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Harmonic analysis PQM data in 150kV grid of TSO *TenneT* in Brabant, The Netherlands

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Abstract. **This paper aims to provide an insight into the measured background changes of harmonics due to operational changes in a typical Dutch transmission grid. Multiple use cases on different locations throughout a meshed 150kV grid have been considered. The nodes that were studied had measured exceedances of planning levels or were indicated to be critical for the future in earlier studies. This study provides an insight into the measured response of harmonics with respect to different operational changes such as specific scheduled outages that occurred and the impact of capacitor banks. Per use-case, individual conclusions are reported. The analysis was conducted on data of power quality meters (PQM) and various other data sources provided by the Dutch TSO *TenneT*. Data-processing, visualization, and computations were performed using Python. These results are useful for model validation, planning purposes, and maintaining power quality.**

Key words- Background harmonics, power quality, high-voltage

1. Introduction

THE Dutch grid consists of the (extra) high voltage transmission grid (>110kV) operated by the transmission grid operator *TenneT*, and the low- and medium voltage distribution grids operated by the DNOs. One of the tasks in operating the high voltage grid is to avoid unwanted interference between connected parties caused by poor power quality.

In the Netherlands, the limits for power quality are given in the national grid code, the *'Netcode Elektriciteit'* [1]. This grid code has to be respected and complied with by all network operators and connected parties. All parties connected to the *TenneT* grid have a power quality meter (PQM) for continuous PQ registering. The network operators provide an annual report [2].

Harmonics are one of the power quality parameters to be assessed as they may cause interference and malfunctioning of equipment and could speed up the aging process of components [3]. The grid code specifies limits for the total harmonic distortion (THD). Indicative planning levels of IEC 61000-3-6 are used as internal quality objectives of the utility. Both the THD and individual harmonics are measured and monitored by *TenneT*. Exceedances of planning levels are listed in a separate PQM event list and serve as a warning. An example of a mitigation measure can be the application of a passive or active harmonics filter, which is an expensive and complex procedure.

In the last years several new developments have come up that may have a negative impact on the harmonic levels in the grid. For example, the growing use of high-voltage cables replacing overhead lines. These additional cables lower the resonance frequency of the system, which amplifies already present background harmonics [4][5]. In addition, the growing number of renewable energy sources and other power electronics within the grid lowers the overall short circuit power, which reduces the grid's ability to counteract harmonics [6]. Internal, theoretical studies were carried out to analyse the impact.

The aim of this paper is to analyse measured PQ data in a 150kV grid and estimate the background amplification due to operational changes in the grid. The main focus will be on nodes that have recorded exceedances of planning levels. The influence per harmonic order is by convention depicted in amplification factors, calculated with respect to the background harmonic levels prior to an event. These factors provide more insight into the impact of events that are happening in the grid and can be used by *TenneT* for model validation.

2. Theoretical background

This section describes basic theory and concepts, elaborates on the methodology, and explains the used data inputs.

A. Mathematical representation of harmonics in the grid

The transmission system is a complex environment. This is due to the complex system impedance, the large extent of connected parties that may cause harmonics, and the time-variant operational conditions such as peak/off-peak load, outage conditions, and corresponding reactive power compensation. Also, individual loading of connected parties may change over time.

A simplified model can be used for analysis of the impact of operational changes. A schematic representation of the interaction between the connected party and the grid at the PCC/POE can be seen in Fig. 1.

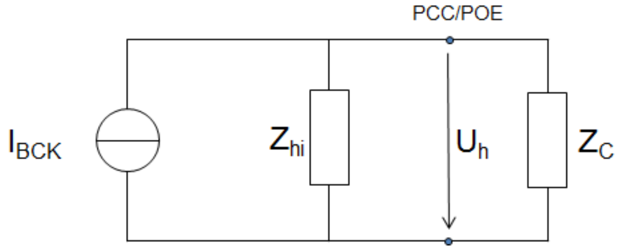

Fig. 1 - Equivalent harmonics circuit model of *TenneT* grid [7].

