©Kadmy – stock.adobe.com

Dr. Florian Soyka

Institute for Occupational Safety and Health (IFA) of the German Social Accident Insurance (DGUV)
Division: Accident Prevention: Digitalisation – Technologies
Unit: Machine Safety, Industrial Security and Implants

Alte Heerstrasse 111, 53757 Sankt Augustin, Germany

E-mail: florian.soyka@dguv.de

Internet: www.dguv.de/ifa

This text was first published in German in the journal "sicher ist sicher" (Issue 2 & 3 in 2020).

Comparison of methods for assessing pulsed magnetic fields

Teaser

High electric currents generate strong magnetic fields, for example during resistance welding. In order to ensure safety at the workplace, these magnetic fields must be considered in the course of a risk assessment. Increasingly, these fields are pulsed fields generated by power control systems, and special methods are required for their assessment. The article compares two such methods and discusses problems that may arise in practice during measurement and assessment.

Introduction

Magnetic fields are generated wherever an electric current flows. Modern control engineering enables the time characteristic of the current to be adapted to the requirements of the application. Increasingly, non-sinusoidal, pulsed current patterns are generated. A classic example of such an application is resistance welding (see title image). A range of power control methods can be used to generate these current patterns. These include phase-angle control of AC current pulses (pulse width modulation), capacitor discharge currents with exponential current characteristics, or direct currents generated by inverters (with superimposed ripple currents caused by the switching frequency of the inverter). Common to these applications is that they generate low-frequency, non-sinusoidal magnetic fields which must be assessed in the course of risk assessment. The German occupational safety and health (OSH) ordinance on electromagnetic fields (EMFV, [1]) specifies the use of state-of-the-art time-domain assessment methods for this purpose. Two methods are currently in use, the time-domain assessment method (TDA) in accordance with DGUV Regulation 15 [2, 3, 4, 5] and the weighted peak method (WPM) [6, 7, 8]. This article describes both methods in general terms and explains their respective benefits and drawbacks in their application.

Assessment methods for fields with non-sinusoidal time characteristics

The permissible exposure values (action levels) for electromagnetic fields (EMFs) are specified for continuous sinusoidal waveforms [1]. The action levels are defined as maximum permissible amplitudes and differ according to the frequency of the waveform. For many applications, this is sufficient. However, applications emitting fields with non-sinusoidal signal characteristics are increasingly being used.

For the assessment of pulsed signals (i.e. containing dead times) with arbitrary time characteristics $g(t)$, methods are therefore required which enable the discrete frequency components of the signal to be evaluated in order for unacceptable exposure at the workplace to be avoided. The principles of the methods and differences between them will first be summarized below, followed by a more detailed discussion of the difficulties arising in practice.

The time-domain assessment method (TDA)

With the TDA, it is possible to manually assess the time course of a signal that has already been measured with reasonable effort; manually in this context means that a computer-aided analysis tool is not required for the assessment. This was an important aspect when the method was originally introduced in 2001. The signal $g(t)$, which may have an arbitrary time course, is parsed and approximated with the use of four basic types: sinusoidal, trapezoidal, triangular and exponential pulses. Besides the amplitude, the maximum slope of $g(t)$ is also transferred to the basic types. In the next step, it is possible to derive a continuous sinusoidal signal (with an equivalence frequency and amplitude) from the parameters of the basic types. This sinusoidal signal has a stimulus effect comparable to that of the original signal. This transformation of $g(t)$ to a continuous, sinusoidal signal makes comparison with the action levels straightforward [3]. Detailed step-by-step instructions for the TDA together with examples can be found in DGUV Informative publication 203-038 [5].

As use of the method over many years has shown, all fields occurring in practice to date can be assessed by means of these four basic types. Where the signal comprises superposition of multiple basic types, multiple equivalence frequencies are also extracted and assessed individually. The physiological principles of nerve stimulation are such that additive superposition of the stimuli does not occur [9]. The parsed individual spectral components must therefore be assessed separately.

Ultimately, only the spectral component with the greatest stimulation effect (in consideration of the respective action levels) is relevant for exposure assessment.

A similar method which also extracts an equivalence frequency and uses it to assesses the signal was described by Reilly and Diamant in 2002 [10]. This method considers the internal electric field strengths within the body, whereas the TDA assesses the external magnetic fields. The relationship between internal and external fields can be determined by means of a coupling model [9]. External magnetic fields are used for assessment for occupational safety and health purposes since, in contrast to the electrical field strengths within the body, they can be measured directly at the workplace.

