Optimization of Electric Machine Designs—Part II

THIS Special Section on "Optimization of Electrical Machine Designs" summarizes the state-of-the-art on the latest researches carried out on the topic, both in the academic and industrial environments. Basically, all the electrical machine topologies and optimization techniques have been discussed in this Section, suggesting to the readers interesting solutions of several optimization problems related with modern applications. The second part of the special section (the first one has been published in the December 2017 issue of the IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS) includes 20 papers from a total of 44 accepted contributions. The studies included in the Part II are categorized in Table I and are hereafter outlined to some extent in order to help the readers to quickly compare the main peculiarities of the mathematical approaches and the practical implementations. This second part of the "Special Section on Optimization of Electric Machine Designs" starts with the hot topic of the cost and efficiency optimization. In particular, item 1) in the Appendix approaches the problem for premium induction motors, using a multiphysical field collaborative optimization method based on genetic algorithm. The thermal distributions have been considered to meet the design requirements.

Item 2) in the Appendix shows how to optimize the fins on the housing of totally enclosed fan cooled electrical machines. The study is independent of the specific motor topology, and it is very useful to determine, depending on a large set of parameters, the best candidates for further CFD analyses. The possibility to simultaneously compute the fluid and heat flow in short time allows automatic evaluation of large numbers of possible designs.

The Part II paper categorization of this Special Section presents a second set of four papers focused on the permanent magnet synchronous machines, that is, Table I from items 3) to 6) in the Appendix, where it is possible to appreciate the variety of optimization algorithms used. In item 3) in the Appendix, a general methodology for multiobjective optimization, under multiple operating conditions, is proposed for selected fractional slot concentrated winding PMSMs. The computational time to get a solution for multiobjective problems has been reduced applying an objectives reduction algorithm. The impacts of multiple operating points on the design objectives have also been investigated, both from the sensitivity analysis and conflict analysis point of view.

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TABLE I
CATEGORIZATION OF THE WORKS INCLUDED IN PART TWO OF THE SPECIAL SECTION

Item	EM topology	Optimization algorithm	Multiple-Objective	FEM-based
1	IM	GA		√
2	TEFC EM	DE		√
3	PMSM	EA	√	
4	PMSM	DE		√
5	PMSM	GS	√	√
6	PMSM	HA		
7	PMSM+SyRM	GA	√	√
8	Line-start SyRM	HJA		
9	IPM	SSOS	√	√
10	IPM	PSO		√
11	IPM	DE		√
12	IPM	GB		
13	IPM	n.a.	√	√
14	FSM	GA	√	√
15	Linear FSM	GA	√	
16	Linear FSM	GA	√	√
17	Linear PMSM	DE	√	
18	Linear SRM	n.a.	√	√
19	Linear SRM	GS	√	√
20	Tubular PMSM	SNO		√

EM topology: Induction Machine (IM), Total Enclosed Fan Cooled (TEFC) Electrical Machine, Permanent Magnet Synchronous Machine (PMSM), Synchronous Reluctance Machine (SyRM), Interior Permanent Magnet machine (IPM), Flux Switching Machine (FSM), Switched Reluctance Machine (SRM).
Optimization Algorithm: Genetic Algorithm (GA), Differential Evolution (DE), Evolutionary Algorithm (EA), Grid Search (GS), Heuristic Algorithm (HA), Hooke-Jeeves algorithm (HJA), Sequential-Stage Optimization Strategy (SSOS), Particle Swarm Optimization (PSO), Gradient-based strategy (GB), Social Network Optimization (SNO).

Item 4) in the Appendix deals with the application-oriented robust design optimization method of PM motors. The target is not only to improve their performances but also to increase the manufacturing quality by reducing the production costs. In order to reduce the high computational effort required by the huge number of selected parameters, as well as to improve the optimization efficiency, a multilevel robust optimization method based on differential evolution algorithm has been used.

Item 5) in the Appendix describes the optimal design chain of a circular winding PMSM targeted to high torque density and low vibration. Four optimization objectives have been set for these purposes. Three different slot-pole combinations have been simultaneously considered in the optimization process, and a large-scale design-variable scanning was performed for all the motors. Imposing acceptance constraints on selected performance objectives, 12 designs were extracted by the Pareto frontier. The correlation between performance objectives and design variables has been examined by means of a multifactor regression approach.

