Experimental and theoretical assessment of power frequency electric field individual protective means

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Abstract. Electromagnetic field levels at workplaces may exceed permissible limit values. In this case the individual protective means use obligatory. There are presented the date of typical samples of conductive suits (under work in power frequency electric field) testing by simulation and in experiment. Individual protective means screening factors were changed from 42.26 to 52.43 dB. The averaged electric field level inside of conductive suit was 220 mV/m in case of simulation. The induced electric fields in human body tissues with conductive suit were 0.003–0.150 V/m. The results show that conductive suit use allows reducing the induced electric filed levels and ensures worker safety.

1. Introduction
One of the actual issues of occupational and environmental safety is human health protection from the adverse influence of various factors, electromagnetic field including ensuring. Electromagnetic field (EMF) levels at workplaces may exceed permissible limit values (PLV) – hygienic standards compliance with which ensures the staff health preservation. In case of EMF levels PLV elevated additional approaches and methods of personnel protection are required. Occasionally the only possible way to protect worker from EMF exposure is individual protective means (IPM) use.

Occupational health and safety under maintenance and exploitation of electrical installations require the elimination of potentially adverse human health effects of power frequency EMF exposure. The protection from electric field (EF) under maintenance and exploitation of electrical installations is provided by IPM use primarily. An important task to ensure safe occupational conditions near the elements of power transmission systems (extremely and ultra high voltage overhead transmission lines, open and closed switchgears) is to reduce the high intensity power frequency (PF) EF (50/60 Hz) lower than PLV by IPM use.

The basis for occupational safety ensuring is PF EF levels compliance to PLV according to hygienic safety standards. According hygienic criteria as protection from for human health unfavorable factor, IPM should provide the required EF intensity attenuation. At the present time, there are quantitative and qualitative differences in the approaches to EF exposure assessment and regulation, which are established by national and international safety standards.

In accordance with the SanPiN 2.2.4.3359-16 «Sanitary-epidemiological requirements for physical factors in the workplace» [1] PF EF permissible limit values in the Russian Federation are depended on time of occupational exposure. Russian hygienic standards of 50 Hz EF are among the most "strict" of the entire world, depending on exposure time. PLV are from 5 kV/m to 25 kV/m (from all work day
up to 10 minutes per shift) as is shown in table 1. In case of EF level is higher 25 kV/m the use of protective equipment is obligatory [2].

Individual protective means include clothes (overalls or jacket, trousers/semi overalls), head protection, gloves and/or mittens and boots, made of electrically conductive materials. At the same time, all IPM elements must be electrically connected to each other, forming a closed shell around human body, EF penetration preventing, according to the principle of "Faraday cells".

According to international approaches PF EF are regulated not only by incident EF value but induced electric field strength too.

Table 1. Power frequency (50 Hz) electric field occupational exposure permissible limits values according to International and Russian hygienic requirements.

| Exposure value                  | SanPiN2.2.4.3359-16 [1] | ICNIRP 2010 [3] | Directive 2013/35/EU [4] |
|---------------------------------|--------------------------|------------------|--------------------------|
| Incident EF (kV/m)              |                          |                  |                          |
| 5 (all work day)                |                          | 10               | 10                       |
| 5-20 (depending on time)        |                          |                  |                          |
| 25 (≤10 min)                    |                          |                  | 20                       |

Internal electric field (mV/m):

- Low value (CNS tissue of the head)
- High value (All tissue of the body and head)

Table: 100, 800, 140, 1100

The main IPM (conductive suit) characteristic is the shielding coefficient (Кп). Кп is attenuation external EF (possible hazard) under IPM to safety levels [5, 6]. EF IPM properties must comply with TR TS 019/2011 «On the safety of personal protective means» [5] and GOST 12.4.172-2014 «Set of individual shielding for protection against electric fields of power frequency. General technical requirements and control methods» requirements, defining 30 dB as minimum permissible shielding factor [6].

The goal of this study was to assess the protective properties of typical samples of modern IPM (EP-1 and EP-3 types), designed for staff protection from PF EF, which takes into account the requirements of national and international safety regulations and guidelines. The objectives of the study included laboratory measurements of IPM shielding properties and the IPM simulation of laboratory test conditions.

In this regard, to assess the IPM protective properties evaluated the EF levels inside and outside of IPM, as well as EF magnitude induced in the human body.

The shielding properties of 4 IPM samples for protection of personnel from PF EF (2 EP-1 and 2 EP-3) were evaluated for work on the ground (ground potential). Laboratory testing of IPM protective properties, the possibility of EF attenuation by the shielding suit were evaluated. Then, using simulation the levels of induced EF in the human body IPM shielding coefficient was obtained as a result of tests.