Manual assessment of the signal gives rise to implicit effects, which will be discussed in more detail below. Experts are able to use their experience in order to detect patterns in the signal. In contrast to a computer-based interpretation, the expert him or herself assumes the function of a filter. He or she decides which signal type is present and can, for example, identify noise or measurement artefacts and assess their relevance comparatively easily. Together with his or her background knowledge of the installation under test and its functional principle, the expert is able to assess the signal for its plausibility. In other words, in an ideal case, the expert knows what signal form should be expected (e.g. number of pulses, phase angle, dead times), and can bring this knowledge to bear during the assessment. On the one hand, manual assessment introduces a risk of error and a subjective element into the assessment. On the other, the plausibility check of the assessment is a direct part of the process, thereby reducing the risk of unnoticed measurement artefacts of any kind leading to unrealistic assessments.

Our experience has shown measurement artefacts to constitute factors which should not be neglected and which are able to lead to false assessments, especially in fully automated assessment processes (see Measurement probes). It is therefore recommended that the measurement, measured values and assessment always be checked by an expert for plausibility.

The manual procedure may give rise to minor variability in the result between measurements assessed by different persons; this may be attributable to differences between individuals in how precisely they read off values. In practice, these variations are negligible, since the action levels include safety factors which can tolerate the measurement uncertainties to be anticipated. In addition, measures are always taken in occupational safety and health that are easy for the user to implement and may include further safety factors. Where, for example, safety distances from the field source must be observed, they are usually rounded up to obtain a convenient dimension. This often yields an additional safety factor.

Weighted peak method

As early as 1998, the guidelines issued by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) stated that a Fourier analysis can be performed for pulsed, low-frequency fields in order for the frequency spectrum subsequently to be assessed by means of the reference level (permissible values) and a summation formula [11]. This method of assessment is conservative, since the individual assessments for the various frequency components do not always needed to be summated. In this context, the guidance document explicitly states that the additivity of the stimulus effect at multiple frequencies must be reviewed. It does not explain however how the review can be performed. It should include consideration for the physiological process of nerve stimulation, which generally does not readily lend itself to analysis. Assessments have therefore generally been conducted based upon the conservative assumption of additivity.

In 2003, ICNIRP published a statement introducing the concept of the weighted peak method [6]. This recognizes in the first instance that use of the summation formula described above yields very conservative results. This method is therefore probably unsuitable for critical exposure situations in the field, since it may for example lead to excessive safety distances being specified. The WPM is then described as an alternative method. In this method, the complex-valued frequency components of the signal are multiplied by a weighting factor which is frequency-dependent and adjusts both gain and phase. In contrast to the original summation formula, this method both takes account of the phases of the components, and adjusts them. The method is thus still additive, but considers the phase relationships. The real component of the weighting factor is defined as the reciprocal of the action levels. The frequency components are thus effectively normalized to the action levels as a function of the frequency. If the individual components weighted in this manner are recombined to form a total signal in the time domain, the "exposure index" (EI) can be derived from the maximum of the absolute values of this signal [8]. Where the EI lies between 0% and 100%, the exposure is permissible; above 100%, the action levels are exceeded.

As will be shown below, knowing the time course of the weighted signal $h(t)$ is advantageous for checking the plausibility of the WPM assessment. The calculation steps are as follows:

$$EI = \max(|h(t)|) = \max\left(\left|WPM\left(g(t)\right)\right|\right) \tag{1}$$

where the step $h(t) = WPM\left(g(t)\right)$ describes the weighting. In the discussion below, $h(t)$ will be referred to as the weighted WPM signal from which the exposure index can be calculated by formation of the absolute value and subsequently the maximum value.

It should be noted that the WPM can also be used for polarized, spatially three-dimensional signals. Conversely, the TDA is defined only for one-dimensional signals. In the majority of practical applications however, the measured, spatially three-dimensional signal can be represented one-dimensionally by a coordinate transformation.

The ICNIRP statement of 2003 further sets out that the WPM can either be implemented and applied directly in an instrument in the form of a filter recreating the defined transfer function, or applied mathematically subsequent to measurement by means of a Fourier analysis. It is further acknowledged that differences in the assessment may arise according to whether the WPM is implemented in the form of a filter (continuous variation of the reciprocals of the reference levels and phase factors), or calculation is performed by means of the piecewise defined values (Figure 1). Continuous variation corresponds more closely to the physiological principles upon which assessment of the fields is based. These differences are explicitly described again in the annex of the non-binding 2010 ICNIRP guidelines [7], in which deviations of up to 3 dB (factor of 1.4) in the weighting factor and of up to 90 degrees in the phase factor are explicitly tolerated. The use of filter elements is thus possible, and automated assessment is simplified in principle. This shows that more than one means exist of implementing the WPM approach. It is therefore important to define precisely how the WPM is applied in each individual case, in order for reproducible results to be obtained.

