SIMPLIFIED MAGNETIC FIELD EVALUATION FOR WORKERS WITH CONDUCTOR LOOPS

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ABSTRACT

The Directive 2013/35/EU of the European Parliament [1] is designed to protect workers against the risks of electric, magnetic and electromagnetic fields. Therefore, it is obligatory to evaluate all workplaces with sources causing these fields. This paper shows a simple method for evaluating magnetic fields of electrical energy systems. The method is safe and conservative though with little overestimation, fast and easy to implement even for non-specialists and requires less documentation work.
This paper will give the formulas as well as the verification for this method.

INTRODUCTION

In any electrical installation, like public grids, substations, distribution boxes and industrial networks there are several sources of magnetic fields. In general, these installations have:

- complex geometrical shapes and
- time depending load distributions.

Hence, the resulting field is very depending on the actual load flow and the point of evaluation within the installation.

A measurement of the field just shows one snapshot at a specific time. If there is only one source, an extrapolation of the field to higher values of the load is possible. This simple situation hardly occurs in practice; typically, several sources of electromagnetic fields are present. Even if the operator would be able to operate all feeders with maximum load for the moment of the measurement a different load flow might cause higher exposure.

Obviously, there is the possibility of modelling a substation or distribution box in detail with commercial programs and calculate the magnetic field for several worst-case load distributions in order to find out the maximum magnetic field in all accessible areas. However, this modelling needs a huge effort of time for a specialist concerning:

- collecting data for the necessary 3D modelling (e.g. currents, geometry, harmonics),
- the modelling itself,
- figuring out the worst-case scenarios,
- and the documentation of the results.

In Austria a working group of the national standardization committee (authors are members) is elaborating a national guideline OVE R 27. There, we address the problem in an innovative way. (see also paper 1671, CIRED 2019)

The approach: Only the knowledge, that in all points of proof (PoP) the magnetic field is below the Action Levels AL [1], is necessary for evaluation. There is no need to know an actual value of the magnetic field at each point in the working area [2]. A simplified method for assessing the requirements for the magnetic fields delivers sufficient results as a basis for the evaluation.

INFINITE STRAIGHT LINE

The well-known relation for the magnetic flux density B (T) of a single infinite straight conductor in air with a current I (A) and a distant earth return path at the distance d (m), is given in the following formula (magnetic field constant $\mu_0 = 4\pi 10^{-7}$ Vs/Am:

$$B = \frac{\mu_0}{2\pi} \cdot \frac{I}{d}$$

The reference Distance D_R (m) is defined as follows:

$$D_R = \frac{\mu_0}{2\pi} \cdot \frac{I \cdot k_H}{AL}$$

If there is a dominant frequency, it is sufficient to use a harmonic factor $k_H(\mathrm{p.u.})$ and the magnetic flux density B of the dominant frequency to calculate the Action Level Quotient AQ (p.u.):

$$AQ = \frac{B}{AL} \cdot k_H$$

The harmonic factor k_H considers the relevant frequency spectrum in the magnetic field because of harmonics in the current and the frequency response of the action value curves. It can be evaluated from field or current measurements, using the respective action value curve. For more details, see [3].

$$k_H = \frac{AQ}{AQ_1}$$

We define the Action Level Quotient *AQ* either as the sum of the Multi-Frequency-Rule or otherwise the sum using the Weighted Peak Method according to [4] and AQ_1 as the quotient of *B* and the *AL* at dominate frequency (fundamental frequency).
The distance D_R is also a conservative guess for the necessary distance or so called action distance D_A to agree with the given *AL* even for two- and three-phase loops (2~, 3~). The actual necessary safety distance is always below this distance.

For example, for a 3~ power cable with a current I = 1000 A, an approximate k_H of 1.2 for MV-systems [3] and the low *AL* at 50 Hz from 1000 µT the distance D_R results in 0.24 m. Therefore, for distances greater than 0.24 m from the centre of any conductor of the cable, the magnetic field complies with the *AL*. If the cable is buried deeper than 0.24 m for this single source, the safety requirements of the directive are fulfilled.

If there is more than one source eg. two cables, the *AQs* of each source have to be summed up.

