HARMONIC FACTOR EVALUATION FOR ELECTRIC AND MAGNETIC FIELDS USING SYMMETRICAL COMPONENTS

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ABSTRACT

In this paper a method for consideration of harmonics for the calculation of low frequency electric and magnetic fields of electrical power systems is presented. To reduce evaluation effort harmonics factors are established which are evaluated from the analysis of real measured voltage and currents using Fourier transformation, symmetrical component analysis and weighting functions according to the guidelines from ICNIRP (1998 and 2010). The impact of a zero sequence systems in voltage on electric fields on the base of an application example is shown. Further it is verified, that this method will lead to a worst-case estimation of the field exposure. Typical values for the harmonic factor and obstacles in the evaluation of the harmonic factor due to e.g. windowing, averaging are discussed.

INTRODUCTION

During environmental impact assessment of high voltage overhead lines (OHL), high voltage cables, power stations or substations, the planning engineers are faced with the evaluation of the electric and magnetic field exposure in advance. Since the consideration of harmonics is demanded by several standards for exposure assessment (e.g. ICNIRP guidelines), there is a need of knowledge about the possible occurrence of harmonics. Therefore a method is needed to consider these harmonics easily for a forecast of the low frequency fields including safety aspects, but with the scope not to overestimate unnecessarily.

Because the simultaneous exposure to fields of different frequencies j is additive in its effect, harmonics have to be considered by applying e.g. following conservative criteria for external fields according to the guidelines of ICNIRP[3]:

$$ER_E = \sum_{j=1Hz}^{10MHz} \frac{E_j}{E_{L,j}} \leq 1 \qquad (1)$$

$$\text{and } ER_B = \sum_{j=1Hz}^{10MHz} \frac{H_j}{H_{L,j}} = \sum_{j=1Hz}^{10MHz} \frac{B_j}{B_{L,j}} \leq 1 \qquad (2)$$

ER_E and ER_B are the resulting exposure ratios of the electric or magnetic field, E_j and H_j ($B_j=\mu_0 H_j$ in air) the electric or magnetic field strengths at the frequency j and $E_{L,j}$ and $H_{L,j}$ are the reference values at the frequency j.

These restrictions (1) and (2) are known as very conservative for an application on signals with harmonics, because the real phase angle information is neglected and all spectral components are considered to be in phase. Nevertheless the less conservative evaluation in compliance with [2], [3] using filtering or the phase angle information of the harmonics cannot be applied, because up to now typical phase angles of harmonics in voltage or current of distribution or transmission systems are rarely available.

In case of distorted voltages or currents the application of formula (1) or (2) in practice results in a set of field calculations for each harmonic. To reduce evaluation effort a harmonic factor k_H will be established which will be calculated considering symmetrical components of typical current or voltage harmonics. Using this factor the field calculation has to be done only for the fundamental frequency.

This approach is applied on two different shaped single circuit tower designs of 110-kV-OHL (fig. 1). The distance between the lowest phase conductor and ground is considered with h_S=10 m. The calculation of the electric field strength of this OHL is done by charge simulation method.

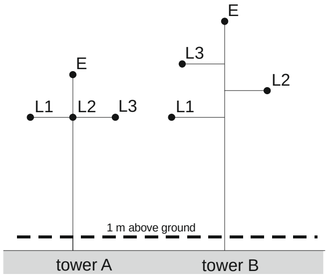

Fig. 1: Single system tower designs of 110-kV-three phase overhead line

HARMONIC FACTOR K_H

Because of the principal analogy between the evaluation of the electric and magnetic field, only the evaluation of the electric field is shown in the following.

Single phase system

General, for a single-phase-system it can be assumed, that a resulting exposure ratio for the electric field strength ER_E according to the guidelines [1] or [3] can be calculated from the electric field strength of the fundamental frequency E_1, corrected by a harmonic factor k_H, and the reference value $E_{L,\nu}$ at fundamental frequency (3):

$$ER_E = \sum_{\nu=1}^{n} \frac{E_\nu}{E_{L,\nu}} = \frac{E_1}{E_{L,1}} \cdot \sum_{\nu=1}^{n} \left(\frac{E_\nu}{E_1} \cdot \frac{E_{L,1}}{E_{L,\nu}} \right) = \frac{E_1}{E_{L,1}} \cdot k_{H,E}$$
$$= ER_{E,1} \cdot k_{H,E} \quad \text{with} \quad k_{H,E} = \sum_{\nu=1}^{n} \frac{E_\nu}{E_1} \frac{E_{L,1}}{E_{L,\nu}} \qquad (3)$$

