Ecodesign of Low-Voltage Systems and Exposure to ELF Magnetic Fields

Original
Ecodesign of Low-Voltage Systems and Exposure to ELF Magnetic Fields / Pastorelli, MICHELE ANGELO; Mitolo, M.; Tartaglia, Michele; Freschi, Fabio. - STAMPA. - (2010), pp. 1-6. (Intervento presentato al convegno IEEE 2010 Industrial and Commercial Power Systems Technical Conference (I&CPS) tenutosi a Tallahasee (Florida) - USA nel 9-13 May 2010) [10.1109/ICPS.2010.5489887].

Publisher:
IEEE

Published
DOI:10.1109/ICPS.2010.5489887

Ecodesign of Low-Voltage Systems and Exposure to ELF Magnetic Fields

Massimo Mitolo, *Senior Member, IEEE*
Chu & Gassman
559 Union Ave.
Middlesex NJ, 08846
mmitolo@chugassman.com

Fabio Freschi, Michele Pastorelli and Michele Tartaglia
Dipartimento Ingegneria Elettrica
Politecnico di Torino, corso Duca degli Abruzzi 24
10129 Torino (Italy)
fabio.freschi@polito.it

***Abstract* – The Ecodesign of modern residential and commercial low-voltage systems implements energy and equipment cost savings, optimizing the size of the distribution system without compromising their functionality or causing environmental contamination, including electromagnetic pollution. Protection of persons against shock hazards should result increased, and the electrical interferences among power systems reduced.**

To achieve the aforementioned improvements, a possible Ecodesign calls for an earthing system utilizing single-phase separation transformers installed in the unit, grounded at the mid-point of their secondary side. The introduction of a source of magnetic fields into the premises at the power frequency of 60/50 Hz (i.e. extremely low frequency, ELF) might expose persons to their potential adverse health effects, as well as, sensitive electronic equipment to disturbances.

This paper seeks to clarify this matter by evaluating the ELF magnetic fields as produced by the user's own transformer and by other units eventually present in the vicinity.

Index terms – Bonding, Earthing, Ecodesign, Grounding, Grid, ELF magnetic fields, Separation transformers.

I. INTRODUCTION

The *Ecodesign* of modern residential and commercial low-voltage systems implements energy and equipment cost savings, optimizing the size of the distribution system without compromising its functionality, or causing environmental contamination, including electromagnetic pollution. Because of a wise design, protection of persons against electric shock hazard is also increased, and the electrical interferences among power systems are greatly reduced.

A possible *Ecodesign* of an electrical distribution system, requiring limited power demand, can be carried out by confining the ground fault current to a definite metallic return path, not involving, then, the earth. This can be achieved through single-phase separation transformers (ST), buffering the supply source and the loads (Fig. 1) [1 and 2].

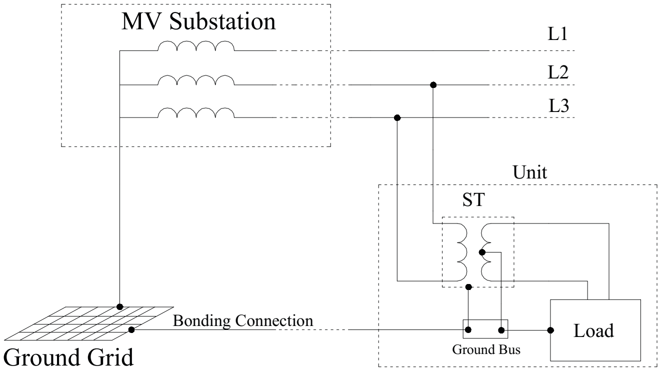


Fig.1 TN – Island Grounding System: single-phase separation transformer, grounded at the secondary winding, supplying user's unit.

The ST is earthed at the mid-point of its secondary winding, via a connection to the medium-voltage substation grid (user- or utility-owned).

For equipotential purposes all the extraneous-conductive-parts (EXCPs), such as water pipes, building steel frame, concrete encased re-bars, etc., are linked together, where they enter the structure, and to the ST's secondary mid-point.

In addition, the possibility to supply loads with both phase-to-phase and phase-to-neutral voltages, would allow the adoption of equipment manufactured in different countries and operating at different voltages. Thus, different systems and standards, i.e. NEC and IEC, could be freely adopted. This option would eliminate technical obstacles and discourage market barriers.

