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Impact of Changes in Limit Values of Electric and Magnetic Field on Personnel Performing Diagnostics of Transformers

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Abstract: Electric and magnetic fields accompany technical personnel in their working environment (work exposure). That is why many countries have the appropriate regulations. The impact of electric and magnetic fields on humans is still not fully recognized. This is the reason why the limit values of its intensity in many countries differs significantly. The article presents changes in the stress limits of the electric and magnetic fields in Poland at the turn of the last dozen years. The last such change was the result of a Directive of the European Union (2013/35/EU). The effects of changes in limit values on the working conditions of technical personnel performing diagnostics of high voltage transformers or working in the immediate vicinity of such transformers are presented. The article shows that recent changes have improved the working conditions of technical personnel in relation to the electric field and worsened the conditions taking into account the magnetic field.

Keywords: diagnostics of high voltage transformers; electric and magnetic field stress

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1. Introduction

1.1. Hazards and Effects of Electric and Magnetic Fields on Humans

The electric and magnetic fields in recent years have aroused negative feelings among the public. In the international literature, you can find many articles where the negative effects of the field on people are presented. However, it should be emphasized that until the 1970s, the electric and magnetic fields were not associated in a negative way.

The first important piece of research on the negative impact of electric and magnetic fields on humans was initiated by live work [1], which was developed in the early 1960s. However, the breakthrough in the perception of the field, especially magnetic, negatively affecting humans dates back to 1979, with the publication of a study by N. Weitheimer and E. Leeper, where they report a higher than average incidence of leukemia among children, caused by the immediate vicinity of overhead power lines. Since then, the development of research referring to the impact of electric and magnetic fields on humans has been noticed.

Currently, there is a lot of research related to the impact of electric and magnetic fields on humans [2–4]. Most often, these works concern the influence of the field generated by overhead high voltage lines (50/60 Hz). The most frequently analyzed parameter is the current that will be generated in the human body as a result of the interaction of electric and magnetic fields. [5–7]. The research also concerns the impact of the field on people during live work [8]. Researchers are analyzing the effects of the field on psychophysiology [9], blood [10], stress [11], and the structure of human cells [12]. Many studies have been devoted to the effects of the high frequency field on the human body [13–15]. Researchers are analyzing the impact of the field generated by wireless energy transmission systems [16] and metro stations [17]. Recently, much attention has been paid to the impact of the field generated in electric cars on passengers [18]. Relatively few articles concern the impact of the field generated at high voltage distribution stations, especially near power transformers, on technical personnel [19].

It should be added that research on the influence of the field on humans is a difficult issue, because the lower limits of field perception by humans are as much as 100 kV·m^{-1} (electric field) and 10 kA·m^{-1} (magnetic field), and the presence of animals only in a field with an intensity of 500 kV·m^{-1} may result in their death, caused not by the influence of the field, but by electric shock [20,21].

The effects of electric and magnetic fields on humans can be broadly divided into two categories—thermal and non-thermal. The latter is divided into immediate effects, usually in the form of an induced current in the human body, and effects felt after a longer period, which are the result of damaged biological structures [5,7].

1.2. Thermal Effect

The best known effect of electric and magnetic fields is the thermal effect. Its essence lies in the increase in body temperature to a value that can cause protein coagulation. The most exposed to this effect of the field are human organs that are located close to the field, i.e., skin and limbs, and those that are characterized by ineffective blood circulation, i.e., the gallbladder and the lens of the eye. The reports of radar operators, describing cases of eye clouding and cataracts, are the best example of this.

The thermal effect is most often the results of the interaction of a high frequency electric and magnetic field (from 300 MHz). The physical quantity describing this area is the surface power density expressed in W·m^{-2}.

On the basis of research, it has been proven that the thermal effect occurs in the presence of a field with a density of more than 100 W·m^{-2}. However, below 10 W·m^{-2}, this effect is unlikely. There are countries where the thermal effect is treated as a criterion for the selection of the limit value of the power density, e.g., the United States, where the limit value of the power density is equal to 100 W·m^{-2}. Mobile phones are of great concern in the area of the high frequency field. However, they have not been found to have a negative impact on humans, although they may be a source of a small and local increase in temperature. Based on research, it has been proven that such phones generate a field with a density of several W·m^{-2} (older models) and less than 1 W·m^{-2} (modern models) [14,15].

1.3. Effect in the Form of Induced Current

The International Commission on Non–Ionizing Radiation Protection (ICNIRP) recommends that the density of the current induced in the body should not exceed 10 mA·m^{-2}. Too much value of this current can disrupt the work of the human nervous system.

Electric field stress equal to 10 kV·m^{-1} (f = 50 Hz)—the limit value in Poland for environmental exposure—induces a current of 0.5 mA·m^{-2}, while a magnetic field stress of 60 A·m^{-1}—a limit value in Poland for environmental exposure—induces a current of 0.5 mA·m^{-2}. Therefore, taking into account the permissible value of current density, it can be concluded that the Polish regulations, in relation to environmental exposure, are very restrictive because the permissible values of electric and magnetic field stress generate a current with a density 20 times lower than the permissible [22–24].