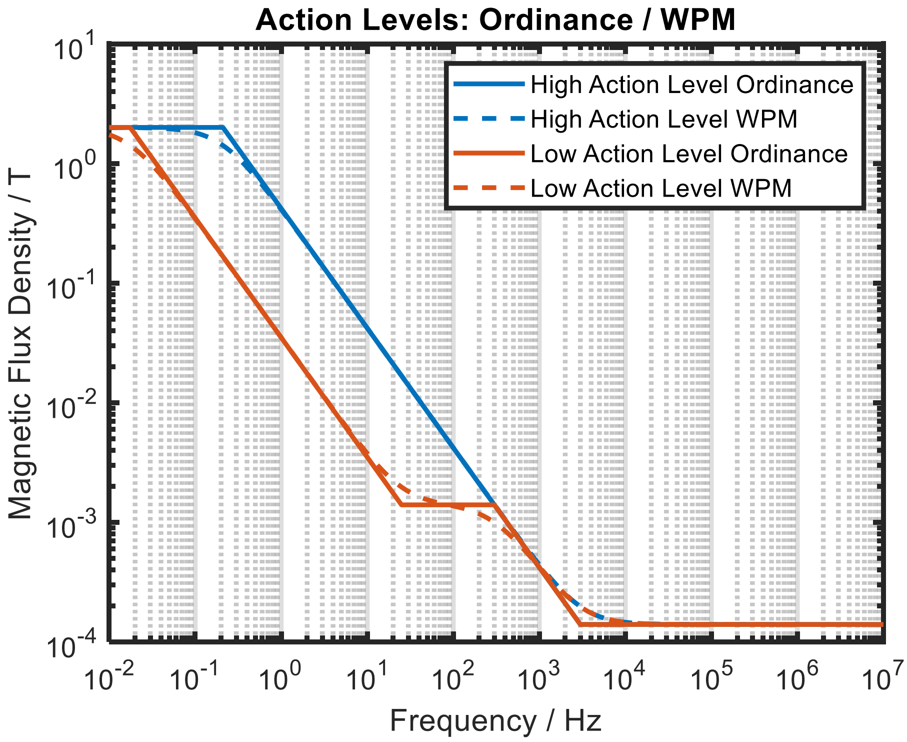

Figure 1: Differences in the action levels between the German OSH Ordinance on electromagnetic fields (EMFV) and the WPM calculation. In the region of the corner frequencies, the WPM may yield deviations of up to 3 dB (factor of 1.4) from the action levels defined linearly piecewise in the EMFV.

The differences between the WPM implementation in the time and the frequency domain are described in Annex D3 of the EU EMF guidelines [8]. The EMFV requires the WPM to be implemented in the time domain [1]. However, the EMFV contains no provisions concerning the deviations in the weighting factor from the table values or on further details of how exactly the WPM should be applied.

The issue of the lack of a precise specification and reference implementation of the WPM in the time domain based on the EMFV was discussed in working groups of experts. It was proposed that the deviations of 3 dB from the action levels be reduced by the addition of peak filters. Since the WPM assessment can be automated comparatively easily, direct integration of the method into an instrument appears suitable. In this case, the processes of measurement and assessment are no longer to be considered separately, as for example is the case with the TDA. Instead, requirements must also be placed on the quality of the measurement results in order to ensure that the subsequent automated assessment can be performed meaningfully. The working group therefore also discussed the requirements upon the analogue-to-digital converters to be used and the magnetic field sensors in instruments, since the high dynamic range[1] to be covered can lead to considerable problems when noise in the signals is processed (see Noise). Similar considerations have already been published by the manufacturers of measuring instruments [12]. This shows that implementation of the WPM is by no means trivial. For the user of an instrument with integrated WPM assessment, application is very simple, since ultimately only the exposure index in percent is displayed, which is then decisive for the assessment. The underlying complexity remains hidden from the user however, and details of implementation are not usually published in the required depth, or are difficult to comprehend. The potential for errors in assessment is consequently high, since the

---

[1] A measurement device should be capable of measuring amplitudes in the range from µT to T at frequencies between 0 and 400 kHz to permit assessment of most of the low-frequency range. The WPM method can also be used in higher frequency ranges, but in practice the measuring range usually ends in the kHz range.

user cannot check the plausibility of the entire measurement and assessment process. This issue will be discussed in detail below.

The WPM implementation described in this article was performed in MATLAB/SIMULINK. The continuous transfer functions with the values specified in the EMFV are used as filters. The calculations are performed with a fixed increment of 1 µs (1 MHz), which also corresponds to the sampling time of the signals. A further WPM implementation took the form of digital filters in an oscilloscope and was used to produce the results presented here.

