Standardised evaluation of the electric field for meeting safety aspects for workers according to directive 2013/35/EU and VEMF

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Workers in power supply systems are exposed to electromagnetic fields. These fields must not exceed the limit values set out in EU Directive 2013/35/EU (minimum health and safety requirements for workers with regard to exposure to the risk of physical agents (electromagnetic fields)) in order to protect workers against health risks. In Austria, a group of experts from the National Standardization Committee (OVE) has drawn up a national guideline (OVE guideline R 27) in order to prevent the diversity of assessment procedures. In addition, the guide aims to reduce time and effort in evaluation and documentation of electric and magnetic fields. This article provides an overview of the procedure and an assessment of the evaluated distances determined in accordance with OVE guideline R 27 for the protection of workers with regard to electric fields in substations.

Keywords: worker protection; electromagnetic fields; substations; workers; EU guideline 2013/35

1. Introduction

The European directive 2013/35/EU (minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (electromagnetic fields)) [1] has the focus to protect workers from health risks. This directive was implemented 2016 in Austria by a national decree VEMF [2, 3]. The European Standard EN 50647:2017 [8] gives the main instructions for evaluation according to the directive 2013/35/EU of an actual exposed working situation, for example where to measure and how to average. On the one hand, it provides a whitelist for source types that can be neglected, on the other hand, there are no criteria for determining relevance based on distance. Thus, only experts can perform the exposure assessment using this standard.

An expert group of the OVE developed a national guideline OVE-Richtlinie R 27 (R27) [4] to fill this gap and to avoid a diversity of testing, evaluation and documenting methods according the VEMF. A main focus was the applicability of the procedures by safety engineers with only basic knowledge about electric and magnetic fields. So, most of the evaluation can be done by such trained persons and only for few special situations the consultation of EMF-experts is necessary.

2. Procedure of exposure assessment

The main principle of the procedure described in the R27 is, that it is not necessary to know an exact field value in all points. Instead, in few most relevant points (point-of-proof PoP) it is proved that the limits are not exceeded. The proofing is done in a cascade, going from a very rough estimate with only a few parameters to more complex and more accurate estimates as long as the compliance with the action levels (AL) cannot be proven.

2.1 Exposure limits, reference values, action levels, action quotient

The limits of allowed exposure to electric, magnetic or electromagnetic fields depend on the health constitution and qualification of the employees.

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The directives and standards limit the exposure with two types of limits for the frequency range up to 100 kHz:

- Limits for inter-corporal electrical field values:
  - exposure limit value (ELV) [1]
  - basic restrictions [5]
- Limits for external field values for electric and magnetic fields:
  - action level [1] (AL)
  - reference levels [5, 6]
  - electromagnetic compatibility limits (EMC) [9]

The 2013/35/EU defines action levels (AL) which are external field values as electric field strength (\(E\)) and magnetic flux density (\(B\)) and exposure levels (limits for the) for occupational exposure.

In case of pregnancy the Austrian government limits the exposure to the reference level of 1999/519/EG which are the levels according to ICNIRP 1998 [7]. Further for persons with active implanted medical devices (AIMD) as for example cardiac pacemakers the levels of OVE EN 50527-1 [9] provide the limit for the immunity.

In the R27 and in this article all limits of external field values (\(E, B\)) are named as action levels \(AL\). The actual field values are compared with this action levels, the quotient of the actual field value and the action level is the action level quotient \(AQ\).

As long as the \(AQ\) is below 1 (=100 %), the limits of VEMF are met. The definition of the \(AQ\) is necessary to meet the conditions for multi-frequency fields, where the sum of all action level quotients of all relevant frequencies must be taken into account.

### 2.2 EMF-zones

To comply with the different limits for different groups of persons, the working areas are classified in EMF-zones.

The limits of [6] for pregnant workers and [9] for persons with active implanted medical devices are the most restrictive ones. The classification of the EMF zones according to R27 [4] is given in Table 1.

The first step in an evaluation is to draft a zoning map. The evaluator must decide which areas need to be accessible to which group of people. The main objective is to have as few access restrictions as possible. For example, areas outside the fence system of a substation are open to public. These areas must therefore correspond to an EMF zone with the highest requirements – according to Table 1 this is EMF-zone 0. Another example of sections associated with zone 0 would be pathways to office buildings.

