A Theoretical Investigation on Effective Permeability of New Magnetic Composite Materials

Ahmed Thabet and Maurizio Repetto

Nano-Technology Research Centre, Dipartimento di Ingegneria Elettrica,
Aswan University, EGYPT, Aswan, Politecnico di Torino, Torino, ITALY

Abstract: Magnetic composite materials play an important role in broad applications, such as transformers and electrical motors. In this research, it has been predicted the effective permeability of new magnetic composite materials based on Maxwell-Garnett models to specify effects of embedded inclusions. Therefore, it has been investigated on applied formulating new magnetic composite industrial materials by adding various types and percentages of particles (Fe, Silicon steels, Metglas, Co-Fe, Ni-Fe, MgZn_Ferrite, NiZn_Ferrite). All results have been investigated on the significant effect of inclusions distribution, inclusion types and their concentration on the effective permeability of magnetic composite materials; thus it has been controlled and enhanced the characteristics of magnetic industrial materials by using the particles structure of a random distribution of magnetic easy axes of the grains.

Keywords: Magnetic composites, Particles, Predicting, Permeability, Magnetism

1. Introduction

Magnetic Composite challenges traditional materials such as soft magnetic ferrites and electrical steels in applications with alternating magnetic fields. New developments in magnetic materials and new production techniques make magnetic composite material interesting for application in electrical machines. In recent years, many researchers have tried to improve the magnetic properties performance of SMCs, by selecting a suitable material and applying a suitable coating method [1-4] or preparing composites based on the amorphous or nanocrystalline powders [5-8].With respect to the main goal of material science is developing new materials magnetic composite industrial materials. Magnetic composite materials such as concrete mixed with iron particles, synthetic resins including ferrite particles and so on, have been used for electromagnetic shielding in recent years. These composite materials will work also as shields against magneto-static fields. Simplification of the structure by homogenization makes it possible to analyze efficiently [9-14]. A lot of homogenizing rules have been introduced in order to estimate the effective material parameters of the composite materials and mixtures so far. The most well-known rules might be the Maxwell–Garnett formula and the Bruggeman formula [15-19].Predicting the effective magnetic properties of composite materials is of the utmost importance in both academic and industrial research. Maxwell-Garnett's formula, Bruggeman's formula are well established techniques for the evaluation of effective permeability of disordered hetero-structures. Also, it can be proposed permeability effects of magnetic particles on nonmagnetic matrix [20, 21].With the development of modern industry, more and more new large electric machines are widely equipped to meet the need of the development. Soft-magnetic composites with metallic inclusions are common in established industrial applications. Spherical agglomerates with well-connected conductive particles effectively behave as large virtual particle with an additional increase of effective permeability due to the flux concentration in the agglomerate [22]. The new developed materials become particularly important because its physical properties change dramatically with the size and with the local structure of the grains. And so, to be considered for engineering applications, these materials should be of low cost and should be easy to prepare, allowing them to be highly competitive with the already- existing ones used in such engineering

Received: November 9th, 2013. Accepted: July 16th, 2014

applications. With respect to soft magnetic materials that play an important role in broad applications, such as transformers and electrical motors. There is an interest in soft magnetic composites materials because of the demand for miniaturization of cores for power electronic applications, transformers, stators and rotors of electro-motors. These materials are used in electromagnetic applications, can be described as ferromagnetic powder particles surrounded by an electrical insulating film[23-25].So that, in this research, it has been suggested new magnetic composite industrial materials that have been enhanced their magnetic characterization response with respect to types and concentrations of selected particles. Therefore, many different micro-particles are studied to reach the best fillers significantly increase magnetic permeability.

