# MODELLING THE PROPAGATION OF HARMONIC VOLTAGES IN LARGE MEDIUM VOLTAGE DISTRIBUTION NETWORKS

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## *ABSTRACT*

*Harmonic voltages are important power quality (PQ) parameters, mainly caused by non-linear loads that act as harmonic current sources in the network. Modelling the propagation of harmonic voltages in large medium voltage (MV) distribution networks has so far been a challenge, mainly due to huge number of different harmonic sources that have an influence on harmonic voltage distortion in the network. This research uses a methodology of aggregate harmonic source modelling of major customer categories in MV distribution networks, based on several measurements and knowledge from the literature. This paper presents the results of propagation of 5th and 7th harmonic voltages in one large real MV distribution network. The simulations are performed using professional software tool, and two commonly used methods for modelling harmonic sources are applied. The results of harmonic voltage propagation from simulations show a very good match compared to the results from PQ measurement instruments installed in the analysed network. It is shown that the correct propagation of harmonic voltages can be achieved using models, even in large real MV distribution networks. The methodology used is relatively simple, with limited number of measurements needed to develop a model. Therefore, it can easily be applied to other MV networks. The results of this research will be used as an input for a PQ monitoring placement algorithm.*

## INTRODUCTION

Harmonic voltages are important power quality (PQ) parameters, with compatibility levels for public MV networks defined in IEC 61000-2-12 and limits for public distribution networks in Europe defined in EN 50160. Harmonics in electricity networks are caused by non-linear loads that inject harmonic currents into the network, which consequently cause harmonic voltage drops on the network impedances. Dominant non-linear loads in electricity distribution networks are: consumer electronics, modern lighting devices such as compact fluorescent lamps (CFL) and LED-lighting, industrial electronics, heating, ventilation and air conditioning (HVAC) systems, photovoltaics (PV), electric vehicle (EV) charging etc. [1].

For harmonic voltage studies in electricity distribution networks, there are two types of harmonic sources: i) background harmonics from higher voltage levels, coming from harmonic emission in other connected networks and ii) harmonic emission of loads connected to the considered network. Background harmonics are usually modelled as background harmonic voltage source, while harmonic emission of loads is usually modelled as harmonic current sources [1, 2].

Until now, modelling of harmonic voltage propagation in large real MV distribution networks has been a challenge, due to the presence of huge number of different harmonic sources in the network having an influence on harmonic voltage distortion. Consequently, for medium voltage (MV) network studies, aggregate harmonic current source models need to be used to represent harmonic emission of groups of customers in low voltage (LV) networks. There are only a few research papers that verified the simulation results for real distribution networks with PQ measurements, and even less that achieved this for longer time periods (day, week, etc.). Authors of [3] verified the results of simulations with field measurements, but on a relatively small MV feeder and for only one moment in time for each one of several system configurations. Reference [4] verified the probabilistic aggregate harmonic load models, for a period of one day, on a large real 137-bus MV network. Authors of [5]-[6] developed load models for real industrial networks and verified them using PQ measurements, but without analysing longer time periods.

This paper is a continuation of the work presented in [1] and [2]. Paper [1] originally presented a deterministic approach to modelling harmonics in large real MV distribution networks using aggregate harmonic source models of major customer categories. The authors in [1] only used the method of modelling harmonic sources according to the IEC 61000-3-6 summation law. This approach was significantly improved in [2], where also a second method of modelling harmonic sources using both complex phasors was introduced. This paper presents unpublished results on analysis of harmonic voltages propagation in one large real distribution network, by using both modelling methods. The results are verified by PQ measurement instruments, installed in the analysed network, for one analysed week. This is therefore the first paper to verify the results of weekly simulations of harmonic voltage propagation in large real MV distribution networks, while using deterministic aggregate harmonic source models. This approach can be used for analysis of harmonic voltage propagation in multiple other networks, since a straightforward approach and limited number of PQ measurements are used to develop a model. The results of this research will be used as an input for the PQ monitoring placement algorithm.

