Optimization of Electric Machine Designs—Part I

IN MORE and more competitive markets and challenging application areas, it is of primary importance to reduce as much as possible the time-to-market of new and innovative products. As expected, electrical machines follow this nonwritten rule, since they are the most used electromechanical components in all manufacturing sectors. As the electric machine is the backbone of any electric drive, maximizing their performance takes top priority. Advances and trends in mathematical modeling and computer simulation, together with the availability of sophisticated optimization techniques, have opened the way to a new approach for electrical machine design. The already-proven reliability of the today's optimization strategies allows speed up of the final product definition, reducing the prototyping needs for project validations, and minimizing development and manufacturing cost. The potentialities offered by the modern optimization techniques are grown of interest for industry year after year, giving the reason for their massive penetration into the design chain. Due to the intrinsic multiphysics nature of electrical machines, as well as the multiple requirements imposed on their characteristics (e.g., a high torque and power density, low noise, high reliability, low selling price, etc.), electrical engineers usually face complex multiobjective optimization problems. The vastness of the cases, both in terms of possible electromagnetic structures, materials properties, and specific applications, pushed the Guest Editors to propose this "Special Section on Optimization of Electric Machine Designs" to the Editors of the IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS.

This Special Section received strong interest and feedback from designers and researchers involved on the topic: interest that is proved by the initially submitted contributions (134) and the 44 papers published in Part I and Part II. These papers illustrate the current state of the art, latest advances, and future trends of electrical machines design by using optimization methodologies. The Guest Editors are pleased to briefly sum up the first 24 papers included in Part I of this Special Section.

For a quick overview of the manuscripts (also listed in the Appendix), see Table I, where the papers are sorted according to the machine topology and the used optimization algorithm. Table I itemizes whether the study is dealing with a multiobjective optimization technique and whether the electrical machine is modeled in the optimizer by means of the finite-element method (FEM) or surrogate models (e.g., analytical equations). Note that the multiobjective definition refers to the mathematical specification of the optimization problem. Thus, a single cost function of two or more weighted performance indices is considered as a single-objective optimization problem. On the other hand, a problem featuring at least two optimization objectives is defined as a multi-objective.

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

Item	EM topology	Optimization algorithm	Multiple objective	FEM based
1	IPM	GA		√
2	PM-assisted SyRM	DE	√	
3	Line-start SyRM	DE	√	√
4	SyRM	RSM	√	√
5	IPM	GS		
6	PMSM	PSO		√
7	PMSM (generator)	GA	√	
8	PMSM	GA	√	
9	PMSM	PSO		
10	PMSM (generator)	MSM		√
11	PMSM (generator)	SQP		
12	High-speed PMSM	DE		√
13	High-speed PMSM	n.a.		
14	Multiphase IM	GA	√	
15	IM	GA	√	
16	Dual-stator IM	GSE	√	
17	High-speed IM	DE	√	
18	Multiphase SRM	GS	√	√
19	Hybrid FSM	PSO	√	√
20	dc-excited FSM	GS		
21	Dual-port FSM	TS		√
22	MGM	TS	√	√
23	MG	DE	√	
24	MGM	GA	√	√

EM Topology: Synchronous reluctance machine (SyRM), interior permanent magnet machine (IPM), permanent magnet synchronous machine (PMSM), induction machine (IM), switched reluctance machine (SRM), flux-switching machine (FSM), magnetic-geared motor (MGM), and magnetic gear (MG).
Optimization Algorithm: Genetic algorithm (GA), differential evolution (DE), response surface methodology (RSM), grid search (GS), particle swarm optimization (PSO), multidimensional secant method (MSM), sequential quadratic programming (SQP), global search (GSE), Tabu search (TS).

Considering the optimization algorithm characterization, it was defined in terms of general mathematical methods and not in accordance with any specific algorithm implementation.

As expected, the researchers mainly focused their attention to nonconventional electrical machines, for which the sizing design schemes are not so well consolidated as for the more traditional solutions. However, more traditional machine topologies, as the induction ones, can also benefit from optimization techniques, in particular, when challenging applications are under investigation.