On the basis of simulation calculations, the density of the current inducing in the human body under an overhead high voltage line of 380 kV (I = 700 A) was determined. The calculated values of current density were as follows: legs 0.007 mA·m^{-2}, head 0.046 mA·m^{-2}. None of the determined density values exceeded 10 mA·m^{-2}.

1.4. Effect Recorded after Prolonged Exposure of Electric and Magnetic Field

Many concerns are raised by electric and magnetic fields as a cause of cancer. Research on the effects of the field on humans is conducted in different ways. These are in vitro studies (a) involving the separation of DNA cells and the analysis in the laboratory of the effect of the field on these cells; in vivo (b), consisting of a field impact study on animals; carried out on a group of volunteers (c); and epidemiological research conducted on a certain population of people who have been subjected to the influence of the field during their work (d).

These studies are characterized by some imperfections. In vitro studies (a) do not provide the possibility of using the defense mechanisms at the disposal of the entire human body, because only selected DNA cells participate in the research. These mechanisms include: adaptive, compensatory, and regenerative. In turn, the results of animal studies (b) are not so easy to transfer to humans because of a different physique. On the other hand, studies on volunteers (c) have the negative feature that they concern a group of people who were subjected to field influence only during the experiment. Epidemiological studies (d) on a group of people are impossible to carry out because such a population does not exist [25].

Studies on the interaction of electric and magnetic fields are the subject of extensive research around the world. Based on them, it can be concluded that the negative impact of the field on human DNA has not been proven. It is not easy to tell if there is an effect of the field on heart rhythm, pressure, ECG, and EEG, because literature sources often give contradictory results. The same applies to the magnetic field as a cause of cancer.

Analysis of the impact of the field on animals (b) proves that magnetic field can be the cause of cancer. However, these studies are carried out in a field of thousands of $A \cdot m^{-1}$, to which people are not exposed either in their workplace or outside it.

The results of studies in Sweden and the USA are of concern. According to them, leukemia among children can be caused by a magnetic field equal to 0.33 $A \cdot m^{-1}$. However, there are no reports describing the negative impact of the electric field on cancer.

It is worth emphasizing that the interaction of the magnetic field is not a linear relationship, which significantly hinders the proper interpretation of the research results. In a field above 12 $A \cdot m^{-1}$, the human body showed no reaction, which was not confirmed for lower field values. The phenomenon of the "window" is explained by the adaptive properties of the organism [26,27].

Reputable agencies and world organizations state that the electric field is not a source of diseases. In the case of the magnetic field, CIGRE (International Council on Large Electric Systems, working group 36.06) and NIEHS (National Institute of Environmental Health Science) suggest continuing the study, as the impact of this field is not satisfactorily understood [28].

A completely different point of view on the issue of the interaction of electric and magnetic fields allows us to assume that their presence strengthens the immune system of people and minimizes the effect of "clean hands".

1.5. Summary of the Hazards and Effects of Electric and Magnetic Fields on Humans

Electric and magnetic fields should not be seen as a source of danger to humans. This field is the source in special circumstances of a thermal effect that is characteristic only of high frequencies. The field can also induce current, but this requires a large value of its intensity, which exceeds those under the overhead high voltage line [29]. There is a discussion about the field as a source of diseases, even though there is no conclusive evidence that electric and magnetic fields are the source of various ailments.

When adopting Directive 2013/35/EU, which is the basis for the current changes to the permissible values for electric and magnetic field stress in the work exposure, the European Parliament and the European Council adopted the following statement in recital [7]:

> *"This Directive does not address the suggested effects of distant exposure to electromagnetic fields, as there is currently no well-established scientific evidence of a causal link in this regard. However, where such well-established scientific evidence becomes available, the [European] Commission should consider the most appropriate measures to take account of those effects and inform the European Parliament and the [European] Council thereof by means of a report on the practical implementation of this Directive. In carrying out this obligation, the Commission should take into account not only the relevant information received from the Member States, but also the latest available research results and new scientific knowledge resulting from data in this field."*

2. Limit Values of Electric and Magnetic Field Stress in the World

2.1. Different Approaches to Limit Values of Electric and Magnetic Field Stress

People, like most living organisms, are not equipped with electric and magnetic field receptors. The exception are the eyes, which record electromagnetic fields from the visible light range. On the other hand, there is evidence of a negative impact of the field, of relatively high intensity, on living organisms. For this reason, the values of the field stress should be subject to appropriate adjustments.

However, there are many different approaches to regulation, regarding the electric and magnetic field stress. Among them, one can distinguish, among others, the proposal of a maximum reduction in the limit values. Another approach, completely different from the one previously presented, assumes that the field stress should not be limited, since there is no conclusive evidence of their negative impact. There are also indirect approaches, according to which unnecessary exposure to the field should be avoided or its normative limits should be established [30].

The proposal to limit the maximum permissible values of the intensity, as you can guess, is the most expensive proposal. The financial resources needed for its implementation should be associated with the reconstruction of the electric power system and consumer equipment powered by electricity. An excellent example of this approach is Italy, where the limit value for magnetic field stress, with a frequency of 50 Hz for environmental exposure, has been reduced to 0.4 $A \cdot m^{-1}$ in built-up areas. As experts have calculated, in Milan alone, the costs of converting the lines to a voltage of 132, 220, and 380 kV, due to their adaptation to the new regulations, will amount to about EUR 24 billion, which will result in an increase in the price of electricity by about 40 % [28,30].

