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Magnetic Fields of Devices during Electric Vehicle Charging: A Slovak Case Study

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Abstract: The aim of this contribution is to identify and quantify the magnetic field parameter (MP) devices for charging electric vehicles (EVs). An EV is a mobile device. The EV remains a mobile device even when it is charging in a fixed charging stand. ICNIRP and SBM standards apply to stable devices. A magnetic field (MF) creates local gradient fields that change cyclically over time near the charging stations. The rotating vector MF is a specific parameter. An MF is evaluated by its strength and spatial changes. The triaxial fluxgate magnetometer VEMA-041 was used for the measurements. The MF was observed in the frequency range of 0–250 Hz, and the magnetic induction density was from $T \times 10^{-9}$ T to 2×10^{-5} T, with a sensitivity of 1.7 nT. The MF analysis was performed within the time and frequency range. The rotating vector MF was identified at the measurement points. Measurements were realized for the charge under the following parameters: cables, 600 A; transformer, 250 kVA (22 kV/400 V); a cab-fixed charging stand, and an AC/DC charger in the EV. EV charging was performed with 6.6 kW of power and 43-kW fast charging. The measured results were satisfactory, according to the ICNIRP and SBM 2015 standard. The values measured at a distance of 1 m from the wall of the transformer were $B_{RMS} < 2 \mu\text{T}$. B_{RMS} values $< 3 \mu\text{T}$ were measured in the space of the cable's entry into the distribution box. EV values should not be assessed under this regulation. However, an EV is a mobile device. In the selected EV sample (a first-generation Nissan Leaf), a frequency of 10 Hz and its multiples were detected during charging. The frequencies were generated in an AC/DC charger in the EV. These frequencies reached $B_{RMS} < 0.2 \mu\text{T}$ in the driver's footwell. The maximum value of the MF rotating vector was $B_{total} < 0.3 \mu\text{T}$ and was directed to the crew area of the EV. The AC/DC charger generated $B_{RMS} = 0.95 \mu\text{T}$ in the driver's footwell. It is necessary to look for new tools for evaluating MFs for EVs, such as the standards used for stable sources today. These standards should be based on dosimetric principles.

Keywords: magnetic field; magnetic field source; charging stands; AC/DC charger in electric vehicle; fluxgate magnetometer; rotating magnetic field vector

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1. Introduction

The development of electric vehicles entails new risks related to the existence of MFs. Europe has experienced the development of recommendations, special guidelines, and standards for assessing the impact of EMFs with various frequency sources, including ELF sources, since 1995 [1–9]. The magnetic field emitted by the source is a specific type of field. The emitted MF's description using cyclic symmetric functions in both the time and frequency domains is now the basis of the ICNIRP recommendations. Standards in the Slovak Republic are taken from these recommendations.

The ICNIRP's reference levels for static magnetic fields (the magnetic flux density) are 40 mT for the population and 200 mT for employees [2], whereas the Earth's magnetic field ranges from 30 to 60 μ T, depending on the Earth's position. Concerning time-variant fields, the exposure is limited to EMFs [3,4]. Regarding multiple frequency sinusoidal exposure, the ICNIRP [4] states that all contributions should be considered cumulative so that the following global limit can be met:

$$\sum_{j=1}^{10 \text{ MHz}} \frac{B_j}{B_{\text{limit},j}} \leq 1 \quad (1)$$

where B_j is the field magnitude at each given frequency and $B_{\text{limit},j}$ is the reference level corresponding to that frequency. The expression for the magnetic field H is analogous. IEEE C95.6 [8] is a standard defining the exposure level to protect humans against adverse effects from exposure to electric and magnetic fields at frequencies from 0 to 3 kHz. Because none of the above reviews concluded that any hazard from long-term exposure has been confirmed, the standard IEEE C95.6 [8] does not propose limits on exposures necessary to protect against adverse short-term effects.

The ICNIRP issued a new recommendation for the area up to 1 Hz (also called static EMG fields) as a peak-to-peak limit in 2014 [5]. The shift occurred in the views on the rate of magnetic induction change defined by the parameter dB/dt .

If the MF exceeds a threshold by approximately 2 T, the field may be strong enough to cause dizziness and other sensory sensations such as a metallic taste in the mouth, according to the manual [5,10]. Oravec [11] considers these effects of MFs to be safe, but they may negatively affect one's ability to work. At present, the ICNIRP considers MFs with a value of 8 T to be the threshold for limiting peripheral nervous system activity [12]. The threshold of 8 T provided by the ICNIRP for limiting the peripheral nervous system holds only at frequencies below 1 Hz. A separate group consists of chemical changes in human metabolism resulting from the influence of MFs [11]. The changes are not considered significant if the density of the magnetic flux is less than 7 T [13]. This fact is supported by MRI devices [14].

