New Magnetic Materials for Electrical Machines and Power Converters

THE last decade has been characterized by a continuous demand for high-efficiency electrical machines and power, which have to be designed to obtain high power density with high efficiency and at the same time reduced costs. Among the several design approaches typically used to achieve these targets, the adoption of high-quality magnetic materials is one of the most common ones. For this reason, the magnetic steel manufacturers have improved the performances of their materials by increasing the permeability and the saturation levels while at the same time reducing the specific iron losses. Magnetic materials characterized by new metallurgical technological processes and different compositions have been introduced in the market, enlarging the possible choices available to the electromagnetic device producers. As a consequence, the year after year increasing typology of magnetic materials with new compositions, material processing techniques, and supplied forms makes it challenging to choose the most suitable material for a specific machine design.

These considerations have pushed the Guest Editors to propose this "Special Section on New Magnetic Materials for Electrical Machines and Power Converters" to the Editors of the IEEE Transactions on Industrial Electronics. The Special Section was fully approved, and it achieved strong interest and feedback from researchers of the electrical machines and drives community. For this Special Section, 32 manuscripts were submitted for the peer review evaluation. From these papers, 17 were accepted for publication in the Special Section. All the accepted papers include experimental activities to validate the proposed solutions. They now represent a comprehensive reference list for the researchers interested in this Special Section topic. The Special Section opens with a paper presented by the Guest Editors in collaboration with Steve Sprague (of Proto Lamination, Inc.), concerning the status and trends of soft magnetic materials used in electric machines and power converter devices [item 1) in the Appendix]. The paper gives an overview on the magnetic materials used in electrical machines. In particular, silicon-iron, nickel-iron, and cobalt-iron lamination steels, as well as amorphous and nanocrystalline magnetic materials and soft magnetic composites are analyzed. Furthermore, research, development trends, and current use of these materials are presented as well. The other papers can be subdivided into three categories. The first category is concerning the impact of the new magnetic materials on the electrical machine design. The first paper investigates the effect of soft magnetic material, Si-Steel, and Co-Iron on the high-speed machine design and compares the effects of stack length, number of winding turns, outer diameter, and no-load magnetic flux density of the machine with regard to its performance [item 2) in the Appendix]. The second paper presents an attempt to evaluate the building factor of a stator core made of nonoriented silicon steel laminations. The stator core is used in a synchronous motor with buried permanent magnets in item 3) of the Appendix. The third paper presents the core losses and performance characteristics of a small power induction motor with the core made from different electrical steel sheets, supplied from mains and variable frequency inverter at 50, 100, and 200 Hz [see item 4) in the Appendix]. The fourth paper deals with the results of measurements, calculations, and computer simulations, leading to the determination of the stator core's building factor of a fractional power synchronous reluctance motor [see item 5) in the Appendix]. The fifth paper presents a new voltage controlled static magnetic device called "magnetic flux valve." This device is mainly used in a magnetic circuit to actively control the magnetic flux through the magnetic circuit. The magnetic flux valve has a laminated structure of two different layers made of a magnetostrictive material and a piezoelectric material, respectively [see item 6) in the Appendix].

The second category groups papers concerning the determination of the magnetic material properties and the related manufacturing process. Item 7) in the Appendix proposes the modeling and measurement of the magnetic properties of soft magnetic composite (SMC) materials under both alternating and rotational magnetic excitations, together with the approach of calculating the corresponding core losses in electromagnetic devices using soft magnetic composite cores. Item 8) in the Appendix deals with a new testing method that uses a simple experimental test setup to characterize the magnetic properties of solid ferromagnetic material. The basic experimental results from the new setup are compared to results from the three-dimensional (3-D) finite-element analysis. The Item 9) in the Appendix presents an improved 3-D tester for the measurements of 3-D magnetic properties of core materials. Item 10) in the Appendix deals with the design optimization of a high-speed switched reluctance motor for automotive traction applications. In presence of high-speed operation and high electrical frequency, the authors analyze the effects that influence the accurate calculation of the core loss coefficients used in the calculation of the iron loss during the motor design stage. Items 11) in the Appendix presents two different computer modeling approaches for the simulation of the Ni-Fe alloy rotational magnetizations. The models are identified and validated using experimental data.