The first part of the Special Section opened with five papers focused on interior permanent magnets (IPMs) and synchronous reluctance machines (SyRMs). It is unquestionable that for these complex rotor geometries, the adoption of optimization techniques can lead to well-quantifiable positive results for the shape and position of the flux barriers. In particular, item 1) in the Appendix presents the adoption of a coarse mesh of the FEM geometrical models of IPM machines. Since the target is the design of motors with large high-efficiency operation regions, the proposed combination of genetic algorithm (GA) and coarse meshes has proven to be a valuable solution to accelerate the overall optimization process.

Item 2) in the Appendix deals with the differential evolution (DE) based optimization of five-phase, external rotor, permanent magnet (PM) assisted SyRM. The optimal designs are focused on the flux barrier number and their shaping to include both rare-earth and ferrite PMs. As a result of the optimization and the prototyping steps, the pros and cons of the adoption of the two PM types have been quantified for the considered application.

Item 3) in the Appendix shows the use of a DE-based stochastic optimization to evaluate the parameters that maximize the synchronous torque. A reduced set of only five parameters has been considered; due to machine nonlinearities, the optimization objectives are evaluated by means of FEM model. Measurements on a real prototype well match with the optimization results.

The interesting application of the low-speed flywheel energy storage system is discussed in item 4) in the Appendix. The study proposes the optimal design of SyRM, based on the response surface methodology and 2-D FEM models, as an affordable alternative to induction machines (IMs). Sensitivity analysis and the design variable screening devoted to the computational effort reduction are presented together with experimental activity.

In item 5) in the Appendix, it is proven that an "*assistant*" IPM rotor can be properly optimized, manufactured, and mounted in IPM machines in order to improve the accuracy of the measured position by using low resolution hall sensors. In this way, a performance optimization of the IPMs control can be easily obtained.

The second set of electrical machines presented in Part I of this Special Section is constituted by eight papers related to the permanent magnet synchronous machines (PMSMs), as summarized in Table I from items 6)–13) in the Appendix. Looking to that, it is possible to appreciate the variety of the applications, as well as the today's optimization algorithms for such machines. The first paper dealing with PMSM, i.e., item 6) in the Appendix, is focused on the optimization of small machines for high volume mass production. From the optimization scenario viewpoint, different aspects for reducing the complexity of the multidomain optimization are considered, and potential sources of errors are discussed. Prototypes have been produced and tested, validating the calculations.

Item 7) in the Appendix describes an analytical model of a PM synchronous generator suitable for mixed-integer constrained multiobjective optimization. In the study, six objective functions have been considered. This approach is also useful for teaching purposes of electrical machines

Item 8) in the Appendix reports design optimization aspects specifically focused on short-term duty cycle electrical machine operating in extreme environments conditions (both for high temperature and altitudes of aerospace applications). A nondominated sorting genetic algorithm (NSGA-II) based on both surrogate and FEM models is used to optimize efficiencies and power density, with relatively low computation time.

In item 9) in the Appendix, an analytical method is proposed in order to optimize the cogging-torque waveform to improve the operation of two excitations electromechanical energy harvester. The analytical model is based on equivalent current sheets of the PMs, while the optimization procedure is a modified particle swarm optimization (PSO) algorithm. The study includes FEM validations of the proposed approach. Item 10) in the Appendix presents further research about the optimization of the cogging torque in PMSMs. In this approach, the cogging torque is obtained by shaping the stator geometry of the machine. An application example constituted by an out-runner PM generator integrated in an electromechanical energy harvester is presented for validation purposes.

Item 11) in the Appendix deals with the multiphysics design optimization of a PM synchronous generator. The optimization objective is the cost reduction comprising the static power converter presence. Sequential quadratic programming is used as the optimization algorithm to get the desired multiphysics approach.

Item 12) in the Appendix proposes the use of a hybrid DE algorithm and a particular memory mechanism for the optimal design of a 22 000 r/min PMSM. The motor is developed as a propulsion system of an electric vehicle, and the proposed optimization procedure has been experimentally validated by prototype testing.

