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- Case studies and modelling requirements –

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SIMULATION AND MEASUREMENT OF HARMONIC PROPAGATION IN MV-SYSTEMS - CASE STUDIES AND MODELLING REQUIREMENTS –

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KEYWORDS

Voltage quality, harmonic propagation, modelling requirements

ABSTRACT

Simulation tools can be used to determine the voltage quality in MV and LV distribution systems already before connecting new heavy loads producing high harmonic currents like converter-fed furnaces or motor drives to the power supply system. To keep the harmonic levels below the compatibility levels, necessary measures have to be proposed and verified. Usually measurements of the resulting harmonic levels are only possible after the permission for the connection is given.

This paper discusses the impact of various input parameters which are needed to obtain realistic simulation results of harmonic propagation. Furthermore the capabilities and limitations of such computer simulations are highlighted.

1 INTRODUCTION

Increasing harmonic levels in the supply voltage of MV and LV power systems are a well-known fact. Voltage quality becomes a factor of increasing importance especially regarding sensible customers which may be influenced by voltage harmonics. Before connecting harmonic sources to the MV power system, an examination of the resulting harmonic level is necessary. The admissible part of the harmonic voltages caused by the different customers is defined by VDEW-recommendations in Germany [1], which are used in addition to IEC 1000-2-2:1990 [2]. In most cases comprehensive measurements are carried out only after the installation was set in operation.

In principle the resulting harmonic levels and the frequency-dependent system impedances can be determined in advance using one of the existing simulation tools. However, the quality of the data set is of tremendous influence to achieve a successful simulation. A major problem is the investigation of the actual basic harmonic load of the system. The quality of the measurements has to be checked with respect to exactness and representative values. The variation of loads in the investigated system as well as the industrial reactive-power compensation systems have to be regarded. The resulting uncertainties should be restricted as far as possible. The impact of the various input variables on the calculation results are given in the following.

2 MEASUREMENTS

2.1 Measurement system

In order to carry out harmonic measurements, modern PC-supported measuring systems in accordance with IEC 1000-4-7:1991 [3] should be applied. This standard defines all parameters for harmonic measurement, such as:

- Measuring error of voltage and current
  5 % U_m resp. 0,15 % U_n and 5 % I_m resp. 0,5% I_n
  (U_m and I_m : measuring value,
  U_n and I_n : nominal input range of system),
- suitable voltage and current transducers,
- usage of FFT with definitions of scanning frequency, windows, etc.,
- statistical evaluation method.

The digital PC-supported measuring system [4] used here meets these requirements.

2.2 Measuring method

The measurements done for the examples presented in chapters 5 and 6 were carried through for one week each. The measuring kernels of the installed current transformer (I_{sec}=5 A) and voltage transformer (U_{sec}=110V/√3) were used as sources for the inputs. The harmonic analysis was made for an interval of 160 ms of each second.

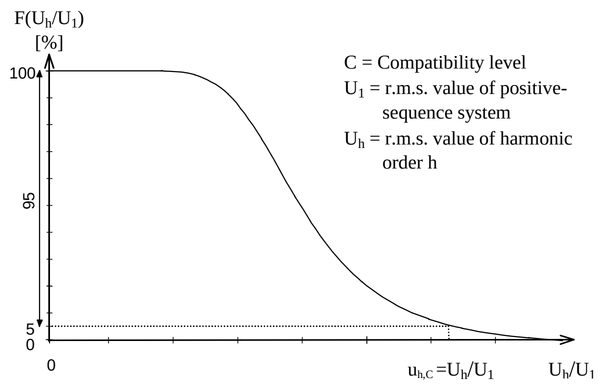

Figure 1. Cumulative distribution function of the harmonic voltage levels

To enable the valuation of measured harmonic voltage magnitudes compatibility levels are fixed in

[2]. They are not defined by their absolute maximum level, but may be exceeded by 5 % of the measured values [5]. Figure 1 shows the cumulative distribution function of the harmonic voltage levels to visualise the meaning of the so-called 95 %-value. In order to derive these values, the operating time of the harmonic sources in the industrial plants from Monday till Friday each day from 6 a.m. to 8 p.m. was taken as base.

