

Characterization of the Magnetic Induction Field produced by Secondary Substations

G. Cangemi¹, A. Cataliotti¹, G. Cipriani¹, V. Di Dio¹, A. Lipari¹, R. Miceli¹, G. Tinè²

¹*Department of Energy, Information Engineering and Mathematic Models (DEIM), University of Palermo, Viale delle Scienze, 90128 Palermo, Italy, email: giovanni.cangemi01@unipa.it, acataliotti@ieee.org, giovanni.cipriani@unipa.it, vincenzo.didio@unipa.it, alessandro.lipari@unipa.it, rosario.miceli@unipa.it.*

²*Consiglio Nazionale delle Ricerche (CNR), Istituto di Studi sui Sistemi Intelligenti per l'Automazione (ISSIA), Via Dante Alighieri, 12, 90141 Palermo, Italy, email: tine@pa.issia.cnr.it*

Abstract – The aim of this paper is to develop a methodology for measuring the magnetic field distribution around the prefabricated secondary substations in vibrated reinforced concrete, as well as the definition of a methodology to determining the maximum value of magnetic induction produced by the substations in correspondence to nominal current of the transformer. As proposed has been developed in conformity with laws and standards and can be applied to active and passive secondary substations. The experimental validation of the proposed methodology, carried out by a measurements campaign whose results are reported, confirms the validity and returns a versatile and simple tool for the verification of the quality targets required by current legislation.

Keywords— *field measurements of magnetic induction, human exposure, distribution substation, distance of first approximation (DPA).*

I. INTRODUCTION

In recent decades, the population exposure to electromagnetic fields has increased, this fact has sparked a growing concern and attention. At present it has not been established a clear correlation between human exposure to the fields at mains frequency and the occurrence of some types of cancer. The International Agency for Research on Cancer (IARC) classified the electromagnetic fields generated by transformer substations, transmission and distribution lines of electricity as agents "possibly carcinogenic to humans", enclosed in Group 2B [1]. This group include the suspected carcinogen agents for which there is limited evidence of carcinogenicity in humans and inadequate evidence of correlation to animal models. Moreover, in literature epidemiological studies do not support a causal link between magnetic fields and cancer [2]. However,

the urban areas, characterized by the presence of multiple sources of field and increasing penetration of medium and low voltage networks, are by way of precaution, areas of focus for the correct assessment of exposure to electromagnetic fields.

The anthropogenic contribution to the electromagnetic fields is predominant compared to those of natural origin. In this framework, particular attention is paid to the assessment of the fields produced by the secondary substations installed in the urban areas, due to the close proximity to the population. Indeed, since the magnitude of the electric field produced by the secondary substations is modest and well below the attention values, the evaluation only of the magnetic induction field is required.

The aim of this article is the characterization of the magnetic induction field distribution around typical structures of secondary substations. A new procedure to measure the magnetic induction field values is proposed and verified on two prefabricated secondary substations in vibrated reinforced concrete (VRC). Moreover, a method to calculate the maximum induction magnetic field, in the equilibrate load condition, is presented.

II. TECHNICAL LEGISLATION IN THE FIELD OF ELECTROMAGNETIC POLLUTION

In July 12, 1999 the European Union Council issued the 1999/519/EC Recommendation "on the limitation of exposure of the general public to electromagnetic fields (0 Hz to 300 GHz)" [3]. As a consequence the Member States of the European Union have assumed a protection framework based on Recommendation into their national legislation. In Italy, the Recommendation has been implemented as Framework law n. 36 of February 22, 2001 "On protection from exposure to electric, magnetic and electromagnetic fields" [4]. The main framework law objective regard the definition of the following actions: protect against acute health effects produced by

electromagnetic fields; take precautions against possible long-term effects. To meet those objectives in [4] the exposure limit, the attention value and the quality target were introduced and the related limit values were reported in Italian DPCM of July 8, 2003 [5],[6]. In Table 1 the limit values for the mains frequency (50 Hz) are shown.

Table 1. Electromagnetic field limits for power lines.