Differences between TDA and WPM

In contrast to the fully automated WPM, the non-automated TDA requires the user to perform each step manually and examine the measured signal. The advantage of the TDA is that the user is consequently an integral part of the assessment process and can check the individual steps for plausibility. This requires expert knowledge of the measurement and assessment process and an understanding of which signal components are a particular source of stimulation and which are not. Where signal characteristics are complex and contain many different frequency components however, applying the TDA manually until the component most relevant for the assessment has been found may be a very time-consuming process. Analysis software for this purpose would be advantageous. This should not, however, lead in turn to the expert user no longer checking the assessment.

If every potential situation occurring in practice is to be covered, measurement and assessment of electromagnetic fields is a very complex topic that can be fully automated only with difficulty, if at all.

The benefits of the WPM are its rapid execution and, compared to the TDA, objectified frequency analysis by the use of filters. In the TDA, the user must identify the four specified signal forms in the measurement signal. This is a subjective process, and the results may therefore differ from one user to the next. This problem does not exist in this form with the WPM. Conversely, measurement artefacts or noise may significantly distort the assessment when the WPM is used. Ideally, this is noticed by the user, who corrects the measurement signal prior to assessment. This correction however also represents a subjective use of filters until the signal characteristic matches the user's expectations. In this respect, both methods exhibit a similar problem; it is merely evident at different points.

Application of a transparently implemented WPM with scope for plausibility checks of the individual steps by the expert user constitutes an effective assessment method. Provided it is applied by experts, the same is true of the TDA. Both methods may lead to inadmissible assessments if used incorrectly or with poor-quality measurement signals as the input.

With the TDA, only the equivalence frequency component with the highest stimulus effect in consideration of the respective action levels is relevant for the final assessment, i.e. assessments of individual frequency components are not added to each other in any way. The situation is different in this respect for the WPM and may therefore lead to differences in assessment; generally, the WPM yields a more conservative assessment as a result. For example, if two discrete signals of different frequency have amplitudes that both just match the upper action levels for their respective frequencies, the maximum of the weighted WPM signal is equal to 200% (Figure 2). In the TDA, the two signals are assessed individually, and exposure is thus equal to the upper action level.

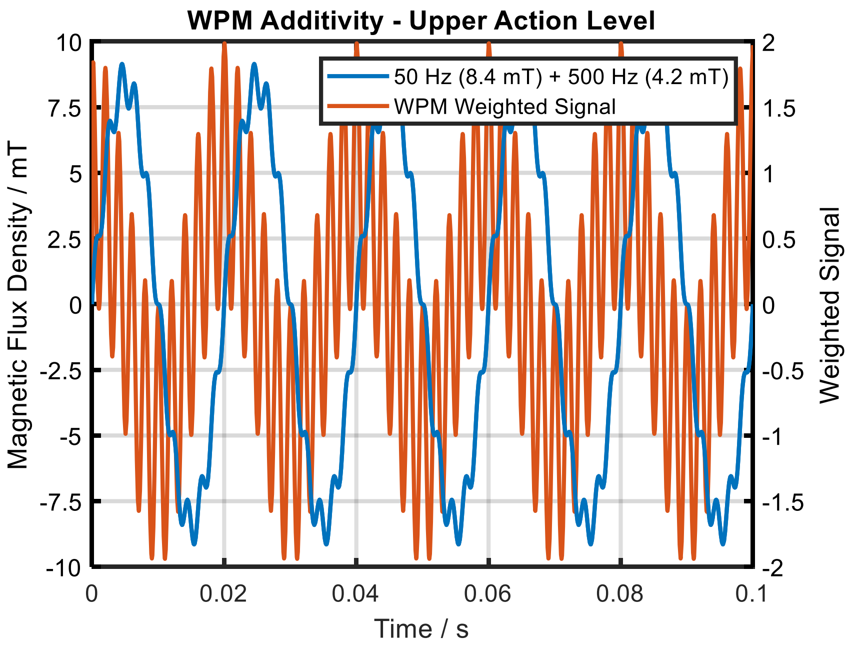

Figure 2: Exemplary presentation of the additivity of the WPM. A superposition of a 50 Hz and a 500 Hz sinusoidal signal serves here as the input signal. Each signal on its own has an amplitude just reaching the upper action level for its frequency. The maximum of the weighted WPM signal is thus 2 = 200%. In the TDA, the two signals are assessed individually, and exposure is thus equal to the upper action level.

The addition of a possible gain factor (V factor [4]) in the TDA may lead to the result deviating from that yielded by the WPM by the order of magnitude of the V factor. Direct comparisons between the methods should therefore be made only with a V factor of one. Where this is case, the results yielded by the two methods are often comparable [12, 13]. Some studies have however revealed major differences between assessments performed by the two different methods on some signal forms even at V=1 [14].