2. Analytical Model

In our research, it will be focus on applied the calculation techniques for estimating the effective permeability of magnetic composite industrial materials which consists of micron/submicron-sized particles that embedded in different matrices; considering random structure of magnetic particles in the base matrices. So that, based on the previous analytical models[11, 15] have been used to formulate theoretical models for predicting the effective permeability of magnetic composite materials. With respect to Maxwell-Garnett formula that plays an important role in 2D composite materials[11], the effective permeability for random distribution of particle size as 2-D spherical shapes significantly as follows:

$$\mu_{eff} = \mu_m + 2\mu_m \frac{\mu_i - \mu_m}{\mu_i + \mu_m - \varphi(\mu_i - \mu_m)} \tag{1}$$

Where,
μ_i is permeability of inclusions in the composites,
μ_m is permeability of main matrix of the composites,
φ is the volume fraction of inclusions inside the main matrix.

And so, with respect to Bruggeman formula [11] that is another famous homogenizing rule for predicting the effective permeability for symmetrically distribution of particle size as 2-D circular cylinders shapes significantly as follows:

$$(1 - \varphi)\frac{\mu_m - \mu_{eff}}{\mu_m + \mu_{eff}} + \varphi\frac{\mu_i - \mu_{eff}}{\mu_i + \mu_{eff}} = 0 \tag{2}$$

With respect to the inclusions of the actual composites are not always similar to spheres or cylinders, the above formulas not be satisfied. Thus, more accurate approach estimation [15], the structure of magnetic composite material is assumed to be periodic, and the unit cell, which is the minimum volume is regarded as a homogeneous magnetic substances as shown in Fig. (1). The effective permeability of magnetic composite materials is defined on the basis of magnetic energy balance in the unit cell, and it is assumed, in this approach, that the original cell and the homogenized cell include equivalent magnetic energy when both unit cells are immersed in equivalent magnetic field.

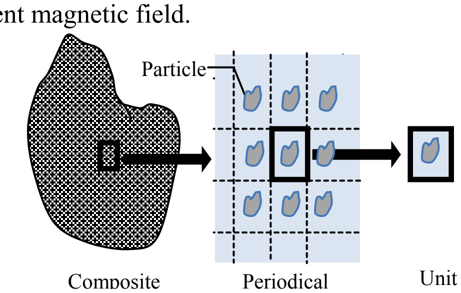


Figure 1. Schematic for homogenization of magnetic composite materials.

Thus, this method has possibility to apply to any structure. The effective permeability of magnetic composite materials is given as follows:

$$\mu_{eff} = \frac{\int_{S_{homo}} |B_{homo}\cdot| dS}{\int_{S_{homo}} B_{org}\cdot H_{orig}\, dS} \tag{3}$$

Where,
S_{homo} is the square of the original cell, B_{homo} is the magnetic flux density, H_{orig} is the magnetic field. Whatever, the elements of effective permeability of magnetic composite structure materials as follows:

$$\mu_{eff}^{x} = \frac{\left(B_{homo}^{x}\right)^{2} \cdot S_{homo}}{\int_{S_{homo}} B_{org}\cdot H_{orig}\, dS} \tag{3.i}$$

$$\mu_{eff}^{y} = \frac{\left(B_{homo}^{y}\right)^{2} \cdot S_{homo}}{\int_{S_{homo}} B_{org}\cdot H_{orig}\, dS} \tag{3.ii}$$

Magnetic materials, particularly fillers sized show a significant change in physical, electrical, and magnetic properties in contrast to their bulk counterparts due to their high surface to volume ratio of the grains. Thus, influences of types, and concentration of inclusions gran size will be shown on the performance of effective magnetic permeability of the composite. The effective permeability μ_{eff} of the suggested magnetic composite industrial materials can be predicted by using the above approaches based on inclusions permeability, weight percentages of inclusions inside the matrix and main matrix permeability of magnetic composite materials. Therefore, it can be estimated the effective permeability of magnetic composite that has been characterized by adding various percentages of magnetic fillers random distributions in matrix material as [15].

3. Selected Particles and Magnetic Industrial Materials

Magnetic composites can be described as ferromagnetic powder particles surrounded by an electrical insulating film. The choice of magnetic composite material is complex and depends on many factors like frequency, size of the component, physical strength and the magnetic properties. This research illustrates the effects of particles size like Iron high purity particles (single crystals in preferred directions), Silicon steels, Metglas, Co-Fe, Ni-Fe, MgZn_Ferrite, and NiZn_Ferrite for fabricating composite and nanocomposite industrial materials.Table1depicts the main electrical description properties of usage particles for enhancing magnetic properties of composite industrial materials.