Another extreme solution is the proposal not to limit the value of the electric and magnetic stress at all. The argument of the proponents of this approach is the lack of conclusive evidence about the harmfulness of the field. The results of research of one research center, testifying to the harmful effects of the field, are not usually confirmed by the work of other centers. For this reason, in many countries, such as Canada, France, Spain, Switzerland, and until recently the US, there are no restrictions on the electric and magnetic fields stress. In the US, it was only under pressure from public opinion that energy companies created appropriate regulations [31,32].

However, the most common approach in many countries to the problem of regulating the electric and magnetic fields stress are intermediate solutions. One of them is the application of the ALARA principle, the abbreviation of which is derived from the first letters of the words, as low as reasonably acceptable. The essence of this principle is to limit the field stress as low as it is reasonably achievable, and, therefore, not requiring large expenditures of costs associated with the reconstruction of the power system. An example of the application of this principle is the US, where it is additionally recommended to conduct further research on the effects of the field on living organisms [30,32,33].

Another intermediate solution is to use appropriate criteria when selecting the limit values of field stress. The most commonly used criteria are the intensity of the thermal effect and the density of the current induced in the human body [23,30–37].

2.2. Environmental and Work Exposure

In most countries, the limit values for electric and magnetic field stress refer to environmental and work exposure. Environmental exposure concerns this group of people who do not have to be aware of the impact of the field on it. In turn, work exposure refers to a group that is aware of the impact of the field on it. This group often only includes employees of the broadly understood electric power industry, working at the transmission and distribution station, which is not always the case. This group should also include people who, in the course of their work, know that they are subject to the influence of the field. For this reason, this group should be expanded, among others, to include employees of steel mills (induction furnaces), GSM stations, or people working near radars. This group should also include some employees completely unrelated to the electric distribution

system. An example would be office workers if they work in a building where there is a medium voltage transformer. Such situations occur in older buildings.

Normally, in relation to environmental exposure, only limit values of intensity are determined without a time limit for staying in the field. It is different in the case of work exposure, in relation to which limit values are usually set and often the maximum time spent in the field. This means that the work exposure limit values are usually higher than those for environmental exposure. Therefore, the time spent in a field of higher intensity should be limited. However, there are some exceptions to the rules described above. There are countries where time constraints can be distinguished in relation to both environmental and work exposure, an example of which is Germany. There are also countries where there are no time limits at all, in relation to both exposures. Yet another example is the legislation in Bulgaria, where field stress limit values are regulated only for work exposure.

In many countries, limit values may depend on the type of exposure and the purpose of the area where the field may be present. It is necessary to take into account, among others, such places as residential areas, parking lots, road intersections, road intersections with a high voltage line, or the area that is the border of the line corridor. Usually, the limit values apply to the whole body, although there are countries where there are some exceptions to this rule, according to which limbs can be exposed to a field of greater intensity than the rest of the body.

As you can see, many different approaches are used to determine the permissible values of field stress. It is not surprising, therefore, that many international organizations are inclined to unify them [30–33,38].

2.3. Review of the Global Intensity Limit Values for Work Exposure

Table 1 shows the limit values for electric field stress for work exposure for different countries. These values range from 10 to 250 $kV \cdot m^{-1}$. The most common value is 10 $kV \cdot m^{-1}$. Most countries use only one value, above which stay is prohibited. The exception is Hungary, which gives two limit values for long and short times. Another exception is Austria, where the permissible residence time is inversely proportional to the electric field stress. The next exception is the Netherlands, where limit values depend on parts of the human body.

Table 1. Limit electric field stress E in selected countries for work exposure (f = 50/60 Hz) [39].

Country	E [$kV \cdot m^{-1}$]	Comments
Australia	10 ÷ 30	limit time, h, $t < 80 \cdot E^{-1}$
Austria	10	
Bulgaria	25	
Czech Republic	10	
UK	10	
Korea	10	
Hungary	10	no time limit
	30	short time
Croatia	10	
US	25	
Netherlands	62.5	acceptable level for torso and head
	250	acceptable level, excluding the torso and head

Table 2, as well as Table 1, gives the permissible values of magnetic field stress for work exposure. As you can see, the dispersion of limit values is quite large from 400 to 20,000 $A \cdot m^{-1}$. The most commonly reported limit is 400 $A \cdot m^{-1}$. In the case of Australia, Hungary, and the US, a certain gradation was applied, taking into account the residence time or individual parts of the human body.

Table 2. Limit magnetic field stress H in selected countries for work exposure (f = 50/60 Hz) [39].