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The papers of the third category deal with the iron losses, which represent an important issue in the electrical machines and magnetic devices efficiency. Item 12) in the Appendix demonstrates that the hysteresis losses should be taken into account during the machine design process. In particular, measurements and simulations have shown that for specific machine designs, hysteresis losses in NdFeB, SmCo, and ferrite magnets can be the source of significant additional ac losses that may lead to too high permanent magnet operating temperatures and thus a reduction in the machine efficiency. Item 13) in the Appendix presents a comparative study of different static hysteresis models coupled to the parametric magneto-dynamic model of soft magnetic steel sheets. Both mathematical and behavioral as well as physically based approaches are discussed with respect to the ability to predict the dynamic hysteresis loop shape such as iron loss under pulse width modulation excitations. Item 14) in the Appendix deals with the prediction of the energy losses in soft magnetic materials under arbitrary induction waveforms when a dc bias is added to the reference waveform. The parameters of the statistical theory of the loss model are obtained by exploiting pre-emptive conventional measurements only. By this new simplified method, analytical expressions for the loss components are obtained under general supply conditions, including dc-biased induction waveforms. Item 15) in the Appendix presents a new modeling technique for calculating the instantaneous power loss in ferromagnetic materials without considering their magnetization history. The description of the approach includes the required standard measurement setup, the nonlinear loss modeling itself, and an extensive verification of ring specimen measurements for different flux density waveforms and frequencies. In addition, a detailed comparison to well-known iron loss models is included as well. In item 16) of the Appendix, the global operating point dependent losses of induction machines are studied utilizing a local transient loss formulation. Particular attention is paid to the effect of different electrical steel grades tailored either to low losses or better magnetization behavior. Item 17) in the Appendix proposes a classification of different approaches for modeling the cutting degrading effect on the magnetic properties of electrical steel sheets. The aim of this paper is to provide a tool that enables the selection of the most suitable cutting method for a given design task, taking the influence of the cutting process into consideration.

ALDO BOGLIETTI, *Guest Editor*
Dipartimento Energia
Politecnico di Torino
10129 Turin, Italy

ANDREA CAVAGNINO, *Guest Editor*
Dipartimento Energia
Politecnico di Torino
10129 Turin, Ital

ANDREAS KRINGS, *Guest Editor*
ESD/Machines and Drives Team
ABB Corporate Research Sweden
72178 Västerås, Sweden

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APPENDIX
RELATED WORK

1) A. Krings, A. Boglietti, A. Cavagnino, and S. Sprague, "Soft magnetic material status and trends in electric machines," *IEEE Trans. Ind. Electron.*, vol. 64, no. 3, pp. 2405–2414, Mar. 2017.
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Aldo Boglietti (M'04–SM'06–F'12) was born in Rome, Italy. He received the Laurea degree in electrical engineering from the Politecnico di Torino, Turin, Italy, in 1981.

He is currently a Full Professor at the Politecnico di Torino. He is the author of more than 200 papers in the fields of energetic problems in electrical machines and drives and in electrical machines thermal analysis.

Prof. Boglietti was the Chair of the Electrical Machines Committee of the IEEE Industry Applications Society from 2012 to 2013, and the Chair of the Electrical Machines Technical Committee of the IEEE Industrial Electronics Society from 2009 to 2010.

Andrea Cavagnino (M'04–SM'10) was born in Asti, Italy. He received the M.Sc. and Ph.D. degrees in electrical engineering from the Politecnico di Torino, Turin, Italy, in 1995 and 2000, respectively.

He is currently an Associate Professor in the Dipartimento Energia, Politecnico di Torino. He is the author or coauthor of more than 180 papers published in technical journals and conference proceedings. His research interests include electromagnetic design, thermal design, and energetic behavior of electrical machines.

Dr. Cavagnino is the Past Chair of the Electrical Machines Technical Committee of the IEEE Industrial Electronics Society and an Associate Editor of the IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS and the IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS. He is a Reviewer for several IEEE TRANSACTIONS and other international journals.

Andreas Krings (S'09–M'15) was born in Cologne, Germany. He received the Dipl.Ing. degree in electrical power engineering from RWTH Aachen University, Aachen, Germany, and the Ph.D. degree in electrical engineering from KTH Royal Institute of Technology, Stockholm, Sweden, in 2008 and 2014, respectively.

He is currently a Senior Scientist with the ABB Corporate Research Center, Västerås, Sweden. His research interests include losses in electrical machines and magnetic materials, as well as the electromagnetic and thermal design of electrical machines.

Dr. Krings is an Associate Editor of the IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS and a Reviewer for IEEE TRANSACTIONS and other international journals.