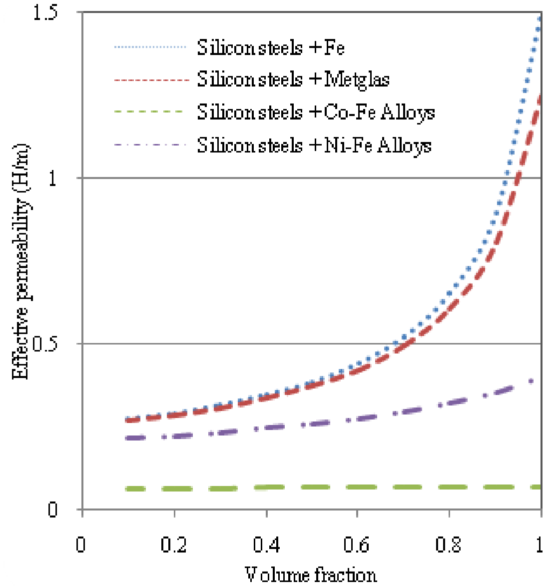
Table 1. Electric and magnetic property of selected Particles and magnetic industrial materials

Materials	Electric and Magnetic Properties	
	μ (H/m)	ρ (Ω.m)
SILICON STEELS	$93x10^{-3}$	$45x10^{-8}$
Fe (HIGH PURITY)	$1500x10^{-3}$	$10x10^{-8}$
METGLAS	$125x10^{-2}$	$142x10^{-8}$
CO-Fe	$70x10^{-3}$	$40x10^{-8}$
Ni-Fe	$400x10^{-3}$	$55x10^{-8}$
MgZn_FERRITE	□$8x10^{-4}$	0.5
NiZn_FERRITE	$2x10^{-5}$-$8x10^{-4}$	300

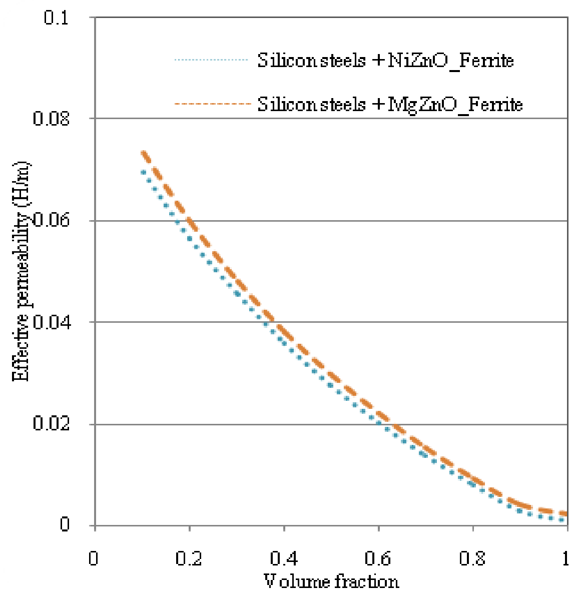
4. Results and Discussions

Most magnetic composite materials change their magnetic properties in response to the new particles, however; overall magnetic behavior of the composite materials can vary widely, depending on the structure of the material, particularly on its electron configuration. The following results explain the characterization response of the suggested magnetic composite materials with respect to various types and concentrations of selected particles.

