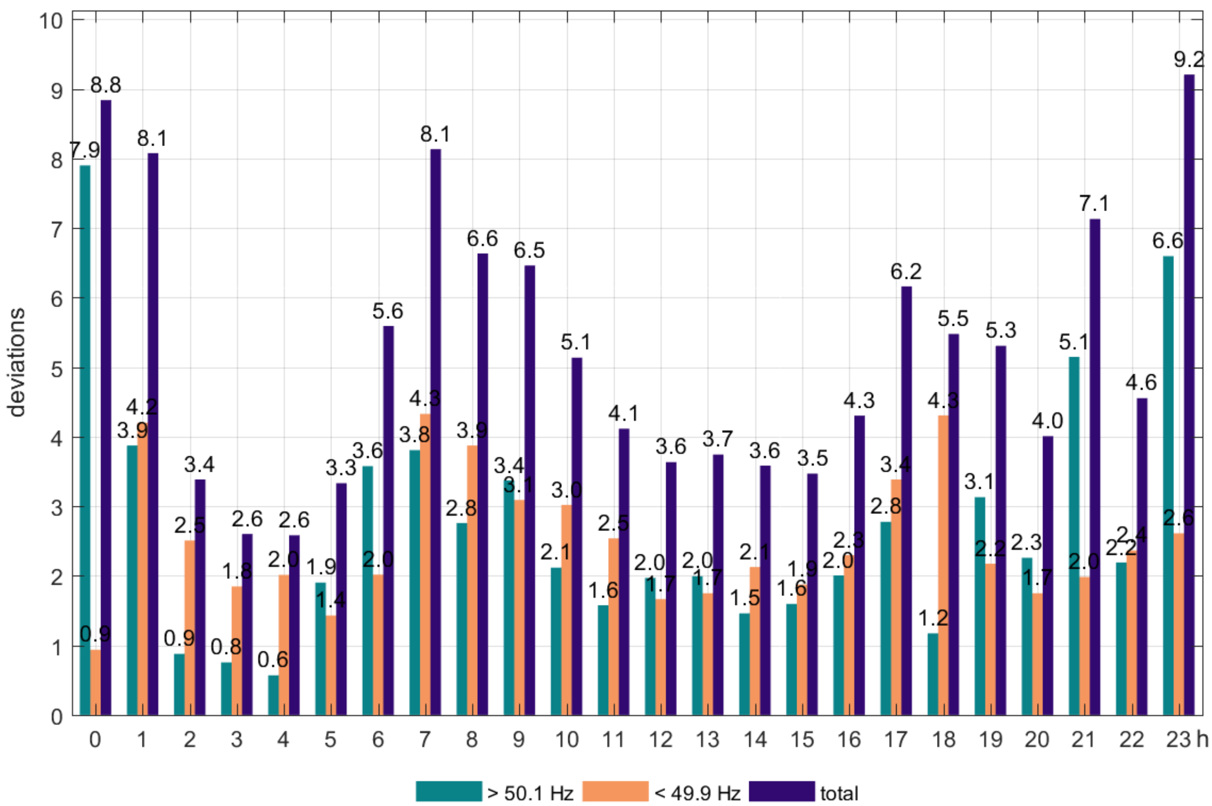
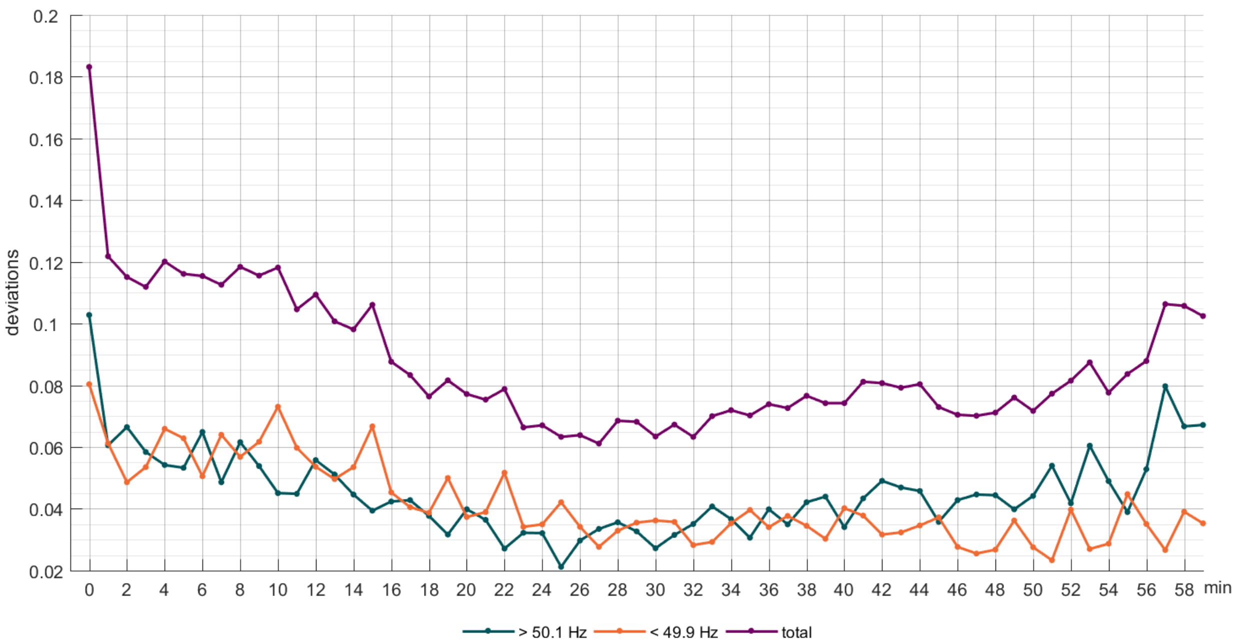


Figure 3.49 represents the average number of threshold crossings for every minute inside the hour. Most crossings take place within the first minutes of the hour. During the first 30 minutes of the hour, the frequency crosses 49.9 Hz more often, while more crossings of 50.1 Hz take place in the latter part of the hour.

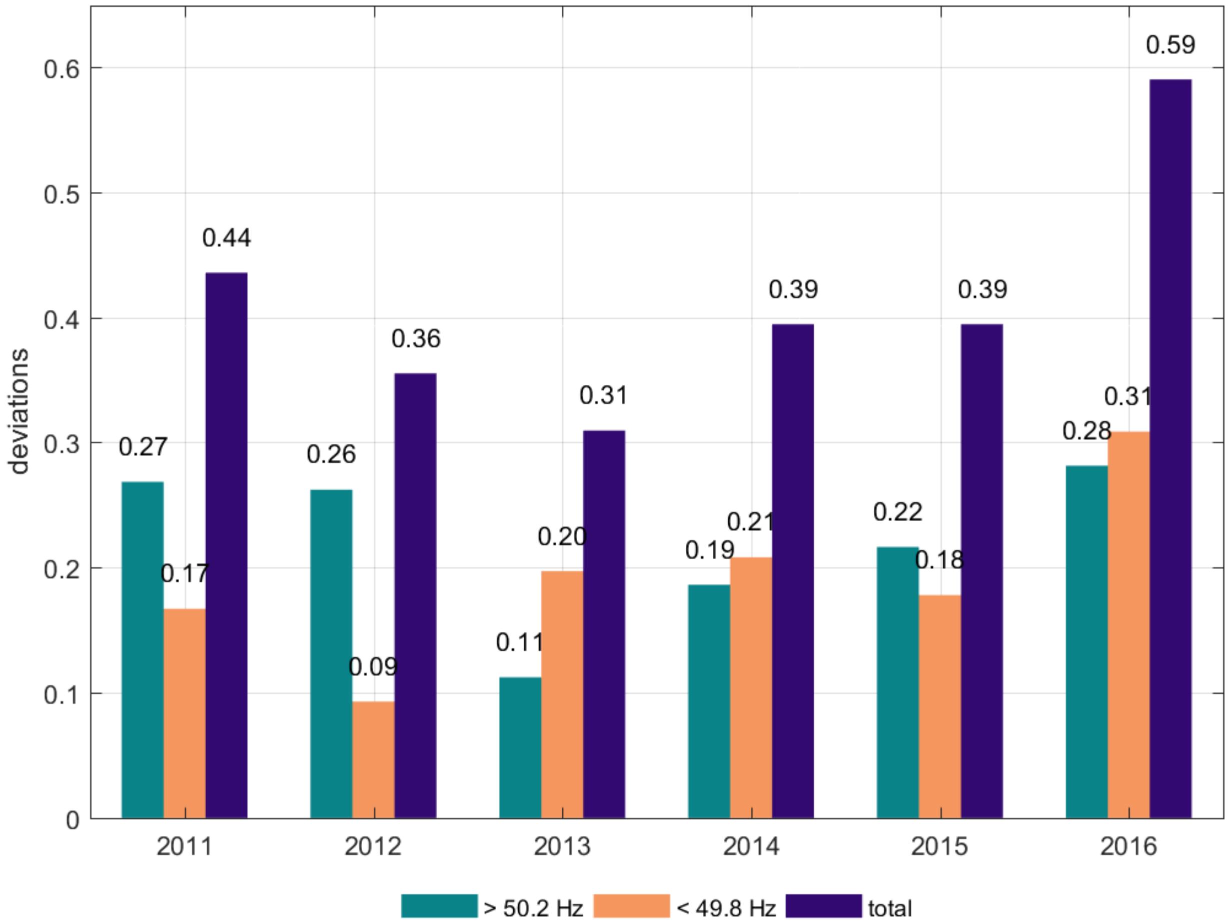
Figure 3.49**. **Average number of threshold crossings for every minute of the hour in 2016



3.6.2 Number of 49.8-50.2 Hz crossings

Figure 3.50 represents the average number of frequency deviations per day that exceeded ±200 mHz. The number is significantly higher in 2016 than in 2011-2015.

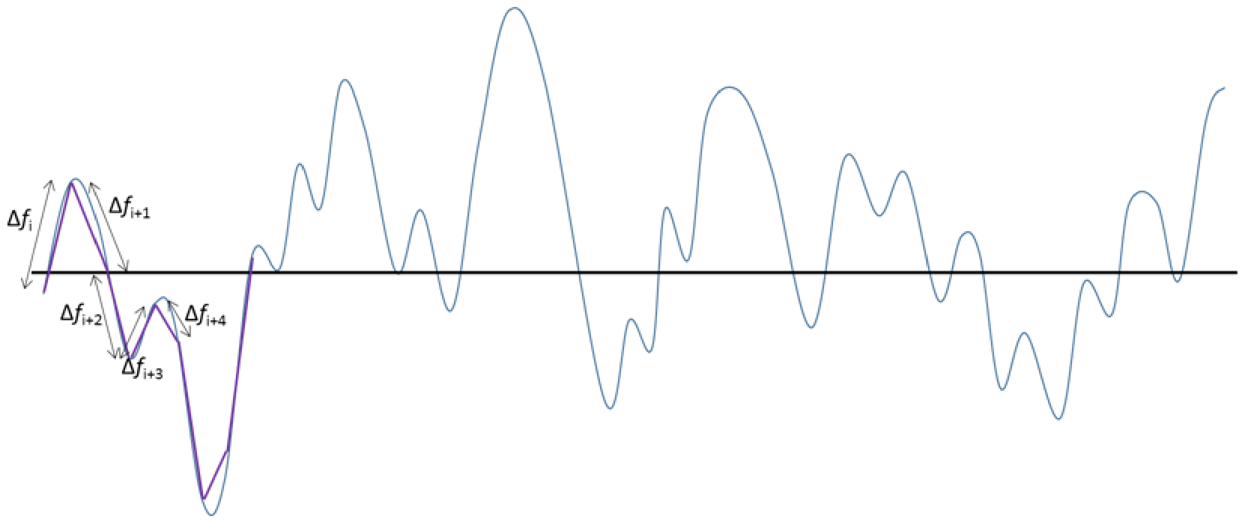
***Figure 3.50**. Daily average number of frequency deviations larger than ±200 mHz for years 2008-2016*



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 3.51. 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 3.51 is the formula for frequency path, where Δt is the length of the time step (in this case 0.1 s).

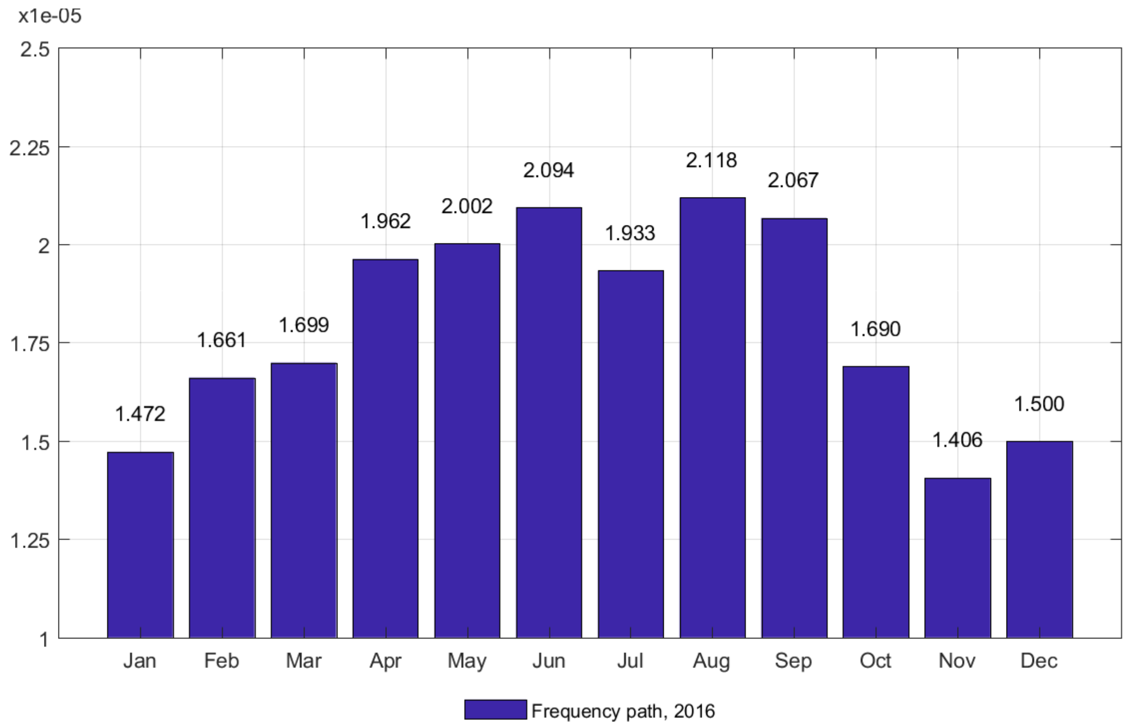
Figure 3.51**. **Frequency quality index: Length of the frequency path [7]



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

Figure 3.52 represents the frequency path for each month in 2016. On average, the path has been longer in the middle of the year from April to September.

***Figure 3.52**. Length of the frequency path month by month in 2016*



The frequency path for every day of the week shows in Figure 3.53. There has been little to no variation in frequency path between the days. During weekends the path has been slightly longer on average.

***Figure 3.53**. Length of the frequency path for every day of the week in 2016*

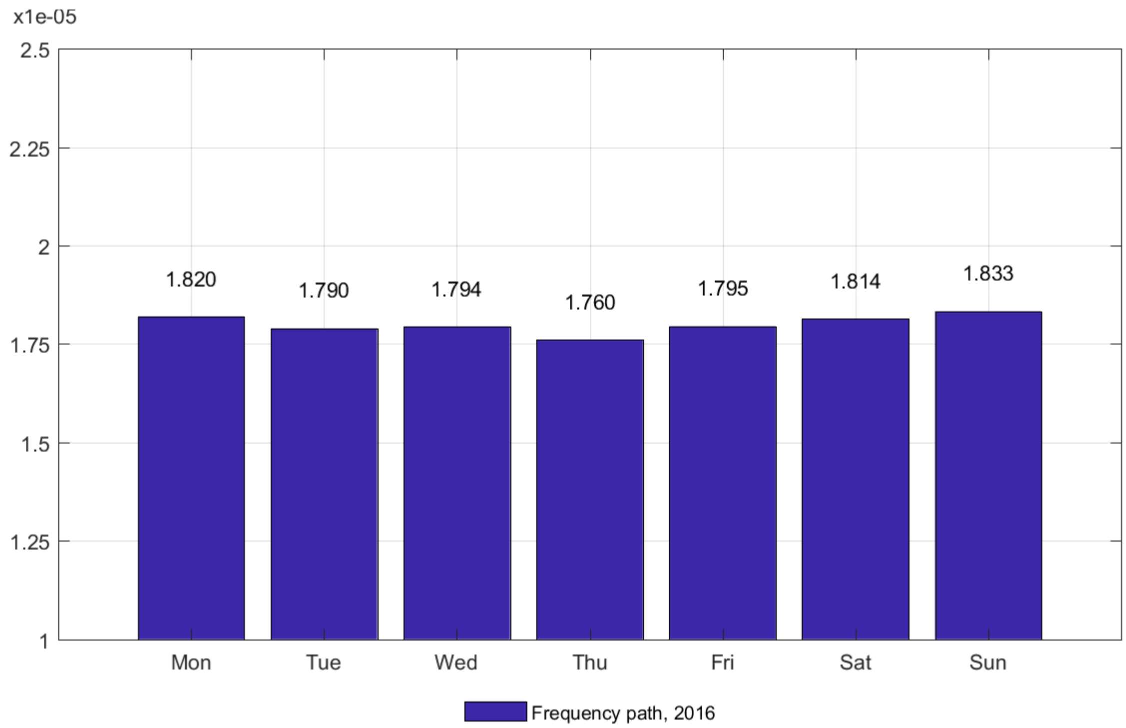


Figure 3.54 shows the frequency path during the day. The path is longer closer to the shift of the day and shorter around noon.

