A new method to assess harmonic grid congestion in MV-networks

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ABSTRACT

To perform more accurate calculations to assess harmonic pollution in MV grids, a new method is proposed to fine-tune a simulation model. The method uses the calculation of harmonic power levels for all MV feeders and HV/MV transformers based on measurements done in the field. A case study has been done to evaluate the method.

INTRODUCTION

Some regions experience the introduction of rapidly expanding industries. Though these installations individually comply with the standards, because of poor filtering, simultaneous operation provokes a general harmonic problem in the MV grid. Negotiations with the customers to install harmonic filters, following the regulation guidelines, lead to different opinions on the 'honest' share of the burden. Sometimes installing a harmonic filter might shift the problem to higher frequencies.

In these situations, it is not always clear which client/feeder is the victim or the producer of harmonics. The behavior can even differ from one harmonic frequency to another, and is variable in time. A pragmatic way of objectively presenting the situation in the discussions with the client is hence most desirable. Next to that, a software model which allows to reproduce the real situation and assess future case scenarios is also needed to evaluate the impact of possible mitigation solutions for the harmonic congestion.

The following presents a new method to answer the needs. Through a measurement campaign, it is feasible to determine the fundamental and harmonic phasors of voltages and currents. The measurements are done simultaneously at the HV/MV transformer, and at all the MV feeders involved. Next, the fundamental and harmonic powers are calculated. It allows to identify which feeders/clients are contributing to the problem compared to others. In a next step, the measurements can be used to enhance a NEPLAN simulation model to be able to reproduce the real situation, as well as investigate future scenarios.

HARMONIC MEASUREMENT CAMPAIGN

In order to analyze the repartition of harmonic pollution, a measurement campaign was conducted in cooperation with the DNO during two weeks. The measurements were done at a substation in Belgium. An overview of the structure of the substation is given in Figure 1. Two HV/MV transformers feed a double busbar system. The two busbars are normally not coupled. The largest industrial site is separated from the other feeders and supplied by transformer 2 present at the substation. On the other busbar, two residential feeders as well as two other industrial sites are present, and supplied by transformer 1. A capacitor bank is present at the substation. The voltage level at MV is 15 kV, at HV it is 70 kV.

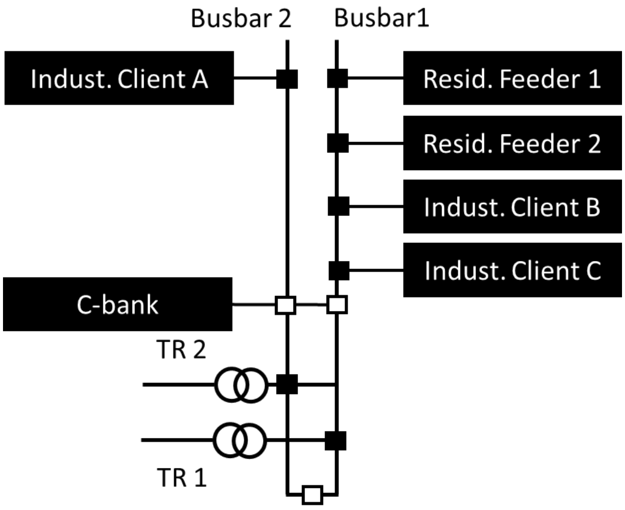

Figure 1: Overview of the substation

A two-week measurement campaign was conducted, employing IEC61000-4-30 class A measurement equipment. Next to that, during the whole duration of the measurement campaign, the full waveform was sampled.
At the MV busbar, the voltages of both busbars were sampled, as well as all currents of the three phases of the feeders and the transformers. At the HV side of both HV/MV busbar, an HV busbar was present, where voltage measurements were also conducted and current measurements of the HV/MV transformers.
Some feeders consist of multiple cable bundles where, for practical reasons, only one cable bundle was measured. Equality in power flow in the other cable bundles is assumed.
Next to that, during the measurement campaign, some operations were conducted by the DNO to see the influence on the harmonic pollution. During a two-hour period, the capacitor bank was connected to busbar 2, and sometime later the busbar coupler was closed. The effect

on the total harmonic distortion of the voltage (THD) is shown in Figure 2. In normal situations, THD is about 5 % at the MV level. It can be seen from this that switching on the capacitor bank on busbar 2 increases the THD from 5 % to 9 % at busbar 2, while also raising the THD at the HV grid from 2.5 % to 3 %. Closing the coupler of both busbars slightly decreases pollution on both busbars.