Frequency	Physical	Exposure limit	Attention value	Quality target
50 Hz	Electric Field	5 kV/m	-----	-----
	Magnetic Induction	100 μ T	10 μ T	3 μ T

In order to assure the public's protection against electromagnetic field, in the area near to the power lines or secondary substations, off-limits zones are defined in [7]. In this regulation a simplified procedure to determine the power lines or secondary substations off-limits zones is provided with the introduction of the distance of first approximation (DFA). For the secondary substations the DFA is understood as distance from each wall (the top, and side walls) [8] beyond which the magnetic field must have values less than 3 μ T. To calculate the DFA a simplified physical model is introduced. A three-phase line with currents equal to the rated value of the power transformer (low voltage side) and a distance among the cables equal to the actual diameter (conductor plus insulation) are considered. In this way the model is described from the equation (1).

$$\frac{DFA}{\sqrt{I}} = 0.40942 \cdot x^{0.5241} \quad (1)$$

where I is the rated current of power transformer and x is the actual diameter of the cables.

III. MEASUREMENT METHODOLOGY OF MAGNETIC INDUCTION FIELD IN SECONDARY SUBSTATIONS

In order to verify the compliance with the limits defined by the standards for the public health protection, a measurement methodology for the electromagnetic characterization of secondary substations has been developed. In accordance with the currently standards and laws [9-10], some requirements of the measurement procedures are defined. The main requirements are as follows:

- the electric field outside the secondary substations takes values that generally are not significant, for this reason, usually its measurement can be neglected;
- the measurements must be carried out in the absence of any "disturbing elements". Therefore, the field measurements, in proximity of ferromagnetic materials, should be avoided;
- analyze in advance the load diagram of the substation and perform the measurements presumably when the peak load occurs;
- for a correct evaluation of the field spatial distribution and to obtain an accurate assessment of human exposure the field should be measured at three different heights from the base of these secondary substation (1 m – 1.5 m - 1.7 m) [11].

The measurement points number should be chosen so as to obtain a field spatial distribution around the substation; the disposition of these points defines a three dimensional grid which returns a mapping of the magnetic induction field generated. Each measurement is characterized by the maximum value of the magnetic induction recorded over a period of 1 minute. At the end of the measurement, the magnetic induction data recorded in the instrument memory, are transferred into a pc for their next processing by means a program ad hoc developed. In particular, the analysis of the measurements will give rise to level curves, that provide the spatial distribution of the magnetic induction field in the neighborhood of the substation.

IV. MEASUREMENT RESULTS

For the characterization of the magnetic induction field produced by secondary substations, a series of measurements has been carried out on two secondary substations named "K" and "Z". Both the distribution substations are in vibrated reinforced concrete (VRC) and their dimensions are 440x244x270 cm and 665x244x255 cm, respectively. Both substations are equipped with a 630 kVA MV/LV power transformer. In Fig. 1 a detail of the transformer connections installed inside the substation Z is shown. The PMM8053A instrument [12], used for the magnetic induction field measurements, is shown in Fig. 2. In order to measure the fundamental and harmonic components of the induction magnetic field, a 500 Hz bandwidth has been selected.

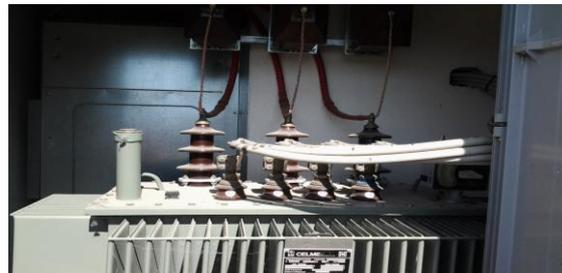


Fig. 1. Particular of 630 kVA MV/LV power transformer.



Fig. 2. PMM 8053A instrument with EHP 50 C probe.

For both substations the measurements were performed at three different heights from the base of the secondary substation (1 m – 1.5 m - 1.7 m). The load current values, during the measurements, were 737A and 150A for K and Z secondary substation, respectively.

For the K substation, 48 points have been identified for each of the three heights (144 measurement points). For the Z substation, instead, 51 points have been identified (153 measurement points). Three more points for Z substation have been required in order to get a more careful evaluation of the field around the substation itself.

As suggested in [9], for each substation, the average exposure levels are calculated and in Table 2 and 3 the obtained values are reported. The measurement results were processed by computer and the spatial distribution of magnetic induction field are reported in Fig. 3 and Fig. 4 for the K and Z substation respectively.

Table 2. Average exposure level for the substation K.