2. Materials and methods
Tests of the IPM shielding properties were carried out on the high-voltage EF power frequency test setup. The setup is open air condenser, with plate sizes of 2.4x1.8 m², the distance between the plates is 0.7 m. The high-voltage setup provides a uniform electric field in the area of the placement of the human body phantom dressed in the tested IPM. EF exposure levels were from 5 to 85 kV/m. The EF measurement was carried out by a portable electric field analyzer EFA-300 (Narda, USA) with
calibrated isotropic electric probe using a fiber optic cable. The probe was placed in a free space inside the body human body phantom. EF values were determined under levels of the external EF, simulated the possible occupational exposure. EF measurements were carried out on a body phantom without IPM, and then on phantom dressed in conductive suit. The screening factor was estimated according to the formula (1), where $E_1$ is the results of electric field measurements without protective suit and $E_2$ - with a suit:

$$K_s = 20 \lg \frac{E_1}{E_2}$$

Simulations were carried out using the software product SEMCAD X v.14.8 («SPEAG AG», Switzerland). The Finite-Difference Time-Domain method (FDTD) was used for the calculation for the low frequency range. The resolution of the numerical models was constant for two type of IPM (EP-1 and EP-3).

In numerical simulation to experimental test conditions reproduce, the models of the setup, including a plane-parallel capacitor, screening set and human body phantom, were developed. The capacitor consists of two metal plates, the size corresponding to the real test setup. The upper plate was set to provide a sufficiently uniform EF with 70 kV/m voltage in the work area of the test phantom. The bottom plate was grounded. As real body phantom, a numerically heterogeneous phantom of the human body was used, with 1.77 m high and 72.4 kg weight from Virtual Family [7].

In the simulation used in the conventional dosimetric modeling of the dielectric properties of the tissues of the human body (electrical conductivity and dielectric permittivity) in the tested frequency range [7]. The model of the shielding set is represented by a set of cylinders of different diameters from 2 to 4 mm thick, connected to each other and roughly repeated the shape of the human body. The material of the elements of the set was set as a metal with zero potential.

3. Results and discussion

After laboratory tests were obtained averaged values of $K_s$ for IPM different samples (figure 1). Under PF EF levels from 5 to 85 kV/m average $K_s$ was 48.73 dB (EP-1), 52.43 dB (EP-3) and 42.27 dB, 51.25 dB (washed EP-1 and EP-3). Noticeably decrease $K_s$ was mentioned after IPM washing. EP-3 shielding properties was better than EP-1.

![Figure 1. Experimental results of shielding coefficient values assessment for different IPM samples.](image-url)
Inside EP-1 EF levels were from 0.027 to 0.303 kV/m, inside the EP-3 – from 0.017 to 0.202 kV/m. EF levels of washed EP-1 were from 0.058 to 0.63 kV/m, washed EP-3 – from 0.021 to 0.225 kV/m (after 10 washes). Inside EP-1 and EP-3 EF levels increased after IPM washing.

According to experimental results shown in figure 1, the considered IPM samples satisfy with current technical requirements, and its shielding factors are higher than minimum permissible value of 30 dB. The measured inside the IPM electric field levels are less than 1 kV/m and don't exceed International and Russian hygienic standards for occupational electromagnetic field exposure. As test measurements of electric field levels were performed only for one point in human body phantom it is important to estimate the IPM shielding efficiency for whole body volume. For this goal, the numerical simulation with human body phantom was used.

The developed numerical model of test setup was verified by means of the EF spatial distribution compared with experimental results of EF measurements inside air capacity. The IPM test condition models were based on the compatibility of these data.

IPM numerical model was exposed to of 70.62 kV/m EF level and provided shielding coefficient value of 50.13 dB. The averaged EF level inside IPM model was 220 mV/m. The selected values of external EF strength and shielding efficiency were almost equal to experimental data.

The assessment of EF levels induced in human body tissues was conducted for worker body model exposed to 70.62 kV/m EF level and for worker body dressed in IPM model exposed to the same level. The spatial distributions of internal EF for each case are shown in figure 2 in different scales.

**Figure 2.** Spatial distributions of EF induced in human body tissues for cases: 1) – worker body without IPM; 2) – worker body dressed in IPM.
The simulation results show that the induced EF distributions inside human tissues in the case of IPM model (figure 2, 2) is high non-symmetric when compared with human body exposed non-shielded EF. This can be caused by IPM model inaccuracy and incomplete. However, the induced EF levels are reduced significant in the shielded field, see table 2.

**Table 2.** The numerical simulation results of induced electric field value in human body.

| Tissue     | Worker without PPM | Worker with PPM |
|------------|---------------------|-----------------|
| Brain      | 0.473               | 0.037           |
| Cerebellum | 0.081               | 0.029           |
| Spinal Cord| 0.217               | 0.008           |
| Heart      | 0.160               | 0.003           |
| Muscle     | 3.543               | 0.150           |
| Lungs      | 0.159               | 0.004           |
| Liver      | 0.128               | 0.005           |
| Spleen     | 0.091               | 0.004           |

Presented in table 2 EF levels induced in several organs of human body exposed by high-intensity 50 Hz EF which elevated the international norms. For example, for brain and muscle these values are 4 times higher than ICNIRP [3] basic restriction levels and can cause injuries for worker. IPM use allows reducing the induced EF levels and ensures worker safety.

The shielding EF is one of the basic principles for worker protection against high intensity PF EF. The EF strength measurements are used for experimental assessment of IPM shielding efficiency and provide data compared with hygienic standards. The results of such tests can be insufficient and incomplete, and numerical simulation might be used as additional technique.

**References**

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