Advanced ripple control signal calculation tools for DNO's

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ABSTRACT

Simulation models of MV grids are used to study the behaviour and performance of ripple control signal installations. Through measurements done in the MV grid, the modelling of the impedance of loads at the signal frequency could be enhanced significantly. This results in more precise simulations of signal attenuation and network impedance at the signal frequency.

INTRODUCTION

Despite the rise of smart grid technologies, it is for the DNO's in Belgium clear that the currently employed ripple control signal technology will be used for many years to come in the distribution grid. The system is used to remotely switch tarification modes at the consumers and control public lighting. Typically, an MV substation is equipped with a signal source which injects command messages into the medium voltage grid. In Belgium there are several frequencies used, such as 180 Hz, 283 Hz, and 1350 Hz. The majority of the installations works at 180 Hz. The command messages are picked up by receivers at the consumer.

The ongoing expansion of the distribution grid and the increasing number of connections is a threat to the good functioning of the system. Changes in the nature of the loads, due to more use of power electronics, together with the increasing installation of renewable energy sources on the medium and low voltage grid, can have a significant impact on the performance of the ripple control. Typically two types of problems arise, which lead to a signal level below the minimum threshold at the receiver. On the one hand there can be a lack of signal power at the injection point, which results in an overall unacceptably low signal level. On the other hand, along a feeder a high attenuation may occur which results locally in unacceptably low signal levels. The aim of the DNO is to track down problematic cases and to avoid them in the future, by overall assessment of the distribution grid. Traditional calculation methods and empirical rules-of-thumb, employed by the DNOs to assess the overall situation and typical case studies, do not produce the desired results and need to be improved.
The aim of the research presented in this paper is to investigate a new proposed method on more precise load modelling techniques at the signal frequency.
The method was developed from empirical data collection from measurement campaigns and evaluated in a case study.

ASSESSMENT OF THE NETWORK IMPEDANCE

In accordance with the prescriptions of the Belgian federation of grid operators (Synergrid), the impedance at the signal frequency of any consumer connection to the MV grid is evaluated by the following rule:

$$Z_{signal} \geq 0.4 \times Z_{50\,Hz}$$

This can also be expressed in the following way using factor K_N:

$$K_N = \frac{Z_{50\,Hz}}{Z_{signal}} \leq 2{,}5$$

Z_{signal}, the impedance of the consumer at the signal frequency, can be calculated through simulation or measured during a measurement campaign. [2]
Strictly speaking, the impedance $Z_{50\,Hz}$, is calculated with the allocated power for the connection of the client and calculated as:

$$Z_{50\,Hz\,THEORETIC} = \frac{U_C^2}{S_N}$$

With U_C the nominal voltage at the connection point, and S_N the allocated apparent power.
$Z_{50\,Hz}$ can also be measured, which leads to higher values, since very seldom the customer uses the whole allocated power. Throughout this report, $Z_{50\,Hz}$ is calculated as:

$$Z_{50\,Hz\,MEASURED} = \frac{U_{MEAS}^2}{S_{MEAS}} = \frac{U_{MEAS}}{I_{MEAS}}$$

Typically, for new installations, Z_{signal} is calculated by simulating the network in a commercial software, and using the worst-case situation.
For the frequency behaviour of the loads (impedance) at the signal frequency Z_{signal}, often the method explained in the method from the CIGRE working group CC02 is used [1]. Grid operators tend to use the same method of modelling, to assess the network impedance at 50 Hz and at the signal frequency.
One of the main problems with this method is the correct modelling of MV/LV injection points. These injection points are often modelled as a single load, characterised by a known or estimated active and reactive power consumption at 50 Hz. The net consumption of power is often resistive or slightly inductive (power factor around 0.95). In reality, the injection point contains a MV/LV transformer, a LV busbar and a huge LV cable network, which at the signal frequency can play an important role, resulting in a far lower impedance value compared to the impedance value at 50 Hz.
In the classic modelling method mentioned above, inductive loads at 50 Hz would result in a higher

impedance at the signal frequency, while the impedance for resistive loads would remain status quo at the signal level:

$$Z_{signal} \cong R + j.2\pi.f_{signal}.L$$

As a result, calculations made with the classic modelling method tend to estimate higher impedance values due to the lack of detailing of the network at the LV level. The same can also occur when large industrial installations (with MV/LV injections) are modelled likewise.

EMPIRICAL DATA COLLECTION FROM MEASUREMENT CAMPAIGNS

Through a number of measurement campaigns performed at several locations in Flanders, the impedance of actual MV grids was investigated. Several locations were chosen, depending on the used signal frequency, and the nature of the loads.