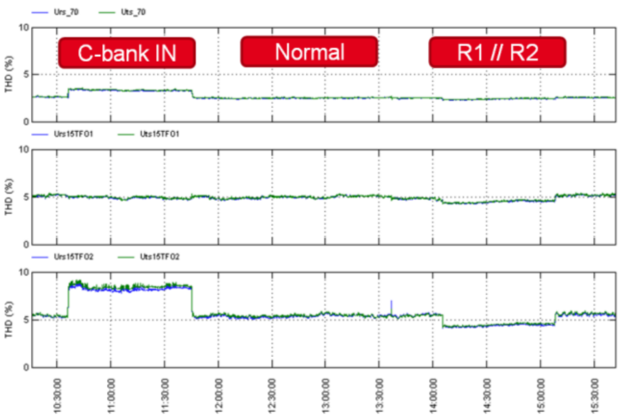

Figure 2: Measured THD during operations: THD at HV level (top), THD busbar 1 (middle), THD busbar 2 (bottom)

In a next step, all harmonic components in the waveform were calculated, based on 200 ms averages. In principal, the 5th, 7th, 11th and 13th harmonic form about 90 % of the harmonic energy. These results were used to calculate the harmonic power levels, by multiplying harmonic current phasors with harmonic voltage phasors. For each harmonic, the equivalent harmonic active and reactive power are presented in a bar graph, next to the resulting measurement error. This is shown in Figure 3, as an example during normal operation for the 5th harmonic. Summing feeder powers and transformer powers should result in a zero result according to Kirchoff's law. The summation results are shown by the blue bars in the figure.

In general, the resulting error increases for higher harmonics. For higher harmonics, the measured levels decrease. This is because current measurements using current clamps become less. Secondly, the industrial sites, depicted in Figure 1, are in reality fed by multiple parallel cable bundles. During the measurement campaign, only one bundle was measured, assuming an equal current distribution in all bundles. For higher harmonics, this introduces errors as well.

Another observation from the calculation of the harmonic powers is the fact that for some feeders the direction of harmonic power flow changes with the harmonic level. This is shown in Figure 4.

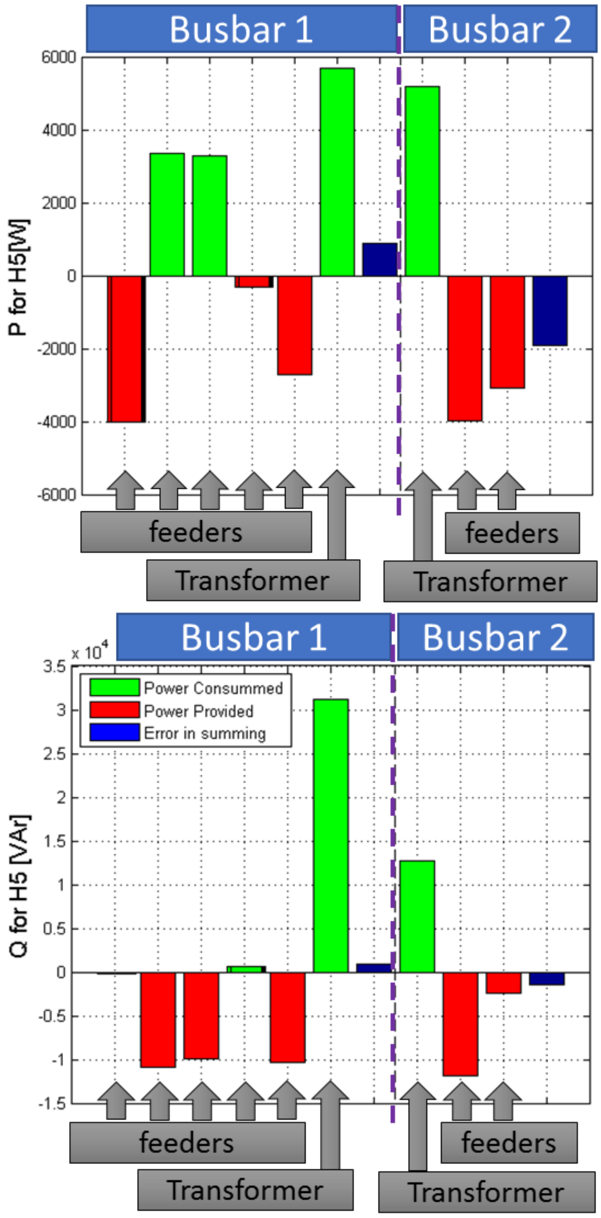

Figure 3: Harmonic Power Comparison (snapshot)

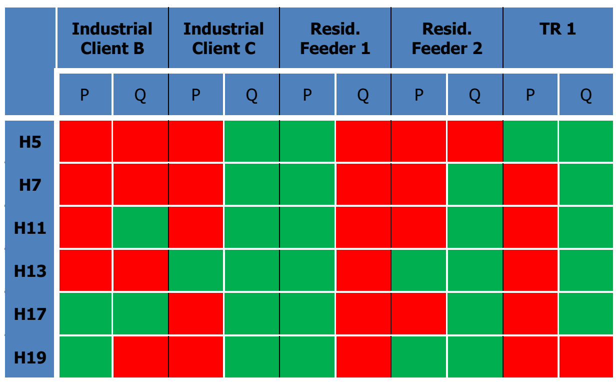

Figure 4: Busbar 1 - Harmonic Power flow direction: green indicates power consumption, red indicates power production