A proposed distribution system is shown in Figs. 2 and 3.

978-1-4244-5602-4/09/$25.00 Â© IEEE 2010

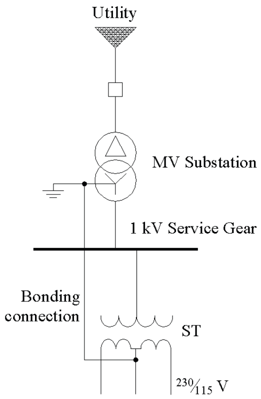


Fig.2 Proposed one-line for an *Ecodesign* distribution system.

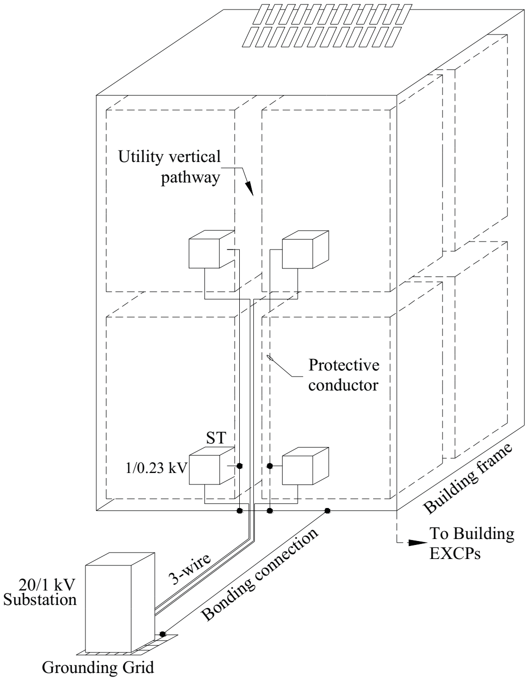


Fig.3 *Ecodesign* of a distribution system in a commercial building.

The introduction of a new source of extremely-low-frequency (ELF) magnetic fields into the premises, additive to the fields caused by regular appliances, might expose both persons to an increased adverse health effect, and sensitive electronic equipment to disturbances.

These authors have evaluated the ELF magnetic fields into the building unit, taking into account the contribution due to other neighboring STs. In addition, in the calculation of the magnetic fields, the authors have taken into account the single-phase currents flowing through both the low-voltage windings and the feeder supplying the main panel in the unit, whose magnitudes are three times higher than in three-phase conditions.

For calculations purposes, the nameplate of the ST, in compliance with [3] or [4], is assumed as follows:

- Single-phase, Dry type, Low Sound, Energy Efficient (low core losses), with mid-point tap, suitable for indoor applications.
- S_n=37.5 kVA
- Primary Voltage= 1kV
- Primary Current = 37.5 A
- Secondary Voltage= 230V
- Secondary Current = 163 A
- Voltage-Impedance z = 4%
- Frequency = 50/60 Hz

II. TRANSFORMER DESIGN

The ST considered is a single-phase transformer with a “C”-shaped core, cooled by natural air convection (Fig. 4). The primary and secondary windings are distributed on both the transformer’s columns, and the low voltage winding is wounded close to the iron core. The dimensions of the ST are (in cm): 17Wx27Lx45H. The magnetic core is constructed by oriented grain laminated iron sheets (thickness 0.35 mm). The design magnetic induction in the transformer core is 1.8 T, which corresponds to iron losses of 1.685 W/kg at 50 Hz; the induction is nearly constant in columns and yokes. The windings isolation is guaranteed up to the temperature of 120 °C. The magnetic flux density has been assumed a constant design parameter both at 50 and 60 Hz.

Transformers designed to operate at 60 Hz have smaller dimensions than 50 Hz transformers, thus, they cause less severe magnetic pollution. In order to be conservative, in this paper we have not considered the reduced size typical of the 60 Hz design.

The design of single-phase transformers with rating exceeding 10 kVA is not standardized in Europe, where, more cost-effective three-phase transformers are used. It is important to note, though, that the ST grounded at the mid-pint would allow the same full load amps (163 A) both in the USA (115 V line-to-mid-point)) and in Europe (230 V line-to-line). This solution makes the same transformer suitable in both worlds.