Country	H [A·m^{-1}]	Comments
Australia	400	no time limit
	4000	no longer than 2 h per day
	20,000	only for legs and hands
Austria	400	
Holland	480	
Croatia	400	
Korea	400	
UK	400	
US	960	for whole body
	4800	only for legs and hands
	9600	only for palm and foot
Bulgaria	960	
Czech Republic	400	no time limit
Hungary	400	no time limit
	4000	for short time

Analyzing the data in Tables 1 and 2, it is difficult to determine what criteria the legislator followed in individual countries when establishing limit values for electric and magnetic field stress. This information is difficult to obtain because the relevant regulations do not usually contain any explanations. According to the author, legislators in individual countries were most often guided by one of the intermediate criteria, which is the ALARA principle—as low as reasonably acceptable.

To sum up, it should be said that both the permissible values of electric and magnetic field stress vary significantly from country to country. Usually, there is only one acceptable value of the field, above which the presence of employees is prohibited. Some countries use a gradation of limit values that take into account the residence time, the intensity value, or the appropriate part of the human body. It is not surprising, therefore, that international organizations, including the European Union, are making efforts to harmonize, as far as possible, the limit values for electric and magnetic field stress for work exposure.

3. Purpose and Scope of Work

The aim of this article is, firstly, to present changes in the limit values of the electric and magnetic field stress with a frequency of 50 Hz in the work exposure in Poland, and, secondly, to present the effects of mentioned changes on the working conditions of technical personnel performing diagnostics of high voltage transformers or operating in the immediate vicinity of such transformers.

There are diagnostic methods for transformers that require that during the tests the transformer works, so it is under voltage and current load. These methods include, first of all, the measurement of partial discharges (PD) by various methods, such as the electrical (traditional) method, the acoustic emission (AE) method, and the antenna method–ultra high frequency (UHF) method [40–46]. This method requires measurements of partial discharges over a period of several hours. In such a situation, the transformer is a source of electric and magnetic fields that affect technical personnel.

The overwhelming number of diagnostic methods is carried out on a switched off transformer. These methods include, among others, measurement of water content in transformer insulation (recovery voltage method—RVM, frequency response analysis—FRA, polarization and depolarization current—PDC), insulation resistance measurement, tap changer condition analysis, and others [47–52]. In such a situation, the tested transformer is not a source of electric and magnetic fields. However, a few meters away there is usually a second transformer, typically switched on to voltage and loaded with current. Such a transformer is already a source of electric and magnetic fields, although to a lesser extent.

The last change of mentioned limit values of electric and magnetic fields was a consequence of the Regulation of the Minister of Family, Labor and Social Policy of 27 June

2016. This Regulation was a direct consequence of Directive 2013/35/EU of the European Parliament and of the Council of 26 June 2013 on the minimum health and safety requirements, regarding the exposure of workers to the risks arising from physical agents (electromagnetic fields) (twentieth individual directive within the meaning of Article 16(1) of Directive 89/391/EEC).

This directive was a long-awaited legal act of the European Community because it unifies as far as possible the regulations on limit values for electric and magnetic field stress in EU countries. Until the introduction of the directive, the limit values differed significantly in relation to the work exposure.

The limit values of electric and magnetic field stress in the work exposure have changed relatively often at the turn of the last dozen or so years in Poland:

- 29 November 2002 [53];
- 6 June 2014 [54];
- 27 June 2016 [55].

Regulations on the permissible values of electric and magnetic field stress in the work exposure in Poland introduce the concept of "zone", depending on the value of field stress. These zones are divided into two groups, i.e., a protection zone and a safe zone. The former includes a danger, hazard, and intermediate zone.

A danger zone shall be deemed to be an area where presence is not permitted or is permitted provided that adequate personal protection is provided. A hazard zone is an area where staying is allowed but with time constraints that depend on the intensity value. The parameter determining the limit time of stay in this area is dose D. The next zone is the intermediate zone, where stay is limited to the duration of one working shift. The last one is the safe zone. This is an area where the duration of stay is not subject to any regulations.

The permissible dose of electric and magnetic fields D is expressed by the following formulas [30–32]:

$$D_E = E^2 \cdot t \quad (1)$$

$$D_H = H^2 \cdot t \quad (2)$$

where D_E is the permissible value of electric field dose $[(kV \cdot m^{-1})^2 \cdot h]$, E—electric field stress $[kV \cdot m^{-1}]$, t—residence time in field [h], D_H—permissible magnetic field dose $[(kA \cdot m^{-1})^2 \cdot h]$, H—magnetic field stress $[kA \cdot m^{-1}]$. As you can see, the formulas for the dose, according to Polish regulations, are the result of square of the field stress and time expressed in hours.

Using the Formulas (1) and (2), the permissible residence time t in a field of a given value can be determined so that the permissible dose D is not exceeded:

$$t = \frac{D_E}{E^2} \quad (3)$$

$$t = \frac{D_H}{H^2} \quad (4)$$

The permissible dose value for the electric field in Poland is $D_E = 800\ (kV \cdot m^{-1})^2 \cdot h$, while for the magnetic field is $D_H = 0.32\ (kA \cdot m^{-1})^2 \cdot h$. This means that Formulas (3) and (4) can take the following form:

$$t = \frac{800}{E^2} \quad (5)$$

$$t = \frac{0.32}{H^2} \quad (6)$$

4. Changes in the Limit Values of the Electric and Magnetic Field Stress with a Frequency of 50 Hz in the Work Exposure in Poland

