Authors: Vladimir Ćuk
Konstantinos Tzanakakis
Department of Electrical Engineering, Electrical Energy Systems

Checked by: prof. J.F.G. (Sjef) Cobben
Frans van Erp (Tennet)

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Insights in the impact of special projects on voltage quality in the HV/EHV networks

Contents

1 Introduction

This report gives the herald analyses of the impact of ‘special projects’ connected to the High Voltage (HV) and Extra High Voltage (EHV) network of Tennet. The analyses are preformed to create understanding in the nature of the projects.

The HV network consist of the 110 kV and 150 kV voltage levels, and the EHV networks consists of 220 kV and 380 kV voltage levels. Installations connected to these voltage levels can influence voltage quality in large areas. To verify if the influence of the special projects is within the adopted reference values, the influence of these installations on the voltage quality is assessed.

1.1 Locations covered by this and future investigations

1.1.1 Complete list of special projects

The following installations/substations were identified as the special projects:

1. NorNed – High Voltage Direct Current (HVDC) converter station, connection to the network of Norway, 380 kV;

2. BritNed – HVDC converter station, connection to the network of UK, 380 kV;

3. Betuweroute – 25 kV AC railway connected to the 150 kV network:

   3.1. Europoort,

   3.2. Alblasserdam,

   3.3. Waalhaven,

   3.4. Tiel,

   3.5. Zevenaar;

4. Capacitor banks, connected to:

   4.1. 380 kV network:

      4.1.1. Eemshaven convertor substation,

      4.1.2. Diemen,

      4.1.3. Krimpen;

   4.2. 220 kV network:

      4.2.1. Ens,

4.2.2. Weiwerd;

4.3. 150 kV network;

4.4. 110 kV network;

5. Underground cable

5.1. 380 kV network:

5.1.1. Bleiswijk,

5.1.2. Wateringen;

5.2. 150 kV network;

5.3. 110 kV network.

1.1.2 Special projects covered by this report

Due to the present availability of permanent measurement equipment, some of the mentioned locations cannot be analysed with measured data at this moment. Moreover, computer models of these locations cannot be evaluated with measured data. On-site measurements with portable equipment are difficult to install and expensive for the voltage levels in question.

Before applying additional measurement equipment the design of the measurement system needs to be analysed based on the specifics of the location and the nature of the impact on the network. In other words a study must be performed to achieve the observability of the influence of a specific installation.

Thus, some of the mentioned locations are not considered in this report. Only the locations with present permanent measurements, or in the closest substation of the same voltage level, are analysed, namely:

1. NorNed HVDC – Eemshaven;

2. BritNed HVDC – Maasvlakte;

3. Betuweroute railway – Alblasserdam and Waalhaven[1];

4. Capacitor banks - Diemen and Weiwerd;

5. Underground 380 kV cable - Bleiswijk and Wateringen.

Results of the analysis with present permanent on-location measurement devices are an input to the second phase of the impact analyses.

[1] * - At substations Alblasserdam and Waalhaven, monitoring equipment is of class S; therefore, the usage of measured data is limited.

2 Methodology of analysis

There are no normative methods to determine the impact of a project/installation on Power Quality in the network. Guidelines for the assessment procedure are given in a part of the IEC/TR 61000-3 group of technical references [1]–[3] and the CIGRE review of assessment techniques [4].

The methods used in this report can be divided into two groups, as suggested in [5]:

1. Analysis of disturbance levels with and without the object of consideration;

2. Analysis without switching the object under consideration.

The differences of the two approaches and some details about the methods are given in the following sections.

2.1 Analysis of disturbance levels before and after the object under consideration is placed into operation

This type of analysis is based on the division of disturbance levels when the observed project (or installation) is in and out of operation. By observing the disturbance levels with and without the object of analysis, and with an assumption that there are no significant differences in the rest of the network during the observation period, the impact of the project can be estimated as the difference between the two levels. This type of analysis uses only voltage measurements (it does not use current measurements). When possible, this type of analysis utilises measurements of disturbance levels before and after the project is put into operation.

Another option is analysing long-term measurements, e.g. months or years, which include periods of time in which the object was going in and out of operation. The statistical measurements, e.g. percentile levels (values not exceeded for a given percentage of time), are compared then for periods of time with and without the installation, to determine the influence. This approach requires either the measurements of consumed/generated power or information of switching events, e.g. from a SCADA system, synchronised with the measurements of disturbance levels.

In this report, the second option was used (utilizing power measurements and switching events). For NorNed and the two Betuweroute substations (Alblasserdam and Waalhaven), power measurements are available. For the capacitor banks at Diemen and the HV cable at Bleiswijk and Wateringen the switching actions are logged with a precise time stamp.

For BritNed, no power or current measurements are available at the moment. At substation Weiwerd (220 kV capacitor bank), were no switching events during the observation period. This limited the analysis to a comment of the disturbance levels measured at the location.

2.2 Analysis based on the correlation of voltage with current and power measurements

This type of analysis requires both the values of the voltage and current. Due to this, it is possible to estimate the influence of the installation without disconnecting it. A number of versions of this method is described in [4].

An advantage of this method is that it can use the measurements in which the installation in question was operated without a stop. The disadvantages are that it requires measurements/simulations of characteristics of the current as well (not only the RMS value, but also the characteristics associated with the observed voltage disturbance), and that certain assumptions need to be taken regarding the network response, e.g. the network impedance.

For most of the analysed phenomena this method could not be used, because on most locations measurements of the current are not available. Regarding harmonic distortion, for NorNed the data could be analysed also using methods which use current measurement data. On other locations, computer simulations were used for quantifying the impact of the object.

2.3 Observation period

According to the Netcode [6], the disturbance levels are determined based on measurements for a one week period and compared to the limit, for most PQ phenomena. Since this condition needs to be met during every week in a year, compliance to the limits can be checked based on disturbance levels of all individual weeks or a disturbance levels calculated for the whole time period. In this report, the disturbance levels are determined based on time periods longer than one week – several months or a whole year. In this way the assessment can be based on a single comparison of a single level to the reference value, instead of comparing the level of each individual week (e.g. 52 values for a whole year).

2.4 Operation conditions assessed in the analysis

The requirements for the quality of the supply voltage, as specified in the Netcode Elektriciteit [6] and the standard NEN-EN 50160:2010 [7], should be satisfied under normal operating conditions.

The normal operating conditions for which the HV and EHV networks are planned are defined in the Begrippenlijst Elektriciteit [8] as conditions of the network under which the energy transmission can take place according to network planning. This includes operation during a fault of a single network component (e.g. a transformer, overhead line, substation busbar, etc.), also with a possibility that another component was already disconnected due to maintenance.

According to the Netcode, the design of all HV and EHV network needs to satisfy all transport conditions, also during a fault of a freely chosen network element or disconnection of a freely chosen production unit [6]. More details are given in [6] and [8].

2.5 Computer simulations

The estimation of the emission of a single project can be performed by a computer simulation. In this case the emission of other contributors can be switched off to single out the emission of the observed disturbance source. Another strong advantage on computer simulations is the possibility to assess different network configurations, which may not be available in measurement results.

On the other hand, a drawback of computer simulations is the additional uncertainty of the results due to assumptions regarding models of components and composition of loads. This can partly be mitigated by using available measurements as inputs and the basis for assumptions (e.g. loading levels in the network).

The simulations presented in this report were performed on a Digsilent Power Factory model of the HV/EHV network, in all parts except for the transient analysis of the 380 kV cable, which was done in PSCAD and Matlab.

2.5.1 Network model

The Power Factory model of the network was made by adapting the model developed for [9], which includes the combined 380, 220, 150 and 110 kV network of TenneT in the Netherlands as well as the cross-border connections. Where needed, the initial conditions for electromagnetic transient simulations and harmonic load flows are calculated based on the results of a load flow, with loadings of individual buses based on [10].

All cables and overhead lines are modelled using distributed parameters. Because of the high frequencies considered in this analysis, the physical length of the lines and the wavelength of the currents and voltages may have the same order of magnitude. Even shorter lines have to be treated as long lines at higher frequencies, where the wavelengths of the signals become shorter.

The skin effect is taken into account, based on a generic (commonly used) geometry of HV/EHV lines. At resonant frequencies the dominant system components consist of the series resistance and shunt conductance. The resonant frequency is not affected by changes in the series resistance magnitude, however, the peaks (magnitudes) of the impedance are.

For electromagnetic transients, a reduced network model is used, up to at least three substations away, including the transformers connected to them. The rest of the network is represented by a number of equivalent external grids, whose values: Short-circuit power and X/R ratio, were calculated using maximum short circuit currents, connected to the substations on the borders of the reduced model. The choice of three busbars was made because in a previous study [11] the model consisted of the network up to two busbars away from the studied busbar. The additional busbar should reveal that more degrees of freedom taken into account do not alter the results significantly, given a reduced representation of the network. Simulation results for capacitor banks are in good agreement with [11], which shows that the modelling up to two busbars is already sufficiently accurate. In reality the larger size of the network is providing more damping during switching events. The previous study [11] was used for sizing equipment, and therefore favoured pessimistic conditions and assumptions.

The PSCAD model used for the simulations of the 380 kV cable includes the complete 380 kV network, with a reduced complexity of substations and corresponding connections at locations which are distant from the observed cable [12].

2.5.2 Model validation

The performance of the computer model of the network is dependent on the network configuration and the loading levels of substations. A direct comparison with measured values can never lead to identical results, as the composition of loads - e.g. shares of linear and non-linear loads or inductive and capacitive loads, are generally not known for any moment in time. Therefore, a certain uncertainty of the model has to be taken into account, with no exact quantitative criterion of an acceptable model.

The impedance-frequency characteristic of the network “seen” from a chosen busbar can be compared directly to the measurements of voltage and current harmonics for harmonic orders with significant disturbance levels, if both are available. Regarding network unbalance, if measurements of sequence components of voltage and current - RMS values together with phase angles of the fundamental component - are available, the sequence impedances can be compared as well. Additionally, waveforms of simulated transients can be compared with measured voltage waveforms, if transient recordings are available.

In the absence of all required measurements, e.g. current measurements, there are two options for partial validation of the model. The first option is the analysis of the recorded voltage signals during a manifestation of a transient voltage. Digital Fourier Transformation of these signals gives a spectrum and allows to some extend an assessment of the system’s resonant points. The spectrum is than compared with the impedance-frequency characteristic of the computer model. The second option is comparing the matching of resonant frequencies with the measured quasi-steady-state levels of the harmonics. The two mentioned methods can only validate the resonant frequencies, but not the magnitudes of impedance or voltage harmonics.

Therefore, whenever possible, the model performance was analysed directly by comparison with voltage and current measurement, and in other cases a partial validation was performed.

3 Impact of the HVDC converter station NorNed

3.1 Introduction

Even though AC transmission of electrical energy is well established due to its high reliability and efficiency, in certain conditions the application of DC transmission at high voltages – High Voltage Direct Current (HVDC), is better suitable [13]. One of the main applications of HVDC is transmission of power across the sea – long underwater links. In these conditions, HVDC has the following advantages:

1. The inductance and capacitance of the cable do not limit the maximum length or the transmission capacity, since no charging current is needed in the steady state;
2. A DC link makes an interconnection of two AC systems with different frequencies or control philosophies possible;
3. The power flow can be controlled fast and flexibly, thus improving stability;
4. HVDC transmission results in lower line costs and losses, above a certain length of the line (typically in the range of several tens / few hundreds of kilometres).

The NorNed HVDC link joins the power systems of the Netherlands and Norway. The cable has a transmission capacity of 700 MW and a total length of 580 km [14]. The link was completed in May of 2008. As all other cross-border links, it enhances the security of supply of both countries . At the same time, the link allows a more efficient economic dispatch for power plants and trading options in both countries.

3.2 Influence of HVDC on PQ

HVDC links influence, as any other installations connected to the grid, the supply voltage RMS (level) in the system. The voltage level is for instance changed by: cross-border import/export power, availability of network elements, loads, production and the power of the converter. The consumption of reactive power by the converter also leads to a change in the supply voltage level. Therefore, the converters are always compensated by the installation of capacitor banks and/or filter banks, to minimize this influence.

As many power electronic converters, HVDC converters are a source of harmonic currents. The injection of harmonic currents can lead to an increase of voltage distortion in the network. For this reason, all large HVDC converters are equipped with passive harmonic filters, which minimise their impact on the voltage distortion in the network.

Due to the symmetrical topology of used converters, HVDC links are not a significant source of voltage unbalance in the network. Therefore, the impact of HVDC links on unbalance is not treated in this report.

3.3 Description of the analysed location

The converter stations are situated at the Eemshaven substation - located in the north of the Netherlands and at the Feda substation - in the south of Norway. A 580km submarine cable operating at ±450kV, designed to operate continuously at 700MW, is connecting the two converter stations. The 380kV network around the converter station is shown in .

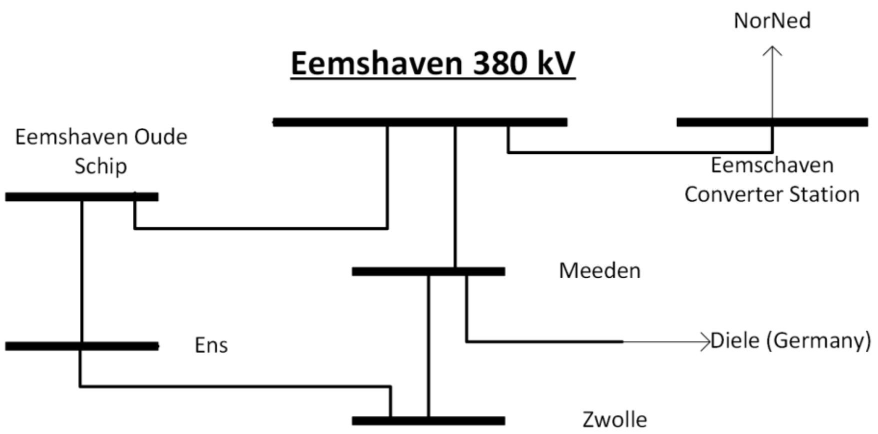

Figure 1 Schematic of the 380 kV and 220 kV networks around the Eemshaven converter station

In order to compensate for the consumption of reactive power of the converter, two shunt capacitor banks of 106 Mvar each are installed. To eliminate the production of harmonics, two 48 Mvar double tuned $11^{th}/13^{th}$ order filters and two 60 Mvar high pass (24^{th} and higher order) filters have been connected to the converter station of Eemshaven.

3.4 Influence on supply voltage variations

3.4.1 Analysis of disturbance levels with and without the object of consideration

To analyse the influence of NorNed on the voltage levels, the 10-min voltage magnitude recordings are paired with the 15-min power transmission via the HVDC link. In Figure 2 this comparison is shown for the first half of January 2012.

It can be observed that the deviations of NorNed exported power lead to deviations of the voltage level (increase of power leads to a decrease of voltage level and vice versa). Further deviations are visible at times with no (or insignificant) power variations of NorNed. These variations are caused by the rest of the network and other cross-border links. During most of the time, the deviations originating from the rest of the network and the cross-border links are larger.

A statistical analysis of the data for approximately 8 months of 2012 is done. The 99.9% probability values of the average Line-to-Line and Line-to-Neutral Voltage, is presented in Table 1. The nominal operating voltage level of substation Eemshaven is 380 kV.

During the observed time period (eight months of 2012), the supply voltage variations were lower than the reference value (the ±10 % limit of the Netcode [6]). Additionally, the variations were lower than ±10 % for each week during the observation period, as required by [6].

The histograms of the voltage level when the power of the link is equal or close to the nominal (P > 700 MW), both importing and exporting, are shown in Figure 3.

Direction of power	99.9% lower / upper value of Line-to-Line Voltage (kV)	99.9% lower / upper value of Line-to-Neutral Voltage (kV)
Importing	397.43 / 415.75	228.96 / 238.42
Exporting	399.91 / 417.64	231.63 / 241.12

Table 1 Statistics of the supply voltage variations at NorNed

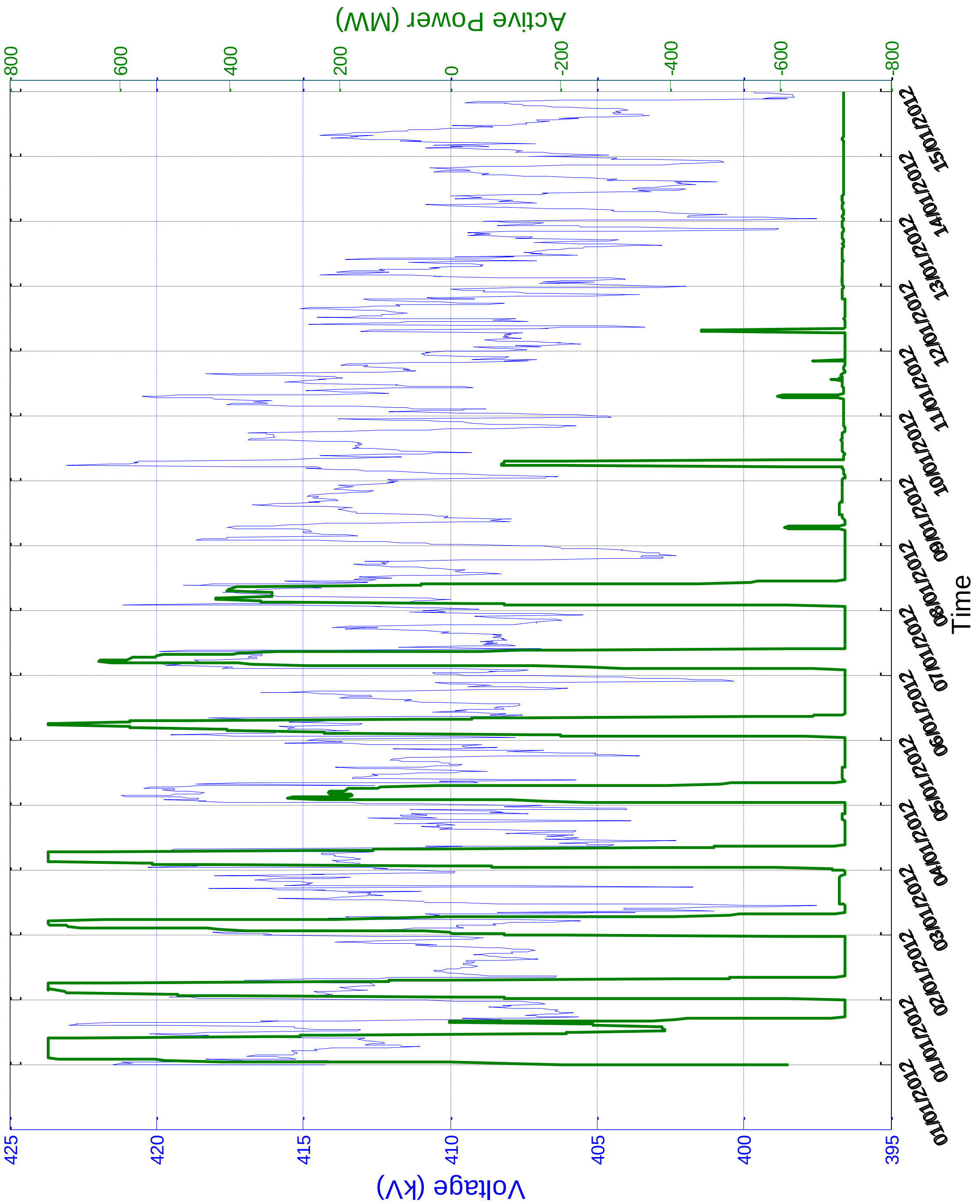

Figure 2 Relation between the Line-to-Line voltage magnitude and the transmitted real power of NorNed; first half of June 2012

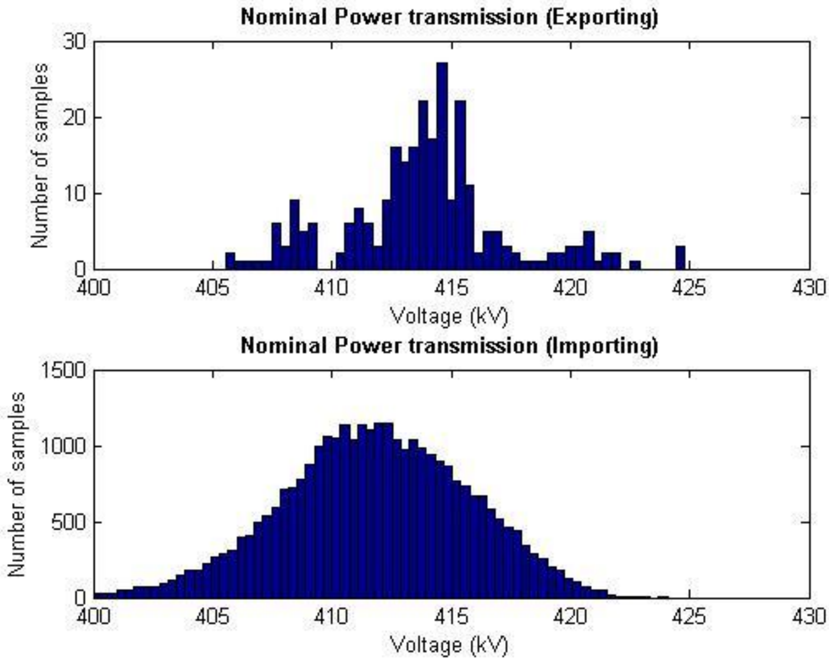

Figure 3 Histograms of the voltage level during time intervals of nominal power transmission

3.4.2 Simulation results

The effect of NorNed on the voltage level is examined with a simulation, in which the effect of the HVDC link can be isolated from other deviations in the network. The simulation was done in the following conditions:

1. no power is transmitted via NorNed;
2. power is imported from Norway;
3. power is exported to Norway.

Regarding the influence of other network components, the following conditions were considered:

1. All production units and lines available (base case)
2. Without production of the Eemshaven power plant
3. A single 380 kV overhead line between substations Meeden and Eemshaven disconnected
4. A single 380 kV overhead line between substations Meeden and Eemshaven disconnected and without production of the Eemshaven power plant
5. A single 380/220 kV/kV transformer in substation Eemshaven 380 kV
6. A single 380/220 kV/kV transformer in substation Eemshaven 380 kV and without production of the Eemshaven power plant
7. A single 380 kV overhead line between substations Eemshaven and Eemshaven Oost
8. A single 380 kV overhead line between substations Eemshaven and Eemshaven Oost and without production of the Eemshaven power plant

The results of the simulations are presented in Table 2.

Condition of NorNed	Line-to-Line Voltage (kV)
No transmission	402.8
Importing	402.4
Exporting	403.7

Table 2 Simulated influence of NorNed on supply voltage variations: base scenario, lowest and highest voltage level

The lowest voltage level occurs in the case with a disconnected single over-head line between substations Eemshaven 380 kV and Eemshaven Oost 380 kV, with no production of the Eemshaven power plant. The highest voltage level occurs in the case of a single 380 kV overhead line between substations Eemshaven 380 kV and Meeden 380 kV out of operation, and with the NorNed link importing maximal power from Norway.

The results of the simulation are in accordance with the analysis of measurement data, with higher voltages when exporting and lower voltages when importing. The supply voltage variations due to the NorNed HVDC link are lower than the reference values.

3.5 Influence on harmonic distortion

3.5.1 Analysis without switching the object under consideration

The analysis is performed with the use of the measurements of the year 2012, made available by TenneT. The assessment of harmonic emission level is done without switching of the installation, and it is based on two different methods, described in Chapter 2:

1. a simple statistical approach from simultaneous measurements of voltage harmonics and the power transmitted;
2. a study on the correlation between the harmonic current and voltage at the Point of Evaluation by processing long duration simultaneous measurements of harmonic voltages and currents.

The harmonic orders evaluated are the characteristic ones up to the 49^{th} (11^{th}, 13^{th}, 23^{rd}, etc.) and the non-characteristic harmonic orders 3^{rd}, 5^{th}, 7^{th} and 9^{th}.

The recorded measurements taken into account consist of 10-min based Line-to-Neutral Voltage values and 15-min based current and power recordings. When data with different measuring time period need was compared, the data was resampled to a time base of 30 minutes.

3.5.1.1 Correlation of voltage distortion and power transmitted

The relation between the total harmonic distortion of the voltage and the apparent power of the NorNed HVDC link is shown in Figure 4.

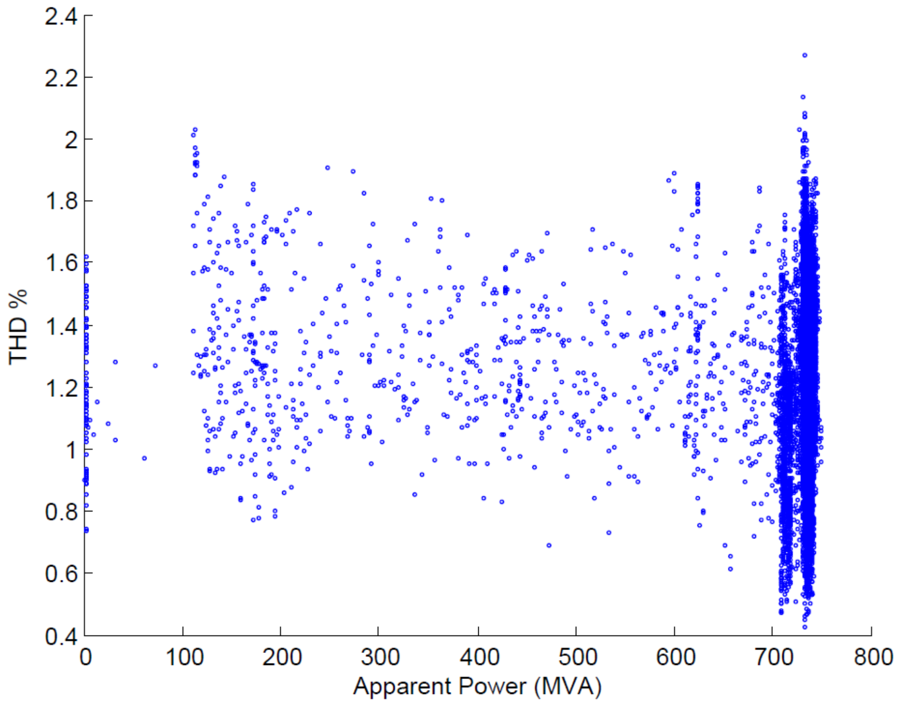

Figure 4 Relation between the total harmonic distortion of the voltage to the apparent power transmitted through NorNed

The THD values remain at low levels throughout the power spectrum. The deviation at higher power transmission is greater. The greater number of samples can have an impact on this distribution. It can be noticed that the THD value is not strongly correlated to the power of the NordNed link, which implies that the THD value mostly originates from other sources in the network.

In Appendix A the plots of harmonic distortion of individual harmonic orders as a function of the apparent power can be found. A strong correlation can be seen for the characteristic 11th and 13th harmonic orders (which are characteristic harmonic orders of the converter), where the harmonic distortion increases as the power transmitted is increasing. This relationship is clear for the values of the power from 100 until approximately 500 MVA, while after that point the value of the distortion is reduced and kept at lower levels. The same holds for the 23rd and 25th harmonic orders. As far as higher order harmonics are concerned, the deviation of the harmonic distortion increases and the correlation is not strong. After each plot showing the relationship of harmonic distortion with power, histograms of the harmonic distortion of the voltage and the current for power transmission above 700 MVA can be found.

According to this method, the background harmonic voltage is evaluated by extrapolation of the harmonic voltage to the situation where there is no power transmitted. There are not many points with this conditions, and the data is largely scattered and with large deviations, so it is difficult to determine the background level of distortion. As described in[4], “The major disadvantage of this approach is that it gives acceptable results in practice only when the installation under consideration brings a significant contribution to the global distortion at the PCC”, which is not the case of NorNed. Due to this reason, the method of correlating harmonic voltages with harmonic currents leads to unreliable data in this case. Therefore the values calculated with this method cannot be compared with the design limits given in [17].

The 95% probability values of the measured harmonic distortion[2], at NorNed, both voltages and currents, at nominal power transmission (P > 700 MW) are presented in Table 3.

Harmonic Order	Voltage HD (%)	Current HD (%)
3	0.126	0.240
5	1.303	2.282
7	1.334	3.383
9	0.075	0.248
11	0.263	1.652
13	0.205	0.683
23	0.103	0.365
25	0.114	0.306
35	0.107	0.473
37	0.088	0.275
47	0.072	0.312
49	0.060	0.25
THD	1.642	4.129

Table 3 95% probability values of harmonic distortion of voltage and current of NorNed, at nominal power transmission (P > 700 MW)

The harmonic distortion of the voltage is well in accordance with the planning levels, as defined in [1] and the limits of the Netcode [6].

3.5.1.2 Correlation between the harmonic current and voltage at the Point of Evaluation

In the case of the 11th harmonic, shown in Figure 5, a drawback of this method can be seen. The measured harmonic current and voltage distortion levels are less than the contribution calculated through this method. The same situation is observed in the case of the 35th, 47th and 49th harmonic orders. This is also related to the comment for the background levels in section 3.5.1.1, the assessment technique suffers from inaccuracy in the case that harmonic source is not dominant at the point of evaluation, leading to a weak correlation of voltage and current harmonics.

Due to this, for these harmonic orders a conservative approach could be used - instead of using the calculated values, we can assume that the entire measured harmonic distortion, contribution of NorNed and the other sources in the network, of the harmonic orders: 11th, 35th, 47th, and 49th has to be lower than the indicative planning limits, respectively: 1,5%, 0,58%, 0,43% and 0,42%. Hence, the emission level of these harmonic orders is assumed to be the 95% probability value of all measurements. In Table 4 all estimated voltage distortion levels are given, together with the indicative planning levels of IEC 61000-3-6 [1] for HV and EHV voltage levels. Even with this conservative method, the emission levels for voltage distortion are in accordance to the indicative planning limits set by [1]. The plots results of other harmonic orders are presented in Appendix A.

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2 including both background and emission of NorNed

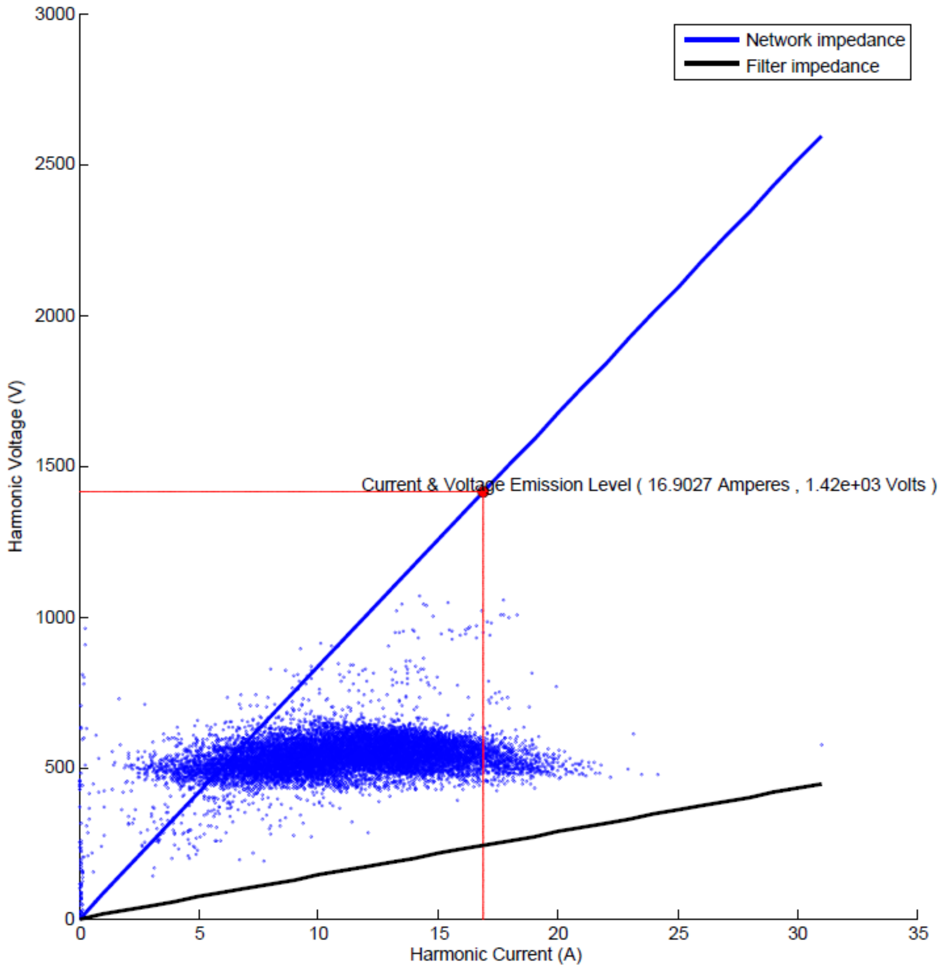


Figure 5 11th harmonic voltage as a function of the harmonic current for NorNed

Harmonic Order	Voltage emission level (V)	HD (%)	Planning levels IEC [1]
3	48.9	0.02	2
5	666	0.28	2
7	2630	1.11	2
9	34.6	0.01	1
11	622	0.26	1.5
13	119	0.05	1.5
23	285	0.12	0.87
25	125	0.05	0.82
35	251	0.11	0.58
37	226	0.09	0.55
47	167	0.07	0.43
49	140	0.06	0.42
THD [%]	1.19		3

Table 4 Voltage distortion of individual harmonic orders at the NorNed link

3.5.2 Simulation results

The 95% probability values of the measured harmonic currents, as calculated in the analysis without switching the object under consideration, were used as an input for a simulation, in order to examine the influence of the converter of NorNed. This simulation calculates the voltage distortion in substation Eemshaven only due to the NorNed HVDC link, including the filter banks, which is directly the impact on the network without the background distortion. The analysed cases (production conditions and disconnected network elements) are the same as for the simulations of supply voltage variations.

The resulting harmonic voltages on the converter station of NorNed are presented in Table 5 for the case with the highest impact of NorNed on voltage THD – with a single over-head line between substations Eemshaven 380 kV and Meeden 380 kV disconnected. In the remaining cases there were no significantly higher values of individual harmonic orders, with most of the levels lower than the presented results.

Harmonic Order	**Harmonic Distortion in %**	**Planning levels IEC** [1]
3	0.02	2
5	0.70	2
7	0.73	2
9	0.06	1
11	0.63	1.5
13	0.26	1.5
23	0.27	0.87
25	0.38	0.82
35	0.09	0.58
37	0.04	0.55
47	0.02	0.43
49	0.02	0.42
THD	1.31	3

Table 5 Harmonic distortion of the voltage caused by NorNed – simulation results

The calculated voltage distortion levels confirm that the influence of the NorNed HVDC link is within the planning levels, limits, and allocated distortion levels specified in the design phase [1], [6], [15].

3.6 Conclusions for the influence of HVDC converter station NorNed

The voltage levels do not differ significantly when the power is being exported or imported by NorNed. The computer simulations of slow voltage variations confirm the measured data, that export of NorNed lowers the voltage and import elevates the voltage. The voltage variations due to NorNed are lower than the reference value of ±10 % during the whole observation period (eight months of 2012).

Due to the symmetrical topology of used converters, HVDC links are not a significant source of voltage unbalance in the network, and were therefore not analysed in this aspect.

The analysis of the harmonic distortion is based on the two methods proposed by [4]. A statistical approach based on: the correlation of voltage harmonic voltage distortion and power, and a correlation of the harmonic voltages and currents, are evaluated.

The results show that the harmonic emission levels cannot be determined by measurements because NorNed is not a dominant source of distortion, and as a consequence measured harmonic voltages are not correlated to the power and current of NorNed.

The overall values of harmonic distortion measured at the substation are within the grid planning levels of [16] and therefore within the compatibility levels of the grid code [6].

The measurements and analysis revealed that NorNed is not a dominant disturber, therefore harmonic emission of NorNed is estimated based on simulations. The harmonic voltages generated by NorNed’s injected harmonic currents are within the emission planning levels specified in the design phase [17].

4 Impact of the HVDC converter-station BritNed

4.1 Introduction

The reasons for the application of HVDC links are described in section 3.1. In the same manner as the NorNed link connects the Netherlands to Norway, and for the same reasons, the BritNed link is a connection to the power system of United Kingdom (UK). The BritNed link has a transmission capacity of 1000 MW (1 GW) and a total length of 254 km. The link is operational since April of 2011 and it is connecting the growing UK portfolio of wind generation in the North Sea with the Netherlands and enhancing the security of supply of both countries.

4.2 Influence of HVDC on PQ

The influence of HVDC on PQ is explained in section 3.2. As in the case of NorNed, this report focuses on the impact on supply voltage variations and harmonic distortion in the network.

4.3 Description of the analysed location

The converter stations are situated at the substation Maasvlakte, located west of Rotterdam and at the Isle of Grain, on the southern bank of the Thames Estuary in the UK. A 254 km submarine cable operating at ±450 kV DC, designed to operate at 1000 MW, is connecting the two converter stations [16]. The 380kV network around the converter station is shown in Figure 6.

In order to eliminate the converter's generated harmonics, four AC filter banks have been installed at Maasvlakte. A 90 Mvar double tuned 12th/24th filter and a 225 Mvar single tuned 3rd harmonic filter have been connected to the Maasvlakte substation, in addition to two filter banks of 225 Mvar each, consisting of two branches, a 90 Mvar double tuned 12th/24th branch and a 135 Mvar single tuned 5th harmonic filter branch.

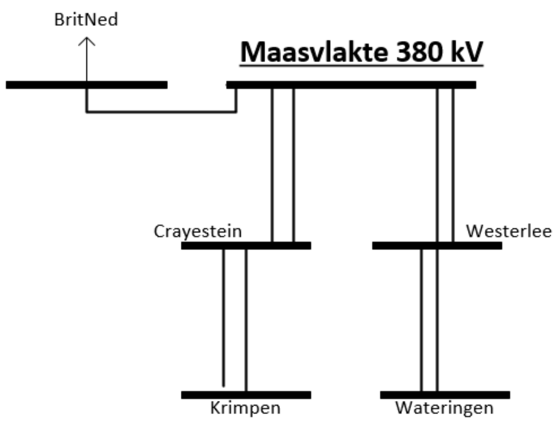


Figure 6 Schematic of the 380 kV network around the Maasvlakte Station

In substation Maasvlakte there are no current and power measurements at the moment. Due to this, the analysis is limited to simulations and analysis of voltage measurements without the assessment techniques which require current measurements.

4.4 Influence on supply voltage variations

4.4.1 Analysis without switching the object under consideration

A statistical analysis of the measurement data of slow voltage variation gives the 99.9% values and the average Line-to-Line and Line-to-Neutral Voltage, presented in Table 6. Due to the lack of power measurements, there can be no comparison between the periods when BritNed is in use and when not and consequently it's impact cannot be directly assessed.

The normal operating voltage of substation Maasvlakte is 380 kV. The 99.9% values during the observation period (approximately five months) are lower than the reference value (the ±10 % limit of the Netcode [6]). Additionally, the variations were lower than ±10 % for each week during the observation period, as required by [6]. The histogram of the voltage level at substation Maasvlakte is shown in Figure 7.

99.9% lower / upper value of Line-to-Line Voltage (kV)	Average value of Line-to-Line Voltage (kV)	99.9% lower / upper value of Line-to-Neutral Voltage (kV)	Average value of Line-to-Neutral Voltage (kV)
396.92 / 411.49	404.74	228.82 / 237.41	234.24

Table 6 Line-to-Line and Line-to-Neutral Voltage values of substation Maasvlakte

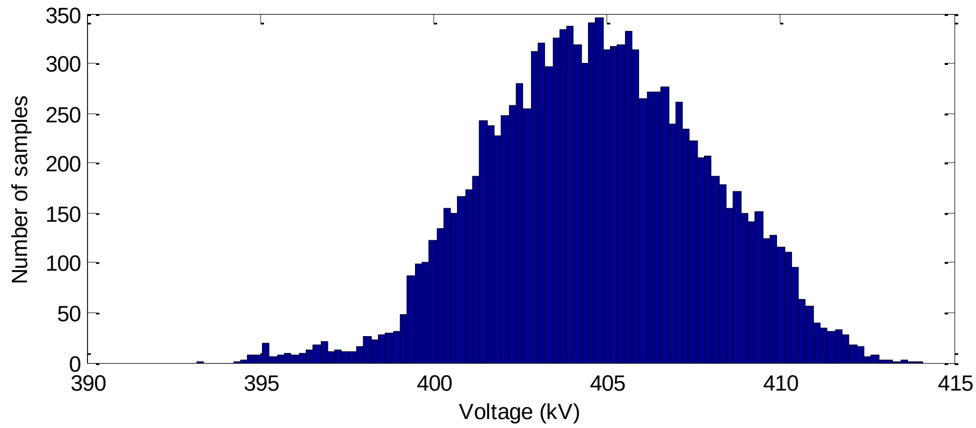


Figure 7 Histogram of the voltage levels (average Line-to-Line voltage) at substation Maasvlakte

4.4.2 Simulation results

The effect of BritNed on the voltage level is examined with simulations, by evaluating three different cases of power flows, in the following HVDC link conditions:

1. no power transmission via BritNed;
2. importing maximal power from the UK;
3. exporting maximal power to the UK.

Each of these three cases are investigated in the following network conditions:

1. all network components and production available (base case);
2. without production in the Maasvlakte power plant;
3. without a single over-head line between substations Maasvlakte and Simonshaven;
4. without a single over-head line between substations Maasvlakte and Simonshaven and without generation in the Maasvlakte power plant;
5. without a single over-head line between substations Maasvlakte and Westerlee;
6. without a single over-head line between substations Maasvlakte and Westerlee and without generation in the Maasvlakte power plant;
7. without a single 380/150 kV/kV transformer in substation Maasvlakte;
8. without a single 380/150 kV/kV transformer in substation Maasvlakte and without generation in the Maasvlakte power plant.

The results of the simulations are presented in Table 7. The lowest voltage level is found in case of exporting power while a single 380/150 kV/kV transformer is disconnected in substation Maasvlakte 380 kV and with no generation in the Maasvlakte power plant. The highest voltage level is found in case of importing power via the HVDC link and with a single over-head line between substations Maaskvlakte and Simonshaven disconnected. In all cases the supply voltage variations are lower than the reference value.

Condition of BritNed	Line-to-Line Voltage (kV)
No transmission	417.3
Importing	413.0
Exporting	420.8

Table 7 Influence of BritNed on supply voltage variations: base scenario, lowest and highest voltage level

4.5 Influence on harmonic distortion

4.5.1 Analysis without switching the object under consideration

The analysis is performed with the use of the measurements of the year 2013, made available by TenneT. Since no current and power measurements exist in the substation at present, the assessment of harmonic emission level cannot be accomplished in the way it is achieved in the case of NorNed, presented in Chapter 3.