### 2.3 Points of proof (PoPs)

Evidence of compliance with the EMF zones’ requirements is provided at a limited number of points (PoPs) within or at the boundary of the zones. These PoPs must be chosen so that these points include the worst case – the highest possible field values – of the area. For these relevant points typically the most accessible points in the surrounding of the strongest sources (high currents, high voltages) will be chosen. Usually, these are accessible points as close as possible to the strongest field sources. For sources outside the zone boundary, a PoP must also be at the next point at the zone boundary to the source. Due to the limited number of selected points, it is not necessary to analyze the entire work area in detail.

### 2.4 Check radius, relevance distance and action distance

The first assessment in the selected PoPs is to check the number of relevant sources. In R27 a source is relevant – it has to be taken into account – when the action quotient \(AQ\) is

- (a) higher than 0.5 for electric fields,
- (b) higher than 0.2 for magnetic fields

The distance to any active part of the source, where the \(AQ\) does not exceed this relevance value is defined as the relevance distance \(D_a\).

The check radius is the distance with the highest relevance distance for a source type, e.g. for example, for a 400 kV overhead line, the worst case of all possible configuration (phase configuration, highest voltage or current, ...).

The action distance \(D_a\) is the distance from any active part of a source to the PoP where the \(AQ\) for that single source is less than 1 (100 %).

If there is more than one relevant source, the \(AQs\) of all sources must be summed. The check is passed when this sum is less than one.

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**Table 1. Classification of EMF-zones**

| EMF-zone | Action level (AL) or limit | AL 50 Hz E-field kV/m | AL 50 Hz B-field µT | Restricted access for: |
|----------|----------------------------|------------------------|---------------------|------------------------|
| 0        | 1999/519/EG OVE EN 50527-1 | 5                      | 100                 | Nobody |
| A        | Reference levels according to ICNIRP2010 | 5 | 200 | Pregnant workers, persons with AIMDa |
| B        | Action levels according to 2013/35/EU | 10/20 | 1000 | Pregnant workers, persons with AIMDa persons without instructionsb |
| Cs       | Exposure limit sensory (ELV sensory) | | | Pregnant workers, persons with AIMDa persons without instructionsb young workersc |
| Ch       | Exposure limit health (ELV health) AUT decree: Only in specific cases if no reduction is possible | | | Pregnant workers, persons with AIMDa persons without instructionb young workersc |
| X        | Exceeding exposure limits for employees | | | All persons |

\(\text{a AIMD} \ldots \text{active implanted medical devices.}\)
\(\text{b Instructions according necessary distances.}\)
\(\text{c Workers who are younger than 18 years or have less than 18 months of relevant training.}\)
3. Testing the exposure to magnetic fields
The formulas and the principle of the evaluation of the magnetic field with loops are described in detail in [10–12].

4. Testing the exposure to electric fields

4.1 Parameters for electric field
The electric field strength at 50 Hz is limited to 5 kV/m for public exposure (AL Zone 0), and 10 kV/m for occupational exposure (low AL Zone B). Up to 20 kV/m (high AL Zone B) is permissible if the persons are demonstrably informed and instructed that higher electric fields can occur. The R27 stipulates that all persons with access to Zone B must be demonstrably instructed, therefore the high action levels can be allowed here.

The electrical field strength near an overhead (non-insulated) power system depends on:
- voltage level, for evaluation the maximum operation voltage (i.e. 123 kV, 245 kV, 420 kV) is used,
- geometry of non-insulated conductors,
- radius of the conductors,
- shielding cases,
- grounded surfaces in vicinity of the system.

In R27, to demonstrate compliance, it is recommended to measure the electric field strength in the PoPs and scale to the maximum voltage. However, to reduce the number of measurements required, it is very convenient to have relevance and action distances. In the following, the calculations for determining the distances defined in R27 will be explained.

4.2 Model for calculation of relevance distances and action distances
The basis of the calculations of the electric field is the analytical method of mirror charges for a plane (2D) configuration.