This harmonic factor k_H can be calculated directly from the harmonics of the voltage U – or in case of the magnetic field from the current I - and the field calculation has to be done only once for the fundamental frequency, as long as the following relation between the harmonics (index ν) and fundamental frequency (index 1) is valid:

$$\frac{U_\nu}{U_1} = \frac{E_\nu}{E_1} \quad \text{or} \quad \frac{I_\nu}{I_1} = \frac{B_\nu}{B_1} \qquad (4)$$

The harmonic factors $k_{H,U}$ and $k_{H,I}$ can then be calculated using voltage and current instead of field quantities as shown in the following formulas (5). In order to highlight this, U respectively I are added to the index of k_H.

$$k_{H,U} = \sum_{\nu=1}^{n} \frac{U_\nu}{U_1} \frac{E_{L,1}}{E_{L,\nu}} \quad \text{or} \quad k_{H,I} = \sum_{\nu=1}^{n} \frac{I_\nu}{I_1} \frac{B_{L,1}}{B_{L,\nu}} \qquad (5)$$

It must be mentioned that this simple approach is valid for single phase systems only and therefore can be used for e.g. railway systems, as long the current distribution between the participating conductors is more or less frequency independent.

Three phase (3~) systems

In this paper it is proposed to apply the well known concept of symmetrical components to calculate the resulting field exposure for 3~systems.

A more simple approach for 3~systems would be to calculate the $k_{H,U}$ for each phase voltage and then take the mean value $k_{H,Umean}$ of them for the exposure calculation. In that case harmonics would be treated as positive sequence systems only.

It's quite evident that zero (0) sequence system results in a different field profile than positive (1) and negative (2) sequence systems. For this reason, the calculation of the exposure ratio has to be split in the following way:

$$ER_E = \frac{E_1^0}{E_{L,1}} \cdot k_{H,U}^0 + \frac{E_1^1}{E_{L,1}} \cdot k_{H,U}^1 + \frac{E_1^2}{E_{L,1}} \cdot k_{H,U}^2 \qquad (6)$$
$$= ER_{E1}^0 \cdot k_{H,U}^0 + ER_{E1}^1 \cdot k_{H,U}^1 + ER_{E1}^2 \cdot k_{H,U}^2$$
$$\text{with} \quad k_{H,U}^{(0,1,2)} = \sum_{\nu=1}^{n} k_{H,U,\nu}^{(0,1,2)} = \sum_{\nu=1}^{n} \frac{U_\nu^{(0,1,2)}}{U_1^1} \frac{E_{L,1}}{E_{L,\nu}}$$

Since positive (1) and negative (2) sequence systems result in the same field profile, the calculation can be simplified to:

$$ER_E = ER_{E1}^0 \cdot k_{H,U}^0 + ER_{E1}^1 \cdot k_{H,U}^{1+2} \qquad (7)$$

ER_E ………….. total exposure ratio including harmonics

ER_{E1}^0 ………… exposure ratio of the zero sequence system for the fundamental frequency

$k_{H,U}^0$ …………… harmonic factor for the zero sequence system

ER_{E1}^1 ………… exposure ratio of the positive sequence system (=negative sequence system) for the fundamental frequency

$k_{H,U}^{1+2} = k_{H,U}^1 + k_{H,U}^2$. resulting harmonic factor for positive and negative sequence system

The symmetrical components of the current or voltage can be evaluated after Fourier Transformation of sampled phase signals using the transformation into symmetrical components (see therefore e.g. [4]).

Effect of mixture of symmetrical components

In theory under ideal symmetrical circumstances, harmonics of order 3n ($n \in \mathbb{N}^*$) form a zero sequence system, harmonics of order 3n+1 form a positive sequence system and harmonics of order 3n-1 form a negative sequence system. In real power systems a mixture of the symmetrical components of each harmonic exist. E.g. the zero sequence system in voltage for the fundamental frequency in networks with resonant grounded starpoint at normal operation can be up to 10% of the positive sequence system. In fig. 2 the calculated electric field strengths in 1 m above ground for tower A and B from fig.1 with a mixture of U_1^0 and U_1^1 are shown.