For the purpose of measuring the limit values for the dB/dt change, the reference levels at a frequency of 1 Hz recommended today are

$$\frac{dB_0}{dt} = 2\pi f \sqrt{2} B_{\text{RMS}}, [\text{T} \cdot \text{s}^{-1}] \quad (2)$$

To calculate the magnetic induction over time, the parameter of the root mean square B_{RMS} is recommended:

$$B_{\text{RMS}} = \sqrt{\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} [B(t)]^2 dt}, [\text{T}] \quad (3)$$

Current knowledge suggests the importance of dealing with sources with frequencies up to 3 kHz, which are in the three frequency ranges according to the ICNIRP [5], namely 1–8 Hz, 8–25 Hz, and 25–3000 Hz. Frequencies of 0–1 Hz form a separate group considered static from a frequency point of view.

The SBM 2008 [9] standard (amendment 2015) classifies a source into four categories: up to 20 nT, 20–100 nT, 100–500 nT, and above 500 nT. In comparison with the ICNIRP [5], it also contains a recommendation for time-based exposure to MFs and gives preconditions for dosimetric measurements. A separate group consists of epidemiological studies where the MF limit is recommended to be 500 nT [15].

The influence of MFs on humans is influenced by several factors, such as the distance from the source of the MF, objects standing between the source of radiation and the person, and the output (directional characteristic) of the source. In technical practice, 50- or 60-Hz MF devices are most frequently used. Only some devices and procedures use sources with

frequencies below 50 Hz. There are also processes [16,17] which use frequencies lower than 50 Hz (e.g., demagnetization, welding and special drives). These sources have been given minimum attention. The issue of the impact of MFs on technical equipment is addressed in the field of compatibility [13,18]. The second area is the impact of MFs on humans. This issue is treated within work safety, working environment, and work hygiene [11,19].

The MF measurements performed near the EV charging stands detected, at a distance of 10 cm from the stand, values of $B_{RMS} < 50 \mu\text{T}$ at currents up to 200 A [20]. Some of the measurements indicated that the limit values for MFs in the vicinity of up to 10 cm from the cover of the stand were exceeded [21].

The asymmetric effect of the interaction between the source and the biological material can be observed even at small values of the MF in animals and humans. The difference in approach between the SBM and the ICNIRP indicates a discrepancy in this issue. Electro mobility raises further questions in this area.

The Situation in Slovakia

EU Directive 2013/35/EU [6] was reflected in Slovakia in Act No. 355/2007, Coll. [22] on the protection, promotion, and development of public health. The limit values for MFs are given in Slovak Republic Regulation No. 344/2020 [23] (Table 1), which are based on the requirements of the EU Directive 2013/35/EU [6], IEEE C95.6 [8], and ICNIRP standards [4,5].

Table 1. Magnetic induction values B from 1 Hz to 10 MHz (Slovak Republic) [23].

Frequency Band	$B_{a,lower}$ [μT] (Effective Values) Citizen	$B_{a,higher}$ [μT] (Effective Values) Staff	B [μT] for the MF Exposure of Limbs (Effective Values)
$1 \text{ Hz} \leq f < 8 \text{ Hz}$	0.05	0.05	0.04
$8 \text{ Hz} \leq f < 25 \text{ Hz}$	0.1	0.1	0.06
$25 \text{ Hz} \leq f < 300 \text{ Hz}$	0.21	0.16	0.08
$300 \text{ Hz} \leq f < 3 \text{ kHz}$	0.24	0.27	0.09
$3 \text{ kHz} \leq f \leq 10 \text{ MHz}$	0.17	0.19	0.06

The MF exposure evaluation of the population is carried out by assessment, measurement, or calculation [24]. The values obtained are compared with the so-called action values [24], which must not be exceeded in places citizens can access. The experimental procedure was assigned by Bulletin of the Ministry of Health of the Slovak Republic No. 36/2019 [25], which applies to measuring systems and systems for processing measured data with a frequency range from 100 kHz to 6 GHz, which can be extended up to 300 GHz if required, according to the Bulletin of the Ministry of the Health of Slovak Republic No. 36/2019 [25], and it is necessary to follow the given methodological instructions OOFŽP-7674/2010 [24]. Measurements below 100 KHz are not regulated by national regulations.