***Figure 3.54**. Length of the frequency path for every hour of the day in 2016*

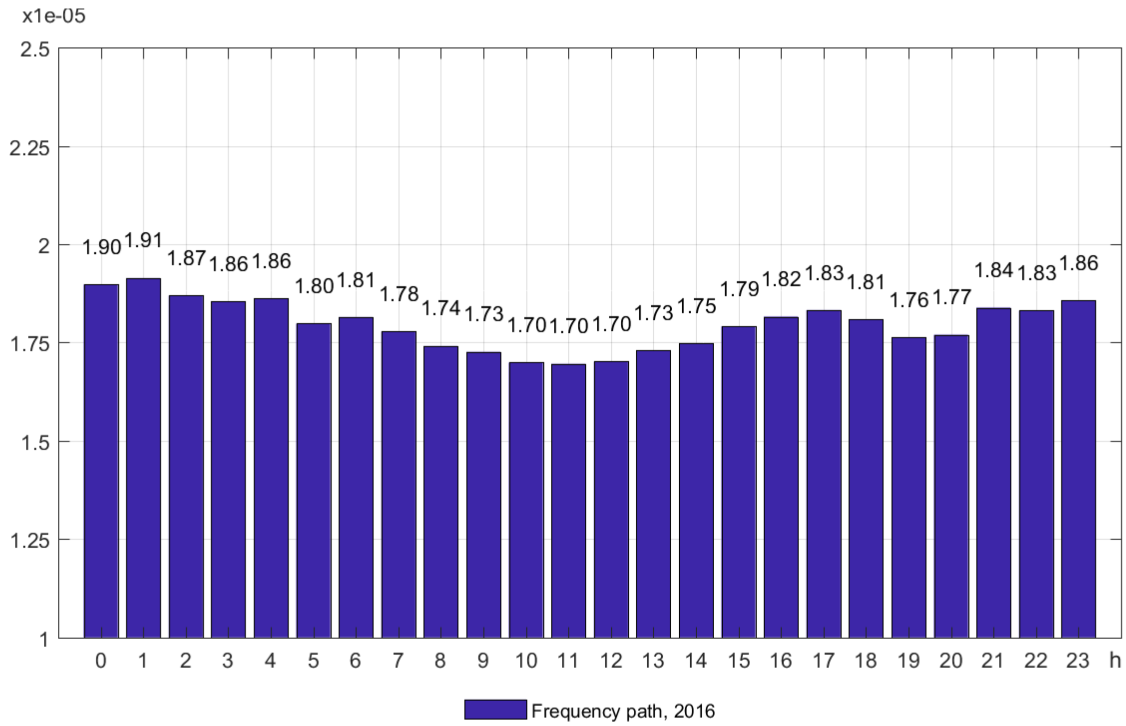
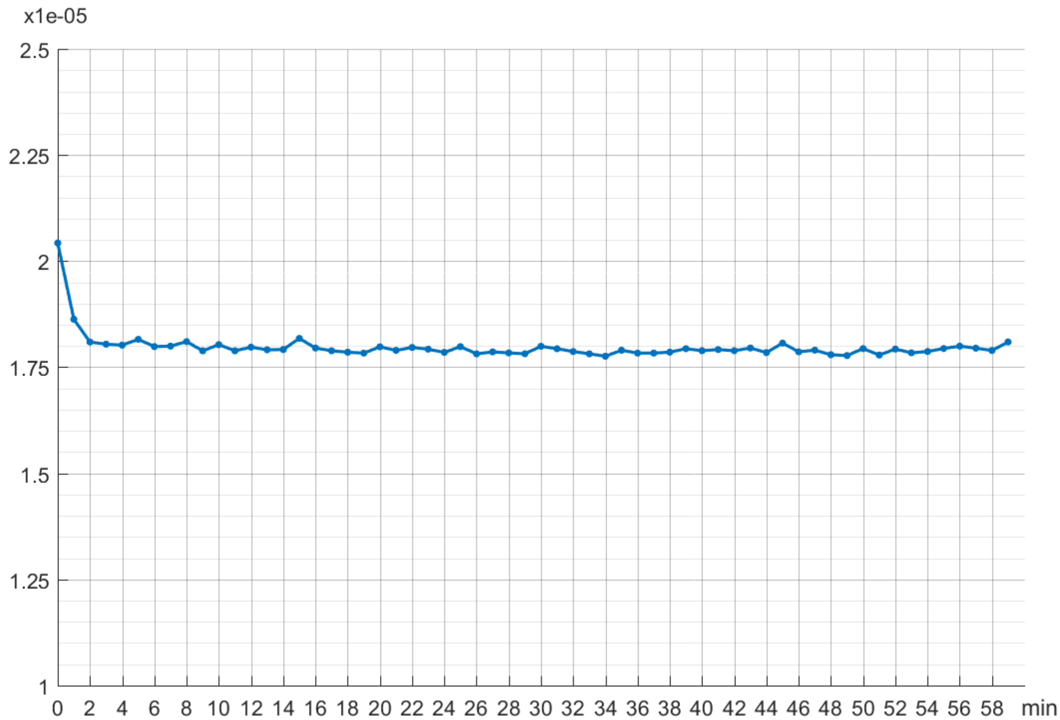


Figure 3.55 represents the average frequency path for every minute inside the hour. The path is longer during the first minutes of the hour, but otherwise it stays pretty even throughout the hour.

***Figure 3.55**. Length of the frequency path for every minute of the hour in 2016*



3.8 Amount of frequency oscillation

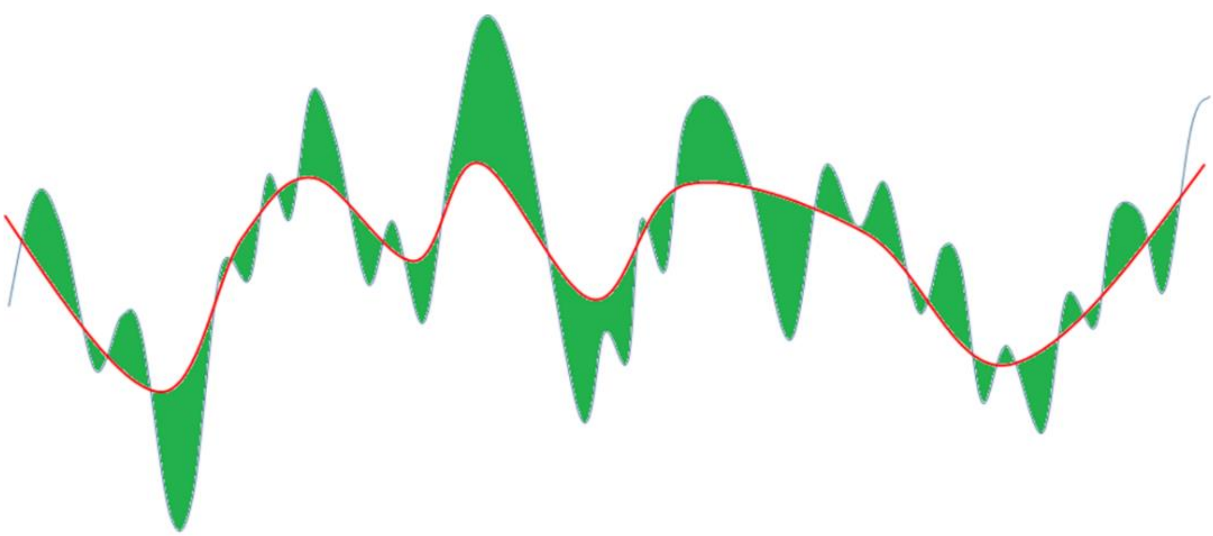
Frequency of the Nordic synchronous system oscillates constantly. Time period of the oscillation is approximately 40 to 90 seconds. This behavior is a natural characteristic of the system but it can be influenced through adequate settings of system reserves. Oscillation has an increasing effect on the 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 [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 3.56 [8].

***Figure 3.56**. 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 3.57. Frequency bands corresponding to the 40-90 s and 30-240 s bands are marked on the figure. Figure 3.58 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 3.57. 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]

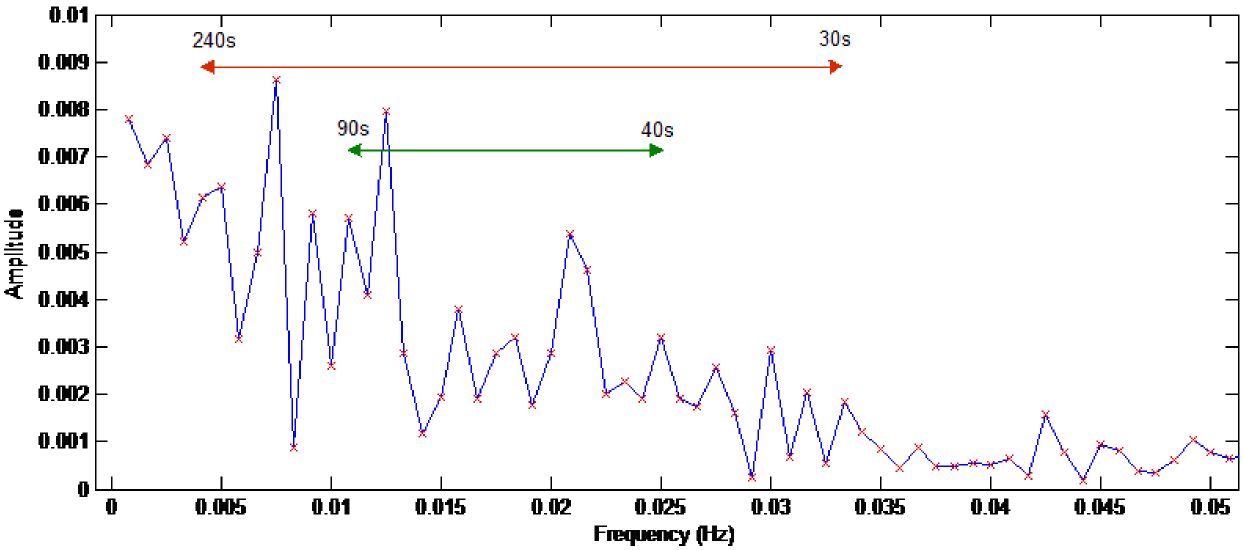
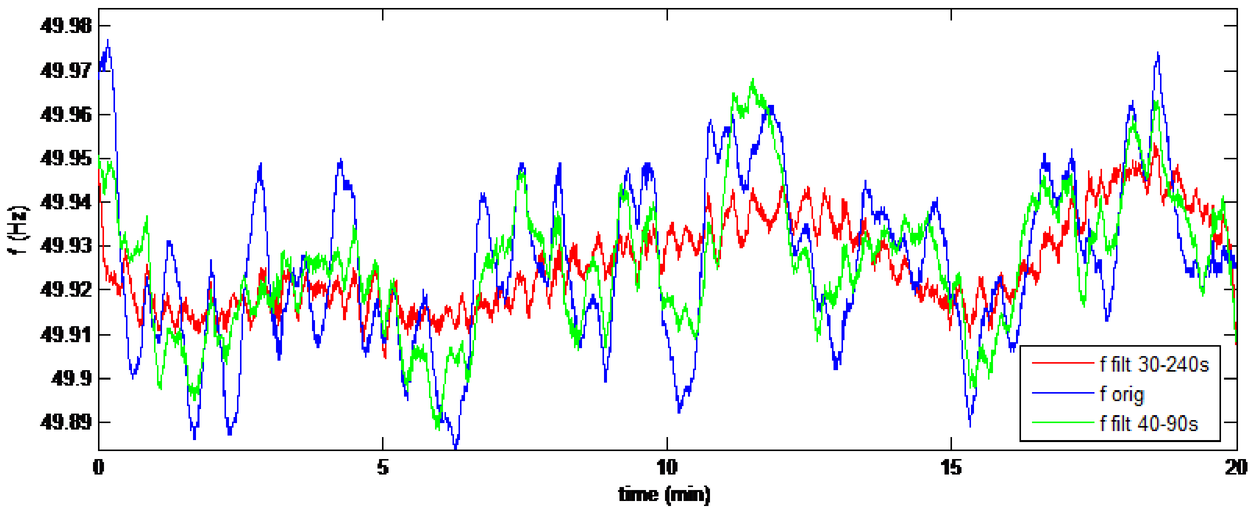


Figure 3.58. Original frequency (blue), frequency with 40-90 s band filtered (green) and frequency with 30-240 s band filtered (red). First 20 minutes of December 2012 are shown (UTC+2) [8]



3.8.2 Amount of oscillation

Figure 3.59 shows hourly values and 24 hour moving averages for the amount of oscillation in 2016. 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. There is a slight drop in oscillation at the end of July. January had the least amount of oscillation in 2016.

Figures 3.60 and 3.61 contain the previously mentioned 24 hour moving averages for years 2011-2013 and 2014-2016, 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.

Figure 3.59**. **Amount of oscillation in 2016

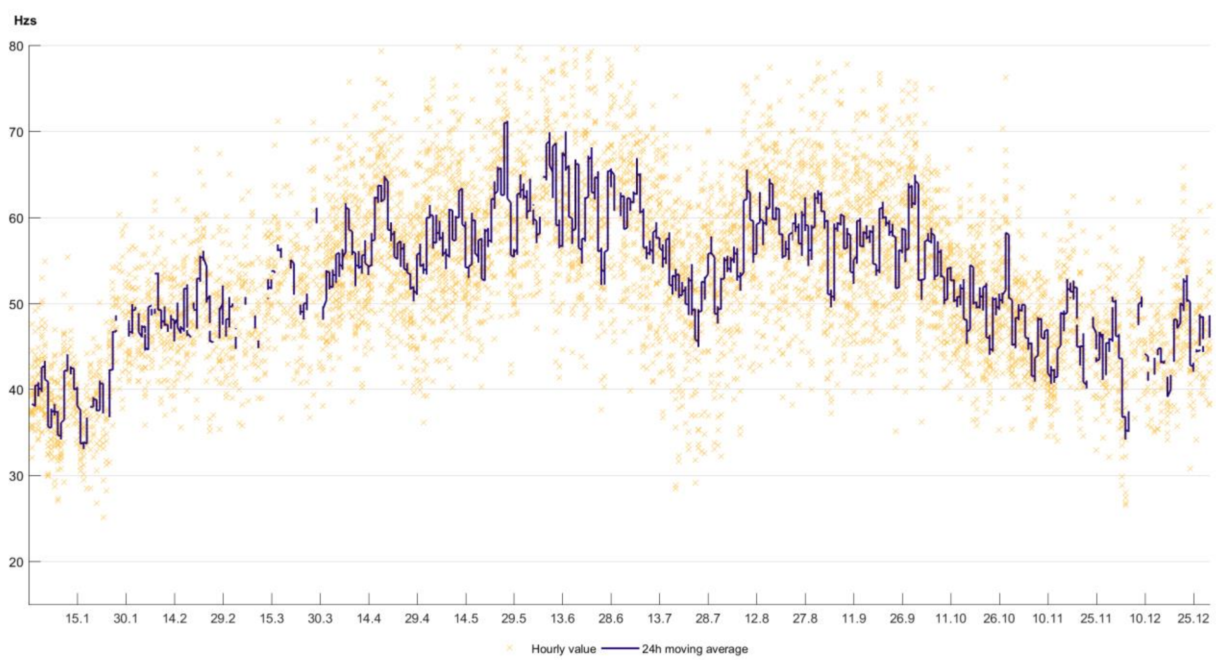


***Figure 3.60**. Amount of oscillation in 2011-2013*

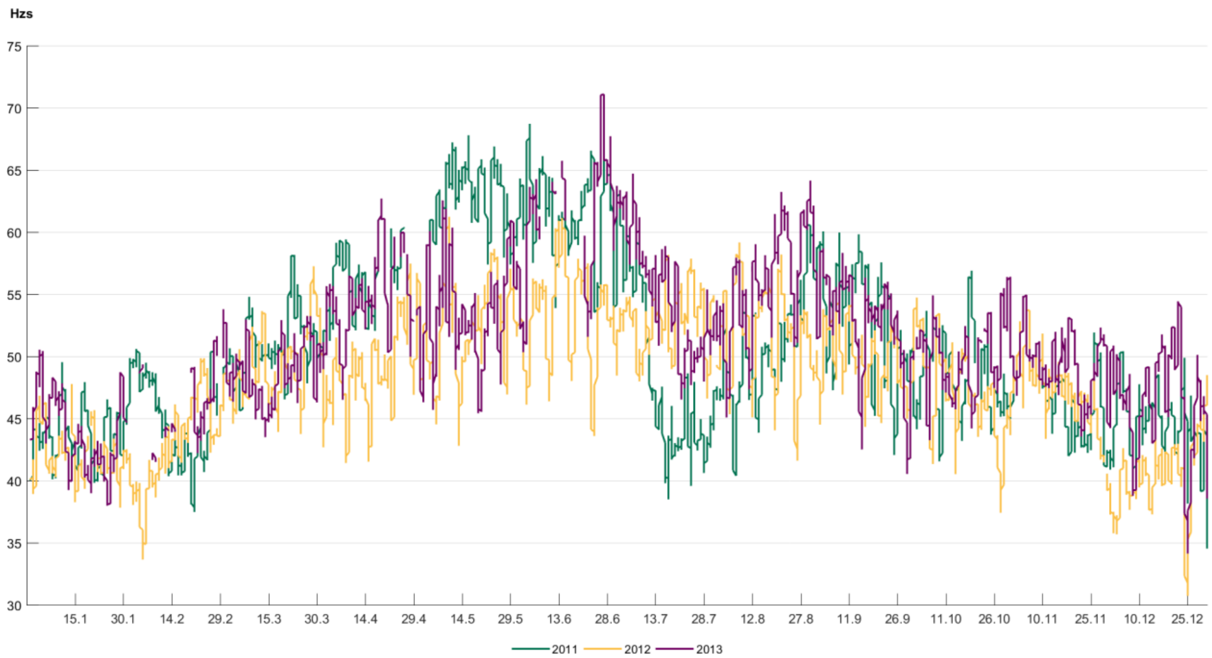
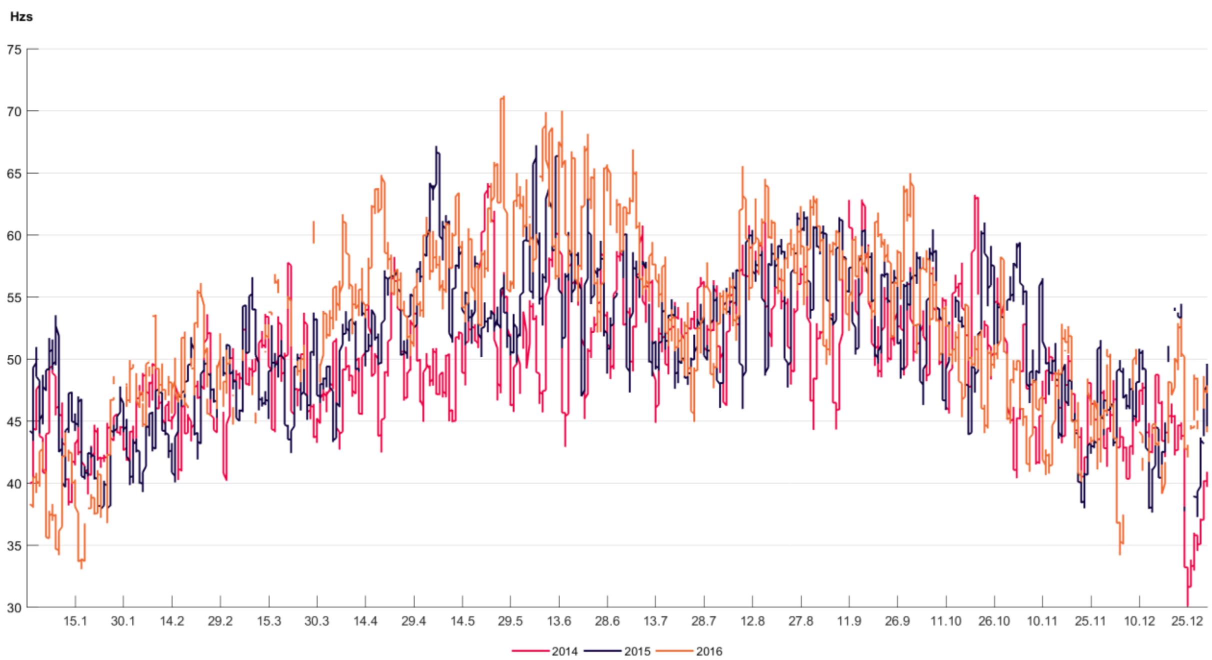


***Figure 3.61**. Amount of oscillation in 2014-2016*



Mean value of the oscillation and standard deviation for each month from 2011 to 2016 are shown in Table 3.24 and 3.25. Figure 3.62 represents the same information in a visual form. In year 2016 frequency has oscillated the most between May and September. Frequency oscillated more in 2016 than in previous year 2015. Year 2016 has been among the worst years in terms of oscillation.

