MAGNETIC FIELD RISK EVALUATION OF WORKERS IN INDOOR DISTRIBUTION SUBSTATIONS

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ABSTRACT

The scope of this paper is on magnetic field exposure of workers in indoor medium to low voltage (MV/LV) distribution substations. In this paper we present magnetic field hazard evaluation based on measurements, specifications to execute them and specifications for risks assessment procedure. Action values were exceeded in several working tasks but limit values were not exceeded.

1. INTRODUCTION

Due to possible health effects of electric and magnetic fields, International Commission on Non-Ionizing Radiation Protection (ICNIRP) has published guidelines, in which upper limits for occupational exposure have been presented [6,7]. Based on the guidelines European Parliament and Council have adapted a Directive on minimum health and safety requirements regarding the exposure of workers to electromagnetic fields in 2004, which will be nationally implemented in 2012 [5]. In power distribution the main source of exposure is the magnetic field induced by high currents, typically found occasionally on the low voltage side of distribution substations. To be able to comply the Directive and the forthcoming legislation power distribution companies as well as authorities are seeking for guidelines and concepts how to evaluate the risk for exposure on magnetic field in power distribution environment.

General risk assessment is a part of occupational health risk protection. It includes also magnetic field risk evaluation. According to the Directive the magnetic field exposure limit value is not allowed to be exceeded at all. Therefore, if the action value is exceeded in some working environment further actions are needed to ensure that the limit value is not exceeded. Possible actions are magnetic field mitigation or dosimetry, in which induced currents in the body of the worker are evaluated. Dosimetry can be carried out with advanced calculation or measurement methods [9].

In this paper magnetic field risk evaluation is based on genuine magnetic field exposure measurements. They include broadband magnetic field and exposure measured synchronously with load currents, total harmonic distortion of the magnetic field, magnetic field exposure ratios for workers, and total harmonic distortion of the load current. Based on these results further conclusions on the risks are made by an occupational hygienist.

2. METHODS

2.1. General risk assessment

Risks which are arising in working with electricity distribution are classified based on BS 8800 general risk classification procedure [1], which is a two dimensional evaluation procedure involving the health consequences and the probability of occurrence, which both have three classes. Table 1 presents the classification of the BS 8800.

<table>
<thead>
<tr>
<th>Probability of occurrence</th>
<th>Consequence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Highly unlikely</td>
<td>Trivial</td>
</tr>
<tr>
<td>Unlikely</td>
<td>Tolerable</td>
</tr>
<tr>
<td>Likely</td>
<td>Moderate</td>
</tr>
<tr>
<td></td>
<td>Substantial</td>
</tr>
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<td></td>
<td>Intolerable</td>
</tr>
</tbody>
</table>

Employers are responsible for carrying out the risk evaluation. Occupational health care personnel can collaborate with them about the evaluations of the health effects of the physical inputs. Also authorities enforcing forthcoming legislation based on the directive 2004/40/EC will collaborate. Especially in cases of high and complicated risks the use of an external evaluator is recommended.

Risk assessment means an objective point of view of the risk specialist. This can mean that, e.g., the magnetic field exposure can be experienced to be high, but the risk is still insignificant with respect to other risks.

General risk management means all different operations, which can be executed to decrease the risks. Usually the risks cannot be removed, but the residual risk can be managed, e.g., with insuring against hazards, outsourcing the work, or using personal protective equipment. As well, anticipation, leadership, training, and development of practices are parts of the risk management. Fig. 1 presents the overall magnetic field exposure measurement and risk
assessment procedure.

2.2. Hazard evaluation

According to ICNIRP and the EU Directive, the actual maximum cumulative magnetic field, \( K \), normalized to the 50 Hz magnetic field component, \( B_1 \), can be obtained as the maximum value of the sum of magnetic field harmonic components \([2,5–10]\), thus the exposure ratio, \( R_b \), is:

\[
R_b = \frac{B_1}{B_{L,1}} - K,
\]

where \( B_{L,1} \) is the 50 Hz action value of magnetic flux density (500 µT for workers).