For the single straight line approximation the *AQ* at a distance *d* can be evaluated with:

$$AQ = \frac{D_R}{d}$$

Because the summation of the *AQs* is very conservative, only sources with an *AQ* higher than 0.2 have to be considered. Therefore, the relevance distance D_0 (m) is defined as the distance to any conductor where the *AQ* is less than 0.2. With this distance, relevant sources can be identified simply.

MODELLING WITH CONDUCTOR LOOPS

In order to get more accurate results and thus less overestimation, the actual conductor configurations are approximated with simple rectangular conductor loops as shown in the following Figure 1.

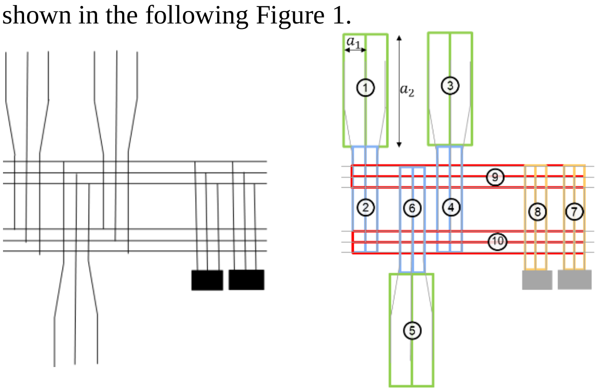

Figure 1: Plan view of a substation with 2 busbars and 5 branches, left: original plan view, right: approximation with three phase loops (1 to 10)

Each loop has the parameters distance between the phases a_1, length of the loop a_2, reference distance D_R (defined through phase current *I*, harmonic factor k_H and action level *AL* as shown above).

The following table 1 shows the formulas for simplified calculation of *AQ* at distances *d*, for 2~ and 3~ loops:

Table 1: Formulas for calculating AQ of 2~ and 3~ loops

Constraints for **2~ loop** ($a_2 > a_1$ otherworse exchange a_1, a_2)		
$d < a_1$	$a_1 \le d < a_2$	$d \ge a_2$
Max AQ at distance d		
$AQ = D_r/d$	$AQ = D_r a_1/d^2$	$AQ = D_r a_1 a_2/d^3$

Constraints for **long 3~ loop** $a_2 > \sqrt{3} \cdot a_1$		
$d < \sqrt{3} \cdot a_1$	$\sqrt{3} \cdot a_1 \le d < a_2$	$d \ge a_2$
Constraints for **short 3~ loop** $a_2 \le \sqrt{3} \cdot a_1$		
$d < \sqrt{\sqrt{3} \cdot a_1 a_2}$		$d \ge \sqrt{\sqrt{3} \cdot a_1 a_2}$
Max AQ at distance d		
$AQ = D_r/d$	$AQ = D_r a_1 \sqrt{3}/d^2$	$AQ = D_r a_1 a_2 \sqrt{3}/d^3$

If a distance to the loop to a specified AQ is needed (*AQ*=1 for Action level distance D_A, *AQ*=0.2 for relevant distance D_0), the following formulas of Table 2 shall be used.

Table 2 Formulas for calculating
the action distance $D_A = d(AQ=1)$ and
the relevance distance $D_0 = d(AQ=0.2)$ of 2~ and 3~ loops

Constraints for **2~ loop** $a_2 > a_1$		
$D_r/AQ < a_1$	$a_1 \le D_r/AQ < a_2$	$D_r/AQ \ge a_2$
Distance d for not exceeding AQ		
$d = D_r/AQ$	$d = \sqrt{D_r a_1/AQ}$	$d = \sqrt[3]{D_r a_1 a_2/AQ}$

Constraints for **long 3~ loop** $a_2 > \sqrt{3} \cdot a_1$		
$D_r/AQ < \sqrt{3} \cdot a_1$	$\sqrt{3} \cdot a_1 \le D_r/AQ < a_2$	$D_r/AQ \ge a_2$
Constraints for **short 3~ loop** $a_2 \le \sqrt{3} \cdot a_1$		
$D_r/AQ < \sqrt{\sqrt{3} \cdot a_1 a_2}$		$D_r/AQ \ge \sqrt{\sqrt{3} \cdot a_1 a_2}$
Distance d for not exceeding *AQ*		
$= D_r/$	$d = \sqrt{D_r a_1 \sqrt{3}/AQ}$	$d = \sqrt[3]{D_r a_1 a_2 \sqrt{3}/AQ}$

Figure 2 shows the *AQs* for different 3~ configurations, based on formulas given in Table 1.