HARMONIC SIMULATION MODEL ADAPTATION

In this analysis, the MV grid was modelled in NEPLAN. The models are supplied and made by the DNO, and contain the HV/MV transformer, the MV busbar and all MV feeders. Each component (transformer, cables,…) contains the information required to perform a load flow calculation at 50 Hz. The frequency behaviour of the cable and transformer elements of the model are entered using the CIGRE method [1]. The software allows to enter this information for each frequency separately.

The model was altered to perform harmonic calculations and take into account the measurement of harmonic powers.

In a first step, the residential feeders were replaced by a single load connected to the busbar.

In a second step, on all feeders a harmonic source or a load was added to inject/absorb harmonic currents. To decide whether a feeder is consuming or producing harmonic current, the direction of harmonic power is used (as depicted in Figure 4). This way, the model is able to perform a loadflow calculation at 50 Hz as well as at higher frequencies. For each harmonic source or load, the current and the phase can be specified in the model for each harmonic component.

In a third step, the harmonic impedance of the HV/MV transformer was set to obtain the corresponding harmonic voltages at the busbar, compared to the results of the measurement campaign. The HV harmonic grid impedance was calculated using the measurement results at the HV grid side of the HV/MV transformer, though, the value is used more as a reference value. This is shown in Figure 5. It was found that these values are of the same magnitude as the one found by the calculation done in Figure 5.

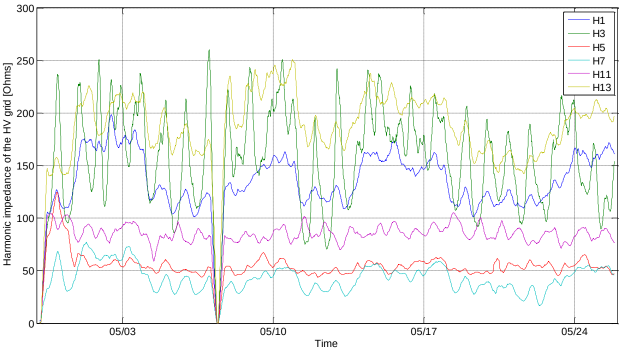

Figure 5: Harmonic impedance of the HV-grid

As a result, the model was tuned by adjusting the HV/MV transformer harmonic impedance for each harmonic component, to obtain the harmonic voltage on the busbar which corresponds to the measurements.

By performing a loadflow calculation at the different harmonic frequencies, the following results were obtained for the harmonic voltages at the busbar (Table 1). The total harmonic distortion level is slightly lower in the simulations compared to the measurements because not all higher harmonics have been modelled.

	THD [%]	H5 [%]	H7 [%]
R1 – MEAS	5.0	4.6	1.34
R1 – SIMUL	4.8	4.5	1.1
R2 – MEAS	5.5	3.3	1.0
R2 – SIMUL	5.3	3.2	1.0

Table 1: Comparison of harmonic voltage levels in the normal situation.

SIMULATION RESULTS

Once the model has been tuned to fit the measurements in the normal situation, simulations can be done with this model. A first scenario contains the coupling of the busbars at the MV level. The test was also performed during the measurement campaign, so the results of the measurement can be compared to the results of the simulation. The results of these simulations are shown in Figure 6 and Figure 7.

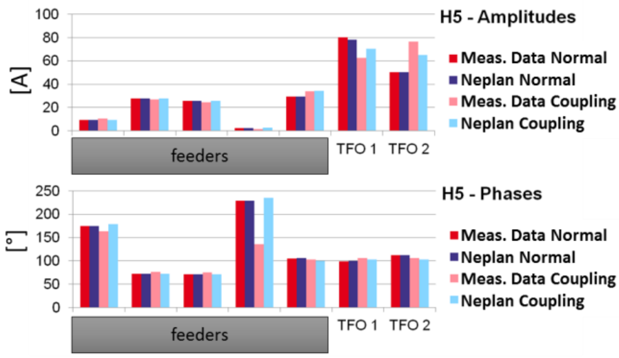

Figure 6: Simulation results for H5 currents [A]: normal situation and situation with busbars coupler closed.