Table 3 and Figure 1 show the limit values for electric field stress at a frequency of 50 Hz for occupational exposure in Poland, changing over the last several years. As can be

seen, the boundary between the danger and hazard zones E_2 did not change and was always equal to 20 kV·m^{-1}. This means that the danger zone occurs when the electric field stress exceeds the value of 20 kV·m^{-1}. The boundary between the hazard and the intermediate zones E_1 has been reduced as a result of recent legislative changes from 10 kV·m^{-1} to 3.33 kV·m^{-1}. Thus, the hazard zone occurs when the electric field stress is currently in the range of 20 to 3.33 kV·m^{-1}. The residence time in this zone shall be determined in such a way that the permissible dose of the electric field D_E is not exceeded. This means that the scope of this zone has expanded towards smaller values of electric field stress, which clearly reduces the time of exposure of workers to the electric field, which should be treated as a beneficial move. The same trend can be observed in relation to the boundary between the intermediate zone and the safe zone E_0. Its value gradually decreased from 5 kV·m^{-1} to 3.33 kV·m^{-1}, and finally to 1 kV·m^{-1}. Currently, the intermediate zone occurs when the electric field stress is in the range from 3.33 to 1 kV·m^{-1}. The time spent in this zone is equal to one working shift. That is, the range of this zone shifted towards smaller values of the electric field stress, which reduces the time of impact of the electric field on people in the work exposure, which should also be seen as a satisfactory action.

Table 3. Electric field stress values E delimiting protection zones for 50 Hz in Poland [53–55].

Year	Electric Field Stress Values E [kV·m^{-1}] Delimiting:		
	Intermediate and Safe Zones E_0	Hazardous and Intermediate Zones E_1	Dangerous and Hazardous Zones E_2
2002	5.00	10.00	20.00
2014	3.33	10.00	20.00
2016	1.00	3.33	20.00

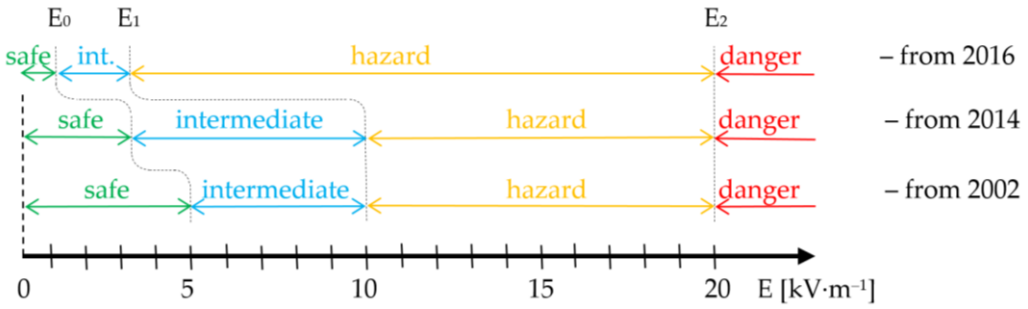


Figure 1. Electric field stress values E delimiting protection zones for 50 Hz in Poland [53–55].

Change in the value of E_1, which define the boundary of the intermediate and hazard zones, cause changes in the time spent in the hazard zone (E_2 did not change). According to regulations from 2002 and 2014, this zone occurred for an electric field stress of 10 to 20 kV·m^{-1}. Based on the Formula (5), a time interval was determined for the limit values of the electric field stress, which was from 8 to 2 h. The E_1 change introduced in 2016, from 10 to 3.33 kV·m^{-1}, caused the time range of staying in the hazard zone to expand from 72 to 2 h.

Table 4 and Figure 2, similarly to Table 3 and Figure 1, show the limit values for magnetic field stress at a frequency of 50 Hz in relation to the work exposure in Poland. The scale of the value of the magnetic field stress H in Figure 2 is not linear to make the graph more readable. As you can see, the limit value between the danger zone and hazard zone H_2 has increased from 2000 to 3200 A·m^{-1}. This means that the danger zone now occurs when the magnetic field stress exceeds 3200 A·m^{-1}, and not as it was in previous years at 2000 A·m^{-1}. Such an increase in the H_2 value results in increased exposure to the magnetic field in the work exposure, which can be perceived as an effect that worsens working conditions. The deterioration of working conditions means that before the changes in the limit values, the employee could not stay in a magnetic field in range of 2000 A·m^{-1}

to 3200 A·m^{-1}. Currently, unfortunately, the employee can already being staying in a field of this scope. A similar trend can be seen in the limit value between the hazard zone and the intermediate zone H_1, the value of which also increased from 200 to 533.33 A·m^{-1}. This means that hazard zone occurs when the value of the field stress exceeds only 533.3 A·m^{-1}, and not 200 A·m^{-1} as before. Such a change also increases the time of impact of the magnetic field on people in work exposure, which is a negative consequence of recent legislative changes. In turn, the limit value between the intermediate and safe zone H_0 was reduced from 66.67 to 60 A·m^{-1}. This means that the intermediate zone begins when the magnetic field stress exceeds the value of already 60 A·m^{-1}, and not 66.67 A·m^{-1}, as it was so far. This reduces exposure to the magnetic field in the work exposure, which is beneficial from the point of view of the impact of the magnetic field on humans.