The recorded measurements taken into account are measured at substation Maasvlakte and consist of 10-min basis Line-to-Neutral Voltages. The 95% probability levels of harmonic voltages and the THD are presented in Table 8, together with the indicative planning levels of [1] for HV and EHV voltage levels.

There are no even harmonics detected in the system during the vast majority of the year, therefore, the values of even harmonics are not shown in Table 8. In addition to that, the value of the harmonic distortion is equal to zero for some odd-order harmonic voltages, either because in the measurements their value was always zero, or because their value was different than zero during very short time intervals (much shorter than ten minutes).

The harmonic distortion of the voltage is well in accordance with the indicative planning levels defined in [17] and the Netcode [6].

Harmonic Order	RMS Value (V)	Voltage HD (%)	IEC planning levels [1]
3	365.81	0.156	2
5	2067.56	0.882	2
7	1449.93	0.618	2
9	0.00	0.000	1
11	831.78	0.354	1.5
13	856.81	0.366	1.5
15	0.00	0.000	0.3
17	101.86	0.043	1.2
19	0.00	0.000	1.07
21	0.00	0.000	0.2
23	204.38	0.087	0.87
25	434.13	0.185	0.82
27	0.00	0.000	0.76
29	0.00	0.000	0.70
31	0.00	0.000	0.66
33	0.00	0.000	0.2
35	178.70	0.076	0.58
37	0.00	0.000	0.55
39	0.00	0.000	0.2
	THD [%]	1.157	3

Table 8 The 95% probability values of voltage harmonic distortion of all recordings of Maasvlakte

4.5.2 Simulation results

The influence of BritNed on voltage distortion was simulated, to determine the impact without other sources of distortion in the network. Due to the lack of harmonic current measurements, the converter of the BritNed link is modelled as a generic converter of the same type, as defined in [18]. The filter banks are modelled based on the design data. The harmonic current values are calculated based on the nominal power and voltage level. The analysed network condition include the same cases as described for supply voltage variations.

The resulting harmonic voltages at Maasvlakte substation are presented in Table 9, for the case with the highest value of voltage THD, which is the case with a single 380/150 kV/kV transformer disconnected in the Maasvlakte substation.

Harmonic Order	Harmonic Distortion in %	IEC planning levels [1]
11	0.54	1.5
13	0.79	1.5
23	0.71	0.87
25	0.54	0.82
35	0.27	0.58
37	0.04	0.55

47	0.51	0.43
49	0.29	0.42
THD	1.46	3

Table 9 Harmonic distortion of the Voltage due to BritNed; simulation results

In the results of Table 9, the value of the 47th harmonic is slightly higher than the planning level for the corresponding order, given in [1]. On this location harmonics are monitored only up to the 40th order, however, it is safe to assume that the actual values do not reach this level because the measurements of lower harmonic orders are lower than simulated. The reason for that is the generic model of the converter model used in the absence of measurements, which overestimates the injected harmonic currents. This assumption needs to be verified when measurements above the 40th order and measurements of currents become available on this location.

4.6 Conclusions of the HVDC converter station BritNed

The 99.9% measured values during the observation period (approximately five months) are lower than the reference value (the ±10 % limit of the Netcode [6]).

The simulation results which estimate the influence of BritNed without other sources of voltage variations are in line with the measured data, both in the conditions of importing and exporting power.

Due to the symmetrical topology of used converters, HVDC links are not a significant source of voltage unbalance in the network, and were therefore not analysed in this aspect.

The influence of the BritNed link on harmonic distortion cannot be evaluated based on the measured data due to the lack of the corresponding current and power measurements. A statistical analysis is used to evaluate the harmonic distortion at the substation of Maasvlakte and the measurements of the voltage distortion are found to be in accordance with the planning levels defined in [17] and in Netcode Elektriciteit [6]. The influence of the BritNed link on the harmonic distortion is also analysed through simulations. In absence of harmonic current measurements, a model of generic harmonic current injection is used and the influence on harmonic voltages generated by the converter. The results show that the impact is in line with planning levels defined in [17] and in Netcode Elektriciteit [6] on all harmonic orders except for the 47th. It is probable that this result is overestimated due to the model used for injected harmonic currents, however this needs to be verified by measurements.

5 Impact of the Betuweroute railway at Alblasserdam and Waalhaven

5.1 Introduction

Electrified railway systems are used widely around the world as a significant means of mass transportation of people and goods. They make the transportation fast and environmentally friendly, but at the same time pose new challenges to the power grid.

The Betuweroute is a 160 km double track freight railway connecting Rotterdam with Germany and it is part of the Trans-European Transport Networks (TEN-T). The route is electrified with a 25 kV 50Hz AC voltage by specialized traction substations, connected to the 150 kV network of TenneT.

5.2 Influence of electrified railway on PQ

High speed/high capacity railway systems are usually fed by single phase 25 kV systems through traction substations. The train motion and the connection of single phase load to the traction system has impact on PQ. The magnitude of the disturbance is affected by the route profile, the motion of the train, its loading and by the power system configuration.

In electric locomotives single phase converters are used. Compared to normal loads on the high voltage system, the main effect of the locomotives on the high voltage supply system are time varying harmonics and asymmetry. The harmonic currents generated by the locomotive propagate through the traction system to the high voltage power supply systems. The single phase current of the locomotive is translated to a two-phase load on the high voltage supply system.

Voltage fluctuations are caused by the operation of railways, due to the fluctuating demand that depends on the vehicle traffic at the time. The active power is a function of the type of movement of the train: with an acceleration, constant speed and deceleration period, which impose different demands on the network.

The AC single phase electrical traction systems constitute one of the significant sources of voltage and current unbalance in the high voltage supply. The traction loads are supplied two out of the three phases of the electric power system.

5.3 Description of analysed locations

The two 150 kV substations under consideration in this study, Alblasserdam and Waalhaven, supply the railway line with power of the desired characteristics (25kV 50Hz single phase) through single-phase traction transformer substations. Each transformer is connected to two phases of the three-phase system. At the substation of Alblasserdam, phases B and C are connected, while at Waalhaven phases A and B, so that the main feeding system remains as balanced as possible. The 150 kV network around the two substations can be seen in Figure 8 and Figure 9.

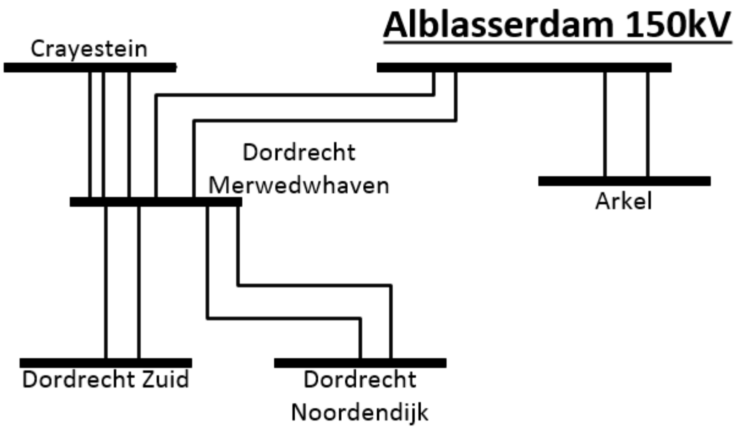


Figure 8 Schematic of the 150kV network around substation Alblasserdam

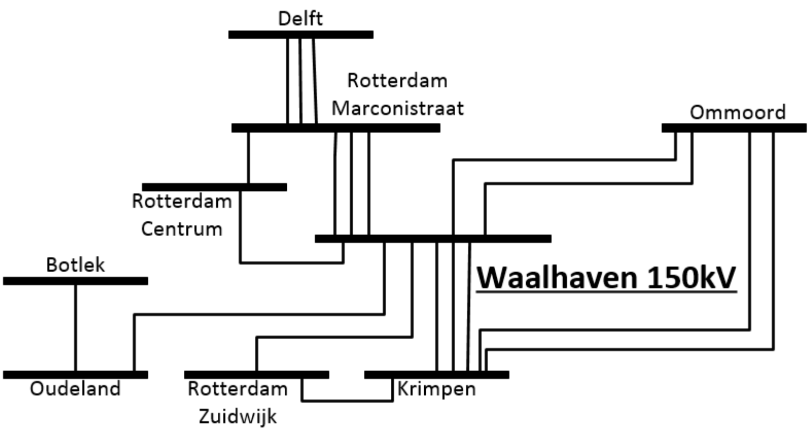


Figure 9 Schematic of the 150kV network around substation Waalhaven

On both locations, measurement instruments are of class “S”, which cannot be used for an official evaluation of voltage quality. Class “S” instruments are used for statistical surveys, for official evaluation only class “A” instruments should be used. However, if the measured values increased with the measurement uncertainty of class “S” are still within the accepted limits, these measurements can be a good indication that the impact of the installation is within limits.

5.4 Influence on supply voltage variations

5.4.1 Analysis without switching the object under consideration

Based on the measurement data of slow voltage variations, the 99.9% values of the 10 minute based values of Line-to-Line voltage values for the whole observation period (close to five months) are calculated, and presented in Table 10. On both locations the 99.9% values are lower than the reference value (the ±10 % limit of the Netcode). Additionally, the variations were lower than ±10 % for each week during the observation period, as required by [6]. For class “S” instruments, the measurement uncertainty for the magnitude of the supply voltage is 0.5 % of the declared supply voltage which is 150 kV in this case. If we add the ± 0.75 kV to the lower and upper 99.9 % values from Table 10, the measurement still satisfy the ±10 % limit with a significant margin.

However, another important detail is that the Netcode [6] defines the limit for 10-min based measurement, while the actual measurements are based on 15 min time intervals.

	Alblasserdam	Waalhaven
99.9% lower / upper value of Line-to-Line Voltage (kV)	150.51 / 158.99	150.93 / 159.24

Table 10 Voltage level (line-to-line) at substations Alblasserdam and Waalhaven

5.4.2 Simulation results

The influence of the Betuweroute on voltage level is examined by simulating the voltage variations caused by the load of a passing train. The input of the model was a single-phase load, connected Line-to-Line between two phases (single-phase transformer connected between two phases of the three-phase system), with a power based on the maximum measured traction power at the two substations. The following transport conditions (contingencies) were considered:

Substation Alblasserdam:

- All lines and transformers available;

- A single 150 kV line between substations Alblasserdam and Meerwedehaven not available;

- A single 150 kV line between substations Meerwedehaven and Crayestein not available;

- A single 380 kV line between substations Crayestein and Krimpen aan den ijssel not available;

- A single 380 kV line between substations Crayestein and Simonshaven not available.

Substation Waalhaven:

- All lines and transformers available;

- A single 380/150 kV/kV transformer at substation Krimpen aan den IJssel not available;

- A single 150 kV line between substations Waalhaven and Krimpen aan den IJsel not available;

- A single 380 kV line between substations Krimpen aan den ijsel and Crayestein not available;

- A single 380 kV line between substations Krimpen aan den ijsel and Diemen not available;

- A single 380 kV line between substations Krimpen aan den ijsel and Bleiswijk not available.

In the case of Waalhaven no significant change is observed, while in the case of Alblasserdam there is a minor voltage drop of 0.18 %, in case of a single outage with a given production. In conclusion, the simulations indicate that the supply voltage variations due to the trains have values lover than the compatibility limits of [6].

5.5 Influence on harmonic distortion

5.5.1 Analysis without switching the object under consideration

The analysis is performed with the use of the measurements of the year 2013, made available by TenneT. The available data are 10-min values of voltage and current THD from substation Alblasserdam. No measurements of individual harmonic orders are available. Due to this, the analysis of harmonic distortion based on measurement data is very limited.

The 95% of the THD of voltage and current are presented in Table 11.

	Alblasserdam
Voltage THD (%)	0.798
Current THD (%)	20.364

Table 11 The 95% probability values of voltage and current THD at substation Alblasserdam

Adding the uncertainty requirement is not possible directly for voltage THD, since uncertainty requirements of the standard [19] are defined only for individual harmonic components. The measured harmonic distortion of the voltage is low and with a significant margin within the indicative planning levels, and limits of the Netcode Elektriciteit [6]. However measurements for individual harmonic orders are also needed to compare the existing levels with the requirements. Due to the very low value of voltage THD, it can be assumed that, given the transport conditions during the measurement period, the individual harmonic orders complied with the requirements.

5.5.2 Simulation results

In order to determine the influence of the Betuweroute on the substations of Alblasserdam and Waalhaven, harmonic current measurements are preferred as the input for the model. Due to lack of such measurements, the harmonic current inputs are based on generic topologies of converters used in trains [20]–[22], in order to simulate the generated harmonic currents of a locomotive. The highest values of currents measured at the two locations were used as the fundamental current to simulate the harmonic current sources, whose spectrum is presented in Figure 10. The resulting harmonic voltages on the two substations are presented in Table 12 and Figure 11. The harmonic voltages are simulated in the same transport conditions (contingencies) as in the case of supply voltage variations.

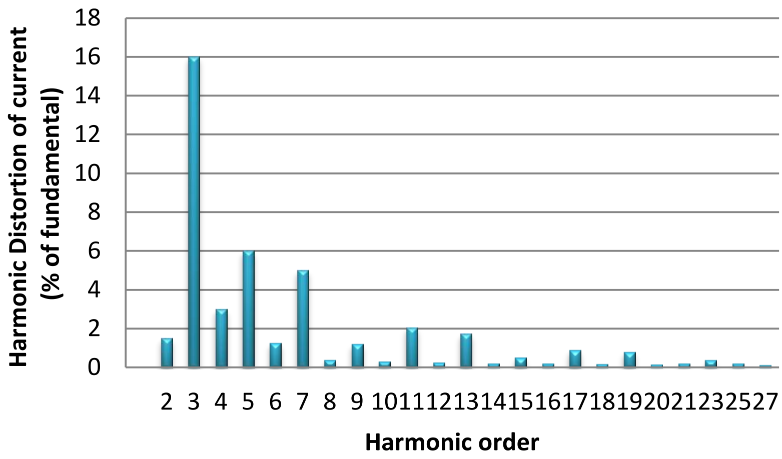


Figure 10 Spectrum of harmonic currents of a traction system used as the input of the model

Harmonic Order	Harmonic Distortion in %	
	Alblasserdam	Waalhaven
2	0.004	0.012
3	0.075	0.194
4	0.020	0.043
5	0.045	0.096
6	0.048	0.032
7	0.145	0.187
8	0.006	0.028
9	0.014	0.092
10	0.003	0.053
11	0.023	0.106
12	0.004	0.006
13	0.041	0.014
14	0.041	0.006
15	0.012	0.039
16	0.002	0.005
17	0.007	0.014
18	0.001	0.002
19	0.005	0.004
20	0.001	0.000
21	0.002	0.000
23	0.005	0.002
25	0.001	0.002
27	0.000	0.002
THD	0.19	0.33

Table 12 Simulation results: harmonic distortion of voltage at substations Alblasserdam and Waalhaven

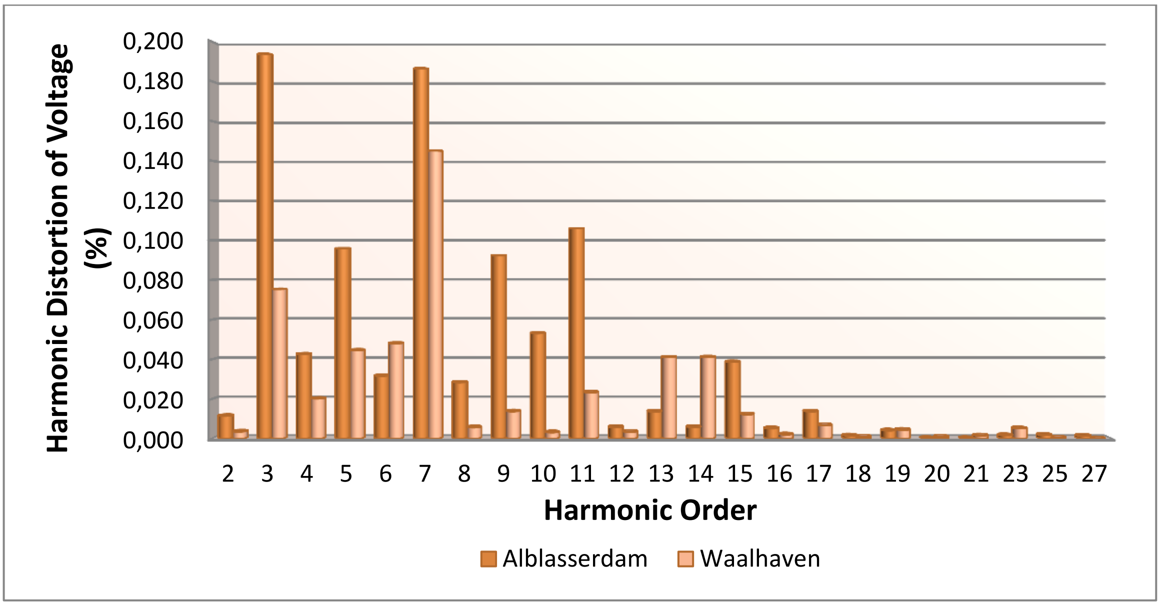


Figure 11 Simulation results: harmonic Distortion of voltage at substations of Alblasserdam and Waalhaven

The harmonic distortion generated is low in comparison to the planning levels of [17] and the compatibility limits of Netcode Elektriciteit [6]. The voltage THD is 0.19% in the case of Alblasserdam and 0.33% in the case of Waalhaven, for the analysed network contingencies.

5.6 Influence on voltage flicker

5.6.1 Analysis without switching the object under consideration

As with the other measurements, the analysis has certain limitations due to the class of the instruments used on the analysed locations. The specified uncertainty for voltage flicker measurement for class “S” instruments is specified in [23] as double of the requirement of [24], which is 5 % of the reading, meaning that for class “S” it is 10 % of the reading. However, due to the lack of measurements of maximal current magnitudes (maximums during the aggregation intervals), the direct impact of traction substations on voltage flicker and fast voltage changes cannot be quantified.

The indicative planning level for HV and EHV systems specified in [2] is a long-term flicker coefficient (P_{lt}) equal to 0.6. This can be used as the requirement for the flicker level for the observed 150 kV substations. The Netcode Elektriciteit [6] for this voltage level requires that the 95 % probability value of the P_{lt} measurements does not exceed 1, and that none of the P_{lt} measurements exceeds 5.

At substation Alblasserdam, the 95 % probability value of the measurements for 2011 is 0.48 (based on the whole year). Additionally, the P_{lt} level was lower than 1 for each week in 2011, as required by [6]. The individual measurements do not exceed the value of 5, except in the cases of voltage dips which should be flagged and ignored, as specified in

[23]. If we add a measurement uncertainty of 10 %, the 95 % probability level is still below 0.6, which satisfies both mentioned requirements. As sample of measurements for a period of about one week is shown in Figure 12.

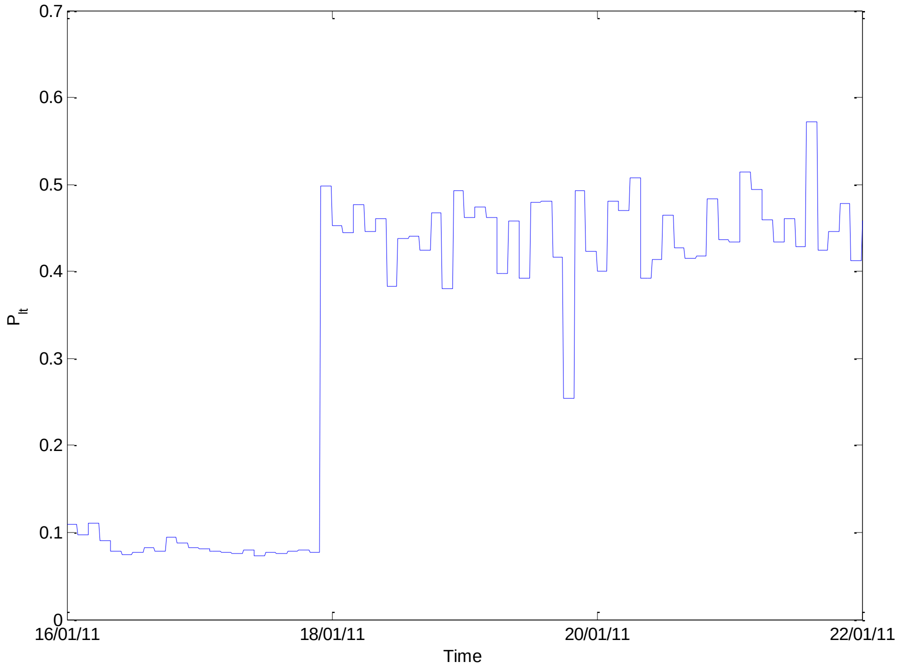


Figure 12 Long-term flicker coefficient, measurement sample for substation Alblasserdam

At substation Waalhaven, the 95 % probability value of the measurements for 2011 is 0.09, which is significantly lower than the two mentioned criteria, also with the addition of measurement uncertainty for class “S” instruments. As sample of measurements for a period of about one week is shown in .

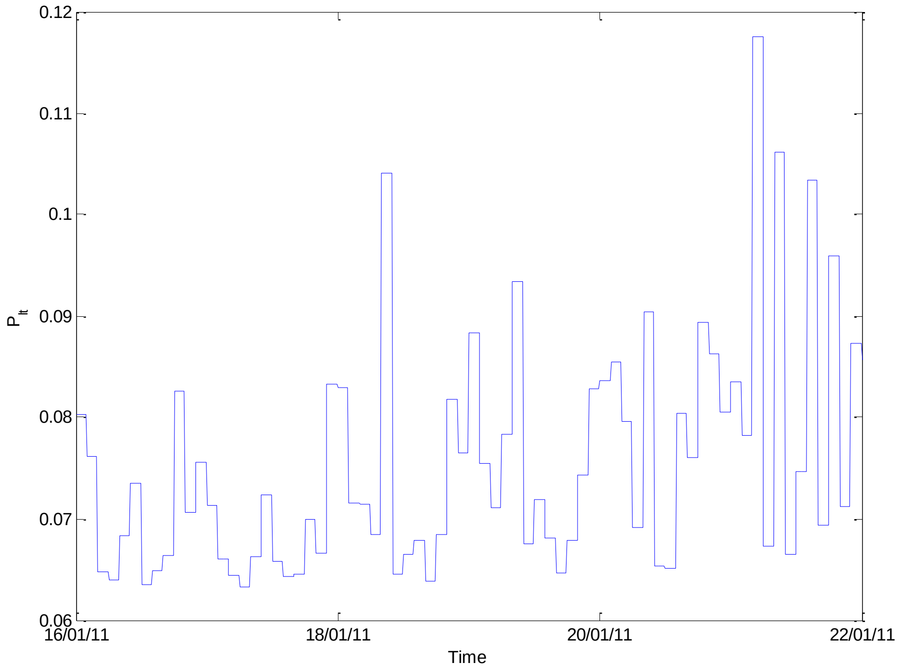


Figure 13 Long-term flicker coefficient, measurement sample for substation Waalhaven

As already mentioned, the impact of traction substations in the 95 % probability levels cannot be quantified due to the lack of measurements.

5.6.2 Requirements for simulations

The analysis of both analysed locations cannot be done by simulation, both for the long-term flicker coefficient and single rapid voltage changes, due to the lack of short-term current measurements. The 15-min based current measurements include a significant averaging effect in terms of the rapid voltage changes which occur during a single 15 minute time interval. Additionally, the rate at which the peaks of current are occurring are also not known due to the same reason. The rate at which rapid voltage changes are occurring is equally important to quantify the influence on voltage flicker. Due to these reason, it was decided not to perform simulations of rapid voltage changes at flicker for the two substations of Betuweroute at this moment. The recommendations for additions/changes in the measurement systems which can quantify these effects are given in a separate report which covers the measurement methods for impact studies.

5.7 Influence on voltage unbalance

5.7.1 Analysis without switching the object under consideration

A statistical analysis of the 10-min based measurements of voltage unbalance, including the 99.9 % probability levels, is presented in Table 13 for both substations.

	Alblasserdam	Waalhaven
99.9% value of Voltage Unbalance [%]	0.1562	0.1882
Average value of unbalance [%]	0.0717	0.0453

Table 13 Voltage unbalance at the two substations of Alblasserdam and Waalhaven

Even with the added uncertainty for class “S” instruments, which is equal to 0.15 % by the standard [23], the voltage unbalance’s values are significantly lower that the limit of 1% set in the Netcode Elektriciteit [6] and the indicative planning level of [25]. The histograms of the voltage unbalance for the two substations are shown in Figure 14.

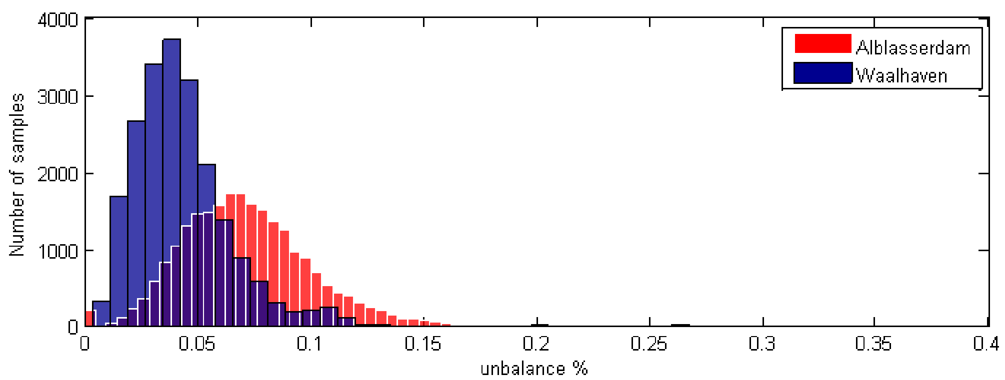


Figure 14 Histograms of the voltage unbalance at substations Alblasserdam and Waalhaven

In Chapter 2, emission level assessment techniques for disturbing installations are proposed. All of them require the measurement or computation of the symmetrical components of voltage and/or current . However in the case of the substations of Alblasserdam and Waalhaven symmetrical components measurements do not exist, nor can be calculated based on the recorded data.

The correlation between the unbalance and the current (representing also the power) of the traction transformer are analysed as an indication of the influence on voltage unbalance. The result are presented in Figure 15 and Figure 16.

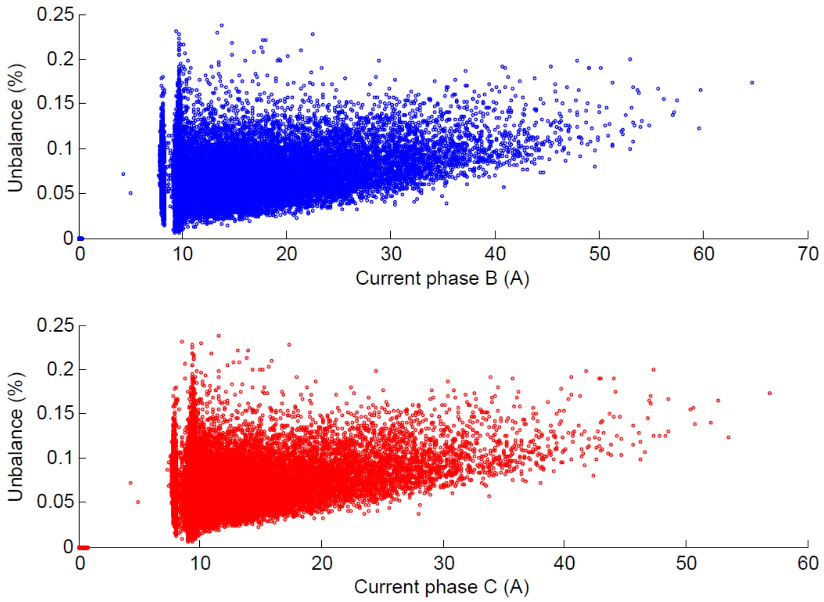


Figure 15 Relation between voltage unbalance and magnitude of the current at substation Alblasserdam

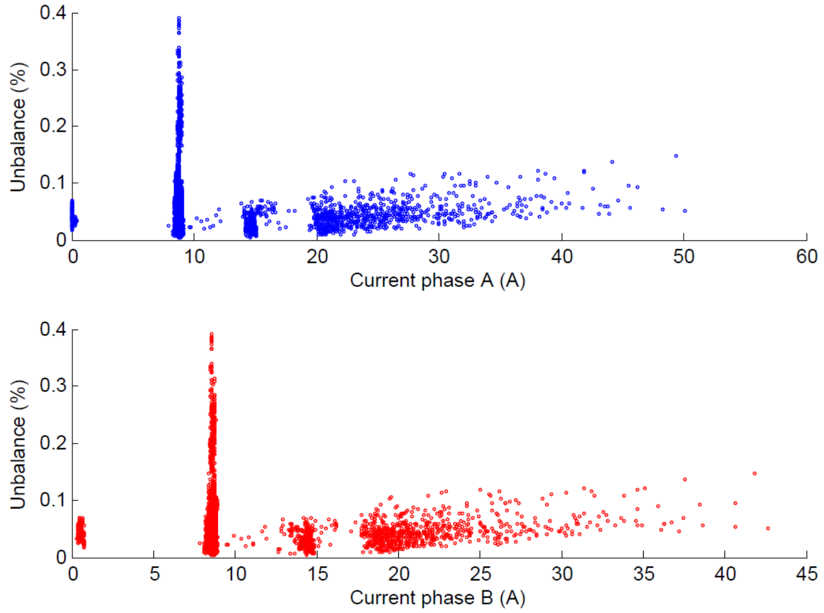


Figure 16 Relation between voltage unbalance and magnitude of the current at substation Waalhaven

In Figure 15 and Figure 16, for current magnitudes above 10 A there is a relatively strong correlation between its value and the voltage unbalance measured at the substations. At lower current magnitudes, it can be observed that most of the recordings are grouped around the region of 8 A, where the unbalance may have higher values, a fact that can be clearly observed in the case of Waalhaven. The scattering of these highest values of unbalance is obviously weakly correlated with the operation of trains. A cause might be the operation of other loads or production in the network.

A method of allocating unbalance levels is proposed in the guideline [26]. The following formula is used to define the acceptable limit of unbalance when the power of the traction system receives its maximum value:

$$A_U = \frac{S_{Tmax}}{S_K} \cdot 100 \leq 1\% \tag{1}$$

where A_U is the allocated unbalance level, S_{Tmax} is the maximum one phase power drawn by the train and S_K is the three phase short-circuit power of the substation which represents all network configurations, meaning the lowest short-circuit level. The allocated unbalance level A_U calculated with the maximum short circuit power (A_{Umin}) is presented in Table 14 (same conditions as for supply voltage variations):

$$A_{Umin} = \frac{S_{Tmax}}{S_{Kmax}} \cdot 100 \leq 1\% \tag{2}$$

For both substations the allocated value is less than the limit of 1%, and the measured unbalance levels: Alblasserdam 0.16 % and Waalhaven 0.19 % are lower than the limit of 1% based on [26].

	Alblasserdam	Waalhaven
$S_{T,max}$ (MVA)	10.2	10.9
S_{Kmax} (MVA)	3226	5385
$A_{U,min}$ (%)	0.32	0.20

Table 14 Calculated minimum unbalance limits at substations Alblasserdam and Waalhaven based on [10]

5.7.2 Simulation results

The effect of the Betuweroute traction-supplies in Alblasserdam and Waalhaven on voltage unbalance is examined also by simulating the load of a train and calculating the voltage unbalance factor *u*, which is the ratio of the modulus of the negative sequence to the positive sequence components of the voltage at fundamental frequency, labelled with U_2 and U_1, respectively.

$$u = \frac{|U_2|}{|U_1|} \tag{3}$$

In a simulation, the negative sequence current is obtained based on the phase to phase connection of the traction transformer, and the measured power values. The results of the simulations are presented in Table 15.

Condition of NorNed	Alblasserdam	Waalhaven
Voltage unbalance factor [%]	0.21	0.09

Table 15 Influence of the Betuweroute on voltage unbalance

The results in both cases are significantly lower than the planning levels defined in [25] and limits of [6]. It can be concluded that in the analysed transport conditions, the voltage unbalance caused by the traction supplies in Alblasserdam and Waalhaven are lower than the limit given in [6].

5.8 Conclusions for the influence of Betuweroute traction substation Alblasserdam and Waalhaven

At the two analysed locations, Alblasserdam and Waalhaven, substations are presently equipped with measurement instruments of class “S”, which are not meant to be used for formal assessment. Due to this, the analysis has certain restrictions with the use of measured data and inputs for the simulations.

The supply voltage variations are analysed based on measured values and computer simulations. The measurements show that the supply voltage variations are within the limits specified by the Netcode [6] and the simulations show that the traction supplies have only a minor effect on the voltage level at both substations, due to the high short-circuit power.

The influence of the analysed Betuweroute substations on the harmonic distortion is analysed only through computer simulations, due to the absence of required measurements. The harmonic current spectrum injected is based on a generic topology, and the results show that the influence on harmonic distortion is acceptable at both substations, for the analysed transport conditions. The measured values of voltage THD are significantly lower than the planning level of [17].

The influence on voltage flicker cannot be determined at the moment with the existing measurement equipment. However, the measurements of the long-term flicker coefficient at both locations indicate that the flicker level is within limits on both locations in respect to the indicative planning level of [2] and the compatibility limit of [6]. This needs to be confirmed by a measurement with class “A” instruments, and the impact can be estimated only when current measurement became available as discussed in section 5.6.

Finally, as far as the voltage unbalance is concerned, the impact of the Betuweroute cannot be estimated based on measurements using the presently available measurement equipment. The simulations show that the Betuweroute’s contribution to unbalance is low given expected high short-circuit power in comparison with the indicative planning level of [25] and compatibility limit of the Netcode [6]. On both locations the measured values of voltage unbalance and the simulated impact of traction substations on voltage unbalance is lower than the planning level of 1% based on [26].

6 Impact of large capacitor banks at Diemen and Weiwerd

6.1 Introduction

In AC networks, reactive power needs to be compensated for the reasons of efficiency and voltage control. Various approaches for power factor control are used in the AC networks. The most commonly used and most cost effective solution is the usage of banks of capacitors, which compensate the reactive power required by loads and lines in the network. Other solutions include overexcited synchronous machines and static var-compensators (SVCs).

6.2 Influence of capacitor banks on PQ

The positive effects of the capacitor banks on the network needs to be coordinated with the impact of capacitor banks on the other PQ parameters. Capacitor banks are known to cause four types of power quality phenomena. The first one is the purpose of the capacitor bank, namely influencing the supply voltage and reactive power balance in the grid. The second, third and fourth power quality phenomena are possible side effects that needs to be accounted for. The second one is the transient over-voltage during switch-on and switch-off. Depending on the impedance of the connection point and the moment when the switch is switched on or off (initial conditions), transient can sometimes lead to short high voltage levels – leading to insulation stress for equipment. Equipment insulation is designed to withstand transients.

The third possible problem are rapid voltage changes which can lead to voltage flicker (visual sensation caused by the voltage variations), also caused by the switch-on or –off tof the capacitor bank. For rapid voltage changes the frequency of occurrence is equally important as the magnitude of the variations (rapid voltage changes which do not happen often given a limited value do not lead to flicker problems).

The fourth power quality phenomenon which is influenced by capacitor banks is voltage distortion - which is indirectly influenced by these devices. As predominantly linear elements, capacitors do not inject considerable harmonic currents into the network, but they alter the frequency dependent impedance of the network. This may lead to higher levels of voltage distortion, especially in resonance conditions.

These three power quality side effect phenomena are analysed analytically, using the available PQ measurements in substations Diemen and Weiwerd. One of the largest capacitor bank units in the Netherlands is located in substation Diemen. It is connected directly to the 380 kV voltage level, and consists of two units, each of them has a rating of 150 Mvar. At substation Weiwerd, a single 150 Mvar capacitor bank is connected directly to the 220 kV level.

On both locations, capacitor banks are arranged as filter banks of the “C” type. The purpose of filter banks is avoiding the negative influence on harmonic distortion, in fact, they are used to reduce the distortion levels in the network. An overview of the effects of capacitor banks on harmonic distortion in the network and the application of filter banks for their mitigation can be found in numerous text-books and articles, e.g. [18].

To minimize the transient effect of switching the capacitor banks on and off, on both locations, synchronized circuit breakers are used. This type of circuit breakers is able to control the initial conditions of the transient, and avoids the worst-case conditions which is possible when the capacitor bank is switched on or off at a random moment. An overview of transient effects and mitigation techniques can be found in [27], [28]. On top of the synchronised circuit breakers, the resistor of the filter also dampens transients during the switching.

6.3 Description of analysed locations and contingencies

The substation at Diemen is operating at two different voltage levels, namely 380 kV and 150 kV. In the 380 kV side it is connected to the substations of Krimpen, Oostzaan, Lelystad and Breukelen. In the 150 kV part it is connected to the substations: Wijdewormer, ‘s-Graveland, Venserweg, Amstelveen, Watergraafsmeer and Bijlmer Noord. The single-pole schematic of the HV/EHV network up to three busbars away from substation Diemen is shown in Figure 17.

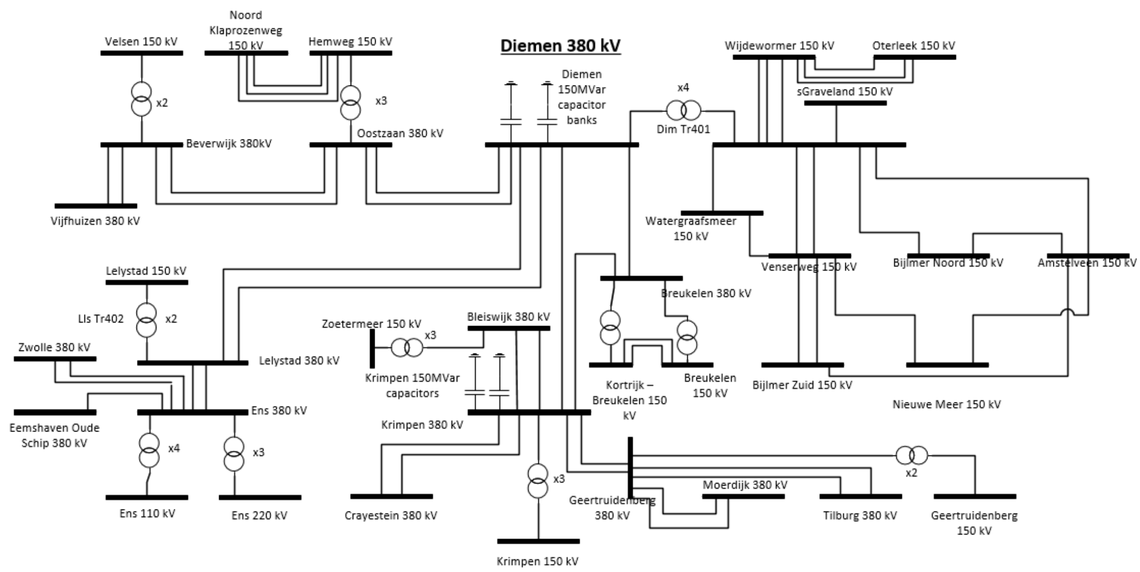


Figure 17 Schematic of the HV/EHV network around substation Diemen

The substation at Weiwerd, operating at 220 kV, is connected to the substations of Robbenplaat, Delfzijl Oosterhorn, Delesto, Meeden (220 kV) and Delftzijl-Weiwerd (110kV). The single-pole schematic of the HV/EHV network up to three busbars away from substation Weiwerd is shown in Figure 18.

The cases simulated, that represent configurations or contingencies of the grid, are presented in Table 16 and Table 17. They include on and off states of transmission lines, transformers, substations and capacitors. In each case the relevant element is taken out of operation. A simulation is performed for each contingency and for each of the cases:

1. no capacitor banks connected;
2. one capacitor bank connected, 150Mvar;
3. in the case of Diemen, both banks connected, 300 Mvar.

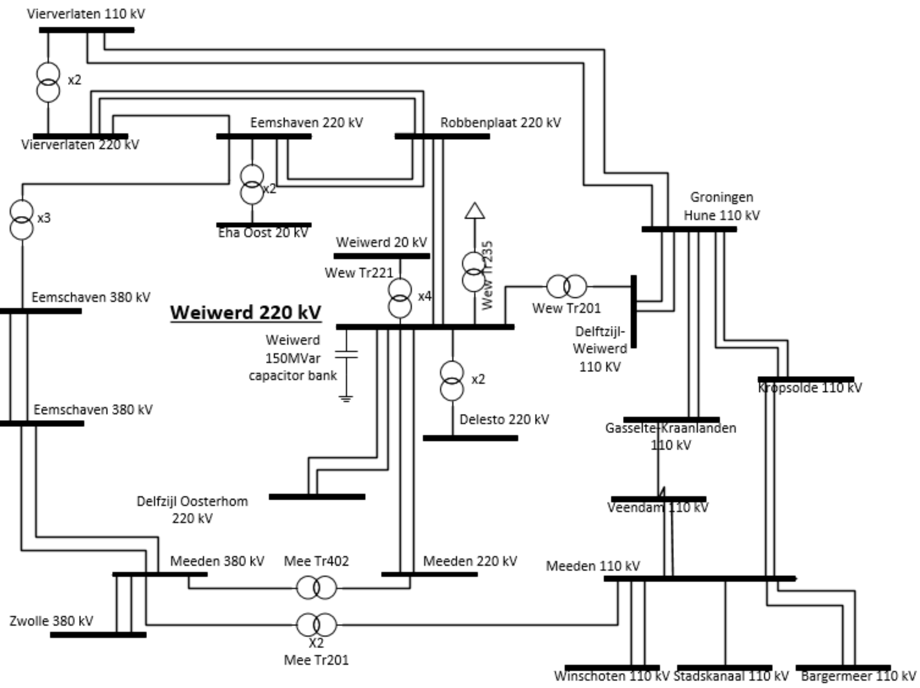


Figure 18 Schematic of the HV/EHV network around substation Weiwerd

At the substation of Krimpen there are two capacitor banks, identical to the ones connected to Diemen. The influence of these capacitor banks on the network impedance of Diemen is also examined. At first, only one capacitor bank is in operation (case XXVII), then both (case XXIX). Finally both cases are simulated again but at the same time there is an outage of the transmission line between Krimpen and Diemen (cases XXVIII and XXX).