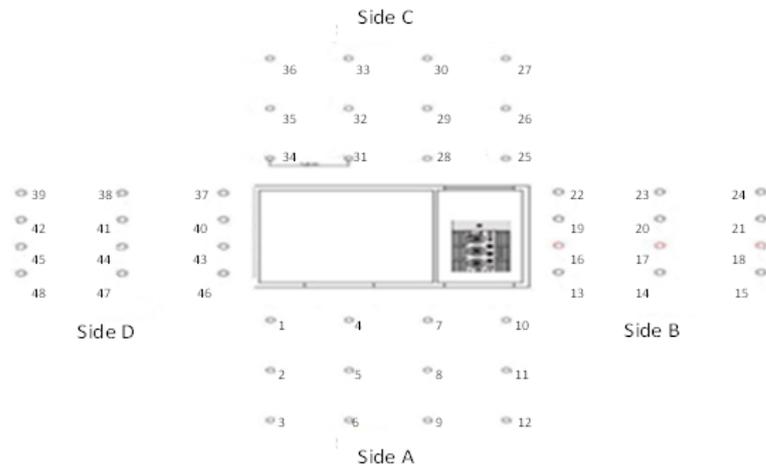
Side	Measurement point	d [m]	Average exposure level [μ T]	Standard deviation σ [μ T]
B	16 (h=0,5)	0.5	24.92	4.21
	64 (h=1,5)			
	112 (h=1,7)			
	17 (h=0,5)	1	7.8	0.60
	65 (h=1,5)			
	113 (h=1,7)			
	18 (h=0,5)	1.5	3.42	0.11
	66 (h=1,5)			
	114 (h=1,7)			

The magnetic induction spatial trends are presented by level curves whose intensity are shown by a color scale (Fig. 3(b) and 4(b)).

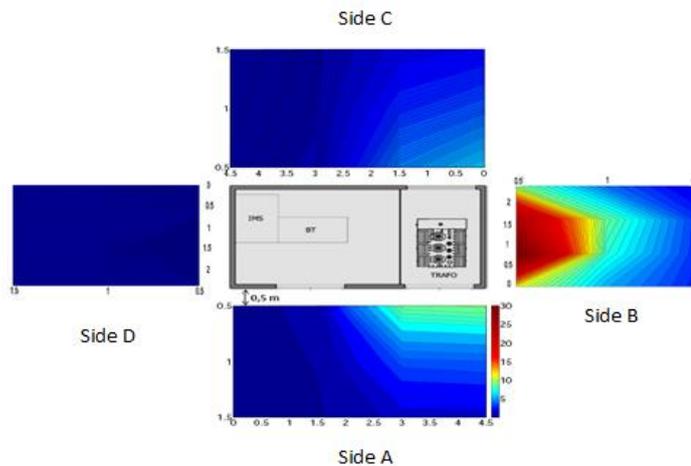
Table 3. Average exposure level for the substation Z.

Side	Measuring point	d [m]	Average exposure level [μ T]	Standard deviation σ [μ T]
C	33a (h=0,5)	0.5	5.82	0.78
	81a (h=1,5)			
	129a (h=1,7)			
	33b (h=0,5)	1	1.43	0.24
	81b (h=1,5)			
	129b (h=1,7)			
	33c (h=0,5)	1.5	0.56	0.08
	81c (h=1,5)			
	129c (h=1,7)			

In Fig. 3(a) and 4(a) the plants and the measurement points of K and Z substations, are reported, respectively. Through these developments it is possible to extrapolate the behavior of the magnetic induction to various distances from the walls of the substations. In Fig. 5(a) and 5(b) the trends of the magnetic induction (related to the side where the maximum value has been measured), along the orthogonal direction to the wall, are shown.

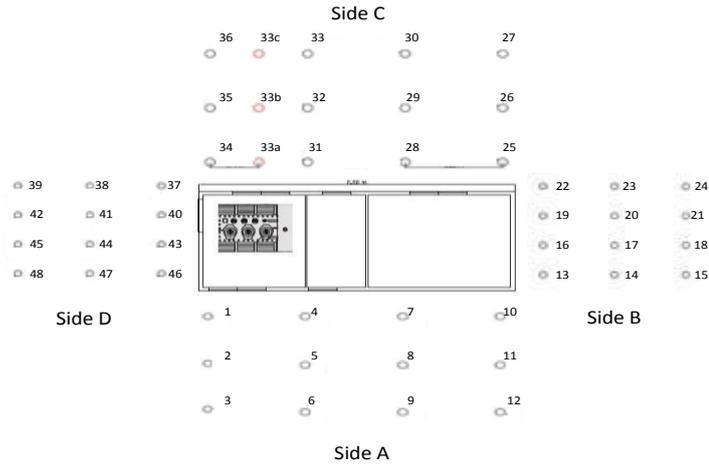


(a) - Substation K - Spatial distribution of the measurement points (h = 0.5m).

