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Shielding of EM fields in induction heating and melting installations

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Abstract

The purpose of the work is to evaluate the EMF levels in the surroundings of particular induction heating installations used for melting metals and some methods for mitigating them. The data from measurements in a metal foundry will be presented and discussed with reference to the limits for occupational environment. In some cases the measured levels overcome the ICNIRP limits. For these cases a deep study to mitigate the exposure levels of the workers has been done by means of numerical simulations. Ad hoc numerical method is proposed and discussed. Some solutions for decreasing the levels of electromagnetic fields (in particular magnetic flux density in the case of induction heating devices) are proposed. These solutions have been tested in the foundry and the field levels after shielding have been compared with the model prediction.

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Introduction

Induction heating devices are widely used in industry with different purposes: heat treating of metals, melting, hardening etc. Each of these applications requires different power levels and different frequency values. Usually in this kind of applications a high current and low voltage are used. For this reason in the surrounding of induction heating installations high values of magnetic flux density can be found, and consequently the machine operators could be exposed to field levels exceeding the ICNIRP limits. The European directive 40/2004/CE imposed to all the E.C. countries to put up national regulations for limiting electromagnetic fields exposure to workers and the public, within the year 2008 (now postpone to 2012); the directive defines the admissible field levels along the electromagnetic spectrum. Among other things, it requires that at installation phase of industrial equipment, those field intensity limits must be respected.

A general approach to investigate electromagnetic fields produced by all the types of induction heating installation is almost impossible, but the evaluation of a particular class of such devices can be proposed. In this paper the typical ambient of a foundry, where induction heating furnaces are used, will be analyzed with respect to the EMF exposure of the operators. A lot of measurements have been done and in some cases these measurements have demonstrated that the *reference levels* proposed in ICNIRP guidelines are overcome. For such cases some different solutions, based on numerical modelling of furnace, for the mitigation of exposure levels of the operators, have been proposed.

A novel computational approach for computing shielding effects of conductive metals, shaped in rectangular foils, has been investigated and applied to the evaluation of shielding effectiveness. In fact, industrial applications that require high currents at frequencies up to

tens of kHz are becoming more and more common. Generally in such applications the magnetic field sources are cylindrical inductors of various sizes, high current bus-bars, high current chokes and transformers. So the easiest way to accomplish a shielding task is to build rectangular boxes containing those sources, by using metallic sheets of various thicknesses.
The model has been developed in such a way to consider that the shielding task is performed by metallic foils, often very close to the high current field source, so the prevalent shielding effect is produced by the induced currents circulating in the shields.
A practical example of application of such method together with the classical FEM will be presented for the mitigation of EM fields in the surrounding of a crucible induction furnace.
Firstly, the numerical model of the furnace has been fitted with the measurements and then the same model has been used for testing the different shielding solutions. By this way a high reduction of time and costs can be obtained and moreover the installation of the shields has been done only one time. After the shields installation a new series of measurements have been done in order to demonstrate the efficiency of the proposed solution. The exposure levels have been reduced in such a way to comply with the ICNIRP guidelines.

1. Description of the case under investigation

In the foundry under investigation nine different induction heating furnaces are present. These furnaces have rated power in the range of 20-120 kW and frequencies in the range of 2-100 kHz. In this paper only one furnace will be taken into consideration and in particular a furnace with a maximum rated power 30 kW and rated frequency 20 kHz. In Fig.1 the furnace layout with the position of points used for EMF measurement, together with a picture of the inductor, are shown. In Table I the measurements of magnetic flux density are reported and compared with ICNIRP limits.

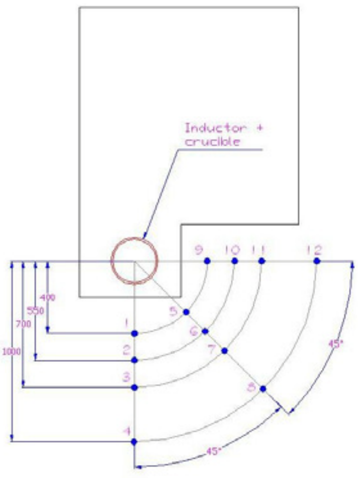

Fig 1: on the left the schematic of the furnace and points where the measurements have been done; on the right a picture of the furnace inductor

The magnetic field measurement instrument was a PMM 8053, with EHP50-A probe, suitable for frequencies up to 100 kHz. The measurements have been done taking into account the real current flowing in the inductor and corrected in such a way to obtain the full power operation for each point. It should be pointed out that there are a lot of points where the safety limit is overcome, and sometimes this value is about 20 times the limit (e.g. at point N. 9).

