VALIDATION AND ANALYSIS OF A MAGNETIC FIELD MEASUREMENT METHOD TO BE UTILIZED IN INDOOR MV/LV SUBSTATIONS

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ABSTRAC

This paper describes validation and analysis of a magnetic field measurement method to be utilized in studies of indoor MV/LV substations. Synchronous magnetic field and load current measurements were performed inside 8 indoor MV/LV substations. The magnetic field measurement point nearby the LV connection was determined by considering public exposure in the residence above the indoor distribution substation. Based on the results and the analysis of the substation structures we will present simple methods to define magnetic fields in the vicinity of indoor MV/LV substations applicable for regular use in power distribution network companies.

1. INTRODUCTION

Measurements of electric and magnetic fields in living and working environment have increased because the public concern on the fields has increased. Due to their possible health effects, the International Commission on Non-Ionizing Radiation Protection (ICNIRP) has published guidelines, in which upper limits for public and occupational exposures have been presented [1]. Based on these guidelines, European Parliament and Council have enacted a Directive on minimum health and safety requirements regarding the exposure of workers to electromagnetic fields in 2004, which has to be nationally implemented in 2008 [2]. In 2003 ICNIRP expanded their guidelines by taking into account the harmonic components of the magnetic field with phase angles [3].

Electromagnetic fields have been studied at the Tampere University of Technology (TUT) since the 1980's. In recent years, the research has concentrated on evaluating exposure to magnetic fields. Previously, we have carried out measurements for selected indoor MV/LV distribution substations where relatively high magnetic field levels were observed or expected. Thereby, there was a clear need for a wider analysis considering different electric system structures and location specific groupings for indoor distribution substations. Previous measurements and their analysis have been reported in references [4, 5, 6].

A TransCat Project (Categorization of indoor MV/LV transformer substations according to magnetic field exposure) was established in 2005 to meet public and authority expectations and requirements. The project was organized by the Finnish Energy Industries, and financed by Tekes (Finnish Funding Agency for Technology and Innovation) and power distribution network companies in Espoo, Helsinki, Oulu, Tampere and Turku. These companies have about 25% of indoor MV/LV distribution substations in Finland. In this paper we describe validation and analysis of a developed magnetic field measurement method. We will also describe how the method can be used to extrapolate results measured in the neighborhood of the LV connection into space above the substations.

2. CHARACTERISTICS OF INDOOR MV/LV DISTRIBUTION SUBSTATIONS

Survey in the TransCat Project considered 53 indoor MV/LV distribution substations. In 12 of those detailed long-term magnetic field measurements were performed. In addition, 250 indoor MV/LV distribution substations have been measured previously in Helsinki. Indoor MV/LV distribution substation structures were grouped based on the height of the LV connection: U is up, M is medium and D is down. The most common structure was "U2, Cables near the ceiling". Together with the structure "U1, Bus bars near the ceiling" they consist 60% of the studied locations. Third structure, where LV connection is near the ceiling is "U3, Shielded LV connection near the ceiling." Medium height structures are "M3, Cables on the wall" and "M1&M2, Back-to-back" where transformer and LV switchgear are side by side and the LV connection is short. M2 is a shielded structure and M1 is not. LV connection was on the floor in structure "D, Cables on the floor." Fig. 1 presents classification of the structures based on the survey. [7]

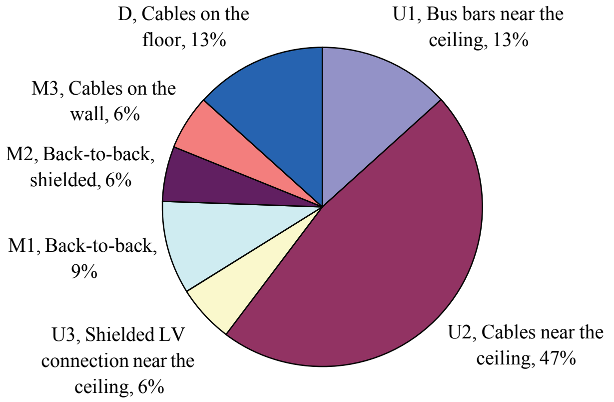

Figure 1. Classification of the studied 53 indoor MV/LV distribution substation structures based on the survey in the TransCat Project. [7]

3. MAGNETIC FIELD EXTRAPOLATION METHOD

Magnetic fields close to LV connections were previously measured by electricity distribution companies inside 250 indoor MV/LV distribution substations for categorization purposes. Afterwards, a need arose to utilize this massive set of magnetic field measurements to evaluate more closely public magnetic field exposure in spaces above the measured substations. Therefore, a magnetic field extrapolation method was developed for the most common substation structures U1, U2 and U3 having LV connection near the ceiling. These structures are most critical on public magnetic field exposure point of view. The extrapolation method can be applied also with M1, M2 and M3 structures to some extend.