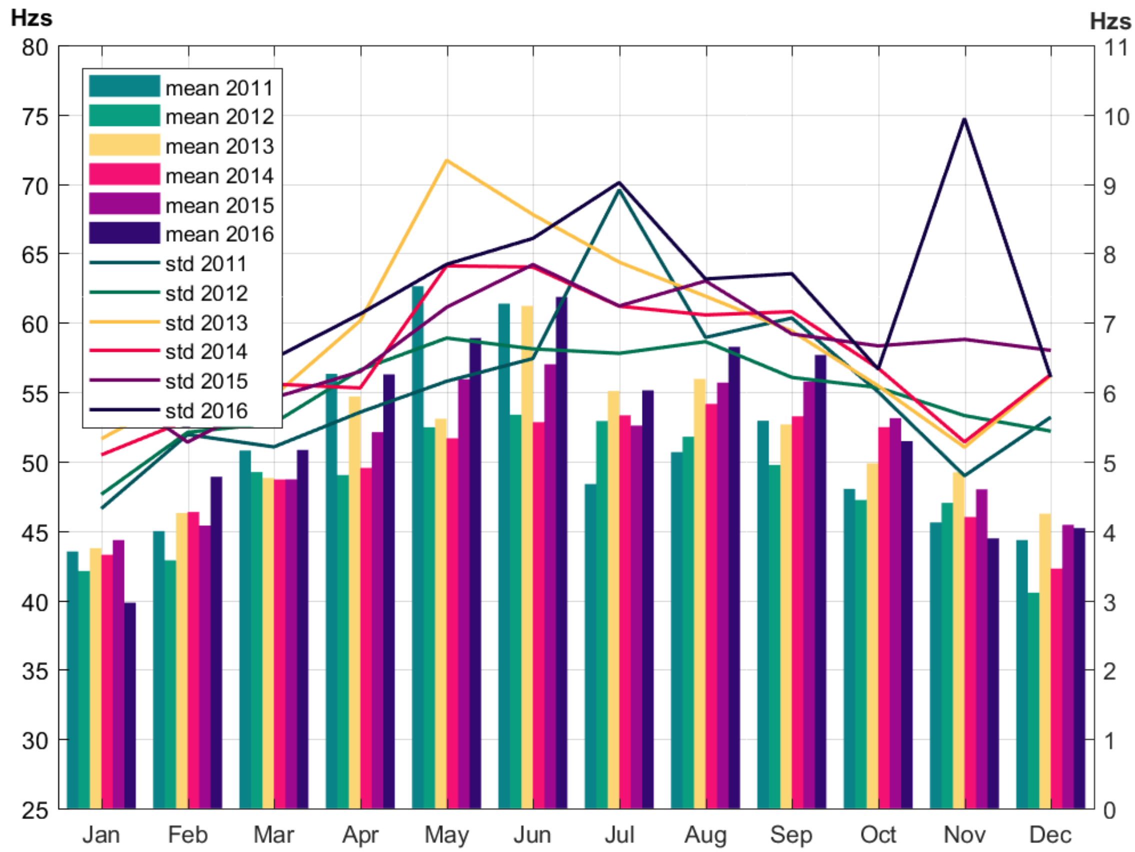
Table 3.24. Mean values and standard deviations for oscillation in years 2011-2013

	Mean value (Hzs)			**Standard deviation (Hzs)**		
Month	**2011**	**2012**	**2013**	**2011**	**2012**	**2013**
January	43.5	42.1	43.8	4.3	4.5	5.3
February	45.0	42.9	46.3	5.4	5.4	6.0
March	50.8	49.2	48.8	5.2	5.6	5.9
April	56.3	49.0	54.7	5.7	6.3	7.0
May	62.6	52.5	53.1	6.2	6.8	9.3
June	61.4	53.4	61.2	6.5	6.6	8.6
July	48.4	52.9	55.1	8.9	6.6	7.9
August	50.7	51.8	56.0	6.8	6.7	7.4
September	52.9	49.8	52.7	7.1	6.2	6.9
October	48.0	47.2	49.9	6.0	6.1	6.1
November	45.6	47.0	49.2	4.8	5.7	5.2
December	44.3	40.5	46.2	5.6	5.4	6.2
Entire year	**50.8**	**48.2**	**51.4**	**6.0**	**6.0**	**6.8**

Table 3.25. Mean values and standard deviations for oscillation in years 2014-2016

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

***Figure 3.62**. Mean values (left y-axis) and standard deviations (right y-axis) for oscillation in years 2011-2016*

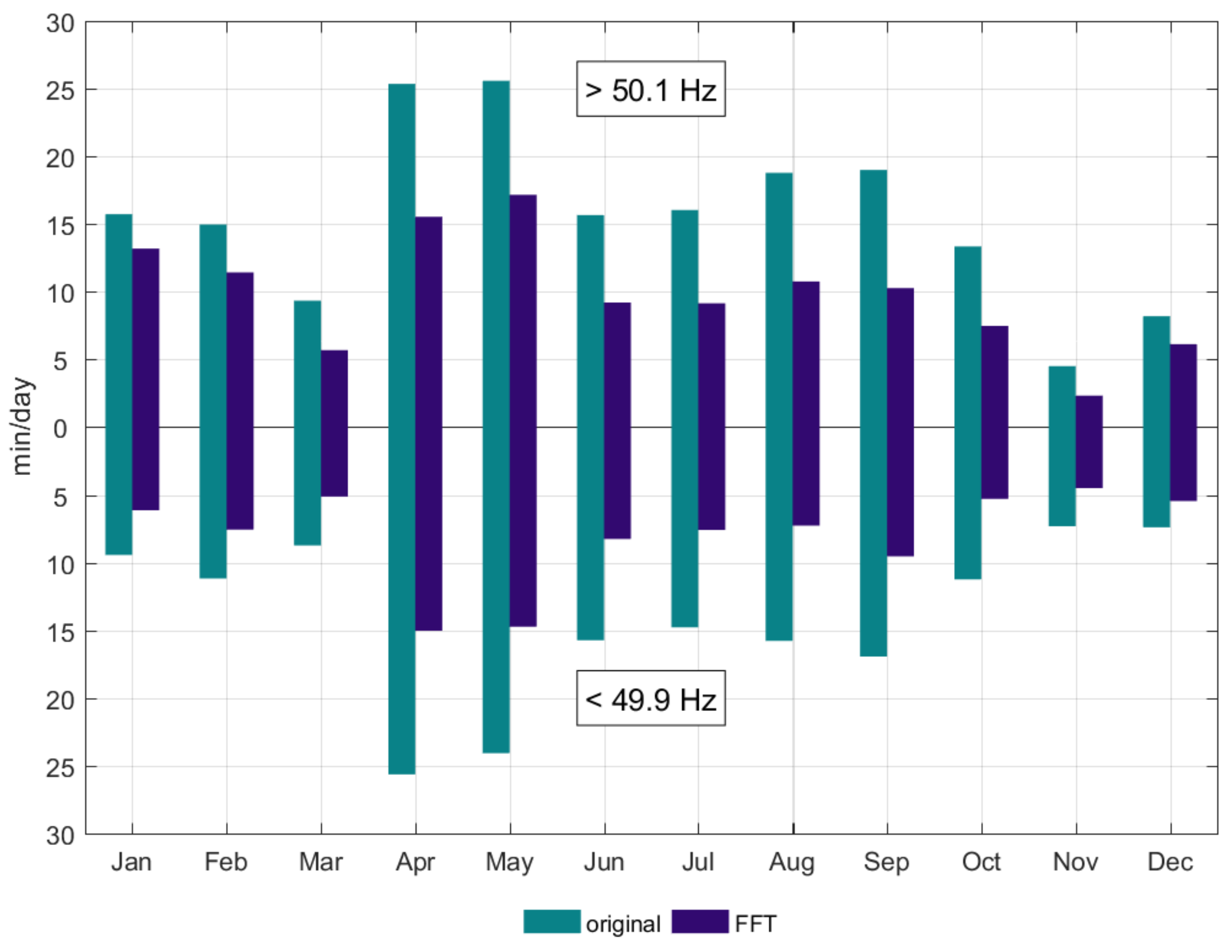


3.8.3 Influence of oscillation on frequency variations

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

Figure 3.63 shows the average minutes per day outside the standard frequency range in 2016 without filtering and after applying FFT-filtering. Figure 3.63 shows the average only for minutes per day outside the standard frequency range that had enough consecutive samples for one hour periods for the FFT-algorithm.

***Figure 3.63**. Average time per day outside the standard frequency range in 2016*



In Figure 3.64, the reduction of time outside the standard frequency range through filtering is presented as percentages of the original values. The results show that filtering leads to significant reduction in time outside the standard frequency range.

***Figure 3.64**. Reduction in time per month outside the standard frequency range after filtering in 2016*

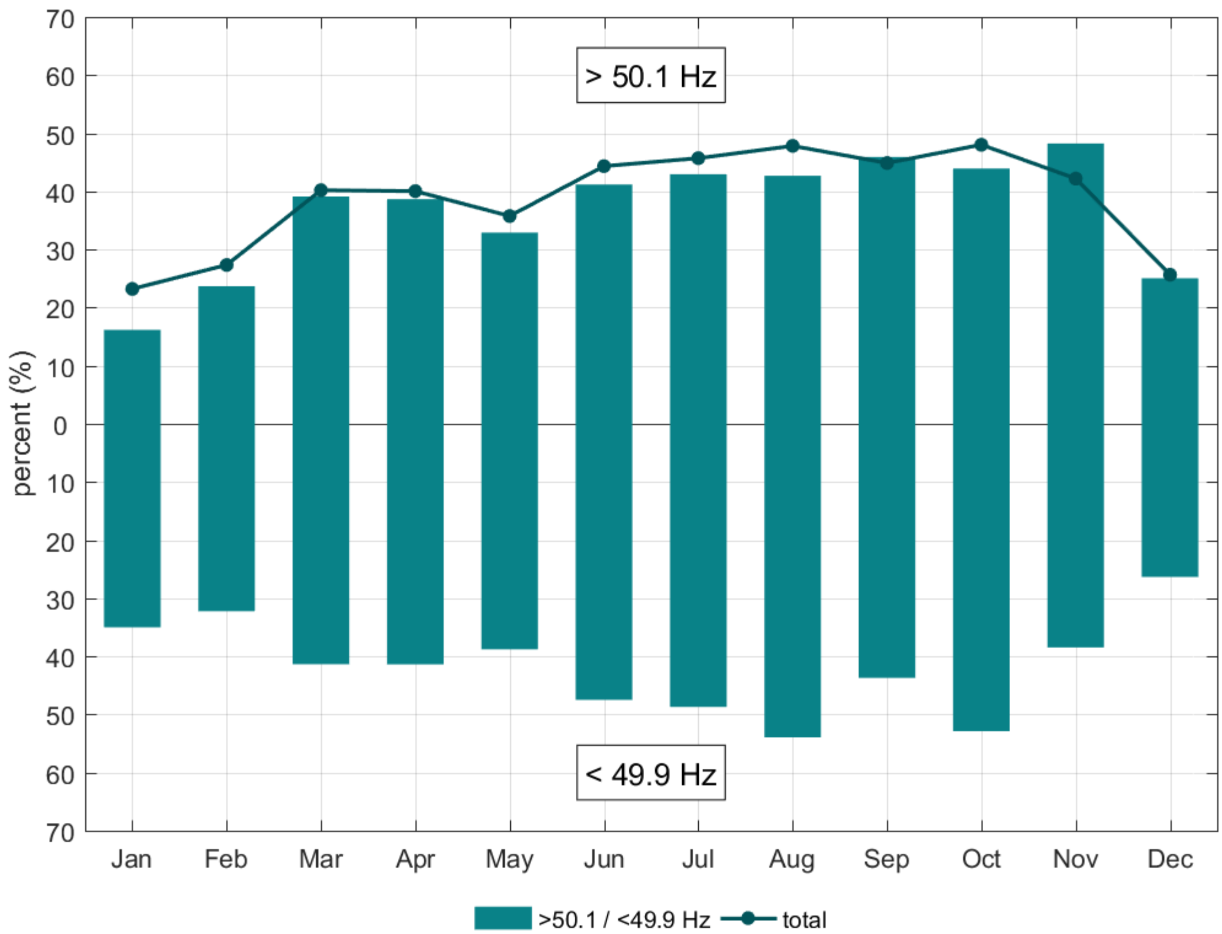
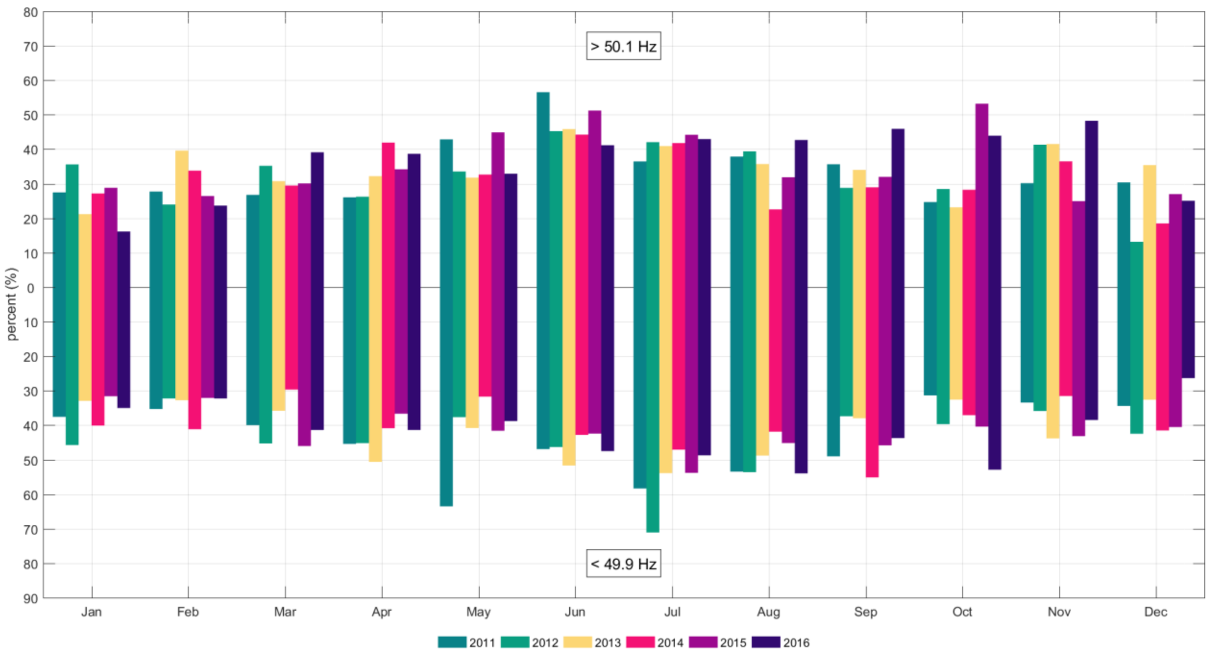


Figure 3.65 represents the reduction in time outside the standard frequency range in percentages month by month for years 2011 to 2016.

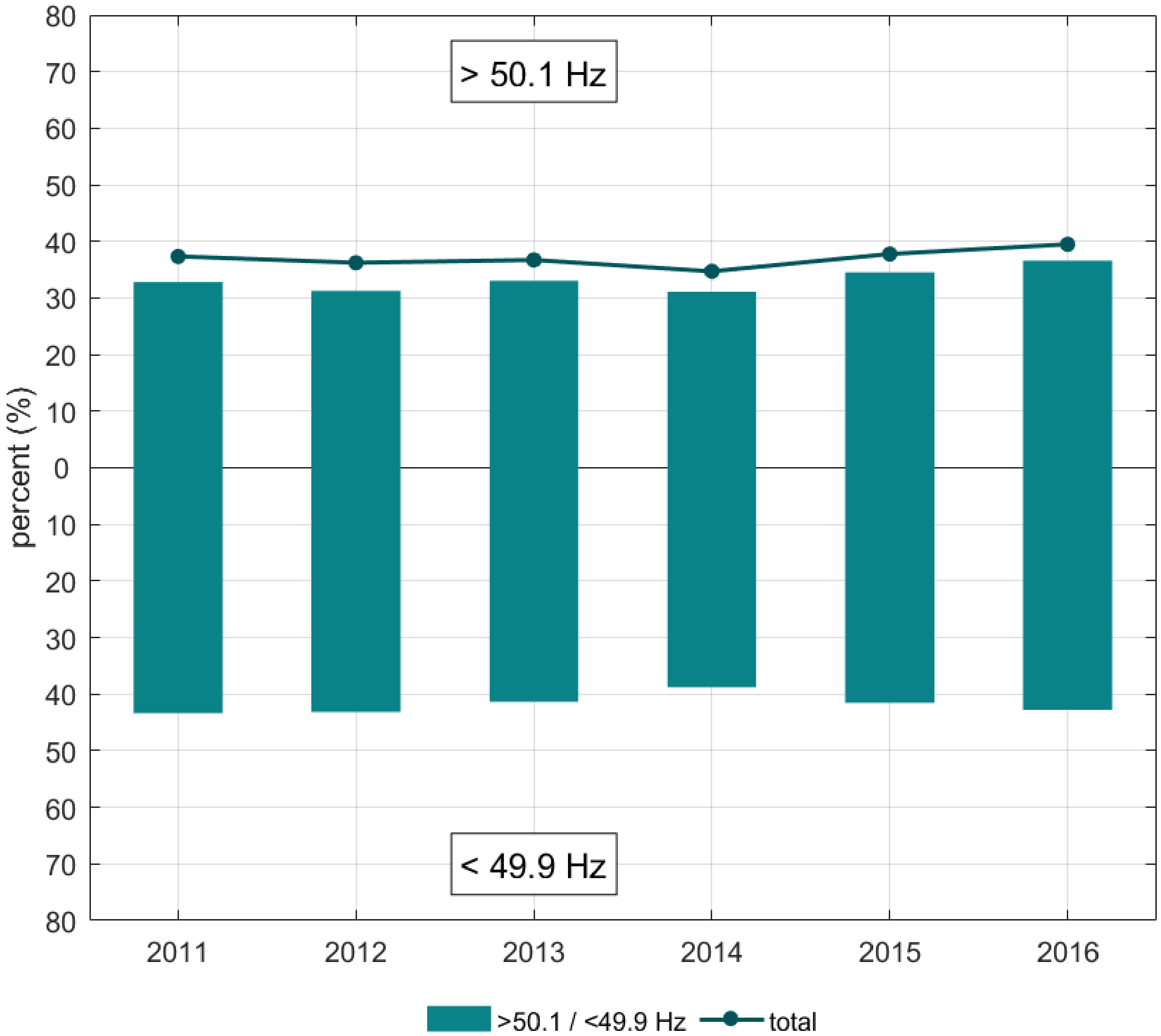
***Figure 3.65**. Reduction in time per month outside the standard frequency range after filtering in years 2011-2016*



In addition to the monthly values presented in the previous figure, results for the entire year in 2011-2016 are shown below in Figure 3.66.