Tab. I: Measurement of magnetic flux density in the points of figure 1

Field measurement without shieldings				
Position	Brms [uT] @ Imis [Apeak]	Imis [Apeak]	Brms [uT] @ corrected current	Brms [uT] limit (ICNIRP)
1	425.0	440	425.0	30.7
2	167.0	440	167.0	30.7
3	67.0	440	67.0	30.7
4	4.5	440	4.5	30.7
5	381.0	440	381.0	30.7
6	28.1	440	28.1	30.7
7	13.7	440	13.7	30.7
8	4.7	440	4.7	30.7
9	510.0	360	623.3	30.7
10	30.0	360	36.7	30.7
11	14.8	400	16.3	30.7
12	3.9	300	5.7	30.7

2. The integral formulation approach for shielding design

Typically the design of shielding for mitigating workers exposure to EMF needs a cumbersome cut and try procedure and the stopping of furnaces for long periods. The use of numerical commercial packages, based on FEM methods, can help the designer in the choice of the optimal parameters but also in this case the design procedure is, sometimes, very long.
The method presented in the paper is based on an integral approach where the shield is subdivided in thin sheets constituted of non-magnetic high conductive material.
The method is able to evaluate the current density J [A/m2] induced in the shield by the magnetic field present in the ambient using a lumped parameters circuit like model. The shield is subdivided in simple volumes (‘bricks’) where J(P,t) is assumed constant as regards amplitude and direction. In figure 2 an example of discretization of a shielding sheet is shown.

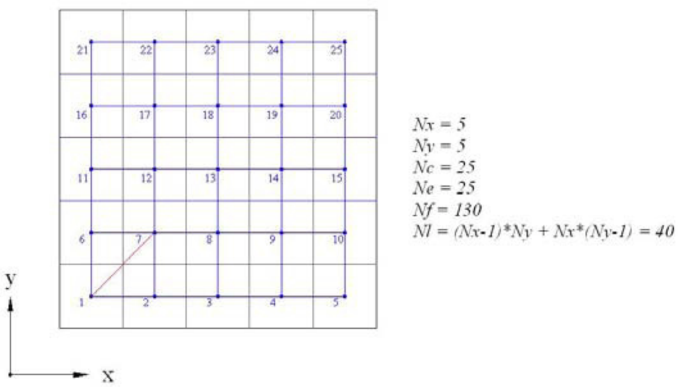

Figure 2: Example of discretization of shielding sheet used for the integral method

The brick baricenters can be assumed as nodes of an oriented graph associated to a circuit with lumped parameters (R,L,M); the magnetic field is considered as source of currents.
The conductive sheet is very thin, and hence J(P,t) can be assumed flowing only in the direction of the largest surface: Jsch (P',t) (where the suffix “sch” means the current density due to the eddy current effect in the shield) and Js (P'',t) (where the suffix “s” means the current density due to the external or primary sources) orthogonal to the sheet can be considered negligeable. We can assume also the conservation of the component of A(P,t), magnetic vector potential, parallel to the interfaces between two different media. Starting from the solution of Poisson equation we can write the following with reference to figure 3:

$$A_S(P,t)=\frac{\mu_0}{4\pi}\int_{Vs}\frac{J_{s\|}(P'',t)}{|P-P''|}dv \qquad (1)$$

$$A(P,t)=A_{sch}(P,t)+A_s(P,t) \qquad (2)$$

The total electric field inside the shield region can hence be calculated by the following equation (3):