This introduction section is followed by methodology section, after which results and discussion section and conclusions section are presented.

## METHODOLOGY

This section briefly presents the methodology of this research, while a complete and detailed description of the methodology is given in [2].

### Analysed medium voltage distribution network

In this research, a real MV network of Netz Oberösterreich GmbH, a Distribution System Operator (DSO) in Upper Austria, was analysed. The chosen MV network is supplied from one 110/30 kV substation by two 110/30 kV (32 MVA, 20 MVA) transformers and two 110 kV lines, with one switched on in normal operation. The declared voltage of the MV network is 29.2 kV. This MV network, in the analysed year, supplied a total of 153 individual 30/0.4 kV distribution transformer substations and 12,347 customers by 7 feeders. The structure of the network is presented in the geographical diagram with feeder colouring in Fig. 1. The length of overhead and cable lines as well as the number and installed power of 30/0.4 kV distribution transformer substations, for all the feeders, is given in Table 1 [1].

The configuration of the customers in the network is shown in Table 2, where the shares of energy consumption/production of different customer categories in the total amount of energy in the network, are provided for the analysed first week of June. It can be noticed that the highest consumption is in the household category, then industry, different small commercial customers, agriculture, etc. [2].

Table 2 also gives information about different harmonic source models assigned in this research to different customer categories. More information on parameterisation of harmonic source models of background harmonic voltages as well as residential, small commercial, industrial and agricultural customers is given below. All customers from the categories of hot water tanks and night storage heating are modelled without harmonic emission. Also, harmonic emission of

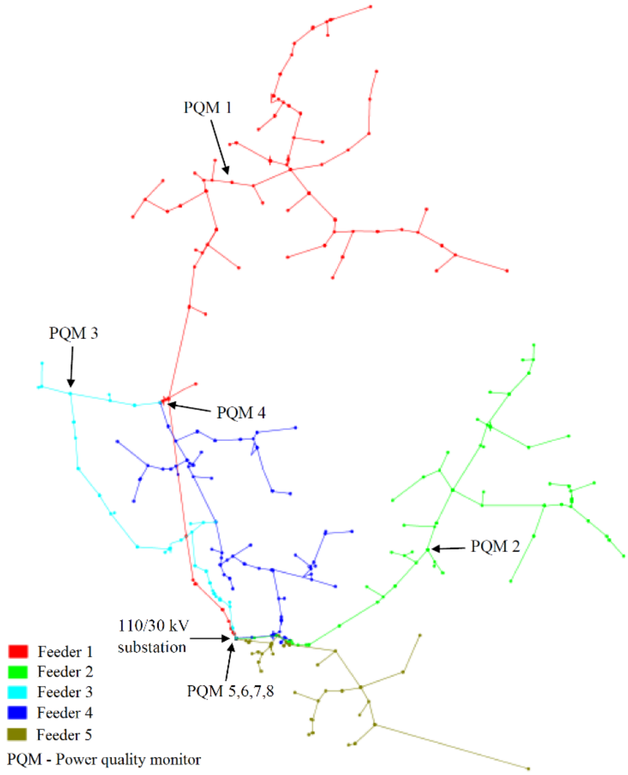

*Fig. 1.* *Geographical diagram of analysed MV network with feeder colouring and locations of power quality monitors (PQMs) [1]*

**Table 1** Network data by MV feeders [1]

| Feeder no. | Overhead lines (km) | Cables (km) | Number of 30/0.4 kV transformer substations | Installed power of transformers (MW) |
|---|---|---|---|---|
| Feeder 1 | 52.8 | 14.7 | 42 | 11.7 |
| Feeder 2 | 37.3 | 3.1 | 35 | 7.5 |
| Feeder 3 | 13.1 | 3.1 | 19 | 5.0 |
| Feeder 4 | 26.2 | 9.8 | 34 | 9.6 |
| Feeder 5 | 22.8 | 3.1 | 21 | 10.0 |
| Feeder 6 | 0 | 0 | TPP own consumption | |
| Feeder 7 | 0 | 0 | Reserve | |