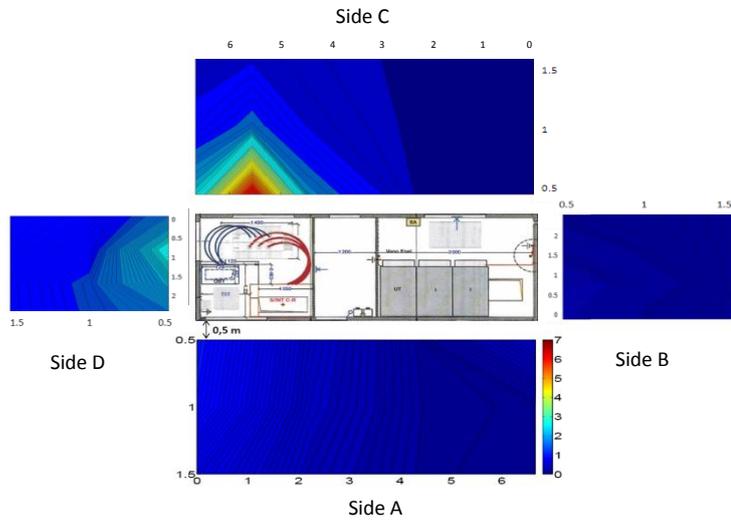


(b) - Substation K - Spatial distribution of magnetic induction [μ T].

Fig. 3. Substation K, (a) Spatial distribution of the measurement points-height, (b) Spatial distribution of magnetic induction.

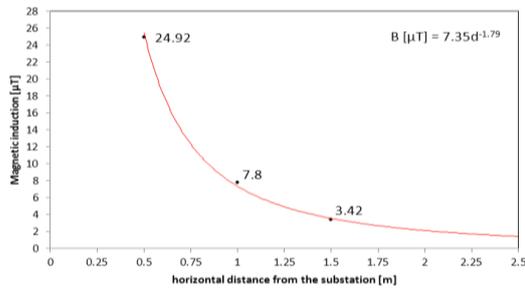


(a) - Substation Z - Spatial distribution of the measurement points ($h = 0.5m$).

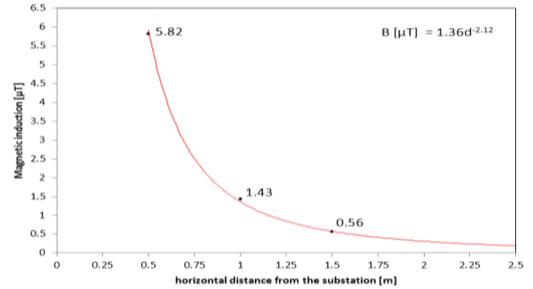


(b) - Substation Z - Spatial distribution of magnetic induction [μT].

Fig. 4. Substation Z, (a) Spatial distribution of the measurement points-height, (b) Spatial distribution of magnetic induction.



(a) – Substation K – Lateral profile of the magnetic induction along orthogonal direction to the B-side wall.



(b) – Substation Z – Lateral profile of the magnetic induction along orthogonal direction to the C-side wall.

Fig. 5. Lateral profile of the magnetic induction along the orthogonal direction to the wall, (a) B-side substation K, (b) C-side substation Z.

V. REPORTING OF MAGNETIC INDUCTION MEASURED VALUES

Generally the current absorbed by the load connected to the power transformer is lower than the rated current. In such cases the field measurements do not correspond at the worst case that represents a difficult conditions to evaluate. In order to obtain the value of magnetic induction at the rated current from the field measured with a lower current, it is necessary to know the type of relation between the current and its field. This relation has been determined by comparing the measured values of magnetic induction with the field calculated using the model described in CEI 106-12 [13]. In particular, the chosen model consider the three phase conductors dislocate in a triangle form and crossed by a three phase balanced currents. The approximate formula to determine the induction magnetic field is shown in equation (2).

$$B(\mu T) = \frac{0.1 \cdot \sqrt{6} \cdot I \cdot S}{D^2} \quad (2)$$

where S is the distance between two cables and D is the distance between the measurement point and the center of the three-phase system. In Fig. 6(a) and 6(b) the comparisons between the measured magnetic induction and the one expected from the theoretical model calculated by (2) are shown, for K and Z substations respectively. To be able to use the model (2) has been necessary to change the parameter D by adding to actual measuring distance, the thickness of the wall of the substation that it is for both 0.10 m. The chosen distances among the cables is equal to twice the real diameter of the cables.