The magnetic field hazard evaluation procedure starts from selection of the method. There are three different methods to carry out hazard evaluation. First method, the indicative measurement, means that 50 Hz magnetic flux density, \( B_1 \), is measured simultaneously with the load current, \( I \), but exposure due to magnetic field harmonics has not been measured. In this case the maximum magnetic field exposure ratio, \( R_{B,\text{Max}} \), can be calculated, as follows

\[
R_{B,\text{Max}} = \frac{KB_1}{B_{L,1}} \cdot \frac{I_n}{I}.
\]  

Second method, the verifying measurement, means that load current, \( I \), and magnetic field exposure ratio, \( R_b \), are measured synchronously with a recording meter. Then, the maximum magnetic field exposure ratio, \( R_{B,\text{Max}} \), can be calculated, as follows

\[
R_{B,\text{Max}} = R_b \cdot \frac{I_n}{I}.
\]  

Third method, the dosimetry, means that phase currents and angles of all magnetic field sources are measured simultaneously, to calculate actual magnetic field. After that induced current density to the body, \( J_1 \), has to be calculated.

Figure 1. Magnetic field exposure measurement and general risk assessment procedure.
In this case maximum current density exposure ratio, $R_{J,Max}$ can be calculated, as follows

$$R_{J,Max} = \frac{KJ_{L,1}}{J_{L,1}},$$  \hspace{1cm} (4)$$

where $J_{L,1}$ is the 50 Hz limit value of current density (10 mA m$^{-2}$ for workers).

Also an alternative method to estimate the current density in the body exists. Dimbylow [4] has provided a way to define magnetic field limit for the internal current density. A 50 Hz current density limit of 1.1 can be used as a reference value for non-sinusoidal field by measuring the actual maximum cumulative magnetic field, $K$, normalized to the 50 Hz magnetic field component, $B_1$, as earlier. According to Dimbylow, a 50 Hz magnetic field of 1820 µT produces the internal current density limit value of a 10 mA m$^{-2}$ [4,9,10]. Accordingly, the maximum current density exposure ratio, $R_{J,Max}$ can be calculated [9,10], as follows:

$$R_{J,Max} = \frac{KB_1}{1820 \mu T} I_n I.$$  \hspace{1cm} (5)$$

First and most simple way to perform the magnetic field hazard evaluation is an indicative measurement. If $R_{J,Max}$ is higher than unity there are three possibilities to continue: to make a more accurate analysis, to reconstruct the magnetic field source or to change the working task and then perform a new evaluation. Second possibility to perform the magnetic field hazard evaluation is the verifying measurement. If $R_{J,Max}$ is higher than unity, there are again three possibilities to continue. Now only dosimetry is available as a more accurate analysis. Third possibility is the dosimetric calculation. If the measured or calculated maximum value of the exposure ratio is not lower than unity with any of the three methods, the working task is denied and actions are needed [2].

2.2.1 Magnetic field measurements

Magnetic field measurements were carried out in 7 indoor distribution substations, which are owned by different urban utilities. Load current measurements have been done synchronously with magnetic field exposure measurements. The measurement system provides magnetic field values, total harmonic distortion (THD) of the magnetic field, magnetic field exposure ratios for public and workers, load current values and THD of the load current. [9,10]

In the measurements up to five 3-axial Hioki 3470 magnetic field meters and one Narda ELT-400 meter (Measurement uncertainties ±3.5% and ±4%, respectively) were used. Measured signals were further processed and stored with data acquisition system NI-DAQPad-6015 and NI-DAQPad-6259 by National Instruments.

2.2.2 Dosimetric calculations

The dosimetric calculations were carried out with a commercial Finite Element Method solver (Sencad X ELF solver v. 13.4) which was used on a workstation with Intel Xeon 5160 processor, 4 GB RAM and Windows XP 64 bit.

The anatomically realistic heterogeneous human model used in the calculations was segmented from MR images of a 34-year-old male whose height was 170 cm and weight 74 kg [3]. The human model was discretized to equal voxels with a side length of 2 mm. The current densities induced in the human model were calculated both in a homogeneous magnetic field and a non-homogeneous magnetic field which was generated by a source based on existing low voltage switchgear from one of the measurement situations (M0347). Each calculation took about four hours.