Regulation 344/2020 Coll. [23] (Table 1) does not have a definition of exposure time. The term “short-term exposure” in 344/2020 Coll. [23] is not sufficient to define the amount of MF energy received over time by an object which has been exposed to a magnetic field. Especially with pulsed MF shocks (dynamic radiation change), this problem is apparent. This also implies the incorrect name “exposure action value”. The value for this variable is B , which is a designation for magnetic flux density and not for doses (Table 1). The term exposure is generally bound to a time frame [11]. Failure to consider the vector substance of MFs, similar to the ICNIRP standards [3–5], leads to ambiguity in the measurement and in the interpretation of the measured values. Depending on the method of measurement and the position of the measuring equipment relative to the source, components B_x , B_y , and B_z in the x, y, and z directions can be measured from a rectangular orthogonal system, and the resulting magnetic induction vector is

$$\vec{B} = \vec{B}_x + \vec{B}_y + \vec{B}_z, [\text{T}] \quad (4)$$

The size of the resulting magnetic induction vector B_{total} is

$$B_{total} = \sqrt{B_x^2 + B_y^2 + B_z^2}, \text{ [T]} \quad (5)$$

The B_{RMS} value is a scalar value. Measurements of the limit values made according to the ICNIRP standards [4,5] were performed for stable sources in Slovakia [26,27]. This is questionable in the case of EV charging. An EV is a mobile device with a built-in converter. In the case of an EV charging stand, these standards can have limited use, taking into account the vector nature of MFs.

The development of electro mobility and charging stations is not sufficiently covered normatively. The ICNIRP limit values as well as the norms in the Slovak Republic are for stable sources. An electric car cannot be considered a stable source.

2. Materials and Methods

2.1. Experimental Method and Experimental Equipment

Each object with an electric charge has its local MF characterizing its status and operation. The MF of the object is formed by the movement of machine elements (e.g., moving, rotating machine elements in the MF of the Earth), which modulate the local MF of the source. The second source of local MF production is the flow of current through electrical devices (e.g., winding of transformers and converters). Equipment for measuring the induced local MF through an electric device was carried out by Oravec et al. as utility model UV8860 [28] and as utility model UV 50084-2019 [29]. Quantification of the MF parameters of the object is possible within the time and frequency range. A discrete fast Fourier transform (DFT) can help analyze the frequency area in detail. Many measurements were made [17,27], mainly in the area of non-contact measurements, confirming the suitability of the method and the VEMA-041 magnetometer. The VEMA-041 is a purpose-built measuring device designed for the measurement of MFs [30–32] for the needs of military aviation. Compared with industrial measuring devices such as those from NARDA [26], the VEMA-041 is more accurate. The frequency range of the VEMA-041 is 0–250 Hz, and the magnetic induction density range is from 2×10^{-9} T to 2×10^{-5} T with a sensitivity of 1.7 nT. The same fluxgate principle proved useful in attitude determination of the satellites skCUBE [13,30,33,34] and GRBAAlpha in 2021 [35] in Earth's MF.

2.2. Measurement and Evaluation of Experimental Data

The evaluation (both in real time and for post-processing) utilized OtVema (open-source) software. This software enables processing of data collected by a magnetometer. The software's primary functions are the visualization of processed data for the user and data recording in accordance with a selected time schedule. Files of magnetometer data are processed and displayed in an oscilloscopic mode on the screen. Figure 1 shows the entire measurement chain used for the measurement [29,36].

Figure 1. Measurement chain and sensor on basis of fluxgate principle.

For the post-processing options in the QtVema environment for MF analysis and dB/dt changes, we selected a display of the frequency spectra, which is a display of the position of the resulting point of the MF parameter of the rotating vector. The rotating vector of the MF has already been presented in the past [37] but was not used in direct experiments. The reason for this was the difficulty of data processing and understanding the local gradient (acyclic) of the MF around the device. The QtVema environment has the tools to accomplish this, and evaluation can be performed online (QtPlot 0.8.5 in OS GNU/Linux distribution UBUNTU 6.06). The sensitivity of the VEMA-04 magnetometers was 1.7 nT/LSB (least significant bit). Full-scale non-linearity was below 0.5% in the measurement range of $\pm 60 \mu\text{m}$. The channels were sampled simultaneously at a rate of 1000 samples per second. The noise spectral densities of the used magnetometers were identified experimentally with long-term measurements and also with the method presented in [33], which were approximately $280 \text{ pT}/\sqrt{\text{Hz}}@1 \text{ Hz}$ and $230 \text{ pT}/\sqrt{\text{Hz}}@10 \text{ Hz}$ for all channels. More information is in [33,34], and the error rate of the VEMA-041 measuring device is listed in [38].

2.3. The Course of the Experiment

The MF represented by parameter B near the EV charging stand is dependent on the current and charging power. The charging power is a function of the current and the operating voltage.