Case ID	Element	kV	Number of Circuits
	Transmission lines		
I	Krimpen - Diemen	380	1
II	Diemen - Lelystad	380	2
III	Oostzaan - Diemen	380	1
IV	Breukelen - Diemen	380	2
V	Diemen - Amstelveen	150	1
VI	Diemen - Bijlmer Noord	150	1
VII	Diemen - 's Graveland	150	2
VIII	Diemen - Venserweg	150	2
IX	Diemen - Watergraafsmeer	150	1
X	Wijdewormer - Diemen	150	3
XI	Beverwijk - Oostzaan	380	2
XII	Beverwijk - Vijfhuizen	380	2
XIII	Krimpen - Geertruidenberg	380	2
XIV	Lelystad - Ens	380	2
	Substations		
XV	Breukelen	380	
XVI	Diemen	150	
XVII	Ens	380	
XVIII	Geertruidenberg	380	
XIX	Hemweg	150	
XX	Krimpen	380	
XXI	Lelystad	380	
XXII	Oostzaan	380	
XXIII	Venserweg	150	
XXIV	Watergraafsmeer	150	
	Transformers		
XXV	Dim Tr401	380/150	
XXVI	Lls Tr402	380/150	
	Interaction with capacitor banks of Krimpen		
XXVII	Krimpen – single capacitor bank connected		
XXVIII	Krimpen – single capacitor bank connected and Krimpen – Diemen line outage		
XXIX	Krimpen – both capacitor banks connected		
XXX	Krimpen – both capacitor banks connected and Krimpen – Diemen line outage		

Table 16 Analysed contingencies for substation Diemen

Case ID	Element	kV	Number of Circuits
	Transmission Lines		
XXXI	Robbenplaat - Schildmeer	220	2
XXXII	Schildmeer - Weiwerd	220	4
XXXIII	Weiwerd - Delfzijl Oosterhorn	220	2
XXXIV	Eemshaven - Robbenplaat	220	2
XXXV	Vierverlaten - Robbenplaat	220	2
XXXVI	Schildmeer - Meeden	220	2
XXXVII	Groningen Hunze - Delfzijl-Weiwerd	110	
	Substations		
XXXVIII	Delfzijl Oosterhorn	220	
XXXIX	Eemshaven	220	
XL	Groningen Hunze	110	
XLI	Meeden	220	
XLII	Robbenplaat	220	
XLIII	Vierverlaten	220	
	Transformers		
XLIV	Meeden Tr201	220/110/20	
XLV	Meeden 380/220	380/220/50	
XLVI	Weiwerd Tr201	220/110/20	
XLVII	Weiwerd Tr221	220/22	
XLVIII	Weiwerd Tr235	220/30	

Table 17 Analysed contingencies for substation Weiwerd

6.4 Influence on supply voltage variations

6.4.1 Analysis of disturbance levels with and without the object of consideration

The influence of capacitor banks in substation Diemen on the voltage level, represented by the measurement of the power quality aspect: ‘supply voltage variations’ is shown in Figure 19, for a period of about two weeks. The reactive power values in Figure 19 only indicate how many capacitor banks are in operation (based on the switching actions), they do not represent actual measurements. The variations which occur at the moment of capacitor switch-on vary from less than 1 % to about 2 %. The supply voltage variation is significantly influenced by the changes in power flows, as can be seen when the capacitor bank is switched off.

The operation of capacitor banks does not lead to voltage variations outside of the bandwidth ±10 % (between 219.393 kV and 241.332 kV, line-to-neutral) in substation Diemen. The histogram of the magnitudes of the supply voltage in substation Diemen for 2012 is shown in Figure 20 (one line-to-neutral), with and without capacitor banks in operation. The voltage level had acceptable levels during the whole year.

At substation Weiwerd no switching actions took place during the available measurement period. Therefore the impact of the capacitor bank cannot be isolated from the measurements. The histogram of the magnitudes of the supply voltage during the first five months of 2014 is given in Figure 21. The voltage level had acceptable levels during the whole observed time interval.

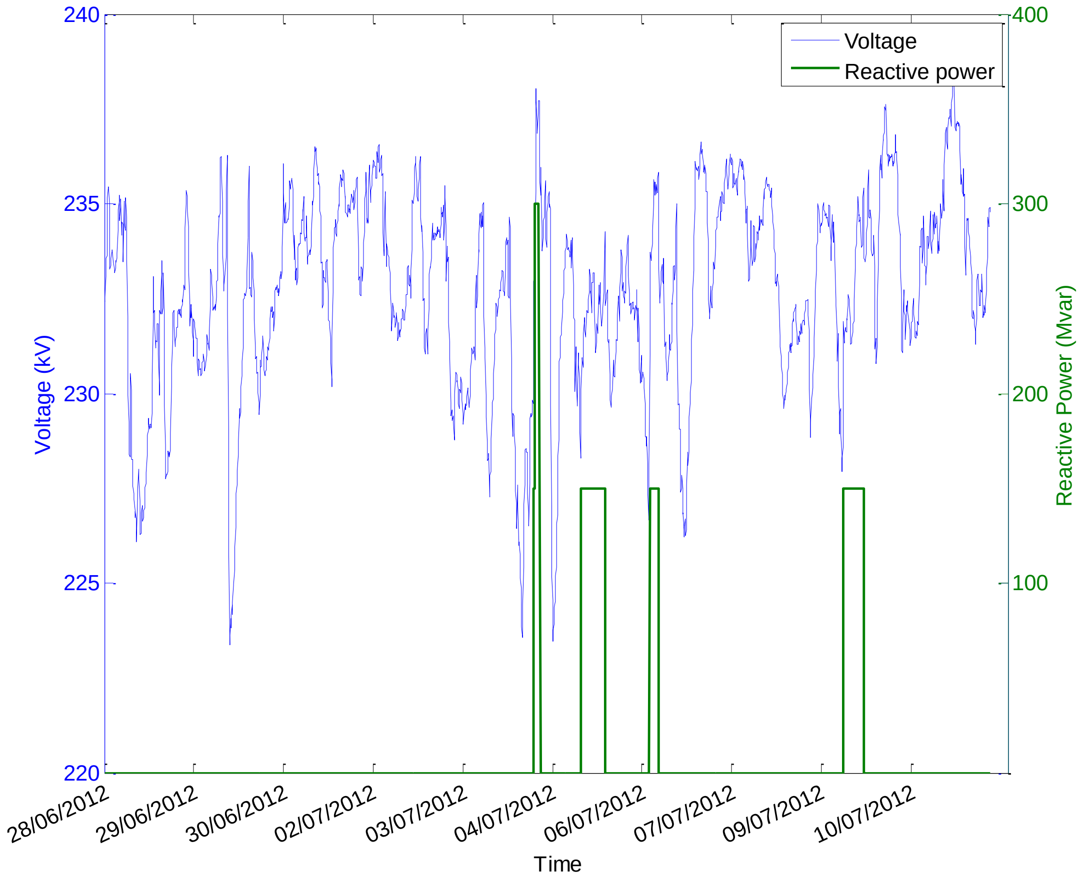


Figure 19 Influence of capacitor bank operation at substation Diemen on supply voltage variations

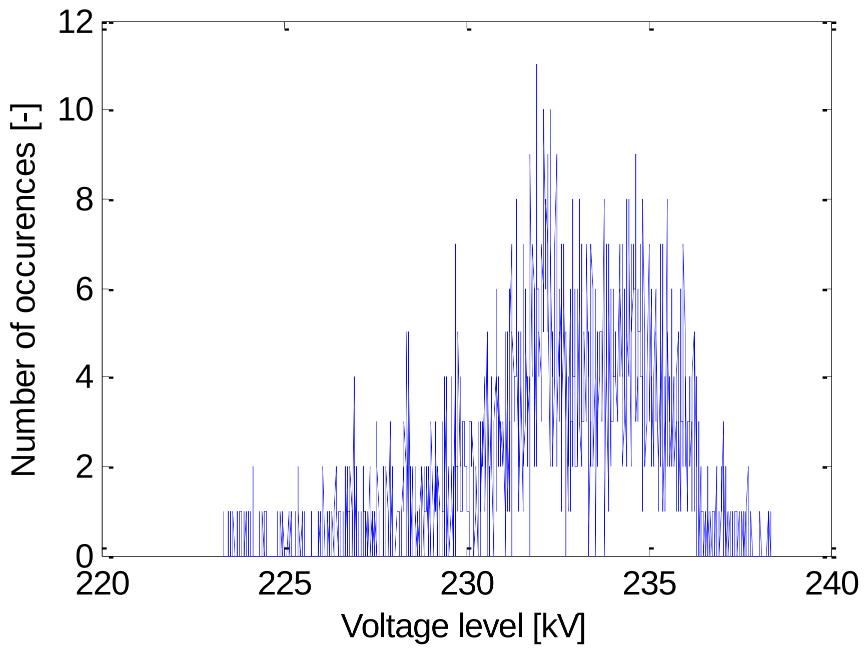


Figure 20 Histogram of voltage levels (line-to-neutral) in substation Diemen during 2012

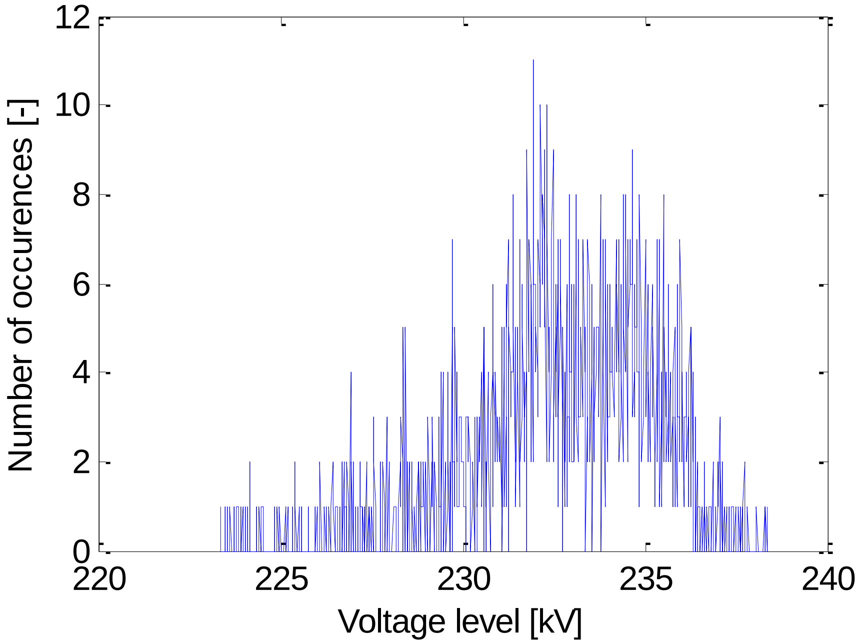


Figure 21 Histogram of voltage levels (line-to-neutral) in substation Weiwerd during the first five months of 2014

6.5 Influence on harmonic distortion

For both substations, the influence on harmonic distortion is analysed based on the simulated influence on the impedance-frequency characteristic of the network (including the network resonances) and the analysis of disturbance levels with and without the object of consideration.

Due to the large amount of simulation and measurement results, only a part of the results are shown in the report. The majority of results are given in Appendix B.

6.5.1 Simulation results for substation Diemen

In Figure 22 the results of the frequency sweep of the base case, where no outages take place, are presented as impedance (*Z*) as a function of the harmonic order. In this figure, three different cases of the base case are depicted. The red line represents the frequency response when no capacitor banks of Diemen’s substation are in operation, the green when one capacitor bank is in operation (150 Mvar) and the blue when both capacitors are connected (300 Mvar).

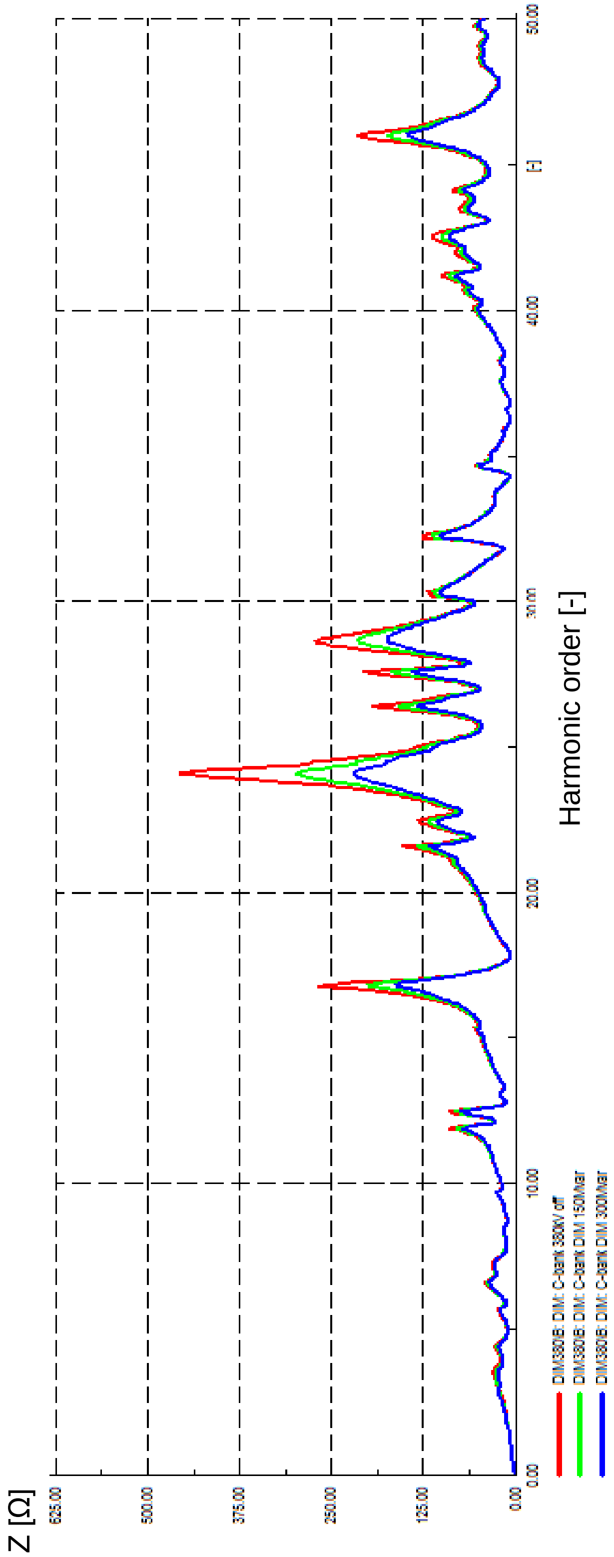


Figure 22 Impedance-frequency characteristic at substation Diemen: (red) no capacitor banks connected, (green) single bank connected and (blue) both banks connected. No outages are considered (base case);

Figure 22 shows that the capacitor banks have a positive effect on the harmonic impedance with broad damping, while they do not shift the harmonic resonance frequencies. When both capacitor banks are in operation the damping effect leads to a further decrease of distortion. This is not surprising, since the capacitor banks are designed as a damped filter.

This damping effect was observed in all the investigated contingencies. The rest of the simulation results can be found in Appendix B. Depending on the element that is taken out of operation each time and the corresponding part of the network that is not connected to the busbar anymore, the harmonic impedance response changes. The resonances shift and their impedance values change. However in all the cases, the capacitor banks have a positive effect on the network impedance. It can also be observed that the further away the outage is taking place, the less impact it has on the impedance at the point of evaluation.

6.5.2 Simulation results for substation Weiwerd

In Figure 23 the results of the frequency sweep of the base case, where no outages are considered, are presented. In this figure, the red line represents the frequency response when the capacitor bank in Weiwerd’s is not in operation and the green line when the capacitor bank is in operation (150 Mvar).

The damping effect of the C-type filter configuration is also clearly visible in the case of Weiwerd. The impact of the capacitor bank at Weiwerd is similar to the one in Diemen; no shift of the resonant points occurs when the capacitor is connected, while at the same time it offers a broad damping effect. Other results of contingencies are presented in Appendix B.

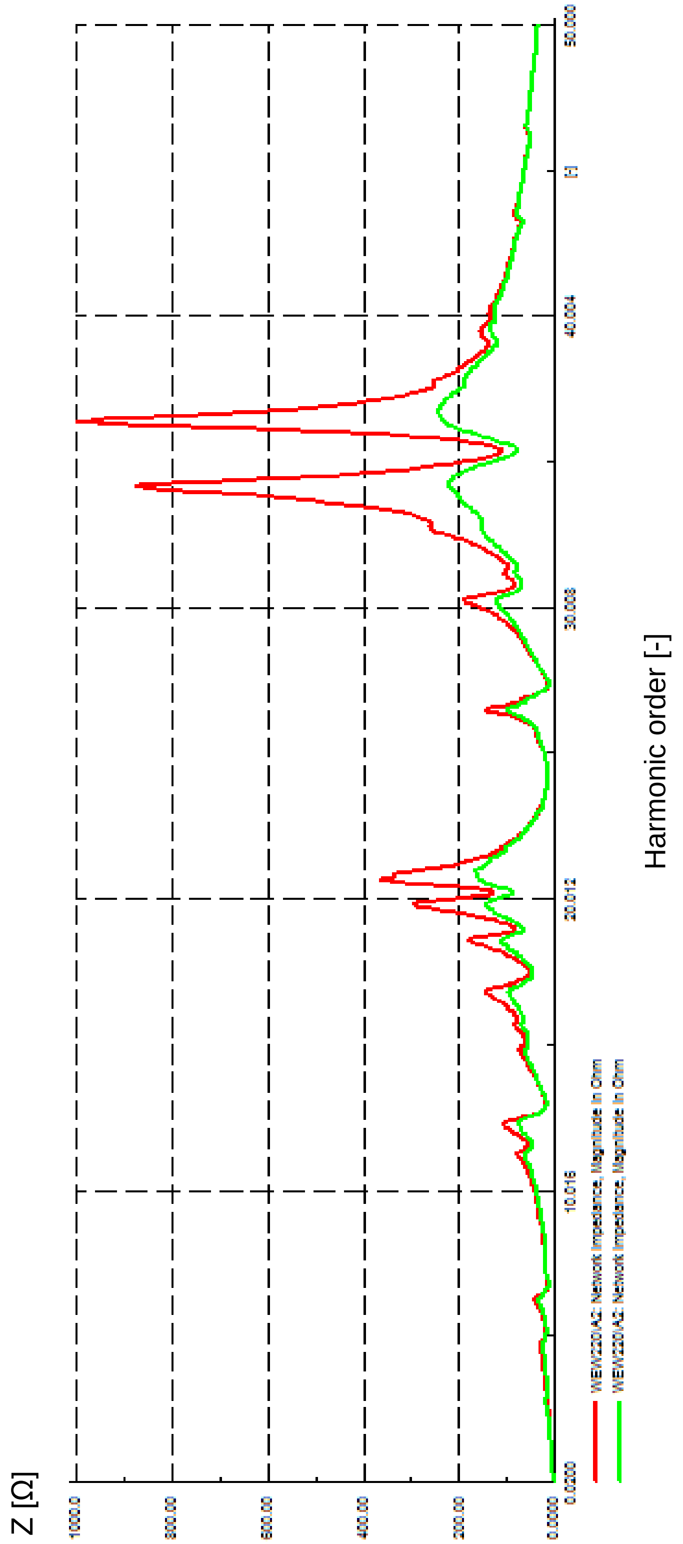


Figure 23 Harmonic impedance at substation Weiwerd: (red) no capacitor banks connected and (green) capacitor bank connected; No outages are considered (base case)

6.5.3 Analysis of disturbance levels with and without the object of consideration for substation Diemen

The impact on disturbance levels is usually defined as a comparison of the emission level measured before and after the observed installation is put into operation, with e.g. time periods of one week before and after. Since there are no measurements available prior to the installation of capacitor banks, this analysis takes into account the harmonic distortion values when the capacitor banks are switched on and off. The information regarding the switching events of the capacitor banks was gathered from TenneT’s control-center for year 2012. The measured levels of harmonic distortion are values of the power quality monitoring system of the cooperating grid operators.

The switching events of the capacitor bank are rare during 2012, thus a statistical analysis of them is not appropriate. In Figure 24 the recorded 10-minute basis voltage THD values are paired with the switching events from July 4th until July 11th 2012. The operation of the capacitor banks is depicted by the nominal reactive power of the capacitor bank(150 Mvar per capacitor bank, not the actual measured values). The analysis is conducted only for the case of Diemen, since no switching events of the capacitor bank of Weiwerd occurred during the observed time interval.

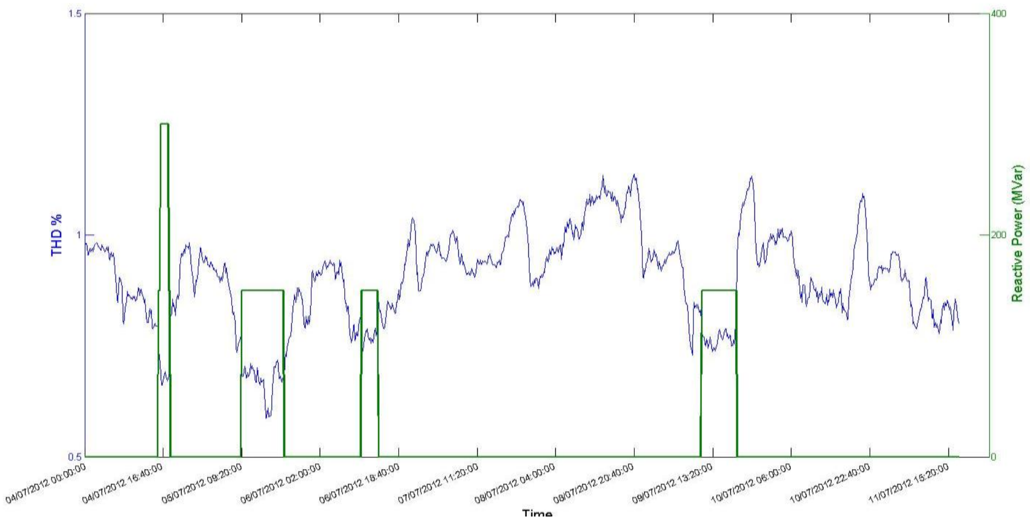


Figure 24 Relation between voltage THD of phase A and capacitor switching at substation Diemen

A clear correlation between the THD and the duty cycle of the capacitor banks can be observed. The THD 'steps' at the moment of switch-in and switch-off; in between the switching moments other parameters influences the THD (e.g. load variations). As shown in the computer simulations, the operation of the capacitors (filters) provides additional damping, resulting in the decrease of the total harmonic distortion. On the other hand, once the capacitor bank is switched off, the THD value rises considerably. The effect can be better observed by isolating one switching event, in this case the one of July 5th, as presented in Figure 25. The average THD value of 30 minutes prior to the switching is 0.76 % and after the connection it reduces to 0.68 %.

In Figure 21 the histogram of the THD values when the capacitor banks are on and off is presented. When one or both of the capacitor banks is connected, the distribution of the THD values has a large number of occurrences in the lower value cells.

The results for individual harmonic orders can be found in Appendix B (odd harmonic orders from the 3rd up to the 13th). There is no clear correlation between the distortion of the third harmonic and the switching events, as seen. This is also expected since the filter is tuned to the 3rd harmonic order (150 Hz) and according to [11], the harmonic voltage amplification level of this configuration reaches its maximum value of 1.1 at 130 Hz, whereas above this frequency the gain factor is less or equal to 1.

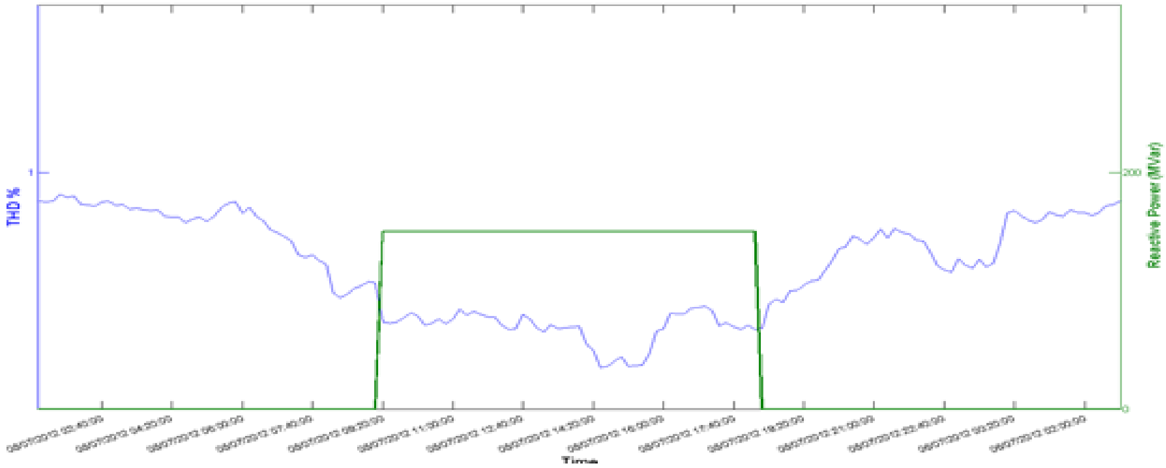


Figure 25 Relation between voltage THD and capacitor operation; zoom-in on one switching event

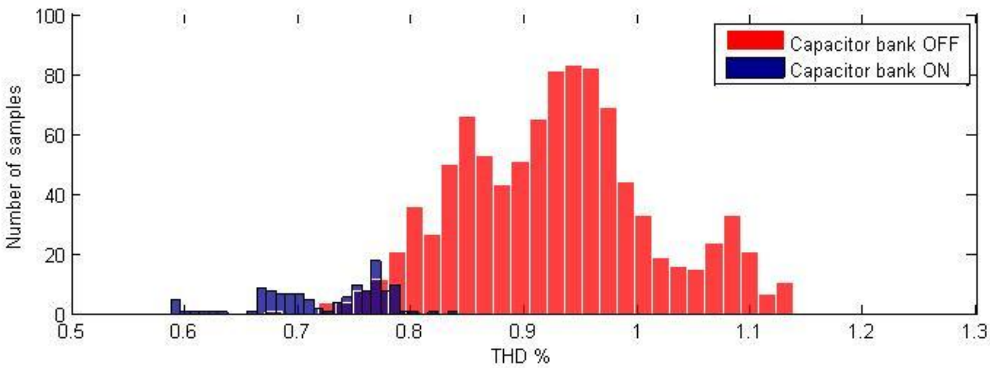


Figure 26 Histogram of THD values of Figure 24 when the capacitor banks are on and off

For most harmonic orders the trend is the same as for the THD; the harmonic distortion is reduced when the capacitor banks come online. The 9th harmonic is not analysed, because the measured values had insignificant levels throughout the year. Since the network configuration is changing, the harmonic injections are fluctuating between two consecutive 10-minute measurement and the distortion levels can be different between the time periods that the capacitor banks are connected and when they are not, the individual figures in some cases cannot be considered to show the correlation decisively. However, they can be regarded as complementary to each other and give an indication of the positive impact of the C-type capacitor banks on the harmonic distortion.

6.6 Switch-on behaviour of capacitor banks

6.6.1 Rapid voltage changes

Rapid voltage changes are characterised by two distinct parameters: 'magnitude of a single rapid voltage change' and 'flicker severity'.

The magnitude of a single rapid voltage change is a single variation of the r.m.s. value of the voltage between two consecutive levels, which are sustained for definite but unspecified durations. Rapid voltage changes of the supply voltage are mainly caused either by load changes in the network user's installations, component switching in the system, faults, or start-ups (inrush currents).

If the voltage during a change crosses the voltage dip and/or the voltage swell threshold, the event is classified as a voltage dip and/or swell rather than a rapid voltage change.

Flicker severity is the intensity of flicker annoyance. Capacitor banks are switched up to a few times a day. Flicker severity is addressed when the switching occurs on the scale of minutes or seconds.

For individual rapid voltage changes, the following requirements can be applied:

1. proposed requirements for rapid voltage changes of the technical report IEC 61000-3-7 [29], which limit RMS variations in HV/EHV systems to 3 – 5 % for up to 4 fast variations per day, 3 % for up to 2 fast variations per hour, and 2,5 % for up to 10 fast variations per hour;

2. requirement for rapid voltage changes in the Netcode Elektriciteit [6]: voltage RMS variations up to 3 % for voltage levels higher or equal to 35 kV, excluding cases of sudden unplanned disconnections of large production or load units.

Taking into account that large capacitor banks are never operated more than 2 times per hour, from all of the mentioned requirements, the most strict one is the requirement for fast voltage variations of [6]: RMS variation of 3 %, so it will be used in this investigation. This requirement is also a normative requirement in the Netherlands.

In the sub-sections 6.6.3 and 6.6.4, the single rapid voltage changes due to the switch-on of capacitor banks in substations Diemen and Weiwerd are analysed with computer simulations. Analysis of measurements is not performed because permanent power quality meters are not able to record single rapid voltage changes at present.

6.6.2 Transient voltages due to switch-on of capacitor banks

A transient voltage is a short duration oscillatory or non-oscillatory overvoltage, usually highly damped, and with a duration of a 20 milliseconds or less. Transient voltages are usually caused by lightning, switching or operation of fuses. The rise time of a transient voltage can vary from less than a microsecond up to a few milliseconds, details can be found in [32].

Transient voltages at the moment do not have particular normative requirements in the PQ standards. The following requirements can be used as possible criterions of deviations:

- Insulation coordination; for different types of over-voltages, equipment is required to withstand overvoltage test as specified in [30]; for example, equipment insulated up to 245 kV should be able to withstand a power frequency overvoltage up to 1.88 p.u. and standard lightning impulses up to 4.29 p.u. These requirements are used for the purpose of network and component design, and reflect the physical behaviour or the grid and its components based on international experience. Parameters regarding power quality are under consideration.

In sub-sections 6.6.3 and 6.6.4, the switch-on transients of capacitor banks in substations Diemen and Weiwerd are analysed with simulations.

Although there are recorded measurements of transient voltages on the two locations, none of them actually corresponds to a capacitor switching event. This is known based of the starting moments of recorded transients, which do not correspond to programmed sequence of synchronized switches which are set to zero crossings of all three phases; a condition that is not fulfilled in any of the recordings.

The actual switching transients at these substations are not recorded because the peaks of these transients are too low for a realistic monitoring trigger, this is explained with computer simulations. Transient triggers of the installed PQ meters are set to a peak equal to 125 % of the nominal value. This is an appropriate value of the trigger, because the magnitude is allowed to vary ± 10 % even without transients, and small variations above these values are not considered harmful, but would lead to unnecessarily large amount of recorded data.

6.6.3 Simulation results for substation Diemen

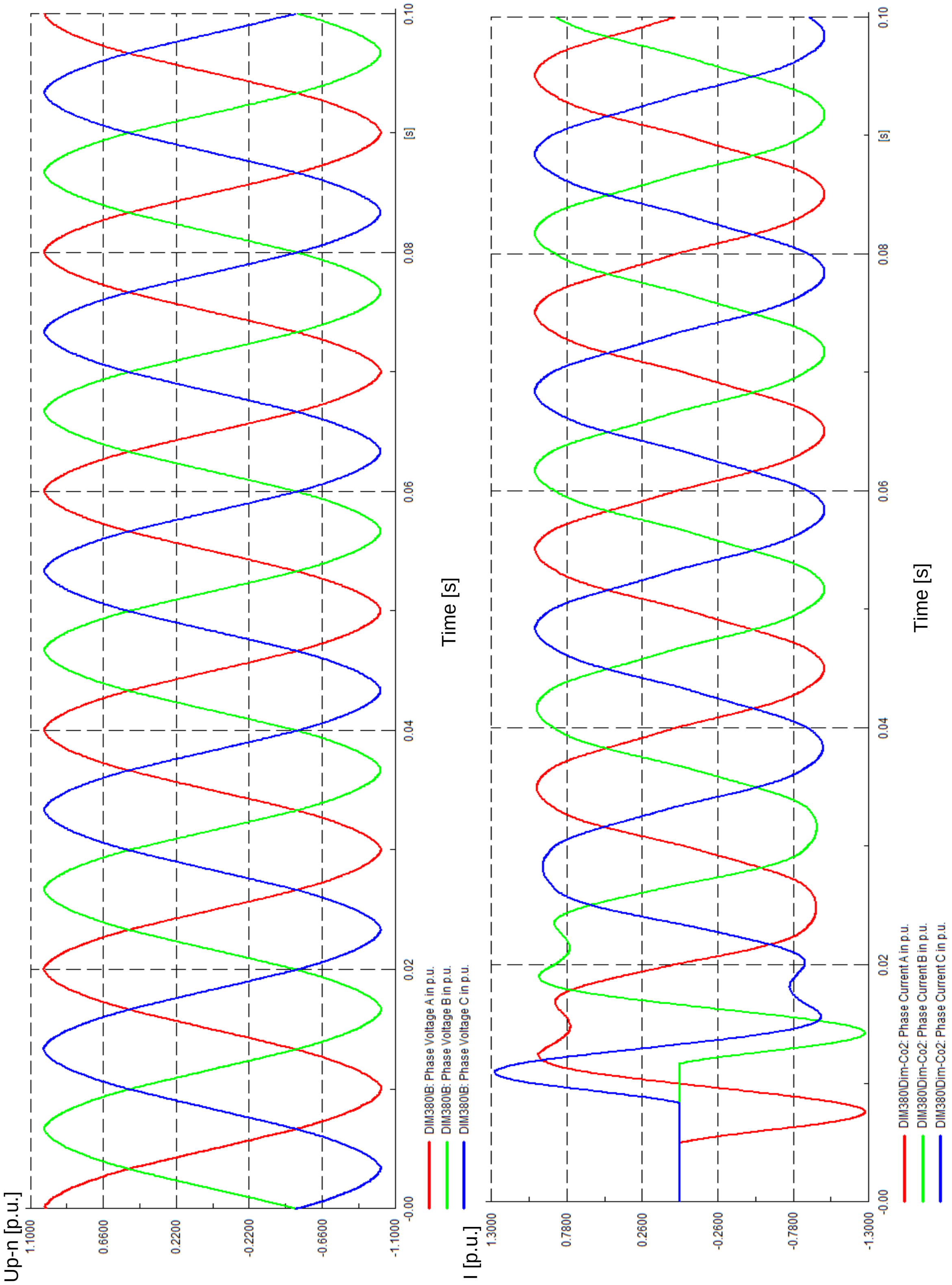
Figure 27 shows the simulation results of the energisation of a single C-type 150 Mvar capacitor bank at the Diemen substation. Figure 27 (a) shows the line-to-neutral voltages $U_{p\text{-}n}$; part (b) are currents I; the results for Line-to-Line voltages can be found in Appendix B.

In the figure it can be observed that the voltage transient is insignificant. The peak value of the voltage is raised up to 1.02 p.u. and the peak of the inrush current of 1.3 p.u. (0.41kA) was calculated. Simulations were also conducted for the case of back to back switching, where the results are almost identical with graphs in Appendix B.

As a worst case it was assumed that all phases of the capacitor are turned on at the same time at 0.02 s, where phase A is at its peak voltage value. Even in this case the over-voltage is minimal and quickly eliminated, while the peak current reached a value of 2.5 p.u. (0.8 kA), as can be seen in Figure 28. The results of back to back switching under the same conditions are identical and presented in Appendix B.

The influence of transport conditions (change of network resonances, e.g. due to the switching state of capacitor banks in substation Krimpen) is found to be of a low importance for the resulting transients.

Regarding the magnitude of simulated transients, the peak values of the voltage are lower than 103 % of the nominal, even without synchronised switching. This means that the individual rapid voltage changes are also within the limit of the adopted criterion, by any definition of RMS and choice of RMS values before and during the rapid voltage change.



(a) (b)

Figure 27 Energisation of a single 150 Mvar capacitor bank at substation Diemen using synchronous switching: (a) line-to-neutral voltages, (b) inrush currents

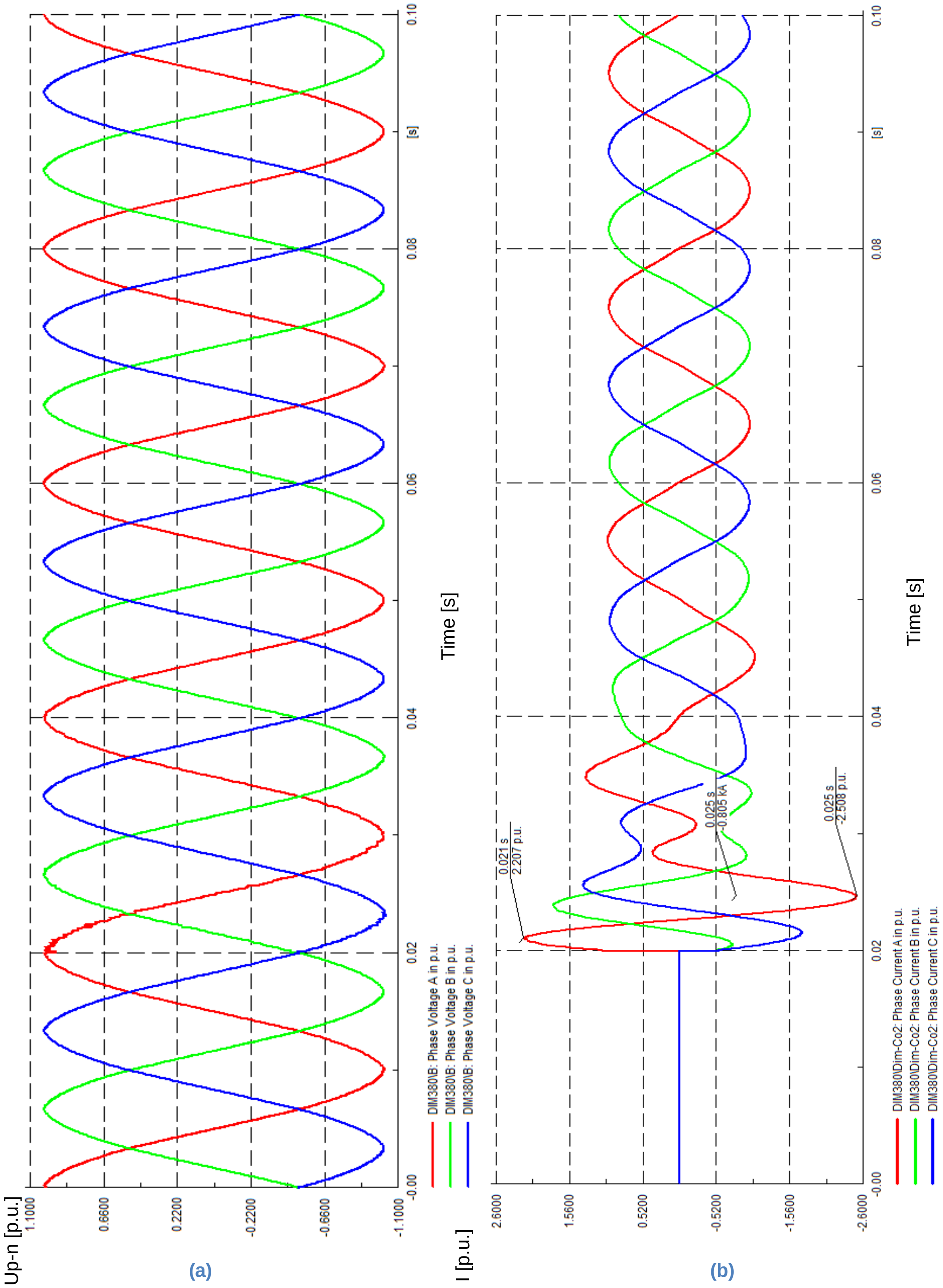


Figure 28 Energisation of a single 150 Mvar capacitor bank at substation Diemen without synchronous switching, worst case for phase A: (a) line-to-neutral voltages, (b) inrush currents

6.6.4 Simulation results for substation Weiwerd

The simulation results of the energisation of the single C-type 220 kV, 150 Mvar capacitor bank at substation Weiwerd substation are presented in Figure 29. The maximum voltage peak due to the switching reaches a value of 1.02 p.u. and the peak inrush current is rated at 1.261 p.u. (0.73 kA).

For the worst case scenario of the capacitor bank of Weiwerd the same switching condition as the ones in Diemen is used (all phases switch at exactly the same time, at t = 0.02 s). The peak Line-to-Neutral Voltage remains below 103 %, which satisfies the adopted criterion for individual rapid voltage changes. The results of this simulation and phase to Line-to-Neutral Voltages can be found in Appendix B. Based on these simulation results, it can be concluded that switching of the capacitor bank at substation Weiwerd leads to acceptable rapid voltage changes.

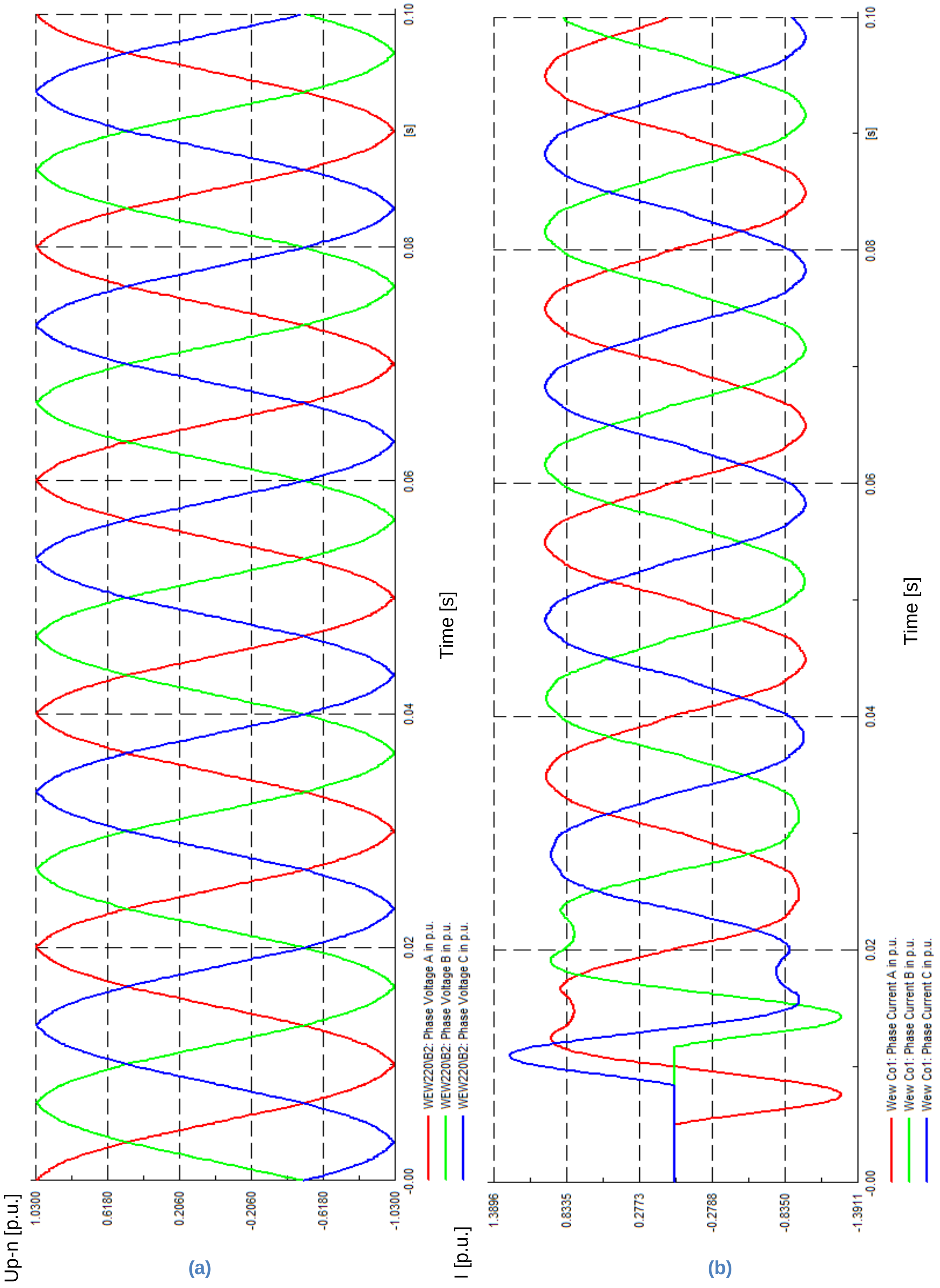


Figure 29 Energisation of a single 150 Mvar capacitor bank at substation Weiwerd with synchronous switching: (a) line-to-neutral voltages, (b) inrush currents

6.7 Conclusions for the influence of capacitor banks in Diemen and Weiwerd

The analysis of the supply voltage variations in substation Diemen shows that the operation of capacitor banks does not lead to high increases of voltage level (supply voltage variations). All measurement points from year 2012 were within compatibility levels of [6], with and without the operation of capacitor banks. Additionally, the variations were lower than ±10 % for each week during the observation period, as required by [6]. The analysis of supply voltage variations in substation Weiwerd shows that the operation of capacitor banks also has a low influence on supply voltage variations.

