Environmental EMC Aspects of Resistance Welding Equipment

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Summary: Resulting from the connection between the change rate of a magnetic field and the induced currents in an exposed human body, pulsating magnetic fields have to be evaluated analysing the waveforms of the field or the field-generating current. A corresponding assessment guideline is given in the German safety regulation on “Electromagnetic Fields” BGV B11. Considering the specific output current waveforms of resistance welding installations, in the paper appropriate procedures to determine the waveform-dependent exposure limits are explained by the examples of an a.c. resistance welding machine and a resistance welding inverter. Based on investigations of the field distribution the occurring actual flux density values are compared to the ascertained exposure limits and a practical method to determine minimum distances ensuring compliance with the given regulations is shown.

1. INTRODUCTION

In both commercial and private fields, there is a constantly growing number of electrical and electronic appliances as well as an increasing density of the power supply mains and of the partially wireless communication networks. For a number of years, attention has therefore been paid not only to the questions relating to the „electromagnetic compatibility of appliances” but also to the effects of electromagnetic fields on biological systems and particularly on people. Concerning these effects and related problems the designation of „electromagnetic environmental compatibility” is used. It must be taken into consideration that the employees at certain workplaces are exposed to substantially higher field strengths than the general population.

In addition to other high-current applications such as induction heating and electroplating, resistance welding is also mentioned in technical literature in connection with the occurrence of relatively high values of the ambient magnetic flux density [4; 6; 8]. Depending on the process variant, the currents used in resistance welding range from a few kA to more than 100 kA. They are guided from the high-current power sources via output circuit conductor loops with designs adapted to the technological joining task to the metal parts to be welded. Not only automated welding devices such as welding robots but also manually operated resistance welding machines and manual welding devices are used. Mostly, the resulting ambient magnetic fields have to be regarded as pulsed fields since most process variants involve discontinuous operation with a succession of welding and non-welding times. In these cases, the duration of one single welding operation associated with field emission extends from a few 10 to a few 100 ms.

2. Field exposure limiting regulations

Nowadays, due to the increasing application of electrical appliances both in commercial fields and in private life, there is a growing consciousness regarding field emission and possible harmful effects on human beings. The “Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (up to 300 GHz)” [5] established by the international Commission on Non-Ionising Radiation Protection (ICNIRP) represent fundamental regulations concerning the assessment and limitation of these types of field exposure. Regarding the exposed people, there are distinguished occupational exposure and general public exposure where the exposure restrictions are more stringent. In the ICNIRP guidelines, frequency-dependent exposure limits are given in form of unperturbed rms values relating to sinusoidal fields. In the case of simultaneous exposure to multiple frequency fields, a sum formula considering the ratios of the occurring frequency components of the field and the respective limit values has to be applied.

In 2004 a directive concerning the protection of employees from risks arising from physical agents (electromagnetic fields) [2] was issued by the European Union. In the document the frequency-dependent exposure limits of ICNIRP guidelines were adopted. The concrete exposure assessment, measurement and calculation shall be ruled by European Standards. With respect to this commitment, at present such standards are being drawn up concerning the field exposure of employees caused by welding equipment. The member states have to transpose the mentioned EU guideline into national guidelines until the end of April 2008. The “Directive lays down minimum requirements, thus giving Member States the option of maintaining or adopting more favourable provisions for the protection of workers …” [2].

One national guideline which has been in force in Germany since 1 June 2001 is the safety regulation on “Electromagnetic Fields” BGV B11 [1] issued by the German Berufsgenossenschaft der Feinmechanik und Elektrotechnik (Professional Association of Precision Mechanics and Electrical Engineering). In addition to exposure limits for continuous fields, in this regulation concerning occupational field exposure also instructions for time-varying fields with pulsed waveforms are given. However, in contrast to the fixed
limits for continuous sinusoidal fields, the permissible values for pulsed fields must be established in each individual case on the basis of the specific waveform of the field parameters.

3. DETERMINATION OF PERMISSIBLE FIELD EXPOSURE VALUES BASED ON BGV B11

In BGV B11 the permissible values are specified for certain exposure areas which are defined in the regulation. Since resistance welding mostly entails short-time operation with a restricted duty cycle, the so-called “area of increased exposure” is primarily relevant for these welding devices. In this region higher values of exposure are permissible than in the “exposure area 1” provided admittance is restricted to authorised people and they stay there only for a limited period. A dwell limitation of two hours per day is valid for the frequency range from 0 Hz to 91 kHz.