Gathering load data for signal frequency of 180 Hz

Measurements were performed during typically one week. Messages last typically about 100 seconds, the magnitude of the 180 Hz signal is varied during broadcasting. The messages are recorded by a measurement device which samples the waveform as a whole, both for the voltage at the place of recording and the current towards the grid.
Messages occur throughout the day on a regular basis.
Through spectral analysis, both 50 Hz and 180 Hz components are derived from the waveform. This allows for the calculation of the impedance at 50 Hz and at 180 Hz.

Some cases were done on a small substation with typical residential households, containing PV pannels. Figure 1 shows the statistical representation of measurements during a one-week period. Two scatterplots link the consumed power (positive sign) of the substation with respectively the impedance at 180 Hz and the K_N-factor. A third histogram links the occurrence of message points with the consumed power. The majority of the points in the scatter plot is located around a power consumption of 5 kW.
Other cases were done on some substations with small industrial sites. An example is given in Figure 2. In this case, there is only power flowing downstream to the substations (negative sign).
Another case is office buildings. An example is given in Figure 3. The building was equipped with PV panels.

In general, the following could be concluded from the measurements. Households have a K_N factor between 1 and 5, with a median around 2.5. The presence of PV inverters tends to lower the impedance at the signal frequency. Small industries and offices have K_N factors between 1 and 5, with a median around 3.5. Regardless of the location of the measurement, similar results were found for each type of load.

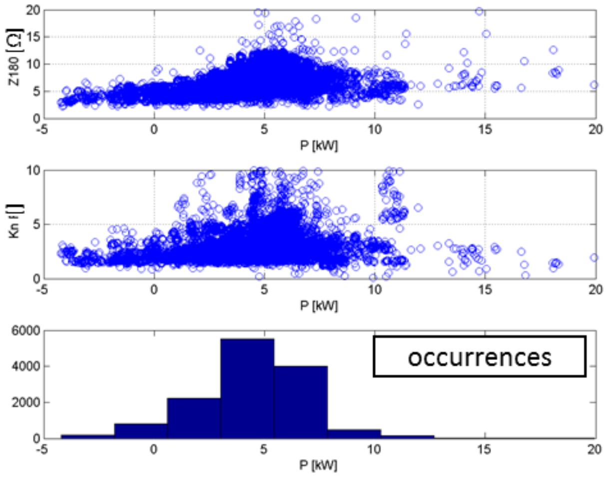

Figure 1: Measurements on typical households

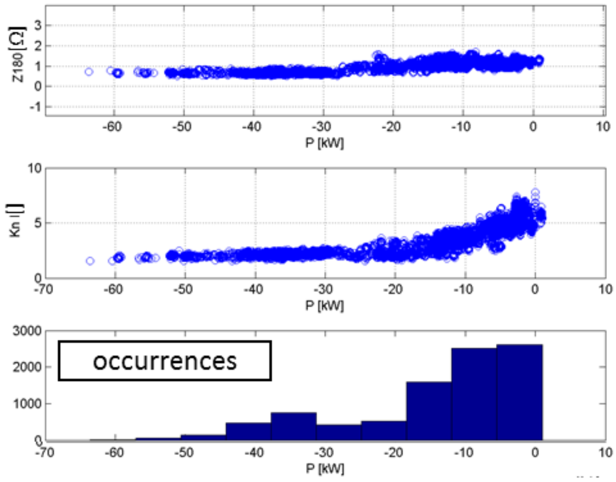

Figure 2: Measurements on a small industrial site

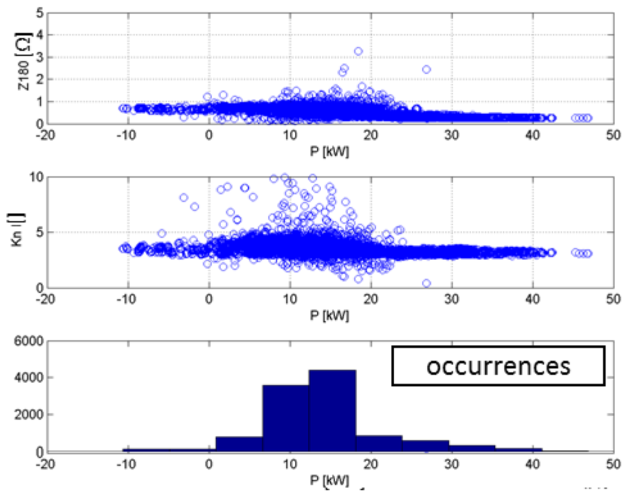

Figure 3: Measurements on an office building.