**Table 2** Customer category groups in the network, with their share in weekly energy consumption and assigned aggregate harmonic source models [2]

| Customer category | Percentage of total weekly energy | Aggregate harmonic source model |
|---|---|---|
| Household | 40.27% | Residential |
| Industry | 28.05% | Industries |
| Small commercial customers | 17.29% | Offices |
| Agriculture | 11.08% | Agriculture |
| Hot water tanks and night storage heating | 4.02% | No harmonic emission |
| Thermal power plant own consumption | 1.34% | Neglected |
| Public lighting, mobile phone base stations | 0.96% | Neglected |
| Photovoltaics | -2.90% | Neglected |
| Other distributed generation | -0.11% | No harmonic emission |
| Total | 100,00% | |

**Table 3** List of power quality monitors (PQM) in analysed MV distribution network [1]

| No. | Location | Voltage level |
|---|---|---|
| PQM 1 | Feeder 1 | 30 kV |
| PQM 2 | Feeder 2 | 30 kV |
| PQM 3 | Feeder 3 | 30 kV |
| PQM 4 | Feeder 4 | 30 kV |
| PQM 5 | 110/30 kV substation – Transformer 1 | 30 kV |
| PQM 6 | 110/30 kV substation – Transformer 2 | 30 kV |
| PQM 7 | 110/30 kV substation – 110 kV line 1 | 110 kV |
| PQM 8 | 110/30 kV substation – 110 kV line 2 | 110 kV |

thermal power plant (TPP) own consumption, public lighting, mobile phone base stations and photovoltaics is neglected, due to their negligible share in total energy consumption in the network [2].

## Existing power quality monitoring system

Netz Oberösterreich GmbH has installed a PQ monitoring system in its MV networks. The system is based on PQ monitoring instruments, which measure all the voltage quality parameters defined in EN 50160. The instruments comply with class A according to IEC 61000-4-30 and measure harmonics up to the order of the 50th harmonic. The instruments are installed at primary 110/30 kV substation and selected 30/0.4 kV substations. All instruments are equipped with time synchronization by GPS receiver. The data is archived in a PQ database [1].

The MV network analysed in this paper has six PQ monitors installed at the 30 kV voltage level and two instruments at the 110 kV voltage level. The list of PQ monitors with voltage levels is given in Table 3, while the geographical locations of the instruments are given in Fig. 1. It can be noticed that there are PQ monitors installed in the primary 110/30 kV substation as well as in four out of five 30 kV feeders [1].

In this research the 5th and 7th harmonic orders were analysed, as the dominant harmonic orders with highest harmonic voltage values in the analysed MV network. Measurements from the PQ monitoring system installed on 110 kV are used for parameterising background harmonic voltages, while devices installed on 30 kV are used for comparison of final results of the model [2].

## Parameterised harmonic sources in the model

Background harmonic voltage magnitudes were parameterised using harmonic voltage measurement results from PQM 7 and PQM 8, which are installed at 110 kV lines supplying the 110/30 kV substation. Background harmonic voltage phase angles were parameterised with additional measurements, since the existing PQ monitoring system does not measure harmonic phase angles. A mobile power quality recorder compliant to IEC 61000-4-30 Class-A was used for this purpose. Voltage waveforms were recorded and later processed with a fast Fourier transform in MATLAB to extract harmonic voltage phase angles [1, 2].

In this research, harmonic current source models of two major customer groups (household and small commercial) were parameterised using measurements of total harmonic current emission of different LV networks, dominated by characteristic customer configurations (residential or office). For this purpose, four measurements of respective LV grids were used [1, 2]:

- Residential area with 336 households in multi-family houses
- Office area with 26 offices
- 1 office building
- 4 office buildings with 1 canteen

These measurements have been carried out using PQ measurement devices of class A, according to IEC 61000-4-30.