Table 4. Magnetic field stress values H delimiting protection zones for 50 Hz in Poland [53–55].

Year	Magnetic Field Stress Values H [A·m^{-1}] Delimiting:		
	Intermediate and Safe Zones H_0	Hazardous and Intermediate Zones H_1	Dangerous and Hazardous Zones H_2
2002	66.67	200.00	2000.00
2014	66.67	200.00	2000.00
2016	60.00	533.33	3200.00

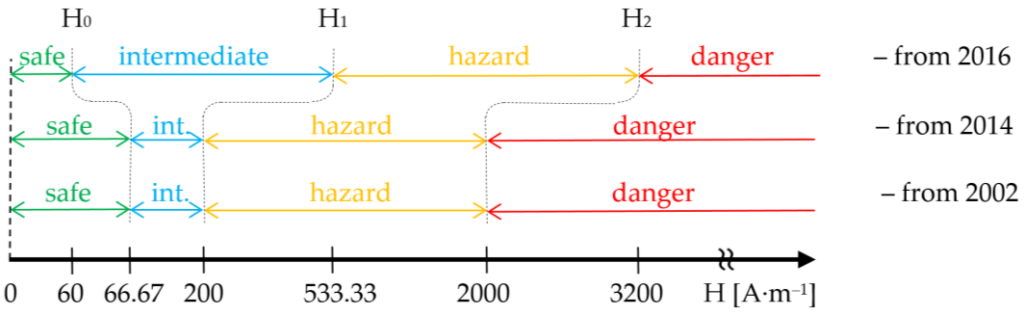


Figure 2. Magnetic field stress values H delimiting protection zones for 50 Hz in Poland [53–55].

Changes in the values of H_1 and H_2, which define the boundaries of the hazard zone, cause changes in the time spent. According to regulations from 2002 and 2014, this zone occurred for an magnetic field stress of 200 to 2000 A·m^{-1}. Based on the Formula (6), a time interval was determined from 8 h to about 5 min. The increase in H_1 from 200 to 533.33 A·m^{-1} and the increase in H_2 from 2000 to 3200 A·m^{-1} change the time interval from about 70 min to 2 min.

Summing up the changes in the values of the intensity separating individual zones, it should be stated that in the case of an electric field, these changes are generally beneficial from the point of view of exposure to the field in the work exposure, because they shorten the time of impact of this field on people. Unfortunately, in the case of a magnetic field, the opposite situation occurs. The intensity values of this field demarcating individual zones have increased. The result is an increase in the time of exposure to magnetic fields.

An interesting fact is the current values of electric and magnetic field stress, separating the intermediate and safe zones E_0 and H_0—the upper limit of the safe zone.

In the case of an electric field, the value of E_0 decreased from 3.33 to 1 kV·m^{-1}, which means that currently the safe zone occurs when the electric field stress does not exceed 1 kV·m^{-1}. The time spent in such a zone is no longer regulated, so it can be infinitely long. At this point, it is worth saying that 1 kV·m^{-1} is also an acceptable value of electric field stress for environmental exposure (Table 5). This means that after many years there was an expected equalization of the electric field stress, which is the upper limit of the safe zone for work exposure and the limit value for environmental exposure.

Table 5. Limit values for electric and magnetic field stress at a frequency of 50 Hz, in relation to environmental exposure in Poland [56].

	Electric Field Stress E $\mathbf{kV \cdot m^{-1}}$	**Magnetic Field Stress H** $\mathbf{A \cdot m^{-1}}$
Places intended for development	1	60
Places accessible to people	10	60

The situation is similar in the case of a magnetic field. The value of H_0 also decreased from 66 to 60 $A \cdot m^{-1}$, which results in the safe zone occurring in an area where the magnetic field stress does not exceed 60 $A \cdot m^{-1}$. This value is also the permissible value of magnetic field stress for environmental exposure (Table 5). This means that in the case of a magnetic field also, the upper limit of the safe zone for work exposure has been aligned with the permissible value of the magnetic field stress for environmental exposure.

5. Effects of Changes in the Limit Values of Electric and Magnetic Field Stress on Personnel Working near Transformers

5.1. Basic Information on the Electric and Magnetic Field Stress near Transformers

The transmission and distribution system of electricity is perceived as the most serious source of electric and magnetic fields. The element of this system that raises the greatest concerns in the context of field emissions are power stations. The most sensitive area of such a station is the area around high voltage transformers.

The author has extensive experience in measuring the electric and magnetic field stress both under high voltage lines and at power stations. Below are the distributions of electric field stress at 110, 220, and 400 kV stations located near high voltage transformers. Presented distributions of electric field stress were measured by the author. The analyzed areas are places where, according to the author and technical staff, the highest intensity values of the field stress may occur.