The use of 1 kV as distribution voltage reduces the primary current to about ¼ (i.e. 230 V/1000 V) of the secondary current driven at 230 V. As a consequence, we have lower voltage drops, lower copper losses and lower magnetic fields in the vicinity of the utility vertical pathway (Fig. 3).

The model of the separation transformer (Fig. 4) includes the ferromagnetic core, the windings and the low-voltage connection to the main panel. In this model, we have neglected eventual differences between the magnetic motive forces induced by primary and secondary currents, and a uniform current density distribution is assumed throughout the cross-sectional sections of the windings.

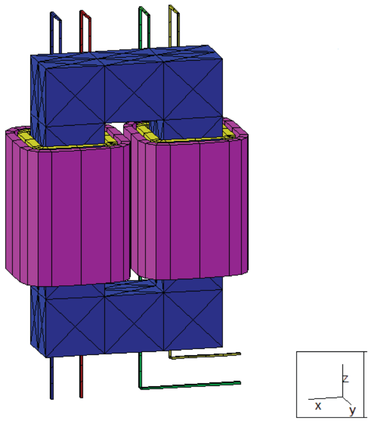


Fig. 4 Model of the separation transformer.

III. MAGNETIC FIELD SIMULATION

A. Magnetic field in the vicinity of the transformer

As shown in Fig. 4, the magnetic domain under study has a three-dimensional structure which is non-homogeneous and that may exhibit non linearity in the core. In our analysis we are mostly interested in the transformer's magnetic leakage flux, which can invest persons and/or electrical and electronic apparatus.

Field simulations have been performed, assuming a quasi-stationary magnetic field. The computation program is based on the Finite Formulation of the Electromagnetic Field, coupled with integral boundary conditions [7]. This approach allows the computation of the flux density distribution in any point of the equipment. In our case, the magnetic field distribution is analyzed along planes parallel to the main system of coordinates (Fig. 4), which are also parallel to walls and floor. In order to evaluate the accuracy required by the simulations, three cases have been compared:

- a 3-D model which neglects input and output connections;
- a 3-D model without the transformer, which includes only its output connections;
- a complete 3-D model with transformer and its input/output connections;

Ferromagnetic nonlinearities play a negligible role in the evaluation of the leakage flux distribution of the ST.

The results are represented in Tab. 1 by means of maps with different colors. Colors show the levels of flux density on a square surface of area 1m x 1m, located on three planes at 0.5 m from the axis origin. The represented magnetic flux density levels are computed according to the standard space and time rms representation [8,11]:

$$B = \sqrt{B_x^2 + B_y^2 + B_z^2} \qquad (1)$$

where:

B_x , B_y , B_z are the rms flux densities with reference to a sinusoidal periodic time variation.

The computation results can be so summarized:

1. Only a simulation that includes the transformer model adequately predicts the order of magnitude of flux density.
2. The model, created per [4] for transformers with a rated power ranging from 100 to 2500 kVA, which is based only on the representation of the low-voltage wirings, gives approximate results at 0.5 m from the boundary of the windings. This is probably due to the fact that this distance is comparable with the transformer's dimensions.
3. The most severe magnetic fields are found along a plane parallel to the x-y plane, which becomes the worst area, as far as human exposure. However, if the z-axis is parallel to the building's vertical axis, the exposure along the x-y plane is no longer critical, being parallel to the floor.
4. The maximum calculated flux density amounts to 23.8 µT along the plane yz.
5. The worst conditions occur on a plane parallel to the floor within the cable path region.

An interesting result is shown in Fig. 5, which represents the decays in the amplitude of the flux density, as a function of the distance perpendicular to the aforementioned planes. Starting point is the central point of the square 1m x 1m. These results are obtained by using the complete model, which includes both transformer and low voltage connections.

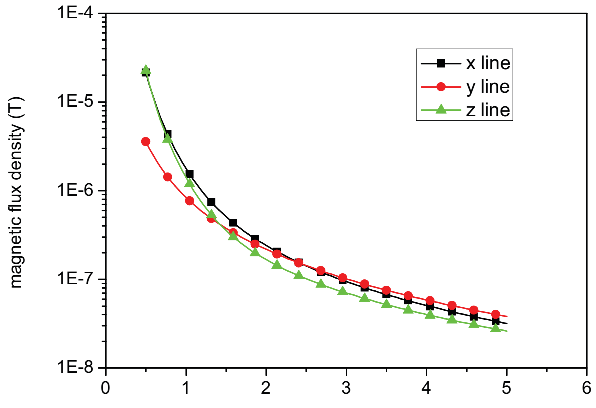


Fig. 5 Decay of flux density along coordinate axes

The magnetic flux density in a plane orthogonal to the axis of the transformer secondary cables (Fig. 6) shows a significant field variation with the distance, such that an intensity of less than 1 µT is found at distances greater than 1 m.