When the WPM is used, the user should ideally be able to view the time characteristic of the weighted WPM signal against the input signal, in order to be able to assess the plausibility of the result. This has been seen in practice to permit detection of measurement artefacts, which, if undetected, could lead to assessment artefacts. Furthermore, the user should be aware of the deviations of up to 3 dB (factor of 1.4) in certain frequency ranges, in order to be able to take these into account during the WPM assessment (Figure 3). Specifically, this means that where spectral components are present in this frequency range, the assessment should be examined closely, for example by comparison by means of the TDA, in order for a realistic and documented assessment decision then to be reached. Unfortunately, a clear "yes/no" decision cannot easily be reached in borderline cases, as several different methods are legally permissible and may deliver different results owing to their parameter assignment. In these borderline cases, it is therefore all the more important for an assessment backed up by expertise to be performed. This issue is mitigated in part by the incorporation of safety factors in the action levels. This should not however lead to automated measurement and assessment being trusted without verification.

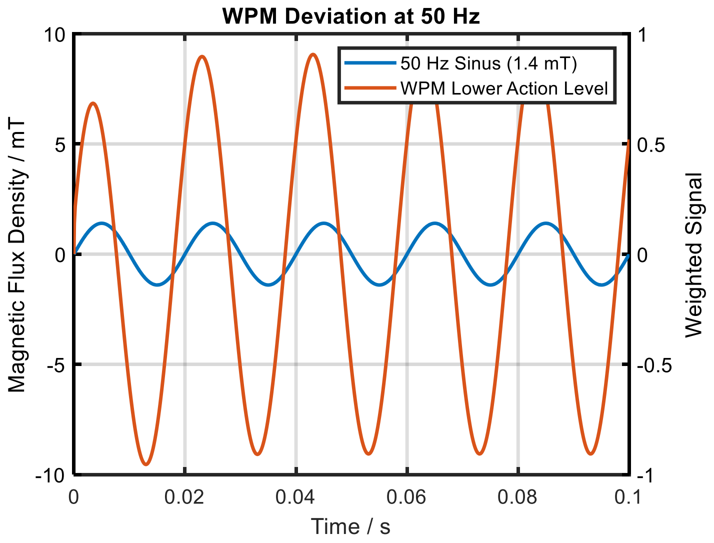

Figure 3: To illustrate the deviations of up to 3 dB, a 50 Hz sinusoidal signal with an amplitude of 1.4 mT was assessed by means of the WPM. In accordance with the EMFV, the amplitude of 1.4 mT corresponds precisely to the lower action level, i.e. the weighted WPM signal in this case should have a maximum of 1 = 100%. Instead, owing to the continuous filters, the magnetic field is underestimated.

A staggered approach with a combination of different methods is in principle also conceivable, such as initial assessment by means of a WPM integrated into the measuring instrument. If the limit value (exposure index) is not exploited to the full and the case not therefore borderline, it is very likely that the action levels will not be exceeded when the time-domain assessment method is used. If the case is borderline however, it may be advantageous to review the WPM assessment for plausibility in stages, in order for example to use the weighted WPM signal to find the critical points in the input signal under assessment. Alternatively, assessment could be performed by means of the TDA to obtain a better understanding of the situation at hand. Should this not yield a clear result, the support of experienced experts should be enlisted who can then analyse the exposure situation more precisely, possibly also by means of simulation analyses.

Difficulties presented by fully automated measurement and assessment

Where measurement is performed fully automatically and the result of assessment is reduced to a "green" or "red" lamp on the instrument, many false assessments will be made, some of which are shown here by way of example.

Operating states

One factor is whether the installation under assessment is in fact switched on. This may at first glance appear trivial, but practical experience has shown that unqualified personnel may have great difficulty in determining the operating state of an unknown machine under assessment. The signal characteristic of a measurement can be very useful in this respect and support review of the plausibility. Should however the signal characteristic not be checked, or not even be visible at all on the measuring instrument because the latter yields the result of assessment only in the form of the exposure index, an incorrect assessment may easily result.

The switch-on and switch-off phases are important operating states, since they are usually accompanied by particularly strong magnetic fields, which are of only short duration. In general, pulsed fields can occur only for fractions of a second. In order to permit an appraisal in such cases of whether the relevant pulse has been measured, it is essential for the signal characteristic to be examined by an expert familiar with the context. An automated instrument may simply not have recorded the brief pulses, for example because the relevant signal was not recorded in the dead time during measurement range switching. For this reason, automated range switching should be switched off during the measurement of pulsed fields, and a suitable measuring range selected manually. An automated system can and will of course function reliably in general. The risk of an intermittent pulsed signal being detected only partially or not at all, resulting in a false assessment, cannot however be ruled out entirely. The signal must therefore be checked for plausibility prior to the assessment.