The results of the harmonic impedance analysis by computer simulations show that the C-type capacitor banks at substations Diemen and Weiwerd have a positive effect, by providing broad damping and consequently minimising the amplitudes of resonances, while at the same time their operation does not result in shifts of the resonant frequencies. In the case of Diemen, when both capacitors banks are in operation, the mitigation is higher than with a single capacitor bank.

The results of the analysis of the impact of the capacitor banks on the harmonic distortion based on measurements is in good agreement with simulations. When the capacitor banks are connected the total harmonic distortion is reduced, as well as the distortion of most individual harmonic orders. In conclusion, capacitor banks at substations Diemen and Weiwerd have a dampening (positive) influence on harmonic distortion in the network.

The simulation results of the switch-on behaviour of the capacitor banks showed that the resulting rapid voltage changes are acceptable by the adopted criterion for individual rapid voltage changes - variations up to 3 % of the nominal RMS value. The synchronous switching as well as the filter-configuration of capacitor banks minimise the effect of switching. Even without synchronised switching, rapid voltage changes do not exceed the adopted limit, which is in good agreement with the results of a previous study [11].

The lack of actual transient voltage recordings during capacitor switching events also confirms the lack of significant transient voltages due to capacitor switching. As explained in section 6.6.2, there are no measurements of switching transients at these substations because the peak voltage does not exceed the trigger level of 125 % of the nominal. Even without these measurements it is safe to conclude that capacitor banks in substations Diemen and Weiwerd cause switching transients that are in line with limits of the insulation co-ordination [30].

7 Impact of the 380 kV cable at Bleiswijk and Wateringen

7.1 Introduction

The Randstad380kV is a project of TenneT for the expansion of the 380 kV transmission system in the Randstad [31], in order to ensure the power supply of the area which encompasses major industrial cities. The Zuidring, the new connection of the substations of Bleiswijk and Wateringen, consists of 380 kV underground power cables connected to overhead lines.

7.2 Influence of HV/EHV cables on PQ

Compared to overhead lines, underground cables have greater shunt capacitance and lower series reactance, resulting in larger production of reactive power. Cable charging capacitance, whose equivalent is normally seen as being parallel to the system, may affect the system resonance characteristics considerably. This change of the system impedance can change the distortion level.

The switching of cables leads to voltage transients. Since the cable is normally in operation, the switching does not occur regularly as in the case of capacitor banks. Due to this, the transients do not occur frequently enough to cause voltage flicker, but only as a consequence of network reconfiguration (e.g. for maintenance) or in the case of a fault. For this reason, the switch-on behaviour of cables should be analysed only in respect to voltage transients, and not in the scope of voltage flicker and rapid voltage changes.

7.3 Description of analysed locations

The route between substations Bleiswijk and Wateringen is approximately 22 km long, comprising of 10.8 km of underground cable and 11.2 km overhead lines. The cable connection consists of two circuits, each circuit requiring two cables per phase. The 380 kV cables are XPLE insulated single core cables, thus six cables are needed for each circuit. Open trench design has been adopted for the placement of the underground cable. There are different trench types along the route, since the cables need to be placed deeper in agricultural areas [32].

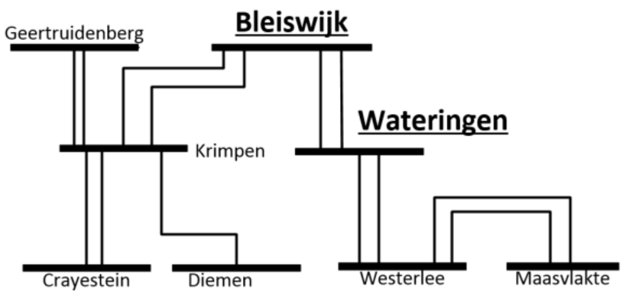


Figure 30 Schematic of the 380kV network around substations Bleiswijk and Wateringen

7.4 Influence on harmonic distortion

7.4.1 Analysis without switching the object under consideration

The analysis is performed with the use of the measurements of the year 2014, made available by TenneT. The recorded measurements taken into account are measured at Bleiswijk and Wateringen substations and consist of 10-min based line-to-neutral voltages.

On both analysed locations, the measurement devices do not record any values of harmonic distortion while the busbar is not energised – i.e. while the cable is not connected. Therefore, for the few occasions while the cable was not in service during the observed time interval no comparison can be made as with/without the cable in service. The 95 % probability values of the harmonic distortion of voltage and the THD with the cable in service are presented in Table 18. Only odd harmonic orders are presented, since all even order harmonics have negligible 95 % probability values.

	Bleiswijk		Wateringen	
Harmonic Order	Voltage HD (%)	RMS Value (V)	Voltage HD (%)	RMS Value (V)
3	0.14	326	0.12	273
5	0.77	1832	0.83	1959
7	0.52	1221	0.56	1325
9	0	0	0.00	0
11	0.47	1116	0.44	1061
13	0.43	1009	0.47	1121
15	0	0	0.00	0
17	0	0	0.04	104
19	0	0	0.00	0
21	0	0	0.00	0
23	0.15	360	0.22	521
25	0.1	231	0.41	961
27	0	0	0.00	0
29	0	0	0.04	105
31	0	0	0.00	0
33	0	0	0.00	0
35	0.11	257	0.09	210
37	0.04	105	0.07	182
39	0	0	0.00	0
THD	0.972%		1.219%	

Table 18 The 95 % probability values of harmonic voltage distortion for the substations of Bleiswijk and Wateringen

On both locations the harmonic distortion of the voltage, both the individual harmonic orders and the THD, are in accordance with the indicative planning levels as defined in [17] and Netcode Elektriciteit [6].

7.4.2 Simulation results

The impact of the 380 kV underground cable on harmonic distortion is analysed with simulations, as the influence on the harmonic impedance of the two substations in question. The network impedance of substations Bleiswijk and Wateringen is calculated under different system configurations and the resonant points are evaluated.

The conditions of simulated cases are presented in Table 19. The effect of the elements that are electrically in the vicinity of the substations of Bleiswijk and Wateringen is analysed. The changes observed in the resonant frequencies are also noted. They consist of outages of transmission lines and substations. In each case the relevant element is taken out of operation. In all cases it is assumed that no other changes take place in the network configuration.

Case ID	Disconnection of element	kV	Resonance frequency Bleiswijk (order)	Resonance frequency Wateringen (order)
	Transmission Line			
I	Base Case			
II	Bleiswijk – Krimpen	380	-	-
III	Krimpen – Crayestein	380	-	-
IV	Krimpen – Diemen	380	-	-
V	Wateringen – Westerlee	380	10.6	10.6
VI	Westerlee - Maasvlakte	380	10.6	10.6
	Substations			
VII	Wateringen	150	11.6	11.6
VIII	Zoetermeer	150	11.6	11.6
IX	Krimpen	380	8, 10.8	8
X	Krimpen	150	-	-
XI	Crayestein	380	10.4	10.4
XII	Diemen	380	15.2, 42.4	15.2
XIII	Westerlee	380	8	8
XIV	Maasvlakte	380	8.4	8
XV	Maasvlakte	150	4.8	4.8

Table 19 Analysed contingencies for the 380kV underground cable

In Figure 31 and Figure 32 the results of the first six cases are shown. The results of remaining cases are given in Appendix C. In all the figures below the harmonic impedance of the base case (case I) as seen from the substation in question of the base case (case I) is presented for comparison. The amplitude of the resonant points is also noted.

In the base case, no resonances are observed near the frequencies at which harmonic currents of loads characteristically have significant values (5^{th}, 7^{th}, 11^{th} and 13^{th}). The lower order resonances are located around the even order harmonics, which have very low levels in the network (both for voltages and currents).

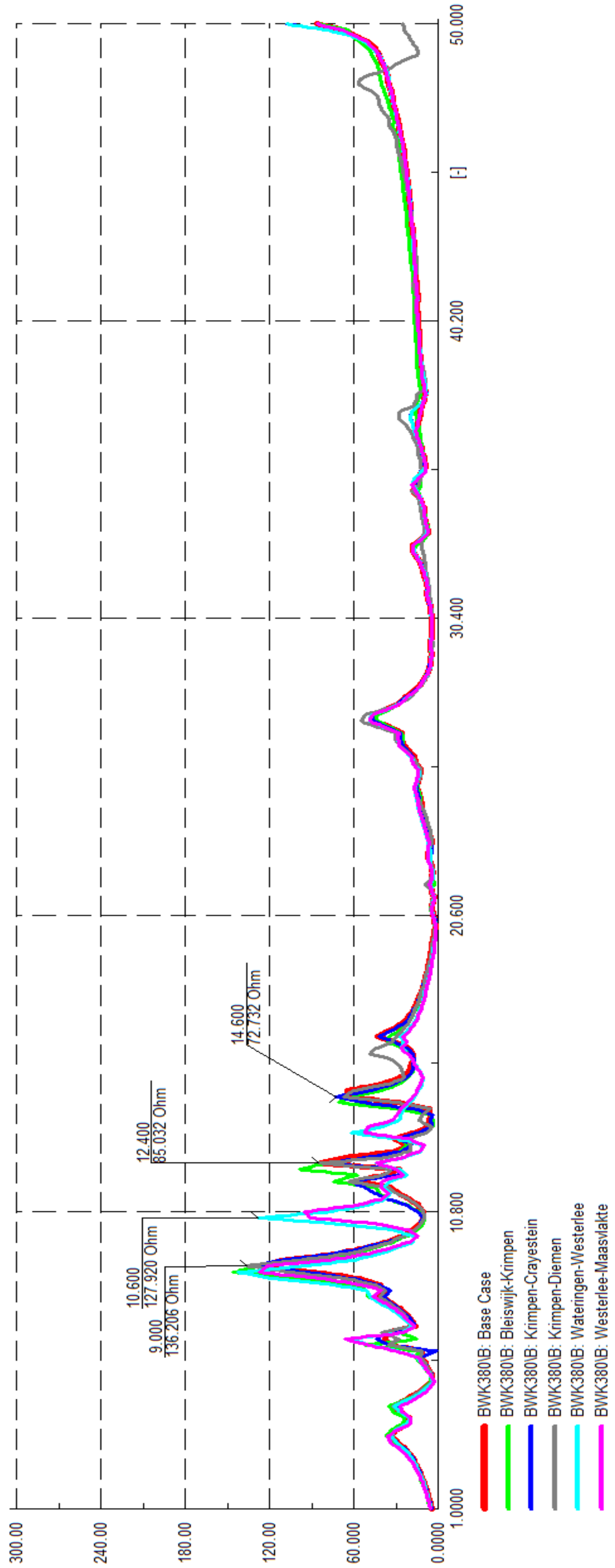


Figure 31 Harmonic impedance Z (Ω) as a function of the harmonic order in Bleiswijk for the cases I – VI, according to Table 19

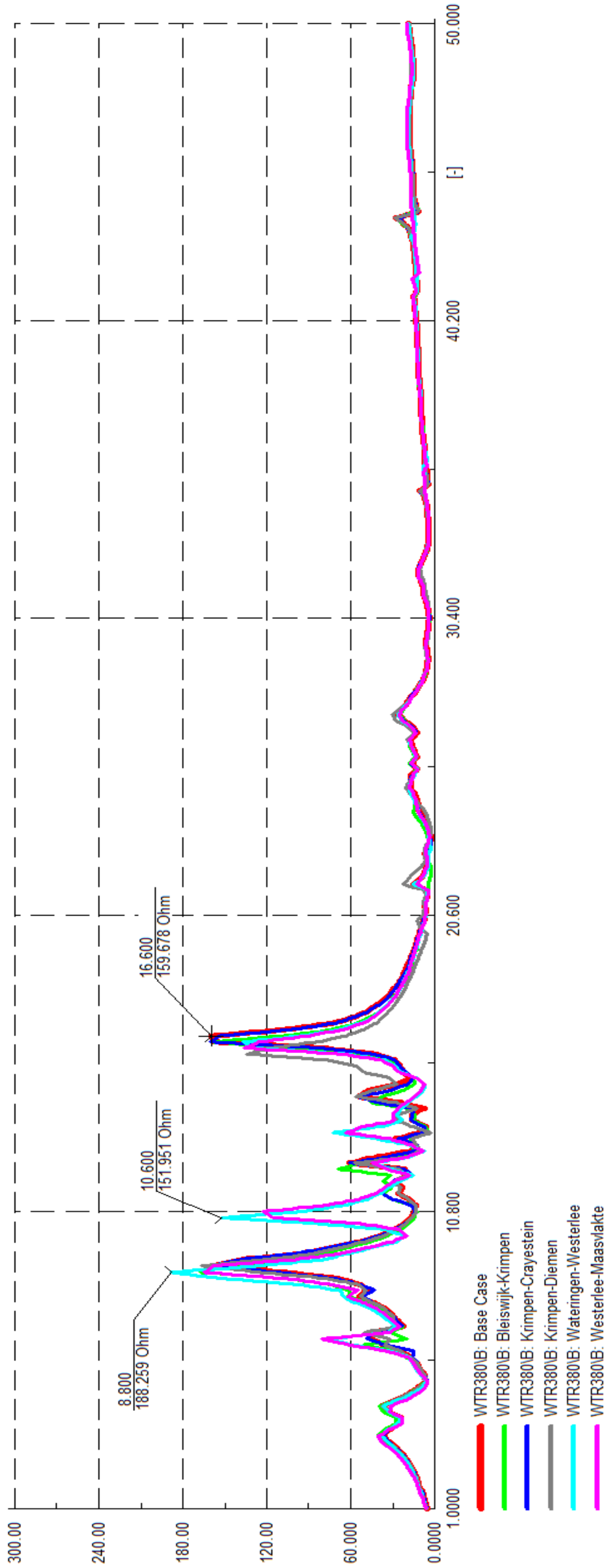


Figure 32 Harmonic impedance Z (Ω) as a function of the harmonic order in Wateringen for the cases I – VI, according to Table 19

In other analysed cases, the combination of several network components of the system affects the resonant frequencies. Depending of the element that is taken out of operation and the corresponding part of the network that is not connected to the busbar anymore, the harmonic impedance response changes. Resonant points shift and their impedance values change and/or new resonances are created.

The outage of a single circuit has a limited effect on the harmonic impedance of the substations of Bleiswijk and Wateringen, and the further away it is, the less it's impact is. When both busbars of substations are taken out of operation a greater impact can be seen (cases VII – XV). The biggest impact is observed by the unavailability of the busbar system either in the 380 kV substations of Diemen or Maasvlakte (corresponding to cases XII and XIV respectively), both of which are connected to power plants and a number of networks of lower voltage levels. The outage of single transformers and C-type filters (present at Diemen and Krimpen) has virtually no influence, thus the results are not presented here. However in all the simulated cases, the impedance amplitude of the resonant points does not obtain extremely high values, the highest being in the case of the outage of the 380 kV Maasvlakte substation (270 Ω). Values very close to zero (due to series resonances) that would lead to the generation of high harmonic currents, are not observed either.

In Table 20, the largest observed amplification factors of voltages for selected harmonic harmonic orders which commonly have significant levels (namely the 5^{th}, 7^{th}, and 11^{th}) are presented. The amplification factor is defined as the ratio of the harmonic impedance of the observed case to the harmonic impedance of the base case. It is an indication of the harmonic amplification that could occur in the observed scenario.

Case ID	Outage of element	kV	Amplification factors for selected orders					
			Bleiswijk			Wateringen		
	Transmission Line		5^{th}	7^{th}	11^{th}	5^{th}	7^{th}	11^{th}
V	Wateringen – Westerlee	380			3.69			3.75
VI	Westerlee - Maasvlakte	380			4.20			4.28
	Substations							
VII	Wateringen	150		3.30			2.35	1.40
IX	Krimpen	380		2.56	6.45			
X	Krimpen	150					1.82	6.57
XIII	Westerlee	380				1.97	2.34	2.89
XV	Maasvlakte	150	3.52		1.85	2.91		1.89

Table 20 Amplification factors for selected harmonic voltages due to outages of elements

The calculated amplification factors do not represent the possible amplification of harmonic voltages directly, but only of the portion which is caused by the injection of harmonic currents at the observed busbars. However, in such situations, increased levels of harmonic distortion could be expected.

7.5 Switch-on behaviour of the 380 kV cable

The switch-on behaviour of the 380 kV cable between substations Bleiswijk and Wateringen is analysed from the view-point of rapid voltage changes, voltage dips/swells (short duration over-voltages) and transient voltages.

The cable is being switched on or off very rarely, with a frequency in the order of months. This does not lead to a repetitive light intensity annoyance (In the case of capacitor banks, rapid voltage changes were analysed because their switching can occur within several hours).

Regarding voltage dips/swells, the threshold is set by standard [23], as a decrease or increase of the single-cycle RMS value, sliding at every half cycle, by 10 % or more of the sliding voltage reference. This is equivalent to the requirement for rapid voltage changes in this case.

As discussed in Chapter 6, transient voltages at the moment do not have particular normative requirements in the PQ standards. One requirement which can be used as a reference is specified in [30]: equipment insulated up to 245 kV should be able to withstand a power frequency overvoltage up to 1.88 p.u. and standard lightning impulses up to 4.29 p.u. These requirements are used for the purpose of network design, and power quality requirements are still under consideration.

7.5.1 Measurement and simulation results

A detailed study of the transient behaviour of the 380 kV cable is made in [12]. The representative switch-on conditions and network representation are also defined there, and based on the analysis it is chosen to analyse switch-on based on the open end of the cable in substation Wateringen as representative. This report summarises some of the results of [12]. The switch-on transients of the 380 kV cable in substation Wateringen are analysed based on simulations and measurements.

The method used to model the parallel connection of cables in the simulation model is explained in [33]. The details of the frequency-domain solver and cable and overhead line configuration are presented in [34]. The remaining details of the model are given in [12].

The model is based on the network state from year 2013, according to the capacity and quality plan from 2011 [10]. The basic scenario includes all of the main network components in service. The worst case of the moment of switching (starting phase angle) was investigated with a “statistical switch” (a uniform distribution of switching conditions and deviations between the three phases), as explained in [12].

For the validation of the simulation model, one measurement was available. The results of the measured and simulated transient, seen from the busbar of substation Wateringen when one of the two parallel cables is energised at substation Wateringen, while the other cable is already connected from both sides, are shown in Figure 33.

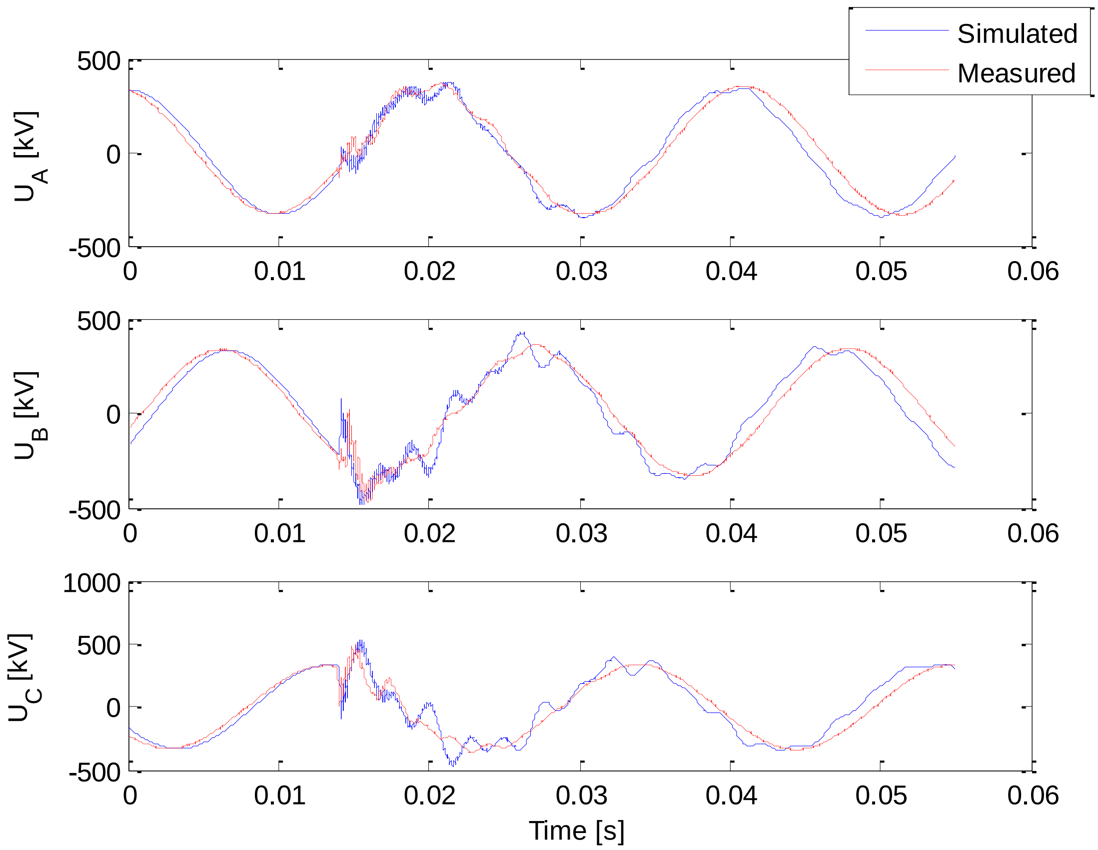


Figure 33 Measured and simulated voltage at the busbar of substation Wateringen when the cable is energised at substation Wateringen.

In Figure 33 it can be seen that the switch-on moment is located very close to the peak value of the voltage in phase “C”, a few degrees from the peak. The difference to the actual peak value does not lead to very different simulation results. According to the simulations, the worst case scenario of the switch-on behaviour at the open end of the cable occurs when one of the phases is at its positive or negative peak value. As switching of the cable belongs to predominantly capacitive transients, it is fair to assume that the voltage of the busbar will also have the maximal transient voltage when switched on at the peak of the voltage (even though some magnitude difference is expected when compared to the voltage at the open end of the cable, due to the termination impedance of the substation and part of the network connected to the substation). It can be accepted that the presented measurement and simulation represent the switch-on behaviour with the highest voltage deviation.

There is a good match between the measurement and simulation results. The simulations include less system damping, and therefore the simulation results are slightly pessimistic in comparison with the measurements (which leaves some safety margin in the analysis). It can be observed that the transient phenomenon lasts longer in the simulation, and with a slightly higher peak value.

The time-change of the RMS used for evaluation of voltage dips/swells and rapid voltage changes is shown in Figure 34. In the measurements, the maximal RMS voltage deviation (based on single cycle calculation) is +7.1 %, which is larger than the limit both for rapid voltage changes, and lower than the threshold for voltage dips and swells. In the simulation, the maximal deviation is +10.2 %, as mentioned, due to the slightly lower system damping in the model.

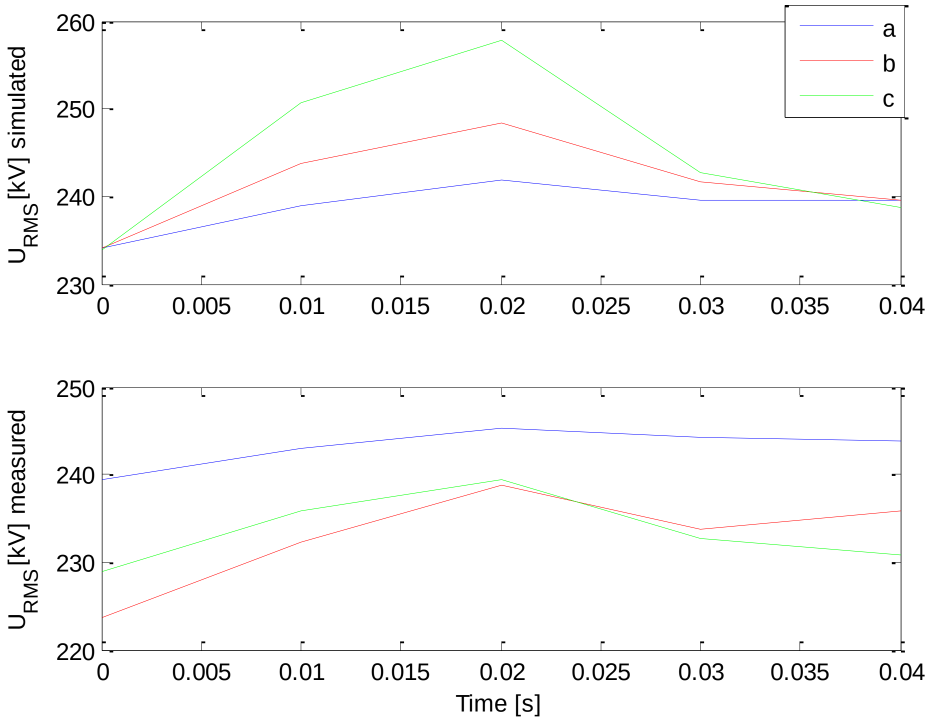


Figure 34 RMS values of the voltages shown in Figure 33

Regarding the peak instantaneous value of the transient voltage, the measured peak value occurring in phase “C” is equal to 496.8 kV, which is 1.53 p.u. of the nominal peak value. The peak value in the simulation is equal to 530.2 kV, which is 1.63 p.u. of the nominal peak value. Both values are lower than the maximal value of transient peak specified for insulation coordination. Presently there are no power quality requirements for peak instantaneous values during transients.

7.6 Conclusions for the influence of the 380 kV cable between Wateringen and Bleiswijk

The influence of the 380 kV cable between substations Wateringen and Bleiswijk was evaluated in respect of harmonic distortion and switch-on behaviour, including voltage dips/swells, rapid voltage changes and transient voltages.

The influence on harmonic distortion is first analysed from the available measurements of voltage distortion. On both locations the measured voltage distortion is within the specified limits and planning levels. The influence of the cable on system resonances was analysed with simulations. It was found that in normal operating conditions the cable does not lead to a significant increase of the network impedance at frequencies which have excitation in the network. In some of the analysed network conditions, which include operation without one of the large substations, the network impedance does show an increase of the network impedance at frequencies of interest.

The switch-on behaviour of the cable was analysed based on computer simulations and one transient measurement which was used to verify the computer model. The simulations are in good agreement with the measurement, and they showed that the measurement gives a good representation of the worst case scenario of the switch-on conditions (starting moment located a few degrees from the positive peak of the phase “C” voltage). Both the measurement and simulations, using the time change of the voltage RMS, show that the switch-on of the cabledoes not lead to voltage dips orswells. Regarding the rapid voltage variations, switching of the cable leads to variations greater than the limit of 3 % specified in the Netcode [6]. The peak value of the transient voltage is also acceptable, according to the requirements for insulation coordination, both in the measurement and simulation.

8 Conclusions of the analysis

The analysis of the influence of special projects of TenneT on PQ can be summarised as:

8.1 NorNed

The measurements show that voltage levels do not differ significantly when the power is being exported or imported via the NorNed HVDC link. The computer simulations confirmed that the influence on supply voltage variations is within the limits of [6].

Regarding the harmonic distortion, the results of the analysis based on measurements show that both the harmonic emission levels as well as the overall values of harmonic distortion measured at the substation are within the design requirements [15]. The influence of the NorNed link on the harmonic distortion is also analysed through simulation of the network and the harmonic voltages generated by the converter’s injected harmonic currents which confirmed that the influence is lower than specified in [15].

8.2 BritNed

The measurements of the voltage level show that the supply voltage variations are lower than the limit given in [6]. The influence of the BritNed link cannot be isolated from the measured supply voltage variations due to the lack of power and current measurements. The simulation results which estimate the influence of BritNed without other sources of voltage variations in the network showed that the influence of the link on voltage level is lower than the limit, both in the conditions of importing and exporting power.

The influence of the BritNed link on harmonic distortion also cannot be evaluated based on measured data due to the lack of current measurements. The measurements of harmonic voltages show that the harmonic distortion is lower than the limits of [6] at substation Maasvlakte, however, the influence of the converter station cannot be isolated in the measurements. The influence of the BritNed link alone on the harmonic distortion is analysed through computer simulations. The results show that the impact is lower than the design requirements given in [35], on all harmonic orders except for the 47th. It is probable that this result is overestimated due to the model used for injected harmonic currents, however this needs to be verified by measurements

8.3 Betuweroute traction substations Alblasserdam and Waalhaven

At the two analysed locations, Alblasserdam and Waalhaven, substations are presently equipped with measurement instruments which are not suitable for formal assessment. Due to this, the analysis has certain restrictions with the use of measured data and inputs for the simulations.

The supply voltage variations are analysed based on measured values and computer simulations. The measurements show that the supply voltage variations are lower than the limit given in [6] and the simulations show that the traction supplies have only a minor effect on the voltage level at both substations.

The influence of the analysed Betuweroute substations on the harmonic distortion is analysed only through computer simulations, due to the absence of required measurements. The results show that the influence on harmonic distortion is lower than the planning levels given in [1].

The influence on voltage flicker cannot be determined at the moment with the existing measurement equipment. However, the measurements of the long-term flicker coefficient at both locations indicate that the flicker level is lower than the limit given in [6], on both locations, but currently without the possibility to analyse the impact of traction supplies on the measured levels. The analysis can be completed only with additional measurement data.

Regarding the voltage unbalance, the impact of the Betuweroute cannot be estimated based on measurements due to the lack of current measurements. The measurements show that the total unbalance level is lower than the limit given in [6], at both substations. The simulations show that the Betuweroute's contribution to unbalance is lower than the indicative planning level of [25]. On both locations the simulated influence on voltage unbalance is lower than the allocated level calculated based on [26].

8.4 Capacitor banks at substations Diemen and Weiwerd

The analysis of the supply voltage variations at bubstations Diemen and Weiwerd shows that the operation of capacitor banks leads to supply voltage variations lower than the limit given in [6], at both locations. The analysis of measurement was also confirmed by computer simulations for all of the analysed transport conditions.

The results of the harmonic impedance analysis by computer simulations show that the capacitor banks at substations Diemen and Weiwerd have a positive (damping) influence on harmonic distortion in the network, due to the C-type filter configuration of these capacitor banks on both locations, leading to a decrease of THD at both locations. The results of measurements are in agreement with simulations.

The simulation results of the switch-on behaviour of the capacitor banks showed that the resulting rapid voltage changes are lower than the adopted reference value for individual rapid voltage changes. The switching of capacitor banks in both substations also cause transient voltages lower than required for insulation coordination [30].

8.5 HV cable (380 kV) between Bleiswijk and Wateringen

The influence on harmonic distortion is first analysed from the available measurements of voltage distortion. On both locations the measured voltage distortion is within the specified limits and planning levels. The influence of the cable on system resonances was analysed with computer simulations. It was found that with all lines and transformers available, the cable does not lead to a significant increase of the network impedance at frequencies which have excitation in the network. In some of the analysed network conditions, which include operation without one of the large substations, the network impedance does show an increase of the network impedance at frequencies of interest, while the increase in magnitudes of harmonic voltages cannot be determined without the values of injected harmonic currents.

The switch-on behaviour of the cable was analysed based on computer simulations and one transient measurement which was used to verify the simulation model. The simulations are in good agreement with the measurement, and they show that the measurement gives a good representation of the worst case scenario of the switch-on conditions. Both the measurement and simulations, using the time change of the voltage RMS, show that the switch-on does not lead to voltage dips or swells. The resulting variations are however higher than the 3 % requirement for rapid voltage changes, given in the Netcode [6]. The peak value of the transient voltage is lower than required for insulation coordination, both in the measurement and simulation.

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10 Appendix A – additional information for NorNed

10.1 Correlations of voltage distortion to the transmitted power

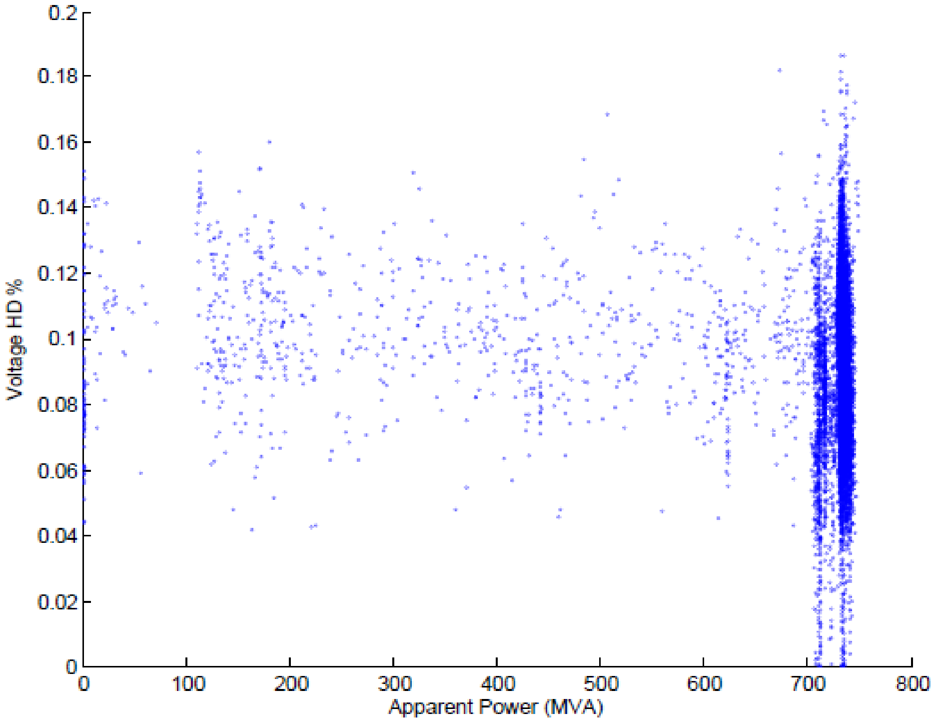


Figure A. 1 Harmonic distortion of voltage as a function of the apparent power (3rd harmonic)

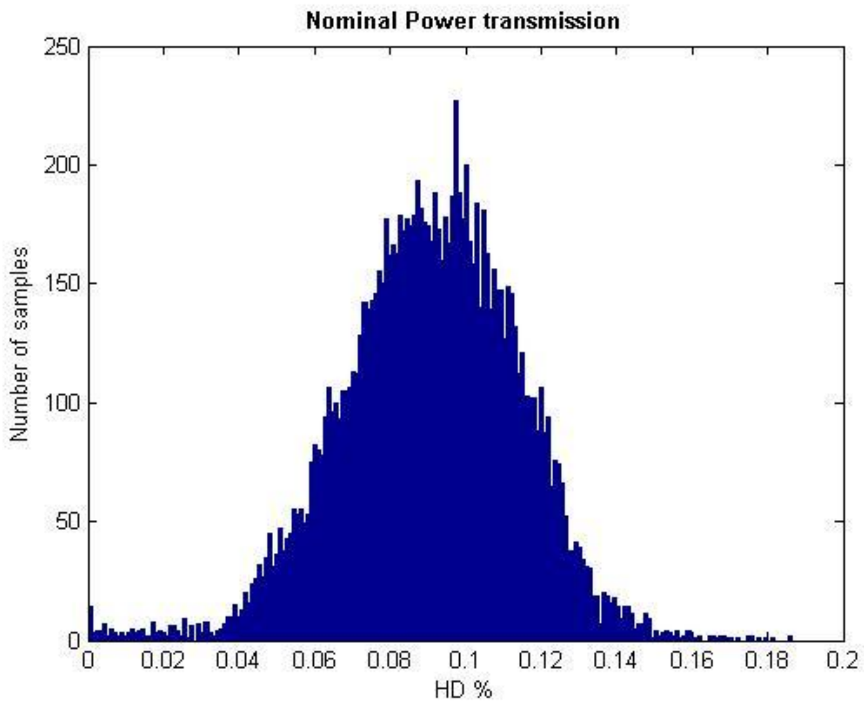


Figure A. 2 Histogram of harmonic distortion of Voltage for nominal power transmission (3rd harmonic) | P > 700 MW

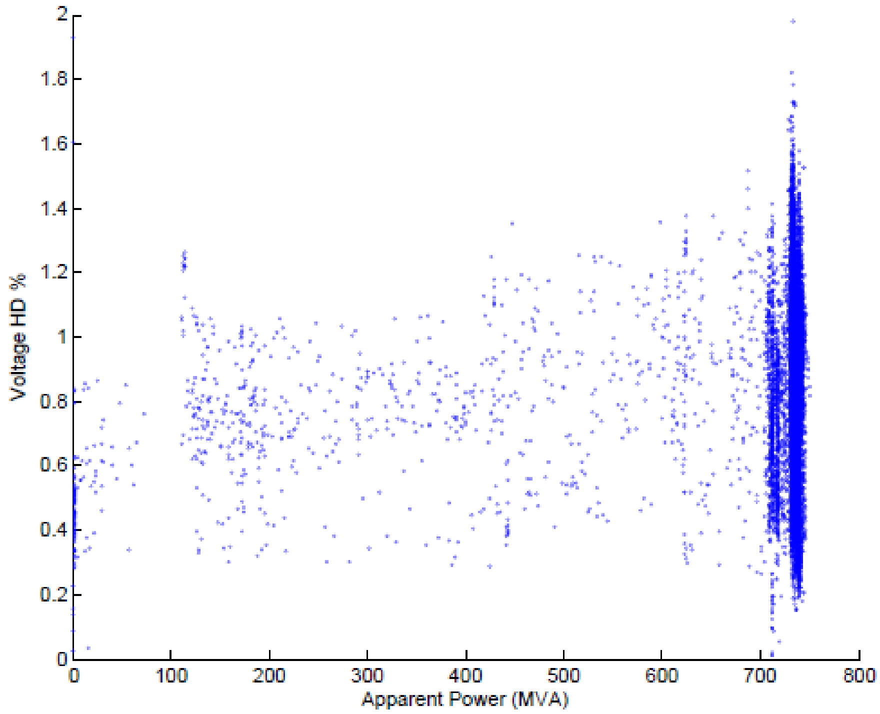


Figure A. 3 Harmonic distortion of voltage as a function of the apparent power (5th harmonic)

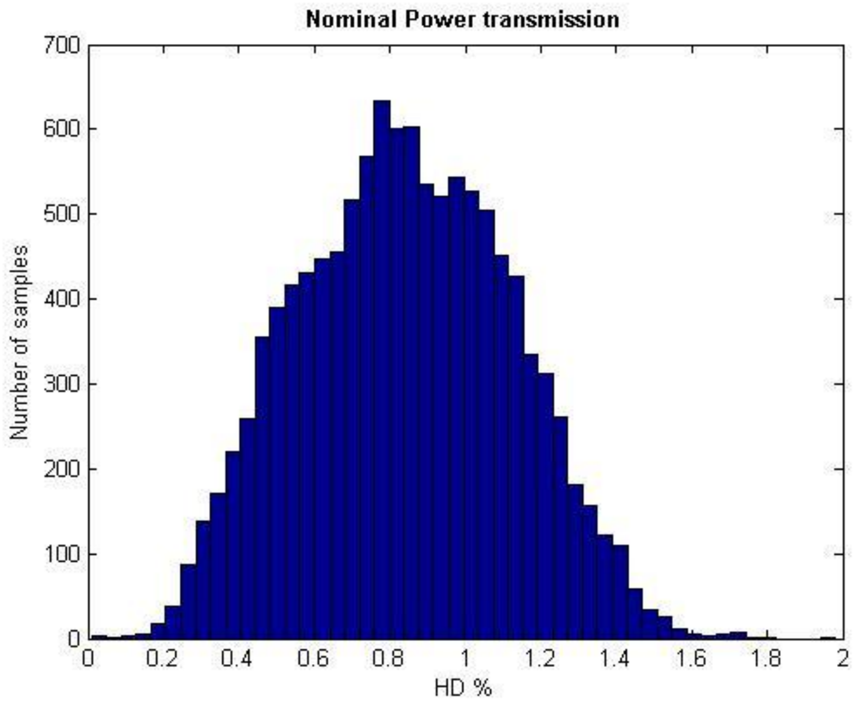


Figure A. 4 Histogram of harmonic distortion of Voltage for nominal power transmission (5th harmonic) | P > 700 MW

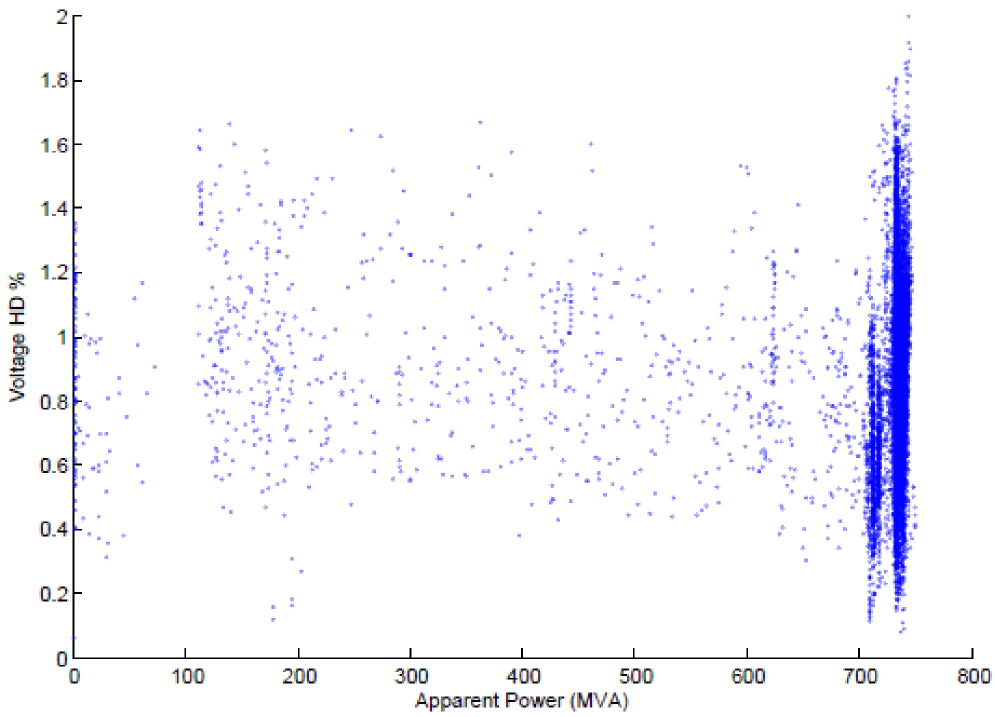


Figure A. 5 Harmonic distortion of voltage as a function of the apparent power (7th harmonic)