A. Characterization of Silicon steels Magnetic Composites



a. Effect of Soft magnetic particles

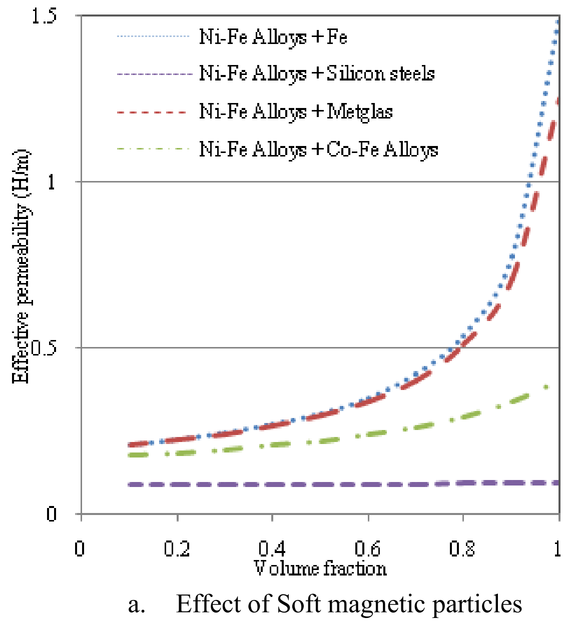


b. Effect of Ferrite magnetic particles

Figure 2. Effective permeability of Silicon steels composites with various volume fractions of particles

Figure 2a shows the effective permeability of Silicon steels magnetic composites noting that Iron and Metglas particles are the best inclusions for enhancing the effective permeability of magnetic composite, then; Alloys particles have the second order for enhancing the effective permeability of magnetic composite industrial materials. Figure 2b shows the effective permeability of Silicon steels magnetic composites that has been decreased by adding various percentages of MgZn, and NiZnFerrite particles randomly distributions in silicon steels matrix material.

B. Characterization of Ni-Fe Alloys Magnetic Composites

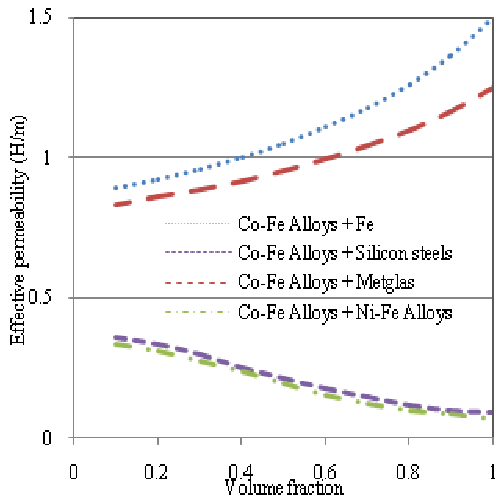


b. Effect of Ferrite magnetic particles

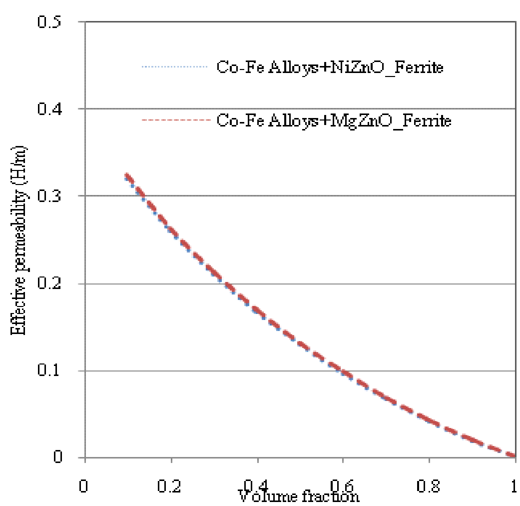
Figure 3. Effective permeability of Ni-Fe Alloys composites with various volume fractions of magnetic particles

Figure 3a illustrates the effective permeability of Ni-Fe magnetic composites, it describes that Iron and Metglas particles are the best inclusions for enhancing the effective permeability of magnetic composite, then; Silicon steels particles have the second order for enhancing the effective permeability of magnetic composite industrial materials. However, Co-Fe Alloys particles aid to decrease the effective permeability of magnetic composite industrial materials. Studying effects of Ferrite particles came based on Ferrites compositions that are chemical compounds consisting of ceramic materials with iron oxide as their principal component. Many of Ferrite particles are magnetic materials and they are used to make permanent magnets, ferrite cores for transformers, and in various other applications. Figure 3b shows the effective permeability of Ni-Femagnetic composites, noting that the effective permeability of NiZnFerrite/Ni-Fe Alloysmagnetic composite is higher than the effective permeability of MgZnFerrite/ Ni-Fe Alloysmagnetic composite.