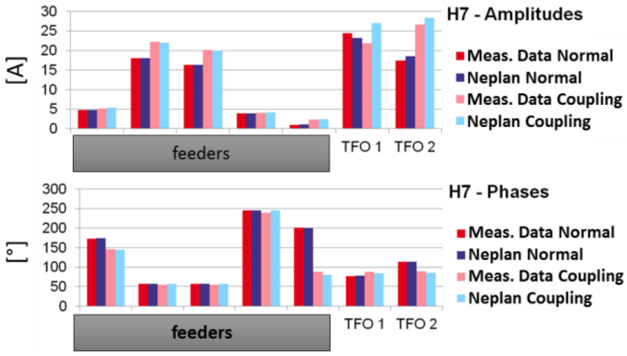

Figure 7: Simulation results for H7 currents [A]: normal situation and situation with busbars coupler closed.

The resulting harmonic voltage levels, compared to the measurements are shown in Table 2. Only slight differences can be noticed with regard to the measurements, smaller than 1 % THD.

	THD [%]	H5 [%]	H7 [%]
R1/2 – MEAS	4.9	4.1	1.5
R1/2 – SIMUL	4.4	4.35	1.0

Table 2: Comparison of harmonic voltage levels with busbars coupled.

A second scenario contains the connection of a capacitor bank on the MV busbar of transformer 2. The capacitor bank's rating was 6 MVAr, and modelled accordingly in the software. A small leakage inductance was added as well. The simulation results are given in Figure 8.
The resulting harmonic voltage levels, compared to the measurements are shown in Table 3. Only slight differences can be noticed with regard to the measurements, smaller than 1 % THD.

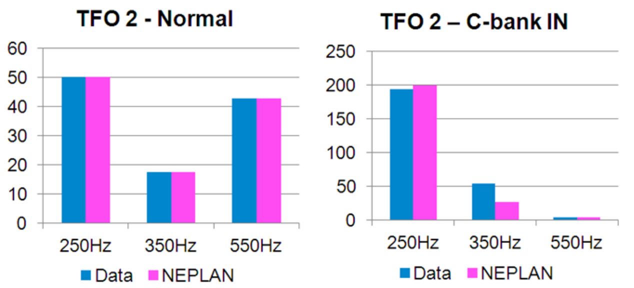

Figure 8: Harmonic currents [A] for normal situation and with connected capacitor bank on busbar 2.

	THD [%]	H5 [%]	H7 [%]
R2 – MEAS	8.0	7.0	2.2
R2 – SIMUL	7.5	6.4	1.0

Table 3: Comparison of harmonic voltage levels with capacitor bank connected to busbar 2

A third scenario contains the addition of a HV/MV transformer to the MV busbar to solve the harmonic congestion present at the substation. Simulations were made for a connection on busbar 1. The additional transformer is similar to transformer 1. This scenario could not be tested in reality, so only the results of the simulations are shown in Figure 9. The results of the calculation show a reduction of the harmonic voltages by about 50 %.

CONCLUSIONS

The proposed method employs the results of a measurement campaign to determine harmonic pollution levels (voltage and current). Harmonic powers were calculated and compliance of Kirchoff's law was more or less the case.

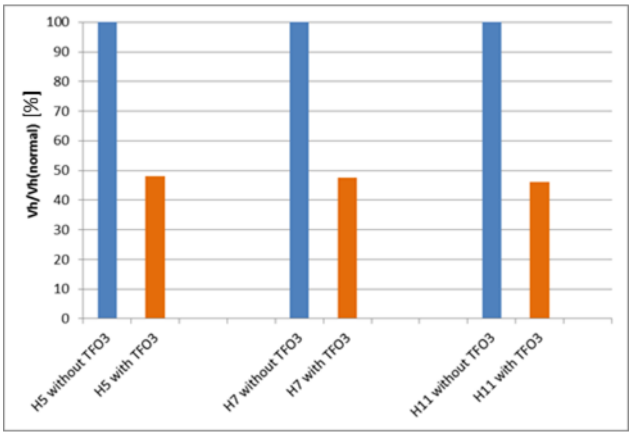

Figure 9: Simulation results H5, H7, H11 voltages [%]: situation without and with additional HV/MV-transformer.

A harmonic source/load depending on the flow direction of the harmonic powers was added to the different loads in the simulation models to allow harmonic analysis. The size of the harmonic sources or the harmonic impedances is derived from the harmonic powers. Finally, the model is further tuned by finding the harmonic impedance of the HV/MV transformer and the HV grid resulting in the same harmonic voltage levels as measured in the case-study. The fine-tuned model is tested by simulating different scenarios, such as the closing of the busbar coupler and the addition of a MV capacitor bank on the busbar. These scenarios were reproduced and measured in reality and were used to check coherence with the simulation results.
The fine-tuned model proved to be accurate and is used to test other scenarios, such as the addition of a transformer on the busbar to solve harmonic congestion present at the substation.
The main disadvantage of the method is the necessity to perform a detailed measurement campaign to obtain the harmonic power emissions/consumptions.

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[1] Robert A., Deflandre T., 1997, "Guide for assessing the network harmonic impedance", *CIRED 97, 2-5 june*, No. 438.