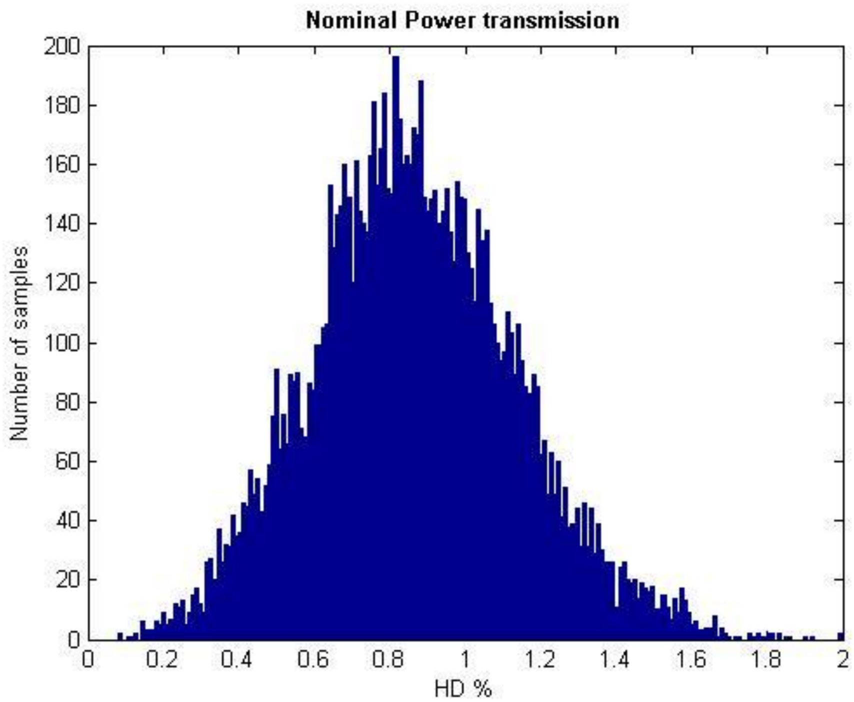


Figure A. 6 Histogram of harmonic distortion of Voltage for nominal power transmission (7th harmonic) | P > 700 MW

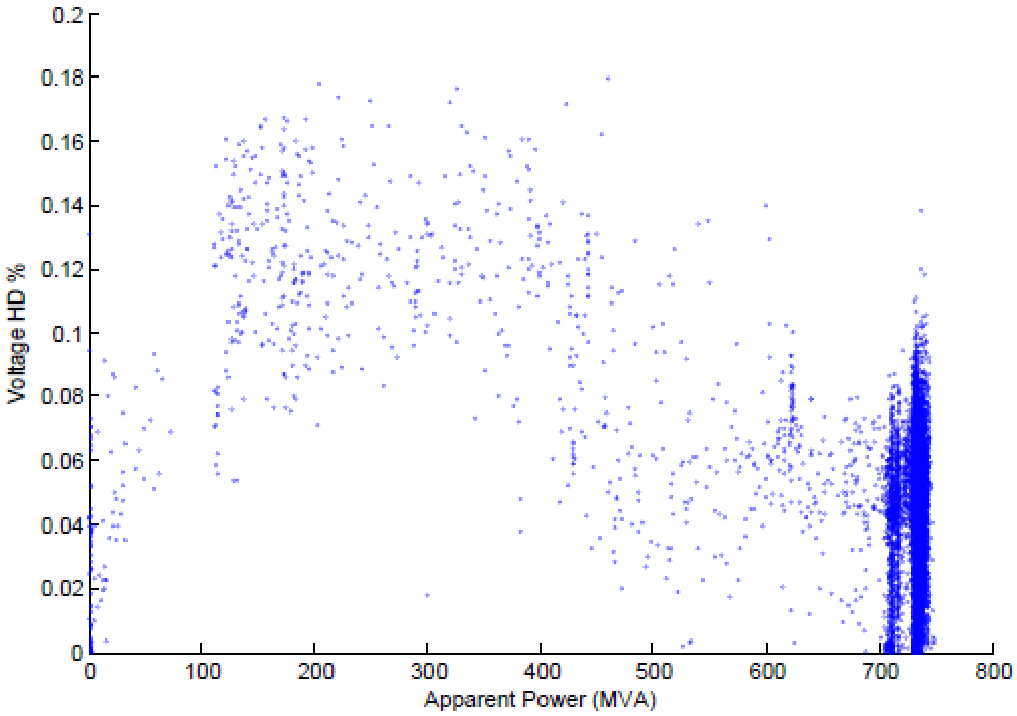


Figure A. 7 Harmonic distortion of voltage as a function of the apparent power (9th harmonic)

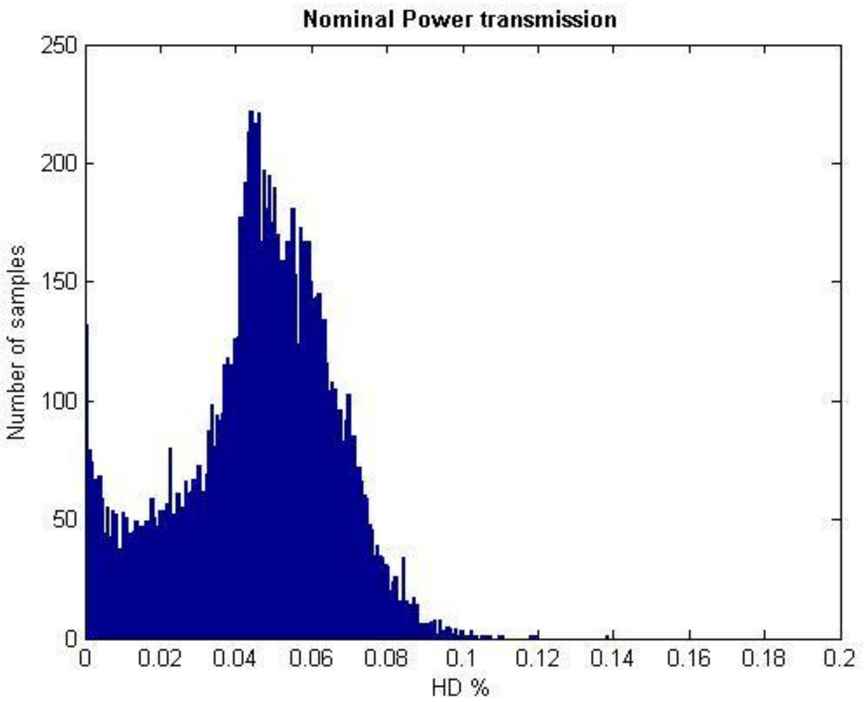


Figure A. 8 Histogram of harmonic distortion of Voltage for nominal power transmission (9th harmonic) | P > 700 MW

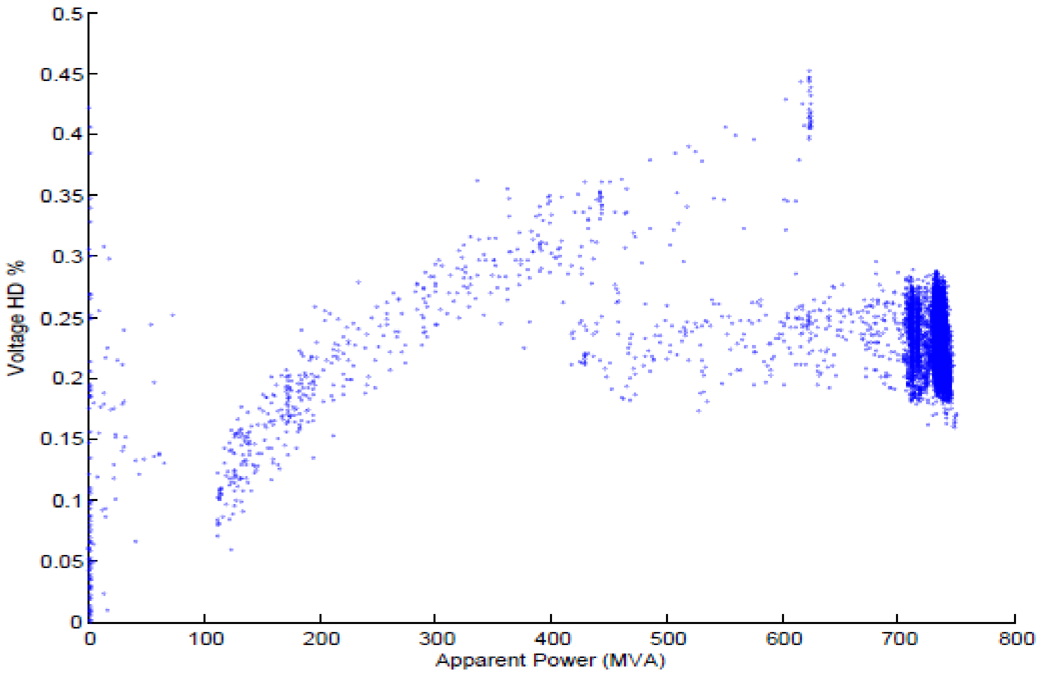


Figure A. 9 Harmonic distortion of voltage as a function of the apparent power (11th harmonic)

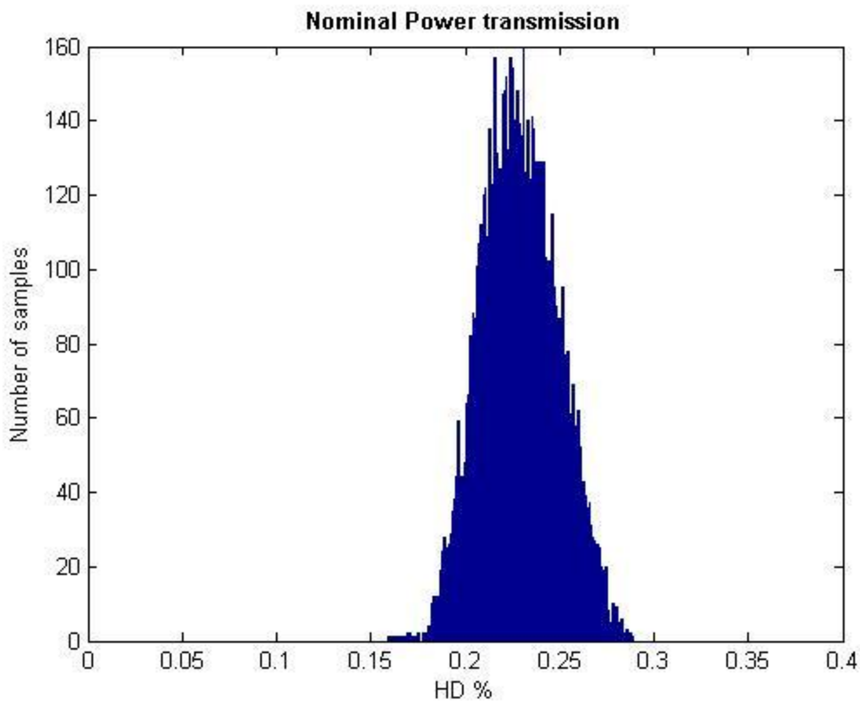


Figure A. 10 Histogram of harmonic distortion of Voltage for nominal power transmission (11th harmonic) | P > 700 MW

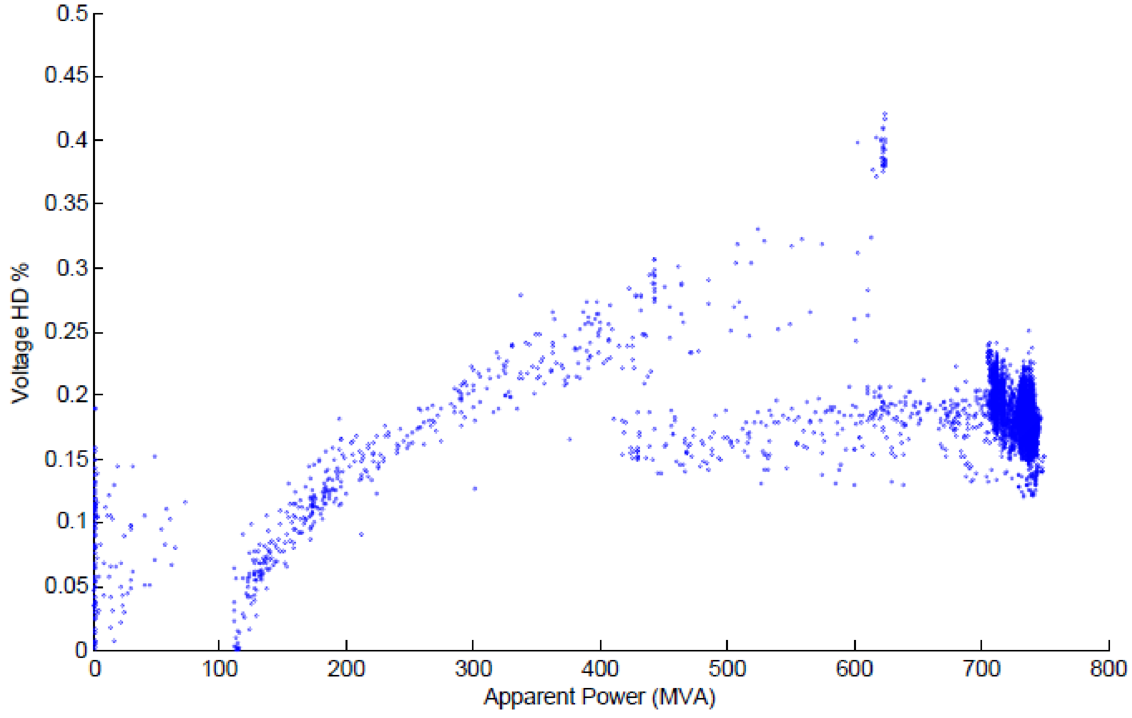


Figure A. 11 Harmonic distortion of voltage as a function of the apparent power (13th harmonic)

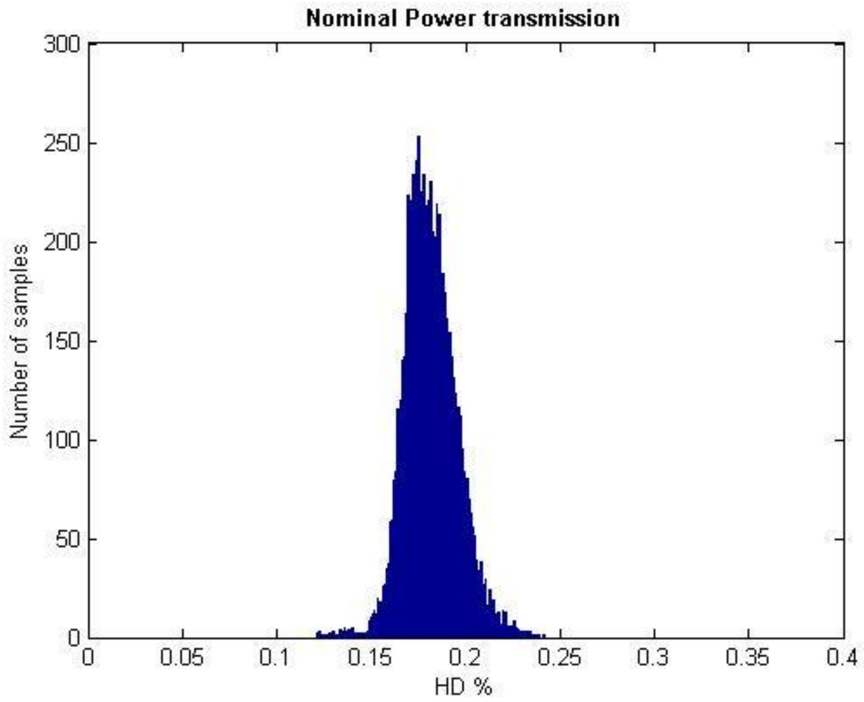


Figure A. 12 Histogram of harmonic distortion of Voltage for nominal power transmission (13th harmonic) | P > 700 MW

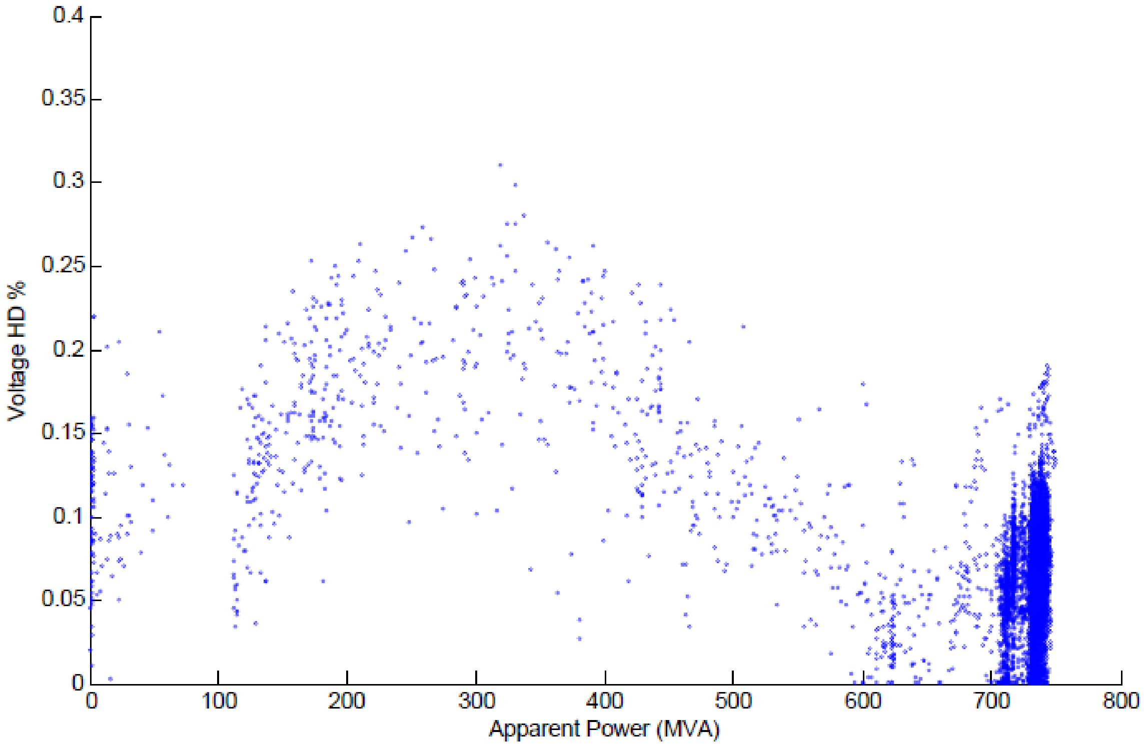


Figure A. 13 Harmonic distortion of voltage as a function of the apparent power (23rd harmonic)

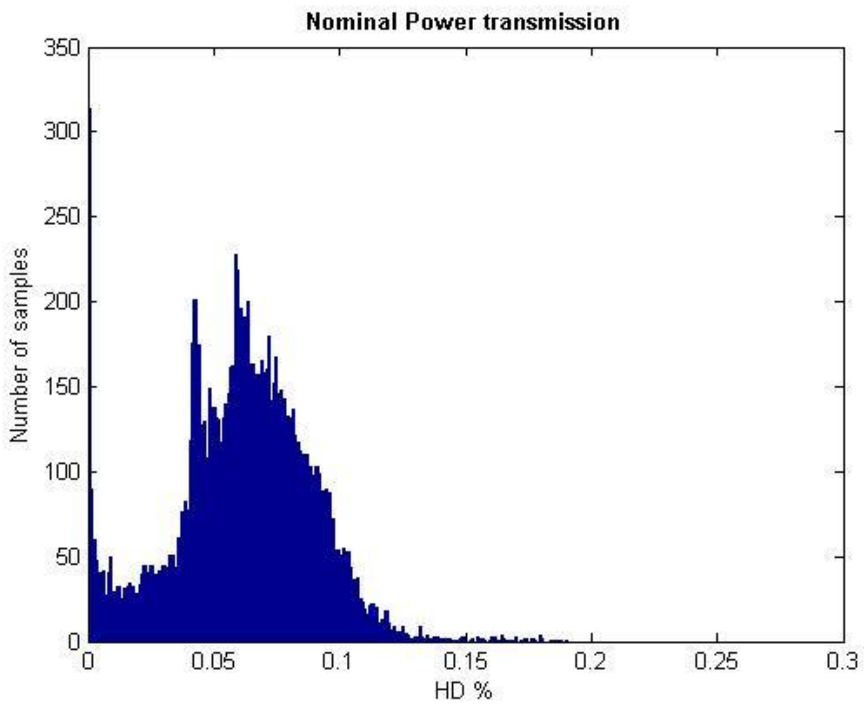


Figure A. 14 Histograms of harmonic distortion of <u>Voltage</u> for nominal power transmission (23rd harmonic) | P > 700 MW

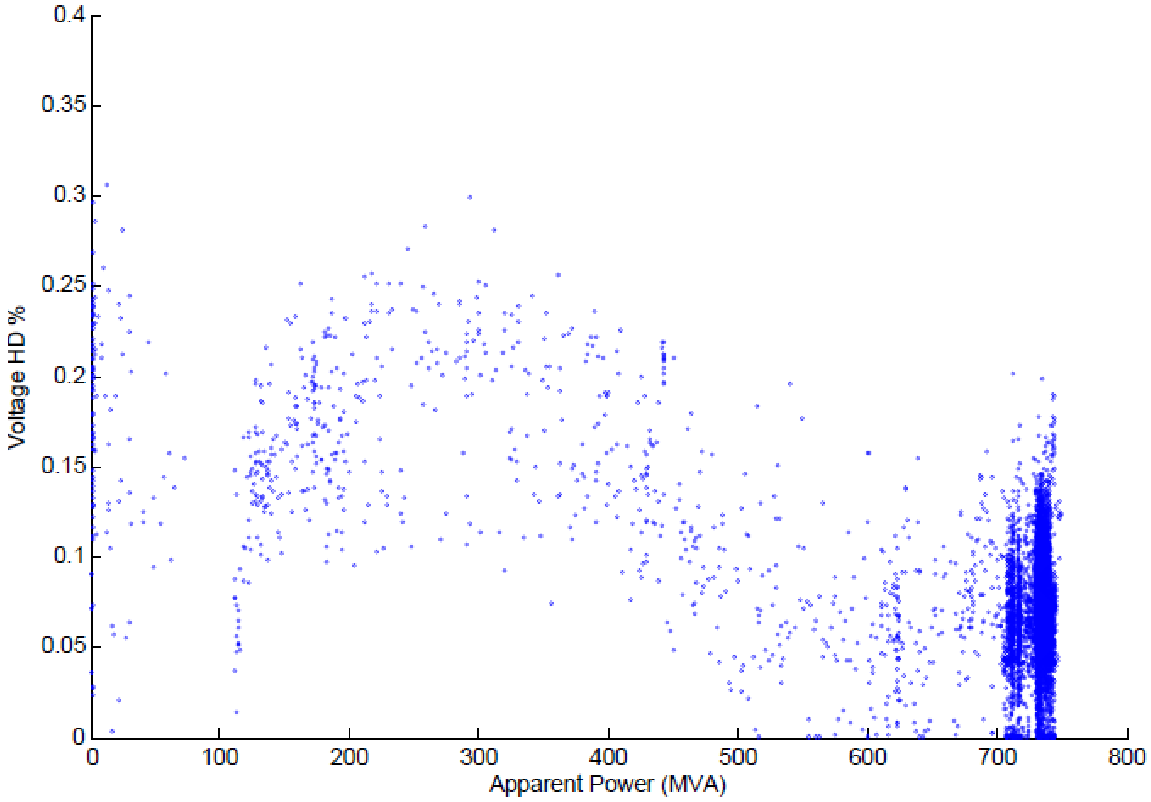


Figure A. 15 Harmonic distortion of voltage as a function of the apparent power (25th harmonic)

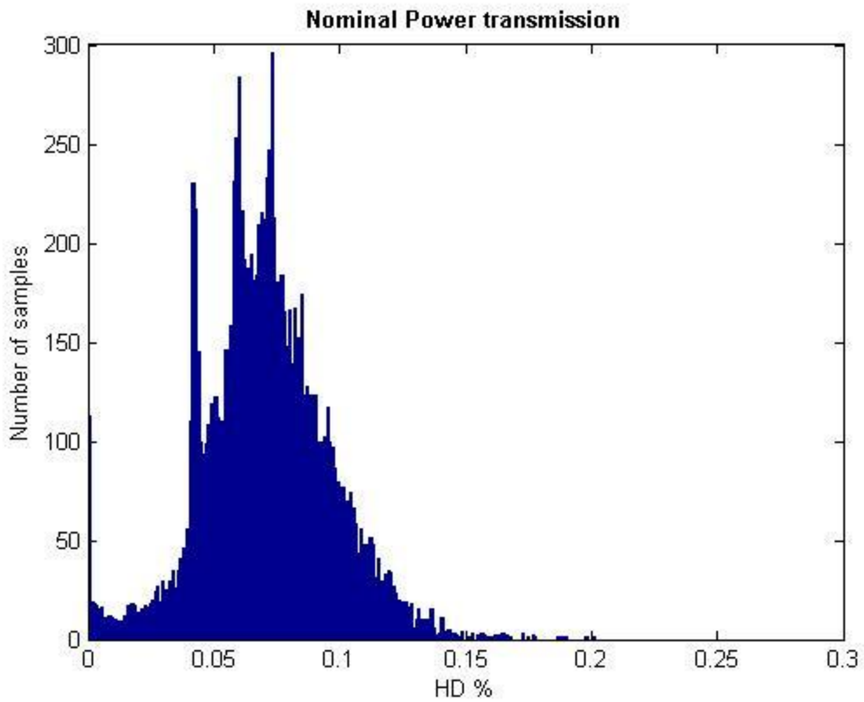


Figure A. 16 Histogram of harmonic distortion of <u>Voltage</u> for nominal power transmission (25th harmonic) | P > 700 MW

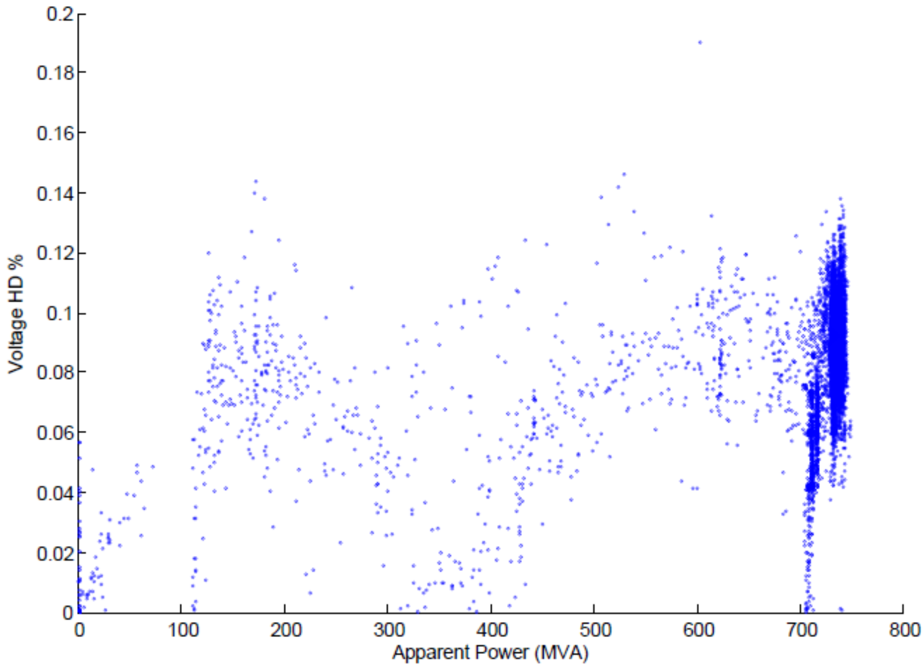


Figure A. 17 Harmonic distortion of voltage as a function of the apparent power (35th harmonic)

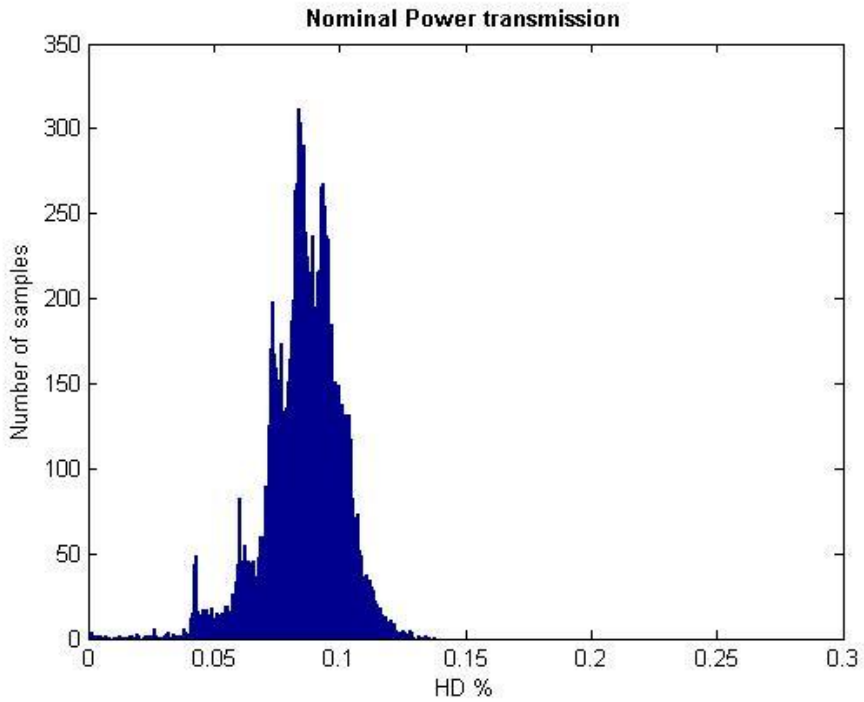


Figure A. 18 Histogram of harmonic distortion of Voltage for nominal power transmission (35th harmonic) | P > 700 MW

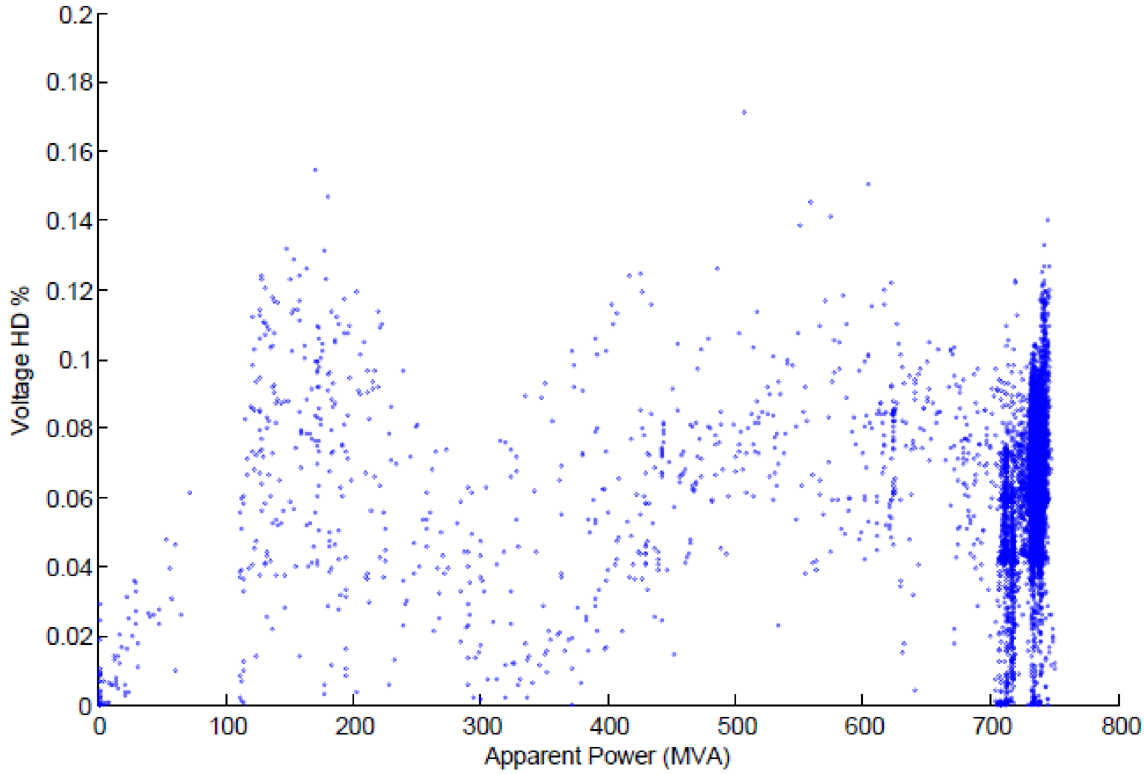


Figure A. 19 Harmonic distortion of voltage as a function of the apparent power (37th harmonic)

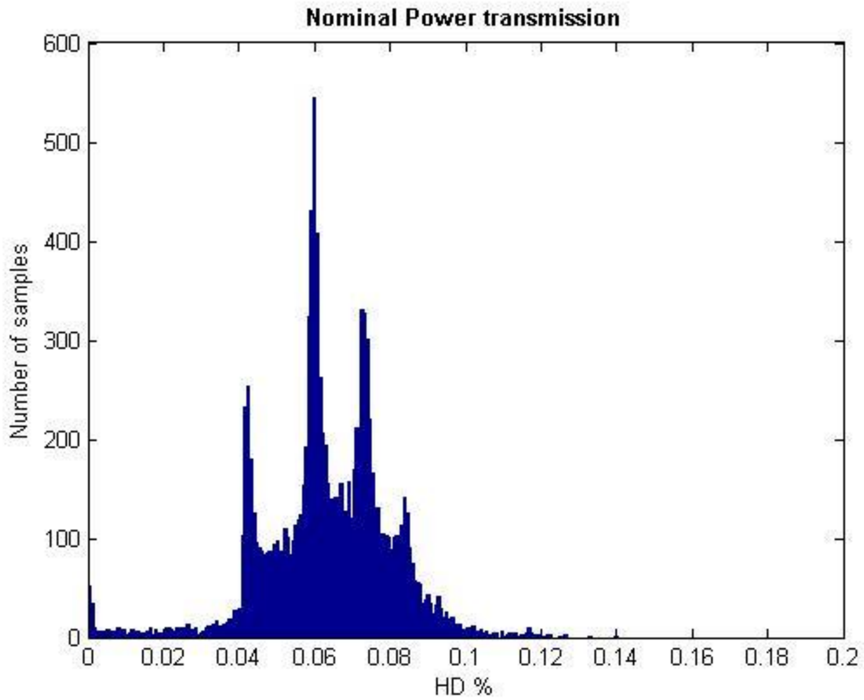


Figure A. 20 Histogram of harmonic distortion of Voltage for nominal power transmission (37th harmonic) | P > 700 MW

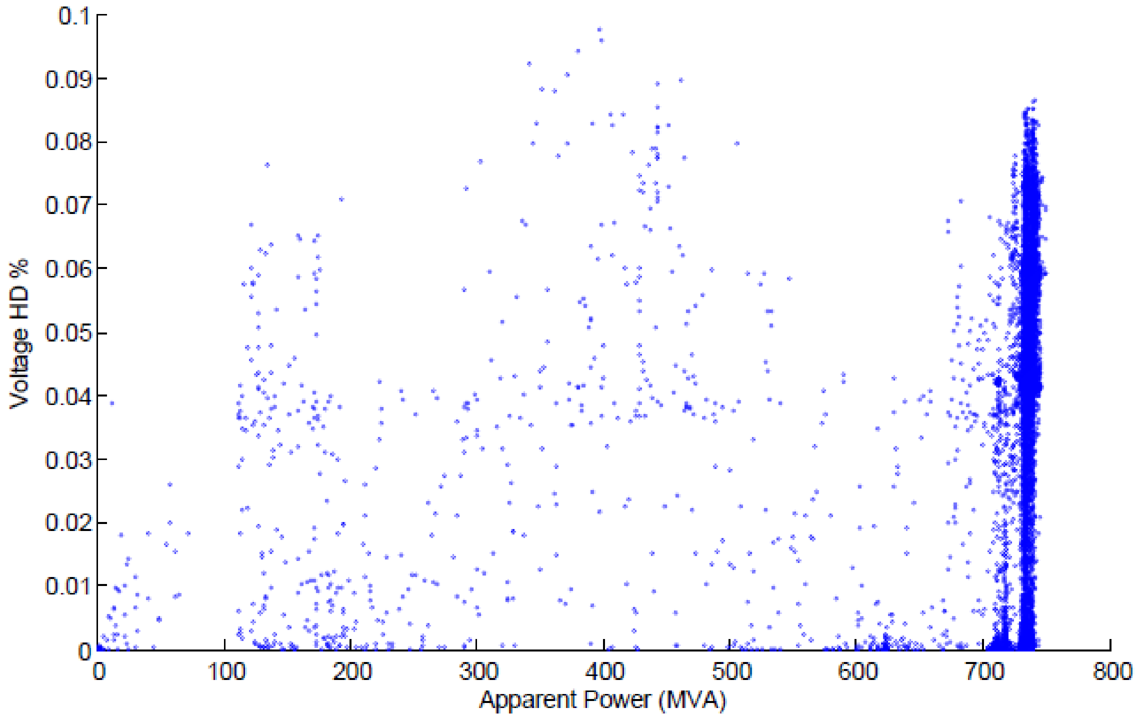


Figure A. 21 Harmonic distortion of voltage as a function of the apparent power (47th harmonic)

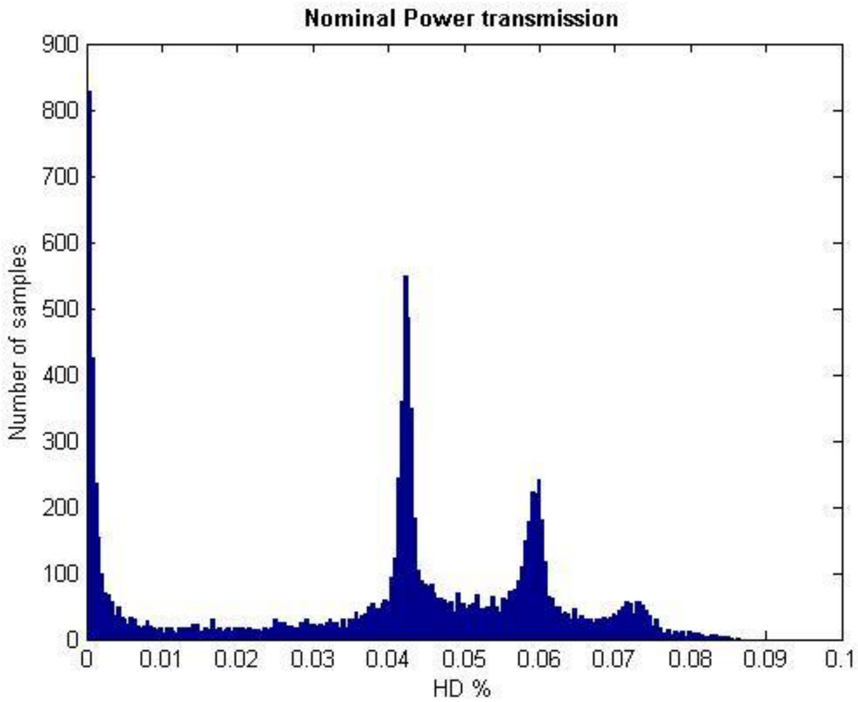


Figure A. 22 Histogram of harmonic distortion of Voltage for nominal power transmission (47th harmonic) | P > 700 MW

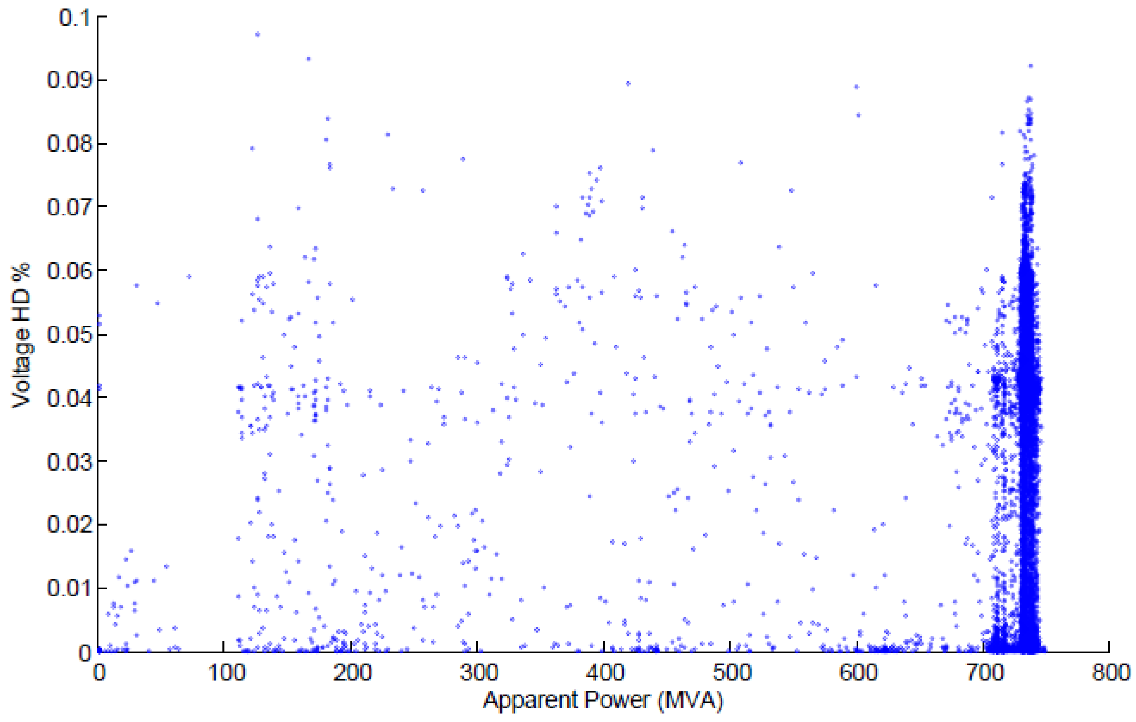


Figure A. 23 Harmonic distortion of voltage as a function of the apparent power (49th harmonic)