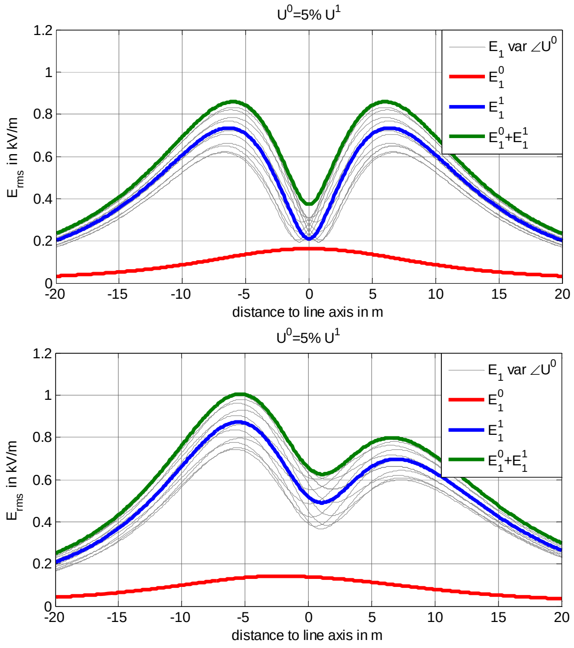

Fig. 2: Electric field strength of tower A (above) and tower B (below) with the symmetrical components of the fundamental frequency U_1^1=70 kV, U_1^0=5%U_1^1, U_1^2=0 for different phase angles of U_1^0

The grey lines show the rms-values of electric field strength calculated with phase voltages which result from different

phase angles of U_1^0(E_1^0 var $\angle U^0$).
E_1^1 (blue) is the result of only the positive sequence system, E_1^0 (red) of only the zero sequence system. It can be seen, that the sum of these two rms-values (green) is greater or equal than the values of the combination with different phase angles (light grey).
Therefore, if the phase angle between U_1^0 and U_1^1 isn't known in advance or when it can vary in a big range, the sum of E_1^0 and E_1^1 automatically leads to a worst case scenario.
The same is valid for the combination with a negative sequence system and for harmonics.
Generally that can be expressed for all harmonics of order ν with the following formula:

$$\max(E_\nu(\underline{U}_\nu^0,\underline{U}_\nu^1,\underline{U}_\nu^2))\Big|_{\angle U_\nu^0,U_\nu^2} \le E_\nu(\underline{U}_\nu^0)+E_\nu(\underline{U}_\nu^1)+E_\nu(\underline{U}_\nu^2) \quad (8)$$

E_ν are the rms values of the ν^{th} harmonic.

Application with a real spectra

A typical example for a real voltage spectrum for a 110-kV-network split in symmetrical components is given in fig 3.

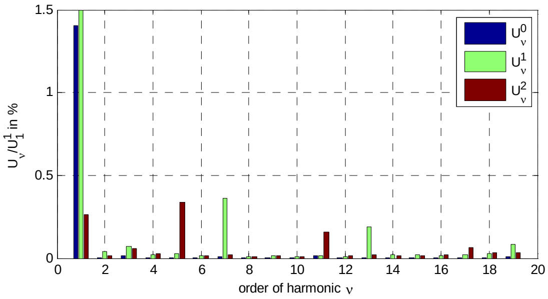

Fig. 3: Voltage harmonics in % split in symmetrical components of voltage signals

Except for the fundamental frequency, the zero sequence system hardly exists. Contradictory to theory also the 3rd harmonic mainly consist of positive and negative sequence systems. It can be seen, that – in accordance with theory – the 5th , 11th and 17th harmonics build primarily a negative sequence system and the 7th, 13th and 19th a positive sequence system. Considering the reference values of ICNIRP 2010 for public exposure with harmonics up to the order of 20 results in k_H^0=0.024, k_H^1=1.103 and k_H^2=0.067 for this example.
The results for the exposure ratio ER_E of tower A, 1 m above ground for a calculation with these k_H and the calculation for each harmonic is compared in the fig. 4. Additionally an simple approach with a mean k_H of the three phases ($k_{H,Umean}$=1.134) is shown.
On one hand it can be seen, that at each distance the ER_E resulting from calculations with harmonic factors with symmetrical components (green) is higher than the ER_E ($U_{\nu,L1}$,$U_{\nu,L2}$,$U_{\nu,L3}$) obtained by a set of field calculation using the spectrum of the phase voltages (blue).
On the other hand the simple approach with a mean $k_{H,Umean}$ of the phases (red) would lead to an underestimation in some areas.
An overestimation (green > blue) solely establishes due to the mixture off the symmetrical systems.

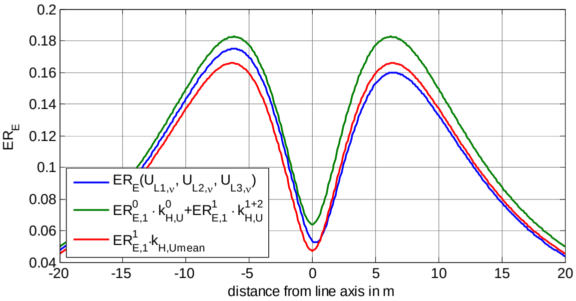

Fig. 4: Exposure ratios ER_E calculated with 3 different approaches for tower A.