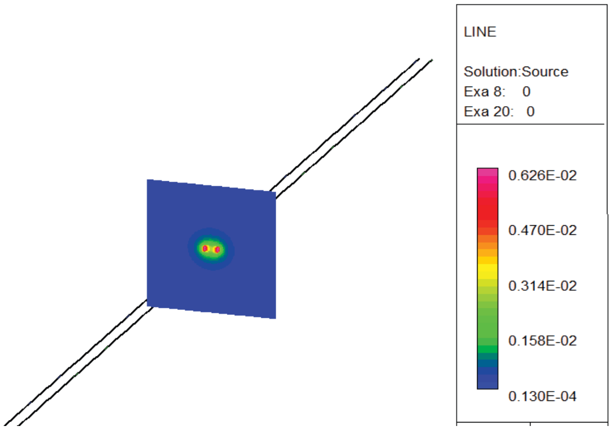


Fig. 6 Magnetic flux density in a plane perpendicular to the axis of the transformer secondary cables.

B. *Magnetic field in the vicinity of connections and lines*

In any point of the space away from the transformer, the magnetic field can be evaluated by means of the Biot-Savart law. The magnetic field depends on the electrical currents in each single conductor of the network (k = 1, .., K). At the instant t_i, the value of the magnetic flux density $\boldsymbol{B}$ in the generic point P_s is given by:

$$\boldsymbol{B}(P_s) = \mu_o \sum_{k=1}^{K} \frac{1}{S_k} \int_{L_k} I_k \boldsymbol{u}_k \times \nabla\psi dl \qquad (2)$$

where μ_o is the permeability of the air, $\psi = 1/4\pi r$ is the Green function, and S_k is the section of the conductor through which I_k flows with local direction $\boldsymbol{u}_k$. To be conservative, it has calculated the field produced near the transformer terminals, between the secondary winding and the main panel, where the current may reach the nominal value of 163 A. In other points, the magnetic field greatly decreases (Fig. 6). The magnetic flux density is less than 1 μT at about 30 cm from the secondary feeder.

The magnetic field near equipment is independent of their supply, and its calculation is not in the scope of this paper. The order of magnitude of such fields have been published in [5].

IV. COMPARISON OF CALCULATED VALUES AND RECOMMENDED LEVELS OF EXPOSURE.

The analysis of the effects of ELF magnetic flux density on human health requires different safety levels with respect to the human exposure:

- maximum permissible flux density to avoid immediate effects;
- maximum permissible average flux density in the case of prolonged or continuous exposure, to avoid cumulative and long term effects.

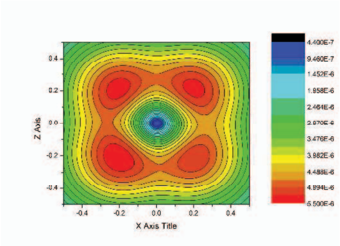
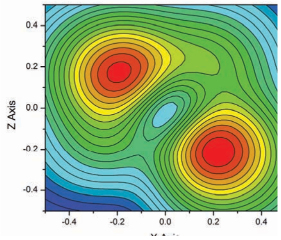
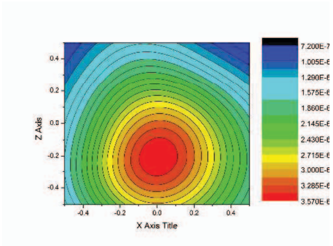
In our case, the calculate values, reported in Table 1, are well below the threshold of 100 μT, as recommended by the European Commission [9]. However, they are greater than the threshold of 3 μT imposed in Italy, for new electrical installations, in space regions surrounding magnetic sources [10].