Item 6) in the Appendix shows the optimization of a multiphase fractional-slot concentrated winding. By using a heuristic algorithm, the optimal winding configurations have been selected and subsequently investigated in term of their torque production capability. For this purpose, a dedicated "*winding performance*" index has been introduced by the authors.

As a "*bridge*" between the permanent magnet and the synchronous reluctance machines, item 7) in the Appendix proposes the integration of the two aforementioned motor topologies in the same electrical machine. The complexity of this electromechanical device is solved by the authors by applying multiobjective optimizations based on finite element analysis for the identification of the Pareto frontiers.

The group of papers from items 8) to 13) in the Appendix deals with the synchronous reluctance and interior permanent magnet machines. Item 8) in the Appendix describes the complete design stages for a single-phase line-start synchronous reluctance motor. The design optimization adopts the modified Hooke–Jeeves algorithm. The cost function takes into account machine materials, capacitor, energy loss capitalized cost, and some other specific penalties.

The optimal design of an IPM synchronous generator is presented in item 9) in the Appendix. The overall optimization strategy is defined as sequential-stage optimization strategy, and it is a combination of different algorithms and techniques. In particular, the authors used the Taguchi method to obtain, with a reduced effort, initial design solutions. Then, the optimal result is defined by using the surrogate assisted genetic algorithm.

Item 10) in the Appendix proposes a modified particle swarm optimization algorithm for optimal designs of an electrical machine (an IPM is considered as a study case). Compared with the conventional algorithm, the authors conclude that their approach requires fewer function calls, maintaining the same search quality. In particular, they quantify the reduction of the function calls from a minimum of 6.3% to a maximum of 44.4%, depending on the considered test function.

The focus of item 11) in the Appendix is on the reduction of computational efforts required for single-objective constrained optimizations of a traction IPM motor, under extensive use of finite element analyses. The basic idea is to immediately stop the simulations when a constraint is violated. Therefore, with respect to the conventional differential evaluation algorithm, the proposed one is able to manage inequality constraints.

Item 12) in the Appendix proves the existence of additional eddy current losses on the lateral plates used to retain the magnets of IPM motors. With the need to reduce these extra-losses, the authors performed a topology optimization of the retaining plates, assuming the plate volume as constraint. The objective function is targeted to minimize the shape complexity (maintaining the required stiffness) and maximizing the electrical resistance of the plates.

The last paper dealing with IPM motors, i.e., item 13) in the Appendix, investigates the optimal design of the motor-drive system. In particular, it is articulated that solely optimizing the electrical machine could follow fewer optimal solutions compared to a simultaneous optimization of the whole system. The proposed computer-aided design process analyses random samples in the design space. By means of suitable measures, it is decided if the new samples give new information. If not, the process is stopped, and the results are analyzed.

The constrained multiobjective design optimization for wound-field flux switching machines is described in item 14) in the Appendix. The Pareto optimal solutions have been obtained with nondominated sorting genetic algorithm, using a mix of finite element simulations and analytical formulation. The multiobjective problem is defined by the optimization of two different performance measures: i) the minimization of the active mass and ii) the minimization of the torque ripple, together with the power factor maximization.

Looking at Table I, from items 15) to 20) in the Appendix, the "Special Section on Optimization of Electric Machine Designs" ends with six papers related to linear/tubular electrical machines. Item 15) in the Appendix reports the optimal design of double-sided yokeless multitooth linear switched-flux PM machine. Analytical formulations of the permeance model have been initially used to select four optimal combinations of primary slots and secondary poles. After that, these four solutions are first optimized by a single-variable optimization. Then, a global optimization procedure with genetic algorithm is performed.

In item 16) in the Appendix, the human intervened genetic algorithm is tested to optimize a flux switching permanent magnet linear generator. The optimization objectives considered in the study are the maximization of electrical power output and the minimization of the steel core volume.

Item 17) in the Appendix presents the multiple-objective optimization of coreless-type permanent magnet linear synchronous motors. The global optimization adopts the differential evolution algorithm based on analytical formulations for the model, avoiding, in this way, the time-consuming finite element analyses. Based on these results, the authors further conclude that, for this specific case, there exists best concentrated winding combinations in the selected design domain.