The impedance Z_{hi} represents the impedance of the grid. This parameter depends on grid conditions and the harmonic order (h). For modelling purposes, it is assumed that this parameter is known or can be estimated. The impedance Z_c denotes the harmonic impedance of the connected party, or a network part/element (e.g. capacitor bank). Both impedances are considered to be time-variant.

The harmonic voltage U_h at this node is the voltage to be assessed. This voltage U_h is determined by:

1) The background harmonics that are present within the grid modelled as a voltage source V_{BCK},
2) Emission from the connected party (not shown, assumed to be small),
3) Impedances Z_{hi} and Z_c.

Using the Norton equivalent circuit theorem, one can transpose this voltage into an equivalent current source I_{BCK}. In this simplified model it is assumed that this current source is independent of any changes within the grid.

By use of basic circuit theory with *Kirchoff's* current and voltage laws, the following equation (1) for the harmonic voltage can be derived as:

$$U_h = \left(\frac{Z_c Z_{hi}}{Z_c + Z_{hi}}\right) * I_{BCK} = Z_1 * I_{BCK} \qquad (1)$$

A change in the grid (e.g. an outage) changes Z_{hi} to Z'_{hi}. The combined parallel impedance (Z_1) changes in Z_2:

$$U'_h = \left(\frac{Z_c Z'_{hi}}{Z_c + Z'_{hi}}\right) * I_{BCK} = Z_2 * I_{BCK} \qquad (2)$$

The new state of the harmonic voltage at the monitored busbar (U'_h) shows the impact of the changes in the harmonics. The change can also be described by the amplification factors. These are the ratios between the voltages prior and after the change (U_h and U'_h).

The amplification factor k can be calculated as:

$$k = \left|\frac{U'_h}{U_h}\right| = \left|\frac{Z_2 * I_{BCK}}{Z_1 * I_{BCK}}\right| = \left|\frac{Z_2}{Z_1}\right| = \left|\frac{Z_c Z'_{hi}}{Z_c + Z'_{hi}} * \frac{Z_c + Z_{hi}}{Z_c Z_{hi}}\right| \qquad (3)$$

The data of the PQ meters can be used to approximate the amplification factors that occur in the grid. The 10-minute values are continuously registered. Suppose a change occurs at interval t. Per harmonic order, the amplification can be determined by dividing the harmonic voltages of the interval after the change ($t + 1$) and before the change ($t - 1$).

This simplified representation of a network state has its limitations:

- The harmonic source V_{BCK} is in reality a set of different harmonic sources distributed throughout the grid. Each varies in time and the network representation by a single impedance and voltage/current source is not ideal [4];
- The exact determination of harmonic impedances is generally difficult and comes with limited possibilities to define their uncertainties [8];
- The calculations assume a balanced three-phase system and do not take component tolerances into account [7].

Altogether, this implies that the method serves as a good first indication of critical cases.

B. Study Case

The focus of this paper is on the 150kV grid of Brabant. Compared to other areas of the Dutch HV grid, this part has a significant amount of connectees (and thus PQ meters) and many HV cables. Fig. 2 shows the nodes and their geographical locations. The analysed PQ meters are denoted by the *'HSXXX'* expressions in the figure. The location of the capacitor banks is also included.

C. Provided project data and processing approach

A selection of the nodes within the study case is given in Table I. The selection is based on:

- Recorded exceedances of planning levels (noted by *);
- Critical nodes and harmonic orders from an internal *TenneT* study [9].

A subset of these have been analysed in different use cases for this paper.

TABLE I
CONSIDERED 150 KV NODES IN BRABANT

Location	Harmonic order	PQ meter(s)
Bergen op Zoom	11, 17	HS026
Moerdijk	11	HS029, HS030
Etten	11, 23	HS027
Geertruidenberg	23	HS076, HS116
Tilburg West	7, 23	HS098, HS099
Helmond Oost	5*,7*, 23*	HS078, HS079
Maarheeze	5, 7*, 23*	HS086