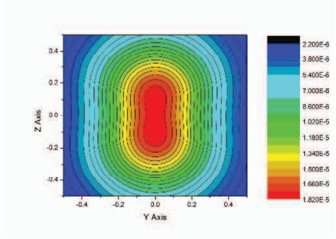
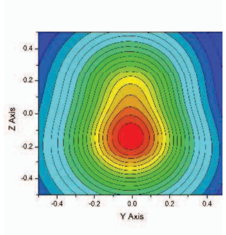
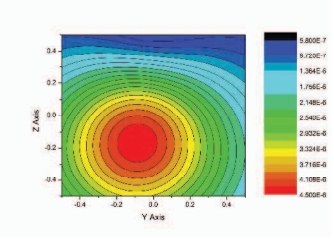
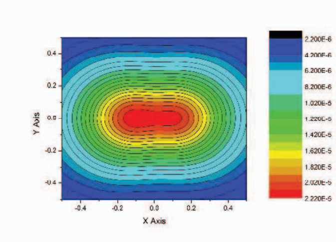
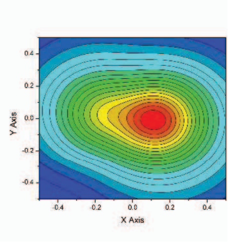
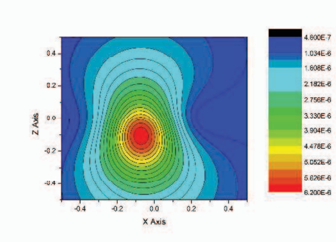
At a distance greater than 0.5 m the flux density is less than the limit of 3 μT. Computations in the utility pathway, as well as in other areas of the unit, are meaningless, as the current's magnitude is much lower than the reference value of 163 A.

V. MAGNETIC FIELD MITIGATION

The above calculations show that magnetic field mitigation strategies are not necessary to avoid health hazards. In the particular case of presence of sensitive electronics equipment to ELF fields, shields based on eddy currents and ferromagnetic material properties can be used to screen the separation transformers [11, 12, and 13].

Table 1 Flux density distribution along surfaces parallel to the planes of coordinates x-z, y-z and x-y.

	only windings	complete transformer (windings and wires)	only LV wires
xz plane y = 0.5 m	 max B = 5.5 μT	 max B = 7.4 μT	 max B = 3.6 μT

yz plane x = 0.5 m	 max B = 18.1 μT	 max B = 23.8 μT	 max B = 4.5 μT
xy plane z = 0.5 m	 max B = 22.1 μT	 max B = 25.2 μT	 max B = 6.2 μT

VI. CONCLUSIONS.

This paper has analyzed the effects of ELF magnetic field produced by separation transformers, employed in the proposed Ecodesign. The results are quite encouraging:

- the use of 1 kV reduces the currents intensity through the distribution system, which, in return, produces weak ELF magnetic fields, even if compared to a three-phase supply system;
- single-phase separation transformers, with no field mitigation, cause a maximum intensity for the ELF magnetic field of 25.2 μT in the region xy, at z = 0.5 m. In this area the adverse impact on persons are minimal. The field decreases up to 1 μT at 1 m from the transformer;
- when the ST is enclosed in a metallic case, a shielding effect takes place with even lower environmental impact.

In essence, it has been substantiated that the introduction of STs in units occupied by persons has no adverse effects as to the magnetic field exposition, confirming the validity of the proposed innovative Ecodesign. As previously said, this design offers remarkable safety features in terms of safety and prevention of interferences among electrical systems upon ground faults.

Although the conclusions are based on a particular type of transformer, it should be noted that this Ecodesign is suitable for systems requiring limited power demand. Therefore, larger transformer ratings, as well as special transformer's design, neither are required nor needed. The results, thus, can be rather general within the proposed model.

VII. ACKNOWLEDGMENTS

These authors wish to thank Prof. M. Repetto for his assistance in the computational aspects of this paper.

REFERENCES

[1] G. Parise, M. Mitolo, "*TN-Island Grounding System*", IEEE-IAS I&CPS Technical Conference, Dearborn, Mi, May 2006, Proceedings of the Conference.

[2] G. Parise, L. Martirano, M. Mitolo, "*TN-Island Grounding System and the House of the Future*", IEEE IAS "Industry Application Society 41st Annual Meeting", Tampa, Fl, October 2006, Proceedings of the Conference

[3] IEEE Std C57.12.01-1998, "*IEEE Standard General Requirements for Dry-Type Distribution and Power Transformers Including Those with Solid-Cast and/or Resin-Encapsulated Windings*"

[4] CENELEC R014-001 (1999), *"Guidelines for the evaluation of electromagnetic fields around power transformers*", Technical Report of CENELEC TC 14, endorsed By the CENELEC Technical Board on April 1999.