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 3.66**. Reduction in time outside the standard frequency range after filtering for years 2011-2016*



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 2011-2016. The same results are presented in a graphical form in Figure 3.67

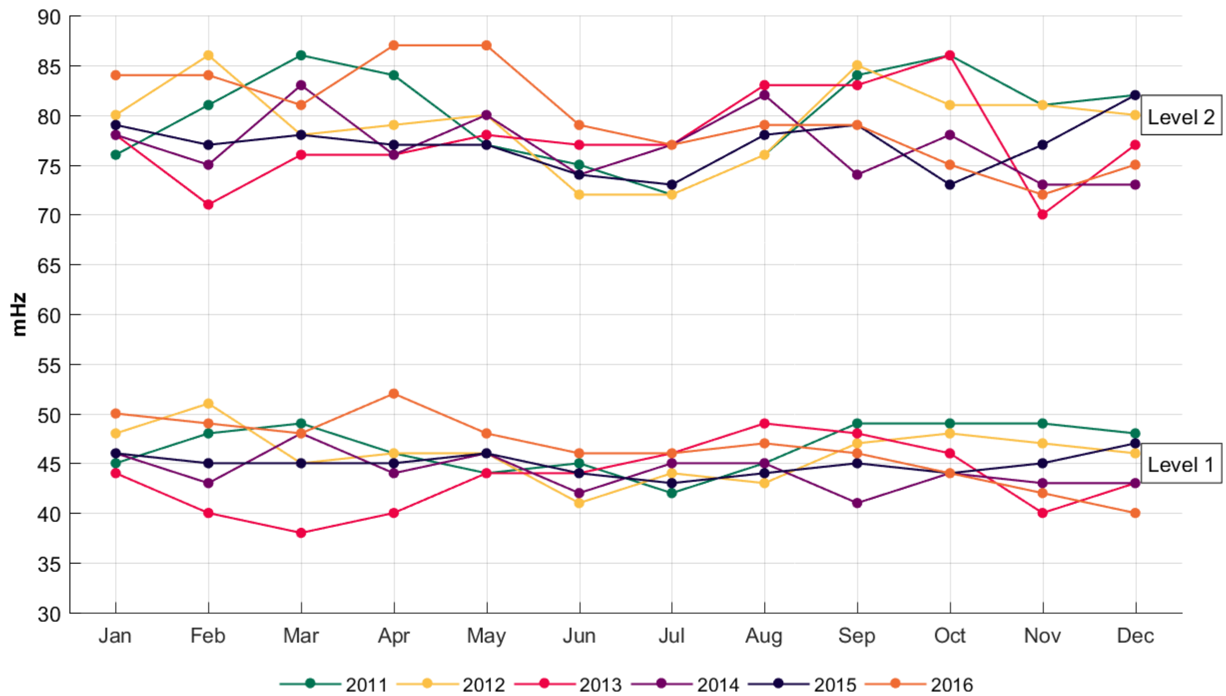
Table 3.26. FRCE Ranges for NE, calculated with 15 min moving averages, years 2011-2013

	2011		**2012**		**2013**	
Month	**Level 1 (mHz)**	**Level 2 (mHz)**	**Level 1 (mHz)**	**Level 2 (mHz)**	**Level 1 (mHz)**	**Level 2 (mHz)**
January	±45	±76	±48	±80	±44	±78
February	±48	±81	±51	±86	±40	±71
March	±49	±86	±45	±78	±38	±76
April	±46	±84	±46	±79	±40	±76
May	±44	±77	±46	±80	±44	±78
June	±45	±75	±41	±72	±44	±77
July	±42	±72	±44	±72	±46	±77
August	±45	±76	±43	±76	±49	±83
September	±49	±84	±47	±85	±48	±83
October	±49	±86	±48	±81	±46	±86
November	±49	±81	±47	±81	±40	±70
December	±48	±82	±46	±80	±43	±77
Entire year	**±47**	**±80**	**±46**	**±79**	**±44**	**±78**

Table 3.27. FRCE Ranges for NE, calculated with 15 min moving averages, years 2014-2016

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

***Figure 3.67**. FRCE Ranges for years 2011-2016 calculated with 15 min moving averages*



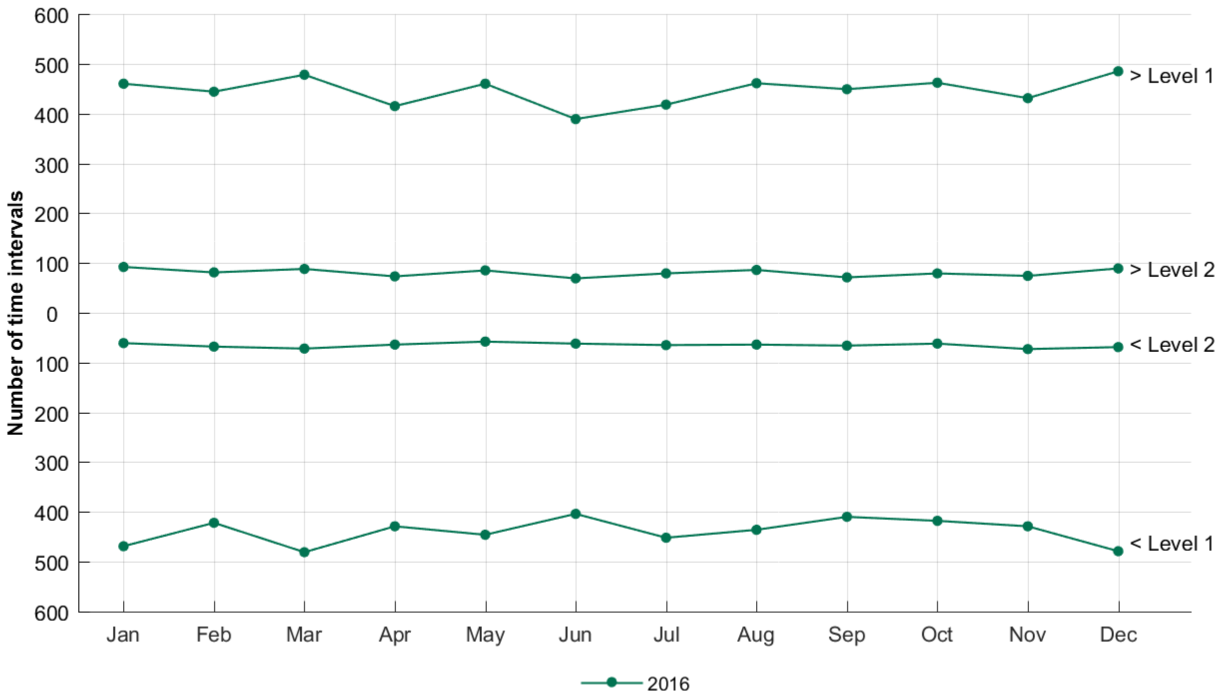
3.9.2 Number of time intervals outside Level 1 and Level 2 FRCE Range

Table 3.28 shows the number of 15 minute time intervals over Level 1 and Level 2 FRCE Ranges in year 2016. 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 3.68 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 2016

	2016			
Month	**> Level 1 (+)**	**< Level 1 (-)**	**> Level 2 (+)**	**< Level 2 (-)**
January	460	469	92	61
February	444	422	81	68
March	478	481	88	72
April	415	429	73	64
May	460	446	85	58
June	389	404	69	62
July	418	452	79	65
August	461	436	86	64
September	449	410	71	66
October	462	418	79	62
November	431	429	74	73
December	485	479	89	69
Entire year	**5352**	**5275**	**966**	**784**

Figure 3.68*. *The number of time intervals over positive and under negative FRCE Level 1 and Level 2 Ranges for year 2016



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 2016. Of the total samples in a period, the 1st, 5th, 10th, 50th, 90th, 95th and 99th percentile are determined. Figure 3.69 shows the definition of deterministic frequency deviation. The resolution of the frequency data was 1 second.

***Figure 3.69**. Definition of deterministic frequency deviation [7]*

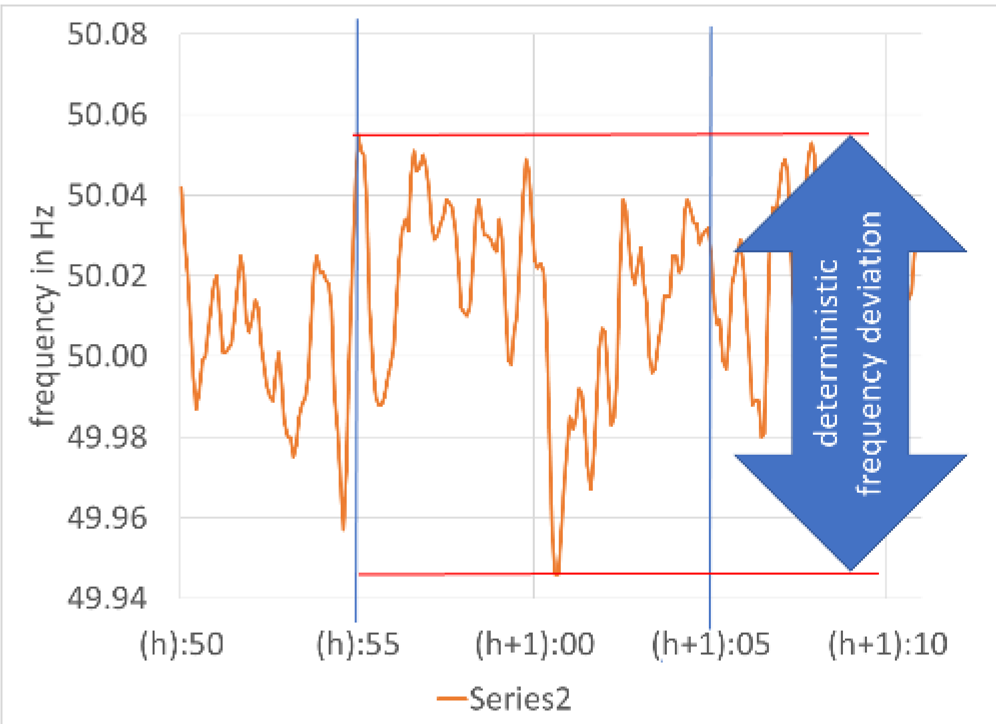


Figure 3.70 represents the deterministic frequency deviation per month in 2016. The 50th percentile stays below zero for the entire year, which indicates that the highest frequency took place before the lowest in more than half of the hour shifts.

***Figure 3.70**. The 1st, 5th, 10th, 50th, 90th, 95th, and 99th percentile of deterministic frequency deviation for every month in 2016*

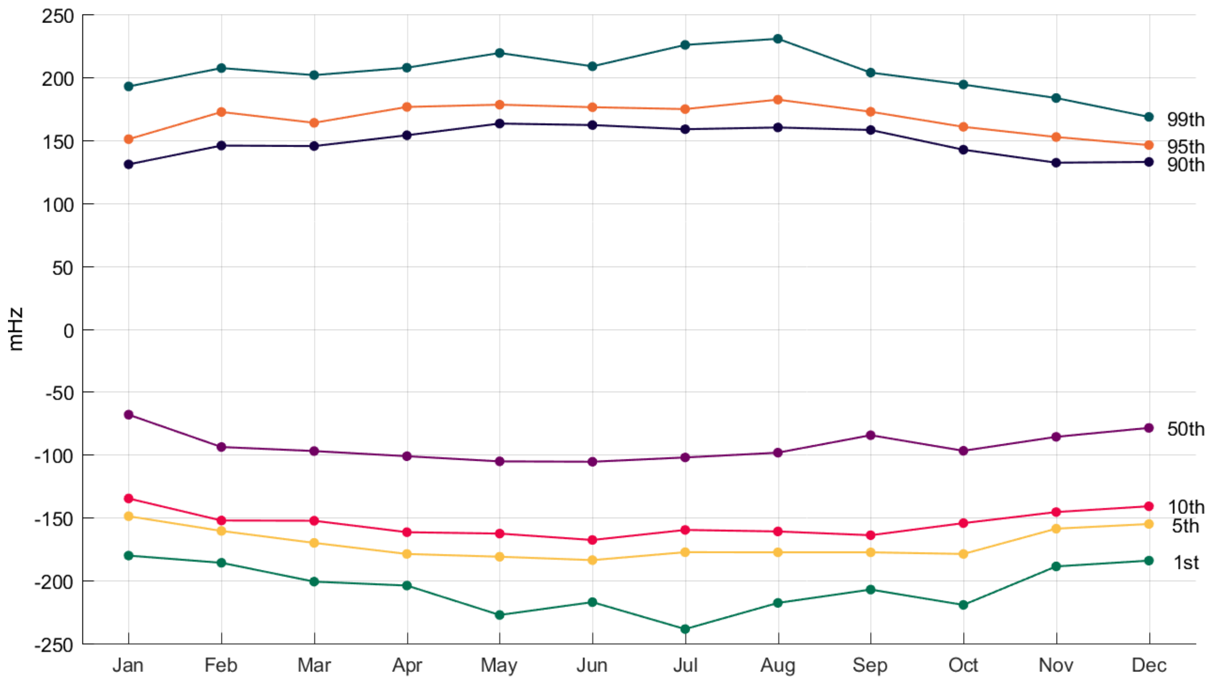
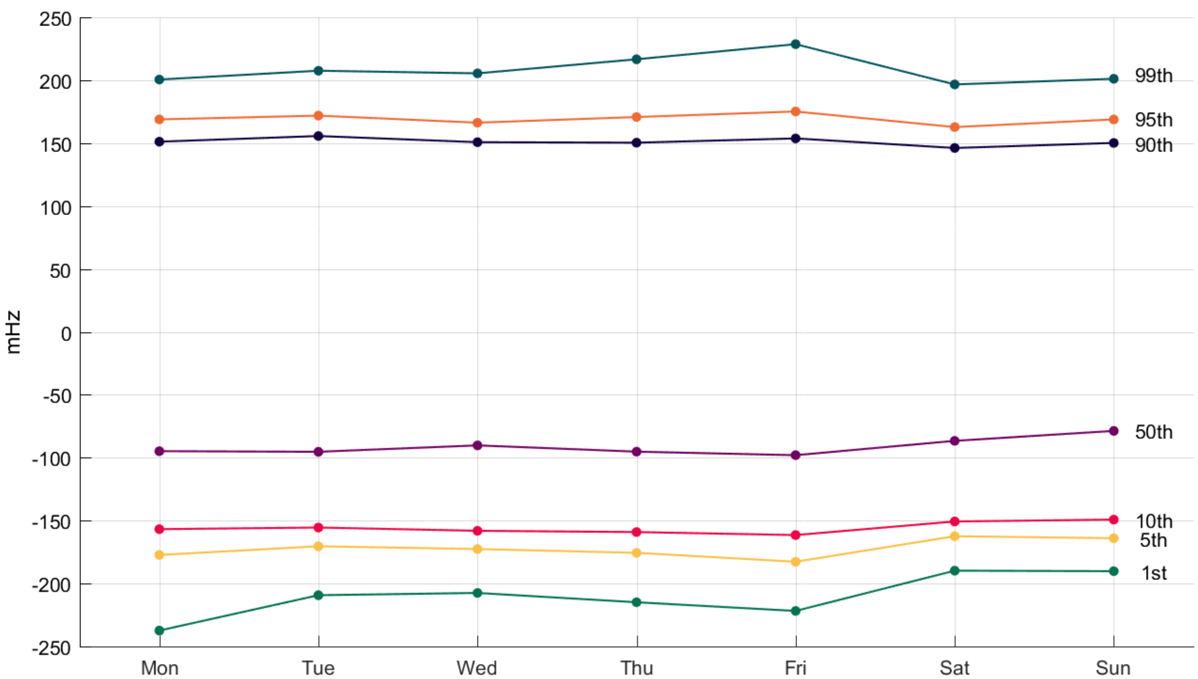


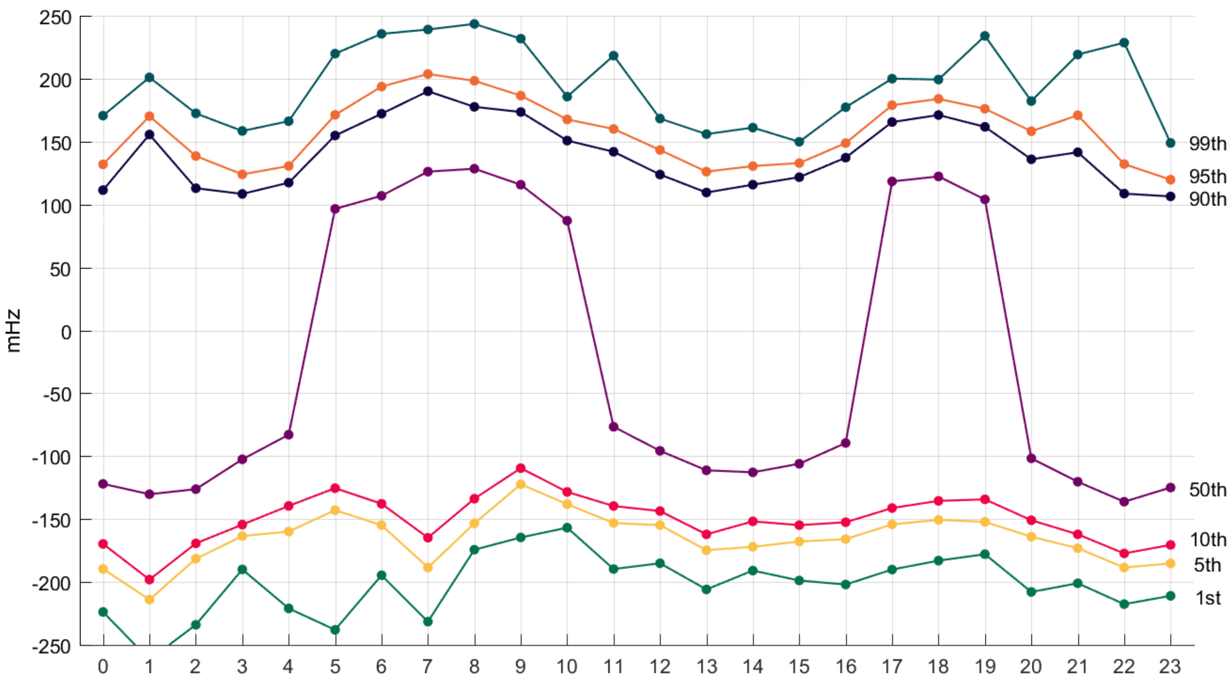
Figure 3.71 shows the percentiles around the hour shift for every day of the week in 2016. The 1st, 5th, 10th and 50th percentile are all a touch higher during the weekends.

***Figure 3.71**. The 1st, 5th, 10th, 50th, 90th, 95th, and 99th percentile of deterministic frequency deviation for every day of the week in 2016*



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

***Figure 3.72**. The 1st, 5th, 10th, 50th, 90th, 95th, and 99th percentile of deterministic frequency deviation for every hour of the day in 2016*



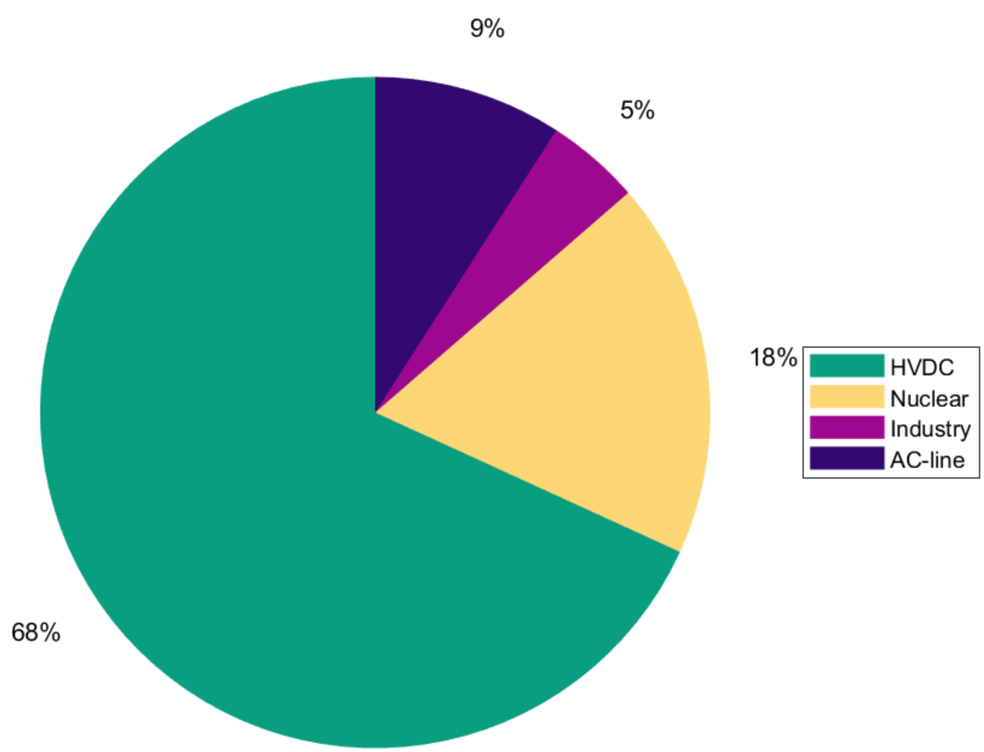
Chapter 4. Frequency disturbances exceeding 300 mHz frequency deviation

This chapter offers information of the major frequency disturbances in the Nordic synchronous system in the year 2016. 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 second most common cause for disturbances were failures in nuclear power production.

***Figure 4.1**. Shares of factors causing over 300 mHz disturbances in the Nordic synchronous system in 2016*



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. Rest of the disturbances were caused by faults in AC-lines and industry, which led to under frequencies.