The charging of the EV was analyzed using two charging stands. In the first case, it was charged up to 6.6 kW. In the second case, it was charged via the fast charger, with a charging power of 43 kW. The analysis was carried out along the entire energy flow chain. The energy flow chain was formed by a transformer, underground cables, and a charging stand. The analysis included an EV charging assessment with a built-in AC/DC converter inside the EV. EV samples of the same make in the first and second generation were used for the measurement. Transformers up to 250 kW (22 kW/400 V) were used. The cables leading up to the stand passed through the ground or the building itself, depending on the location. The experiments were carried out during EV charging. The measurement was carried out at a distance of 0.3 m from the floor stand, at a height of 0.40 m, and on the AC/DC EV converter in the EV engine compartment, (Figure 2) as well as in the driver's footwell and the driver's seat area (under the seat).

Figure 2. Location of the measuring prism during MF measuring. (a) in EV's motor; (b) in in the footwell in EV.

3. Results

3.1. Electricity Transmission and Its Transformation

The MF measurement was made on a three-phase insulated cable leading to the transformer with a current of 600 A at a distance of 1 m. The measuring prism was positioned such that the direction of the "x" axis was in the direction of the imaginary flow of electrical energy. The "y" and "z" axes formed a rectangular orthogonal system with the "x" axis. Figure 3 shows the time courses of B_x , B_y , and B_z in the x, y, and z directions without a one-way component (filtered static component MF).

Figure 3. Time course of B_x , B_y , and B_z without the one-way component.

The time recording of the MF measurement in the footwell was analyzed by the DFT method during the post-processing process. Figure 4 shows the B_x , B_y , and B_z spectra from the time course in Figure 3.

Figure 4. Graphs showing the B_x , B_y , and B_z spectra for the three-phase power insulated cable (600 A) at a distance of 1 m. (a) in the “x” axis direction; (b) in the “y” axis direction; (c) in the “z” axis direction.

Figure 4 displays values of $B_x = 2.71 \mu\text{T}$, $B_y = 3.7 \mu\text{T}$, and $B_z = 0.7 \mu\text{T}$ at 50 Hz. In terms of Equations (3) and (5), a value of $B_{RMS} = 3.25 \mu\text{T}$ was calculated. This value was lower than the limit value stated in Table 1 for a frequency of 50 Hz for all three action levels.

The measured MF values correlated with the values published from 1998–2021 [39–41]. For 400-kV cables in the ground, the 0.05- μT values were measured on the surface of the ground [42]. For cables in houses and office buildings with a current up to 30 A, values up to 1 μT were measured for older cables up to a distance of 0.3 m. For three-phase power cables up to 600 A, values of 5 μT were measured up to a distance of 2 m [43]. The texts of published contributions are not clear about whether these are effective or absolute values, and they are, therefore, only indicative. This fact can be seen in several epidemiological studies [44–47] without defining the parameters of the MF source and the distance from the source.

The charging stands are powered by transformers. The measurements were made on two transformers with different power values and one distribution box. The first measurement was carried out on a 250-kVA transformer located in a brick building. The measuring prism was located 1 m from the perimeter wall of the transformer. The “x” axis

was perpendicular to the perimeter wall, and the “y” and “z” axes formed a rectangular orthogonal system with the “x” axis. The second transformer, with 100 kVA of power, was placed on the ground. The measuring prism was placed 1 m from or at the edge of the object. The detected frequencies from the frequency analysis of the transformers and the distribution box serving as the power supply of the EV charging stands are stated in Table 2.

Table 2. Detected amplitudes B at a frequency of 50 Hz for selected transformers.

Magnetic Induction	Frequency (Hz)	Transformer * 250 kVA (22 kV/400 V)	Distribution Box near the Transformer ** 250 kVA (22 kV/400 V)	Transformer *** 100 kVA (22 kV/400 V)
B_x (μ T)	50	1.27	3	0.82
B_y (μ T)		0.97	0.7	0.3
B_z (μ T)		0.37	0.7	0.35
B_{RMS} (μ T)		1.15	2.21	0.66
$B_{a,lower}$ (μ T)	1000 μ T (limit according to Table 1)			

* Transformer in a brick building, measured 1 m from the building wall on the ground. The x axis was oriented perpendicular to the wall of the building. ** The distribution box was at a height of 1 m above the ground, measured 1 m from the distribution box on the ground, and oriented perpendicular to the distribution box. *** Transformer located on the ground, dry, and measured at the edge of the object on the ground with the x axis oriented perpendicular to the frontage of the object.