To enable the determination of permissible field exposure values, some examples of pulsed waveforms are given in BGV B11 (Fig. 1).

Instead of the quantity \( G \), the electric field strength \( E \), the magnetic field strength \( H \) or the magnetic flux density \( B \) can be inserted. As shown on Figure 1, the time-related parameters \( \tau_p \) and \( \tau_c \) are defined by their assignment to certain functional values. Due to the type of stipulation of these time-related parameters, which can be read from the curves in each case, special consideration is given to the phases with a field alteration.

In the case of resistance welding equipment, the output current flowing in the welding circuit constitutes the dominating magnetic field producing component. In comparison with this, the influences of the considerably lower primary and mains currents were negligible in the conducted investigations. Therefore, the parameters of the ambient magnetic fields and the output currents of resistance welding equipment can be regarded as proportional.

Since only time-related parameters of the curves and not the absolute values of the amplitudes are incorporated into the determination of the permissible values for the magnetic flux density, the output current waveform can also be used for it instead of the curve of the magnetic flux density due to the approximate proportionality of both quantities.

The values for the magnetic field exposure which are permissible in the case in question must be established using the equations given in BGV B11 before comparing them with the existing actual values when pulsed fields are assessed. This process must be carried out according to the waveform specifics of output current and magnetic field parameters which are determined by the power section type of the resistance welding equipment.

However, the actual waveforms usually show significant deviations from the exemplary mathematical functions of BGV B11 or represent superimpositions of these functions. For this reason, the specifications included in BGV B11 must, when the ambient magnetic fields of resistance welding devices are assessed, be adapted in a suitable way to the peculiarities existing with these installations.

The procedure which is derived from BGV B11 and appears to be expedient is to be illustrated here using the example of

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Fig. 1. Waveform examples and parameter definitions given in BGV B11 for the assessment of pulsed fields in the frequency range 0 ... 91 kHz
the alternating-current machine and the medium-frequency inverter. In [7] it is also portrayed for further resistance welding machine types.

3.1. Application of BGV B11 to alternating-current resistance welding machines

The output current waveform of this widespread type of resistance welding machines is characterised by the phase control used for welding current adjustment. With the exception of maximum power this control method causes shortened positive and negative half-waves interrupted by zero-current intervals (Fig. 2). Furthermore, the half-waves are asymmetrical because of the different lengths of the rise- and fall-time intervals and the welding time is limited as mentioned above. Thus, it is impossible to determine the permissible field exposure taking the exposure limits for continuous sinusoidal fields as a basis. To calculate the concrete exposure limits rather the lengths of the rise- and fall-time intervals and the complete duration of field alteration within a given integration time should be taken into account.

So, from the output current waveform belonging to the operating conditions of the machine which are chosen for the magnetic field exposure assessment, the rise time \( \tau_{r1} \) and the fall time \( \tau_{f2} \) are determined. The total amount of all times \( \tau_{p1} \) and \( \tau_{p2} \) within the welding time represents the sum of all times with field alteration \( \tau_p \) within the considered interval.

\[
\tau_D = \sum_{i} \tau_{pi} = 2 \cdot \text{[number of cycles]} \cdot (\tau_{p1} + \tau_{p2}) \quad (1)
\]

According to BGV B11 the \( \tau_f \)-amount has to be ascertained for all field alterations within an integration time \( T_f \). Due to the usual duty cycle of most resistance welding processes, the maximum value of \( T_f \) given in BGV B11 (1 s) can be taken as a basis here and the completion of one welding procedure within this time can be assumed. For rarely occurring shorter welding cycles characterised by an interval between the begins of two successive welding procedures shorter than 1 s the following calculations have to be executed separately. From \( T_f \) and \( \tau_p \) a weighting coefficient \( V \) has to be calculated. According to BGV B11 this coefficient is limited to a maximum value of 8.

\[
V = \sqrt{\frac{T_f}{\tau_D}} \quad V_{max} = 8 \quad (2)
\]

The shorter one of the times \( \tau_{p1} \) and \( \tau_{p2} \) is named \( \tau_{p min} \). It is utilized for the calculation of the so-called frequency of field alteration \( f_p \).

\[
f_p = \frac{1}{4 \tau_{p \ min}} \quad (3)
\]