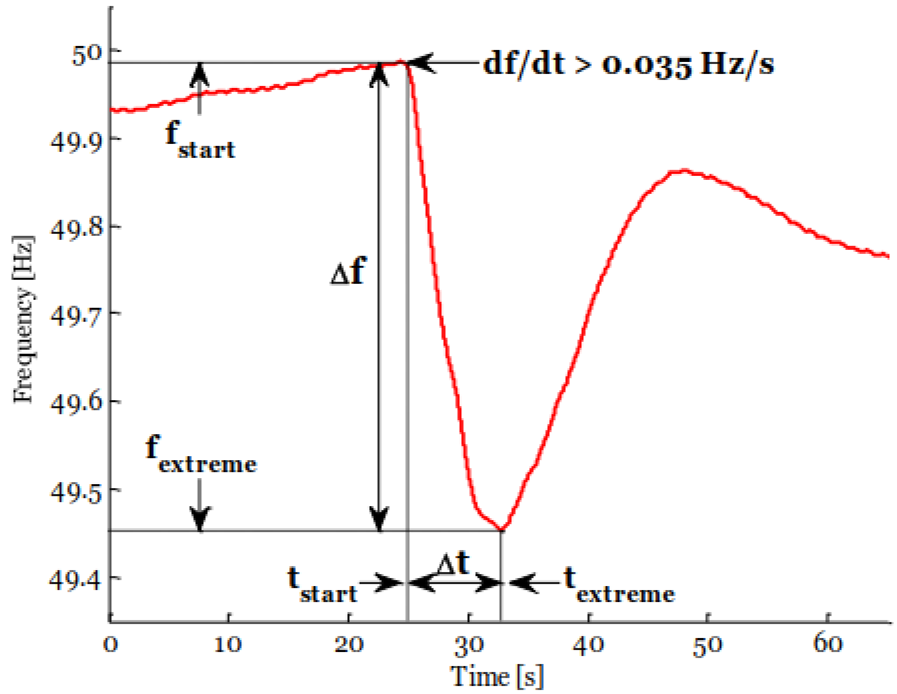
The largest maximum frequency deviation was caused by failure in AC-line on the 4th of July with a value of 0.454 Hz. This also caused the lowest instantaneous frequency of 49.553 Hz. The highest instantaneous frequency value was 50.360 Hz caused by the tripping of HVDC link on the 15th of May.

The following part of the chapter will go into more detail on every disturbance that took place in 2016. 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 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]

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. [11]

More detailed descriptions of the events listed in Table 4.1 are presented afterwards in Figures 4.3-24 and Tables 4.2-23.

Table 4.1. List of disturbance events in 2016

Event date	Δf (Hz)	ΔP (MW)	Δt (s)	E_k (GWs)	Cause	Page
12-Jan-2016 10:22:53	-0.335	1167	9.0	274	Nuclear	109
09-Feb-2016 22:05:28	0.214	880	8.3	252	HVDC	110
20-Feb-2016 10:45:31	-0.348	1000	10.7	227	Nuclear	111
24-Feb-2016 12:30:29	0.228	700	9.0	251	HVDC	112
21-Mar-2016 11:59:50	0.269	723	7.3	248	HVDC	113
06-Apr-2016 13:49:55	0.230	700	6.7	221	HVDC	114
14-Apr-2016 10:07:07	0.234	700	6.7	240	HVDC	115
20-Apr-2016 09:31:18	0.249	700	7.1	224	HVDC	116
21-Apr-2016 11:43:42	0.283	700	7.9	222	HVDC	117
15-May-2016 01:56:13	0.339	720	7.0	162	HVDC	118
18-May-2016 22:08:27	0.266	700	6.3	205	HVDC	119
20-Jun-2016 17:10:09	-0.389	700	8.8	175	AC-line	120
25-Jun-2016 22:28:59	0.347	600	7.1	154	HVDC	121
27-Jun-2016 05:01:25	-0.263	400	8.9	131	Industry	122
04-Jul-2016 14:41:01	-0.454	1026	9.0	192	AC-line	123
12-Jul-2016 14:42:29	0.322	670	8.0	189	HVDC	124
26-Jul-2016 22:52:43	0.337	700	7.9	191	HVDC	125
05-Aug-2016 11:08:09	0.230	500	8.4	188	HVDC	126
12-Aug-2016 21:39:46	-0.313	500	10.8	174	Nuclear	127

28-Aug-2016 23:06:07	-0.244	590	8.4	180	HVDC	128
03-Oct-2016 21:21:17	0.290	700	7.9	205	HVDC	129
08-Oct-2016 23:14:51	-0.358	880	9.4	196	Nuclear	130

***Figure 4.3**. Disturbance 12-Jan-2016 10:22:53*

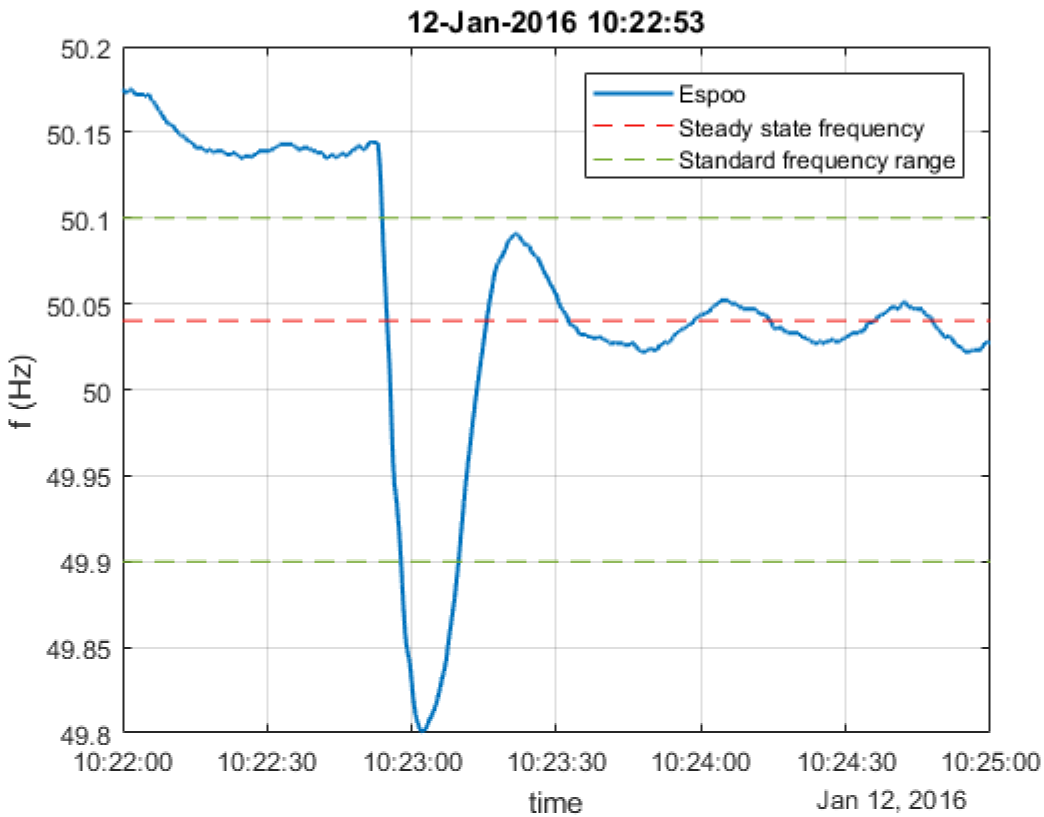


***Table 4.2**. Disturbance 12-Jan-2016 10:22:53*

Date		**12-Jan-2016 10:22:53**	
f_{start}	50.136 Hz	$f_{steady\ state}$	50.040 Hz
$f_{extreme}$	49.801 Hz	$\Delta f_{steady\ state}$	0.096 Hz
Δf	-0.335 Hz	$f_{extreme2}$	50.091 Hz
Δt	9.0 s	$f_{extreme3}$	50.022 Hz
ΔP	1167 MW	damping	23.77 %
E_k	274 GWs	FBF	12122 MW/Hz
cause		Nuclear	

Figure 4.4. Disturbance 09-Feb-2016 22:05:28

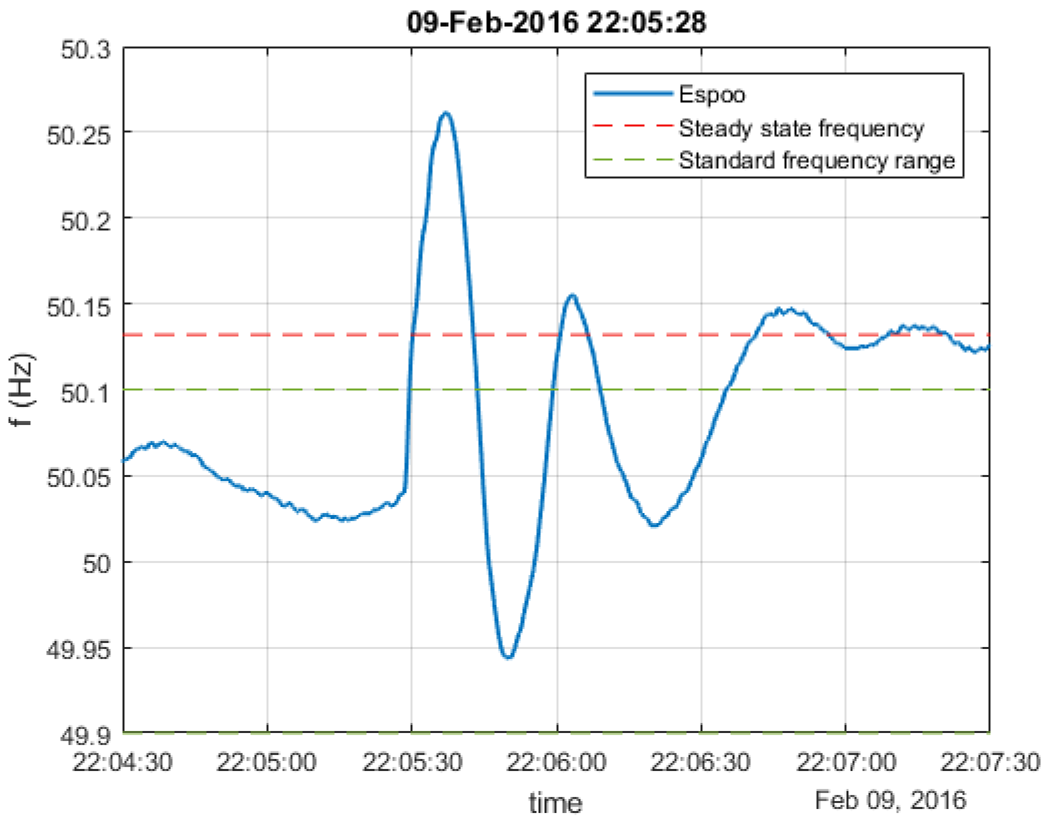


Table 4.3. Disturbance 09-Feb-2016 22:05:28

Date		**09-Feb-2016 22:05:28**	
f_{start}	50.047 Hz	$f_{steady\ state}$	50.132 Hz
$f_{extreme}$	50.261 Hz	$\Delta f_{steady\ state}$	0.085 Hz
Δf	0.214 Hz	$f_{extreme2}$	49.944 Hz
Δt	8.3 s	$f_{extreme3}$	50.155 Hz
ΔP	880 MW	damping	66.53 %
E_k	252 GWs	FBF	10376 MW/Hz
cause		HVDC	

Figure 4.5. Disturbance 20-Feb-2016 10:45:31

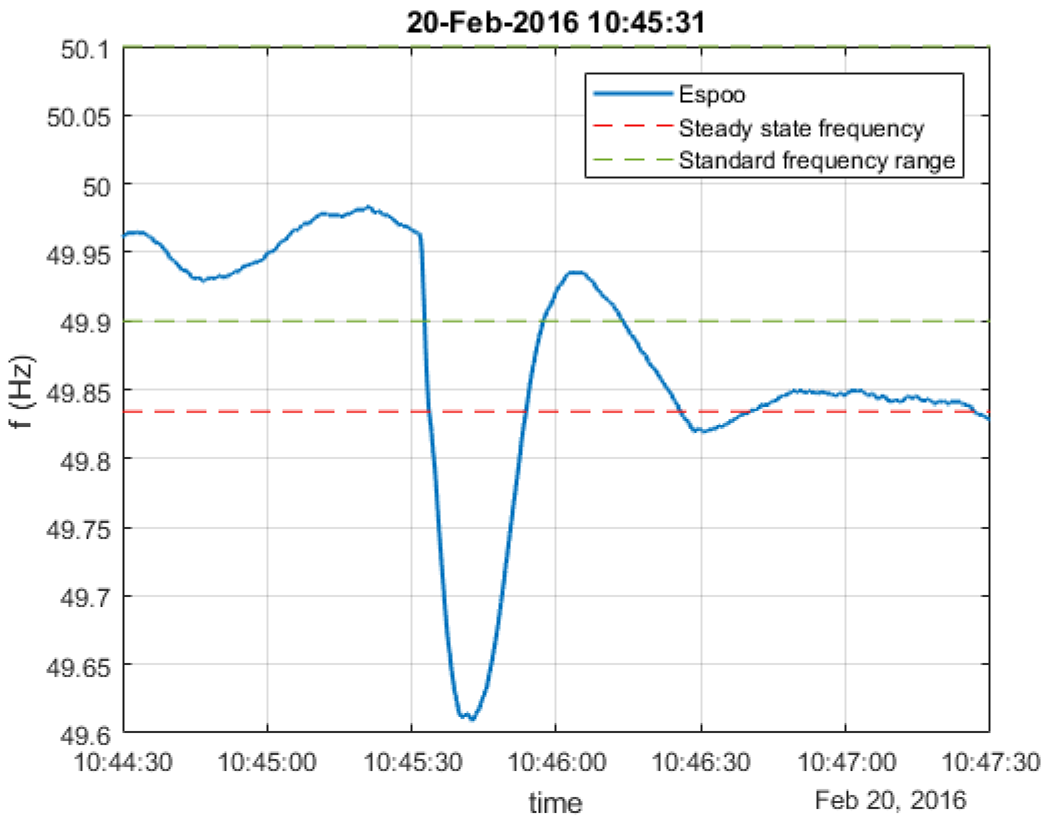


Table 4.4. Disturbance 20-Feb-2016 10:45:31

Date		**20-Feb-2016 10:45:31**	
f_{start}	49.957 Hz	$f_{steady\ state}$	49.834 Hz
$f_{extreme}$	49.609 Hz	$\Delta f_{steady\ state}$	0.123 Hz
Δf	-0.348 Hz	$f_{extreme2}$	49.935 Hz
Δt	10.7 s	$f_{extreme3}$	49.819 Hz
ΔP	1000 MW	damping	35.47 %
E_k	227 GWs	FBF	8133 MW/Hz
cause		Nuclear	

Figure 4.6. Disturbance 24-Feb-2016 12:30:29

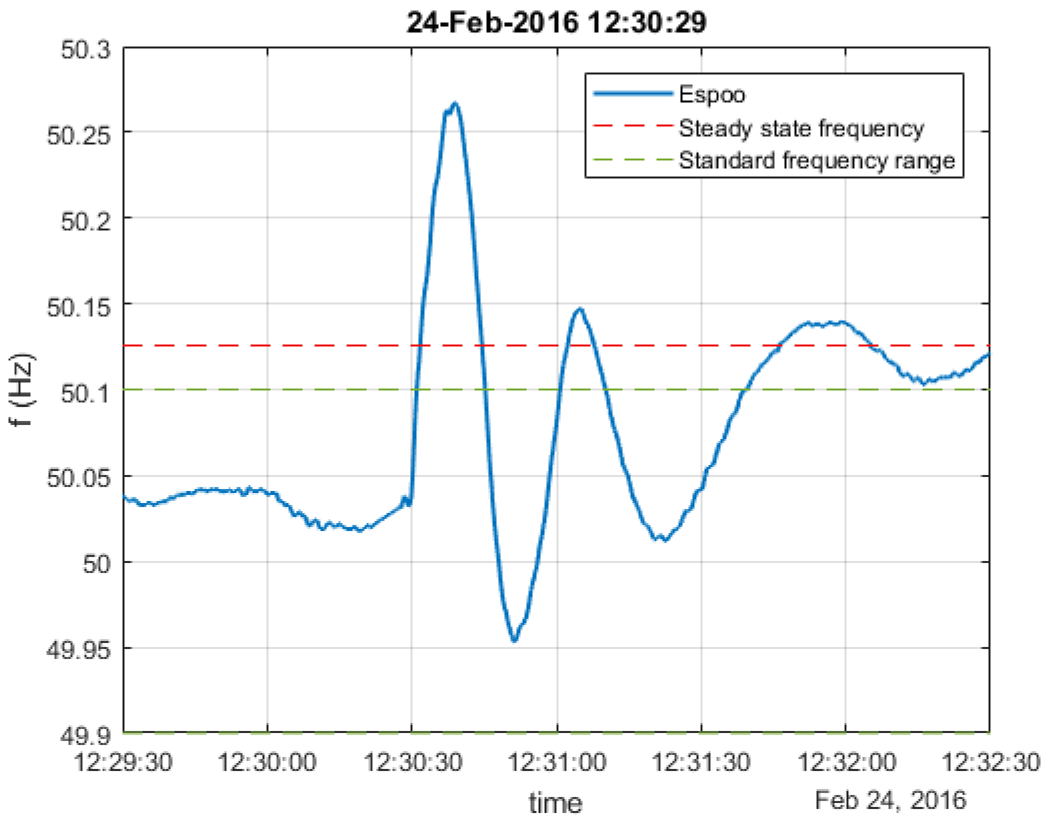


Table 4.5. Disturbance 24-Feb-2016 12:30:29

Date		**24-Feb-2016 12:30:29**	
f_{start}	50.039 Hz	$f_{steady\ state}$	50.126 Hz
$f_{extreme}$	50.267 Hz	$\Delta f_{steady\ state}$	0.087 Hz
Δf	0.228 Hz	$f_{extreme2}$	49.953 Hz
Δt	9.0 s	$f_{extreme3}$	50.147 Hz
ΔP	700 MW	damping	61.74 %
E_k	251 GWs	FBF	8083 MW/Hz
cause		HVDC	

Figure 4.7. Disturbance 21-Mar-2016 11:59:50

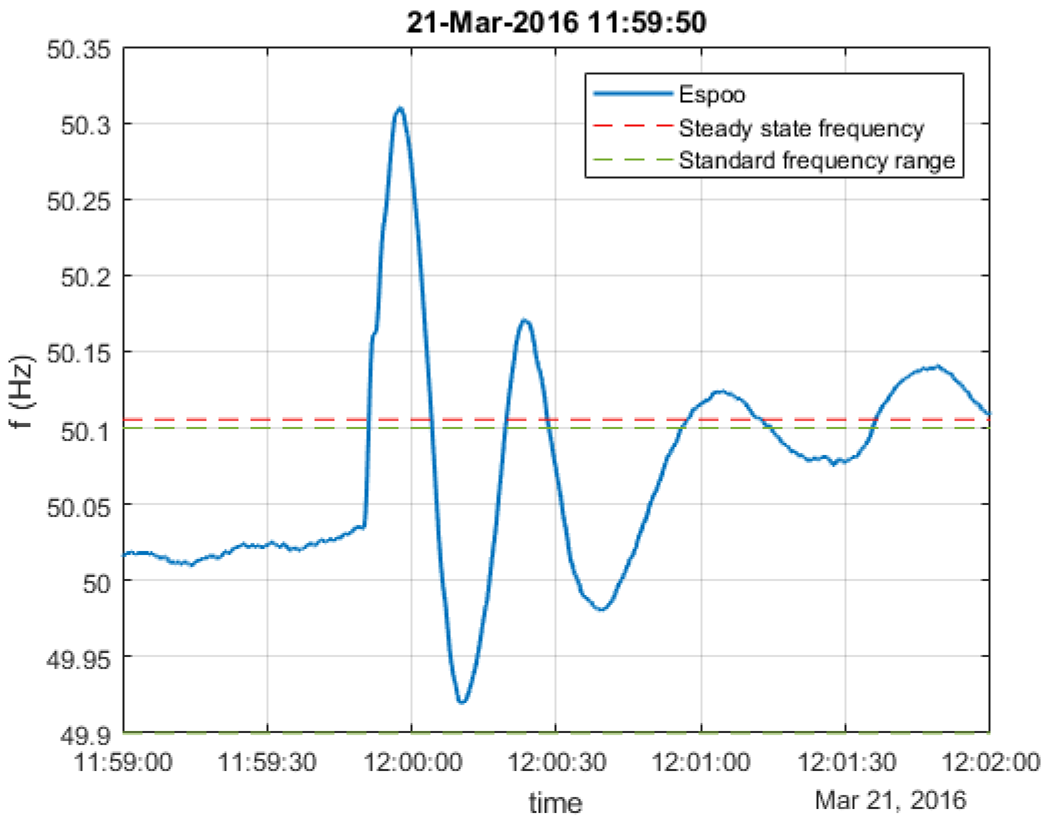


Table 4.6. Disturbance 21-Mar-2016 11:59:50

Date		**21-Mar-2016 11:59:50**	
f_{start}	50.041 Hz	$f_{steady\ state}$	50.106 Hz
$f_{extreme}$	50.310 Hz	$\Delta f_{steady\ state}$	0.065 Hz
Δf	0.269 Hz	$f_{extreme2}$	49.920 Hz
Δt	7.3 s	$f_{extreme3}$	50.171 Hz
ΔP	723 MW	damping	64.31 %
E_k	248 GWs	FBF	11153 MW/Hz
cause		HVDC	