Overlap of field sources

A situation in which several field sources are located close to each other may easily arise in a plant. Here too, the wider context, which cannot be addressed by a fully automated assessment system, is of great importance from an occupational safety and health perspective. Different combinations of operating states of the machines must be tested. It is important to ascertain the relationship between the EMF influences presented by different machines. A fully automated assessment system may lead to the complex situation not being analysed precisely, or worse, may not even enable the user to review the data upon which the assessment is based.

Measuring probes

During measurement of magnetic fields generated by strong current flows (for example during welding), the mutual inductance of the measuring coil in the probe may give rise to signal characteristics that do not properly reflect the actual exposure situation (see Figure 4). If possible, the current flow should be recorded in such situations by means of a Rogowski coil in addition to recording of the magnetic field, in order to permit assessment by a combination of both variables if necessary. Automated assessment alone of the measured magnetic field could yield an incorrect assessment. Automated correction of this measurement artefact is possible only to a limited extent and depends strongly on the field source and the measurement conditions. Expertise in measurement is thus required in order for the relevant signal component to be extracted. A combined measurement and assessment system may tempt the user to forgo separate measurement and assessment and checking of the plausibility.

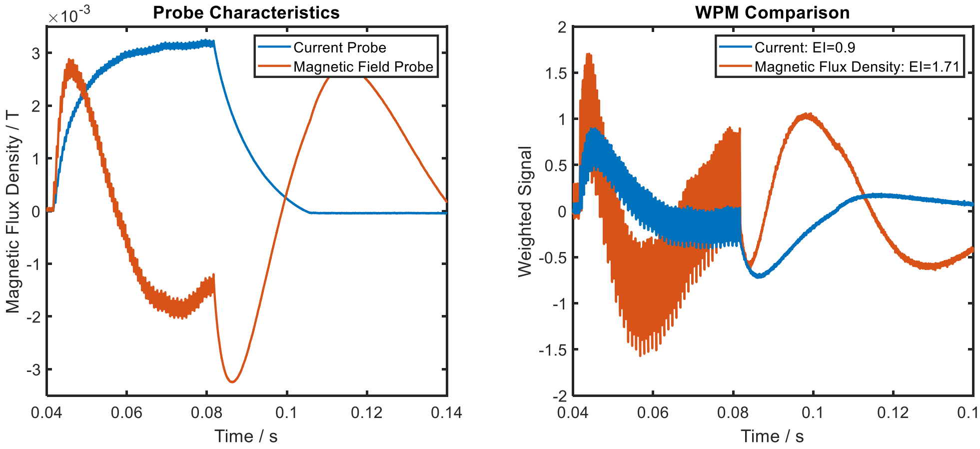

Figure 4: Left: Comparison between measured current and the resulting magnetic field. An oscillating signal is superimposed over the exponential rise in current. Although the current drops to zero after approx. 0.1 s, the B field probe still detects a strong magnetic field. This is not actually present but is a measurement artefact of the coil and is caused by the principle of self-inductance. Right: If the current and the resulting magnetic field are assumed to be proportional, the current characteristic can be scaled to the maximum measured magnetic field strength and the current signal thus interpreted as a magnetic field. This allows the WPM to be applied to the current and the obtained assessments to be compared. The magnetic field signal is shown to be overestimated by 81% compared to the current signal.

Noise

A further important aspect is the influence of any signal noise upon the assessment. Classification of a given signal component as noise and therefore as not relevant to the assessment is based on criteria which the expert determines from the contextual information available to him or her. The noise can then be eliminated, for example by filters, or as in the case of the TDA, by being deliberately neglected by the expert in the course of manual assessment. Where a filter is implemented in an instrument, the parameters of the filter are generally set in advance, and expertise and experience are required in order for the filter's influence to be understood. Fully automatic assessment incites the user to disregard the filter's influence upon the result. This can lead to considerable problems, which will be illustrated by examples. The upper part of Figure 5 shows a 50 Hz sinusoidal signal with an amplitude of 8.4 mT, which just corresponds to the upper action level [1]. The exposure index is therefore 100%. The lower part of the image shows the same signal with 1% noise (uniformly distributed random numbers between +/- 0.084 mT with a sampling time of 1 µs). In a TDA assessment, a user might not even perceive the noise visually and would classify the signal as a 50 Hz sinusoidal wave. A fully automated assessment routine without suitable pre-filtering of the signal would also evaluate the noise together with the signal. Owing to the additivity of the WPM (cf. Figure 2), the maximum amplitude of the weighted WPM signal thus lies above 1.5, resulting in overestimation by more than 50%. In a fully automated assessment, this effect could easily be overlooked, even if the user had examined the input signal. It is therefore also important to check the plausibility of the time characteristic of the weighted WPM signal as well as the value of the exposure index relevant for the final assessment.