Gathering data from a HV/MV substation for 180 Hz

In a second step, the goal was to take one HV/MV substation and perform measurements on the impedance of the HV/MV transformer and the different MV feeders.
Figure 4 shows the results of measurements at the HV/MV transformer. Four boxplot representations show the statistical value of the current at 50 Hz, K_N factor, and the impedances at 180 and 50 Hz.

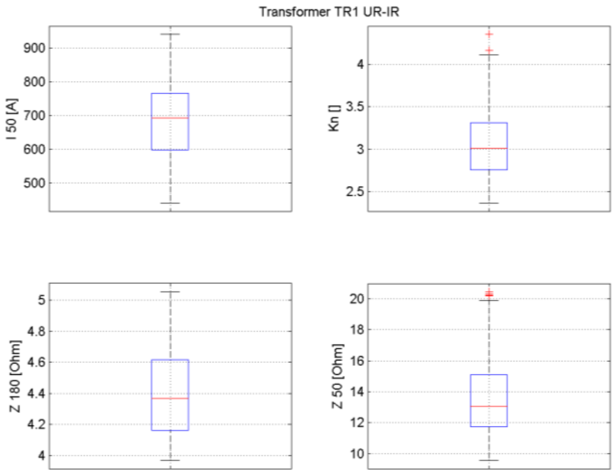

Figure 4: Measurement results on the HV/MV transformer

The same measurements were done simultaneously on the 7 feeders present at the substation. For the sake of simplicity, only the boxplot representation of the 7 feeders is given in Figure 5.

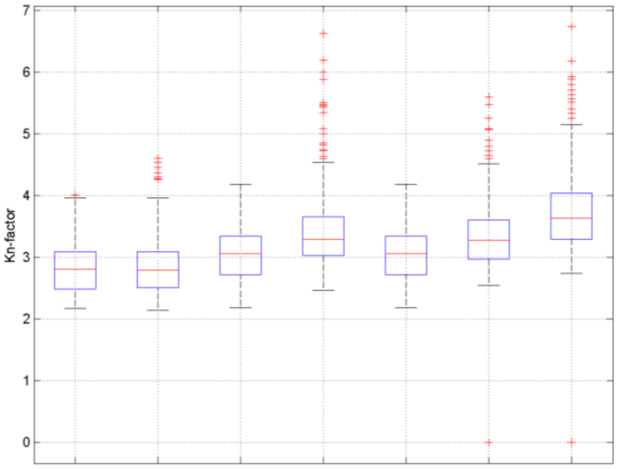

Figure 5: Measurement results on MV feeders.

An additional measurement device was placed in the MV grid, halfway on the second feeder. In this case the current was taken on the MV cable towards the end of the feeder. The measurement results are shown in Figure 6.
At this location, the signal at 180 Hz was attenuated by 7 %.

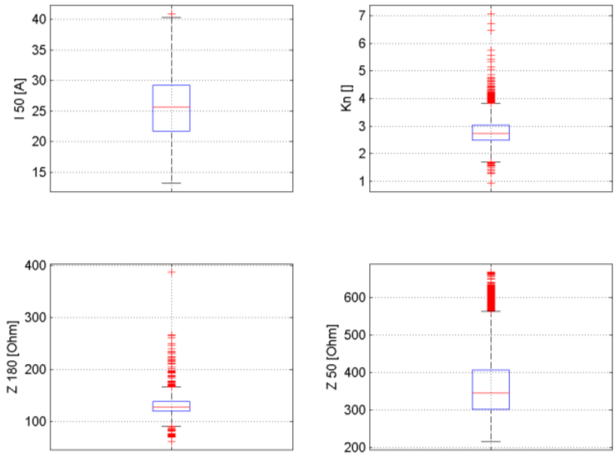

Figure 6: Measurement results half way the second MV-feeder

The measurements show that, regardless of the location, the same K_N factor of 2.5 to 3 was observed. The nature of this substation is a typical countryside village, with many residential customers.

Gathering of data at 283 Hz and 1350 Hz

The signal frequencies 283 Hz and 1350 Hz are less used in Flanders. One measurement case was done for both frequencies on a substations where both frequencies are being used together.
Figure 7 shows the statistical boxplot representation of the K_N factor for all six feeders on the substations at 283 Hz. K_N factors are in this case higher than 3 for most feeders. Feeders 4 and 5 represent two directly connected MV clients with large cogeneration units connected. Most of the time, in this case the 50 Hz impedance is smaller than the 283 Hz impedance when the units inject current in the MV-grid, resulting in a small K_N factor.
A few measurements were done also at some MV/LV transformers. The measured K_N factors are between 2 and 6, with a median value around 3.