Also, the last paper of this group focused on PMSMs, as item 13) in the Appendix deals with a high-speed machine for electric vehicle applications. Taking into account the urban dynamometer driving schedule, a 1-D analytical motor model and a deterministic optimization approach have been adopted by the authors to solve the machine sizing.

As stated previously, Part I of this Special Section also includes research on IMs related to cost and efficiency optimization scenarios and innovative designs. As remarked in Table I, these four papers approach the optimization problem using different algorithms, but all of them adopt multiobjective solutions and surrogate models. This peculiarity is probably due to already proved reliability of the IM analytical sizing schemes.

Item 14) in the Appendix presents the multiobjective optimization of five-phase IMs. The optimal designs are targeted to cost reduction and efficiency increase by using an NSGA-II. As a result of the tradeoff among more than one objective, 14 design variables simultaneously account for the optimization process. FEM analyses of three optimized machines have been included for validation purposes. Item 15) in the Appendix deeply describes how to optimize electrical machine designs (the IMs in the case of the study) by using GA, adding great educational value to the work. This optimization tool represents one of the common solutions when highly nonlinear equation sets describe the mathematical model. Among various constraints, the impact of the rotor cage material (aluminum or copper) on the optimized design have been investigated and validated through tests on laboratory prototypes.

Item 16) in the Appendix shows an attractive brushless double-stator doubly fed IM to be employed in highly reliable wind turbine systems. The proposed electromagnetic structure overcomes some of the drawbacks of the existing brushless doubly fed topologies. Moreover, the design optimization approach is based on the global search (GSE) algorithm and allows for torque and power density maximization of this special machine.

The optimization effectiveness is proved both by FEM models and experimental results.

Item 17) in the Appendix describes the optimization and construction of a 350 kW, 15 000 r/min induction motor, with a slitted solid rotor supported by active magnetic bearings (AMBs). The optimization study is carried out at system level since the mutual influence between the high-speed machine and the AMBs is simultaneously considered when investigating the overall performance. For this reason, the dimensions of the AMB are selected as optimization parameters. The objectives of the optimization, based on a multiobjective GA, cover the electrical machine performance and the rotor dynamics.

Part I of this Special Section ends with seven papers related to complex electromagnetic structures, namely, the switched reluctance motors, flux-switching (or other equivalent) machines, dual-port or magnetic-geared motors (MGMs), and magnetic gears (MGs). These innovative electrical machine topologies definitively benefit from the modern optimization techniques.

Item 18) in the Appendix describes a switched reluctance motor having a stator winding that can be connected both in three- and six-phase mode. A GSE algorithm and FEM models have been adopted with the aim to minimize torque ripple and maximize torque per ampere of the motor. The optimization parameters are arcs of stator and rotor poles. The measured results show good consistency with the simulation ones.

Item 19) in the Appendix presents the concept of a hybrid-excited flux-switching machine for aircraft dc power generation. Due to the complexity of the working principle of this electromagnetic structure, which becomes more intricate by the presence of the dc rectifier, the magneto-static FEM models are used in the optimization process featuring a multiobjective PSO algorithm. The study concludes that the optimized designs having high power density are definitively possible for this aircraft generator.

Single-phase dc-excited flux-switching machines for low-cost and high-speed appliance applications are the subject of item 20) in the Appendix. A new structure has been investigated and optimized to improve the initial torque at some rotor positions. The grid search optimization algorithm has been used for this investigation. The research shows that the optimized machine starts from any rotor position with an initial torque greater than 50% of the rated output torque. However, with respect to comparable counterparts, a slight detriment of the rated torque has been observed.

Item 21) in the Appendix first presents the general theory of flux-modulated electric machines, and subsequently, a novel doubly fed dual-stator motor is discussed. An improved Tabu search (TS) algorithm was adopted to determine the optimal values of the selected motor dimensions. In this study, the optimization objectives were the maximization of the output torque and efficiency. The researchers validated their optimized design solutions by testing a real prototype.