In the case described here, a different procedure could be adopted if the user were to be aware of the high-frequency noise and able to determine that it is not relevant to the assessment. The signal could be pre-filtered in order to suppress the high-frequency noise, and then re-evaluated with the WPM. If the time characteristic of the weighted WPM signal now no longer exhibits noise, this assessment can be accepted. Alternatively, the signal could be evaluated by means of the TDA, and a 50 Hz sinusoidal signal with the measured amplitude assumed for assessment. In this case, the signal is filtered implicitly by the decision to neglect the noise. Both strategies produce the correct result. Regardless of the strategy chosen, it is important that the procedure and the decisions taken be documented. Even if it is determined that the signal under assessment contains too much noise to permit correct assessment, this nevertheless is a purposeful step towards a correct assessment. This step is possible only if the signals can be evaluated by a skilled person.

Our practical experience has shown that unfavourable routing of the measuring cables or extensions between the measuring probe and the main unit in particular can lead to the coupling of interference signals or noise, which are of major significance here.

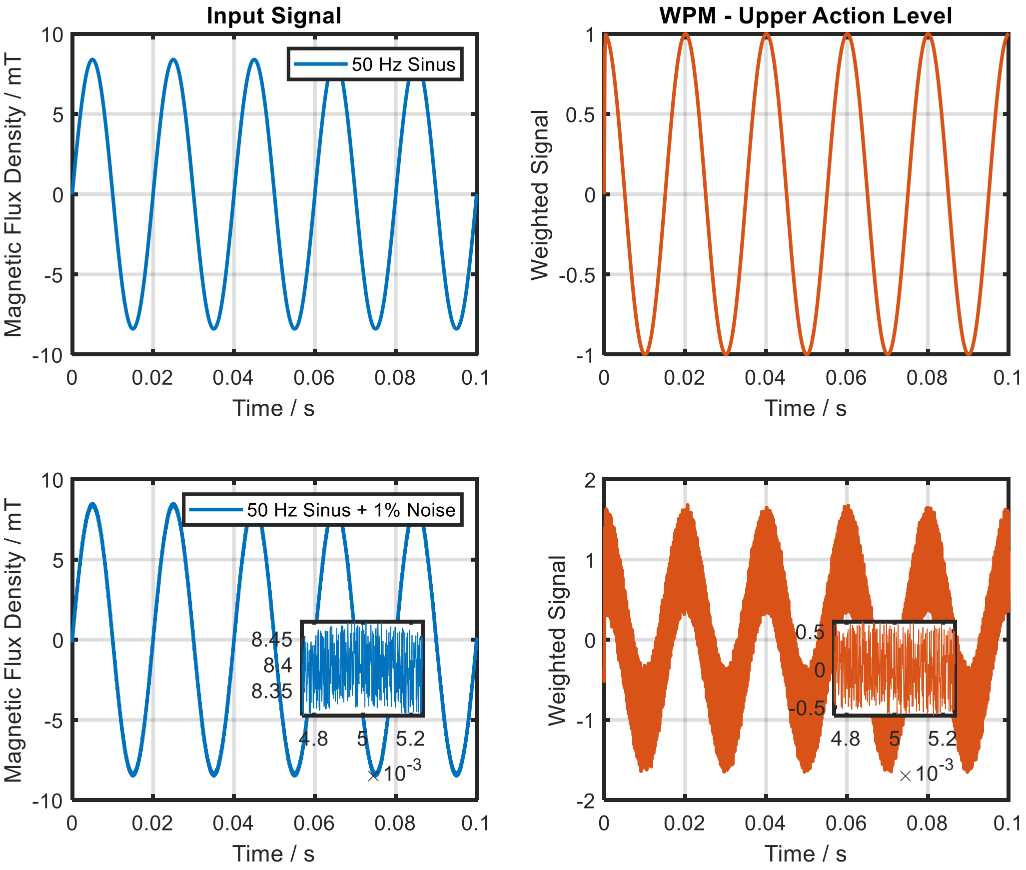

Figure 5: Top left: A 50 Hz sinusoidal signal with an amplitude corresponding precisely to the upper action level. Top right: The corresponding weighted WPM signal, which has a maximum of 100%. The signal bottom left is composed of the same 50 Hz sinusoidal signal together with high-frequency noise. Visually, the difference in the input signal is hardly perceptible; an enlarged section of it is therefore shown here. The difference in the time characteristic of the weighted WPM signal (bottom right) is evident. Owing to the additivity of the WPM, the high-frequency noise has a significant influence upon the weighted WPM signal and the exposure index.