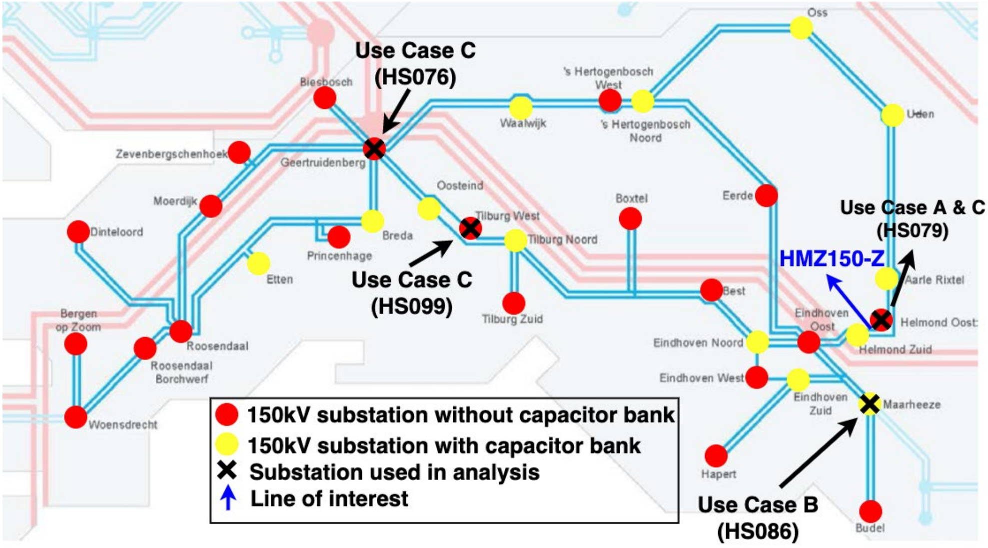

Fig. 2 - An overview of TenneT transmission nodes in the region of Brabant, The Netherlands. See Fig. 5 for a zoomed in version of the line of interest.

For the research, various sources of input data were combined.

- The measurement data of the selected PQ meters has been supplied by *Movares* for the year 2019. This data contains per node all the 10-minute average voltages per harmonic. The harmonic orders that are present within this dataset are the 5^{th}, 7^{th}, 11^{th}, 13^{th}, 23^{rd}, and the THD.
- The archived operational data of the EMS is stored in a separate database. This contains data about specific grid conditions, such as the operational data of capacitors and (scheduled) outages.

D. Determination of Amplification factors

To compare the theory and the existing models to the outcomes of the data analysis, amplification factors are determined. In case of an outage, there are 2 changes (events): at the start and the end of an outage period. Each change has its own amplification factor, which is calculated by dividing the magnitude shortly before and after the event. This approach ensures that the gain is approached as correctly as possible with the provided data, and a minimum of other changes in the system. The moment at which the amplification is determined is derived from the (suspected) linked discrete edges. The mean of the two denotes the average amplification per event interval. The harmonic voltages are determined by a number of parameters (emission of sources, loading, etc.). It should be noted that the assumption is that these do not change significantly during the considered period.

3. Use Cases

This section describes the results of 3 cases:

A) Helmond Oost (exceedances of planning levels).
B) Maarheeze (exceedances of planning levels).
C) An analysis of the 23rd harmonic levels at the nodes Tilburg West, Geertruidenberg, and Helmond Oost.

A. Helmond Oost

Fig. 3 displays a year of measurement data of the PQ meter at the Helmond Oost node (HS079). The planning level per order corresponds with $1\,p.u.$ In general, all harmonics are below their individual planning levels, except for the 5^{th}, 7^{th}, and 23^{rd} harmonic orders. The largest exceedance was recorded in week 29 of 2019.

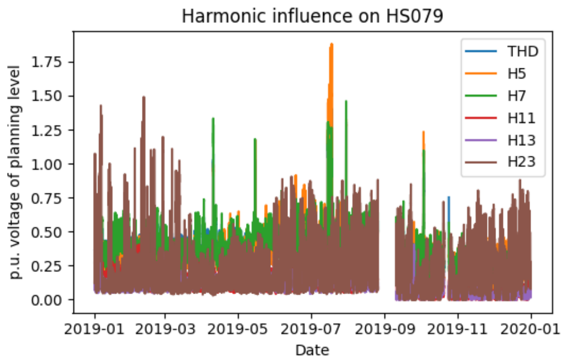

Fig. 3 – Harmonic voltage levels per harmonic order (in p.u. of planning levels) for 2019 at PQ meter HS079 in Helmond Oost. The inconsistencies (gaps and zero-offset) are caused by a PQ meter that has been replaced.