A methodology for parameterising harmonic current source models of industrial and agricultural customers, developed in [2], was used. It is based on the fact that the most common sources of harmonics in industry are variable speed drives (VSD), mostly based on diode rectifiers, that supply motors in industry [2].

## Modelling harmonics in DIgSILENT PowerFactory

A model of the analysed 30 kV network was developed for harmonic load flow in DIgSILENT PowerFactory, a commercial tool for power system analysis. Background harmonics were modelled as harmonic voltage source in the external grid element. Harmonic current emission of LV loads was modelled using harmonic current source objects, for different aggregated harmonic current source models. Thermal loads (hot water tanks and night storage heating) were modelled as resistive impedances. In this research, a balanced harmonic load flow was performed and for this purpose all the loads, distributed generators (DG) and PV’s, as well as all the harmonic current sources and background harmonic voltage source were modelled as balanced. Frequency dependencies of impedances for typical network components in distribution networks, based on the literature, were used in the model. Vector groups of all the transformers were also taken into account. All the measurements were time synchronised to the time zone of the location of the network, and that is Central European Summer Time (CEST), which is +2 hours ahead of Coordinated Universal Time (UTC) [2].

A harmonic load flow for one complete week was performed. In order to automate the calculation of harmonic load flow for every 10-minute interval in one week, a script in DIgSILENT Programming Language (DPL) was developed. Since the interval for calculations was 10 minutes, a total of 1,008 harmonic load flow calculations were performed for one chosen week [1].

Two methods for modelling harmonic sources are used:

1. Modelling of harmonic sources according to the IEC 61000-3-6 summation law
2. Modelling of harmonic sources using complex phasors

### Modelling of Harmonic Sources According to the IEC 61000-3-6 Summation Law

The basic characteristic of this method is that only harmonic magnitudes are defined and the summation of harmonic voltages due to different phase angles of different harmonic sources is done according to the IEC 61000-3-6 general summation law [1], [7]:

$$U_h = \sqrt[\alpha]{\sum_{m=0}^{N} U_{h,m}^{\alpha}} \qquad (1)$$

where:
*h* – harmonic order
$U_h$ – magnitude of the resulting harmonic voltage (order h) $U_{h,m}$ – magnitude of the various m individual harmonic emission levels (order h)
$\alpha$ - exponent as given in Table 4 [7].

**Table 4** Summation exponents for harmonics according to harmonic order, taken from IEC 61000-3-6 [7]

| Harmonic order | α exponent value |
|---|---|
| h < 5 | 1 |
| 5 ≤ h ≤ 10 | 1.4 |
| h > 10 | 2 |

### Modelling of Harmonic Sources Using Complex Phasors

In this method both harmonic magnitudes and phase angles of all the harmonic sources were modelled. Summation of harmonic voltages, resulting from the impact of different harmonic sources, is done in the complex plane [2].

## RESULTS AND DISCUSSION

This subsection presents the results of harmonic voltage propagation in the analysed large real MV distribution network. The propagation of harmonic voltages is expressed in this paper as a transfer ratio between the values of harmonic voltages at different nodes on MV feeders (location of PQM 1, 2, 3, 4) and at the primary 110/30 kV transformer substation (location of PQM 5):

$$r_{\mathrm{Uh}} = \frac{\mathrm{Uh}_{\mathrm{PQM\,X}}}{\mathrm{Uh}_{\mathrm{PQM\,5}}} \qquad (2)$$

where:
*r* – transfer ratio of propagation
*h* – harmonic order
$Uh_{,PQM}$ – magnitude of harmonic voltage (order h) at the node with the location of PQM.

The results for the two modelling approaches are firstly presented as weekly trends of transfer ratio between the node with PQM 1 installed (node with the highest harmonic values among all nodes with PQMs) and the 30 kV bus at the primary 110/30 kV substation (PQM 5). Fig. 2 presents the transfer ratios of 5th harmonic voltage, while Fig. 3 presents the transfer ratios of 7th harmonic voltage. As can be seen from Figs. 2 and 3, the results of the simulations show a very good match with the measurements. The only results that are not presented are the 7th harmonic voltages for the method of modelling using both amplitudes and phase angles, since this method is much more sensitive to input data uncertainty, which is often to be expected when large distribution networks are analysed, as elaborated in detail in [2].