C. Characterization of Co-Fe Alloys Magnetic Composites



a. Effect of Soft magnetic particles



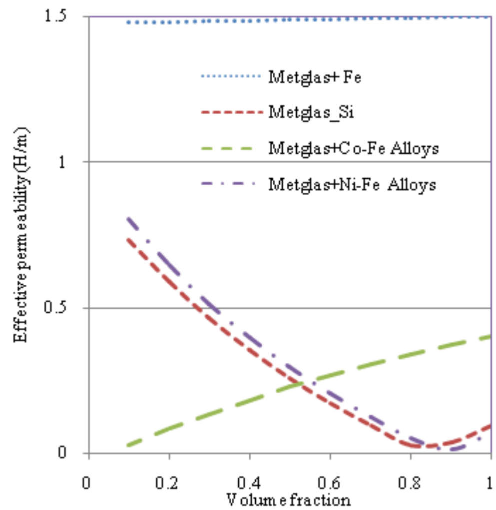
b. Effect of Ferrite magnetic particles

Figure 4. Effective permeability of Co-Fe Alloys composites with various volume fractions of magnetic particles

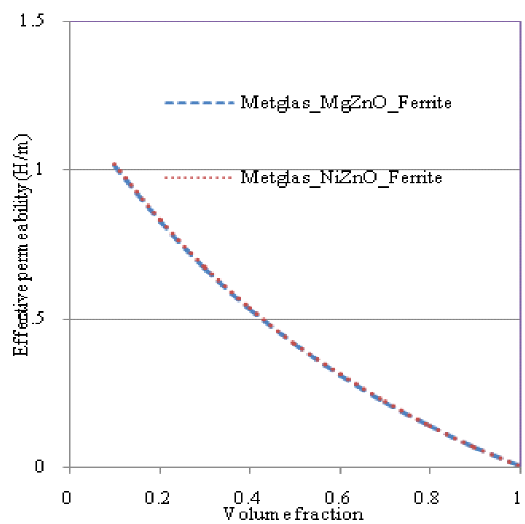
Figure 4a shows the effective permeability of *Co-Fe* magnetic composites, it has been noticed that Iron and Metglas particles record the best inclusions for enhancing the effective permeability of magnetic composite, whatever; Silicon steels and Ni-Fe Alloys particles aid to decrease the effective permeability of magnetic composite industrial materials. Figure 4b shows the effective permeability of NiZnFerrite/Co-Fe Alloysmagnetic composite is higher than the effective permeability of MgZnFerrite/Co-Fe Alloysmagnetic composite.

D. Characterization of Metglas Magnetic Composites

Figure 5a shows the effective permeability of *Metglas* magnetic composites, it has been illustrated that increasing percentage of iron or Co-Fe Alloys particles enhances the effective permeability of magnetic composite, whatever; Silicon steels and Ni-Fe Alloys particles decrease the effective permeability of magnetic composite industrial materials. Figure 5b shows increasing magnetic particles of NiZn Ferrite or MgZn Ferrite toMetglas decreases the effective permeability of the magnetic composite and the effect of these particles is the same.