Magnetic field B_{obs} in the space above the substation can be extrapolated as follows

$$B_{obs} = KB_{meas} \frac{I_{obs}}{I_{meas}} \cdot \frac{d}{0.13\,\mathrm{m}} \cdot \frac{B_{obs,ref}}{B_{meas,ref}}, \tag{1}$$

where K is the cumulative 50 Hz exposure coefficient, B_{meas} the measured magnetic field, I_{obs} the reference load current to be used in the extrapolation, I_{meas} the measured load current, d the phase distance, $B_{obs,ref}$ the reference value for observer presented in Fig. 3 and $B_{meas,ref}$ the reference value for the measurement point presented in Fig. 2. B_{obs} can be directly compared with the magnetic field 50 Hz public guideline value of 100 µT, because cumulative 50 Hz exposure coefficient K takes care of other frequencies.

Magnetic field extrapolation method was developed considering calculated magnetic field for a reference structure and reference load. In the reference structure the phase distance was 0.13 m. PEN conductor current was 10% of load current. Magnetic field of this reference structure, shown in Figs. 2 and 3, is used to extrapolate a corresponding field in the room above the substation from a measured field within the substation. When the magnetic field was measured close to the PEN conductor, the same extrapolation principle was used. Only the reference value $B_{meas,ref}$ for the measurement point had to recalculated.

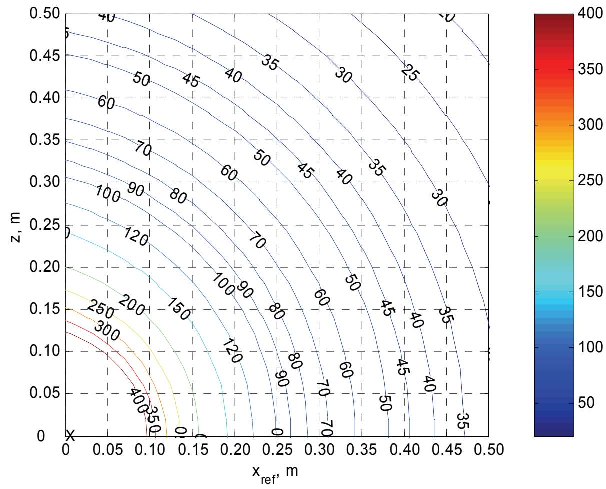

Figure 2. Reference value $B_{meas,ref}$ for a measurement point close to L3 conductor (in the origin).

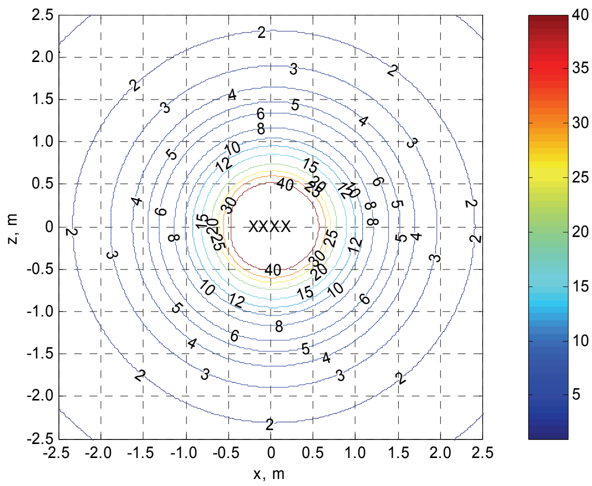

Figure 3. Reference value $B_{obs,ref}$ for an observer (L2 conductor is in the origin).