The time characteristic of the transfer ratios is statistically analysed and presented as 95% quantiles, between all the nodes in MV feeders with PQMs installed (PQM 1, 2, 3, 4) and 30 kV bus at 110/30 kV substation (PQM 5). The results are shown in Table 5, and it can be seen that a very good match between the measurements and the simulations was achieved for both modelling approaches.

The errors between the simulations and the measurements are assessed by mean absolute error (MAE) and mean absolute percentage error (MAPE). The errors are

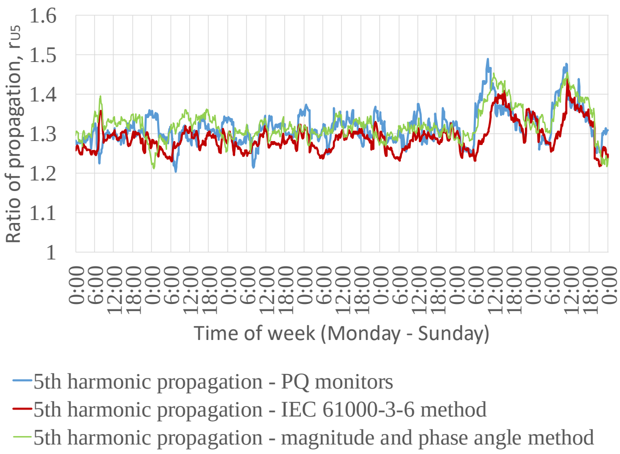

***Fig. 2.*** *Transfer ratios of 5th harmonic voltage from PQ measurements and simulations (between node of PQM 1 and node of PQM 5)*

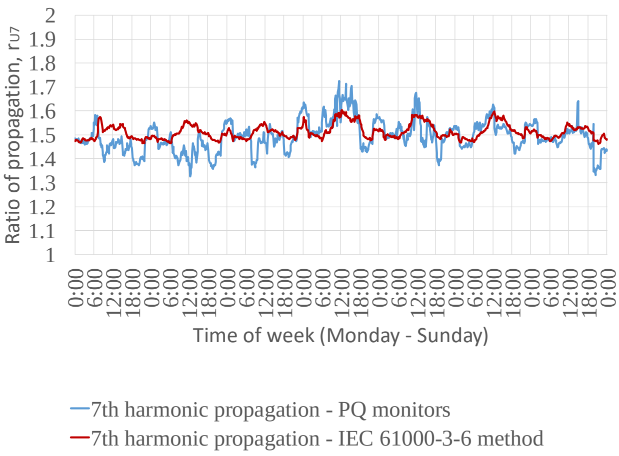

***Fig. 3.*** *Transfer ratios of 7th harmonic voltage from PQ measurements and simulations (between node of PQM 1 and node of PQM 5)*

**Table 5** Transfer ratios of 95% quantiles of harmonic voltages from PQ measurements and simulations

| | PQM 3 | PQM 2 | PQM 4 | PQM 1 |
|---|---|---|---|---|
| 5th harmonic | | | | |
| PQ measurements | 1.02 | 1.05 | 1.02 | 1.32 |
| IEC 61000-3-6 method | 1.01 | 1.03 | 1.06 | 1.28 |
| Complex phasor method | 1.01 | 1.03 | 1.06 | 1.32 |
| 7th harmonic | | | | |
| PQ measurements | 1.02 | 1.04 | 1.06 | 1.47 |
| IEC 61000-3-6 method | 1.01 | 1.02 | 1.07 | 1.49 |

calculated both for the transfer ratio and the time characteristic of the magnitudes of harmonic voltages. The errors are calculated for weekly time series of all the analysed nodes with PQMs.