In the case of a transformer with a power of 100 kVA, the third and fifth harmonics in the direction of the z axis were also identified; however, they were negligible compared with the first harmonic. The measurement of components B_x , B_y , and B_z enabled the identification of the direction in which the maximum magnetic field value was applied. The resulting rotating vector MF [38] provided information not only about the position and pulse of the MF but also the errors [48]. At the same time, it is possible to point out the possibilities of interpretation of measured MP values. The vector position MP enables statistical evaluation, detection of machine failures, and knowledge of the causality of an event. These methods of evaluation can be used in technical diagnostics as well as measurements focused on the interaction of the “source of MP-man (operator)”. Figure 5a shows the end of the rotating vector B_{total} for a field of a cable with a current of 600 A at a distance of 1 m. The rotating vector MP in Figure 5a is a closed ellipse, which determines a cyclic phenomenon at one frequency. Said frequency is shown in Figure 4 (50 Hz). Figure 5b shows the end of a rotating vector B_{total} of a transformer with a power of 250 kVA at a distance of 1 m from the wall of the object. Blue represents the minimums, and red represents the peaks. The position and size of this vector determine spots with increased MF pulse values. Indirectly, the amplitude spectra (Figure 4) indicate the end point of the MF vector. QtVema works in a coordinate system of A, B, and C, corresponding to $A = x$, $B = y$, and $C = z$.

The transformer, compared with the cable, is a more complex device, and manufacturing inaccuracies and the operating load can also cause odd harmonics that change the image of the rotating B_{total} (Figure 5b). The transformer measurements also determined odd harmonics (third and fifth), and the MP image was no longer an ellipse. The rotating vector MP was closed, as it was a cyclically repeating phenomenon. Similarly, sources in the electrical network can generate multiples of 50 Hz [18]. The width of the pattern trace indicated the presence of higher harmonics in the transformer. The location of the end of the rotating vector was displayed online in the QtVema environment.

Figure 5. The end position of the rotating vector B_{total} of magnetic induction of the cable (a) and transformer (b).

The B_{RMS} value for the 250 kVA and 100 kVA transformers and the distribution box complied with the limit values (Table 2) for the frequency of 50 Hz for all three levels.

Many epidemiological studies [49–55] assess the effects on health in the vicinity of transformers in residential houses. The measured values of MF did not exceed $5 \mu\text{T}$ at 50 Hz. The repeatability of these trials is questionable, however, as the distances from the source and the output of the source were not clearly defined. Wide frequency range equipment was used. Only the B_{RMS} value, which was a scalar, was measured. The results can be used for the indicative determination of the interval of B values in the vicinity of transformers. Measurements on the transformers were made at 50 Hz (60Hz).

3.2. AC/DC Converter

3.2.1. Charging with an Inverter Built into the EV

The first measurements were made with the first generation of the Nissan Leaf EV. The charging power was 6.6 kW at 16 A. The position of the converter in the EV was in the space in front of the driver's seat at the level of the steering wheel in the front hood compartment (Figure 2a). The distance between the converter and the position of the measuring prism was less than 1 m. Similarly, as in the case of the cable and transformer, frequency domain analysis was performed (Figure 6).

Figure 6. Magnetic induction values B_x , B_y , and B_z in the x, y, and z directions in the footwell of the EV driver. (a) in the “x” axis direction; (b) in the “y” axis direction; (c) in the “z” axis direction.

Several frequencies can be observed compared with the cable and transformer. These frequencies were caused by the design of the AC/DC converter in the EV. The basic frequency was 10 Hz, and the harmonic multiples were derived from it. The values of the B_x , B_y , and B_z amplitudes correspond to the current during charging. The image created by rotating the end point of the B_{total} vector was closed and cyclic. Table 3 shows the magnetic induction values of B for the individual frequencies shown in Figure 6. The ratio

of the measured value to the limit value B according to Equation (1) was less than one. In the case of the transformer, it can be claimed that in terms of the Slovak legislation, this condition would be satisfactory if this were a stable source for all the action levels. Similarly, the magnetic induction values were measured in the space of the driver seat (Figure 3). A similar finding would be made with regard to the ratio of the action level limit value to the measured values of the MF. The fact is that an EV is a mobile device.

Table 3. The amplitude(s) determined for the respective frequencies. Measurement: footwell of the driver (6.6 kW).