In order to determine the permissible rate of flux density change, diverse formulas which are assigned to certain ranges of \( f_p \) are given in BGV B11. For mains-frequency operated a.c. resistance welding machines it can be presumed that \( f_p \) is always between 1 Hz and 1000 Hz. Furthermore, the considered problem has to be classified into one of the different field exposure ranges given in BGV B11 due to the character of the existing field exposure situation. As mentioned above, the area of increased exposure should usually be taken as the basis in the case of resistance welding machines. Considering these specifications, the permissible rate of change of the magnetic flux density can be calculated using the following formulas:

\[
\frac{dB}{dt}_{max \ permis} = 1.4V \quad (4)
\]

(maximum value of the permissible rate of flux density change in T/s)

\[
\frac{dB}{dt}_{mean \ permis} = 0.72V \quad (5)
\]

(mean value of the permissible rate of flux density change in T/s)

Due to the problems of measurement, the comparison between permissible and actual magnetic field exposure values on the basis of the rate of flux density change seems not to be expedient. In order to facilitate the comparison, the permissible rate of change can be converted into the permissible peak value of the magnetic flux density using the following formula:

\[
B_{peak \ permis} = \frac{dB}{dt}_{mean \ permis} \tau_{p \ min} \quad (6)
\]

The calculation procedure gives results related to the specific resistance welding machine from which the analyzed waveforms have been taken (in this example an a.c. resistance welding machine with 100 kVA rated power and 41.5 kA short circuit output current). The permissible peak values of the magnetic flux density depend on the output current adjustment and the welding time (Fig. 3). Furthermore, they are slightly influenced by the size of the output current loop which is formed by the welding circuit. Hence, the operating conditions given by the welding job determine the resulting field exposure limits.
Fig. 3. Permissible peak values of the magnetic flux density for an a.c. resistance welding machine, area of increased exposure, parameter: welding time \( t_w \) in ms

Fig. 4. Permissible peak values of the magnetic flux density versus welding time \( t_w \) for an a.c. resistance welding machine in the case of maximum power adjustment

Fig. 5. Output current waveform of an inverter type resistance welding machine

Due to the given calculation procedure and the influence of the output current adjustment on the occurring waveforms, an output current reduction results in decreasing \( B_{\text{peak permis}} \)-values. However, reducing the output current, the peak value of the current generally decreases to a higher degree than the \( B_{\text{peak permis}} \)-value. To get a general idea of the range of the resulting field exposure limits, the \( B_{\text{peak permis}} \)-values can be displayed depending on the welding time for the maximum power output current adjustment (Fig. 4).

Resulting from the calculation procedure given in BGV B11, constant \( B_{\text{peak permis}} \)-values arise for usually unrealistically short welding times when the limitation of the weighting coefficient \( V \) occurs. Furthermore, above welding times of 1000 ms the \( B_{\text{peak permis}} \)-values coincide with the field exposure limits for continuous sinusoidal fields. Between these points the \( B_{\text{peak permis}} \)-values decrease with an increasing welding time (proportional to \( 1/\sqrt{t_w} \)).

3.2. Application of BGV B11 to inverter type resistance welding machines

In the case of d.c. resistance welding machines, the d.c. output current is usually superimposed by a 300 Hz ripple caused by the six-pulse rectifier topologies inside the power units of the machines. Performing the exposure limit determination for an inverter type resistance welding machine, an additional ripple with twice the switching frequency of the inverter unit, which is also present in the d.c. output current of the machine, has to be taken into account (Fig. 5). Here, the limit values of each waveform component have to be determined separately and compared to the respective actual magnetic flux density values.

As in the case of the a.c. resistance welding machine, an integration time of 1 s was taken as the basis. Within the integration time the sum of all times with field alterations \( t_D \) has to be determined for all waveform components. The procedure to determine exposure limits is demonstrated in the following by the example of an inverter type resistance welding machine with 180 kVA rated power and 51 kA short circuit output current; the inverter switching frequency is 1 kHz.

**Exponential waveform component**

Concerning the exponential main component of the output current waveform, \( t_D \) has to be ascertained using a formula which is given in BGV B11 for exponential waveforms:

\[
    t_D = \sum_i t_{\text{e}i} = t_{\text{e}r} + t_{\text{e}f}
\]

(7)

It differs from the \( t_f \)-formula (1) which is given for sinusoidal waveforms. The parameters \( t_{\text{e}r} \) and \( t_{\text{e}f} \) designate the intervals within the rising or falling slope, respectively, in which the increase or decrease of 95% of the amplitude of the exponential waveform occurs (see exponential waveform in Figure 1, where only the rising slope is presented and \( t_{\text{e}r} \) is used without the additional index \( r \) identifying the rising slope).