3 SIMULATION METHOD

The computer simulations are carried out by a simulation tool [6,7] which is based on the well-known single phase linear harmonic analysis [8] as visualised in figure 2. Assuming passive equipment with linear U/I-characteristics the stationary harmonic conditions can be calculated for each harmonic order h in the frequency domain by a set of linear equations (1).

$$\underline{\mathbf{i}}_h = \underline{\mathbf{Y}}_h \cdot \underline{\mathbf{u}}_h \qquad (1)$$

$\underline{\mathbf{i}}_\mathbf{h}$ Complex vector of injected harmonic currents $\underline{I}_{h,j}$
$\underline{\mathbf{Y}}_\mathbf{h}$ Frequency dependent nodal admittance matrix
$\underline{\mathbf{u}}_\mathbf{h}$ Complex vector of harmonic voltages $\underline{U}_{h,j}$
j=1...(n+1)

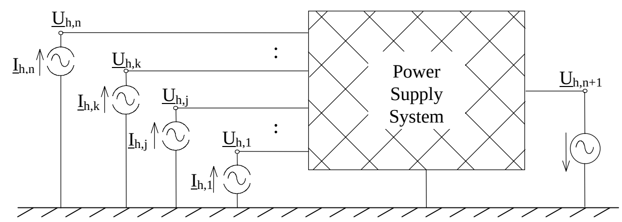

Figure 2. Principle of the linear harmonic analysis

The relations between the vector of injected harmonic currents $\underline{\mathbf{i}}_\mathbf{h}$ and the vector of resulting harmonic voltages $\underline{\mathbf{u}}_\mathbf{h}$ is given by the frequency dependent nodal admittance matrix $\underline{\mathbf{Y}}_\mathbf{h}$ of the system.

The resulting set of linear equations (1) is of order n+1. As the harmonic voltage at node n+1 is known, the set of equations must be reduced by one, i.e. node n+1 is eliminated. Solving the remaining equations with respect to $\underline{\mathbf{u}}_\mathbf{h}$ provides the unknown harmonic voltages $\underline{U}_{h,j}$ at all remaining nodes j=1...n within the system.

Assuming that the system and the harmonic infeeds are absolutely balanced, the harmonics of interest (odd, non-multiples of 3) form a positive or negative sequence system only. Therefore, the zero sequence system is neglected for the calculations. In addition, the interaction between voltage distortion and harmonic currents of non-linear loads are neglected for practical investigations, as they are nearly independent from each other in actual systems with low distortion [9].

4 SYSTEM MODELLING

The frequency-dependent transmission attributes of equipment and loads are modelled with the well-known equivalents consisting of concentrated elements (R, L, C) and ideal transformers with linear U/I-characteristics. Lines, cables and transformers are represented by π-equivalents. For frequencies up to 1 kHz skin and proximity effects can be neglected [9] because the resulting harmonic voltages are only slightly higher in this case [10].

Loads are the main damping elements especially in the range of the resonance frequency of the network impedance. Depending on the U/I-characteristic linear and non-linear loads can be distinguished.

Linear loads are approximately modelled as parallel resonant circuits with lumped resistive, inductive and capacitive elements. The inaccuracy accepted by this model is insignificant compared to the one caused by data acquisition. If the capacitive component is unknown it can be estimated by load factors given in literature which are typical for different consumer groups [11].

The frequency characteristic of loads depends on the composition of the load as well as on the time of day and the season. Detailed measurements may lead to data which can be used for the a.m. linear model as well as for more complex models [12]. If measured data are available over a longer period of time (e.g. one week) also models can be fed which are used for time-sequential calculations via Monte-Carlo-Simulation [13].

Harmonic generators are all loads with non-linear U/I-characteristics including all periodically switched loads [14]. The injection of harmonic currents is modelled by current sources in parallel to a source impedance. This model represents all non-linear loads on the connection point. The harmonic currents lead to harmonic voltages over the system impedance. Overlaying system levels are modelled by harmonic voltage sources summarising all harmonic effects in this system level. Both sources are described by the attributes frequency, magnitude and phase angle of the voltage / current. These models can also be regarded for time-sequential Monte-Carlo-Simulation [13].