Item 18) in the Appendix investigates the linear switched reluctance motor as valuable alternative for vertical linear propulsion application. In particular, a toroidal wound mover and a segmental stator are proposed to improve the copper utilization and flux carrying capability. The machine geometry is optimized from the active payload ratio and force ripples points of view. Analytical equations and finite element analyses were used for selecting the reasonable range of the parameters and for sensitivity evaluations.

Item 19) in the Appendix reports the size optimization of longitudinal-flux double-sided linear switched reluctance motor. The study considers both thermal and weight constraints, as well as duty cycles for the machine operating conditions. Finite element analyses were carried out for the magnetic propulsion force computation, while the applied thermal transient analyses were based on a simplified thermal network. For solving the optimization problem, a grid search algorithm has been used featuring a multivariable optimization chart devoted to miniaturizations and downsizing of the machine.

Finally, item 20) in the Appendix presents the optimization of electrical machines—tubular permanent magnet linear generator for the case of study—devoted to energy-harvesting purposes. In this study, the optimization problem is faced by using the social network optimization. This algorithm is a population-based algorithm, which has been developed in order to guarantee more effective and faster exploration of the solution domain with respect to traditional optimization techniques. The optimization objective is the maximization of the power harvested from road irregularities.

ANDREA CAVAGNINO, *Guest Editor*
Politecnico di Torino,
Turin 10129, Italy

GERD BRAMERDORFER, *Guest Editor*
Johannes Kepler University Linz
Linz 4040, Austria

JUAN A. TAPIA, *Guest Editor*
University of Concepcion
Concepcion 4070386, Chile

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APPENDIX
RELATED WORK

1) W. Li, P. Wang, D. Li, X. Zhang, J. Cao, and J. Li, "Multiphysical field collaborative optimization of premium induction motor based on GA," *IEEE Trans. Ind. Electron.*, vol. 65, no. 2, pp. 1704–1710, Feb. 2018.
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Andrea Cavagnino (M'04–SM'10) was born in Asti, Italy, in 1970. 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 a Full Professor with the Dipartimento Energia, the Politecnico di Torino. He has authored or coauthored more than 190 papers published in technical journals and conference proceedings. His research interests include electromagnetic design, thermal design, and energetic behavior of electrical machines.

Prof. Cavagnino is a Past Chair of the Electrical Machines Technical Committee of the IEEE Industrial Electronics Society and a past Associate Editor of the IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS. He is an Associate Editor of the IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS and a Reviewer for several IEEE TRANSACTIONS and other international journals. From 2011 to the present, he has been the Guest Editor of six Special Sections for the IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS.

Gerd Bramerdorfer (S'10–M'14) received the Ph.D. degree in electrical engineering, in 2014, from Johannes Kepler University Linz, Linz, Austria.

He is currently an Assistant Professor with the Johannes Kepler University Linz. Since 2007, he has been with the Department of Electrical Drives and Power Electronics, Johannes Kepler University Linz, where he is involved in research projects and holds classes in the field of electrical machines, actuators, and power electronics. His research interests comprise the design, modeling, and optimization of electric machines, as well as magnetic bearings and bearingless machines.

Dr. Bramerdorfer is a member of IEEE Industrial Electronics Society and its Electric Machines Technical Committee, as well as the IEEE Industry Applications Society. He constantly serves for the scientific community, e.g., as guest editor, track chair, and topic chair, by organizing special sessions, and as a reviewer for journals and conferences.

Juan A. Tapia (M'03) received the B.Sc. and M.Sc. degrees in electrical engineering from University of Concepcion, Concepcion, Chile, in 1991 and 1997, respectively, and the Ph.D. degree in electrical and computer engineering from University of Wisconsin, Madison, WI, USA, in 2002.

From 2010 to 2014, he was a FiDiPro Fellow with the Academy of Finland at Lappeenranta University of Technology, where he conducts research on permanent magnet machines with the LUT-Energia Group. He is currently an Associate Professor with the Department of Electrical Engineering, University of Concepcion. His research interests include electrical machines design, numerical methods for electromagnetic fields, digital signal processing-based electric machine control, and renewable energy.