Figure 4.8. Disturbance 06-Apr-2016 13:49:55

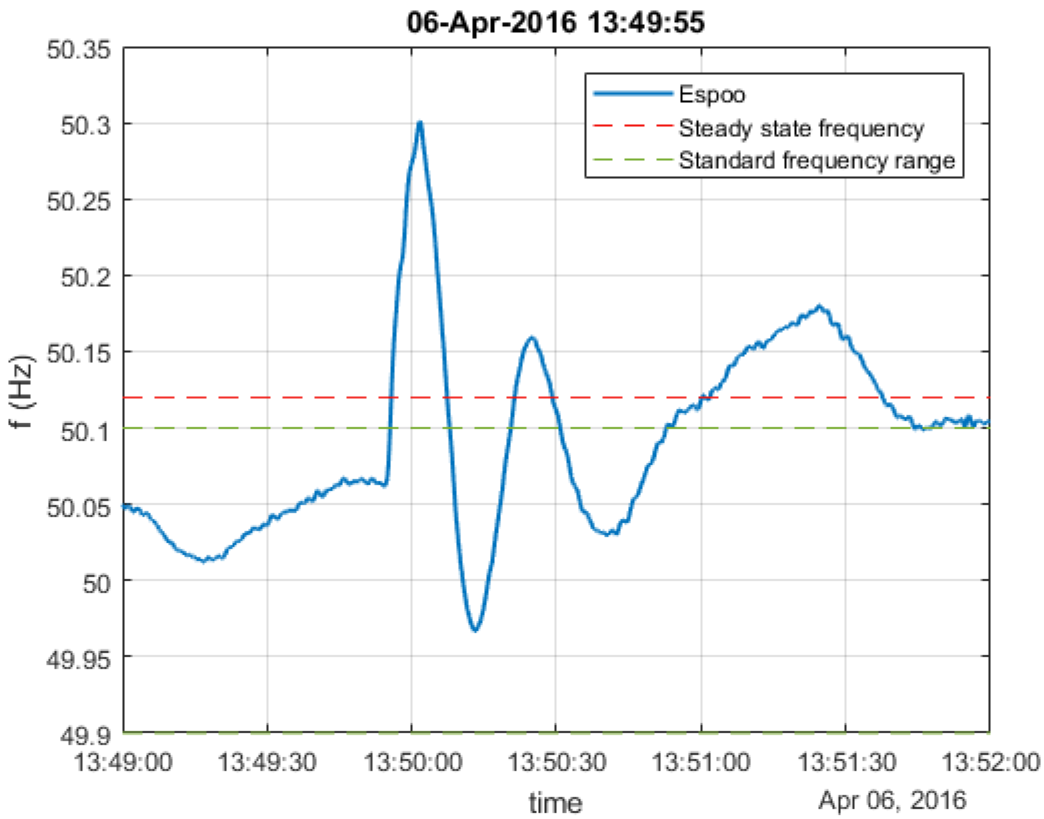


Table 4.7. Disturbance 06-Apr-2016 13:49:55

Date		**06-Apr-2016 13:49:55**	
f_{start}	50.071 Hz	$f_{steady\ state}$	50.120 Hz
$f_{extreme}$	50.300 Hz	$\Delta f_{steady\ state}$	0.049 Hz
Δf	0.230 Hz	$f_{extreme2}$	49.967 Hz
Δt	6.7 s	$f_{extreme3}$	50.159 Hz
ΔP	700 MW	damping	57.58 %
E_k	221 GWs	FBF	14245 MW/Hz
cause		HVDC	

Figure 4.9. Disturbance 14-Apr-2016 10:07:07

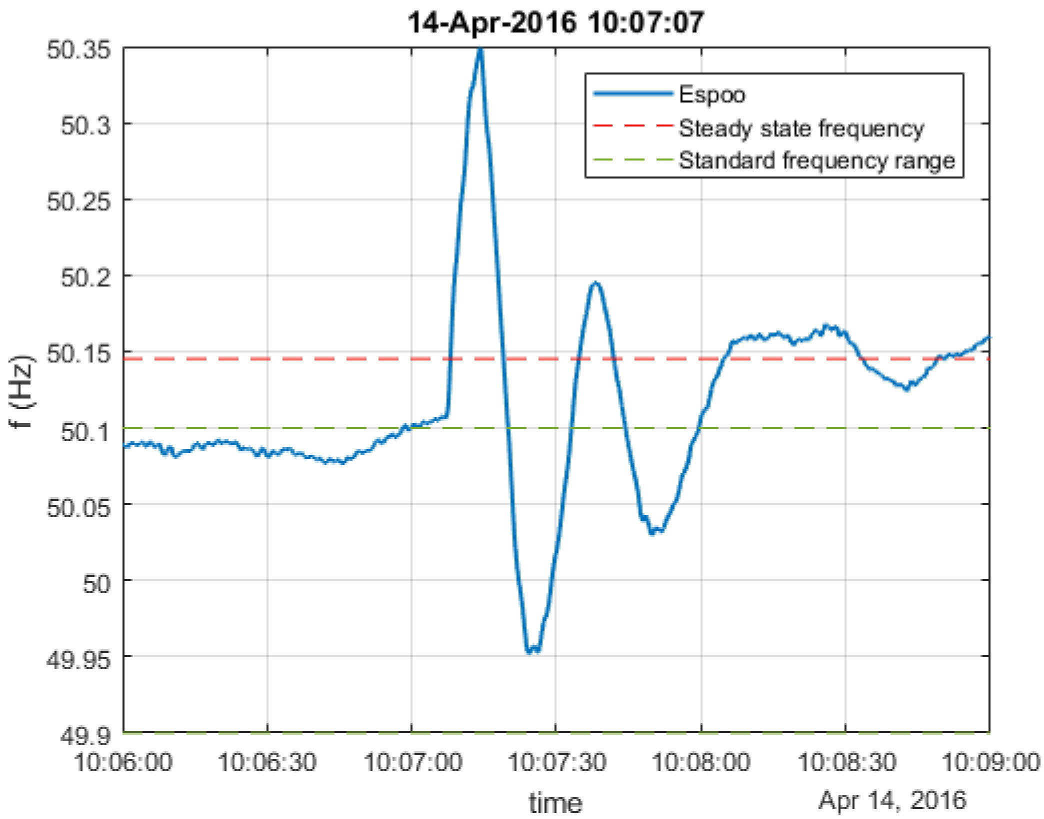


Table 4.8. Disturbance 14-Apr-2016 10:07:07

Date		**14-Apr-2016 10:07:07**	
f_{start}	50.114 Hz	$f_{steady\ state}$	50.145 Hz
$f_{extreme}$	50.349 Hz	$\Delta f_{steady\ state}$	0.031 Hz
Δf	0.234 Hz	$f_{extreme2}$	49.952 Hz
Δt	6.7 s	$f_{extreme3}$	50.195 Hz
ΔP	700 MW	damping	61.25 %
E_k	240 GWs	FBF	22576 MW/Hz
cause		HVDC	

Figure 4.10. Disturbance 20-Apr-2016 09:31:18

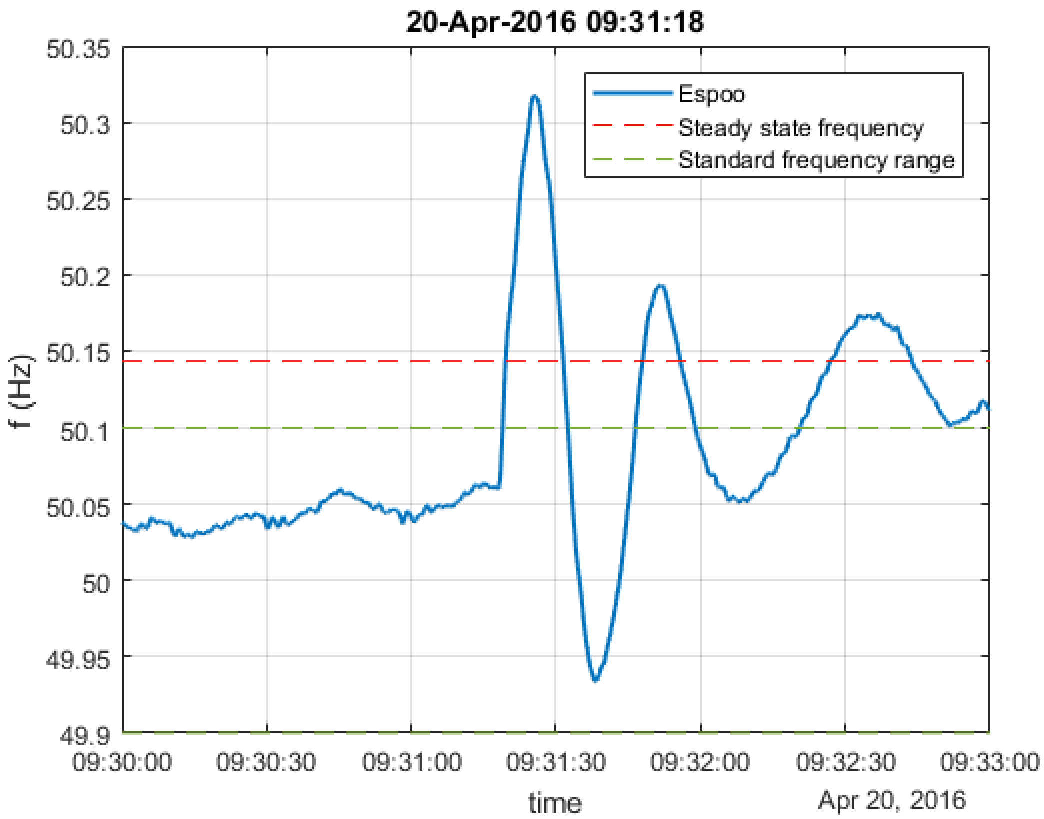


Table 4.9. Disturbance 20-Apr-2016 09:31:18

Date		**20-Apr-2016 09:31:18**	
f_{start}	50.068 Hz	$f_{steady\ state}$	50.143 Hz
$f_{extreme}$	50.317 Hz	$\Delta f_{steady\ state}$	0.076 Hz
Δf	0.249 Hz	$f_{extreme2}$	49.934 Hz
Δt	7.1 s	$f_{extreme3}$	50.193 Hz
ΔP	700 MW	damping	67.60 %
E_k	224 GWs	FBF	9252 MW/Hz
cause		HVDC	

***Figure 4.11**. Disturbance 21-Apr-2016 11:43:42*

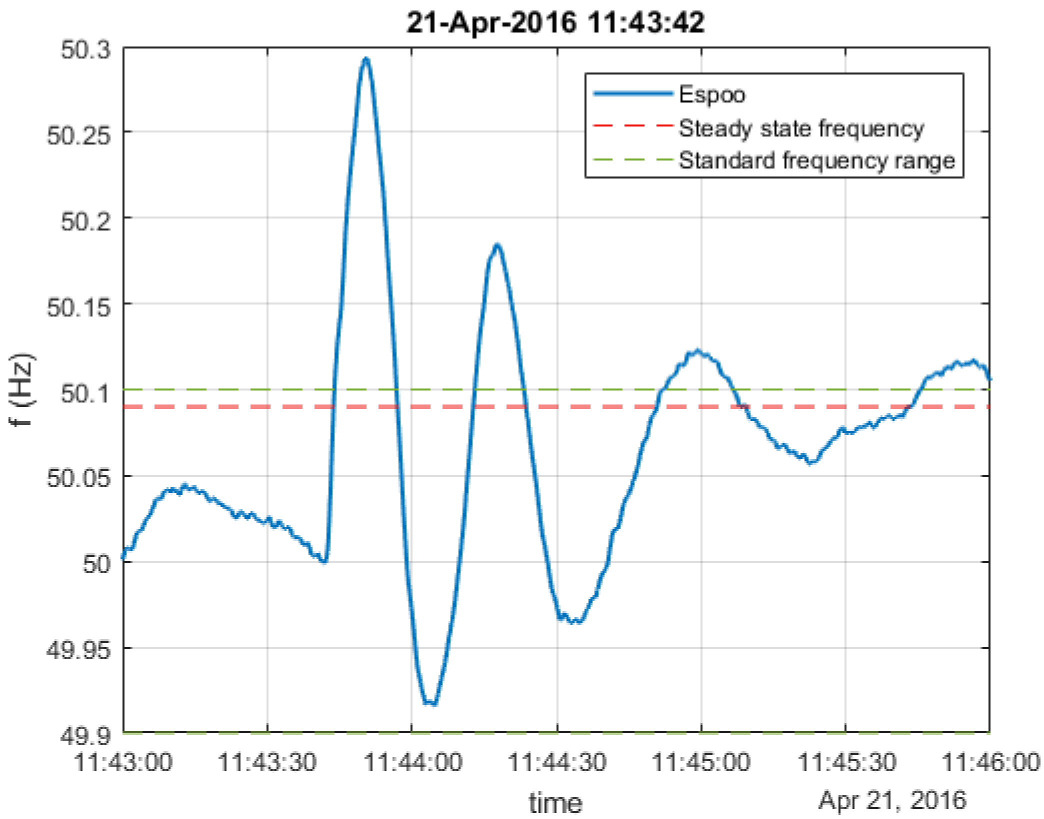


***Table 4.10**. Disturbance 21-Apr-2016 11:43:42*

Date		**21-Apr-2016 11:43:42**	
f_{start}	50.010 Hz	$f_{steady\ state}$	50.090 Hz
$f_{extreme}$	50.293 Hz	$\Delta f_{steady\ state}$	0.080 Hz
Δf	0.283 Hz	$f_{extreme2}$	49.916 Hz
Δt	7.9 s	$f_{extreme3}$	50.185 Hz
ΔP	700 MW	damping	71.23 %
E_k	222 GWs	FBF	8754 MW/Hz
cause		HVDC	

Figure 4.12. Disturbance 15-May-2016 01:56:13

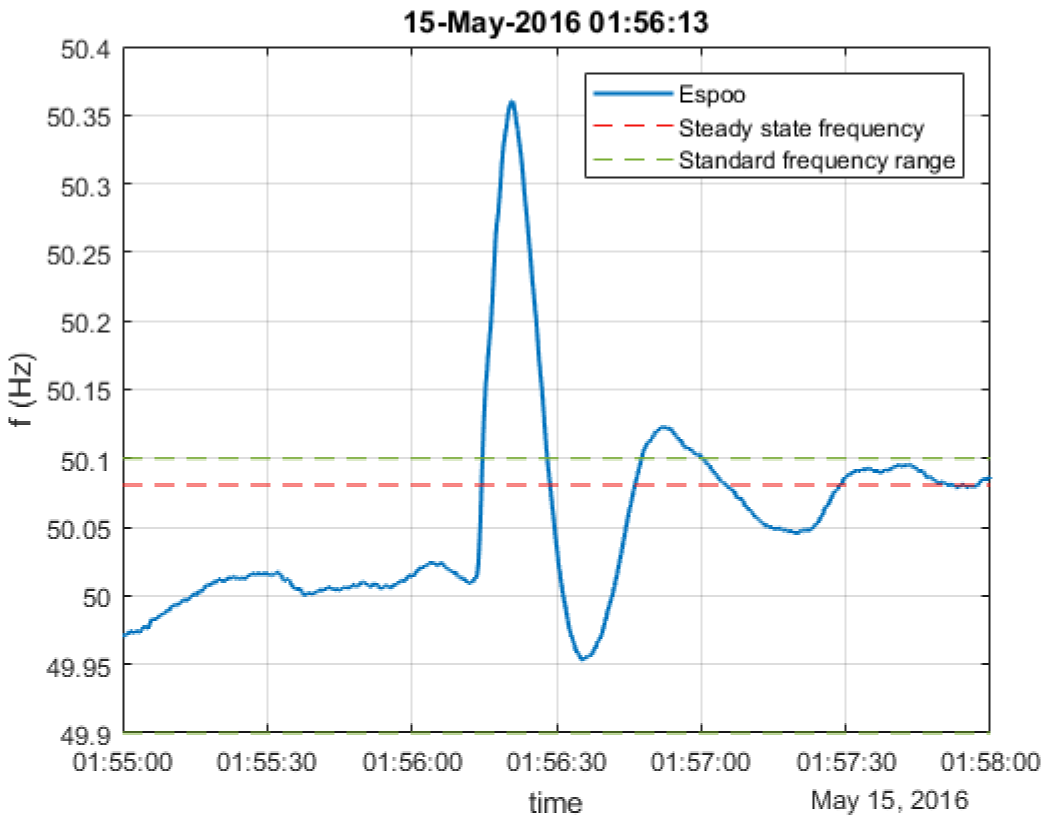


Table 4.11. Disturbance 15-May-2016 01:56:13

Date		**15-May-2016 01:56:13**	
f_{start}	50.021 Hz	$f_{steady\ state}$	50.081 Hz
$f_{extreme}$	50.360 Hz	$\Delta f_{steady\ state}$	0.060 Hz
Δf	0.339 Hz	$f_{extreme2}$	49.953 Hz
Δt	7.0 s	$f_{extreme3}$	50.123 Hz
ΔP	720 MW	damping	41.75 %
E_k	162 GWs	FBF	12017 MW/Hz
cause		HVDC	

***Figure 4.13**. Disturbance 18-May-2016 22:08:27*

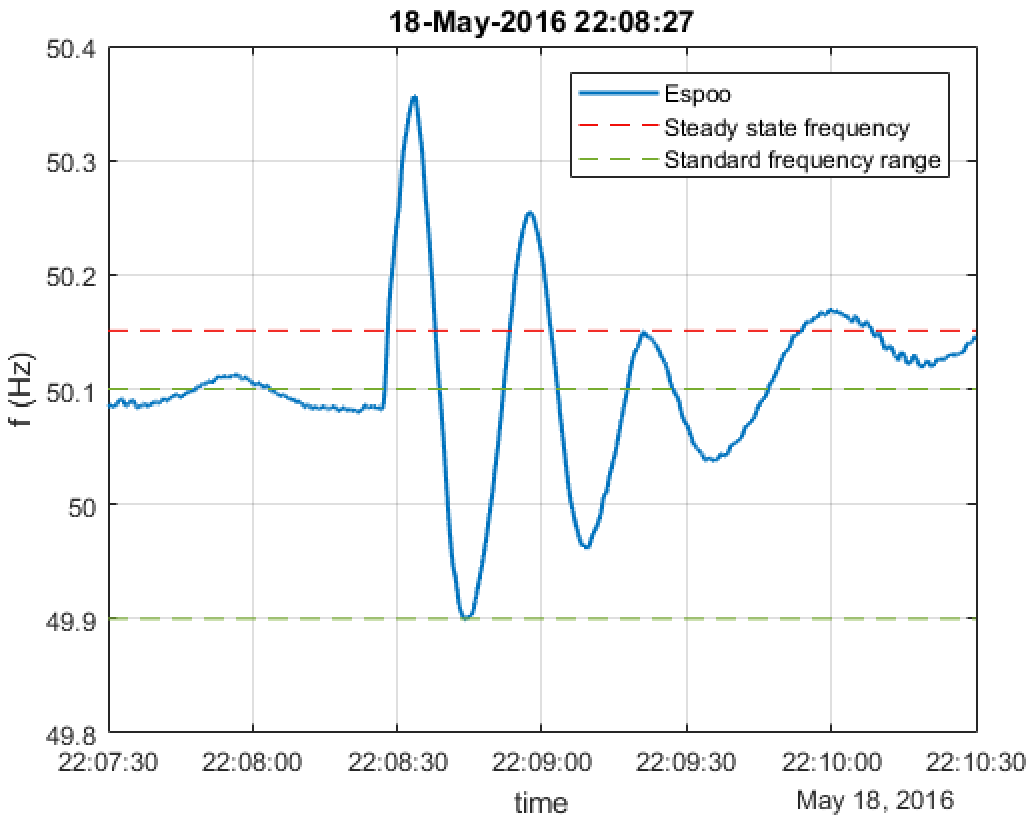


***Table 4.12**. Disturbance 18-May-2016 22:08:27*

Date		**18-May-2016 22:08:27**	
f_{start}	50.090 Hz	$f_{steady\ state}$	50.151 Hz
$f_{extreme}$	50.356 Hz	$\Delta f_{steady\ state}$	0.061 Hz
Δf	0.266 Hz	$f_{extreme2}$	49.899 Hz
Δt	6.3 s	$f_{extreme3}$	50.254 Hz
ΔP	700 MW	damping	77.76 %
E_k	205 GWs	FBF	11542 MW/Hz
cause		HVDC	