The non-linear load models do not regard an interaction between voltage distortion and harmonic currents. Based on this restriction the calculation via linear harmonic analysis is possible, otherwise the system looses its linear behaviour and the simple analysis method cannot be applied. This procedure is well known and state of the art.

5 INVESTIGATIONS

5.1 Example I: Connecting a medium-frequency converter to an urban 10-kV-system

5.1.1 Investigated System

Example I comprises a medium-frequency converter feeding two melting ovens. The converter is connected to an urban 10-kV-system at the point of common coupling (PCC) [15]. Figure 3 gives an overview.

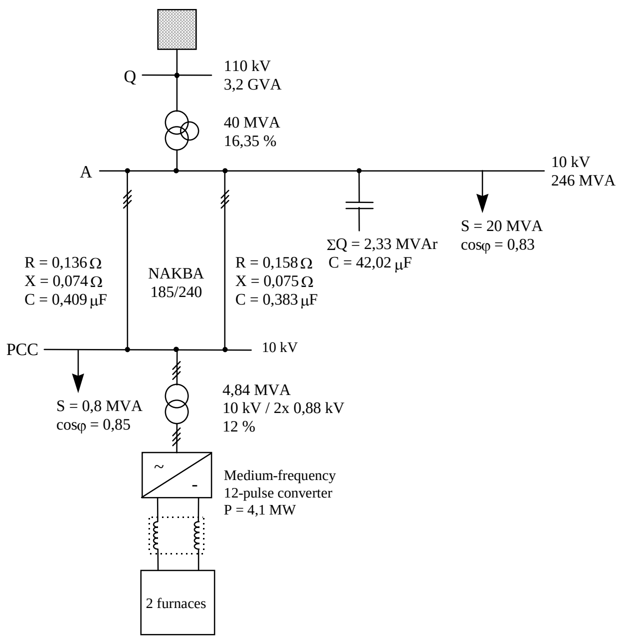

Figure 3. Connection of a medium-frequency converter to an urban 10-kV-system

Node PCC is connected by two parallel 10-kV-cables to busbar A. The MV system is supplied by a 40 MVA-transformer from the 110-kV-system. Further customers are represented by a load with an apparent power of 20 MVA, cosφ=0,83. Besides that cable capacities of 42,02 µF are considered. Further industrial customers with a load of 0,8 MVA, cosφ=0,85, are connected to PCC.

5.1.2 Measurements and Calculations

The system was investigated before and after the connection of the converter. Measurements of the harmonic voltages at node PCC have been carried out with the measuring system [4] described in section 2.1. Additionally the harmonic currents given by the manufacturer were checked.

Table I summarises the 95%-values of all measured values for Example I which usually are used to value measured harmonics [5]. That means 95% of all measured values during the measuring period were less than or equal to this value. Table I includes the harmonic voltages as well as the respective angles for the cases with/without the converter. The measured harmonic currents of the converter are added.

The calculated harmonic voltages are given for the converter connected to the system.

5.1.3 Discussion of Results

The comparison of the results of the measurements before and after connecting the converter to the system shows some interesting effects. Because of the 12-pulse-converter the magnitude of the 11th and 13th harmonic voltages increase considerably as expected as well as for the 23rd and 25th harmonic order. On the other hand the converter behaviour leads to a decreasing level for the 5th and 7th harmonic order.

The calculated results show a good correspondence to the measured values for two reasons: i) The system components are well known in this case including the compensation devices and the actual load situation. ii) The basic harmonic voltage levels including the respective angles have been measured and could be used to parameterise an equivalent at the 110-kV-busbar.