Magnetic Induction	Frequency (Hz)						
	10	20	30	40	50	60	70
B_x (μT)	0.11	0.020	0.017	0.022	0.001	0.0012	0.007
B_y (μT)	0.134	0.022	0.017	0.22	0.01	0.011	0.008
B_z (μT)	0.217	0.036	0.029	0.034	0.014	0.016	0.010
B_{lower} (μT)	0.28	0.05	0.04	0.22	0.02	0.02	0.01
B_{RMS} (μT)	0.19	0.03	0.03	0.16	0.01	0.01	0.01
$B_{a,\text{lower}}$ (μT)	2.5×10^3	2.5×10^3	1×10^3	1×10^3	1×10^3	1×10^3	1×10^3
$B_{\text{RMS},j}/B_{\text{limit},j}$	7.77×10^{-5}	1.31×10^{-5}	2.64×10^{-5}	1.57×10^{-4}	1.21×10^{-5}	1.36×10^{-5}	1.02×10^{-5}

Table 3 clearly shows the substantial representation of the emitted energy of the MF at the frequencies 10 Hz and 40 Hz. The maximum value of the emitted magnetic induction was in the “z” direction. At a frequency of 10 Hz, in the “x” axis direction, it was 24%; in the “y” axis direction, it was 29%; and in the “z” axis direction, it was 47%. The design and location of the charger were decisive for these values.

3.2.2. Charging with Charging Stand at 43 kW Charging Power

The second measurement was made when charging from the 175-kW fast charging stand. The power to be transmitted was 43 kW. The MF occurring in the stand in front of the charging stand at a distance of 0.5 m and at a height of 0.4 m from the ground is displayed in (Figure 7). The “x” axis direction was oriented toward the stand, whereas “y” was positioned horizontally, and “z” was positioned vertically. The axes formed a rectangular orthogonal system.

Figure 7. Magnetic induction values B_x , B_y , and B_z in the x, y, and z directions in front of the charging stand. (a) in the “x” axis direction; (b) in the “y” axis direction; (c) in the “z” axis direction.

In order to identify the MF in the EV compartment, a measuring prism was placed on the AC/DC converter in the engine compartment (Figure 2a). Figure 8 shows the amplitude spectra measured at the AC/DC converter.

Figure 8. Magnetic induction values B_x , B_y , and B_z for the AC/DC converter in the engine compartment of the EV. (a) in the “x” axis direction; (b) in the “y” axis direction; (c) in the “z” axis direction.

By comparing Figures 7 and 8, it is clear that the 50-Hz frequency and its multiples were from the charging stand. The built-in AC/DC converter in the EV worked with a basic frequency of 10 Hz and its multiples.

By comparing the amplitude spectra for the cable (Figure 4), transformer (Figure 8), and spectra in Figure 9, it was obvious that the trajectory pattern of the resulting MF B_{total} vector at the AC/DC converter station would be different (Figure 9). Blue shows the minima, and red shows the peaks B_{total} . QtVema works with the coordinate system A, B, and C, in which A = x, B = y, and C = z.

Figure 9. The end position of the rotating vector B_{total} of the magnetic induction of the AC/DC converter in the EV for the spectra in Figure 6.

The change in polarity of B_{total} is shown in blue and red (Figure 9). The track width indicates the presence of multiple frequencies oscillating around a fundamental frequency of 10 Hz, which is evident from the spectrum analysis of Figure 6. The Z-shaped MP shape (top view) revealed the change. The rotating vector MP was closed, which indicates the cyclicity of the process.

The minimum and maximum values of B_x , B_y , and B_z can be subtracted from the MP shape as illustrated in Table 4. The mean value of the MP (static component) was in the center of the MP pattern around which the rotating MP vector oscillated.

Table 4. The amplitude(s) detected for the corresponding frequencies in the footwell of the driver (43 kW).

Magnetic Induction	Frequency (Hz)						
	10	20	30	40	50	60	70
B_x (μ T)	0.15	0.06	0.05	0.05	0.22	0.04	0.03
B_y (μ T)	0.32	0.11	0.1	0.1	0.21	0.06	0.02
B_z (μ T)	1.35	0.24	0.21	0.16	0.08	0.08	0.05
B_{lower} (μ T)	1.36	0.27	0.24	0.27	0.24	0.09	0.06
B_{RMS} (μ T)	0.95	0.19	0.17	0.19	0.17	0.06	0.04
$B_{a,lower}$ (μ T)	2.5×10^3	2.5×10^3	1×10^3	1×10^3	1×10^3	1×10^3	1×10^3
$B_{RMS,j}/B_{limit,j}$	3.81×10^{-4}	7.47×10^{-5}	1.67×10^{-4}	1.88×10^{-4}	1.69×10^{-4}	6.42×10^{-5}	4.08×10^{-5}

Table 4 also shows, for comparison, specific values in the footwell of the driver. The values are only given up to a frequency of 70 Hz.

The ratio of the measured value to the limit value B according to Equation (1) was less than one for of the footwell of the driver when charging at 43 kW. This result was same as that for 6.6 kW EV charging. The value of 500 nT was reached in the EV compartment.