Typical installed configurations were analysed:
- 6 types of double system overhead lines (OHL) (380 kV, 220 kV, 110 kV, tower type “Donau” and “Tonne”)
- Horizontally arranged busbars and branches with different distances between the phases and a different number of systems....
Table 2. Results of the sensitivity analysis for a horizontal configuration

| Parameter                  | hAQ | hAQ | Dk | Dk | Dk | Dk |
|----------------------------|-----|-----|----|----|----|----|
|                            | Zone 0 | Zone B | Zone 0 | Zone 0 | Zone B | Zone B |
|                            | high AL | low AL | high AL | low AL | high AL |
|                            |       |       |       |       |       |       |
| –                          | 11.5 | 5.1  | 16.7 | 10.1 | 11.5 | 6.9  | 3.7  |
| 1 system                   | 10.9 | 5.0  | 15.3 | 9.7  | 11.0 | 6.7  | 3.6  |
| 2 systems mirrored         | 12.2 | 6.1  | 15.4 | 10.2 | 11.0 | 7.1  | 4.5  |
| 3 systems                  | 11.6 | 5.1  | 17.0 | 10.2 | 11.7 | 7.0  | 3.7  |
| 3 systems mirrored         | 12.5 | 6.2  | 15.1 | 10.5 | 10.8 | 7.3  | 4.5  |
| Conductor pipe r = 80 mm   | 10.9 | 4.8  | 15.7 | 9.4  | 10.7 | 6.4  | 3.3  |
| Conductor rope 1 × r = 37 mm | 9.4  | 4.0  | 13.2 | 7.7  | 8.9  | 5.0  | 2.4  |
| Conductor rope 2 × r = 37 mm | 10.1 | 4.4  | 14.4 | 8.5  | 9.8  | 5.7  | 2.9  |
| Conductor rope 4 × r = 37 mm | 10.7 | 4.7  | 15.5 | 9.3  | 10.5 | 6.3  | 3.2  |
| Distance conductors a1 = 4 m | 10.9 | 4.9  | 15.8 | 9.7  | 11.0 | 6.7  | 3.6  |
| Distance conductors a1 = 5.5 m | 11.8 | 5.1  | 17.1 | 10.3 | 11.7 | 7.0  | 3.8  |
| Distance conductors a1 = 8 m | 12.8 | 5.4  | 18.8 | 11.2 | 12.5 | 7.5  | 4.0  |
| Distance conductors a1 = 10 m | 13.5 | 5.5  | 19.8 | 11.7 | 13.0 | 7.7  | 4.1  |
| Height conductors h2 = 6 m | 11.5 | 5.1  | 16.7 | 10.1 | 10.5 | 6.5  | 3.6  |
| Height conductors h2 = 12 m | 11.5 | 5.1  | 16.7 | 10.1 | 13.1 | 7.5  | 3.8  |
| 3 Sys mirrored, a1 = 10 m, hL = 12.5 m | 17.0 | 5.9  | 21.6 | 15.0 | 15.0 | 9.8  | 5.3  |

hAQ height of the lowest conductor to comply with the action values (AQ = 1) for the electric field strength for people standing on ground; Dk relevance distance (AQ = 0.5); Dk action distance (AQ = 1); a1, distances between the phase conductors

Fig. 3. Averaging of the electric field strength (RMS) for persons standing on ground, height of the conductor hL = 8 m, (ground: y = 0 m). Max(Eavg) 4.3 kV/m at x = 1.5 m

For all these configurations the effective conductor radius was varied by changing the number of bundle conductors and the radius of the conductors. Additionally, different phase positions were analysed:
- six for the double system OHLs (for detail see [9]) the operating case with only one system in operation
- and two for the horizontal configurations;
- same order (L1 L2 L3 L1 L2 L3) or mirrored (L1 L2 L3 L3 L2 L1).

The relevance and action distances for these configurations are determined as follows:

First a calculation path is defined. This is a path with points with distance d to the nearest live conductor (see for example Fig. 1).

The electric fields in high-voltage systems are not homogeneous. However, the action levels have been determined for people in homogeneous fields. According to [13], the fields may be arithmetically averaged over the range that a person would occupy.

In this work, the averaging for the electric field strength (Eavg) is done for a standing person of height 2 m along the middle axis of the person in steps of 0.1 m (Fig. 1).

The persons may stand on ground, a building or a grounded platform (e.g. a scaffolding). Such a platform was modelled as 3 earthed conductors with a radius of 0.125 m at a distance of 0.5 m each.