TYPICAL RESULTS FOR HARMONIC FACTORS

The Association of Austrian Electricity Companies (OesterreichsEnergie) organized a measurement campaign to evaluate typical spectra of harmonics in currents and voltages in low- medium- and high-voltage-feeders in Austrian substations. Most of the measurements were performed with standard PQ-measurement equipment, providing 10 min rms values only. To obtain information about harmonic symmetrical components, additional measurements including phase angle information were done by the authors.
In tab. 1 and 2 typical values of $k_{H,U}$ and $k_{H,I}$, considering harmonics up to the order of 20, for high voltage (HV) medium voltage (MV) and low voltage (LV), are presented. The reference values for electric field strength $E_{L,j}$ didn't change from guideline 1998 [1] to 2010 [3] in the concerning frequency range (50…1000 Hz), thus, the given values are valid for both guidelines. In the case of magnetic field reference values $B_{L,j}$, significant changes for the fundamental frequency and the harmonics have been made. The resulting effect on k_H is shown in tab. 2.

	ICNIRP [1,3]	
	$k_{H,U}^0$	$k_{H,U}^{1+2}$
LV	0.03	1.3
MV	0.02	1.2
HV	0.03	1.25

Tab. 1: Typical values of harmonic factors $k_{H,U}$ for electric field exposure ER_E

Typically, the current's harmonic content in real systems varies strongly with the load situation. For higher load, the relative current distortion – expressed as THD_i - decreases and so does $k_{H,I}$ (fig. 5). Since magnetic field exposure is usually calculated for maximum currents (e.g. thermal rated current), typical values for high loading are given in tab. 2.

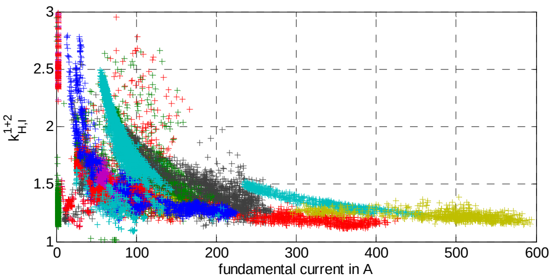

Fig. 5: Typical $k_{H,I}^{1+2}$ *in MV, calculation based on [1]; different colors correspond to different feeders*

	ICNIRP 1998 [1]		ICNIRP 2010 [3]	
	$k_{H,I}^{0}$	$k_{H,I}^{1+2}$	$k_{H,I}^{0}$	$k_{H,I}^{1+2}$
LV	0.5	1.5	0.2	1.2
MV	0.15	1.3	0.1	1.15
HV	0.05	1.2	0.03	1.1

Tab. 2: Typical values of harmonic factors $k_{H,I}$ *(for 'high' load) for magnetic field exposure* ER_B

The harmonic factors $k_{H,I}$ decreases comparing ICNIRP guideline 2010 [3] with 1998 [1]. For typical values of distribution networks the reduction for $k_{H,I}^{1+2}$ is up to 20 %. Because additionally the reference value $B_{L,1}$ for 50 Hz is increased from 100 µT to 200 µT the resulting magnetic field exposure ER_B will be reduced by 55 % to 60 % due to the new guideline.

OBSTACLES FOR THE HARMONICS EVALUATION FOR FIELD EXPOSURE

By applying this method on real systems several so far not satisfying answered questions appeared, which are discussed in this section.

- For practical application it is not clear, up to which order harmonics have to be considered. Including high order harmonics might lead to overestimation due to signal noise. In this paper harmonics up to the 20th order are considered, thus covering the most relevant part of the spectrum.
- High k_H values usually occur only rarely and during a short period of time. There are no clear instructions if, and how averaging of the harmonics or resulting harmonic factors is allowed.
- If evaluation of harmonics is done according to IEC 61000-4-7 [6], phase information is lost during grouping and smoothing process. Symmetrical component evaluation will be impossible.
- Signal sampling without a phase-locked loop might lead to spectral leakage effect and an overestimation of the harmonic factors.
- Current transducers and especially voltage transducers for MV and HV have a nonideal transfer function. Amplitudes and phase angles of higher order harmonics might be falsified.

CONCLUSION

It could be shown, that by applying harmonic factors using symmetrical component analysis from measured voltage or current a worst-case calculation of the exposure ratio for high voltage lines can be done. Additionally, a zero sequence system in the fundamental frequency can be handled very easily.

They proposed method using symmetrical components with the given typical values for harmonic factor is suitable and sufficient for most field exposure evaluations of e.g. projected power lines, which have to be done usually in advance.

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