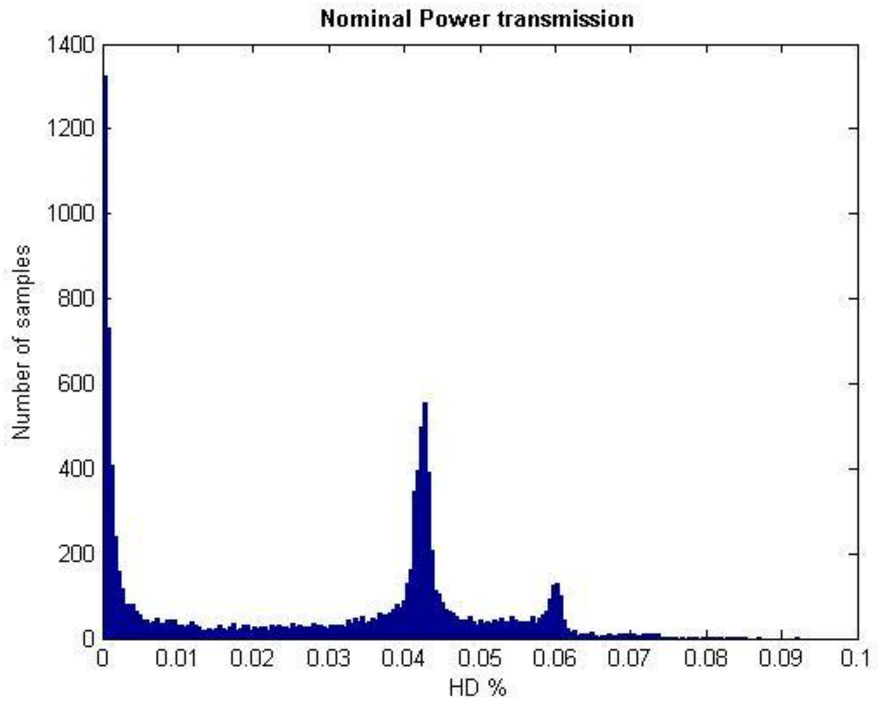


Figure A. 24 Histogram of harmonic distortion of Voltage for nominal power transmission (49th harmonic) | P > 700 MW

10.2 Correlations of voltage and current harmonics

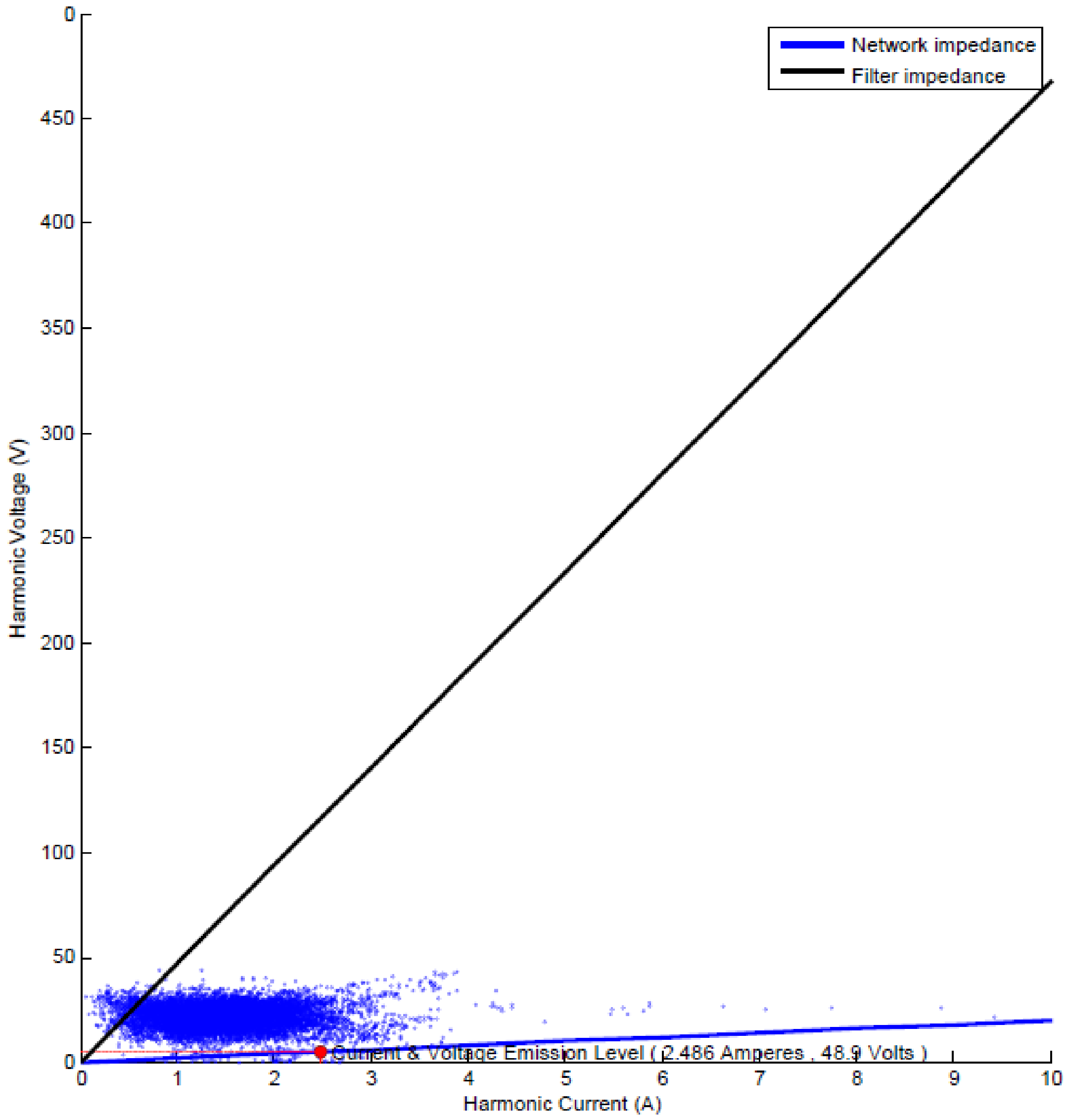


Figure A. 25 3rd harmonic voltage vs current

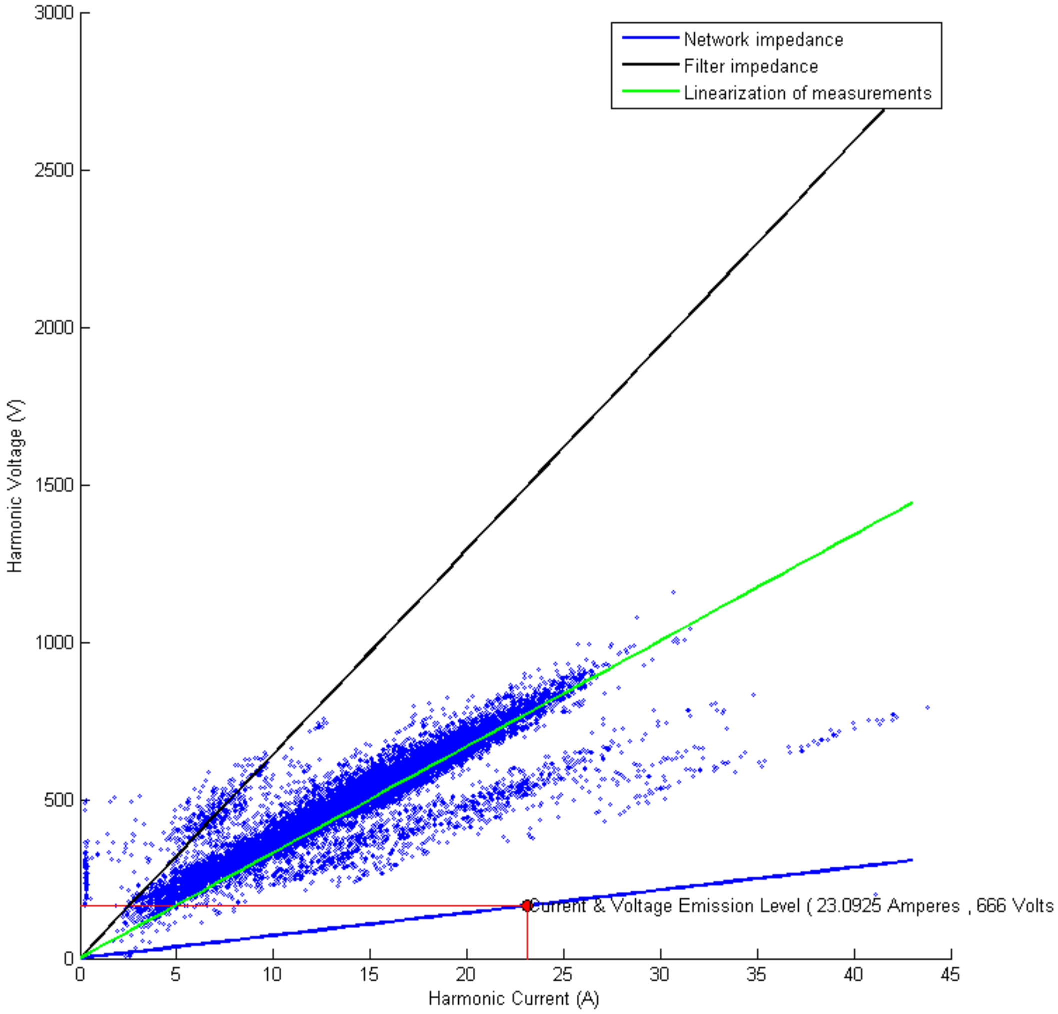


Figure A. 26 5th harmonic voltage vs current

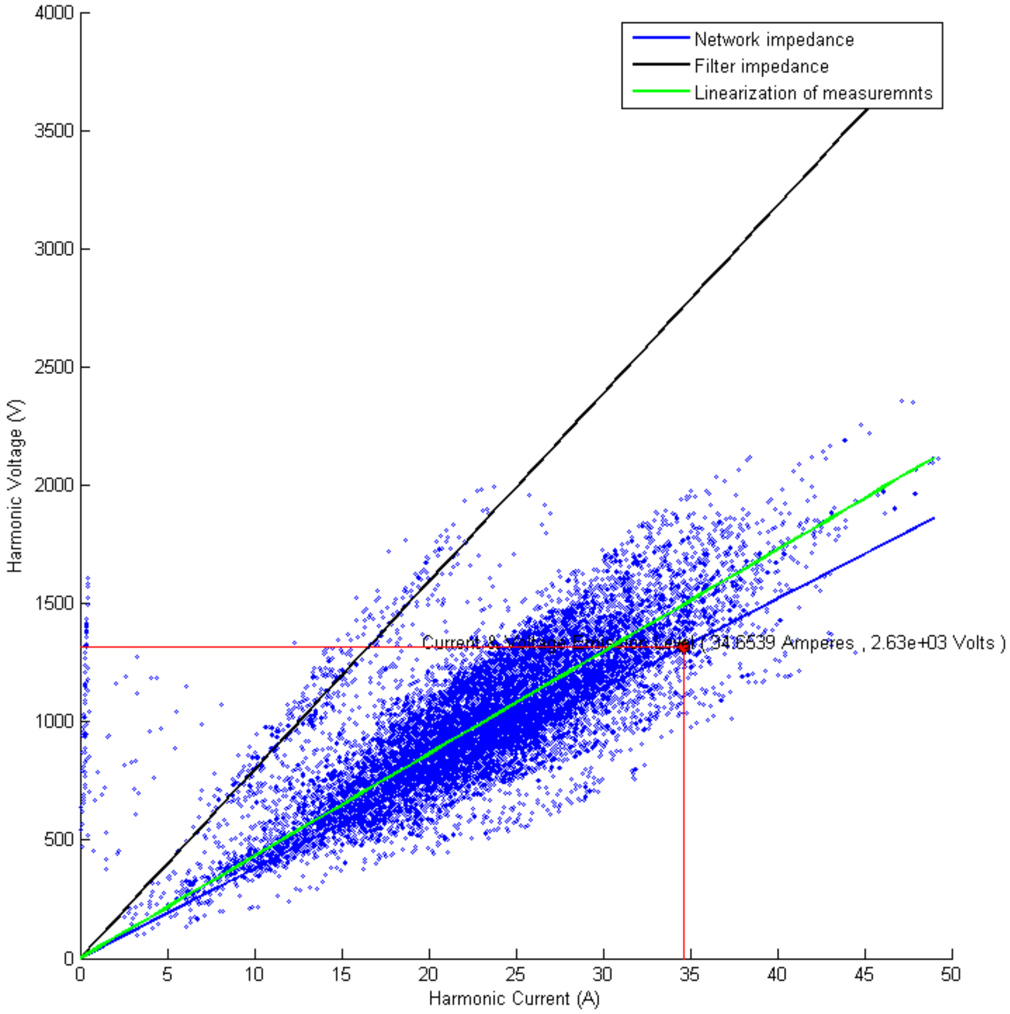


Figure A. 27 7th harmonic voltage vs current

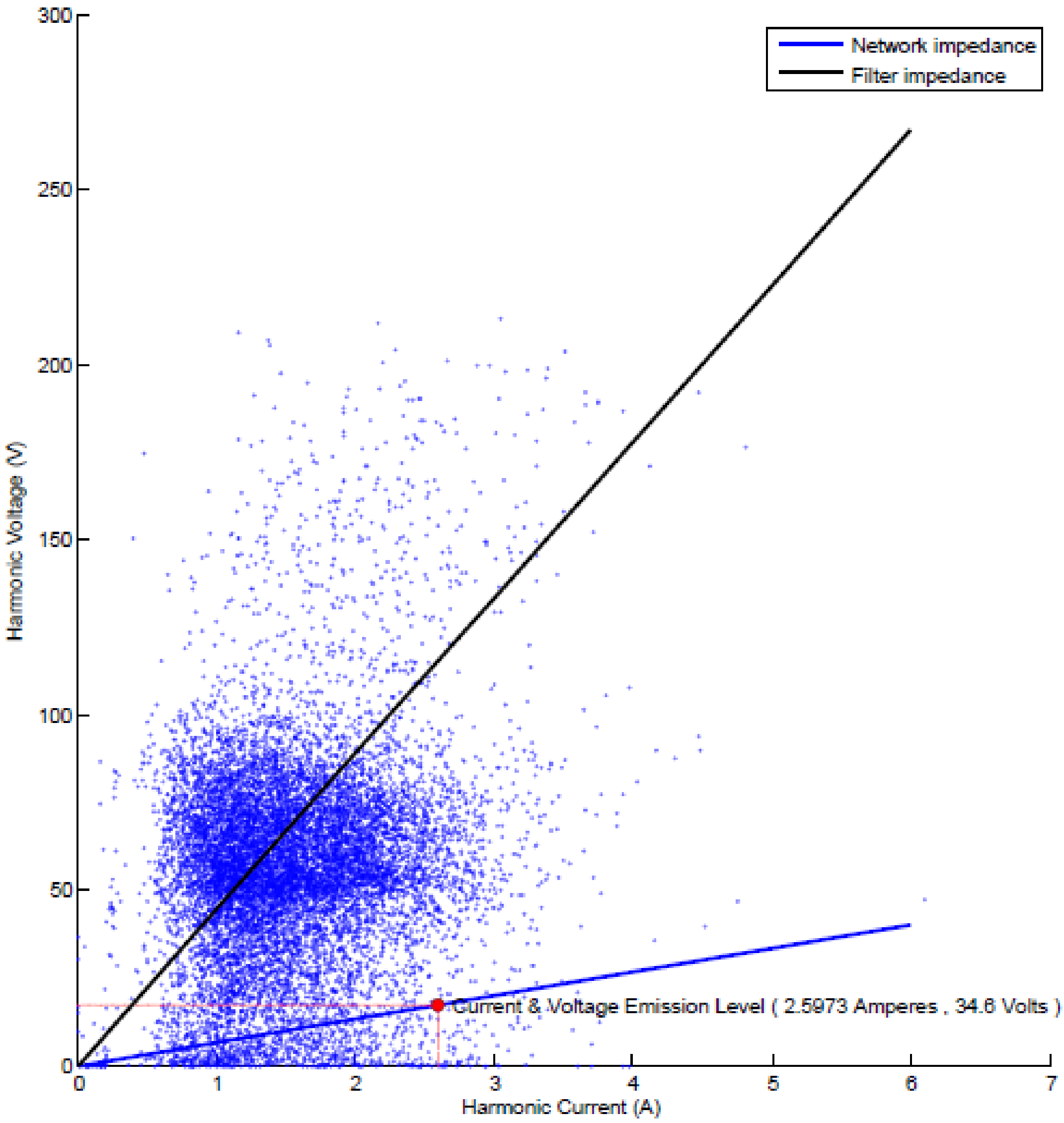


Figure A. 28 9th harmonic voltage vs current

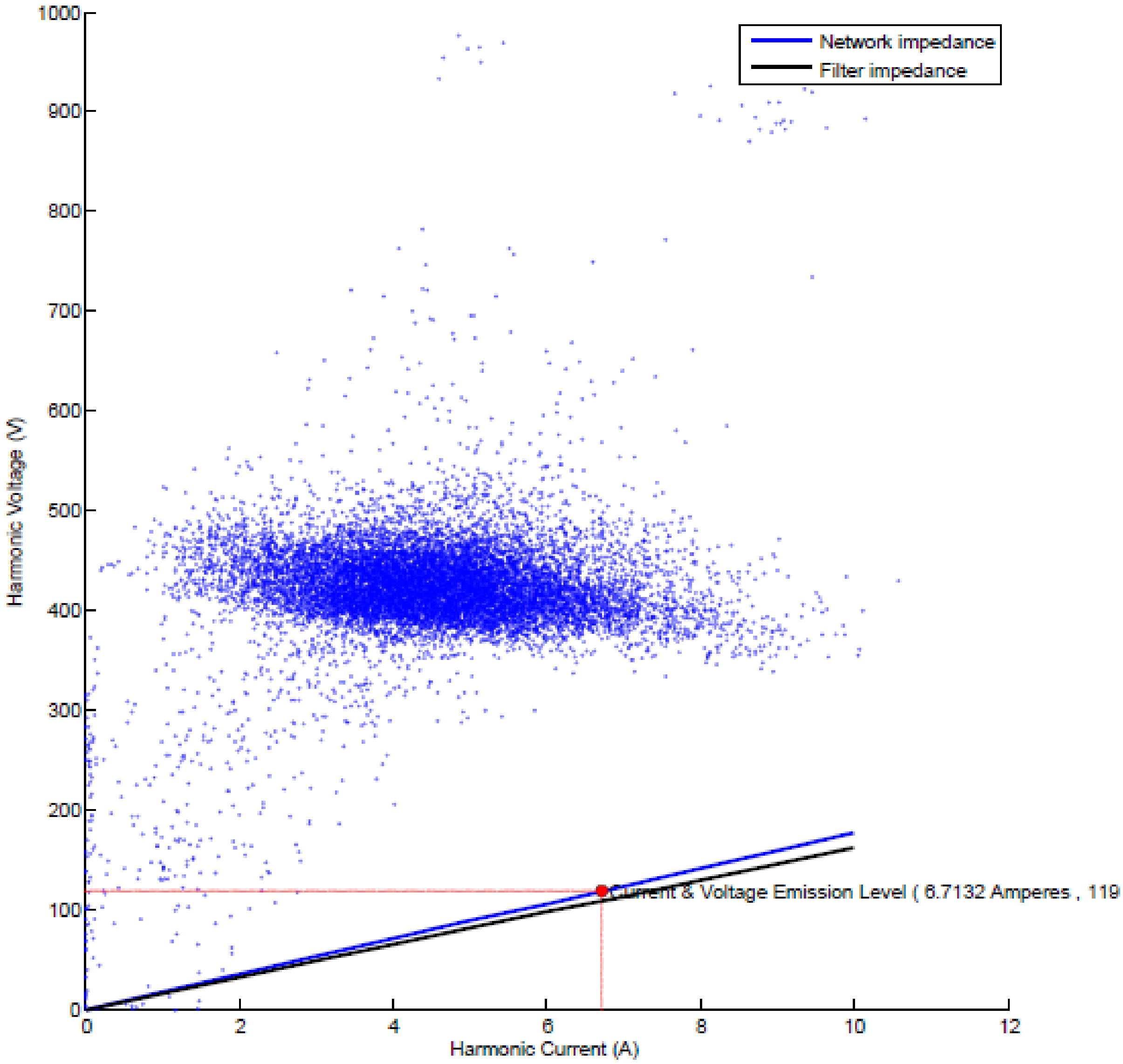


Figure A. 29 13th harmonic voltage vs current

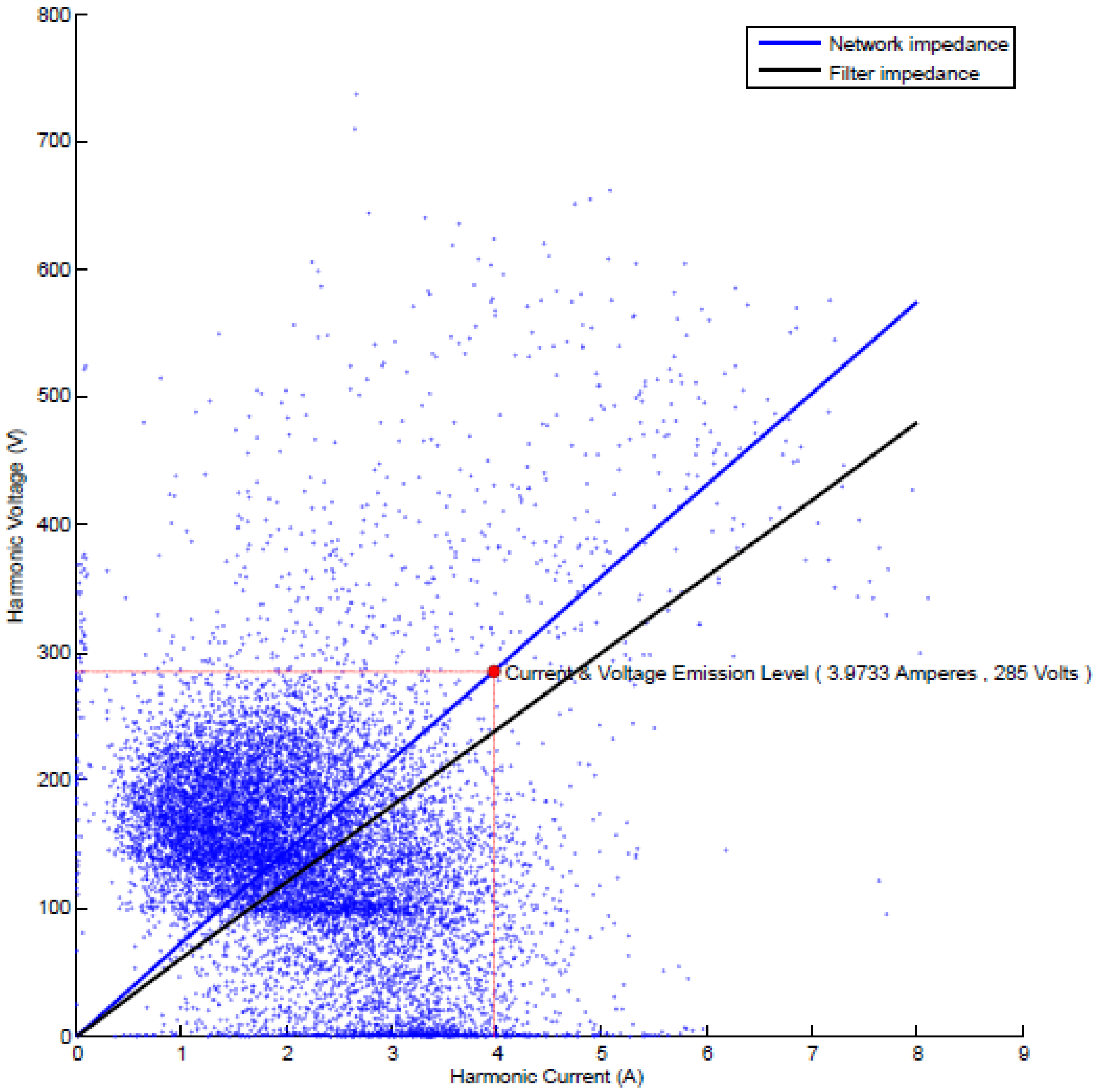


Figure A. 30 23rd harmonic voltage vs current

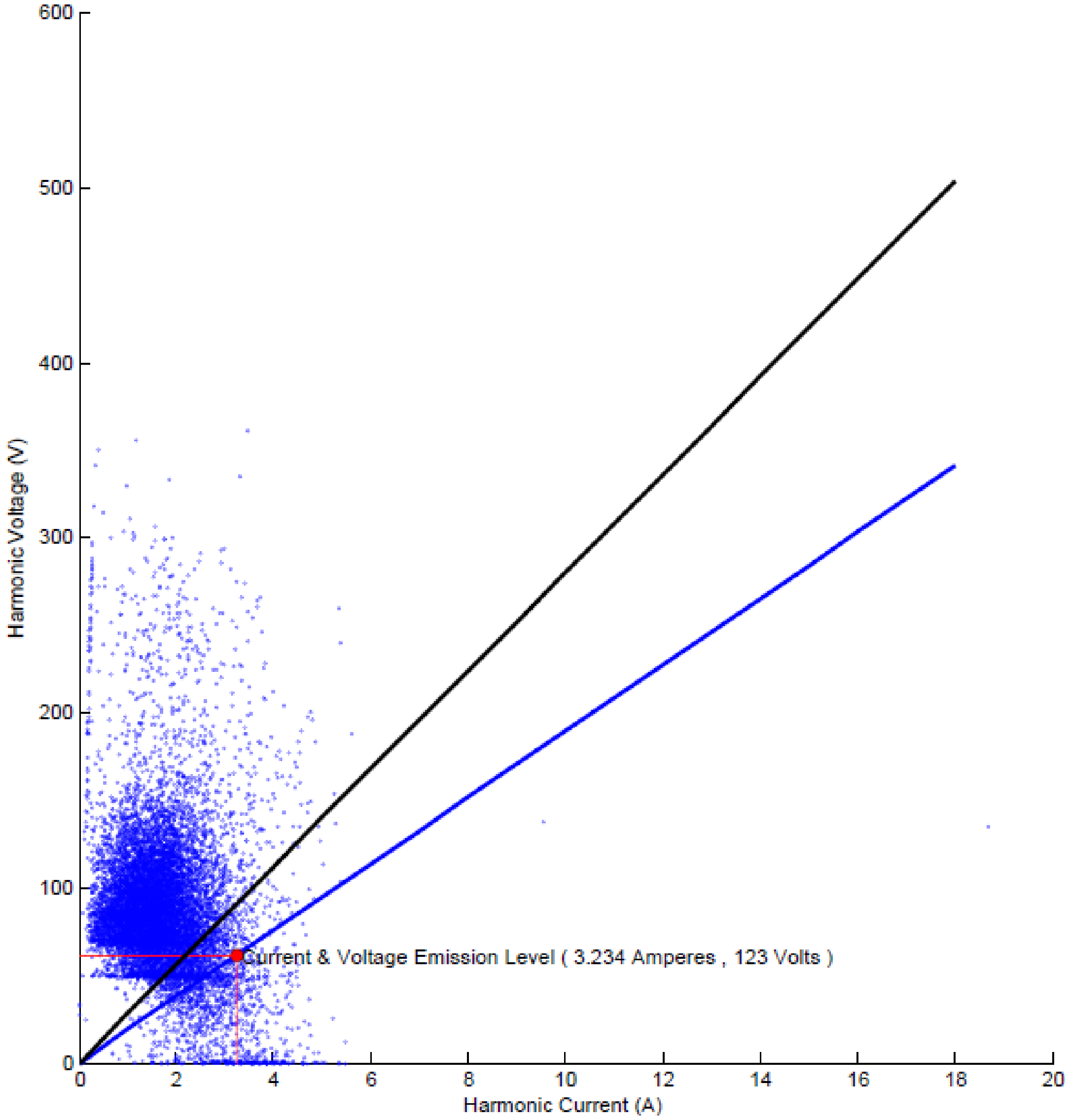


Figure A. 31 25th harmonic voltage vs current

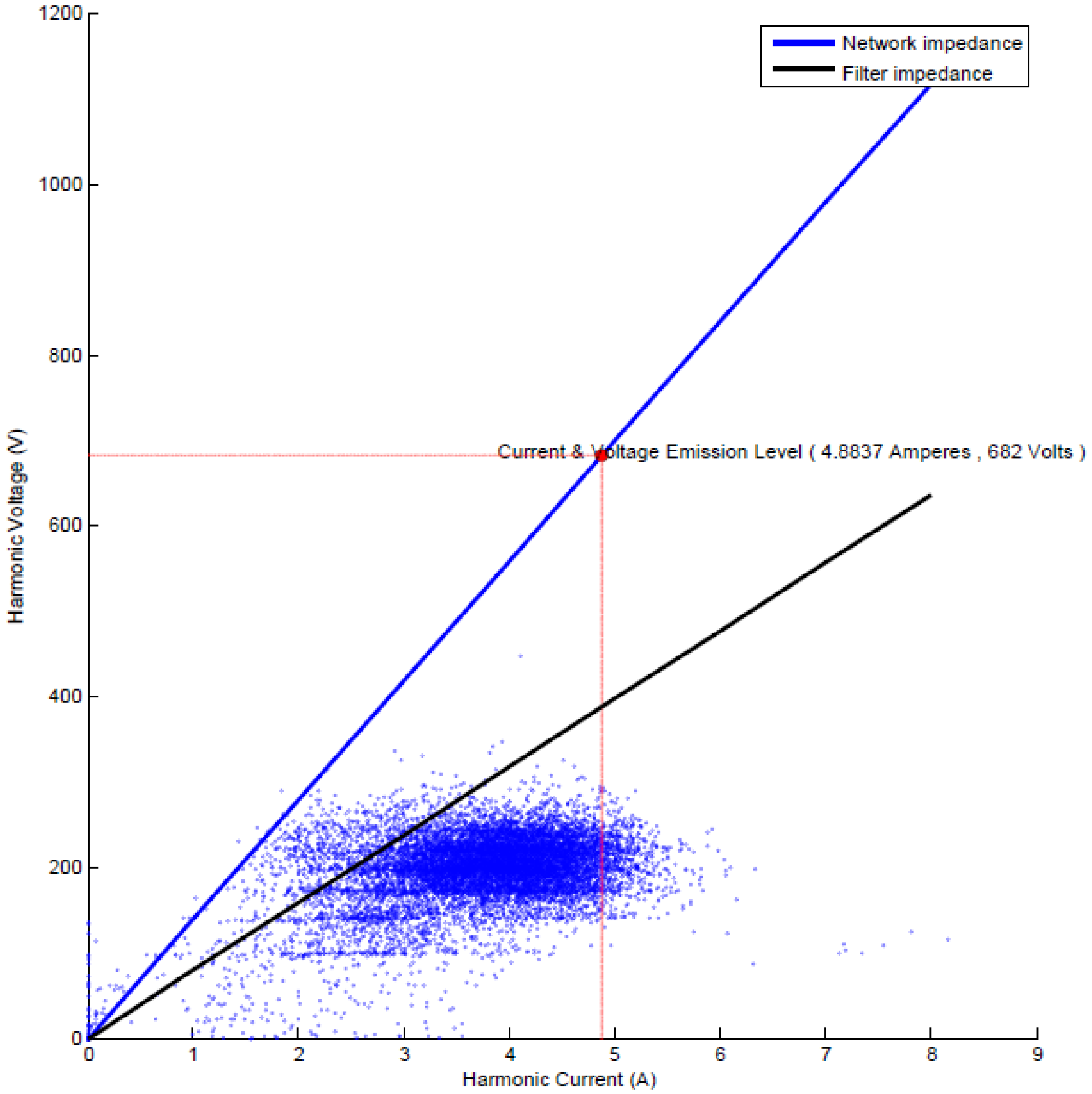


Figure A. 32 35th harmonic voltage vs current

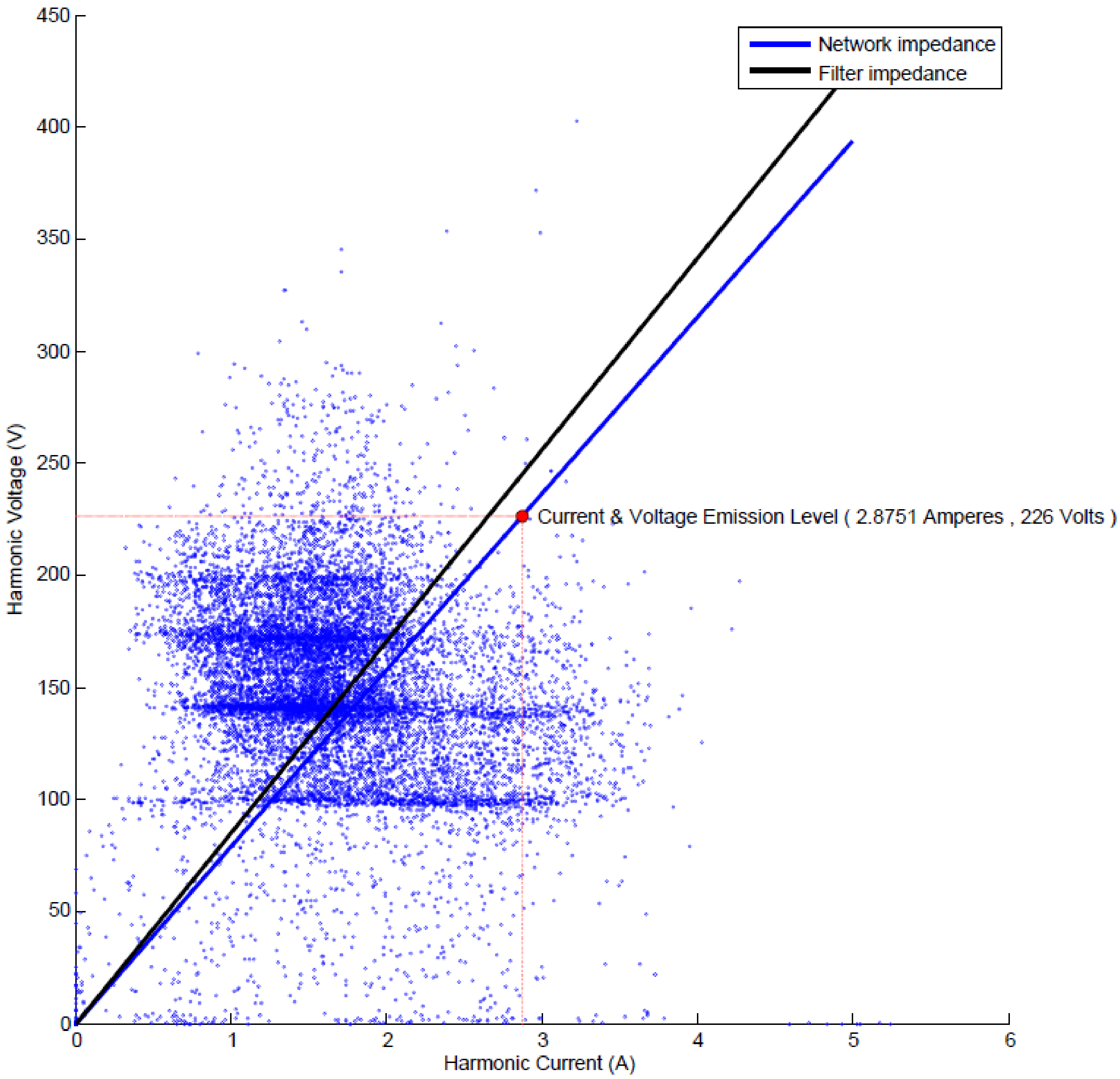


Figure A. 33 37th harmonic voltage vs current

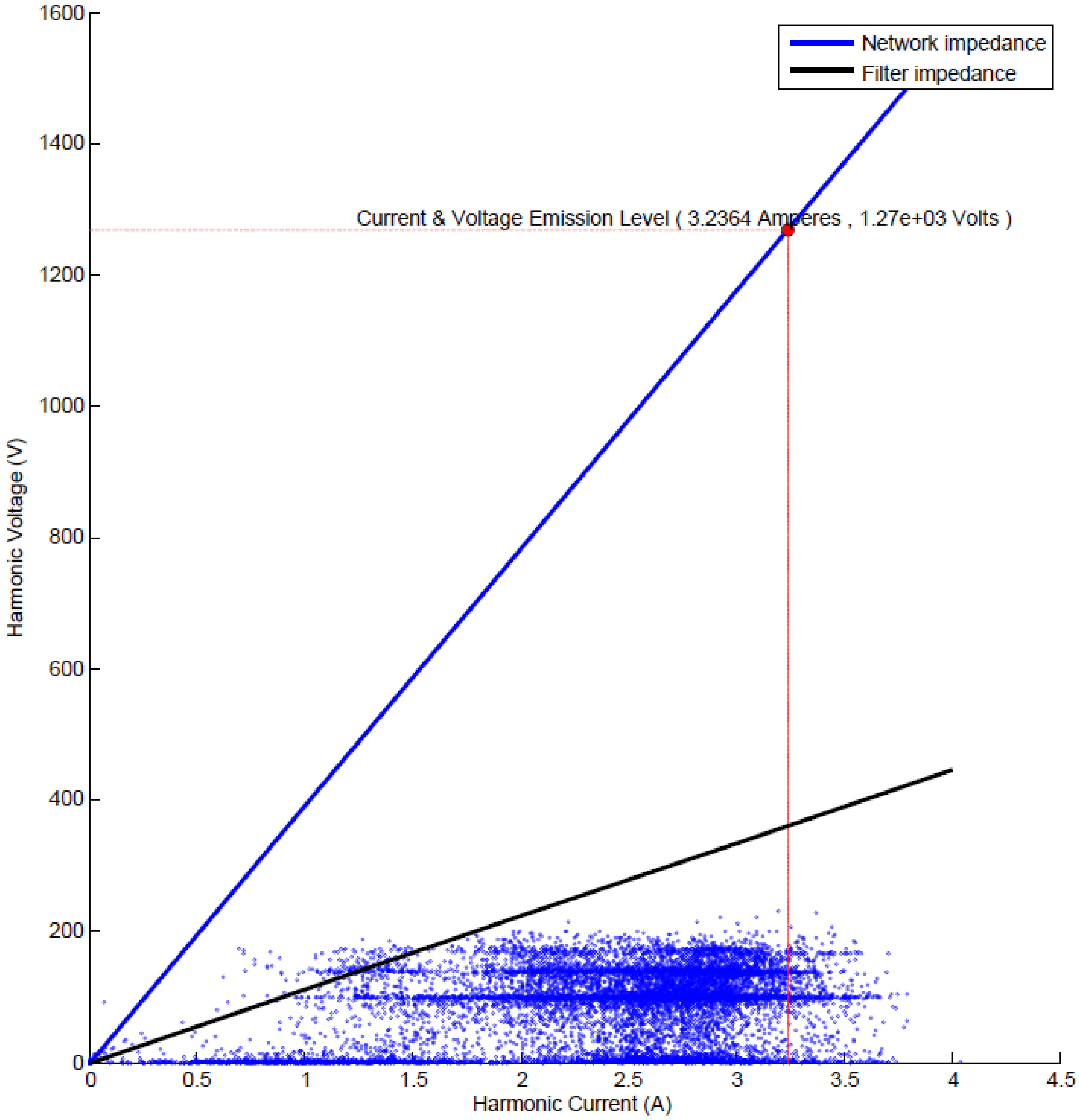


Figure A. 34 47th harmonic voltage vs current

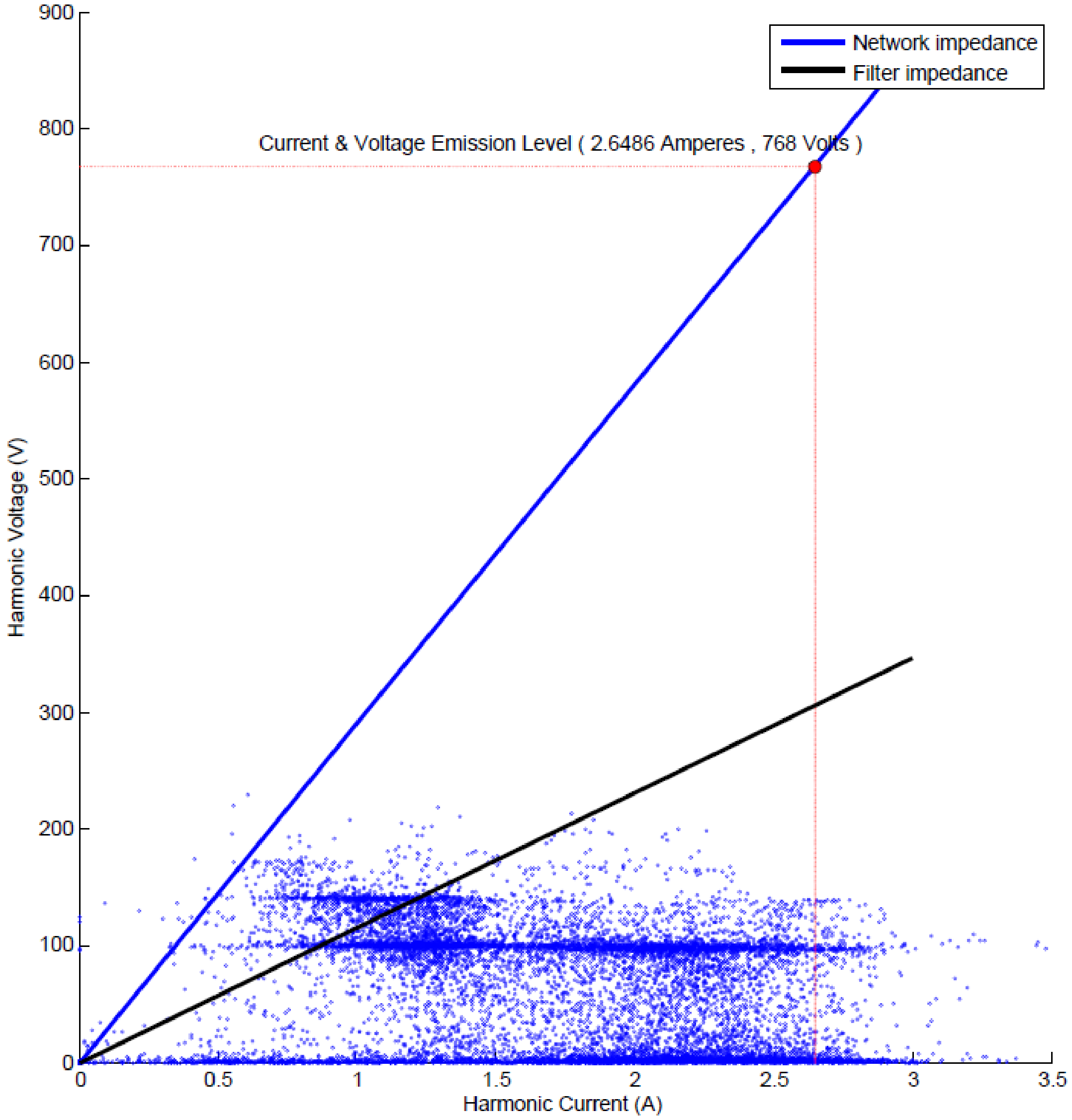
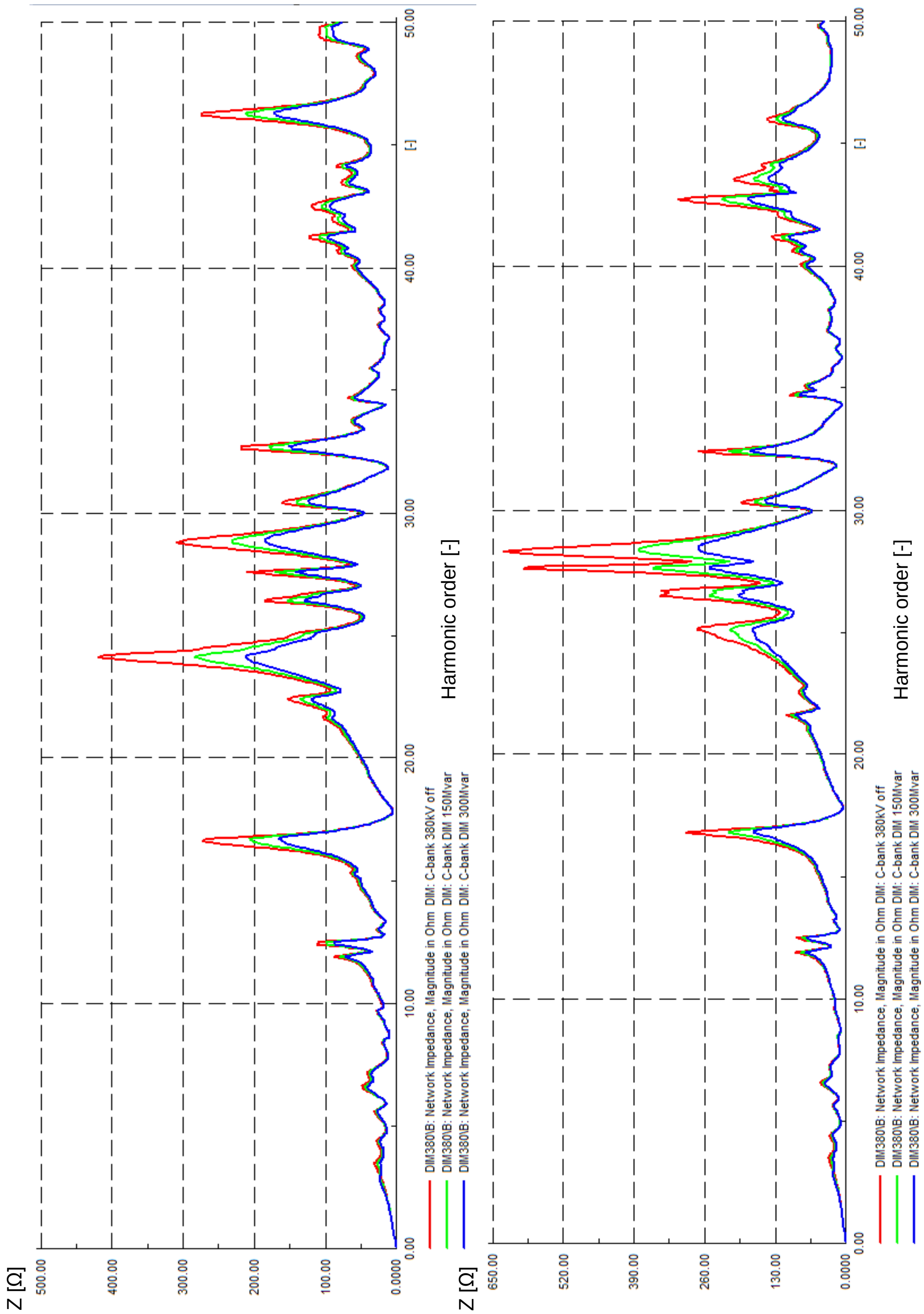