In summary, the electric field strength was arithmetically averaged over 16 points between 0.5 m to 2 m height in the horizontal center of a platform or at the position of the person on ground.

Along the calculation path for each distance d the maximum of the Eavg was determined, in order to get supporting points of the function Eavg = f(d). By linear interpolation between these sampling points, the relevance and action distances can be determined, i.e. the distances necessary to comply with AQ = 1 or AQ = 0.5.

It should be noted that a measurement and calculation of the external electric field strength always takes place in the absence of
Fig. 5. Contour lines for the electric field strength in kV/m (RMS) of a busbar configuration (height of the conductors 8 m, phase to phase voltage 245 kV, with a person on a grounded platform with a minimum distance to the nearest conductor of $d_1 = 3$ m: top: below the busbar ($E_{\text{avg}} = 12.9$ kV/m)); middle: at an angle of 45° ($E_{\text{avg}} = 15.0$ kV/m); bottom: at the same height as the busbar ($E_{\text{avg}} = 11.0$ kV/m).
Fig. 6. Maximum $E_{avg}$ along paths at distances $d$, the distances for specific action levels (AL) are interpolated between the calculated distances.

persons, in the following figures, the persons were drawn only for a better imagination.

4.3 Substations

For substations an analysis of the exposure to fields of staff differs between evaluation for EMF-zone 0 and A, and EMF-zone B.

For EMF-zone 0 the action and relevance distances were evaluated for persons on ground only. This assumption can be justified by the fact that only instructed persons are allowed to stand nearby live conductors on a raised platform.

In the following the calculation steps are shown for an example:

- phase to phase voltage: 245 kV
- distance between the live conductors: $a_1 = 5$ m
- height of the conductors above perfectly conducting ground: $h_L = 8$ m
- phase configuration L1 L2 L3, L1 L2 L3, as shown in Fig. 1
- rigid tubular conductor diameter: 250 mm

In Fig. 2 for this basis configuration the contour lines of the RMS-value of the electric field strength are shown.

In Fig. 3 the electric field strength along a horizontal path in different heights above ground for the same basis configuration is presented. For the further calculation process, the maximum of the averaged field strength (here at about $x = 1.5$ m) is taken into account.

The next step is to determine the Max($E_{avg}$) for different heights of the conductors $h_L$. The results are given in Fig. 4.

In Fig. 5 the evaluation of the electric field for a distance exemplary for three different platform positions is shown. For evaluation of the relevance and action distance $D_0$, $D_A$ out of all positions along the path always the maximum electric field strength at various distances $d$ is evaluated, as done in Fig. 6.

For each geometrical configuration (height of the lowest conductor $h_L$, distances between the phase $a_1$, different numbers of systems (1 ... 4), phase position of conductors, equivalent radius (for a bundle, or for a pipe)) the relevance distances $D_0$ and action distances $D_A$ are evaluated. Further the necessary height of the lowest conductor $h_{AQ}$ to comply with the action values ($AQ = 1$) for the electric field strength for people standing on ground is given. That is a very convenient measure for checking if the height of the bus bars

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Fig. 7. Definition of phase configuration for double systems OHLs "Tonne" and "Donau"

Fig. 8. Calculation procedure for evaluation of the necessary distances for electric fields nearby overhead lines

or feeders is ok for persons working on ground (or walking through the station).

Based on the exemplary configuration described above, the influence of various parameters on the relevance distance $D_0$ and action distances $D_A$ is shown in Table 2. The last row of the table gives the worst-case scenario for a 380 kV busbar configuration. This configuration was the basis for row 4, Table 9 in R27 [4].
4.4 Overhead lines OHL

The analysis for overhead lines is very similar to substations, but the geometry of the tower has much more influence and so this cannot be taken into account with a single factor.

Therefore, for very typical configurations of double system high voltage OHLS in Austria, the “Donau” tower and the “Tonne” tower were analysed.

The phase configuration has high influence on the electric and magnetic field. For a double system OHL there are 36 possibilities to position the phases, while always 6 configurations (simultaneous clockwise and counterclock-wise rotation of all phases) have the same rms-value of the field. In the following Fig. 7 the definition as it is used here is given. More details to phase configurations are given in [10].