Item 22) in the Appendix systematically studies the dual-PM excited machines topology, also known as MGMs. The peculiarity of these electrical machines is to have PM excitations both on the stator and on the rotor. Four dual-PM excited machine concepts are comparatively analyzed and optimized using an improved TS algorithm coupled with FEM. For verification purposes, a stator multitooth-PM machine prototype has been manufactured and tested, confirming the feasibility of the electromagnetic optimized design.

Item 23) in the Appendix deals with the optimization procedure of well-known coaxial MGs. In particular, thermal, mechanical, and magnetic constraints have been considered in a suitable optimization process based on a flexible constrained DE algorithm; the Pareto fronts are presented as the results of the multiobjectives analyses. Looking at the gained results, this paper represents valuable research into developments of specifically adjusted DE-based algorithms.

Like items 22) and 24) in the Appendix, a valuable case study of magnetic-geared machines is considered. In particular, item 24) in the Appendix presents a new magnetic-geared pole-changing hybrid excitation machine. This solution can provide high torque density and improved flux-weakening capability. The optimal candidates are designed considering FEM models and a GA. The prototype has been tested, and the experimental results definitively prove the feasibility of this new hybrid solution, as well as the optimization process predictions.

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APPENDIX
RELATED WORK

1) T. Nakata, M. Sanada, S. Morimoto, and Y. Inoue, "Automatic design of IPMSMs using a genetic algorithm combined with the coarse-mesh finite element method for enlarging the high-efficiency operation area," *IEEE Trans. Ind. Electron.*, vol. 64, no. 12, pp. 9721–9728, Dec. 2017.
2) S. S. R. Bonthu, A. Arafat, and S. Choi, "Comparisons of rare-earth and rare-earth free external rotor permanent magnet assisted synchronous reluctance motors," *IEEE Trans. Ind. Electron.*, vol. 64, no. 12, pp. 9729–9738, Dec. 2017.
3) D. Mingardi and N. Bianchi, "Line start PM-assisted synchronous motor design, optimization and tests," *IEEE Trans. Ind. Electron.*, vol. 64, no. 12, pp. 9739–9747, Dec. 2017.