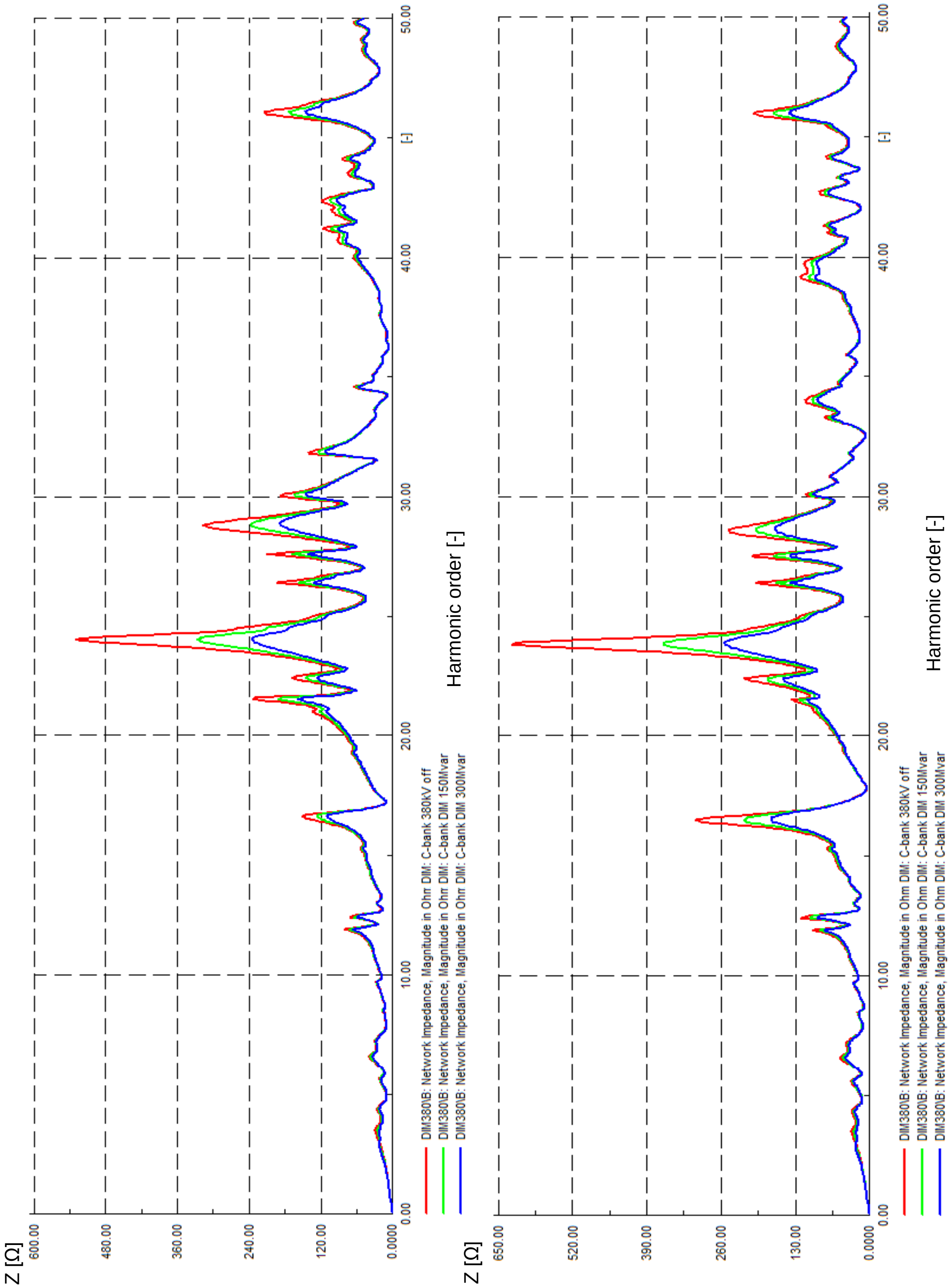
Figure A. 35 49th harmonic voltage vs current

11 Appendix B – additional information for capacitor banks



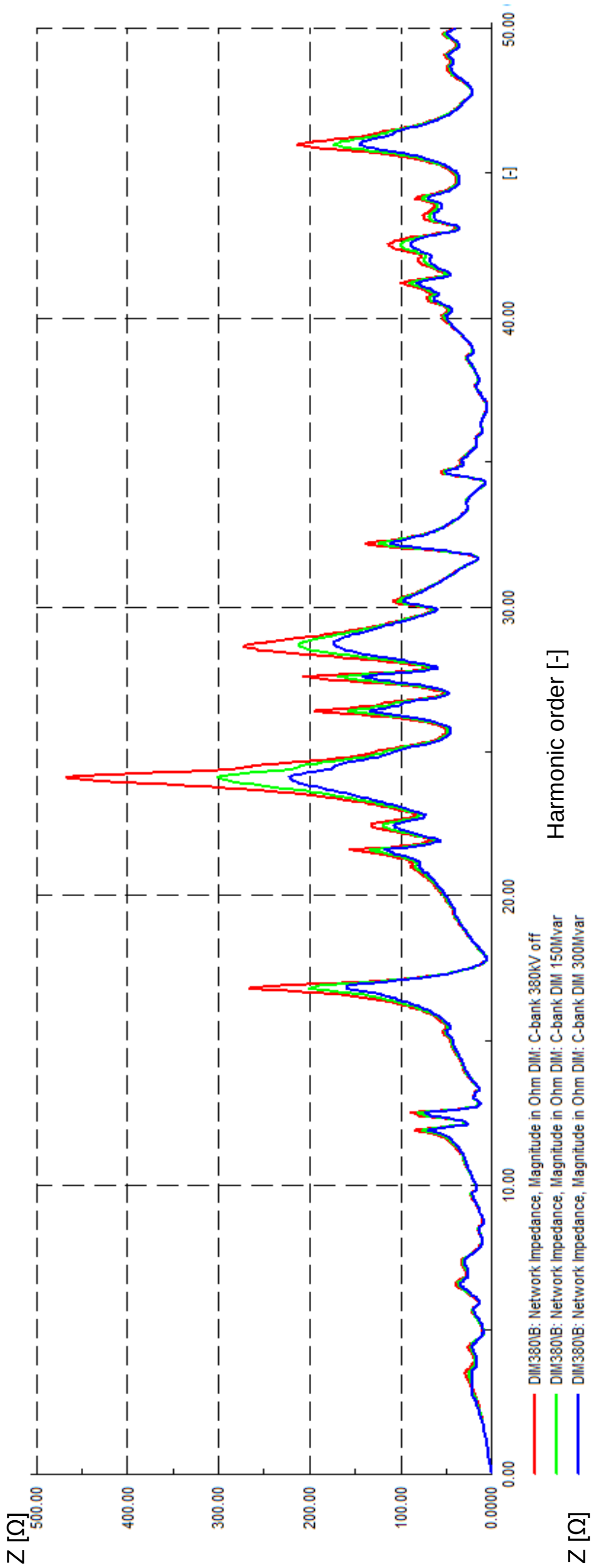
(a) **(b)**

Figure A. 36 Harmonic impedance at substation Diemen: no capacitor banks connected (red), single bank connected (green) and both banks connected (blue); (a) case I, (b) case II

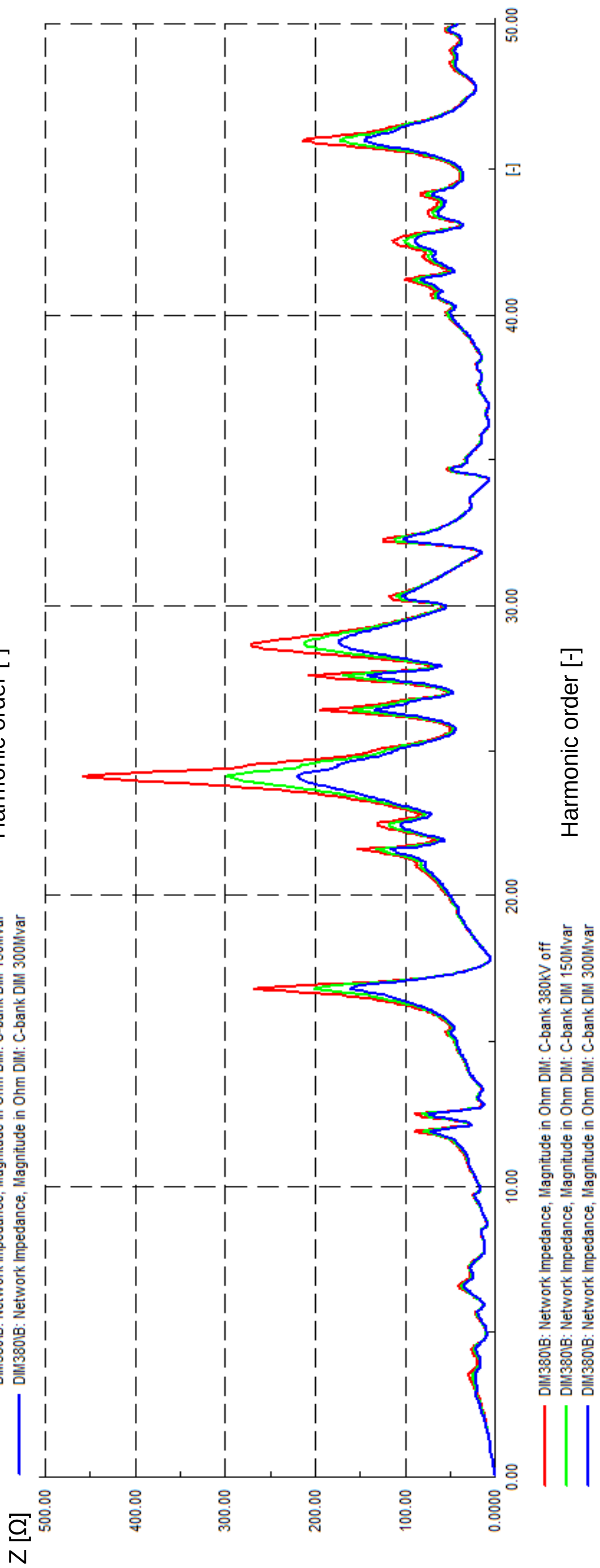


(a) (b)

Figure A. 37 Harmonic impedance at substation Diemen: no capacitor banks connected (red), single bank connected (green) and both banks connected (blue); (a) case III, (b) case IV

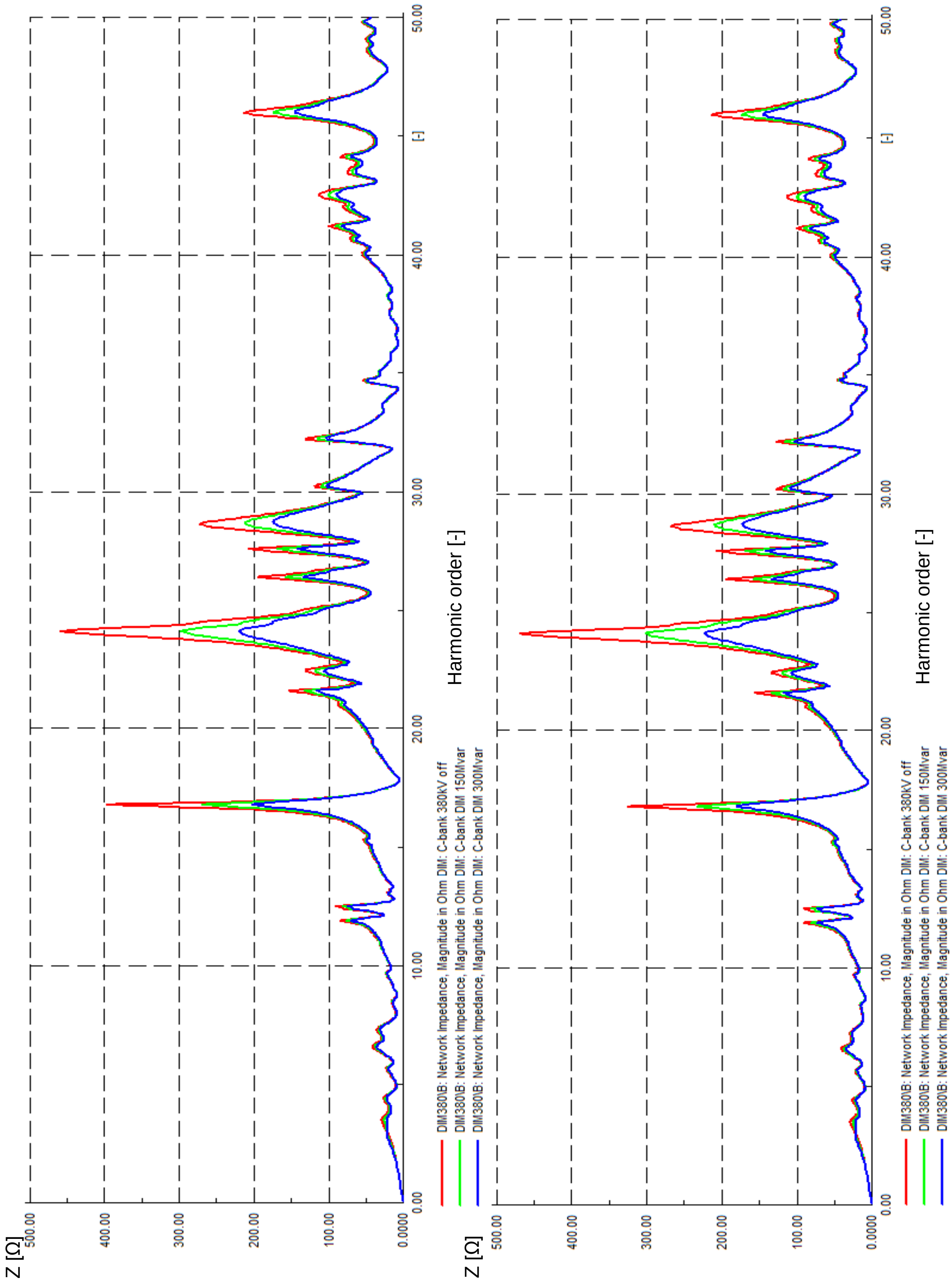


(a)



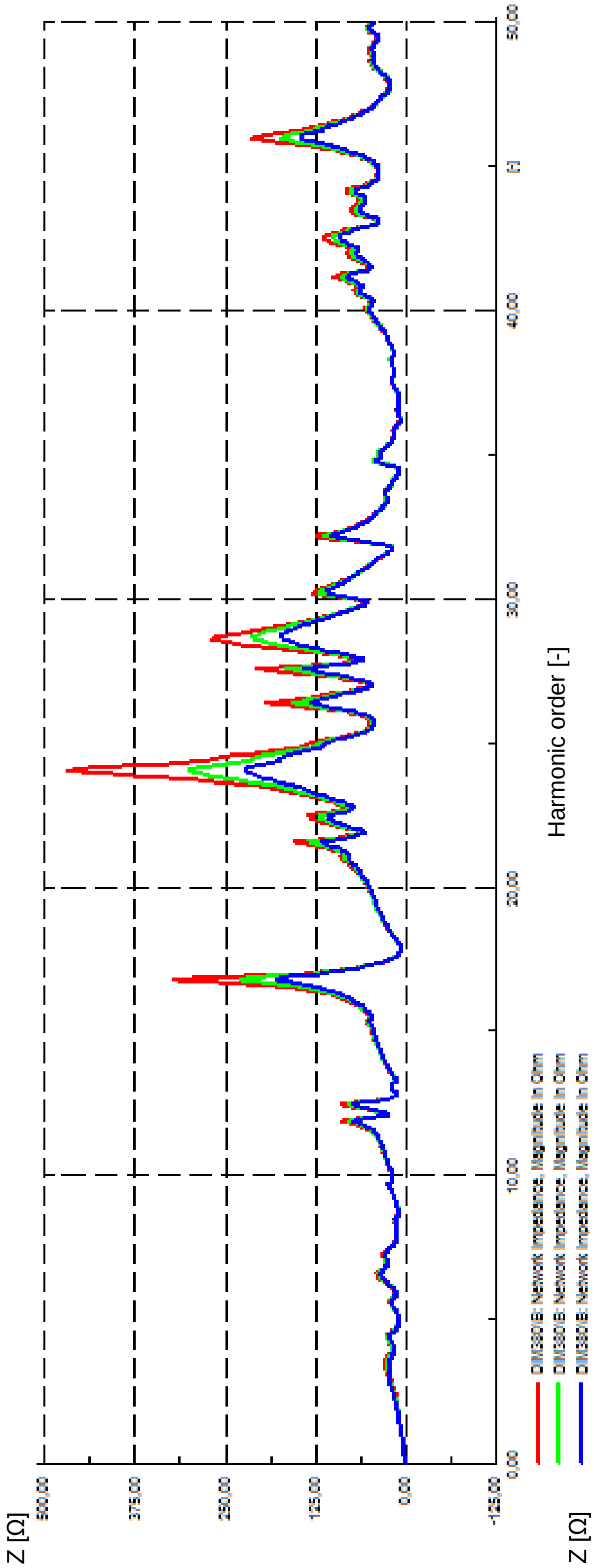
(b)

Figure A. 38 Harmonic impedance at substation Diemen: no capacitor banks connected (red), single bank connected (green) and both banks connected (blue); (a) case V, (b) case VI

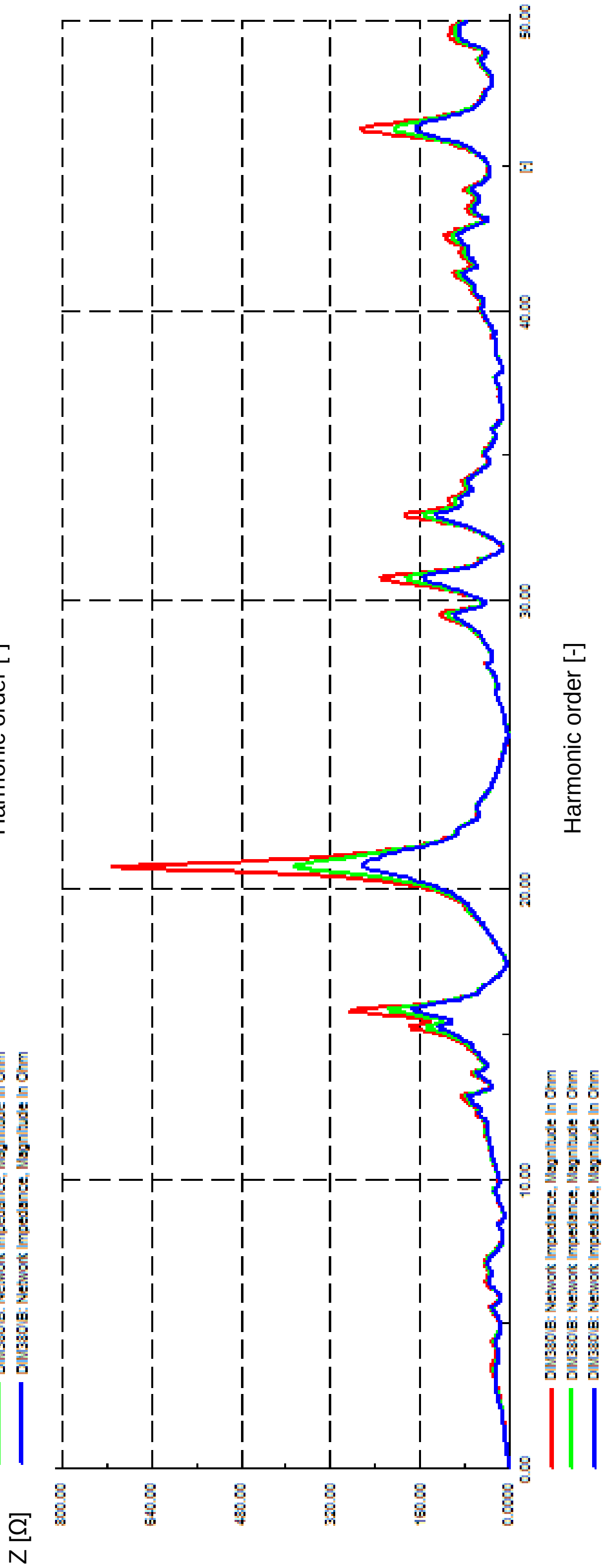


(a) (b)

Figure A. 39 Harmonic impedance at substation Diemen: no capacitor banks connected (red), single bank connected (green) and both banks connected (blue); (a) case VII, (b) case VIII



(a)



(b)

Figure A. 40 Harmonic impedance at substation Diemen: no capacitor banks connected (red), single bank connected (green) and both banks connected (blue); (a) case IX, (b) case XX

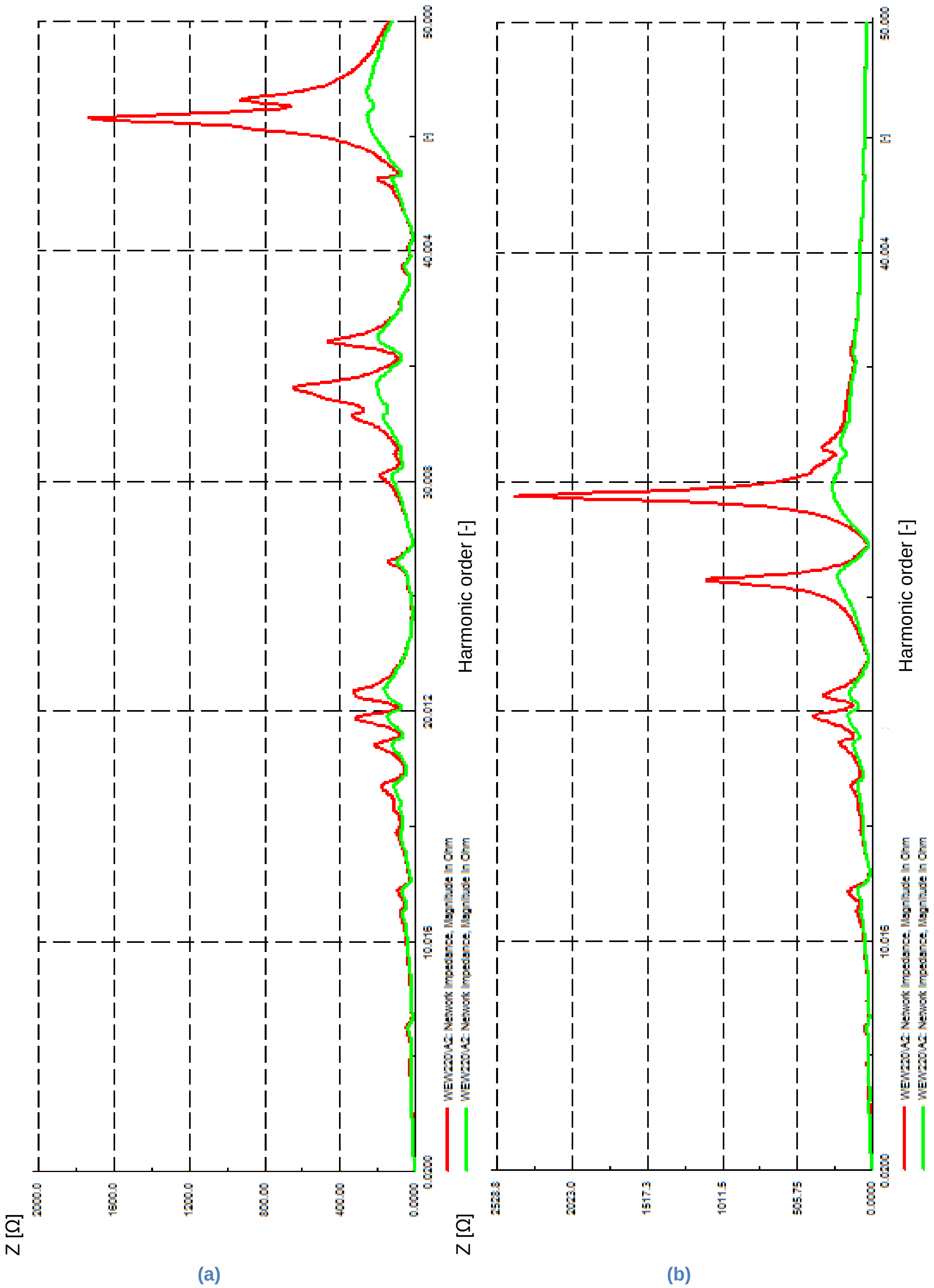
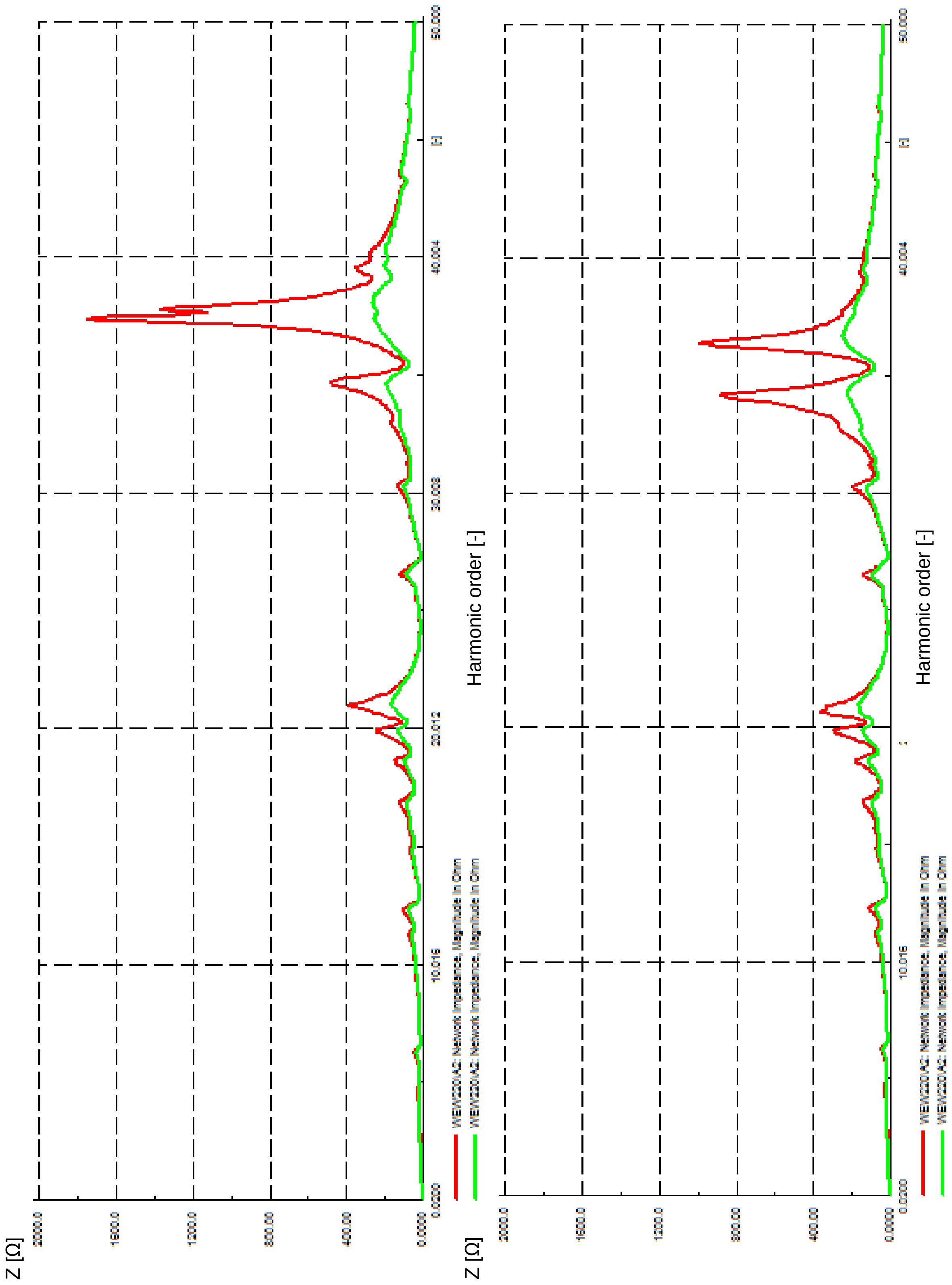
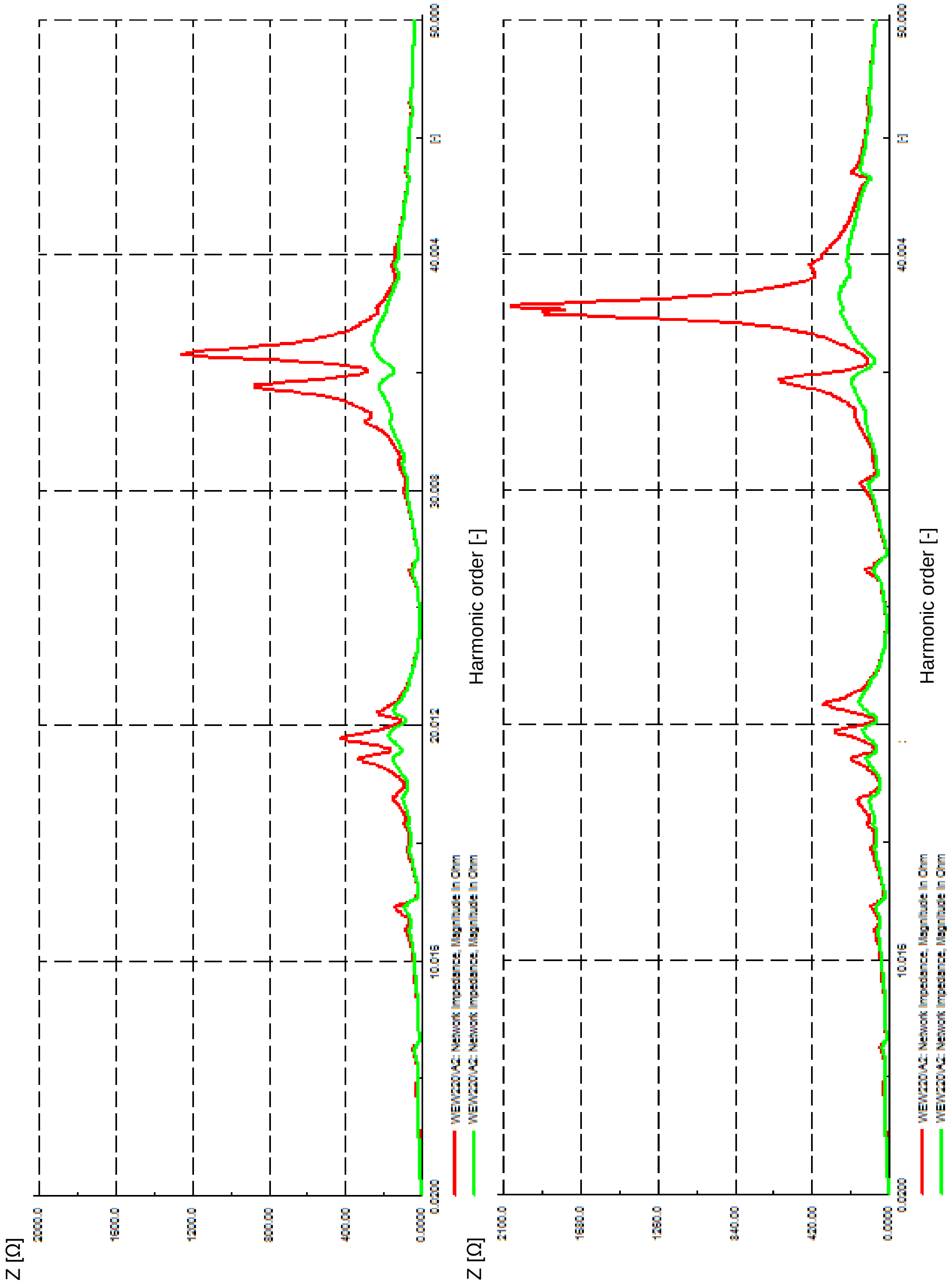


Figure A. 41 Harmonic impedance at substation Weiwerd: no capacitor banks connected (red), single bank connected (green); (a) case XXXI, (b) case XXXII



(a) (b)

Figure A. 42 Harmonic impedance at substation Weiwerd: no capacitor banks connected (red), single bank connected (green); (a) case XXXIII, (b) case XXXIV



(a) (b)

Figure A. 43 Harmonic impedance at substation Weiwerd: no capacitor banks connected (red), single bank connected (green); (a) case XXXV, (b) case XXXVI

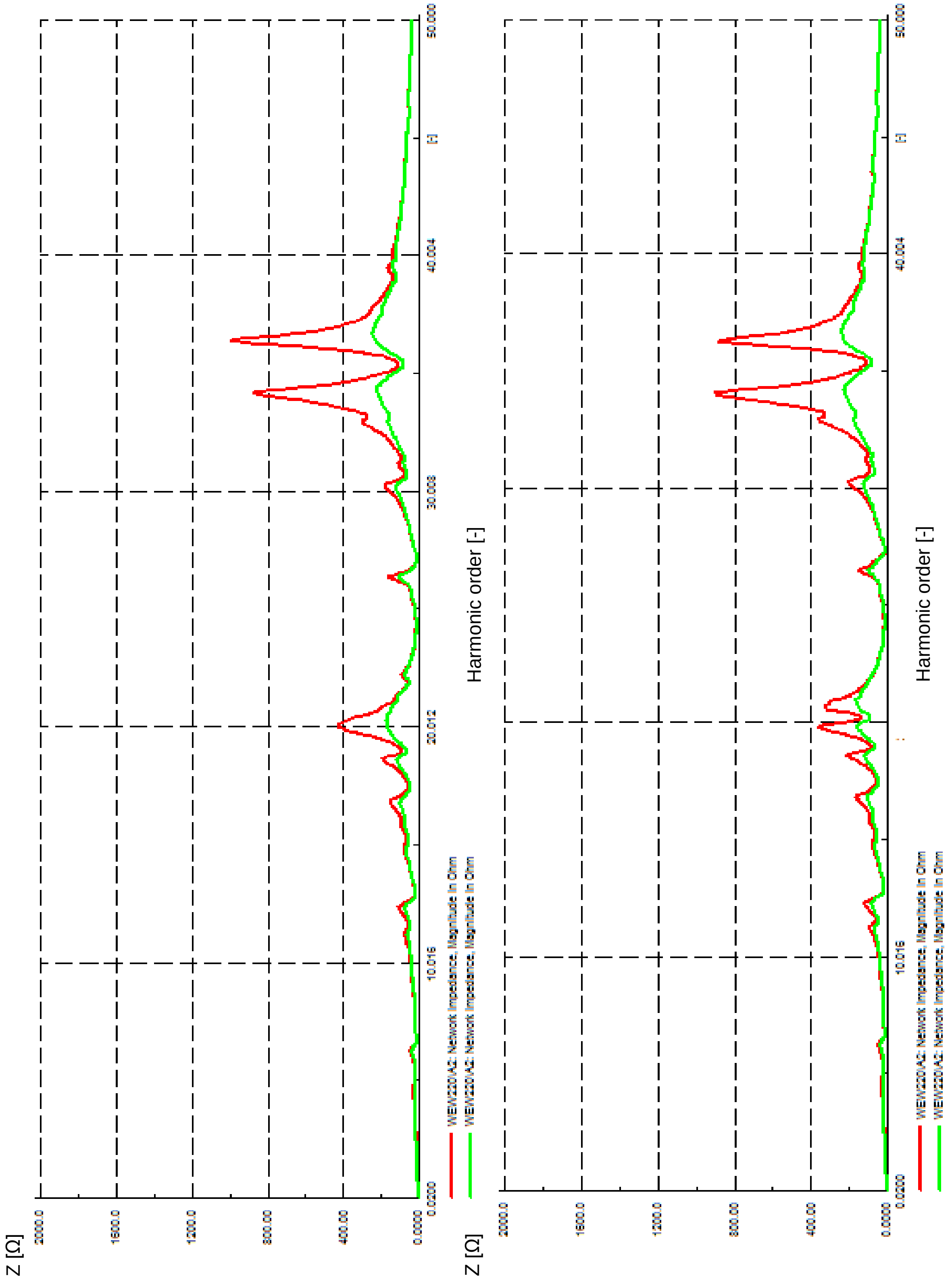
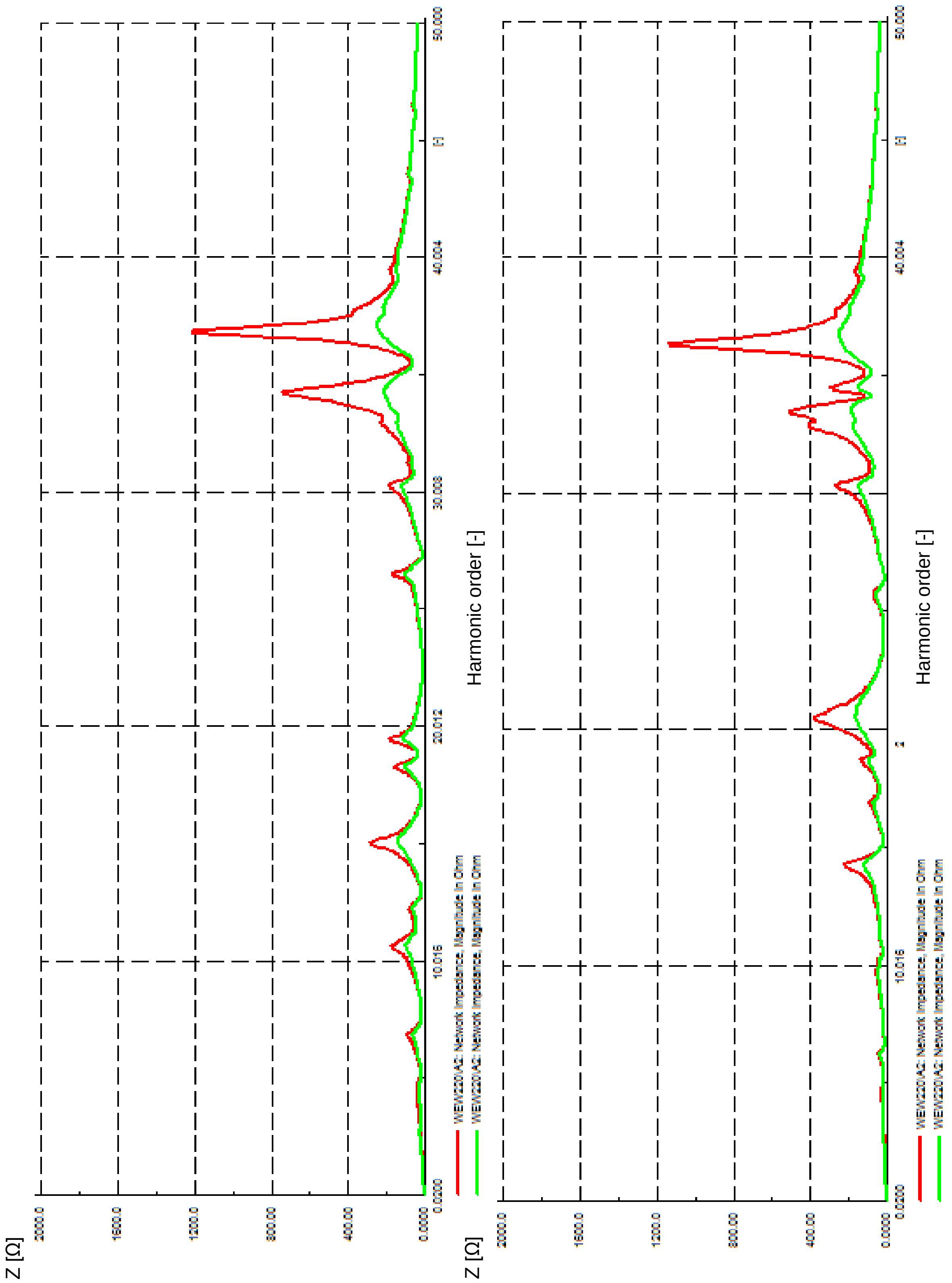
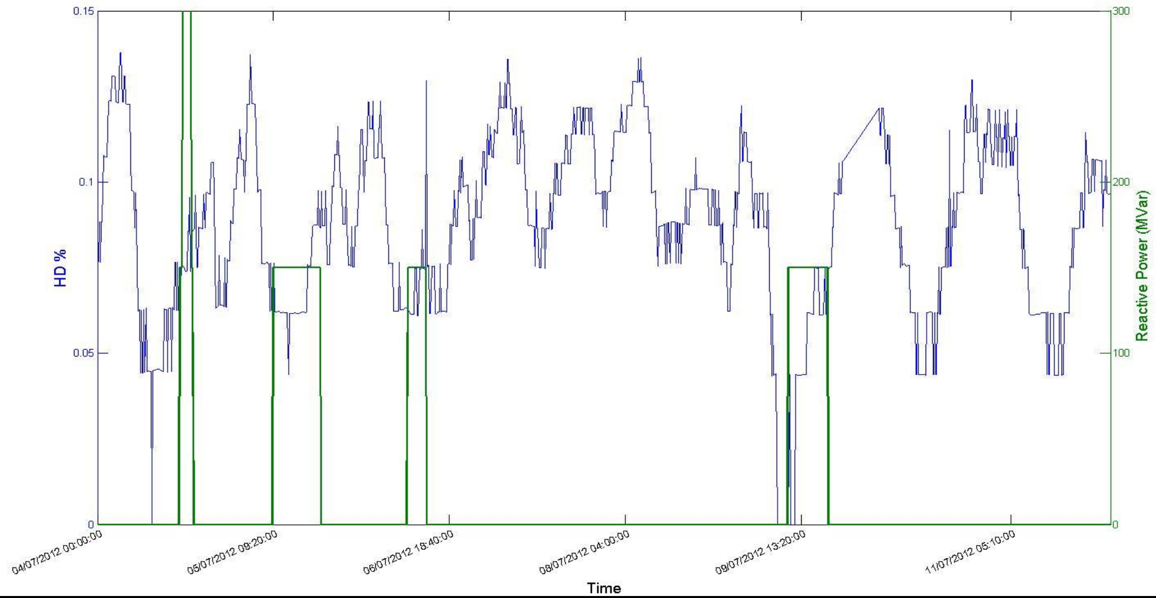