a. Effect of Soft magnetic particles

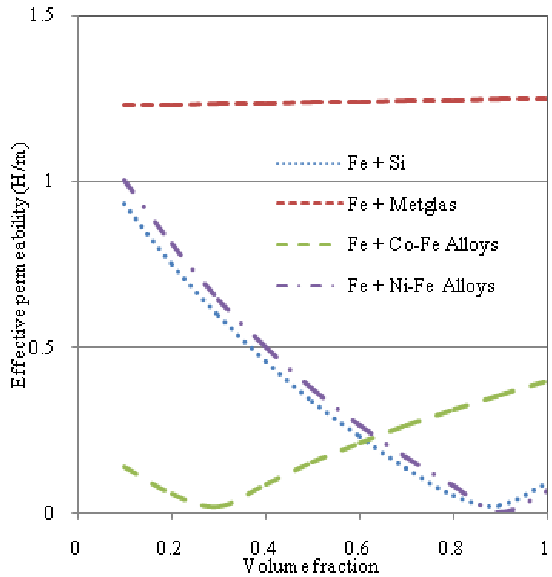


b. Effect of Ferrite magnetic particles

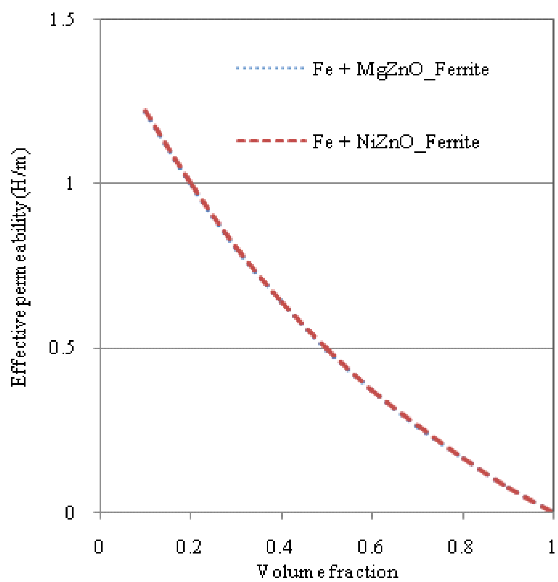
Figure 5. Effective permeability of Metglas composites with various volume fractions of magnetic particles

E. Characterization of Iron Magnetic Composites

Figure 6a shows the effective permeability of Iron magnetic composites, it has been depicted that Metglas and Co-Fe Alloys particles record the best inclusions for enhancing the effective permeability of magnetic composite with increasing their percentages.



a. Effect of Soft magnetic particles



b. Effect of Ferrite magnetic particles

Figure 6. Effective permeability of Iron composites with various volume fractions of magnetic particles

Whatever; Silicon steels and Ni-Fe Alloys particles aid to decrease the effective permeability of magnetic composite industrial materials. Figure 6b shows the effective permeability of NiZn Ferrite/Fe and MgZn Ferrite/ Fe magnetic composites, it has been the same performance for the effective permeability of magnetic composite.

5. Conclusions

Iron, Metglas, and Co-Fe Alloys particles aid for enhancing the effective permeability of Silicon steels magnetic composites. On the otherwise, Alloys particles have the second order for enhancing the effective permeability of Silicon steels magnetic composite materials. But, Ferrite particles and Silicon steels particles have the property for reduction the effective permeability of magnetic composite industrial materials.

6. Acknowledgements

The present work was supported by WELCOME Erasmus Mundus Project between Aswan University, Egypt and Politecnico Di Torino University, Italy.

7. References

[1] H. Shokrollahi and K. Janghorban, "Soft magnetic composite materials (SMCs)," *J. Mater. Process. Techn.*, vol. 189, pp. 1–12, Jul. 2007.

[2] L. A. Dobrzanski, M. Drak, and B. Ziebowicz, "New possibilities ofcomposite materials application: Materials of specific magnetic properties," J. Mater. Process. Techn., vol. 191, pp. 352–355, 2007.

[3] E. A. Périgo, S. Nakahara, Y. Pittini-Yamada, Y. de Hazan, and T.Graule, "Magnetic properties of soft magnetic composites prepared with crystalline and amorphous powders," J. Magn. Magn. Mater., vol.323, pp. 1938–1944, 2011.

[4] P.Kollár, J. Füzer, R. Bureˇs, and M. Fáberová, "AC magnetic properties of Fe/based composite materials," *IEEE Trans. Magn*., vol. 46, no. 2, pp. 467–470, 2010.

[5] P. Kollár, L. Hegedüs, J. Füzer, R. Bureˇs, and M. Fáberová, "AC magnetic properties of vitroperm based composite materials," ActaPhysicaPlonica A, vol. 118, pp. 787–789, 2010.