Inaccuracy of the extrapolated magnetic field B_{obs} can be assumed to depend stochastically on the inaccuracies of the input parameters as follows

$$\Delta B_{obs,stoc} \approx \Bigg[\left(\frac{\partial B_{obs}}{\partial x_{ref}} \Delta x_{ref} \right)^2 + \left(\frac{\partial B_{obs}}{\partial z} \Delta z \right)^2 + \left(\frac{\partial B_{obs}}{\partial I_{PEN,r}} \Delta I_{PEN,r} \right)^2 + \left(\frac{\partial B_{obs}}{\partial B_{meas}} \Delta B_{meas} \right)^2 + \left(\frac{\partial B_{obs}}{\partial d} \Delta d \right)^2 + \left(\frac{\partial B_{obs}}{\partial B_{obs,ref}} \Delta B_{obs,ref} \right)^2 + \left(\frac{\partial B_{obs}}{\partial B_{meas,ref}} \Delta B_{meas,ref} \right)^2 \Bigg]^{1/2}, \tag{2}$$

where $I_{PEN,r}$ is the PEN conductor current divided by the load current.

A sensitivity analysis of the extrapolation method on input parameters is presented in Table 1. The inaccuracy is around 40% with measurements close to LV connection and the accuracy increases with increasing measurement distance from the conductors. Further analyses were carried out by varying PEN conductor current $I_{PEN,,r}$ and the distance to closest conductor (Fig. 4). The analyses seem to be much more inaccurate, when measurements are done from the side of the PEN conductor. Based on these results it can be recommended to apply measurements carried out on L3 conductor side with a minimum distance of 0.2 m.

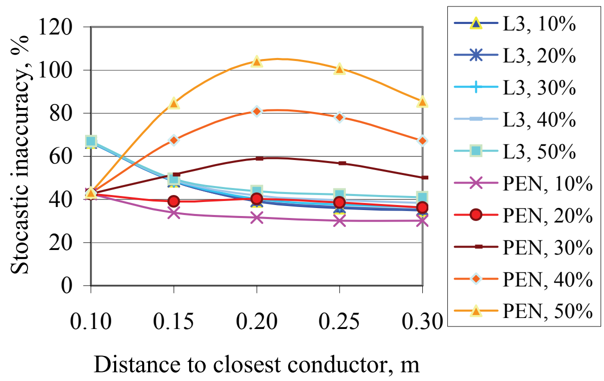

Figure 4. Stocastic inaccuracy of the extrapolation method as a function of distance to the conductor for different PEN currents $I_{PEN,r}$.

4. RESULTS

The magnetic field measurement point (reference point) nearby the LV connections was determined by considering public exposure in the residence above an indoor distribution substation. The structure of the substation and the building was examined before each measurement. In cases, where the LV connection was close to the ceiling, the magnetic field sensor was located under the LV connection at the same distance from the LV connection than the distance between LV connection and ceiling plus the thickness of the ceiling. This measurement set-up and corresponding results have been presented in references [4, 5]. Magnetic field was measured with a 3-axial meter EnviroMentor BMM-3000 (accuracy ±5%, RMS). Measured magnetic field and load current signals were further processed and stored with data acquisition system NI-DAQPad-6015 by National Instruments. [5]

4.1 Exposure to magnetic fields

Synchronous magnetic field and load current measurements were performed inside 12 indoor MV/LV distribution substations during the spring 2006. Eight of the substations had U1, U2 or M2 structure and a summary of their results are presented in Table 2. Below R is the measured exposure ratio to magnetic fields in the room above the substation.

Table 2. Summary of measurement results for studied MV/LV substation structures U1, U2 and M2. [5]

Substation (Structure)	I_{Rated} (A)	I_{load} (A)	K	R
A (U2)	1155	294	2.22	0.27
C (U2)‡	722	178	2.56	0.11
D (U1)	1443	464	1.72	0.48
E (M2)	722	242	1.48	0.28
F (U2)	722	299	1.65	0.46
H (U2)	722	311	1.30	0.86
I (U2)	722	188	1.91	0.19
K (U2)	1155	414	3.56	0.30

‡ special structure: two × tree phase cables

More detailed results were presented previously in reference [5]. Substation loads were apartment houses, office buildings or school buildings including mostly heat loads, fluorescent and tungsten lamps, computers, and other electronic devices. These loads cause harmonics in the load current that increase the total magnetic field in the substation and decrease the allowed reference value of the 50 Hz magnetic field component.