The comparison between calculated and measured values shows that the estimated values of magnetic induction field is conservative and accurate; therefore, it allows to consider reasonably linear the relationship between current and magnetic induction field. In this way, it is possible to define a “carry-factor” as the ratio between the rated current and the measured one. Applying the carry-factor to the measured field the magnetic induction field at the rated current is derived. Considering the average exposure levels, reported in Table 2 and 3, applying the carry-factor, the reported magnetic induction field, related to the rated currents, are calculated and are shown in Table 4. For the two substations it is possible to determine a DFA value equal to 2 m applying the equation (1) and a rated current of 909A corresponding to a 630 kVA power transformer. The assessment of compliance of the theoretical DFA with the calculated value obtained from the measured field has been performed. The magnetic induction field values extrapolated from the curves shown in Fig. 5(a) and 5(b), for a distance of two meters, are indicated in Table 5. In addition, the reported values of magnetic induction field, are also shown in Table 5. The magnetic induction values, calculated at DFA distance, is lower than the target quality of 3 μT , as shown in Table 5.

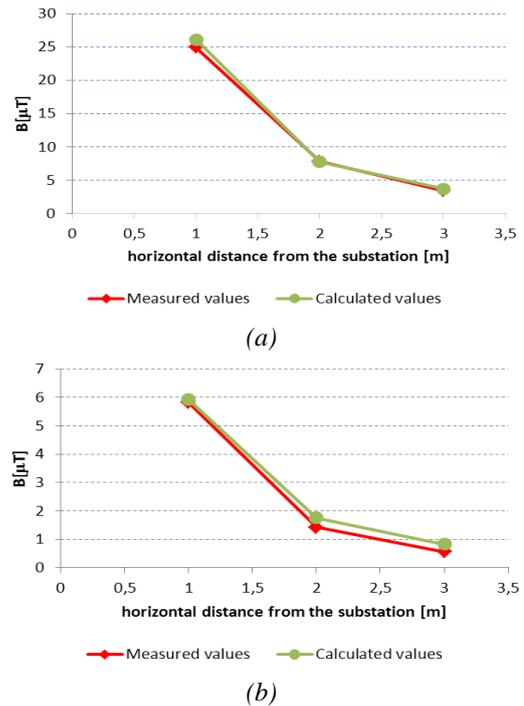


Fig. 6. Comparison between calculated and measured magnetic induction values: (a) K substation; (b) Z substation.

This result confirms the compatibility and the caution of the legislative framework that regulates the emission limits of the field produced by the electrical substations.

Table 4. Measured and reported magnetic induction for K and Z substations.

Substation	$B[\mu T]_{\text{measured}}$	$B[\mu T]_{\text{reported}}$	Nameplate data Trasformer
K	24.92	30.65	Measured current 737 A Rated current 909 A Carry-factor 1.23
	7.8	9.59	
	3.42	4.21	
Z	5.82	35.27	Measured current 150 A Rated current 909 A Carry-factor 6.06
	1.43	8.67	
	0.56	3.39	

Table 5. Magnetic induction values at 2 meters (DFA).

Substation	$B[\mu T]$	$B[\mu T]$
	Interpolated	Reported
K	2.13	2.62
Z	0.31	1.88

VI. CONCLUSIONS

In this work, a new methodology for the detection of the magnetic field distribution around prefabricated secondary substations in vibrated reinforced concrete has been conceived and developed.

The paper, also, proposes a new method that, starting from the knowledge of the measured data and by the value of the rated current of the transformer located inside the substation, allows to calculate the maximum value of magnetic induction in the case of balanced load.

In a more realistic situation of unbalanced currents, however, the methodology is applicable if the neutral is configured in a central position with respect to the triad of the conductors. The method was experimentally validated through measurement series carried out on two different types of prefabricated substation. For both substations a characterization of the magnetic induction field has been developed and its distribution in the surrounding area has been got. The measurements showed that, the maximum values of the field are detected in the external areas of the substation next to the transformer location and its low voltage cables. From the measured values the field values produced under nominal working conditions have been extrapolated. Particularly, the values of the field at the First Approximation Distance (DFA) has been calculated, verifying, for both types of substations, the compliance of the 3 μ T quality target. The proposed methodology, in accordance with the laws and regulations, allows the characterization of the magnetic induction field, produced by active and passive secondary substations, without resorting to measures to be averaged in 24 hours, verifying in quickly and easily the compliance with the quality targets imposed by the legislation.