3 RESULTS

The risk assessment procedure was first carried out for general risks and then completed with magnetic field risks. This gave us a perspective and a criterion to evaluate needs for management of magnetic field risks.

Based on the subjective questionnaire study (N = 18) the most common risks were in the order of significance 1) slipping, stumbling or falling, 2) work environment, 3) electrocution, 4) mental load, 5) ergonomic load, and 6) magnetic field exposure risk. Subjective assessment of the most common dangers was in the order of importance 1) slipping, stumbling or falling, 2) hurry, and 3) traffic. After subjective evaluation of the workers, it was concluded that the substantial and intolerable risks are slipping, stumbling or falling, electrocution, and traffic. Moderate risks were working environment, mental and ergonomic load, magnetic field exposure, and falling off.

3.1. Verifying dosimetric calculations

The dosimetric calculations were validated by comparing the calculated and analytically solved induced current densities in a sphere which was placed in a homogeneous 500 µT magnetic field. The radius of the sphere was 150 mm and conductivity 2 S/m. The calculated current density was 0.7% higher than the analytically solved value.

The exposure to magnetic fields of a low voltage switchgear was assessed with the heterogeneous human model. The highest one voxel peak current density induced in the central nervous system (CNS) of the human model was 9.9 mA m$^{-2}$ for homogeneous 500 µT magnetic field and 3.2 mA m$^{-2}$ for the non-homogeneous magnetic field generated by the low voltage switchgear (M0347). The non-homogeneous magnetic field was approximately 200 µT in the area of the CNS. It varied from 120 µT to 250 µT in the volume occupied by the head. The highest 1 cm$^2$ averaged current density in the CNS was 3.4 mA m$^{-2}$ for the homogeneous 500 µT field and 1.0 mA m$^{-2}$ for the non-homogeneous 200 µT field. The averaged current density value for the homogeneous magnetic field is at the same level as the value given by Dimbylow [3]. The difference is caused by dissimilar anatomical structures of the models.
3.2. Magnetic field exposure

Work tasks were divided to actions of operation and maintenance work. In actions of operation the electricians cannot choose working time conditions, thus they have to do this kind of tasks even during the highest load. In maintenance works the electricians can choose the working time at the lowest load of the day. However, changes in the load of the distribution system can be fast and the load cannot be guaranteed to be under any value lower than the rated current of the transformer. [10]

A survey of working tasks was carried out to find out working distances in different working tasks. In the survey the actual working tasks actions were photographed and working distances measured. The distances of critical organs of electrician to the magnetic field sources were measured or read from the photos to get measurement distances for working tasks.

Fig. 2 presents exemplary measurement results for changing the LV fuse (measurement distance 0.50 m from the LV fuses at the height of 1.70 m). The measured magnetic flux density \( B_1 \) correlates well with the transform load current \( I_{L,V} \). It indicates that load current could be used to scale 50 Hz magnetic field. During the highest \( R_B \) of 0.23 the load current was 680 A. Rated current of the transformer is 1155 A. This means that the maximum magnetic field exposure ratio \( R_{B,Max} \) is 0.39 when using the rated current as a scaling factor in eqn (3).

The survey of the actual working tasks actions and verifying measurement results from 29 working task examples were presented in reference [10]. Action value of unity was exceeded in 4 out of 29 cases, in which the working tasks were “Measuring load current of a LV feeder” in two cases and “Resetting maximum temperature meter of a transformer” and “Adding feeder or cable into a LV switchgear”. When dosimetry was evaluated based on eqn. (5) any of the values of \( R_{B,Max} \) did not exceed the limit value of unity. Exemplary results for working task of measuring load current of a LV feeder are presented in Table 2.

4. CONCLUSIONS

General health risk assessment is a part of occupational protection. It includes also magnetic field risk evaluation. However, magnetic field risks seldom come up in general health risk assessment. Clear correlation exists between load current and magnetic field exposure values providing a systematic way to estimate maximum exposure. Exposure action values were exceeded in several working tasks but no limit values in any of them.

REFERENCES