[6] G. Q. Lin, Z. W. Li, L. Chen, Y. P. Wu, and C. K. Ong, "Influence of demagnetizing field on the permeability of soft magnetic composites," J. Magn. Magn. Mater., vol. 305, pp. 291–295, 2006.

[7] F. Alves, C. Ramiarinjaona, S. Bérenguer, R. Lebourgeois, and T.Waeckerlé, "High-frequency behavior of magnetic composites basedon FeSiBCuNb particles for power electronics," *IEEE Trans. Magn.*,vol. 38, no. 5, pp. 3135–3137, 2002.

[8] Jana Füzerová, JánFüzer, Peter Kollár, LukáˇsHegedüs, Radovan Bureˇs, and MáriaFáberová, "Analysis of the Complex Permeability Versus Frequency of Soft Magnetic Composites Consisting of Iron and $Fe_{73}Cu_1Nb_3Si_{16}B_7$" *IEEE Transactions on Magnetics*, Vol. 48, NO. 4, pp. 1545-1548, April, 2012.

[9] P. Olszewski and I. Saitoh, "Modeling of inner magnetic shielding assemblies cathode ray tubes by 3-dimensional finite element method," *IEEE Trans. Magn.*, vol. 32, no. 5, pp. 4299–4301, Sep. 1996.

[10] Yuan Li, Ming-Jie Tang, Feng-Jiao Wu, Guan-Jun Zhang, Shu-Hong Wang, Suwarno , "Aging Assessment of Power Transformer Using Multi-parameters" *International Journal on Electrical Engineering and Informatics*, Vol. 5, Issue 1, 2013

[11] M. Balasubramanian and S. Venkatesh , "Partial Discharge and Conduction Current Signature Analysis for the Assessment of Transformer Oil Behavior under Accelerated Stress Condition" *International Journal on Electrical Engineering and Informatics*, Vol. 5, Issue 4, 2013

[12] S. Mohamed Ghouse, S. Venkatesh, R.Rajesh, and S. Natarajan, "Effects of SiO2 and TiO2 Nano Fillers in Enhancing the Insulation Breakdown Strength of Epoxy Nano Composite Dielectric under Divergent Electric Field" *International Journal on Electrical Engineering and Informatics*, Vol. 5, Issue 4, 2013

[13] S. Venkatesh and M. Balasubramanian , "Experimental Investigations and Ageing Studies on Effects of Insulating Barriers in Transformer Oil during High Frequency High Voltage Transients in I" *International Journal on Electrical Engineering and Informatics*, Vol. 6, Issue 1, 2014