A significant proportion of the emitted MP energy could be observed in the “z” axis direction when charging the EV with a power value of 43 kW.

Second-generation Nissan Leaf EVs emit different frequencies. This is clear from the comparison of Tables 4 and 5. Energy was transmitted at a frequency of 10 Hz, which was 55% of the energy MP, and at a frequency of 40 Hz, it was 11%. The energy transferred at a frequency of 10 Hz in the “x” axis direction was 8%; in the “y” axis direction, it was 17%; and in the “z” axis direction, it was 75% (Figure 8).

Table 5. SBM standard–2015 [9].

	Category			
	Without	Slight	Significant	Critical
Magnetic Induction (nT)	<20	20–100	100–500	>500

4. Discussion

The results of the measurements show that EVs are a source of MFs. The ICNIRP manual [5] does not address these conditions, as EVs cannot be considered a stable source when being charged. The opposite is a stable stand or charging station in a building with a transformer and cable. So far, there is no standard for mobile devices. The current locations of charging stands in buildings are, by their nature, closer to the building’s hygiene. In the past, unlike with industrial buildings, it was unusual to locate transformers in residential buildings, as is the case in Western Europe. Standards for the hygiene of buildings such as SBM 2015 [9] do not yet have an equivalent in Slovakia [15]. The number of reports at the Slovak Regional Public Health Authority from this area [56] is also indicative of this. MF measurements are performed mainly in industries, where major sources of MFs, electrolysis, induction furnaces, etc. are located.

Fixed charging stations located on the ground in public spaces can be assessed according to the Slovak standards. In this respect, it can be concluded that they are suitable. As shown in Figure 1 and Table 1, the charging stands complied with the 1000- μ T limit value.

If the charging stand is located on the premises or on the walls of restaurants or residential houses, the purpose must be taken into account, and the standard then needs to be selected accordingly. Recommendation SBM 2015 [9] has stricter limit values (Table 5). In a building with multiple sources of MFs, this problem will become even more noticeable.

The comparison of limit values of magnetic induction in Table 5 and measured values in Tables 2–4 would thus place those sources in the categories of significant to critical accord-

ing to SBM 2015 [9]. The difference in limit values of more than three orders of magnitude in the field of occupational safety and hygiene in buildings is an existing problem.

The value of 500 nT is also a limit value in several epidemiological studies [54], which have been conducted for different types of residential buildings and sources of MFs. An epidemiological approach does not require precise causality descriptions and use statistical tools. Exposure time in these studies ranged from 24 h to months.

From the measurement point of view, it was a spot measurement, regardless of the specifications of the source parameters or causality. The above measurements did not consider the vector nature of MFs. The spot measurement of such fields implies having a clearly defined measurement objective and using equivalent procedures. Many epidemiological studies are based on the MF source having an amplitude of 50 Hz without verification. In fact, the network load and transformer errors cause the presence of the third and fifth harmonic MFs. These facts will cause the shape of the MF pattern to change from an ellipse (Figure 5a,b).

The rotating vector of an MF at the measuring point (Figures 5 and 9) as well as the spectra in Figures 4 and 6, Figures 7 and 8 point out the need to reconsider the method of measuring MFs. The local MF gradient in space and case where a person is moving may not produce a true image of reality. An MF is of a vector nature. Tools exist to identify MFs, and a dosimetry approach is a possible solution. The magnetic induction parameter, frequency, and time represent the performance of MFs. This MF performance can be quantified [13].

The MF value is not a number but a form of information. Information makes sense if it is known that there is causality, which is a method of change. An MF is a unique source of information about the change in the state of the device, as well as the environment in which a person is located. Today's tools to describe this situation are insufficient. The B_{RMS} value reported in the ICNIRP standards is not sufficient to quantify changes in MFs. There also exists a change in that the one-way component of an MF is not assessed by the ICNIRP standards. The recommendation of change (0.22 T/s) for frequencies greater than 1 Hz is insufficient. The image of an MF also points to other possibilities of evaluating the change in an MF. Changing dB_{RMS}/dt is not enough. There is also a dB/dt change for the unidirectional (static) value of an MF. This is caused by sharp movements of EVs in the Earth's magnetic field, and dB/dt changes make sense when an EV is moving. This problem can be solved by a dosimetric device that will allow for measuring the all-day dose of MF change for the EV crew.