MAE errors for the transfer ratios are between 0.006 and 0.051 for 5th harmonic and 0.007 and 0.046 for 7th harmonic, while the MAPE errors are in the range between 0.6% and 6.2% for 5th harmonic and 0.7% and 3.1% for 7th harmonic. For time characteristics of the magnitudes of harmonic voltages, MAE errors are between 0.15% and 0.23% for 5th harmonic and 0.19% and 0.32% for 7th harmonic, while the MAPE errors are in the range between 17.8% and 22,4% for 5th harmonic and 21.5% and 24.3% for 7th harmonic. These ranges cover both modelling approaches.

Even though the errors for the transfer ratios are rather small, the errors for the time characteristics of the magnitudes of harmonic voltages point out that the perfect match between the measurements and the simulations was is achieved. As it is discussed in [2], the errors come from the differences in weekly trends between the measurements and the simulations. The exact reproduction of the weekly trend is very challenging and comes from many uncertainties related to modelling the enormous number of harmonic sources and their behaviour during the course of one week.

However, as for the optimal placement of PQM, the correct simulation of the propagation is much more important than reproducing exact weekly trends, the envisaged accuracy of the simulations with respect to the goal has been fully achieved.

## CONCLUSIONS

This paper presented the results of 5th and 7th harmonic voltage propagation in one large real MV distribution network. The propagation, expressed as a transfer ratio, is calculated using two modelling approaches, based on two commonly used methods for modelling harmonic sources. The results are compared with transfer ratios based on real measurements, taken by PQMs installed in this network. This paper analysed both the time characteristic and the 95-%-quantile of the transfer ratios during one full week. The results showed that the propagation calculated based on both modelling approaches achieved a very good match with the propagation based on measurements.

This research has proven that the correct propagation of harmonic voltages can be obtained by simulations, even in large real MV distribution networks. The methodology used is straightforward, with a limited number of measurements needed to develop the model. Therefore, it can easily be applied to other MV networks. For some applications, such as algorithms for optimal PQ monitor placement, only the correct propagation throughout the whole network is needed. Therefore, the results of this research represent an excellent input for such an algorithm, which is a field of research of the authors.

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## REFERENCES

[1] A. Bosovic, H. Renner, A. Abart, E. Traxler, J. Meyer, M. Domagk, M. Music, 2016, "'Validation of Aggregated Harmonic Current Source Models Based on Different Customer Type Configurations", *10th Electric Power Quality and Supply Reliability Conference (PQ 2016),* Tallinn, Estonia

[2] A. Bosovic, H. Renner, A. Abart, E. Traxler, J. Meyer, M. Domagk, M. Music, 2018, " Deterministic Aggregated Harmonic Source Models for Harmonic Analysis of Large Medium Voltage Distribution Networks", *IET Generation, Transmission & Distribution*, submitted for publication

[3] S. M. Williams, G. T. Brownfield, J. W. Duffus, 1993, “Harmonic Propagation On An Electric Distribution System: Field Measurements Compared With Computer Simulation,” IEEE Transactions on Power Delivery, vol. 8, no. 2, pp. 547–552

[4] M.T. Au, J.V. Milanovic, 2007, “Establishing Harmonic Distortion Level of Distribution Network Based on Stochastic Aggregate Harmonic Load Models”, IEEE Transactions on Power Delivery, 22, (2), pp. 1086-1092

[5] C. Venkatesh, D. Srikanth Kumar, D.V.S.S. Siva Sarma, M. Sydulu, 2008, “Modelling of Nonlinear Loads and Estimation of Harmonics in Industrial Distribution System”, Proceedings NPSC 2008 conference, 592-597

[6] S. W. Middlekauf, A. J. Ebel, C. B. Jensen, 2000, “Using harmonic simulation to evaluate facility-wide harmonic mitigation,” Proceedings 2000 Power Engineering Society Summer Meeting, 1075-1079

[9] IEC 61000-3-6: 'Electromagnetic compatibility (EMC) - Part 3-6: Limits - Assessment of emission limits for the connection of distorting installations to MV, HV and EHV power systems', 2008