Table I. 95%-values of measured harmonic voltages and currents and calculated harmonic voltages at node PCC for Example I

	Measurements					Calculation
	Without the converter (basic harmonic level)		Converter	With the converter (resulting harmonic level)		
Frequency [Hz]	Harmonic Voltage [%]	Angle [Degree]	Harmonic Current [A]	Harmonic Voltage [%]	Angle [Degree]	Harmonic Voltage [%]
250	2,94	-124	0,39	2,49	-118	2,90
350	0,82	-102	0,29	0,61	-89	0,804
550	0,38	-118	11,66	0,949	32	0,862
650	0,31	-72	8,06	0,853	-5	0,931
850	not measured	-	0,52	0,061	-12	0,045
950	not measured	-	0,45	0,058	-14	0,033
1150	0,42	-32	3,84	0,572	-25	0,632
1250	0,37	-51	3,56	0,44	-39	0,54

5.2 Example II: Harmonic load of an industrial plant connected to an industrial 30-kV-system

5.2.1 Investigated System

Example II covers an industrial 30-kV-system where a plant operates several arc furnaces, a medium-frequency furnace as well as sundry motor drives (figure 4). Normally the 30-kV-system is a mesh-operated system, but also a second variant is investigated where the cables between busbars B2 and B3 are switched off in B3. The 30-kV-system is fed by two transformers with 31,5 MVA rated power each. The superposed 110-kV-power system is represented by its short-circuit power. Due to lack of information it is assumed that only the mentioned industrial consumer generates harmonics, although there are two further industrial consumers connected to the 30-kV-system.

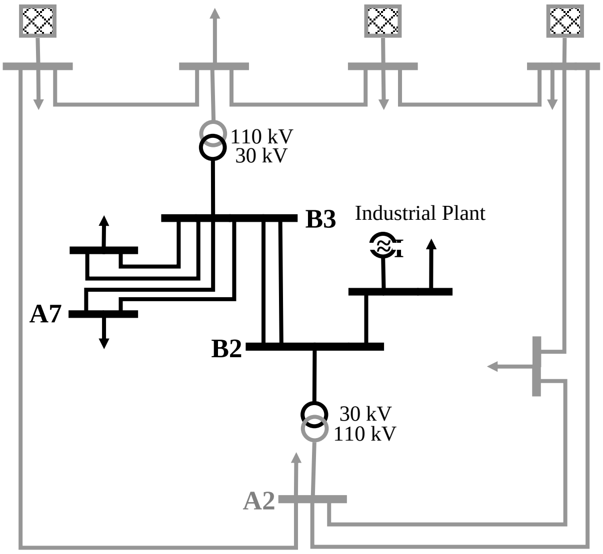

Figure 4. Connection of an industrial plant to a 30-kV-system

5.2.2 Measurements and Calculations

The harmonic voltages were measured at node B2 as well as the harmonic currents of the industrial plant. Unfortunately it was only possible to measure the harmonic voltages for the plant in operation for both variants of the a.m. system topology.

Table II summarises the measurements for harmonic voltages and currents and the calculated harmonic voltages.

5.2.3 Discussion of Results

In contrast to the excellent correspondence between measurement and calculation for Example I the results in the second case are very poor. The resulting harmonic levels are approximately two times higher compared to the measurements. Although a uniform tendency can be recognised. The harmonic levels for the variant „Switched off in B3“ are generally higher than for the mesh-operated situation.

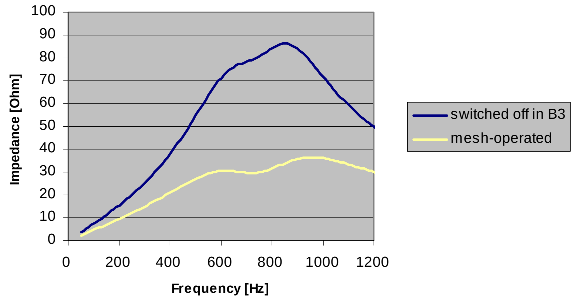

Figure 5. Network impedances depending on the frequency for Example II

Table II. 95%-values of measured harmonic voltages and currents and calculated harmonic voltages at node B2 for Example II

	Measurements			Calculations	
	Industrial plant	Mesh-operated	Switched off in B3	Mesh-operated	Switched off in B3
Frequency [Hz]	Harmonic Current [A]	Harmonic Voltage [%]	Harmonic Voltage [%]	Harmonic Voltage [%]	Harmonic Voltage [%]
250	24,9	1,05	1,65	1,75	2,89
350	16,3	0,95	1,35	1,69	2,93
550	11,3	0,75	1,95	1,93	4,20
650	8,4	0,85	2,75	1,49	3,73
850	6,2	0,35	2,55	1,27	3,24
950	5,3	0,55	1,05	1,12	2,41
1150	2,9	0,55	0,35	0,57	0,97
1250	2,75	0,25	0,25	0,43	0,71

This perception can be confirmed by the course of the frequency dependent impedance at node B2 which can be seen in figure 5. In case of the cables switched off in B3 a parallel resonance between the transformer inductance and the capacities of the switched off cables causes increased impedances at approximately 800 Hz which entails increased harmonic levels in the corresponding variant.