Fig. 4 shows the measured data of week 29. From the top figure, it can be noticed that an event in the grid causes significant changes in harmonic distortion. For the 5^{th} and the 7^{th} this change indicates an increase, and because lower orders are rather dominant, this also means a noticeable increase in the THD. For the 13^{th} and 23^{rd} harmonic orders this change leads to a decrease. The 11^{th} harmonic order seems to be rather unaffected by the event.

The analysis of the EMS data showed that these changes were due to an outage of a circuit connected to the Helmond Oost substation. In Fig. 4 (bottom), the connection of the Helmond Oost substation, with the outage activity of line 'HMZ150-Z' has been plotted. This physical line can also be seen in Fig. 5. The latter of the two figures clearly indicates that when the 'HMZ150-Z' is interrupted, Helmond Oost is only connected via 1 circuit. This reduces the short circuit power and disconnects the substation from the Eindhoven area.

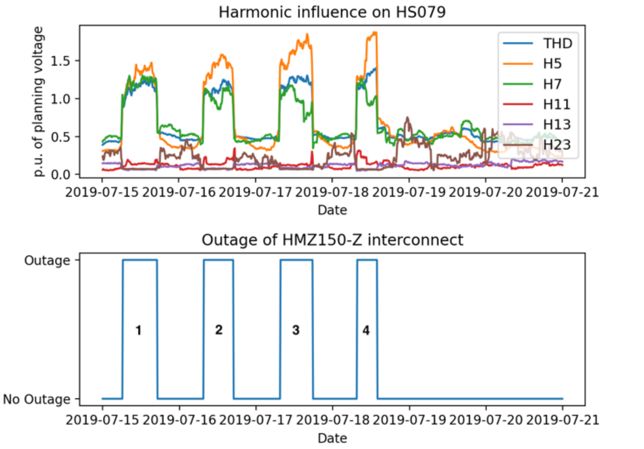

Fig. 4 – Harmonic voltage levels per harmonic order (top) and outage of interconnection HMZ150-Z (bottom) with interval numbering for week 29 of 2019 at Helmond Oost (HS079).

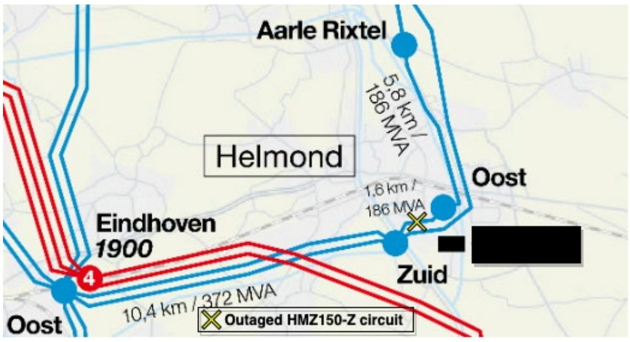

Fig. 5 – Helmond Oost node with outaged HMZ150-Z line.

The intervals at which this line is outaged for maintenance correspond with the intervals of the significant changes in harmonic voltages. This gives a high degree of confidence that these events are the source of the changes in harmonics.

A change in the system due to the disconnection of a line causes a different equivalent harmonic grid impedance Z_{hi}, resulting in voltage differences. Due to the differences in harmonic impedances, the amplification factors differ per frequency. The change of Z_{hi} can result in an increase for one harmonic order and a decrease for another order.

To obtain insight into the magnitude, the amplification factors have been determined. These amplification factors are given in Table II.

***Conclusion Helmond Oost**:*

A.1 – There is a high degree of confidence that the measured exceedances of planning levels were caused by an outage on the branch HMZ150-Z. The reduction of short circuit power resulted for some harmonic orders in higher harmonic levels.