Using formulas (2) and (3), the weighting coefficient \( V \) and the frequency of field alteration \( f_p \) have to be calculated in the same way as explained above for the a.c. resistance welding machine. Again \( \tau_{f_{\text{min}}} \) which is necessary for the calculation of \( f_p \) results from the shorter one of the times \( t_p \), now defined through a rise or fall of \( 1 - e^{-t_{\text{e}r}/2} = (0.792) \), cf. Figure 1.

According the formulas which are given in BGV B11 attached to certain ranges of the \( f_p \)-value to determine the
permissible rate of flux density change, it can be presumed that for the exponential main component of the output current and magnetic flux density waveform, \( f_p \) is always between 1 Hz and 1000 Hz corresponding to the case of the a.c. resistance welding machine. Therefore, the formulas (4) and (5) which were mentioned above for the a.c. machine can be used now in the same way to calculate the maximum value and the mean value of the permissible rate of flux density change for the exponential waveform component of the inverter type resistance welding machine. This is also true for the conversion of the permissible rate of change into the permissible peak value of the magnetic flux density using formula (6).

Resulting from the given calculation procedure there is no influence of the duration of the welding pulse (welding time \( t_w \)) on the permissible field exposure limits concerning the exponential components.

Nevertheless, these exposure limits depend on the output current adjustment (Fig. 6).

**Superimposed 2 kHz-ripple**

Due to the output rectification, the 1 kHz switching operation of the inverter results in a 2 kHz-ripple of the output current waveform. The timing parameters of this 2 kHz-ripple (Fig. 7) are the basis for the determination of the times \( t_{p1} \) and \( t_{p2} \) which must be known for the calculation of the related exposure limits. The ratio of \( t_{p1} \) to \( t_{p2} \) varies with the change of output current adjustment, whereas their sum remains constant. The total time of field alterations related to the 2 kHz-ripple equals the welding time \( (t_D = t_w) \) because the ripple exists all over this time.

Now, according to (2) also a weighting coefficient \( V' \) has to be calculated. Using (3) the minimum of the times \( t_p \) provides the \( f_p \)-value. Here, it is in the range between 1000 Hz and 48500 Hz which is defined in BGV B11. According to that and related to the area of increased exposure the permissible rate of change of the magnetic flux density has to be calculated using the following formulas, which differ from the formulas (4) and (5):

\[
\frac{dB}{dt}_{\text{max \; permissible}} = 1.1 \times 10^{-3} f_p V \quad (8)
\]

(maximum value of the permissible rate of flux density change in T/s)

\[
\frac{dB}{dt}_{\text{mean \; permissible}} = 0.72 \times 10^{-3} f_p V \quad (9)
\]

(mean value of the permissible rate of flux density change in T/s).

Finally, using (6) the permissible peak values of the magnetic flux density can be determined. For the 2 kHz-ripple, these limits only depend on the welding time (Fig. 9).

**Superimposed 300 Hz-ripple**

In addition to the ripple caused by the switching operation of the inverter, the output current of these resistance welding installations is also superimposed by a ripple showing a lower frequency which is determined by the mains frequency and the input rectifier topology. Approximately, this ripple is considered to be load independent and regarded as a triangular waveform for the determination of the \( f_p \)-parameters (Fig. 8).
4. DETERMINATION OF THE OCCURRING MAGNETIC FLUX DENSITY DISTRIBUTION

As a supposition for the evaluation of the magnetic field exposure in the surrounding of resistance welding machines, additionally to the determination of the exposure limits, the occurring flux density distribution has to be investigated. The applied measuring equipment should be able to register the rms and peak values and the waveforms of the magnetic flux density and the output current of the machine as well. In the investigations discussed here, the magnetic field measuring system EM2000 from Symann & Trebbau GmbH was applied. Making use of the approximate proportionality of the output current and the magnetic field, the time-related waveform of the field parameter $B$ and the spatial field distribution were separated in the evaluation. For this purpose, the measured magnetic flux density $B(t)$ was related to the current $i(t)$ (instantaneous values):

$$B' = \frac{B(t)}{i(t)}$$

Figure 10 shows the distribution of the related flux density $B'$ ($B$ related to an output current of 1 kA) in a horizontal plane crossing the centre of the welding circuit of the above-mentioned inverter machine. This way, a current-independent flux density distribution is displayed. Furthermore, the $B$-parameters of the different waveform components can be determined on the basis of the given distribution of the related flux density and the waveform of the respective output current component. This can be done at any point in the investigated surrounding of the machine and for different operating conditions.