The Slovak Republic does not yet perform dosimetry measurements in the framework of construction procedures, neither for the purpose of fixing the charging stands nor for the purpose of assembling the wall boxes in residential houses. A minimum zone with respect to the surrounding area should be established, defining the possibilities for the locations of stable resources with the potential of low-frequency MFs. The current standards allow charging stations to be placed on one wall, even when there is an office or a living space on the other side of the wall. For sources such as transformers and lines, most of the MF parameters can be determined easily, as they operate at 50 Hz and its multiples. The opposite is the condition where switch-based (DC/AC) converters are used (photovoltaic systems).

The efficiency of charging stations per unit of power was lower compared with the transformer (Tables 2, 4 and 5). The challenge in constructing charging stands is to use solutions that will emit less MFs into the surrounding areas. This shall also be detected when measuring efficiency with respect to the unit of performance. Compared with the converter used for EV charging, the transformer is more efficient per unit of power than the charging stands (i.e., AC/DC converters). The MF performance parameter is appropriate if the intention is to compare energy losses across different fields that can be analyzed using a DFT. For the built-in inverter in the EV (Figure 2, Tables 3 and 4), the first harmonic multiples in relation to the MF direction were measured at a specific time. On the basis of the above facts, charging of EVs should be carried out with the driver's and passengers' absence, particularly during quick charging.

Mathematical tools, as well as specific measuring devices, offer options for the application of procedures not only for measuring cyclical courses of MFs but also for pulse spikes [13]. Such phenomena are known from the energetics.

In the area of mobile devices, the component dB/dt , due to the change in the direction of movement of the object in the Earth's MF, is also increasing. During rapid braking, EVs can make changes between 5 and 7 μT in a quarter of a second [13], which is comparable to the MFs in the vicinity of transformers. These effects have not yet been evaluated, and the issue of these local gradient MFs and their rates of change has not yet been standardized.

Any change in the position of the end point of the rotating vector MF is caused by a change in the ambient parameters. They are the result of changes in the dynamics of bodies in the Earth's field and changes caused by local electrical devices in a particular space. The MF image can be used to compare between the recommended MF state and the actual state. The degree of difference defines the extent of the problem. There are existing noise maps and standards, and there should be MF maps for specific modes in EVs. There are also no recommended places in EVs where MFs should be measured during charging. The position of the rotating vector MF gives designers new tools for human protection in prevention already in the phase of EV construction. The issue of electromagnetic compatibility does not solve the issue of the influence of MFs on humans.

5. Conclusions

The ICNIRP standards define MF limit values for immediate consequences. They do not, however, evaluate long-term conditions. The limit values for MFs are defined for stable sources where EV charging stands belong. However, an EV is a mobile device. The effective B_{RMS} value (Table 1), which is a scalar value, was chosen as a representative parameter in these standards for MFs. Experimental experiences and MF measurements in any location and independent direction offer a new view of indicated MFs. The rotating vector B_{total} defined the space and the value of an MF, which was compared with the limit values. Such measurement allowed for identification of the space with the lowest and highest values of MFs in the selected area. As long as a DFT is performed, an MF's performance can be easily determined as a function of the induction, frequency, and time.

The investigated devices when charging electric vehicles (EVs) specifically were a 100-kVA transformer, 250-kVA (22 kV/400 V) transformer, cables of 600 A, a fixed charging stand, and an AC/DC transformer in the EV induce magnetic fields with specific values. Dynamic sources, which were a fixed charging stand and an AC/DC transformer in the EV, had higher values (about 25 μT at a frequency of 50 Hz). At the same time, an increase in the frequency of 100, 150, 200, 250, and 300 Hz for dynamic sources repeatedly induced a magnetic field, but a gradual decrease was monitored in the B_{RMS} values. The obtained values prove the presence of magnetic fields, but with the development of mobility, it is necessary to continue to deal with this issue. Based on the results obtained from the measurements and analyses, it is necessary to focus on the following problems in the future:

- Development of a standard for comparison of emitted MP values for EV charging stands, as there are only standards for stable sources in general.
- Legally, the electric car cannot be considered a stable source. Therefore, it is also appropriate to specify the places in the EV where it is recommended to measure the MP. Such places include the converter, the driver's seat, and the EV passenger.
- The inconsistency of evaluation approaches and standards in the EU indicates the appropriateness of introducing dosimetry measurement. This measurement would make it possible to measure the processes taking place while driving the EV (e.g., during accelerations and recuperation when MPs are also produced, as pointed out in [57]).

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Abbreviations

B_{RMS}	Root mean square of magnetic induction
B_{total}	Maximum value of the magnetic field rotating vector
DFT	Discrete fast Fourier transform
ELF	Extremely low frequency
EMFs	Electromagnetic fields
EV	Electric vehicle
ICNIRP	International Commission on Non-Ionizing Radiation Protection
MRI	Magnetic resonance imaging
MF	Magnetic field

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