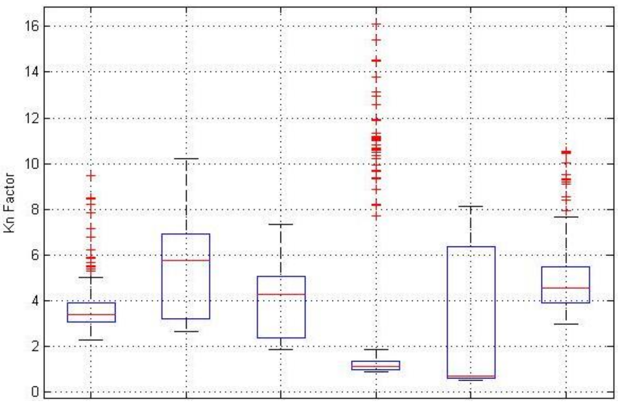

Figure 7: Measurement results on MV-feeders at 283 Hz.

Figure 8 shows the statistical boxplot representation of K_N factor at 1350 Hz for all feeders. The median K_N factor values of the feeders are above 8, except for the feeders with the cogeneration units (4 and 5).
Measurements done at MV/LV distribution transformers resulted in median values of K_N factors of 10 and higher.

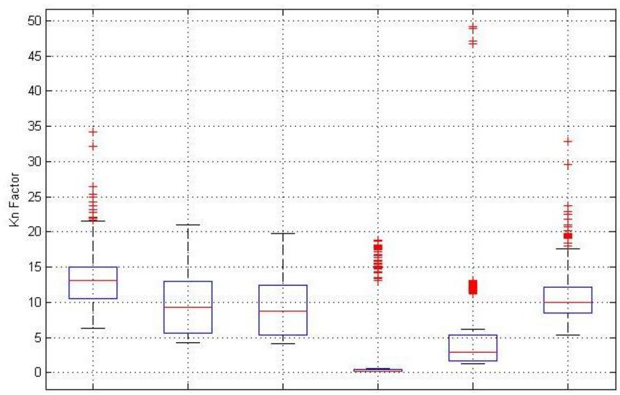

Figure 8: Measurement results on MV-feeders at 1350 Hz.

For these higher signal frequencies, the influence of the cables on the grid is more dominant. The capacitive behavior of the cables tends to lower the signal impedance even more. At 1350 Hz, resonance phenomena strongly influence the evolution of the signal attenuation.

SIMULATION OF MV GRID MODELS AT THE SIGNAL FREQUENCY

In this analysis, the MV grid was modelled in NEPLAN. The models are supplied by the DNO, and contain the HV/MV transformer, the MV busbars 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 [2]. The software allows to enter this information for each frequency separately. The signal source, which is located on the MV busbar can be modelled as a parallel connected generator unit coupled on the busbar, or through a combination of two anti-parallel current sources with a tuned impedance, which represents a series type injection (current based). The second concept is shown in Figure 9 and is used in this analysis.

<u>Simulation at 180 Hz</u>

The frequency dependency of the loads can also be entered in the software. Similar to the other components, for each frequency a value of R/Rn and L/Ln is requested, representing the resistive value of the load at the frequency divided by the value the software calculates at 50 Hz. To obtain a K_N factor of 2.5, this means entering:

$$\frac{R}{R_N} = \frac{1}{2.5} = 0.4$$

For the L/Ln ratio, which represents the inductive value of the load, this means entering:

$$\frac{j.2\pi.f_{SIGNAL}.L}{j.2\pi.f_N.L_N} = \frac{180.L}{50.L_N} = \frac{1}{2.5}$$

or:

$$\frac{L}{L_N} = 0.11$$

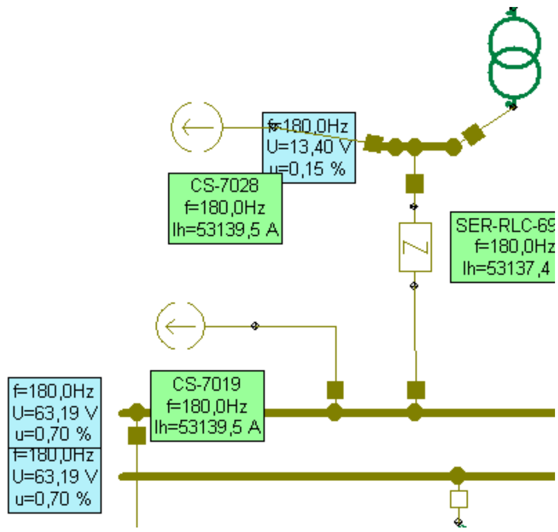

Figure 9: Model of series-type signal injection (current based) in NEPLAN.