The use of the proposed related flux density is also useful to compare field distribution characteristics of resistance welding machines with different mechanical design and electrical parameters. In this case, an analysis based on the considerably differing absolute $B$-values would be difficult.

One characteristic of all the investigated resistance welding machines is that the magnetic flux density is initially proportional to $1/R^2$ and, at a distance as from approximately 10 to 20 cm, becomes proportional to $1/R^3$. This is illustrated in a particularly clear way on the log-log diagram (Fig. 11).

In addition to the investigation of the field distribution by measurement, the magnetic field parameters were computationally determined by means of FEM simulation using ANSYS and furthermore, for selected axes by means of calculation applying the Biot-Savart law. For this purpose the diversity of welding circuits of real resistance welding equipment has been approximated by rectangular conductor loops with diverse sizes and formats; this permitted to establish a catalogue of the distance dependences of the flux density for these machines [3].

The good congruence of the results obtained by means of simulation and computation with the measurements is illustrated on Figure 12 for a particular example. It is shown that simulation and computation give slightly higher values compared to the measurement. The main reason for this is, that the measuring probe always integrates the magnetic flux density over a certain area (in the case of the alternating field probe: 100 cm²) and thus reads a mean value with regard to

Thus, the ascertained time parameters of the slopes are

$$\tau_{p1} = \tau_{p2} = 0.833 \text{ ms}$$

As in the case of the 2 kHz-ripple, $\tau_{p2}$ equals the welding time $t_w$. Due to the $f_{p2}$-value of 300 Hz, the resulting permissible peak values of the magnetic flux density related to this superimposed ripple can be determined using the formulas (5) and (6).

For constant times $\tau_{p1}$ and $\tau_{p2}$, $B_{\text{peak permis}}$ is only influenced by the welding time (Fig. 9) as well as in the case of the 2 kHz-ripple and furthermore independent of the specific d.c. resistance welding machine.
the magnetic flux density which is non-linearly dependent on the distance, while the calculated or simulated values refer to one precise location.

5. DETERMINATION OF MINIMUM DISTANCES

Compliance with the rules limiting possible field exposure of the employees can be ensured by the determination of minimum distances to the field generating devices. Concerning resistance welding machines, the permissible magnetic flux density, which is related to the specific operating conditions of the machine, can be determined as illustrated above with reference to the power unit type of the machine. Then it has to be compared to the actual flux density values occurring in the surrounding of the machine. In the case of a.c. resistance welding machines, this can be done using the absolute magnetic flux density $B$ for the permissible and the actual values, because here output current and magnetic flux density only consist of one waveform component. In the case of d.c. resistance welding machines, all included waveform components (for inverter machines the exponential main component as well as the superimposed 2 kHz and 300 Hz ripple in output current and magnetic flux density) must be taken into consideration. Therefore, it appears to be expedient to operate with the current-related values for the magnetic flux density ($B'$) for both the permissible and actual values. The starting point is the dependence of the related magnetic flux density on the distance established for all relevant directions to the machine. The permissible peak values for the magnetic flux density which arise for the individual waveform components must be divided by the relevant current values of each component. As a result, the permissible values for the magnetic flux density are available in a form related to 1 kA as well and can also be plotted on the corresponding diagram of the distance dependence. This procedure is illustrated (Fig. 13) by the example of the above considered inverter type resistance welding machine.

As a result of this procedure, it can be seen directly, which component leads to the highest value for the minimum distance and thus determines the necessary distance. In the present example, it is the superimposed 2 kHz ripple which indicates the lowest permissible value of $B'$. This makes a minimum distance of approximately 29 cm for the body mandatory. Exposure values which are 2.5 times higher are allowed for the extremities, thus resulting in a distance of approximately 20 cm to be complied with.

6. CONCLUSION

The German guideline BGV B11 gives instructions regarding the evaluation of occupational field exposure caused by pulsed magnetic fields. According to the specifications, the exposure limits depend on the occurring waveforms. That means for resistance welding machines that the permissible field exposure is influenced by waveform and adjustment of output current, welding time and size of the welding circuit – i.e. by parameters which are given by the design of the machine and by the current welding job. For
d.c. resistance welding machines whose output current consists of a superimposition of several waveform components, it is expedient to perform the comparison between permissible and actual magnetic field exposure using a current-related representation of flux density. As a result, the waveform component which determines the minimum distance and the amount of this necessary distance to comply with the guideline, are directly recognisable.

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