4) H. Azizi Moghaddam, A. Vahedi, and S. Hasan Ebrahimi, "Design optimization of transversely laminated synchronous reluctance machine for flywheel energy storage system using response surface methodology," *IEEE Trans. Ind. Electron.*, vol. 64, no. 12, pp. 9748–9757, Dec. 2017.
5) H.-S. Seol, J. S. Lim, D.-W. Kan, J. S. Park, and J. Lee, "Optimal design strategy for improved operation of IPM BLDC motors with low resolution Hall sensors," *IEEE Trans. Ind. Electron.*, vol. 64, no. 12, pp. 9758–9766, Dec. 2017.
6) A.-C. Pop, J. J. C. Gyselinc, D. E. Pint, and I. Vintiloiu, "Optimization of low-power brushless PM-machines for automotive applications with focus on high volume mass production," *IEEE Trans. Ind. Electron.*, vol. 64, no. 12, pp. 9767–9775, Dec. 2017.
7) K. Sindhya, A. Manninen, K. Miettinen, and J. Pippuri, "Design of a permanent magnet synchronous generator using interactive multiobjective optimization," *IEEE Trans. Ind. Electron.*, vol. 64, no. 12, pp. 9776–9783, Dec. 2017.
8) P. Arumugam, E. Amankwah, A. Walker, and C. Gerada, "Design optimization of a short term duty electrical machine for extreme environment," *IEEE Trans. Ind. Electron.*, vol. 64, no. 12, pp. 9784–9794, Dec. 2017.
9) Z. Q. Xue, H. Li, Y. Zhou, N. Ren, and W. Wen, "Analytical prediction and optimization of cogging torque in surface-mounted permanent magnet machines with modified particle swarm optimization," *IEEE Trans. Ind. Electron.*, vol. 64, no. 12, pp. 9795–9805, Dec. 2017.
10) M. Flankl, A. Tüysüz, and J. W. Kolar, "Cogging torque shape optimization of an integrated generator for electromechanical energy harvesting," *IEEE Trans. Ind. Electron.*, vol. 64, no. 12, pp. 9806–9814, Dec. 2017.
11) T. de Paula Machado Bazzo, J. F. Kölzer, R. Carlson, F. Wurtz, and L. Gerbaud, "Multiphysics design optimization of a permanent magnet synchronous generator," *IEEE Trans. Ind. Electron.*, vol. 64, no. 12, pp. 9815–9823, Dec. 2017.
12) D. Fodorean, L. Idoumghar, M. Brevilliers, P. Minciunescu, and C. Irimia, "Hybrid differential evolution algorithm employed for the optimum design of a high-speed PMSM used for EV propulsion," *IEEE Trans. Ind. Electron.*, vol. 64, no. 12, pp. 9824–9833, Dec. 2017.
13) L. Dang, N. Bernard, N. Bracikowski, and G. Berthiau, "Design optimization with flux-weakening of High-Speed PMSM for electrical vehicle considering the driving cycle," *IEEE Trans. Ind. Electron.*, vol. 64, no. 12, pp. 9834–9843, Dec. 2017.
14) L. A. Pereira, S. Haffner, G. Nicol, and T. F. Dias, "Multiobjective optimization of five-phase induction machines based on NSGA-II," *IEEE Trans. Ind. Electron.*, vol. 64, no. 12, pp. 9844–9853, Dec. 2017.
15) S. Mallik *et al.*, "Efficiency and cost optimized design of an induction motor using genetic algorithm," *IEEE Trans. Ind. Electron.*, vol. 64, no. 12, pp. 9854–9863, Dec. 2017.
16) P. Han, M. Cheng, Y. Jiang, and Z. Chen, "Torque/power density optimization of a dual-stator brushless doubly-fed induction generator for wind power application," *IEEE Trans. Ind. Electron.*, vol. 64, no. 12, pp. 9864–9875, Dec. 2017.
17) A. Smirnov, N. Uzhegov, T. Sillanpää, J. Pyrhonen, and O. P. Pyrhönen, "High-speed electrical machine with active magnetic bearing system optimization," *IEEE Trans. Ind. Electron.*, vol. 64, no. 12, pp. 9876–9885, Dec. 2017.
18) Y. Hu, W. Ding, T. Wang, S. Li, and S. Yang, "Investigation on a multi-mode switched reluctance motor: design, optimization, electromagnetic analysis and experiment," *IEEE Trans. Ind. Electron.*, vol. 64, no. 12, pp. 9886–9895, Dec. 2017.
19) A. Nasr, S. Hlioui, M. Gabsi, M. Mairie, and D. Lalevee, "Design optimization of a hybrid-excited flux-switching machine for aircraft safe dc power generation using a diode bridge rectifier," *IEEE Trans. Ind. Electron.*, vol. 64, no. 12, pp. 9896–9904, Dec. 2017.
20) Z.-C. You, S.-M. Yang, C.-W. Yu, Y.-H. Lee, and S.-C. Yang, "Design of a high starting torque single-phase dc-excited flux switching machine," *IEEE Trans. Ind. Electron.*, vol. 64, no. 12, pp. 9905–9913, Dec. 2017.
21) Y. Chen, W. Fu, and X. Weng, "A concept of general flux-modulated electric machines based on a unified theory and its application to developing a novel doubly-fed dual-stator motor," *IEEE Trans. Ind. Electron.*, vol. 64, no. 12, pp. 9914–9923, Dec. 2017.
22) Q. Wang, S. Niu, and L. Yang, "Design optimization and comparative study of novel dual-PM excited machines," *IEEE Trans. Ind. Electron.*, vol. 64, no. 12, pp. 9924–9933, Dec. 2017.
23) M. Filippini and P. Alotto, "Coaxial magnetic gears design and optimization," *IEEE Trans. Ind. Electron.*, vol. 64, no. 12, pp. 9934–9942, Dec. 2017.
24) X. Zhao and S. Niu, "Design and optimization of a new magnetic-geared pole-changing hybrid excitation machine," *IEEE Trans. Ind. Electron.*, vol. 64, no. 12, pp. 9943–9953, Dec. 2017.

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