Conclusion

In conclusion, it can be said that measurement and assessment of electromagnetic fields is a complex subject. In the range close to the action levels, assessment should therefore be performed by an expert and should not be fully automated. Both methods, WPM and TDA, may be used for this purpose, possibly in combination. A preliminary, conservative assessment can be performed relatively quickly by means of the weighted peak method; in this case, the user must check whether the relevant signal has in fact been recorded and that the weighted WPM signal does not contain artefacts. Where the result is close to the action level, an additional assessment by means of the TDA can be performed for good measure in order for an informed decision to be reached. Performance of a plausibility check of the measurements and assessments by an expert is always recommended.

Bibliography

[1] Bundesministerium für Arbeit und Soziales , „Arbeitsschutzverordnung zu elektromagnetischen Feldern (EMFV),“ 2016.

[2] DGUV, Vorschrift 15, 2001.

[3] H. Heinrich, „Assessment of Non-Sinusoidal Pulsed or Intermittent Exposure to Low Frequency Electric and Magnetic Fields,“ *Health Physics,* Bd. 92, pp. 541-546, 2007.

[4] Hannah Heinrich, E. M. F.-Expertengruppe des Bundesministeriums für Arbeit und Soziales, „Forschungsbericht 457 Elektromagnetische Felder am Arbeitsplatz – Bewertung nicht-sinusförmiger und gepulster Felder - Teil 1: Anpassung der Zeitbereichs-Bewertungsmethode (ZBM) für "Gepulste Felder" an die Rahmenbedingungen der Richtlinie 2013/35/EU,“ 2015.

[5] DGUV, DGUV Information 203-038 (BGI 5011): Beurteilung magnetischer Felder von Widerstandsschweißeinrichtungen, 2006.

[6] International Commission on Non-Ionizing Radiation Protection, „Guidance on Determining Compliance of Exposure to Pulsed and Complex Non-Sinusoidal Waveforms below 100 kHz with ICNIRP Guidelines,“ *Health Physics,* Bd. 84, pp. 383-387, 3 2003.

[7] International Commission on Non-Ionizing Radiation Protection , „Guidlines for Limiting Exposure to Time-Varying Electric and Magnetic Fields (1 Hz TO 100 kHz),“ *Health Physics,* Bd. 99, 2010.

[8] Europäische Kommission , „Nicht verbindlicher Leitfaden mit bewährten Verfahren im Hinblick auf die Durchführung der Richtlinie 2013/35/EU Elektromagnetische Felder Band 1: Praktischer Leitfaden,“ 2014.

[9] Hannah Heinrich, E. M. F.-Expertengruppe des Bundesministeriums für Arbeit und Soziales, „Forschungsbericht 400-D Elektromagnetische Felder am Arbeitsplatz,“ 2011.

[10] J. P. Reilly und A. M. Diamant, „Neuroelectric mechanisms applied to low frequency electric and magnetic field exposure guidelines--part II: non sinusoidal waveforms.,“ *Health physics,* Bd. 83, Nr. 3, pp. 356-365, 9 2002.

[11] International Commission on Non-Ionizing Radiation Protection , „Guidelines for Limiting Exposure to Time-Varying Electric, Magnetic and Electromagnetic Fields (up to 300 GHZ),“ *Health Physics,* Bd. 74, p. 494-522, 1998.

[12] H. Keller, „The Weighted Peak Method in the Time Domain Compared With Alternative Methods for Assessing LF Electric and Magnetic Fields,“ *Health Physics,* Bd. 113, pp. 54-65, 7 2017.

[13] D. Brylka, „Vergleich von Bewertungsverfahren nach EMFV für nicht sinusförmige Magnetfelder,“ in *Nichtionisierende Strahlung in Arbeit und Umwelt: 50. Jahrestagung des Fachverbandes für Strahlenschutz e. V.*, 2018.

[14] G. Schmid und R. Hirtl, „Vergleich unterschiedlicher Bewertungsverfahren für Magnetfeldexpositionen mit nicht-sinusförmigem Zeitverlauf im Zuge der Umsetzung der EMF-Arbeitnehmerschutzrichtlinie 2013/35/EU,“ in *Nichtionisierende Strahlung in Arbeit und Umwelt: 50. Jahrestagung des Fachverbandes für Strahlenschutz e. V.*, 2018.

[15] Europäische Kommission, „Richtlinie 2013/35/EU zum Schutz vor der Gefährdung durch physikalische Einwirkungen (elektromagnetische Felder),“ 2013.