[14] H. Waki, H. Igarashi, and T. Honma, "Modeling of reinforced concrete structures for analysis of environmental magnetic fields," in *Computational Engineering I. Nagano, Japan: JASCOME (Japan Society for Computational Methods in Engineering)*, 2004, pp. 117–124.
[15] A. Sihvola, "Electromagnetic mixing formulas and applications" *IEE Electromagnetic Waves Series*, Vol. 47, pp. 63-68, 1999.
[16] E. Tuncer, Y. V. Serdyuk, and S. M. Gubanski, "Dielectric mixtures: electrical properties and modeling," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 9, no. 5, pp. 809–828, Oct. 2002.
[17] A. H. Sihvola and J. A. Kong, "Effective permittivity of dielectric mixtures," *IEEE Trans. Geosci. Remote Sens.*, vol. 26, no. 4, pp. 420–429, Jul. 1988.
[18] K. K. Karkkainen, A. H. Sihvola, and K. I. Nikoskinen, "Effective permeability of mixtures: numerical validation by FDTD method," *IEEE Trans. Geosci. Remote Sens.*, vol. 38, no. 3, pp. 1303–1308, May 2000.
[19] H. Waki, H. Igarashi, and T. Honma, "Estimation of Effective Permeability of Magnetic Composite Materials" *IEEE Transactions on Magnetics*, Vol. 41, No. 5, pp. 1520-1523, May 2005.
[20] L. Z. Wu, J. Ding,a_ H. B. Jiang, and C. P. Neo, L. F. Chen, and C. K. Ong, "High frequency complex permeability of iron particles in a nonmagnetic matrix" J. Appl. Phys. 99, 083905, 2006.
[21] J. Rekosova, R. Dosoudil, M. Usakova, E. Usak, I. Hudec,"Magnetopolymer Composites With Soft Magnetic Ferrite Filler" *IEEE Transactions on Magnetics*, Vol. 49 , Issue: 1, pp. 38 – 41, Jan. 2013.
[22] B. Drnovšek, V. B. Bregar, and M. Pavlin, "Numerical study of effective permeability of soft-magnetic composites with conductive inclusions" *Journal of Applied Physics* 105, 07D546, 2009.
[23] J. Fuzerova, J. Fuzer, P. Kollar, L. Hegedus, R. Bures,and M. Faberova, "Analysis of the Complex Permeability Versus Frequency of Soft Magnetic Composites Consisting of Iron and $Fe_{73}Cu_1Nb_3Si_{16}B_7$" *IEEE Transactions on Magnetics*, Vol. 46, Issue: 2, pp. 440 – 442, Feb. 2010.
[24] M. Anhalt, and B. Weidenfeller, "Permeability of Soft Magnetic FeCoV-Composites for Varying Filler Fractions" *IEEE Transactions on Magnetics*, Vol. 48, Issue: 4, pp. 1545 – 1548, April 2012.
[25] C. Yao, Y. Shimada, G.W. Qin, W. L. Pei, S. Okamoto, O. Kitakami,Y. Endo, and M. Yamaguchi, "Study of Permeability for Composites Including Fe, NiZn Ferrite and Fe-B-P Particles" *IEEE Transactions on Magnetics*, Vol. 47 , Issue: 10, pp. 3160 – 3162, Oct. 2011.

Ahmed Thabet was born in Aswan, Egypt in 1974. He received the BSc (FEE) Electrical Engineering degree in 1997 and MSc (FEE) Electrical Engineering degree in 2002 both from Faculty of Energy Engineering, Aswan, Egypt. PhD degree had been received in Electrical Engineering in 2006 from El-Minia University, Minia, Egypt. He joined with Electrical Power Engineering Group of Faculty of Energy Engineering in Aswan University as a Demonstrator at July 1999, until; he held Associate Professor Position at October 2011 up to date. His research interests lie in the areas of analysis and developing electrical engineering models and applications, investigating novel nano-technology materials via addition nano-scale particles and additives for usage in industrial branch, electromagnetic materials, electroluminescence and the relationship with electrical and thermal ageing of industrial polymers. Many of mobility's have investigated for supporting his research experience in UK, Finland, Italy, and USA …etc. On 2009, he had been a Principle Investigator of a funded project from Science and Technology development

Fund “STDF” for developing industrial materials of ac and dc applications by nano-technology techniques. He has been established first Nano-Technology Research Centre in the Upper Egypt (http://www.aswan.svu.edu.eg/nano/index.htm). He has many of publications which have been published and under published in national, international journals and conferences and held in Nano-Technology Research Centre website.athm@aswu.edu.eg

Maurizio Repetto was born in Genoa in 1960 and took his degree in Electrical Engineering at the University of Genoa in 1985. From 1986 to 1989 he worked on his Ph. D. under the direction of Prof. Molinari at the Dipartimento di IngegneriaElettrica of Genoa University. After taking his Ph.D., he became there researcher in 1990. Since 1992 he is working at the DipartimentoEnergia of the Politecnico di Torino, before as Associate Professor and from 2000 on as Full Professor of Fundamentals of Electrical Engineering. His research interests regard the analysis of electromagnetic components and systems with numerical methods. In particular he is involved in researches on hysteresis in magnetic materials, in automatic optimisation of electromagnetic devices, in optimization applied to the management of energy systems and in other industrial research topics regarding electrical engineering. He is actively involved in several research projects at the national and international level and he is member of the Editorial Board of some specialist journals. In 2009 he has been awarded the ACES 2008 best journal paper award for the paper "A General Framework for Mixed Structured/Unstructured PEEC Modelling", maurizio.repetto@polito.it