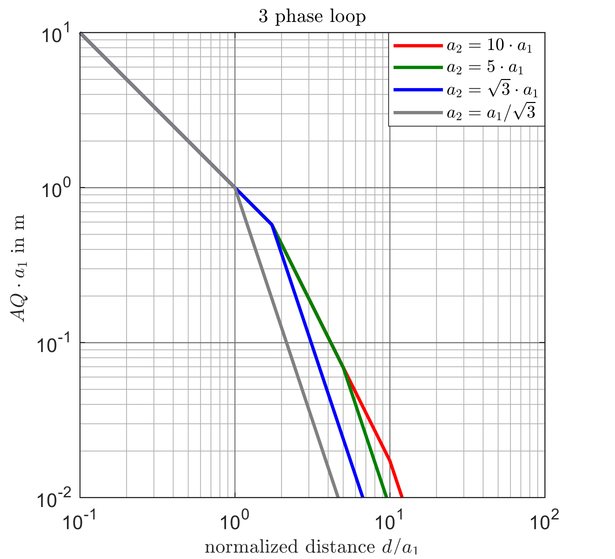

Figure 2: Action Level Quotient AQ for 3~loops with different length a_2 evaluated with the simplified formulas for D_R=1 m;

DETAILED VERIFICATION OF THE SIMPLIFIED FORMULAS

In the following, the maximum *AQ* in defined distances from the 3~loops are exemplarily evaluated with $a_2=5a_1$ and an D_R =1 m.

Therefore the maximum *AQ* in a distance *d* from a 3D-model with symmetric phase currents $\underline{I}_1 + \underline{I}_2 + \underline{I}_3 = 0$ are evaluated. All points of the envelope with a distance *d* to the loop are examined and the maximum is compared with the simplified formulas (Table 1). The envelope is symmetric in all directions (see Figure 3), therefore only 1/8 of the envelope has to be evaluated. This surface consists of four individual areas as described in Figure 3.

The maximum AQs depending on *d* for the individual areas are given in Figure 4. Additionally, the three areas with different gradients for the simplified formulas a given (compare with Table 1).

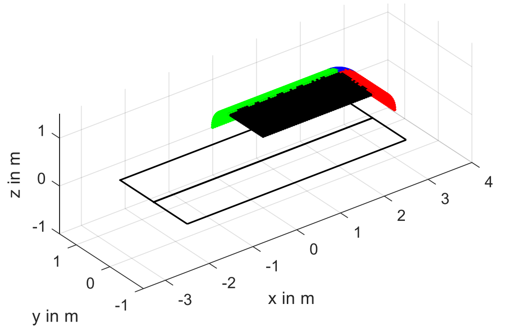

Figure 3: Part of the envelope around the loop for calculation of the maximum AQ, black: rectangle above the loop, green and red: parts of a cylinder around the outer conductor of the loop, and blue a part of the sphere, in the corner.

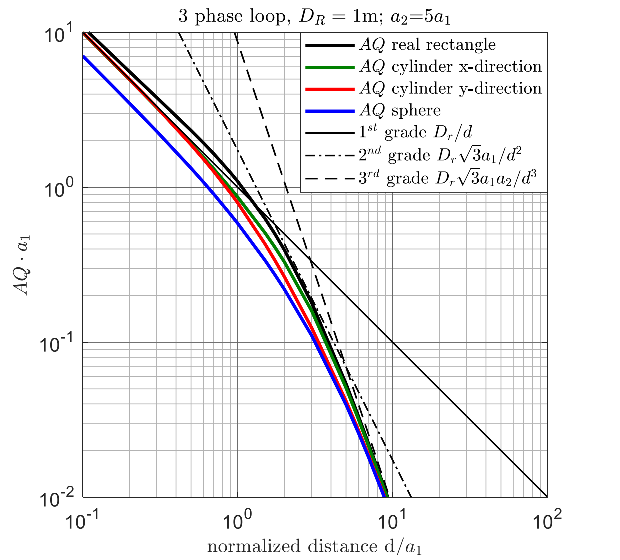

Figure 4: Maximum AQ for individual areas in a distance d for a 3~loop with a_2=5a_1

It can be seen, for d/a_1<1 the maximum *AQ* of the rectangle (black) is slightly higher than the AQ_{simp} of the simplified formula.