Figure A. 44 Harmonic impedance at substation Weiwerd: no capacitor banks connected (red), single bank connected (green); (a) case XXXVII, (b) case XXXVIII

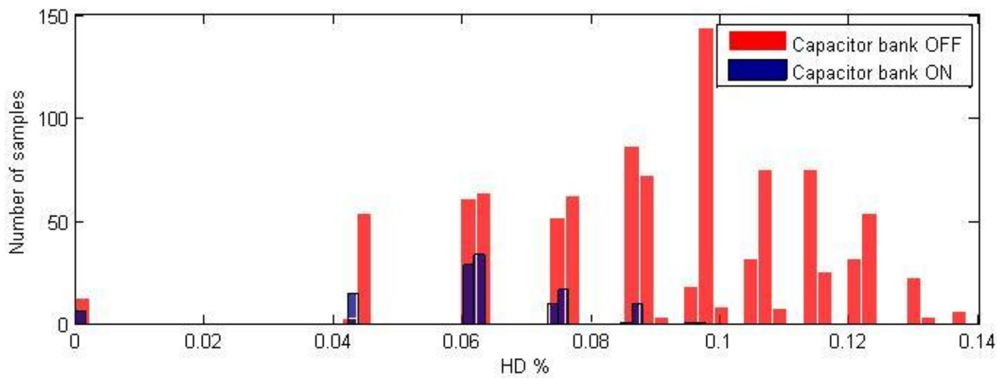


(a) (b)

Figure A. 45 Harmonic impedance at substation Weiwerd: no capacitor banks connected (red), single bank connected (green); (a) case XXXIX, (b) case XL

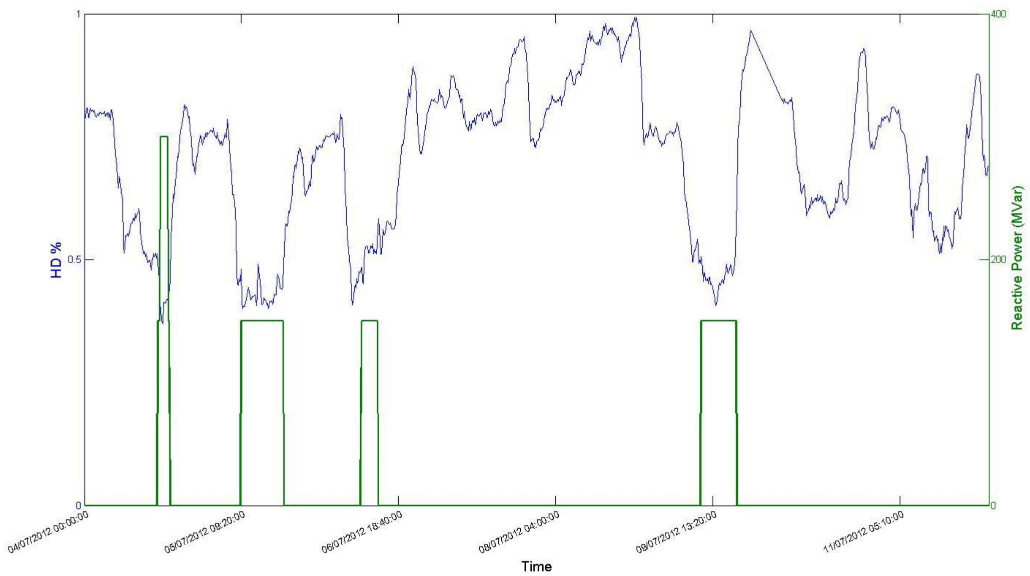


(a)

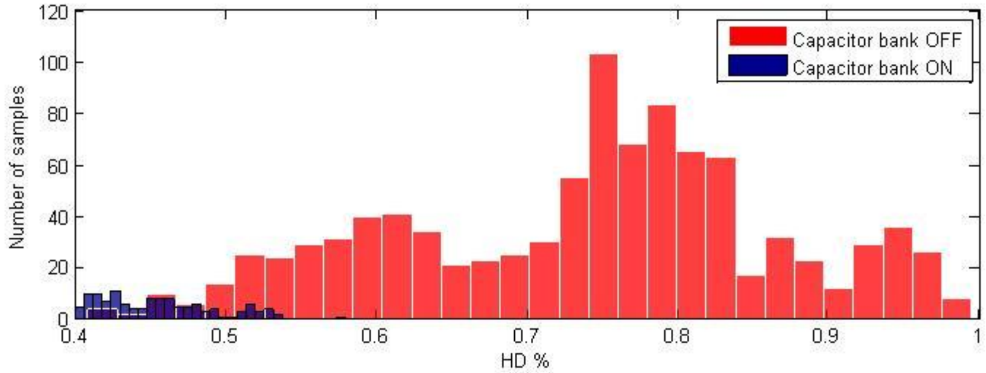


(b)

Figure A. 46 Influence of capacitor bank operation on the 3rd harmonic voltage in substation Diemen: (a) time changes, (b) histogram

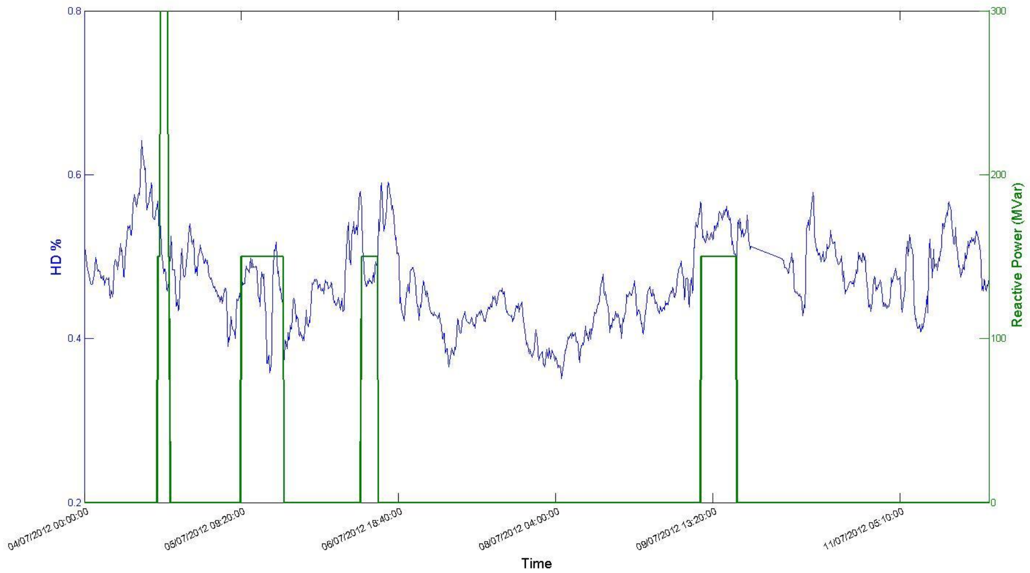


(a)

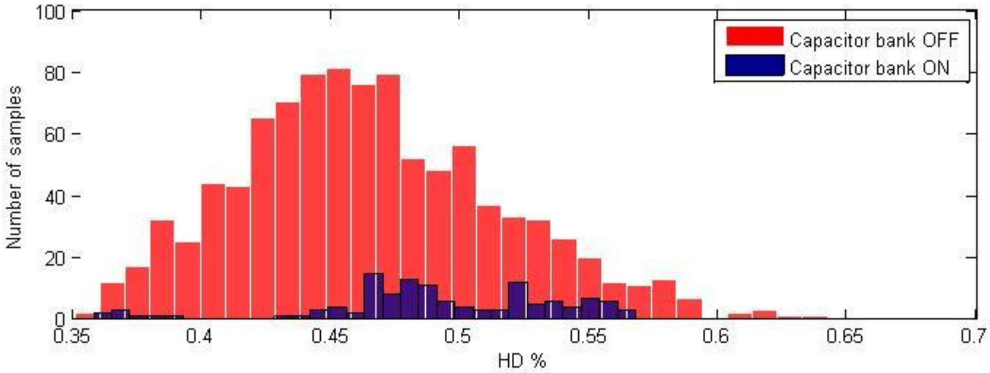


(b)

Figure A. 47 Influence of capacitor bank operation on the 5th harmonic voltage in substation Diemen: (a) time changes, (b) histogram

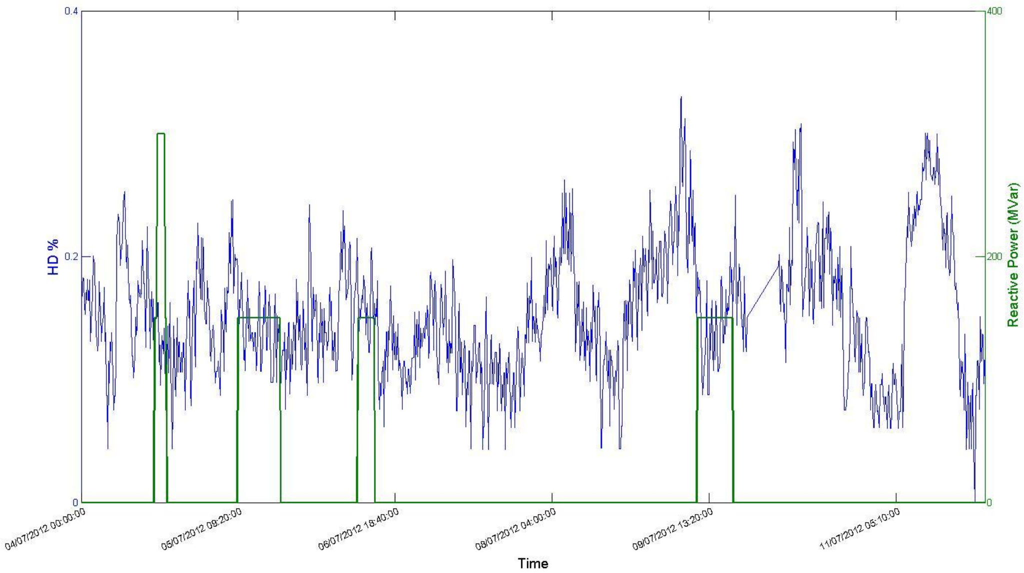


(a)

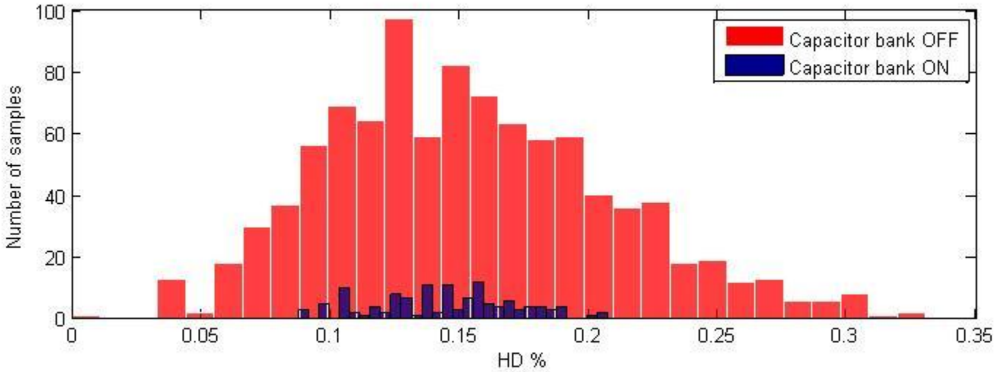


(b)

Figure A. 48 Influence of capacitor bank operation on the 7th harmonic voltage in substation Diemen: (a) time changes, (b) histogram

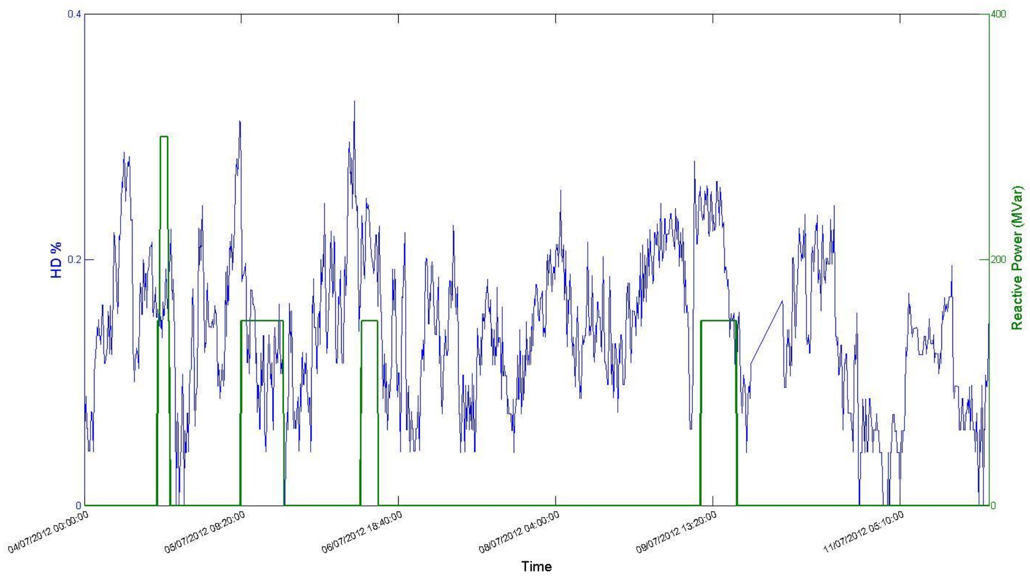


(a)

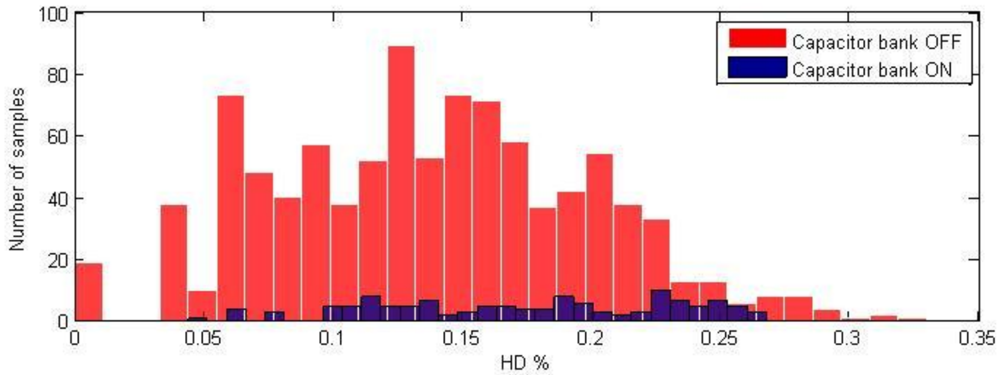


(b)

Figure A. 49 Influence of capacitor bank operation on the 11th harmonic voltage in substation Diemen: (a) time changes, (b) histogram

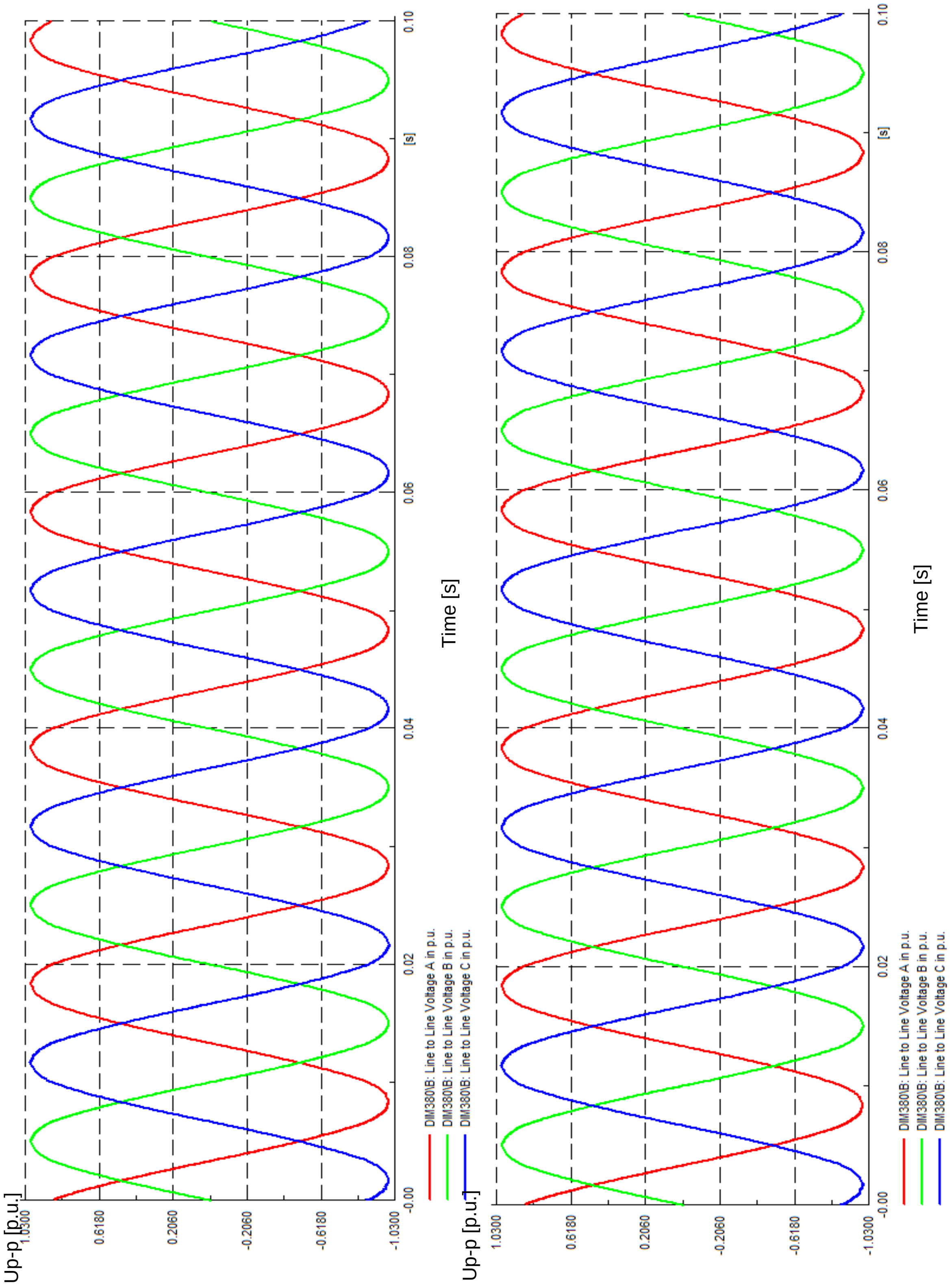


(a)



(b)

Figure A. 50 Influence of capacitor bank operation on the 13th harmonic voltage in substation Diemen: (a) time changes, (b) histogram



(a) (b)

Figure A. 51 Simulated transient at substation Diemen using synchronous switching, energisation of the: (a) first bank, (b) second bank; Line-to-Line voltages $U_{p\text{-}p}$

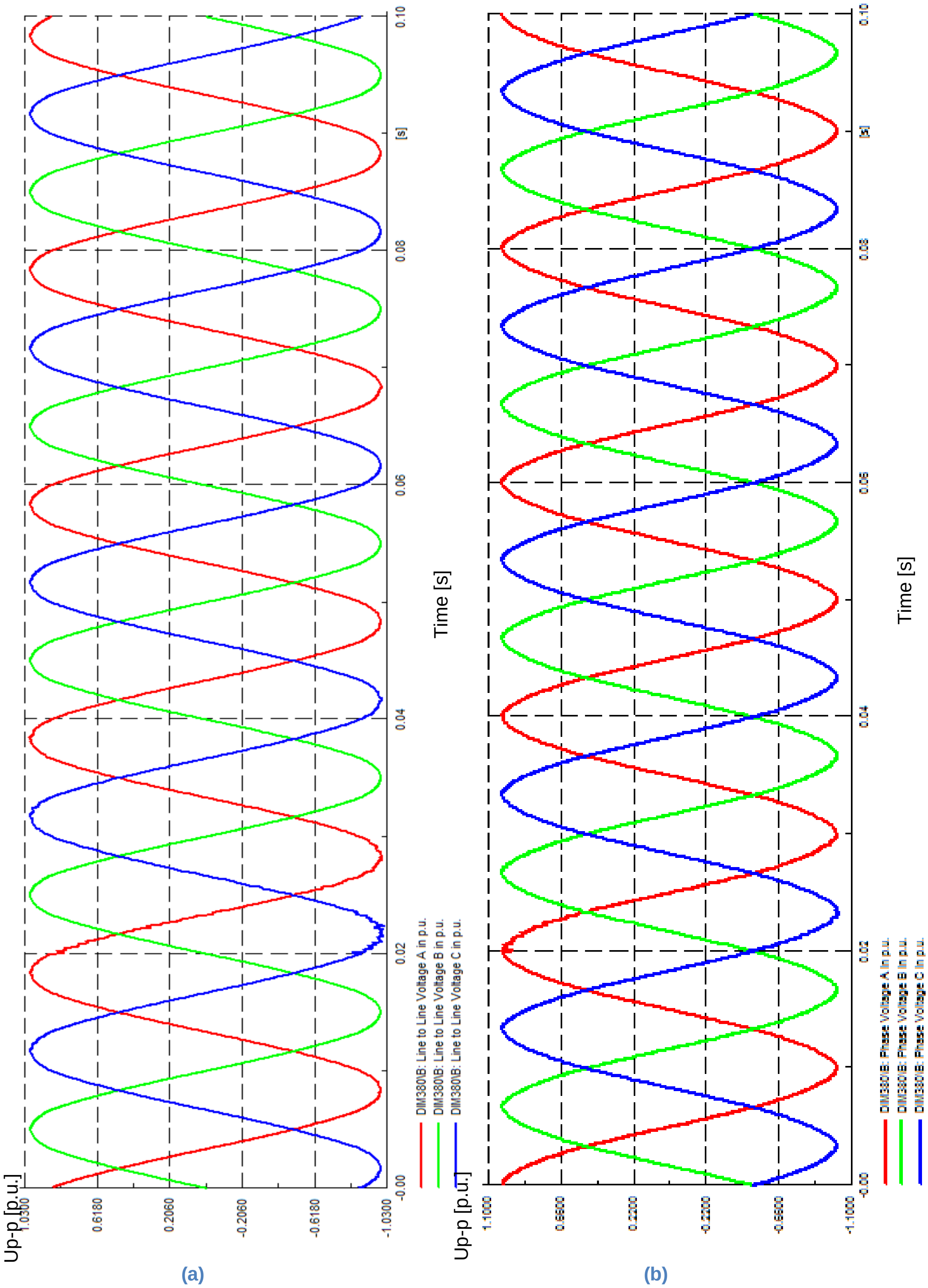
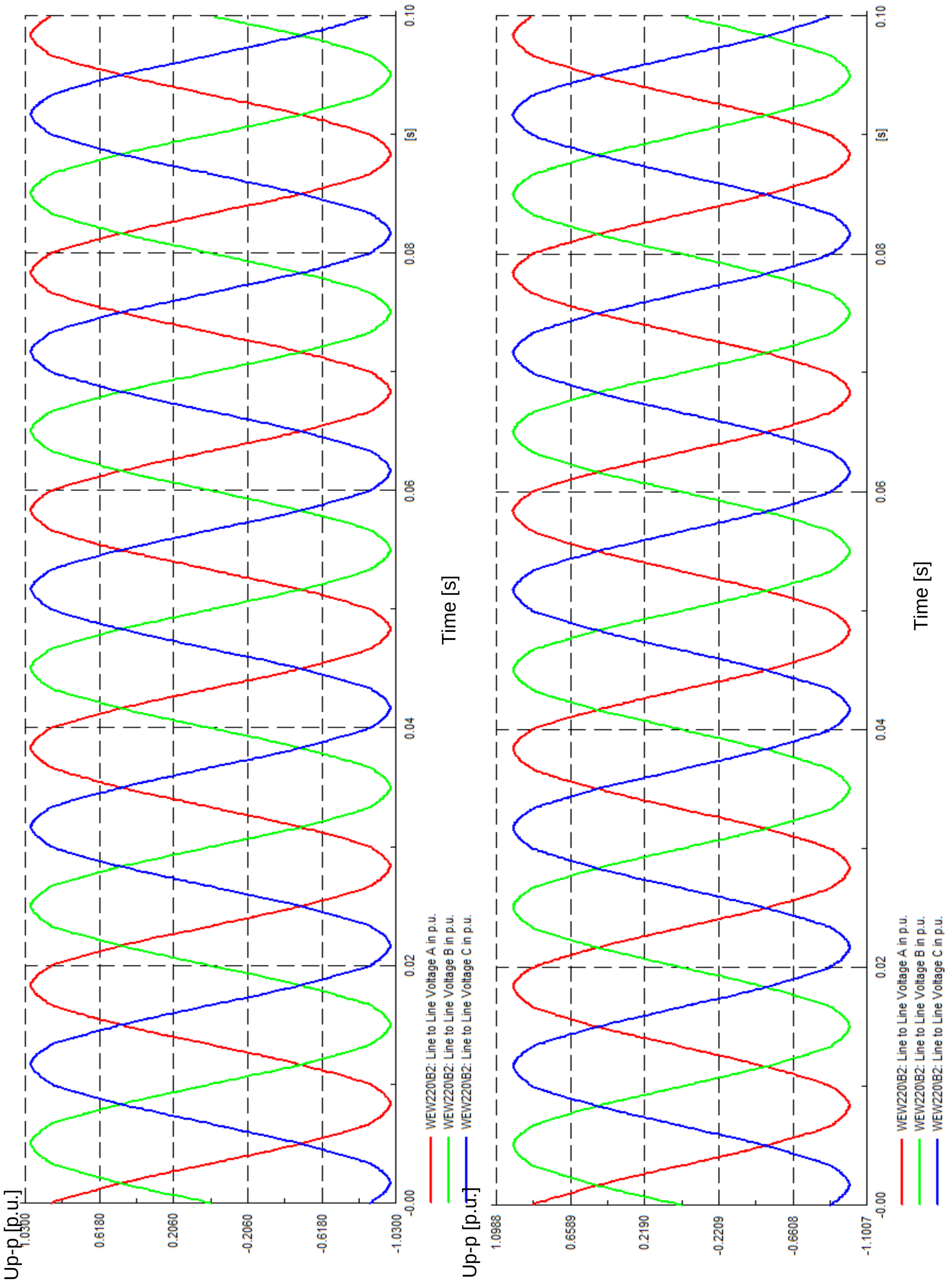


Figure A. 52 Simulated transient at substation Diemen without synchronous switching – worst case of phase A; energisation of the: (a) first bank, (b) second bank; Line-to-Line voltages U_{p-p}



(a) (b)

Figure A. 53 Simulated transient at substation Weiwerd; energysation of the capacitor bank; Line-to-Line voltages U_{p-p}; (a) with synchronous switching, (b) without synchronous switching – worst case of phase A

12 Appendix C – additional information for the 380 kV cable

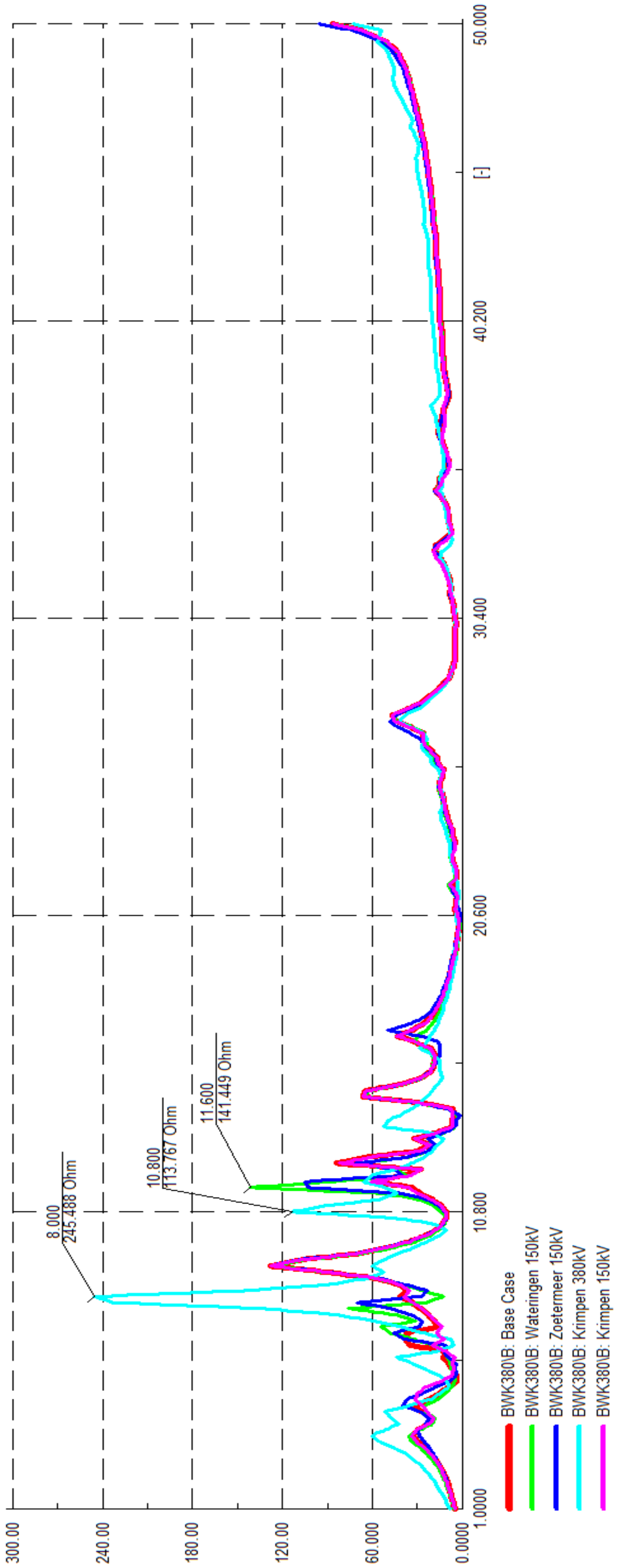


Figure A. 54 Harmonic impedance Z (Ω) as a function of the harmonic order in Bleiswijk for the cases I, VII – X, according to Table 19

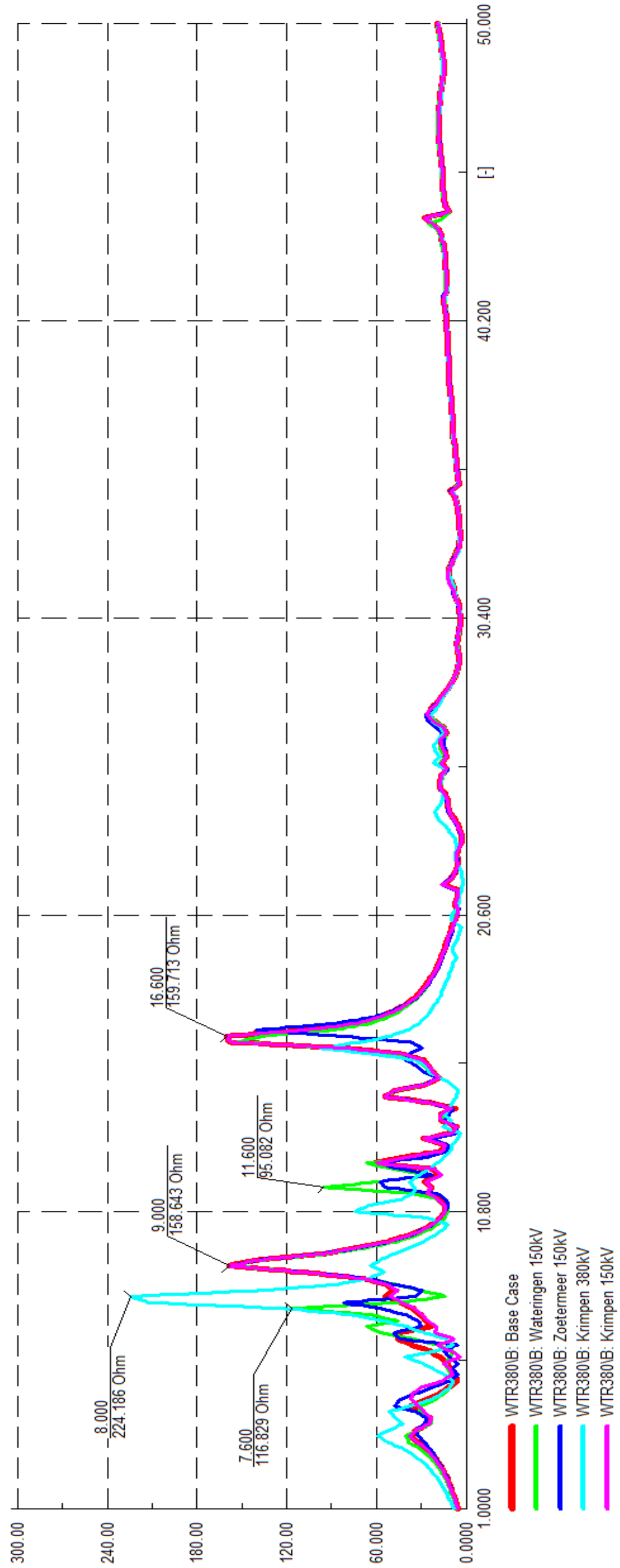


Figure A. 55 Harmonic impedance Z (Ω) as a function of the harmonic order in Wateringen, according to Table 19

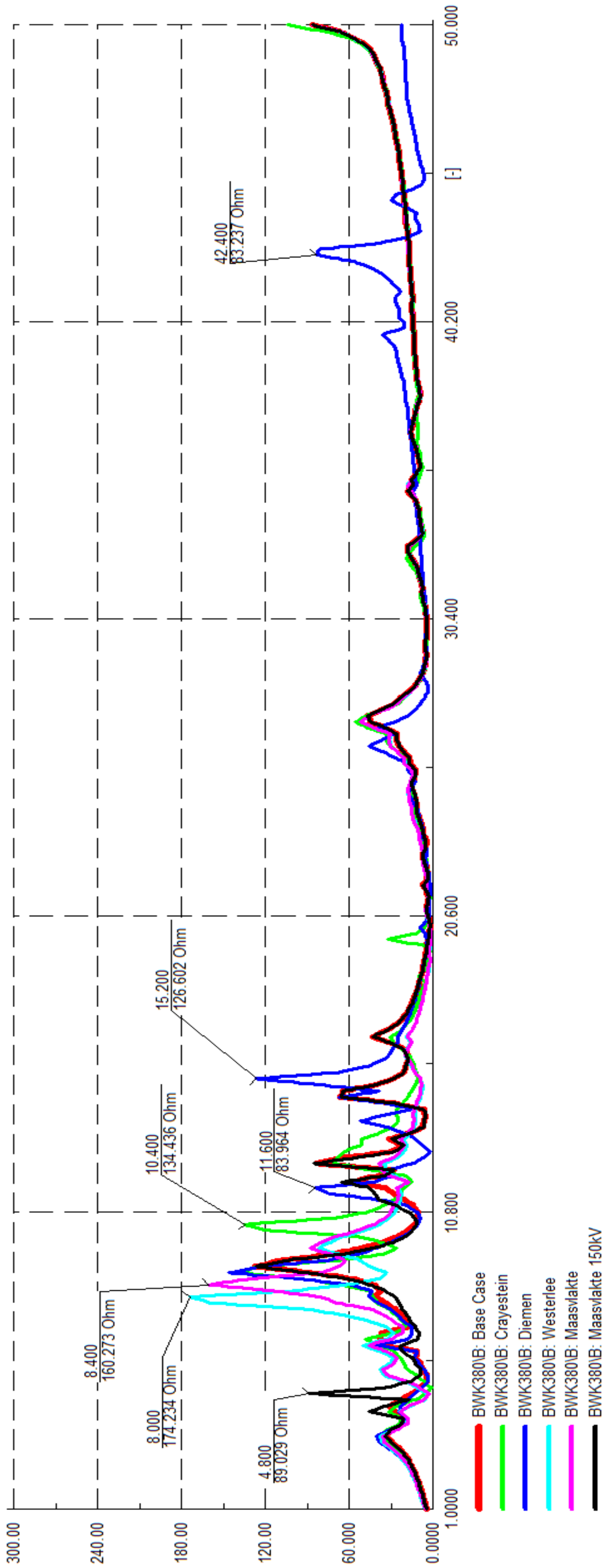


Figure A. 56 Harmonic impedance Z (Ω) as a function of the harmonic order in Bleiswijk for the cases I, XI – XV, according to Table 19

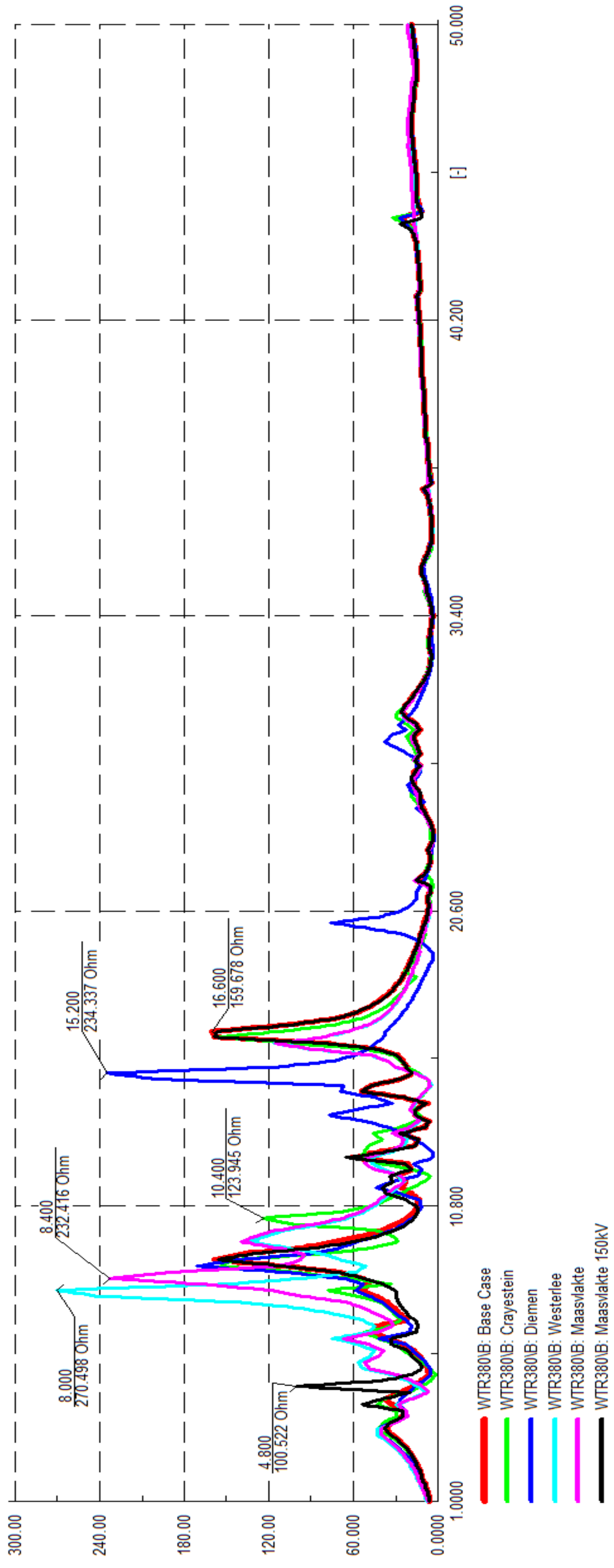


Figure A. 57 Harmonic impedance Z (Ω) as a function of the harmonic order in Wateringen for the cases I, XI - XV, according to Table 19