ACKNOWLEDGMENT

This work was supported by the following research grants:

- PO FESR 2007-13 Sicily, Line 4.1.1.1, Project: REIPERSEI “Reti Elettriche Intelligenti per la Penetrazione delle Energie Rinnovabili nei Sistemi Elettrici delle Isole minori” (Smart grids for the exploitation of renewable energy sources in the little islands of the Mediterranean Sea), CUP G53F110000200004.
- FFR 2012-2013, University of Palermo; Research Project “Sviluppo di dispositivi di misura innovativi di potenza, energia e power quality per la gestione delle Smart Grid attraverso un'opportuna infrastruttura di comunicazione” (Development of new power energy and power quality measurement devices and communication infrastructures for smart grids applications, Project ID 2012-ATE-0395.
- PO FESR 2007-13 Sicily, Line 4.1.1.1, Project: NewCabELARC, CUP G93F12000160004

REFERENCES

- [1] IARC Monographs on the Evaluation of Carcinogenic Risks to Humans VOLUME 80 “Non-ionizing radiation, part 1: Static and extremely low-frequency (elf) electric and magnetic fields – 2002 IARC Press LYON FRANCE
- [2] K J Bunch, T J Keegan, J Swanson, T J Vincent and M F G Murphy; “Residential distance at birth from overhead high-voltage powerlines: childhood cancer risk in Britain 1962–2008” *British Journal of Cancer* 110, 1402-1408,4 March 2014
- [3] Council recommendation of 12 July 1999 on the limitation of exposure of the general public to electromagnetic fields (0 Hz to 300 GHz).
- [4] Legge 22 febbraio 2001, n. 36 “legge quadro sulla protezione dalle esposizioni a campi elettrici, magnetici ed elettromagnetici” pubblicata nella Gazzetta Ufficiale n. 55 del 7 marzo 2001 entrata in vigore il 22 marzo 2001.
- [5] D.P.C.M. 8 luglio 2003 “Fissazione dei limiti di esposizione, dei valori di attenzione e degli obiettivi di qualità per la protezione della popolazione dalle esposizioni a campi elettrici, magnetici ed elettromagnetici generati alla frequenza di rete (50 Hz) generati dagli elettrodotti”.
- [6] D.P.C.M. 8 luglio 2003 “Fissazione dei limiti di esposizione, dei valori di attenzione e degli obiettivi di qualità per la protezione della popolazione dalle esposizioni a campi elettrici, magnetici ed elettromagnetici generati a frequenze comprese tra 100 kHz e 300 GHz”.
- [7] Decreto 29 maggio 2008, Ministero dell’ambiente e della tutela del territorio e del mare, “Approvazione della metodologia di calcolo per la determinazione delle fasce di rispetto per gli elettrodotti”.
- [8] Enel, Linea guida per l’applicazione del paragrafo 5.1.3 dell’Allegato al DM 29 maggio 2008 “Distanza di prima approssimazione (DPA) da linee e cabine elettriche”.
- [9] Norma CEI EN 62110 “Livelli di campo elettrico e magnetico generati da sistemi di potenza in c.a. – Procedure di misura con riferimento all’esposizione umana”, 2012.
- [10] Norma CEI 211-6 “Guida per la misura e per la valutazione dei campi elettrici e magnetici nell’intervallo di frequenza 0Hz – 10kHz, con riferimento all’esposizione umana”, 2001.
- [11] G. Cangemi, A. Cataliotti, G. Cipriani, V. Di Dio, A. Lipari, G. Tinè, M. Melodia “ Caratterizzazione del campo di induzione magnetica prodotto da cabine secondarie” - *L’Energia Elettrica* - maggio-giugno 2014.
- [12] Manuale operativo PMM 8053A sistema di misura di campi elettromagnetici, Documento P/N 8053AIT-50632-2.32 – Copyright © PMM 2004.
- [13] Norma CEI 106-12 “Guida pratica ai metodi de criteri di riduzione dei campi magnetici prodotti dalle cabine elettriche MT/bt”, 2006.