For examination of this underestimation through this simplification, AQ_{simp} is compared to the AQ of the 3D-Modell AQ_{3D}. The following *error* is defined:

$$error = \frac{AQ_{simp} - AQ_{3D}}{AQ_{3D}}$$

If the error is negative, an underestimation through the simplification occurs (Figure 5). The maximum underestimation is about -14% for this configuration ($a_2 = 5a_1$). The configuration $a_2 = \sqrt{3} \cdot a_1$ amounts to the highest underestimation of -17.5 % at $d/a_1 = 0.7$.

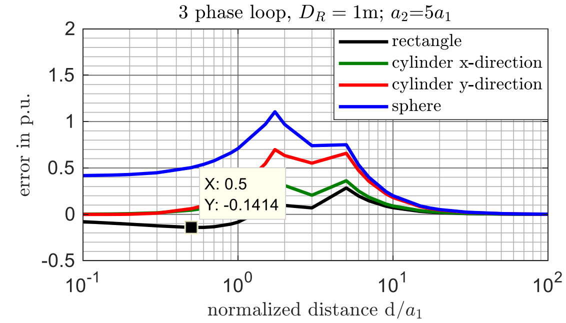

Figure 5: Error through the simplification compared to the 3D-model (negative=underestimation through simplification)

As it can be seen in Figure 5, only for the area of the rectangle and only in a distance $d/a_1 < 1$ an underestimation occurs. The further question is, how probable an underestimation at a certain distance is. for each distance the probability of error is evaluated (Figure 6). We presume, that it is equal probable for a Point-of-Proof to be on any point of the envelope of distance *d*.

Exemplary for a distance at $d/a_1 = 0.5$ the areas where the error is less than -5% are ~25% of the hole envelope. So the probability to choose a PoP within distance d with an error less den -5% is 25%.

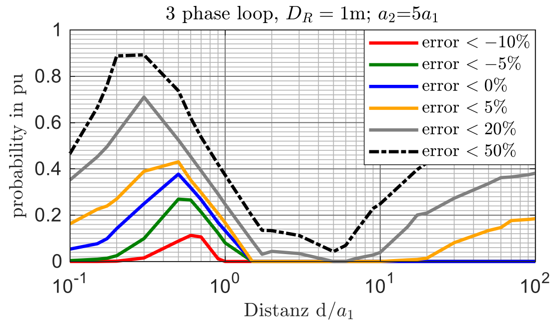

Figure 6: Probability for under- and overestimation through simplified formular rather than 3D-Modelling

The probability of underestimation of lower than -10% (error < -10%) is 0.1, so rather uncertain, the probabiltiy of any underestimation (error < 0%) is at maximum 0.38 at $d/a_1 = 0.5$.

Overall the method is except this small underestimation still conservative - on the one hand because of conservative chosen parameters a_1, a_1, k_H and I and on the other hand through summation of the AQs instead of vectorial addition of the fields – when there are more than one source, as it is shown exemplary in the next chapter.

SEVERAL SOURCES WITHIN A SUBSTATION

The following Figure 7 shows as an example a very simplified substation with one busbar and three branches.

Without the simplified method, first the substation has to be modeled with an appropriate field calculation program, than typically more than one worst-case power flow situations have to be defined, in order to find the maximum *AQ* at each accessible point.

For example for the branches 1… 3:

- scenario 1: I_1=2kA, I_2=0A, I_3=-2kA,
- scenario 2: I_1=2kA, I_2=-2kA, I_3=0A;
- scenario 3: I_2=0A, I_2=-2kA, I_2=2kA

The currents of the parts of the busbar in-between the branches result from these scenarios.

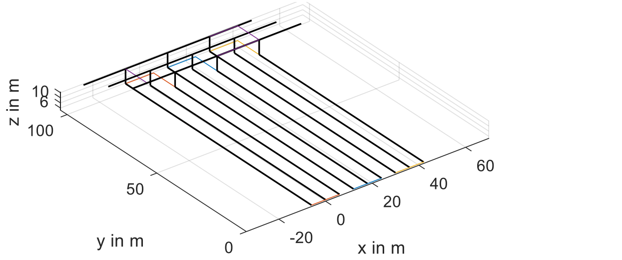

Figure 7: 3D-modell of a substation with 1 busbar and 3 branches, in color the contours of the simplified 3~loops

The maximum *AQs* of all three scenarios are given in Figure 8 at the height of workers head (z=2m).