Figure 4.14. Disturbance 20-Jun-2016 17:10:09

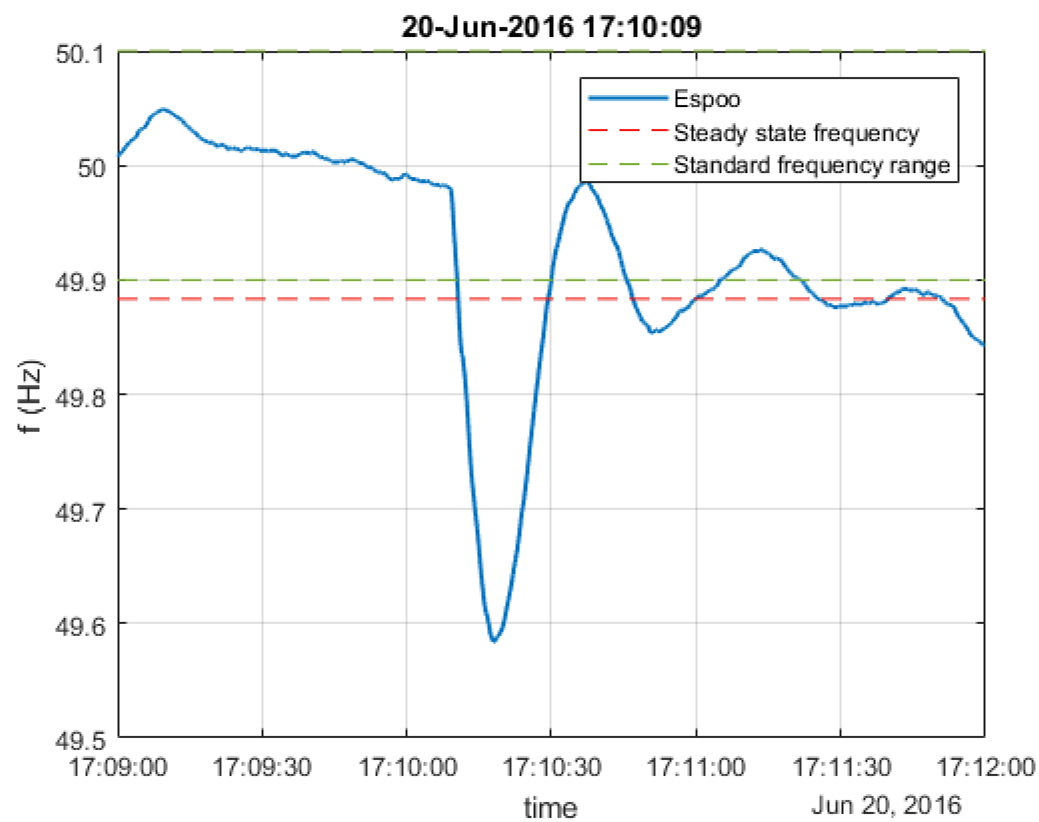


Table 4.13. Disturbance 20-Jun-2016 17:10:09

Date		**20-Jun-2016 17:10:09**	
f_{start}	49.973 Hz	$f_{steady\ state}$	49.883 Hz
$f_{extreme}$	49.584 Hz	$\Delta f_{steady\ state}$	0.090 Hz
Δf	-0.389 Hz	$f_{extreme2}$	49.985 Hz
Δt	8.8 s	$f_{extreme3}$	49.854 Hz
ΔP	700 MW	damping	32.74 %
E_k	175 GWs	FBF	7821 MW/Hz
cause		AC-line	

Figure 4.15. Disturbance 25-Jun-2016 22:28:59

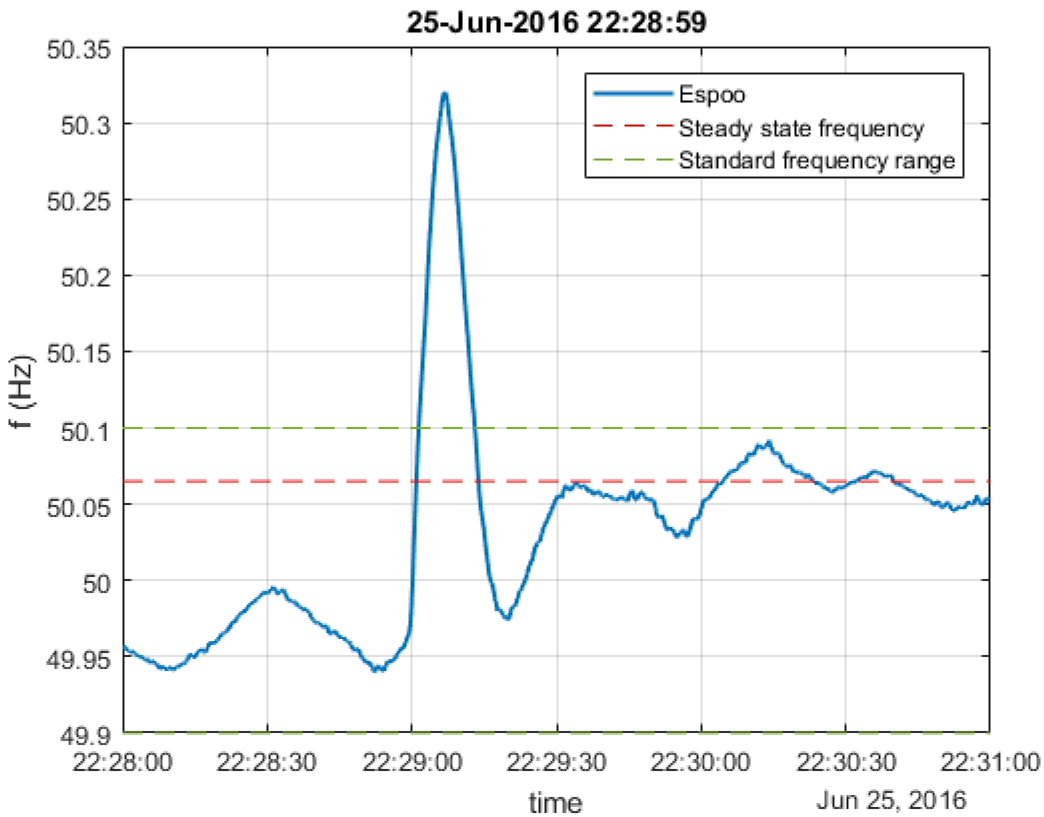


Table 4.14. Disturbance 25-Jun-2016 22:28:59

Date		25-Jun-2016 22:28:59	
f_{start}	49.972 Hz	$f_{steady\ state}$	50.065 Hz
$f_{extreme}$	50.320 Hz	$\Delta f_{steady\ state}$	0.093 Hz
Δf	0.347 Hz	$f_{extreme2}$	49.975 Hz
Δt	7.1 s	$f_{extreme3}$	50.091 Hz
ΔP	600 MW	damping	33.68 %
E_k	154 GWs	FBF	6463 MW/Hz
cause		HVDC	

***Figure 4.16**. Disturbance 27-Jun-2016 05:01:25*

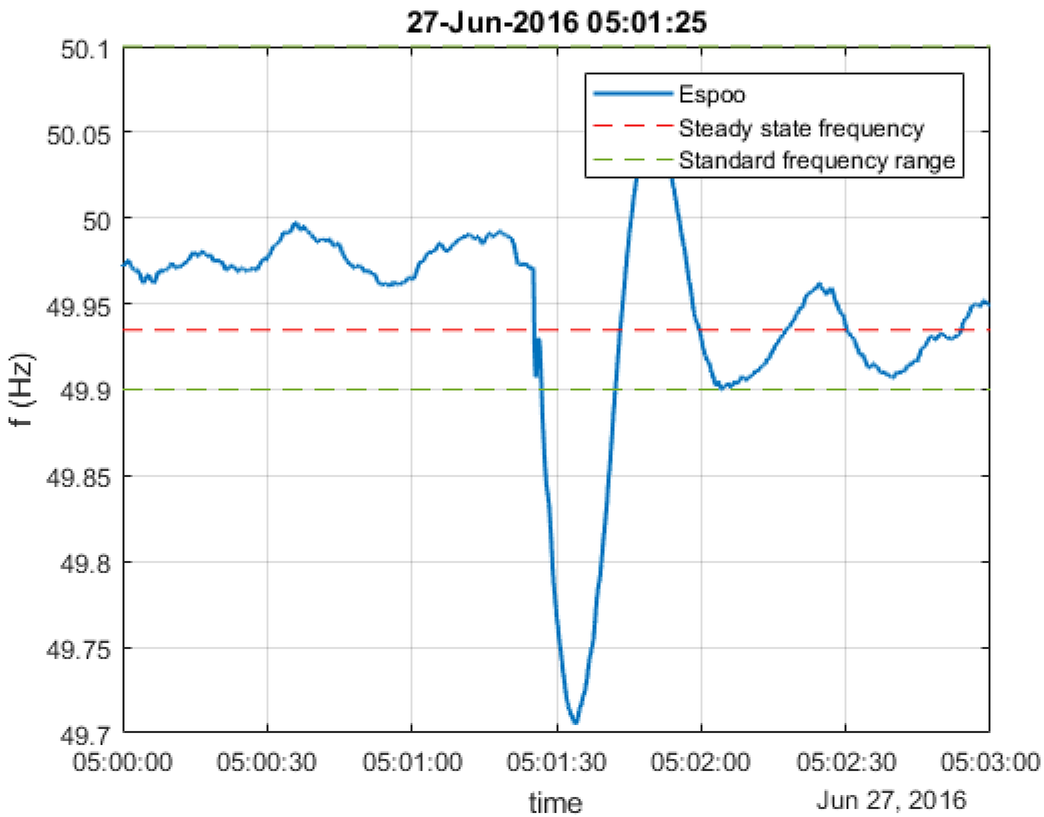


***Table 4.15**. Disturbance 27-Jun-2016 05:01:25*

Date		**27-Jun-2016 05:01:25**	
f_{start}	49.969 Hz	$f_{steady\ state}$	49.935 Hz
$f_{extreme}$	49.706 Hz	$\Delta f_{steady\ state}$	0.034 Hz
Δf	-0.263 Hz	$f_{extreme2}$	50.049 Hz
Δt	8.9 s	$f_{extreme3}$	49.900 Hz
ΔP	400 MW	damping	43.33 %
E_k	131 GWs	FBF	11698 MW/Hz
cause		Industry	

Figure 4.17. Disturbance 04-Jul-2016 14:41:01

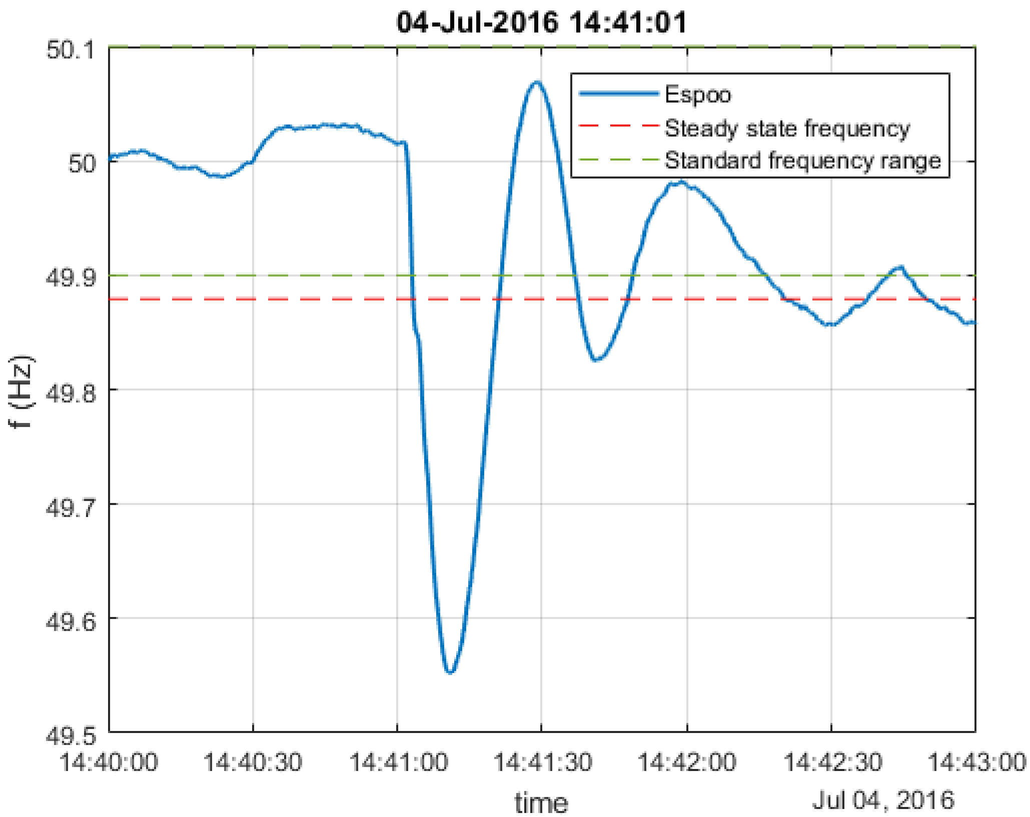


Table 4.16. Disturbance 04-Jul-2016 14:41:01

Date		**04-Jul-2016 14:41:01**	
f_{start}	50.007 Hz	$f_{steady\ state}$	49.879 Hz
$f_{extreme}$	49.553 Hz	$\Delta f_{steady\ state}$	0.128 Hz
Δf	-0.454 Hz	$f_{extreme2}$	50.069 Hz
Δt	9.0 s	$f_{extreme3}$	49.825 Hz
ΔP	1026 MW	damping	47.20 %
E_k	192 GWs	FBF	8008 MW/Hz
cause		AC-line	

***Figure 4.18**. Disturbance 12-Jul-2016 14:42:29*

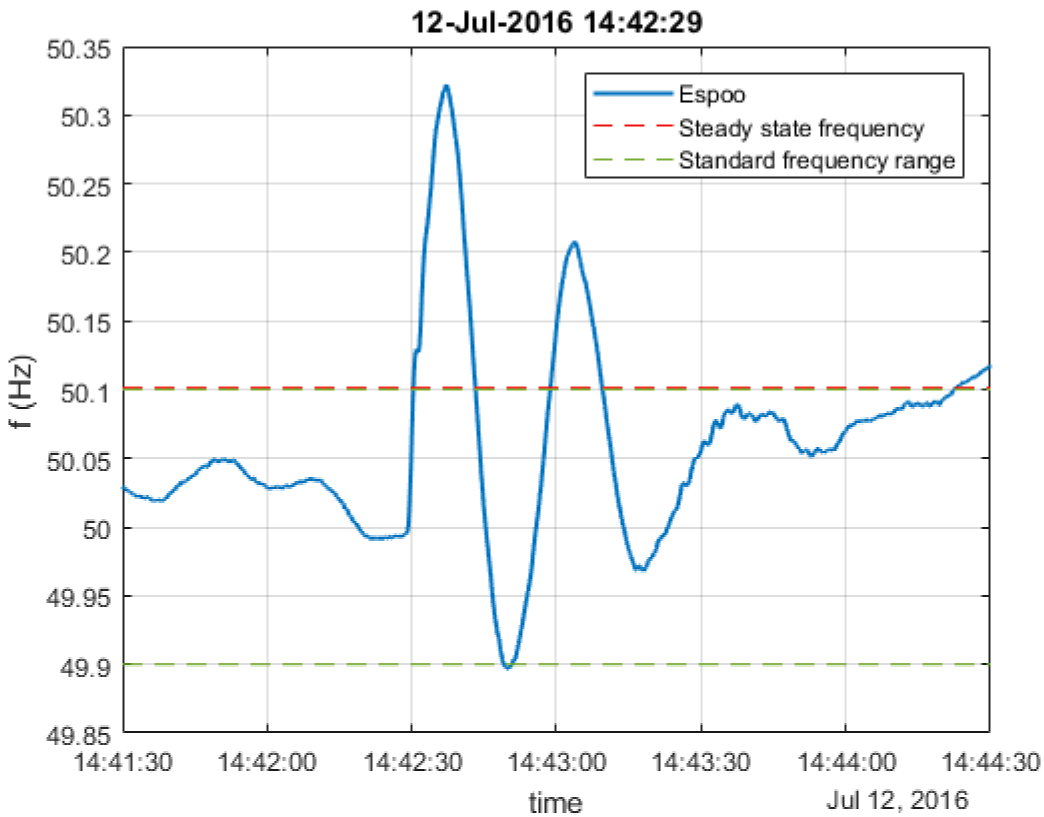


***Table 4.17**. Disturbance 12-Jul-2016 14:42:29*

Date		**12-Jul-2016 14:42:29**	
f_{start}	50.000 Hz	$f_{steady\ state}$	50.101 Hz
$f_{extreme}$	50.321 Hz	$\Delta f_{steady\ state}$	0.101 Hz
Δf	0.322 Hz	$f_{extreme2}$	49.897 Hz
Δt	8.0 s	$f_{extreme3}$	50.207 Hz
ΔP	670 MW	damping	73.09 %
E_k	189 GWs	FBF	6613 MW/Hz
cause		HVDC	

***Figure 4.19**. Disturbance 26-Jul-2016 22:52:43*

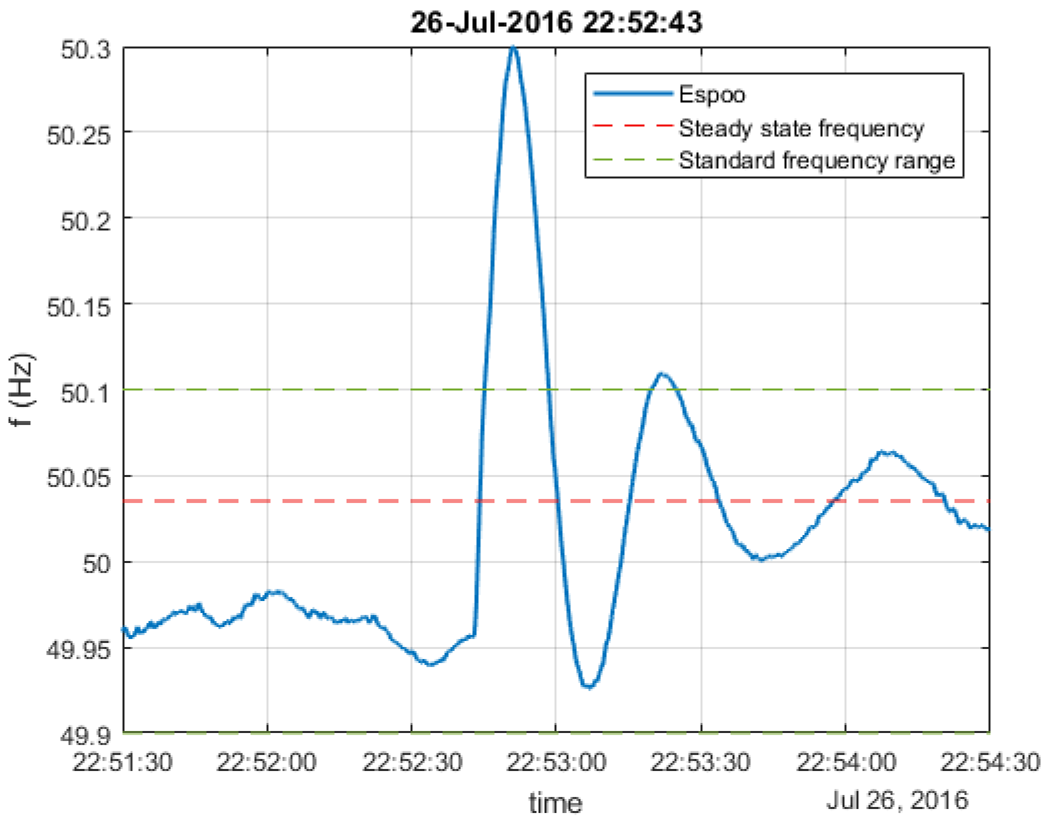


***Table 4.18**. Disturbance 26-Jul-2016 22:52:43*

Date		**26-Jul-2016 22:52:43**	
f_{start}	49.963 Hz	$f_{steady\ state}$	50.035 Hz
$f_{extreme}$	50.300 Hz	$\Delta f_{steady\ state}$	0.073 Hz
Δf	0.337 Hz	$f_{extreme2}$	49.926 Hz
Δt	7.9 s	$f_{extreme3}$	50.109 Hz
ΔP	700 MW	damping	48.94 %
E_k	191 GWs	FBF	9647 MW/Hz
cause		HVDC	