A.2 - Harmonic sources are distributed in the grid. For the 13^{th} and 23^{rd} harmonic orders there is a decrease during the outage period. This could mean that the sources of these harmonic orders were "disconnected" from this node. In the simplified model of Fig. 1, all contributions are clustered as a single emission source. Alternatively, the impedance-frequency characteristic could also experience a decrease due to the circuit change.

TABLE II
AMPLIFICATION FACTORS WEEK 29 2019 – HS079

Harmonic order	Interval 1	Interval 2	Interval 3	Interval 4
THD	2.03 – 2.04	2.19 - 1.49	2.24 – 2.33	2.22 – 2.33
H5	2.44 – 2.04	2.44 - 1.59	2.48 – 2.70	2.62 – 2.56
H7	1.97 – 2.27	2.53 – 1.54	2.24 – 2.50	2.56 – 1.92
H11	1.20 – 1.19	2.42 – 1.19	1.16 – 1.75	2.03 – 1.18
H13	1.47 – 2.14	2.13 – 1.86	1.41 – 1.43	3.03 – 1.53
H23	2.86 – 1.22	1.72 – 1.16	2.04 – 1.12	3.23 – 1.09

Formatted as (left change – right change) per interval/order.

B. Maarheeze

At Maarheeze (HS086), Table I indicates exceedances of planning levels of the 7^{th} and the 23^{rd} harmonic orders in 2019. From the event list, it was seen that over 90% of these exceedances were due to the 7^{th} harmonic order. Therefore, the focus is on this harmonic order using a representative period. Fig. 6 shows the PQM data of weeks 31-33. In addition, the figure also displays the status of three capacitor banks in the vicinity of this node to analyse a possible relation to the measured harmonic levels. Two capacitor banks are located at this substation *(MZ1 = 121Mvar, MZ2 = 33Mvar).* As illustrated by Fig. 6 one of them is always energized.

The measurements show that:

- The 7^{th} harmonic increases if CB MZ1 is energized (intervals 1 & 2).
- If the capacitor bank at Den-Bosch Noord (HTN) is energized the 7^{th} harmonic decreases (intervals 3 & 4). However, the match for the first change of interval 4 is not precise, indicating that other factors also could be of influence.

For h=7 the two capacitor banks at MZ and HTN have an opposite effect.

The harmonic impedance was estimated in a separate study for various contingencies [9]. Fig. 7 shows the impedances of a low loading scenario and is used to illustrate the resonance effect. The resonance occurs near h=7. The energization of the CB MZ1 could result in a decrease of the resonance frequency and a higher harmonic impedance for h=7, resulting in a higher voltage. However, the HTN bank is connected via a long overhead line (reactance). This could result in a lower impedance for h=7, an opposite effect.

Further research for this specific grid situation is necessary to determine the precise influences at the Maarheeze node. This analysis illustrates the complexity of harmonics in a meshed grid, particularly in case of low order resonance frequencies. In a wide area the network may have a significant impact on the voltages.

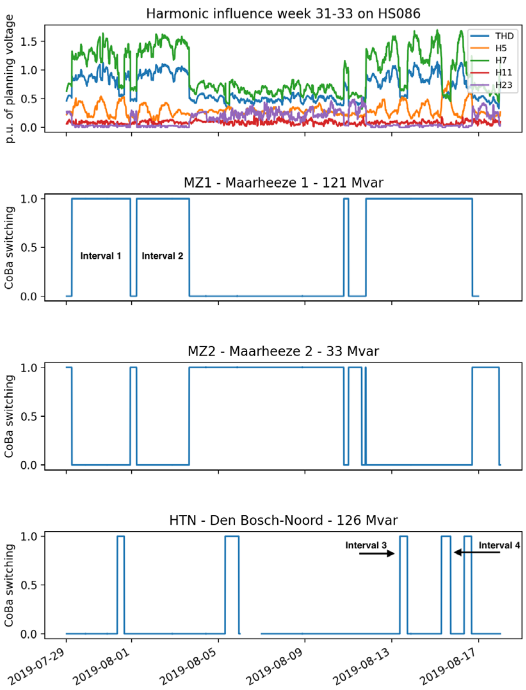

Fig. 6 – Harmonic influence in week 31-33 on node Maarheeze (top), with three capacitor banks (bottom).