For operators and approving authorities it often is sufficient to know about the distances where the ALs for these two standard configurations are met. Special configurations require more detailed analysis.

Workers can not only be situated on platforms but also work on the roof of buildings, for example as roofers, mechanics, chimney sweeper etc. Such buildings can be simulated by an array of conductors, similar to the platform.

A sensitivity analysis showed that the worst case is for high but slim buildings. Therefore, all calculations are done with buildings of horizontal dimension 5 m and variable height.

In the following the calculation steps are shown for an example (see Fig. 8):

- Type “Tonne” with dimensions $x_1 = 8.3$ m, $x_2 = 11.3$ m, $x_3 = 7.5$ m, $h_1 = 8$ m, $h_2 = 9.5$ m
- Phase to phase voltage 420 kV
- Height of the conductors $h_1 = 16$ m
- Phase configuration No. 1 (symmetrical)
- Bundle of 3 conductors with diameter 36 mm each, distance 0.4 m.

In Fig. 9 the contour lines for an exemplary building and OHL configuration are given.

In Table 3 the results for the action distances of two tower configurations, the best (no. 1) and worst (no. 3) phase position and the variation of number of bundle conductors are presented.

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### Table 3. Action distances $D_A$ in m for overhead lines 420 kV, for persons on ground (g) or elevated on a building or platform (e)

| Configuration       | Zone 0 | Zone B, low AL | Zone B, high AL |
|---------------------|--------|---------------|-----------------|
|                     | g      | e             | g               | e               |
| Tonne, phase position 1; 2xbundle | 12.2   | 25.9          | 6.0             | 12.1            |
| Tonne, phase position 1; 3xbundle | 13.9   | 27.9          | 6.7             | 14.2            |
| Tonne, phase position 1; 4xbundle | 15.2   | 29.5          | 7.4             | 15.6            |
| Tonne, phase position 3; 2xbundle | 10.2   | 16.1          | 5.8             | 8.1             |
| Tonne, phase position 3; 3xbundle | 11.2   | 17.6          | 6.4             | 9.2             |
| Tonne, phase position 3; 4xbundle | 11.9   | 18.8          | 6.9             | 9.9             |
| Donau, phase position 1; 2xbundle | 9.6    | 16.7          | 5.1             | 7.3             |
| Donau, phase position 1; 3xbundle | 11.0   | 18.5          | 5.7             | 8.4             |
| Donau, phase position 1; 4xbundle | 12.0   | 19.9          | 6.2             | 9.4             |
| Donau, phase position 3; 2xbundle | 8.5    | 11.9          | 5.1             | 6.3             |
| Donau, phase position 3; 3xbundle | 9.3    | 13.2          | 5.6             | 7.1             |
| Donau, phase position 3; 4xbundle | 9.9    | 14.2          | 6.1             | 7.8             |
The necessary distance raises significantly between a person on ground (g) or elevated (e) on a building. Further the tower type “Tonne” has higher action distances than the type “Donau”, that’s why “Tonne” needs higher distances between conductor and ground than “Donau”.

Due to the strong dependence on the position and height of the building, the worst-case evaluations are unreasonably high. That’s why in R27 only the action distances $D_2$ to plane ground are given. The action distances for persons on buildings might be up to the factor 2 higher.

5. Conclusion and outlook

The paper gives the overview about the background and methods which lead to the action distances $D_2$ and relevance distances $D_2^*$ for electrical fields in the Austrian national Guide OVE-Richtlinie R27.

For electric field evaluation the preferred method for proving compliance is to measure at the point of proof on site. In order to reduce the evaluation effort, the R27 provides relevance distances and action distances to various sources of electric fields, which are based on many Worst-Case-Assumptions and are therefore overachieving. With this distances the points of proofs can be reduced, if the distance of to a source is greater than the relevant distance.

This paper shows the evaluation process of these distances with many worst case assumptions for the most significant electrical field emitters, high voltage overhead lines and substations. For workers on roofs nearby overhead lines as well as workers on platforms in substations, further analysis should be performed. The first step would be to measure the electric fields and compare the results with the here given method.

The R27 is a great help for all employers having to deal with electromagnetic fields of the electrical power systems. The next step would be an implementation phase in Austria to transform this national guide to an international standard.

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