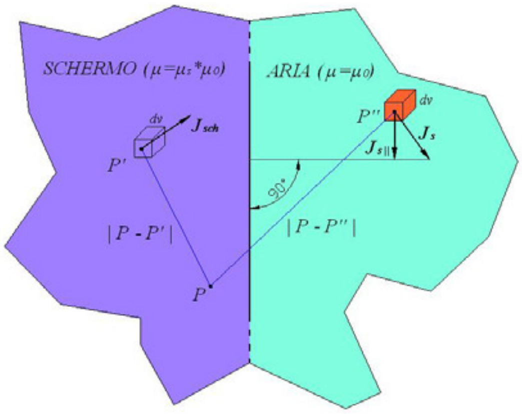

Figure 3: Evaluation of the magnetic vector potential A at the point P as contribution of primary and secondary sources

$$E(P,t)=-\nabla\varphi(P,t)-\frac{\mu_r\mu_0}{4\pi}\frac{\partial}{\partial t}\int_{V_{sch}}\frac{J_{sch}(P',t)}{|P-P'|}dv-\frac{\mu_0}{4\pi}\frac{\partial}{\partial t}\int_{Vs}\frac{J_{s\|}(P'',t)}{|P-P''|}dv \qquad (3)$$

With: E Electric field, φ electric scalar potential, μ magnetic permeability.
With some algebraic passages and with reference to the geometrical and circuit model of figure 4 we can write the final solving linear system for the current associated to the surface S_{hk} of figure 4.

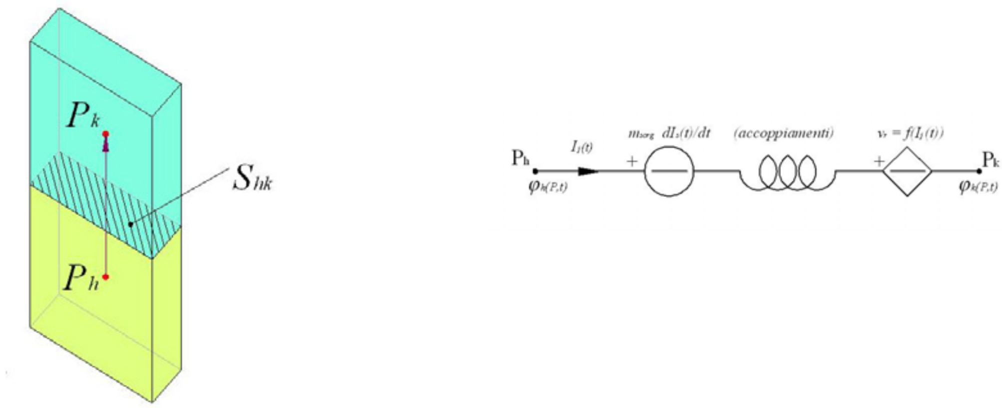

Figure 4: a particular of the mesh and the circuit model associated to it

$$\begin{cases}[A][I_{sch}(t)]=0\\ [B][V(t)]-[M_{sorg}]\frac{dI_s(t)}{dt}=[v_r(t)]+[M_{sch}]\left(\frac{d}{dt}[I_{sch}(t)]\right)\end{cases} \qquad (4)$$

The system (4) which is the typical Kirchhoff laws solution of a circuit can be rearranged in a tree co-tree currents decomposition form in such a way to obtain only one solving system which is shown in equation (5) for time-harmonic regime:

$$\left[\overline{I_{Co}}\right]=-j\omega[L][M_{sorg}]\overline{Is}\left([L][R']+j\omega[L][M']\right)^{-1} \qquad (5)$$

The solution of this system gives the currents and hence the current density inside each brick of discretisation of the shield.

3. Example of application

The method described in the previous paragraph has been implemented in a matlab code and used for a preliminary design of electromagnetic shields constituted by non-magnetic conductive materials. Unfortunately in this specific case the shielding effectiveness of only thin conductive foils is not sufficient to mitigate the electromagnetic field in such a way to reduce the values of magnetic flux density below ICNIRP values as shown in figure 5.