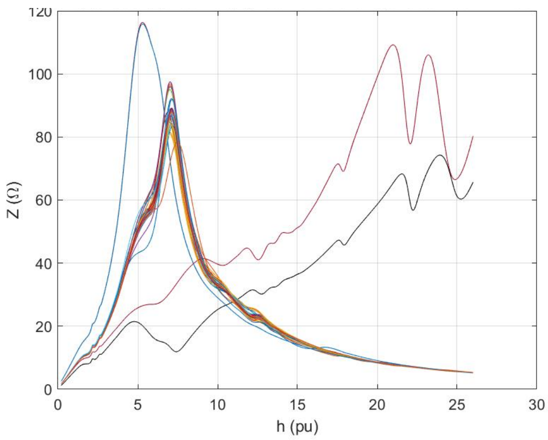

Fig. 7 - Estimated harmonic impedance for various contingencies [9].

For the denoted intervals, the amplification factors have been calculated for MZ1 and HTN, these are given in Table III. For the 7th order, the mean amplification factors have been determined to be 1.86 increasing and 1.56 decreasing, for MZ1 and HTN respectively.

Conclusion Maarheeze:

B.1 – Exceedances of the planning level for the 7th harmonic order occur throughout the year.

B.2 - The measured exceedances have a strong relation to three capacitor banks in the vicinity:

- *In case the capacitor MZ1 is energized, the harmonic levels of H7 increase.*
- *In case the capacitor HTN is energized, the harmonic levels of H7 decrease.*

The effect can be explained, but exact quantification requires more detailed calculations.

TABLE III
AMPLIFICATION FACTORS WEEK 31-33 – HS086

	Maarheeze 1 (MZ1)		Den Bosch-Noord (HTN)	
Harmonic order	**Interval 1**	**Interval 2**	**Interval 3**	**Interval 4**
THD	1.75 – 1.89	1.87 – 1.45	1.35 – 1.45	1.14 - 1.40
H5	1.28 – 1.32	1.45 – 1.01	1.25 – 1.20	1.34 – 1.25
H7	1.88 – 2.04	2.02 – 1.49	1.52 – 1.54	1.19 – 2.00
H11	1.19 – 1.54	1.05 – 1.20	1.86 – 1.20	2.59 – 1.52
H23	4.55 – 9.22	8.33 – 1.06	** - **	1.49 – 1.27

Formatted as (left change – right change) per interval/order. ** = no data

C. Tilburg West (HS099) – Geertruidenberg (HS076) – Helmond Oost (HS079) – H23

The exceedances of planning levels occur for the 23rd harmonic order for a number of nodes in Brabant (Table I). The comparison of the yearly measurements showed a strong resemblance of nearly all nodes in Brabant. The three nodes that showed the most resemblance were Tilburg West (TBW), Geertruidenberg (GTD), and Helmond Oost (HMO). These were analysed together.

The detailed analyses indicated that the level of the 23rd harmonic in Brabant is mainly determined by a set of large capacitor banks; Tilburg Noord, Den-Bosch Noord (largest), Helmond Zuid, and Maarheeze.

The time interval at substation Tilburg West in Fig. 8 is a good representation of the whole year. As can be seen in the figure, the peak values of the 23rd occur when none of the listed capacitor banks are energized. If one or more of them are switched on, the harmonic levels immediately decrease. This effect is even more visible if one enlarges the green marked interval of Fig. 8, including nodes in the vicinity. This is plotted in Fig. 9.

Fig. 9 shows two intervals at which none of the dominant capacitor banks are in operation. For these changes the average amplification factors have been determined per interval (Table IV). This table confirms the general influence of the capacitor banks on the plotted nodes. It also implies that the energizing status of large capacitor banks distributed over a wide area is significant to consider in further studies.