6 PARAMETER STUDIES

As shown in chapter 5 major differences between the measurements and the calculation results can be regarded. To investigate the reasons for these differences the following input data are varied to check the sensibility of the results:

- Basic harmonic level,
- load parameters and
- existence of reactive power compensation devices.

As an important precondition all other system data are assumed as correct, especially the RLCs of cables and transformers.

The investigated industrial plant is in operation from 6 a.m. to 8 p.m. every day. Therefore the basic harmonic level cannot be measured for day load situations. Measurements at night would not be representative due to low load situation. So the important information about the basic harmonic level is missing.

The following investigations are all done for the mesh-operated system.

In table III a harmonic equivalent is assumed causing three different basic harmonic levels (magnitude and phase angle) for 250 Hz which have been derived in order to meet the measured harmonic level of 1,05 % for the converter in operation. As the angles of the harmonic voltages are unknown (unfortunately, the angle of the resulting harmonic level has not been measured) there is no way to decide, which level is close to reality.

Table III. Assumed basic harmonic levels and corresponding simulation results for 250 Hz

30kV Node B2			
Basic Harmonic Level		Resulting Harmonic Level	
Harmonic Voltage [%]	Angle [Degree]	Harmonic Voltage [%]	Angle [Degree]
0,70	-109	1,05	71
1,40	-146	1,05	125
2,10	-139	1,05	165

As table III shows, the basic harmonic level is of utmost importance for the calculation results. Figure 6 further highlights this problem. The complex addition of the basic harmonic level (2,10%, -139°, line 3 in table III) and the measured level of the industrial plant (1,75%, 71°, table II, angle added) leads to the resulting harmonic level (1,05%, 165°). Because of the unknown angles nearly every configuration can be realised.

As a consequence, if it is not possible to determine the basic harmonic load of the system, every harmonic source in the system must be modelled individually in full detail in order to derive good calculation results.

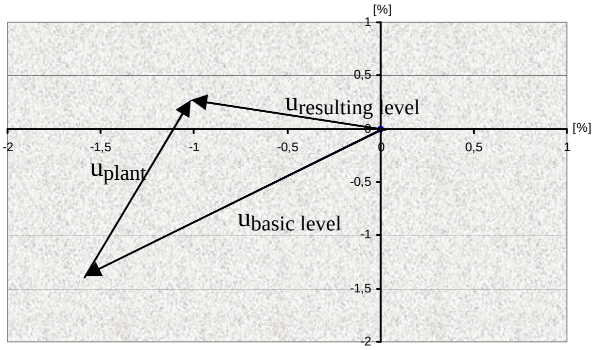

Figure 6. Addition of the complex harmonic voltages at node B2

An additional element of uncertainty in data acquisition are the loads. Figure 7 indicates the impact of the load impedances on the frequency-dependent system impedance. The apparent power of the loads is changed to 80% and to 120% referred to their original value. Table IV contains the results for the harmonic voltages.

Compared with the influence of the basic harmonic levels the influence of the loads is minor. The general shape of the curves is unchanged, i.e. the resonant frequencies are kept constant. Nevertheless it is a problem which should be regarded, because the exact knowledge of the height of the loads and the cosφ is never given as the loads usually will change over time.

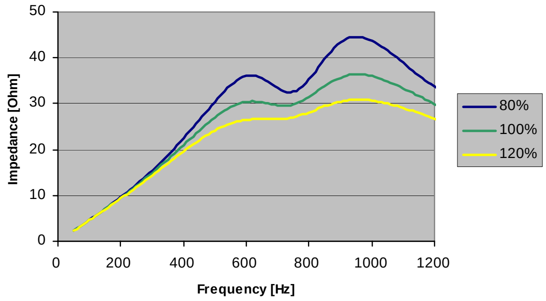

Figure 7. Variation of all loads of the power system of the mesh-operated system

Figure 8 shows the results of the variation of the parameter cosφ of the loads while the apparent power is kept constant. A deviation of the cosφ of 5 % causes only minor changes of the network impedance.