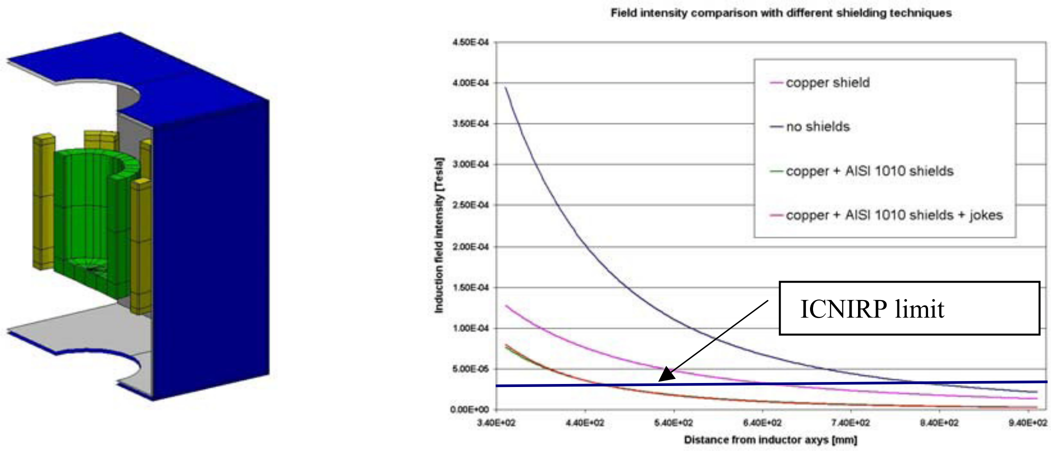

Figure 5: Schematic of different shielding solutions and values of magnetic flux density along a radial line from the center of the inductor

For this reason different FEM models and solutions have been taken into consideration. A first solution has been obtained adding a ferromagnetic material external and just attached to the copper foil and a second solution has been obtained by adding a set of magnetic yokes around the inductor.
For costs reasons the solution of a bimetallic shield only has been adopted and installed. In order to avoid the heating of the shield itself due to the circulation of eddy currents some cuts have been done. The final simulations to check the shielding effectiveness have been performed by a 3D code (Flux 3D) in order to reduce the time of experimental tests during the period of furnace in operation. In figure 6 the practical realization of the shield is shown together with the implementation on the furnace.

Figure 6: The real shield and the implementation on the induction furnace

The effectiveness of the shields was finally checked by in field measurements and the results are presented in table II where the rms values of magnetic flux density are shown after the shield installation and for the same points measured in table I.

Tab. II: Measurement of magnetic flux density (ref. to fig. 1) after shield installation

Field measurement with shieldings				
Position	**Brms [uT] @ Imis [Apeak]**	**Imis [Apeak]**	**Brms [uT] @ corrected current**	**Brms [uT] limit (ICNIRP)**
1	29.0	440	29.0	30.7
2	12.6	440	12.6	30.7
3	6.9	440	6.9	30.7
4	2.9	440	2.9	30.7
5	26.7	440	26.7	30.7
6	11.5	440	11.5	30.7
7	6.8	440	6.8	30.7
8	2.7	440	2.7	30.7
9	52.4	440	52.4	30.7
10	20.7	440	20.7	30.7
11	10.0	360	12.2	30.7
12	4.0	440	4.0	30.7

It should be pointed out that the effectiveness of the shield is very high and only one point remain above the ICNIRP limits. The human exposure in this case can be further reduced by adopting some special operations procedures (like a safe distance or a reduction of power when the operator have to be near to the crucible).

4. Conclusion

In the paper a practical example of design of shielding for mitigation of electromagnetic fields in surroundings of induction heating furnaces has been presented. After the presentation of a novel integral formulation used for the design of conductive non-magnetic shields and to have a rough estimation of the shield efficiency, a complete procedure based on a 3D FEM method has been used in order to evaluate the effectiveness of a real 3D shield geometry for different geometries and used materials. The bimetallic (copper and external ferromagnetic steel) solution has been adopted and implemented and the results obtained are very satisfactory. A deep experimental analysis on the machine has demonstrated, in fact, that with such a kind of shielding the compliance with the ICNIRP recommendations has been reached. The procedure used for mitigating the exposure level around this furnace could be used as a general approach in order to design proper shielding structure, to evaluate the shielding efficiency and to comply with national standards.

References

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