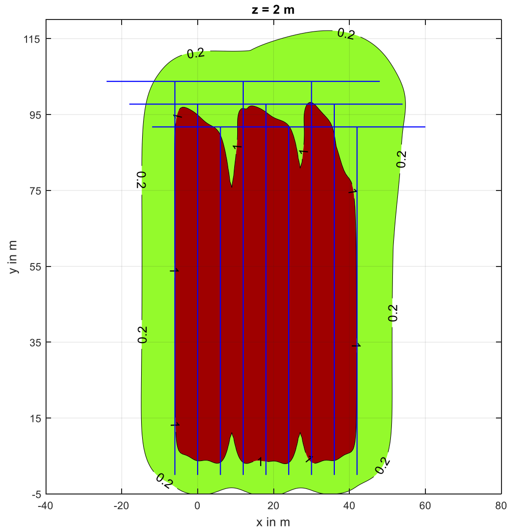

Figure 8: maximum AQ of all power flow scenarios

Figure 9 illustrates the *AQ*s for the first simplified loop and Figure 10 shows the sum of all 4 loops, while loops with *AQ*>0.2 are considered only.

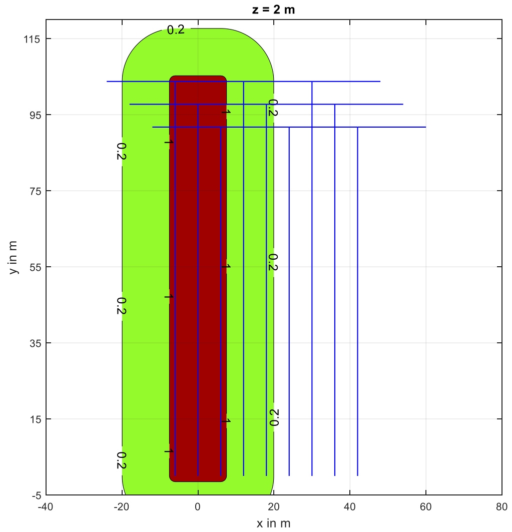

Figure 9: AQ with simplified formulas of the first loop only

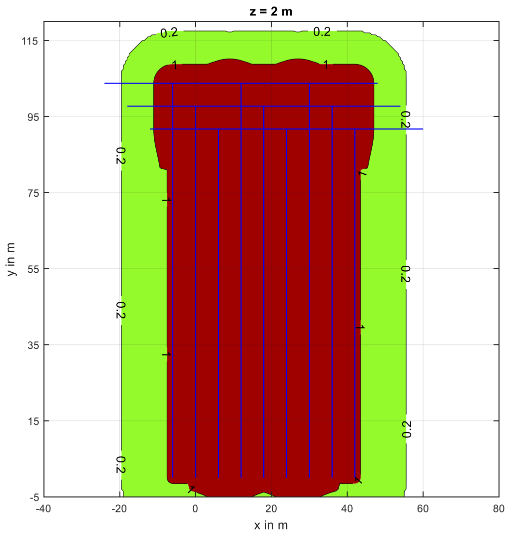

Figure 10: Sum of AQs of all simplified loops, considering only AQs>0.2;

When comparing Figure 8 and Figure 10 it can be seen, that the simplified method doesn't underestimate. Relevant overestimation occurs only in the area of the junctions (the busbar). Here it might be considered to shorten the simplified loops of the branches, if the calculation with the first approach leads not to the desired results.

SUMMARY

The proposed simplified magnetic field evaluation method of electrical energy systems supports the evaluation of workplaces according to the Directive 2013/35/EU of the European Parliament on "minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (electromagnetic fields)" at low frequency (1 Hz to 100 kHz) and has the following advantages:

- It is a quick conservative method and avoids underestimations
- It causes less modelling effort compared to 3D-modelling
- It causes less work for documentation
- It is easy to implement in an valuation tool (for example excel-tabular, web application, or evaluation and documentation software)

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