The author does not present distributions of magnetic field stress, because its values turned out to be relatively small compared to the limit values. As you know, the magnetic field stress is directly proportional to the value of the current and inversely proportional to the distance from current source. Using a very large simplification, assuming that the distribution of the magnetic field at the station is consistent with the distribution of the field around the infinitely long wire through which the current flows, you can use the following relationship to estimate the value of the magnetic field stress H:

$$H = \frac{I}{2 \cdot \pi \cdot d} \tag{7}$$

where I—the current [A], d—the distance from the conductor through which the electric current flows [m]. On this basis of Formula (7), you can roughly estimate the value of the stress H by knowing the current and distance. The H values measured by the author at power stations, close to the high voltage transformers, ranged from a few to a dozen $A \cdot m^{-1}$. Therefore, they are not interesting to analyze in the context of limit values.

5.2. Different Ways to Quantitatively Measure the Electric Field Stress

Methods for determining the electric field stress can be divided into analytical, numerical, and measuring.

Analytical methods consist of determining the value and direction of field stress on the basis of mathematical relationships describing the physics of phenomena. Their use is limited to systems with a simple structure.

Numerical methods consist of an approximate solution of a system of equations describing the electric field stress in the studied area. The limitation of the use of these

methods is due to the fact that in the case of some insulation systems, the equations describing the electric field stress are not fully known.

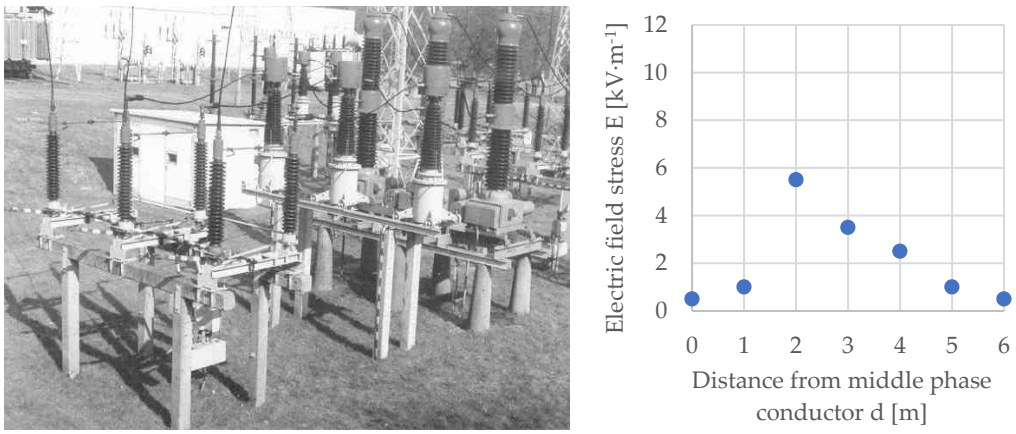
Measurement methods consist of determining the desired the electric field stress based on the measurement of other physical quantities. These methods can be divided into: historical, physical modeling methods using capacitive probes, methods involving potential measurement and non-electrical methods.

The most popular are methods involving the measurement of potential. They consist of measuring the voltage drop on a fragment of the insulation system and, on this basis, determining the value of the electric field stress. The disadvantages of the methods consisting of the measurement of the potential include interference in the original distribution of the electric field, caused by the need to place conductive elements in the tested area and averaging the measurement results from relatively large fragments of the insulation system. In addition, it is not possible to determine the direction of the field strength vector. The advantage of these methods is the ease and speed of taking measurements. For the above reasons, the author decided to carry out measurements of the electric field stress using this method.

In turn, non-electrical measurement methods can be divided into thermal imaging method and electro-optical methods. The thermal imaging method is at the initial stage of development. In contrast, electro-optical methods, among which one should mention the method based on the use of the electro-optical Kerr effect, are promising [57,58]. However, they have not yet been widely used to measure the strength of the electric field on the surface of high-voltage insulation systems.

5.3. Electric Field Distribution near Transformers

Figure 3a shows a fragment of a 110/15 kV high voltage station, and more precisely the area between the power switch and the high voltage 110 kV transformer, where the electric field stress E was measured. Figure 3b shows the distribution of electric field stress E between power switch and high voltage 110 kV transformer. The highest value of intensity E does not exceed 6 kV·m^{-1}. This means that a certain part of this area, until the last change in the regulations in 2016, was qualified as an intermediate zone and now as a hazard zone, for which the duration of residence is subject to restrictions. It can be concluded that the change in the limit values has a positive effect on the degree of protection of technical personnel against the electric field.

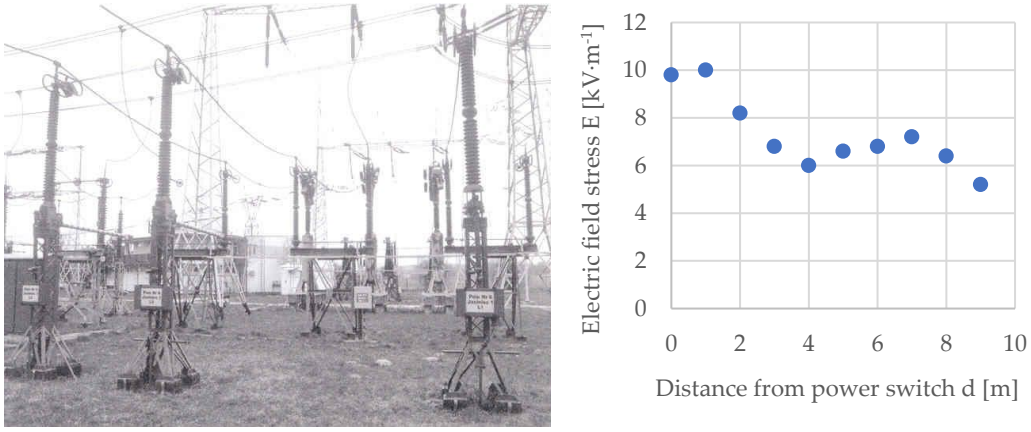


(**a**) (**b**)