In this network, there are several MV connected decentralised production units present, such as cogeneration units or MV connected wind turbines. These units are modelled by means of separate generators placed in the MV grid. The frequency dependency of these generators can also be entered. The impedance values Rn and Ln are calculated based on the power produced by the generator, not the nominal power of the unit. Several production scenarios were tested.

The results of the simulations are shown in
Signal Attenuation [%]

Feeder	Measured	Gen 0 kW	Gen 500 kW	Gen 2 MW
2	7 %	11 %	20 %	30 %

Table 1. For the sake of simplicity, only the resulting K_N factors of the feeders for the different scenarios are listed. The table compares the results of the measurement campaign with the different scenarios considered. The first scenario without decentralized generation (0 kW). The second scenario is the case where production of all generators is set to 500 kW, the third scenario is the case with all generators set to 2 MW.
From the results it can be seen that some feeders are

hardly impacted, since no decentralized generation is present (Feeders 1, 5 and 6).

K_N-values:

Feeder	Measured	Gen 0 kW	Gen 500 kW	Gen 2 MW
1	3.0	2.9	2.8	2.8
2	2.8	2.8	3.8	6.5
3	3.3	3.0	3.9	7.5
4	3.2	3.5	3.9	5.5
5	3.6	2.5	2.4	2.4
6	3.0	2.6	2.6	2.5
7	2.8	2.9	3.8	6.6

Signal Attenuation [%]

Feeder	Measured	Gen 0 kW	Gen 500 kW	Gen 2 MW
2	7 %	11 %	20 %	30 %

Table 1: Simulation results for 180 Hz.

Others experience a rise in the resulting K_N factor when produced power is increased. The explanation for this is twofold. By increasing the produced power, the resulting impedance of the generator is lowered and introduces hence a smaller impedance at the signal frequency on the grid, which results in an increase of the K_N factor. Secondly, a load-balancing action is performed each time to keep the net power balance of the feeder consistent with the measurement. Increasing the power production of the local generators automatically increases the power consumption of the loads locally. This equally results in a smaller signal impedance of the loads. This effect is noticed on feeders 2, 3, 4 and 7.
In some cases, an offset in the calculation of the K_N factor is noticed throughout the scenarios (Feeders 5 and 6), probably related to differences between the feeder model and reality.
Finally, the last row in the table presents the signal attenuation along feeder 2. Compared to reality, we can see that the scenario without local generation units fits best. In this case, at the chosen moment of analysis, the local production of power was quite low.

Simulations at 283 Hz

The same method was applied as for 180 Hz. In this case, the loads are modelled using K_N factor of 3. Equal results were obtained as is the case for the 180 Hz signal frequency. A typical error of 10 % on the signal attenuation was noticed.

Simulations at 1350 Hz

The method used above was tested for 1350 Hz, based on the information obtained in the measurement campaigns. The loads were modelled with a K_N factor of 10. At these higher frequencies, it is much more difficult to have a reliable calculation, since the slightest changes to the grid model already have a big influence. Therefore no useful results could be produced with the simulations.

CONCLUSIONS

Calculations made with the classic modelling method tend to estimate higher impedance values at the signal frequency due to the lack of detailing of the network at the LV level. Through empirical data collection from measurement campaigns, it is known that this method is inaccurate. In reality a huge LV cable network is present which results in far lower impedance values at the signal frequency compared to the 50 Hz impedance.

At 180 Hz, for residential LV grids, the signal impedance is up to 5 times smaller than the 50 Hz impedance (K_N factor). The same is true for small industries and small businesses, regardless of the location of the measurement.
At higher signal frequencies, K_N factors between 2-6 (at 283 Hz) and up to 10 (at 1350 Hz) are observed.

A case study was done at an HV/MV substation and served as an input to enhance the modelling technique for the loads.
The simulation model was altered to take into account the measured signal impedance when performing harmonic load flow calculations at the signal frequency.
At 180 Hz, this technique produced satisfactory results, and the model is able to reproduce reliable signal attenuations along the MV feeders. One point of attention is the modelling of local generators, which must be done with care. It must be avoided to introduce too large decentralized generation units, since this impacts the accuracy of the calculations significantly.
At 283 Hz, equal results were obtained as for the 180 Hz case.
At 1350 Hz, resonance phenomena and parasitic components, often too poorly modelled, prevent simulations from producing reliable results.

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