4.2 Validation of the extrapolation method

Validation of the extrapolation method (equation 1) is presented in Table 3. The last column presents the difference between measured reference magnetic field under the LV connection B_{ref} and extrapolated value B_{obs} from the earlier measurements [4, 5].

Table 1. Stochastic inaccuracy $\Delta B_{obs,stoc}$ of the extrapolation method in a case with measured magnetic field of 320 µT and observation distance of 1.0 m from the conductors. CC is a short of closest conductor.

Measurement point			Inaccuracy term							B_{obs} (µT)	$\Delta B_{obs,stoc}$ (%)
x (m)	z (m)	CC	Δx (m)	Δz (m)	$\Delta I_{PEN,r}$ (%)	ΔB_{meas} (µT)	Δd (m)	$\Delta B_{obs,ref}$ (µT)	$\Delta B_{meas,ref}$ (µT)		
0.10	0.10	L3	0.05	0.05	20	20	0.03	1	5	23	66
0.15	0.15					10			5	41	48
0.20	0.20					10			2	65	39
0.25	0.25					3			1	93	36
0.30	0.30					3			1	126	35
0.10	0.10	PEN	0.05	0.05	20	5	0.03	1	5	83	43
0.15	0.15					3			2	111	39
0.20	0.20					3			1	145	40
0.25	0.25					2			1	183	39
0.30	0.30					2			1	226	36

Table 3. Validation results of the extrapolation method. CC is a short of closest conductor.

Substation	B_{meas} (µT)	CC	d (m)	$B_{obs.ref}$ (µT)	$B_{meas.ref}$ (µT)	B_{obs} (µT)	B_{ref} (µT)	ΔB_{obs} (%)
A	13.9	L3	0.08	81	44	16.6	13.2	-26.1
C	10.2	L3	0.07	44	34	6.6	5.5	-20.5
D	12.5	L3	0.20	51	29	33.7	29.9	-13.0
E	52.0	L2	0.15	23	67	20.6	20.0	-3.0
F	26.8	L3	0.07	60	39	22.2	20.8	-6.9
H	65.3	L2	0.13	87	87	65.3	67.8	3.7
I	11.3	L3	0.07	63	37	10.4	10.3	-1.0
K	3.1	L2	0.33‡	25	25	7.7	9.3	17.3

Inaccuracies of the results in Table 3 are smaller than the theoretical inaccuracies in Table 1. Extrapolated values tend to be also larger than the measured reference values. Extrapolated values underestimated the magnetic field only, when the closest conductor was L2. The highest inaccuracy was -26.1%. Based on these results the extrapolation method seems to be valid.

4.3 Maximum exposure to magnetic fields

We also calculated the maximum magnetic field public exposure ratios for the results extrapolated into the space above the substation. Cumulative 50 Hz exposure coefficient K is considered. Calculated values were compared with results from the reference measurement point. Results are presented in Table 4, where R'_{ref} is measured and R'_{extr} is extrapolated exposure ratio scaled with rated currents of the transformers.

Difference between exposure results is significant with substation A and C, where the extrapolation overestimates the exposure. With the other substations the results are quite consistent.

Table 4. Exposure ratios calculated from the reference measurements of the magnetic fields and from extrapolated values of the earlier measurements.

Substation	R'_{ref}	R'_{extr}	$\Delta R'_{extr}$ (%)
A	1.04	1.45	-39.3
C	0.45	0.69	-53.3
D	1.50	1.80	-20.2
E	0.83	0.91	-9.3
F	1.11	0.88	20.3
H	1.99	1.97	0.8
I	0.74	0.76	-3.4
K	0.83	0.76	8.2

5. CONCLUSIONS

Validation and analysis of magnetic field measurement and extrapolation methods was done in a study of 8 indoor MV/LV distribution substations with synchronous magnetic field and load current measurements. Public exposure in the residence above an indoor distribution substation was determined with a reference measurement and by extrapolating earlier measurements. Based on the results and the analysis both of the methods are valid and can be utilized when defining exposure.

However, several questions remain open for further studies. Distribution of the magnetic field harmonics came up as one of the most important factor. Also the measurement procedure could be developed in the forthcoming studies.

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