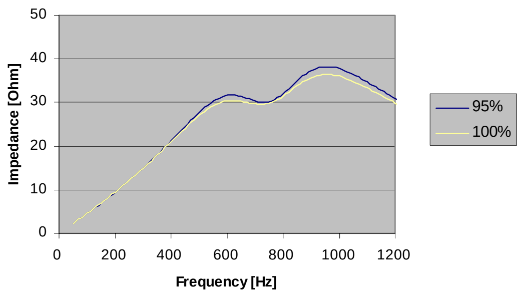

Figure 8. Variation of the cosφ of all loads in the power system of the mesh-operated system

Finally a reactive compensation device (node A7, 6 Mvar) is regarded for the calculations shown in figure 9. The inductor-capacitor unit is tuned to 240 Hz with a quality factor of 20. The course of the impedance shows that not only the harmonics around the 5th order are influenced but that the whole curve is moved to the right. The simulated harmonic voltages are given in table IV.

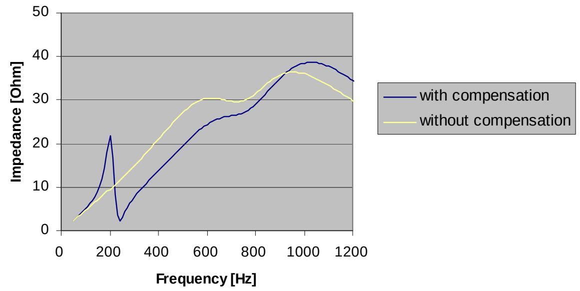

Figure 9. Network impedance with/without reactive-power compensation in A7

Table IV. Simulated 95 %-values of harmonic voltages regarding different loads and a compensation device in A7

	Without Compensation			With Compensation
	100 % load	80% load	120% load	100 % load
Frequency [Hz]	Harmonic Voltage [%]	Harmonic Voltage [%]	Harmonic Voltage [%]	Harmonic Voltage [%]
250	1,75	1,78	1,70	0,39
350	1,69	1,77	1,60	1,03
550	1,93	2,25	1,70	1,47
650	1,49	1,74	1,31	1,27
850	1,27	1,49	1,11	1,20
950	1,12	1,37	0,95	1,15
1150	0,57	0,65	0,50	0,65
1250	0,43	0,48	0,39	0,50

7 CONCLUSIONS

With the help of a digital simulation program the resulting harmonic voltages or the frequency-dependent impedance can be calculated in advance to connecting harmonic producers to the power supply system. Calculations do not relieve the utilities from measurements at all, but some may be avoided especially if the behaviour of the system has been observed in detail for some time.

An essential precondition for the quality of the simulation is the good knowledge of data of the power system. Parameter studies have shown, that especially the knowledge of the basic harmonic voltages is of major importance. Another problem is, that reactive power compensation devices at customer installations are often unknown or their operation times are unknown. As this may cause additional resonances in the frequency dependent system impedance, their impact may be serious and cannot be estimated.

As a general recommendation when using harmonic simulation tools for the consideration of the connection of additional harmonic sources it can be stated:

- If the basic harmonic levels in the system are not known their magnitude and phase angle should be measured and some harmonic equivalent sources should be tuned in a way that the measured values are met. Only then the studies for the additional customers should be carried out.
- If ever possible one should try to obtain data about reactive power compensation devices or filters which may be installed at customer installations.
- Compared to that the amount of the loads tend to have a minor influence on the results.
- The parameters of lines, transformers etc. are well known for the frequency range relevant to harmonic problems.

Based on these information the impact of additional harmonic producer can be simulated in detail and good results can be expected.

8 ACKNOWLEDGEMENT

The authors would like to thank the Stadtwerke Bielefeld for placing data at the disposal and giving the opportunity to carry out measurements of harmonics in their power system.

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