[5] IEC Technical Report 61000-2-7, "*Electromagnetic Compatibility – Part 2: Environment- Section 7: Low frequency magnetic fields in various environments*", January 1998.

[6] IEC Publication 61786, "*Measurement of Low Frequency Magnetic and Electric Fields with regard to Exposure of Human Beings – Special Requirements for Instruments and Guidance for Measurements*" August 1998.

[7] G. Giuffrida, C. Gruosso and M. Repetto, "*Finite Formulation of nonlinear magneto-statics with integral boundary conditions. IEEE Transaction on Magnetics*", 42, pp. 1503–1511, 2006.

[8] ICNIRP Guidelines, "*Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (up to 300 Ghz)*", Health Physics, Vol. 74, No. 4, 1998.

[9] Council Of The European Union: "*Council Recommendation on the limitation of exposure of the general public to electromagnetic fields (0Hz–300GHz)*". 1999 (1999/519/CE).

[10] Italian Law July 28th, 2003, "*Limits of exposure of persons to low frequency electric and magnetic fields*".

[11] Canova, A. Manzin, M. Tartaglia " *Evaluation of different analytical and semi-analytical methods for the design of ELF magnetic field shields*", IEEE Industrial Application Systems, vol. 38, no. 3, 2002, pp. 788-796.

[12] E. Salinas et al., "*Mitigation Techniques of Power Frequency Magnetic Fields Originated from Electric Power Systems*." Electra, vol. 242; p. 75-83, 2009.

[13] E. Salinas et al., "*Guidelines for Mitigation Techniques of Power-Frequency Magnetic Fields Originated from Electric Power Systems"*, Paris: CIGRE, vol. 1, p. 1-172; ISBN: 978-2-85873-060-5, February 2009.

BIOGRAPHIES

Massimo Mitolo (IEEE Senior Member '03), educated in Italy, received the Doctoral Degree in Electrical Engineering from University of Naples "*Federico II*" in 1990. His field of research is in Analysis and Grounding of Power Systems. He is a registered Professional Engineer in Italy, and is currently working as the assistant Electrical Department Head at *Chu & Gassman* in New York. He has authored numerous journal papers, as well as the textbook "*Electrical Safety of Low-voltage Systems*". He is also the recipient of the *Lucani Insigni* Award in 2009, for merits achieved in the scientific field.

Dr. Mitolo is very active within the IEEE IAS Industrial & Commercial Power Systems Department, where he currently is the Vice Chair of the Power Systems Engineering (PSE) Committee, the Chair of the Papers Review Subcommittee, the Chair of the Power Systems Analysis Subcommittee and the Vice Chair of the Power Systems Grounding Subcommittee. He is also an Associate Editor of the PSE IEEE Manuscript Central.

Michele Tartaglia (IEEE Senior Member '08) received the degree (Laurea) in Electrical Engineering in 1971 from Politecnico di Torino. In 1973, he joined the Istituto Elettrotecnico Nazionale "Galileo Ferraris", Torino, Italy, where he carried out theoretical and experimental studies on breaking apparatus and computation of electromagnetic fields in nonlinear devices. Since 1982, he has been an associate Professor at Politecnico di Torino. In 1977, he obtained the *Bonavera* Award for Electrical Engineering from the Accademia delle Scienze di Torino.

His main research interests include the study of breaking apparatus, electromagnetic fields by means of analytical and numerical methods, mitigation of low frequency magnetic fields, security in electrical power systems and rational use of energy. He has authored more than 100 scientific papers. Dr. Tartaglia is a member of the IEEE-IAS and of AEIT (Federazione Italiana di Elettrotecnica, Elettronica, Automazione, Informatica e Telecomunicazioni). He is also a member of CIGRE Task Force Working Group 36.04.01 on "Magnetic Field Mitigation Methods" and of the Technical Committee CT 106 on "Human Exposure to Electromagnetic Fields" of Comitato Elettrotecnico Italiano (CEI). Dr. Tartaglia is also the scientific responsible of research contracts with public institutions and private companies, and is involved in European Community projects.