Figure 4.20. Disturbance 05-Aug-2016 11:08:09

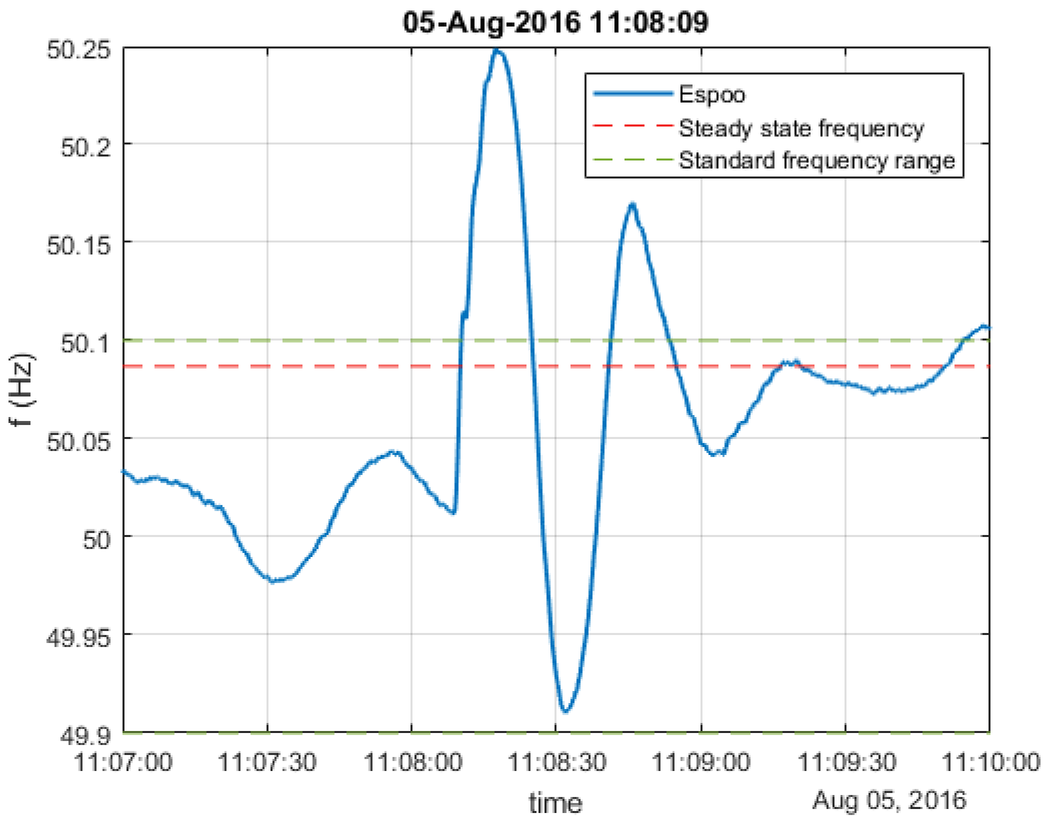


Table 4.19. Disturbance 05-Aug-2016 11:08:09

Date		**05-Aug-2016 11:08:09**	
f_{start}	50.019 Hz	$f_{steady\ state}$	50.087 Hz
$f_{extreme}$	50.249 Hz	$\Delta f_{steady\ state}$	0.068 Hz
Δf	0.230 Hz	$f_{extreme2}$	49.911 Hz
Δt	8.4 s	$f_{extreme3}$	50.170 Hz
ΔP	500 MW	damping	76.72 %
E_k	188 GWs	FBF	7348 MW/Hz
cause		HVDC	

***Figure 4.21**. Disturbance 12-Aug-2016 21:39:46*

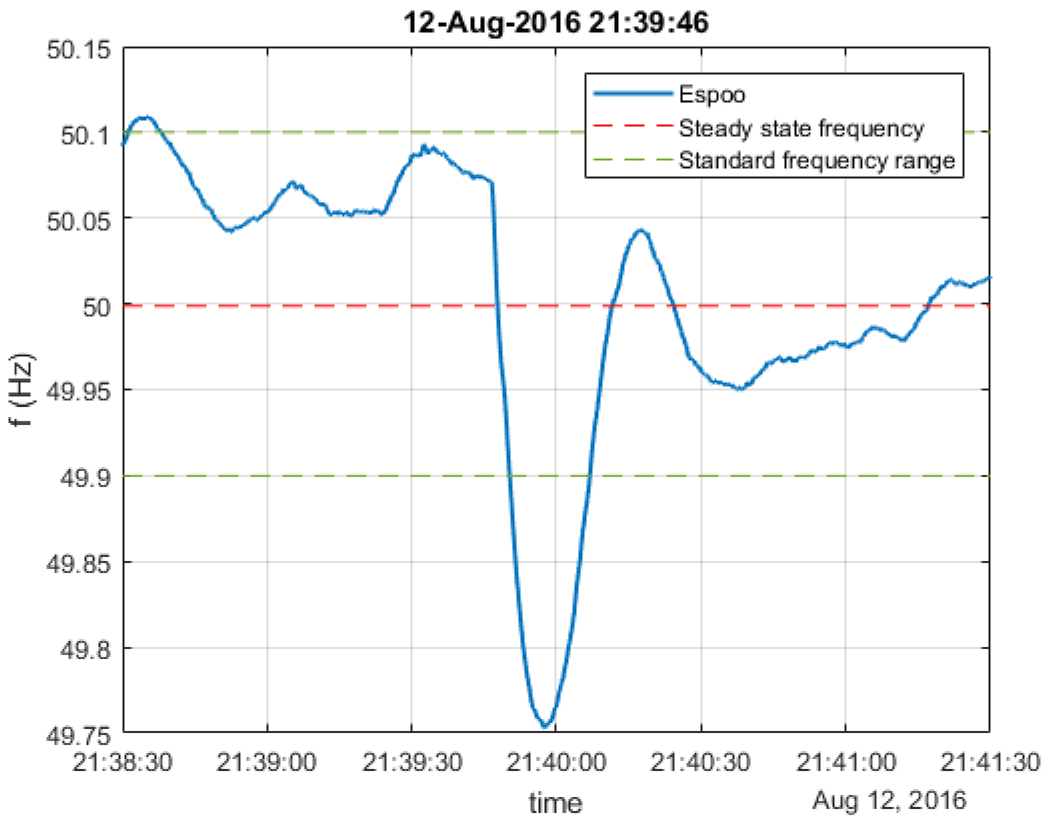


***Table 4.20**. Disturbance 12-Aug-2016 21:39:46*

Date		**12-Aug-2016 21:39:46**	
f_{start}	50.066 Hz	$f_{steady\ state}$	49.999 Hz
$f_{extreme}$	49.753 Hz	$\Delta f_{steady\ state}$	0.068 Hz
Δf	-0.313 Hz	$f_{extreme2}$	50.043 Hz
Δt	10.8 s	$f_{extreme3}$	49.950 Hz
ΔP	500 MW	damping	32.08 %
E_k	174 GWs	FBF	7399 MW/Hz
cause		Nuclear	

***Figure 4.22**. Disturbance 28-Aug-2016 23:06:07*

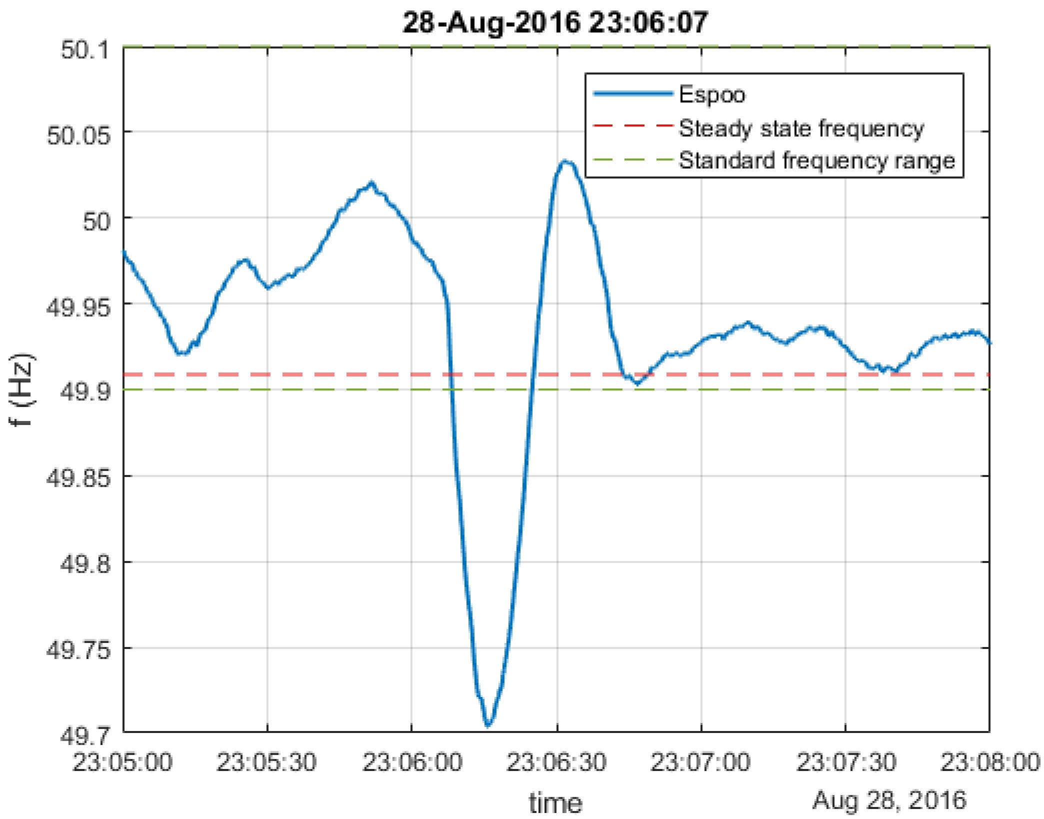


***Table 4.21**. Disturbance 28-Aug-2016 23:06:07*

Date		**28-Aug-2016 23:06:07**	
f_{start}	49.948 Hz	$f_{steady\ state}$	49.909 Hz
$f_{extreme}$	49.704 Hz	$\Delta f_{steady\ state}$	0.039 Hz
Δf	-0.244 Hz	$f_{extreme2}$	50.033 Hz
Δt	8.4 s	$f_{extreme3}$	49.903 Hz
ΔP	590 MW	damping	39.52 %
E_k	180 GWs	FBF	15045 MW/Hz
cause		HVDC	

***Figure 4.23**. Disturbance 03-Oct-2016 21:21:17*

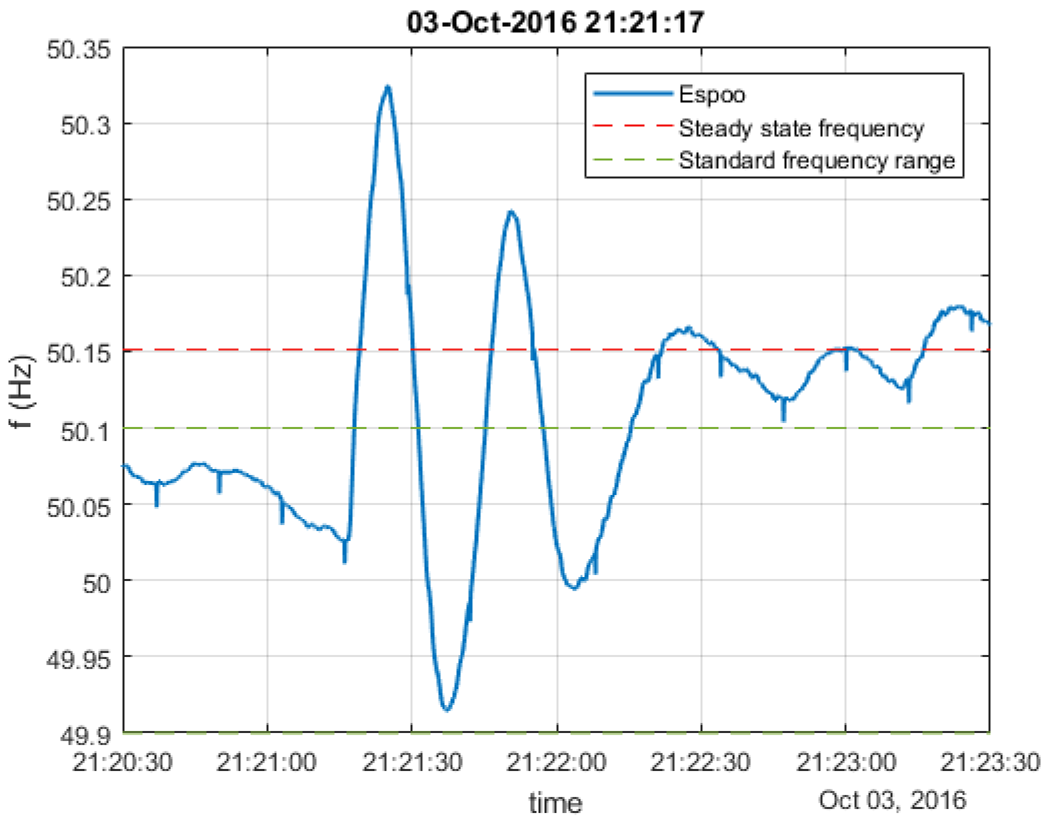


***Table 4.22**. Disturbance 03-Oct-2016 21:21:17*

Date		**03-Oct-2016 21:21:17**	
f_{start}	50.033 Hz	$f_{steady\ state}$	50.151 Hz
$f_{extreme}$	50.324 Hz	$\Delta f_{steady\ state}$	0.118 Hz
Δf	0.290 Hz	$f_{extreme2}$	49.915 Hz
Δt	7.9 s	$f_{extreme3}$	50.242 Hz
ΔP	700 MW	damping	79.95 %
E_k	205 GWs	FBF	5935 MW/Hz
cause		HVDC	

***Figure 4.24**. Disturbance 08-Oct-2016 23:14:51*

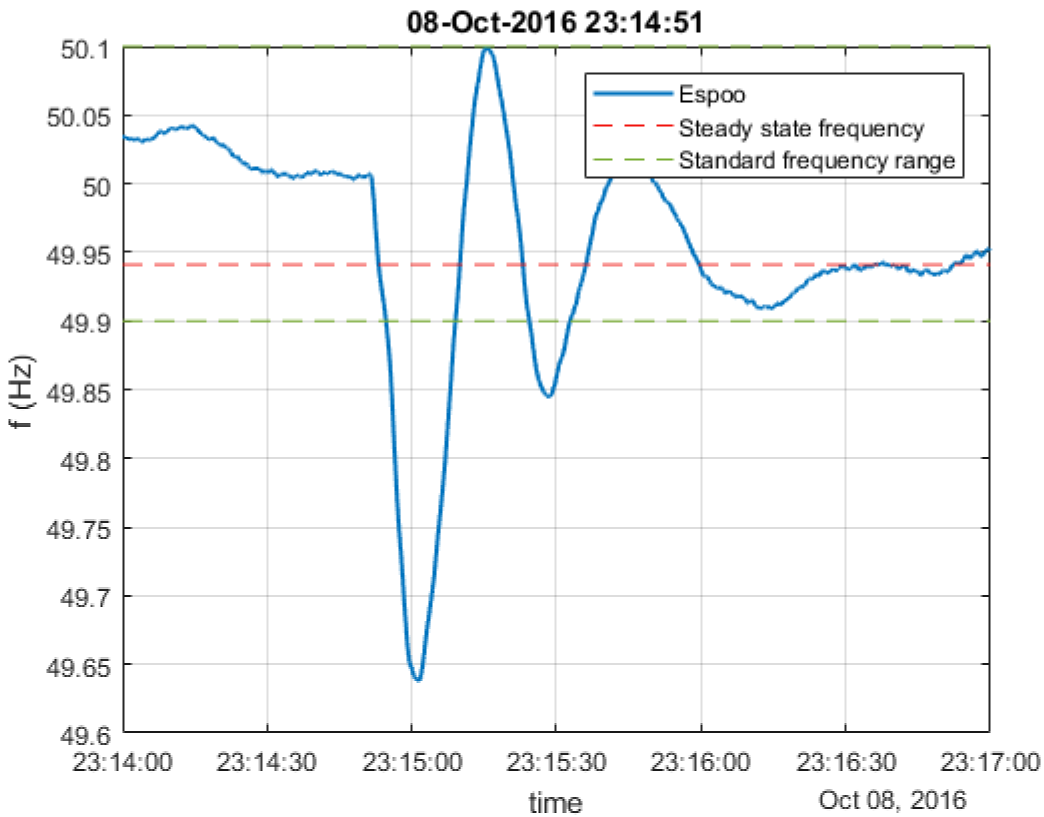


***Table 4.23**. Disturbance 08-Oct-2016 23:14:51*

Date		**08-Oct-2016 23:14:51**	
f_{start}	49.996 Hz	$f_{steady\ state}$	49.941 Hz
$f_{extreme}$	49.638 Hz	$\Delta f_{steady\ state}$	0.055 Hz
Δf	-0.358 Hz	$f_{extreme2}$	50.099 Hz
Δt	9.4 s	$f_{extreme3}$	49.845 Hz
ΔP	880 MW	damping	55.17 %
E_k	196 GWs	FBF	16087 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 2016. The overall quality of frequency was worse than in the previous year of 2015 and among the worst of all the years examined in this report.

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. Highest values in 2016 were observed in April and May. November and December had the best quality of all months in 2016. Typically frequency has stayed within the standard frequency range better at weekends than during the weekdays. This was the case in 2016 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 2016 was higher than in any previous years from 2011 to 2015. The mean value of oscillation was highest in May and June 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 2016 was not an exception in this case.

Removal of the oscillation by filtering the frequency data clearly reduces frequency deviations. The reduction is about 35-40 % with the FFT-filtering method. The reduction is close to 10 % more for under frequency deviations.

There were 22 frequency disturbances in 2016, where the deviation exceeded 300 mHz. By far the most common reason for the disturbances were failures in HVDC links, as they were the cause for nearly 70 % of the disturbances. The amount of frequency deviations exceeding 300 mHz was very similar in 2015 as well.

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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[8] Kuivaniemi M.: "40-90 second oscillation analysis for years 2011 and 2012", Fingrid Oyj, 30.8.2013

[9] Janhunen O-P.: "60 second oscillation analysis for year 2013", Fingrid Oyj, 14.8.2014

[10] System Operation Guideline, The European Comission, 4.5.2016 final provisional version, available at https://www.entsoe.eu/major-projects/network-code-development/system-operation

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