Conclusion H23 TBW, GTD, and HMO:

C.1 – In general, the levels of H23 are strongly related to the set of dominant (large) capacitor banks. High levels of H23 only occur if none of the 3 dominant capacitor banks are active.

TABLE IV
AMPLIFICATION FACTORS FOR H=23
HS099, HS076, HS079

Harmonic order & node	Interval 1	Interval 2
H23 HS099	2.08	2.18
H23 HS076	1.33	**
H23 HS079	4.16	1.92

** = no data

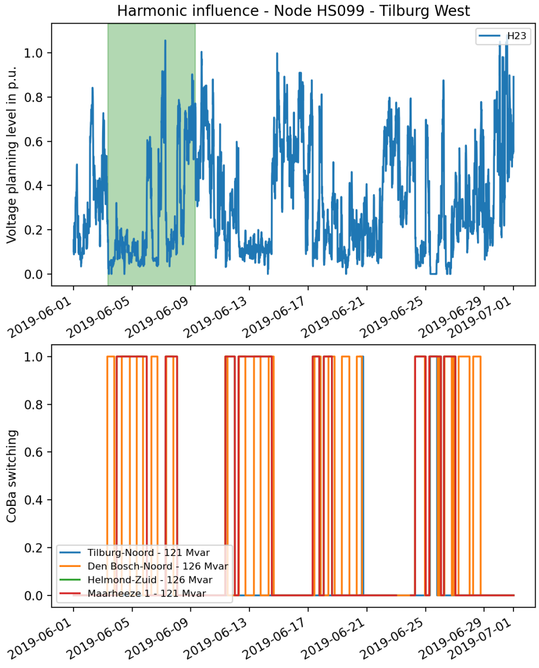

Fig. 8 – Overview of typical voltages of H23 at Tilburg West (top) with the switching activities of the dominant, largest capacitors (bottom). The area denoted in green has been analysed further.

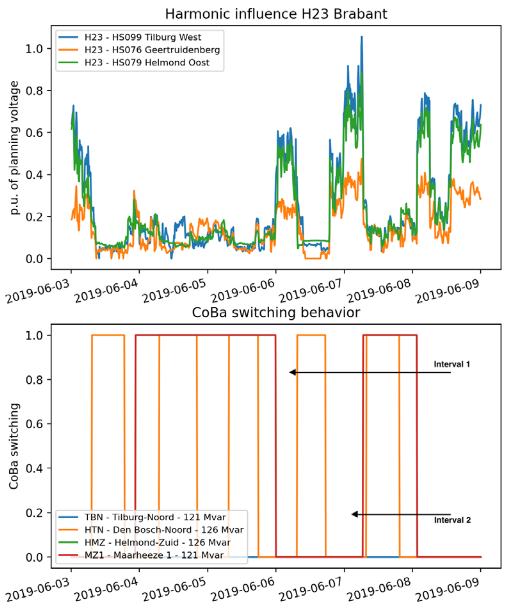

Fig. 9 – Zoomed in plot of nodes Tilburg West, Geertruidenberg, and Helmond Oost (top) and dominant capacitor banks in the vicinity (bottom).

4. Conclusions

The aim of the research was to obtain insight into specific harmonics by the analysis of measurement data for nodes in the 150kV grid in Brabant. Nodes were studied that had measured exceedances of planning levels, or could be critical in the future. The study provides an insight into the measured response of harmonics with respect to different operational changes such as:

1) *Specific outages that occurred.*
2) *The impact of capacitor banks.*

This analysis helps with model validation and planning studies on the impact of new high-voltage cables. Per use-case, individual conclusions are reported. For most cases, a good relationship has been found between the measured changes and topology changes in the grid. Additionally, the measured harmonic gain for a number of events was determined.

The results also illustrate the restrictions of the simplified model with respect to the representation of harmonic sources. Sources in the considered meshed grid are not lumped but are distributed over the grid. Topology changes including capacitor banks have influence over a wide area on the harmonic impedance of a node, which changes continuously. As a consequence, modelling is a complex task. An automated process to correlate information from various data sources could help to obtain and quantify the significant parameters and to improve the validation.

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