Figure 3. High voltage station 110/15 kV (**a**), electric field stress distribution E (f = 50 Hz) on the distance perpendicular to 110 kV conductors between power switch and 110 kV high voltage transformer (**b**).

Figure 4a shows a fragment of a 220/110 kV high voltage station, where the measurements were carried out. Figure 4b shows the distribution of electric field stress E between

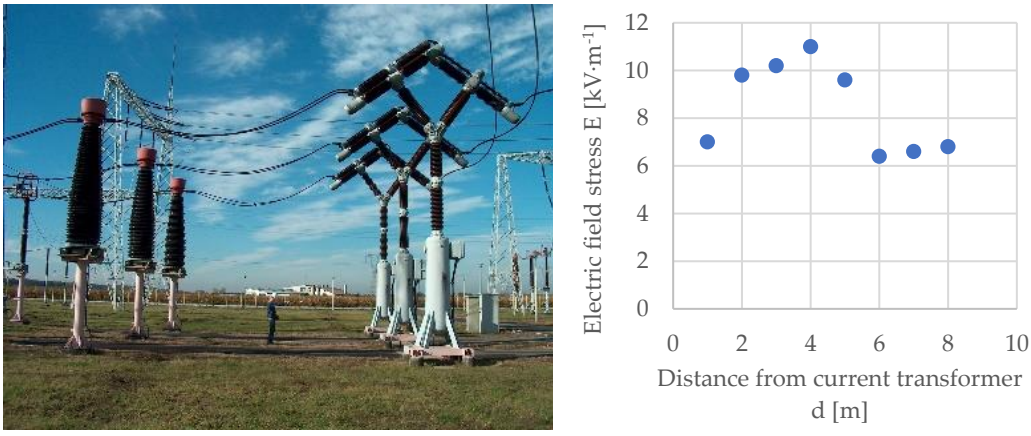
the disconnector and high voltage 220 kV transformer. The highest value of E intensity was equal to 10 kV·m^{-1}. On the basis of the current regulations, it can be concluded that, until 2016, a certain part of this area was qualified as an intermediate zone, which changed its status to a hazard zone. It can, therefore, be concluded that, as in the previous example, the change in the limit values has a positive effect on the degree of protection of technical personnel against mentioned fields.



(**a**) (**b**)

Figure 4. High voltage substation 220/110 kV (**a**), electric field stress distribution E (50 Hz) along the distance parallel to middle phase 220 kV conductor, between disconnector and 220 kV high voltage transformer (**b**).

Figure 5a shows a fragment of a 400/220/110 kV high voltage station. Figure 5b shows the electric field stress distribution E along a span connecting 400 kV current transformer and power switch. The highest value of E intensity exceeded 11 kV·m^{-1}. This means that until 2016, only a small fragment of the analyzed area was a hazard zone. Currently, the danger zone is much larger. It can, therefore, be said that, as in the previous examples, the recent amendments to the legislation have a positive effect on the level of protection of technical staff.



(**a**) (**b**)

Figure 5. High voltage substation 400/220/110 kV (**a**), electric field stress distribution E (f = 50 Hz) along a span connecting 400 kV current transformer and power switch (**b**).

To sum up, it can be said that recent changes have caused certain areas of high voltage stations, especially areas close to high voltage transformers, which until now were intermediate zones, to change their status to a hazard zone. Such a change protects technical personnel more from the impact of an electric field.

6. Conclusions

The introduction of Directive 2013/35/EU of the European Parliament and of the Council of 26 June 2013 on the minimum health and safety requirements for the exposure of workers to hazards caused by physical agents has caused significant changes in the values of electric and magnetic field stress, delimiting individual zones (safe, intermediate, hazards, and dangerous), which until recently were in force in Poland.

With regard to the electric field, these changes are generally beneficial from the point of view of the field's impact in the work exposure, as they reduce the time of exposure of the field to humans. The effect of such changes is the improvement of working conditions of technical personnel at the power station performing diagnostics of high voltage transformer.

Unfortunately, in the case of a magnetic field, we are dealing with the opposite situation. The values of the stress of this field, which are the boundaries of individual zones, have increased significantly. The result is an increase in the time of exposure to magnetic fields, which is a negative thing. Such changes are likely to cause a deterioration in the operating conditions at the electric power station near the high voltage transformer, given the magnetic field.

An important conclusion is that the upper limits of the safe zone, both in relation to the electric and magnetic fields, have been equated (lowered) to the limit values of field stress for environmental exposure, which should be considered a beneficial phenomenon.

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