Emerging Multiport Electrical Machines and Systems—Part I

DISTINCT from the conventional electric machines with only one electrical and one mechanical port, electrical machines featuring multiple electrical/mechanical ports provide a highly efficient, compact, and flexible manner to convert and/or transfer energies among different ports. The additional electrical ports can be used to increase the power rating, enhance the fault-tolerant capability, and control the motion/power flow. The extended mechanical ports are commonly used to decouple the motion, speeds, and/or torque. The multiport feature opens a new era in traditional electric machinery and provides an effective approach to the application-oriented design of new energy conversion systems. Though relatively young, they have experienced rapid developments in terms of available topologies, analysis and design techniques, and control strategies in a wide range of applications, such as electric vehicle/hybrid electric vehicles, high power industrial drives, rail transportation, wind turbine systems, ac–dc microgrids, more electric aircrafts, and so on, during the past decades.

Multiport electrical machines include, but are not limited to, dual-electrical-port single-mechanical-port machines, single-electrical-port dual-mechanical-port machines, dual-electrical-port dual-mechanical-port machines, multi-electrical-port machines and electric actuators with multiple degrees of freedom (DOF) of motion. Extended configurations, like dual-motor drives and n-DOF actuators, are categorized into the family of multiport electrical systems.

The main objective of the Special Section on "Emerging Multiport Electrical Machines and Systems" of the IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS is to provide an opportunity for researchers and engineers from academia and/or industry, to exchange their enlightening ideas on analysis, design, and control of such new machine breeds, to identify the challenges in practical applications and to present the state-of-the-art solutions. In this regard, the Special Section has been very attractive for the scientific community that has submitted a large number of manuscripts covering a broad spectrum of topics. Indeed, 71 manuscripts have been received with only about 40% being accepted for publication, and the hottest topics of the ongoing research and development on the Special Section subject have been dealt with. More specifically, the topics range from design and optimization methods relevant to the multiport feature, novel topologies with comparative evaluation of torque/power density and efficiency, new methods for integrated modeling and analysis, advanced control strategies considering practical deployment, and performance evaluation in various application scenarios. The accepted papers are published in Part I and Part II. For convenience of classification, the 15 papers included in Part I have been grouped as listed in Table I.

TABLE I
CLASSIFICATION OF PAPERS INCLUDED IN PART I THE SPECIAL SECTION

Category	Items
Design and optimization methods considering the multiport feature	item 2) in the Appendix
New topologies with competitive torque/power density/efficiency	items 3) and 4) in the Appendix
New methods for integrated modeling, analysis, and control	item 5) in the Appendix
Advanced control strategies considering practical deployment	items 6)–12) in the Appendix
Performance evaluation in special application scenarios	items 13)–15) in the Appendix
New applications of multiport electrical machines and systems	item 16) in the Appendix

To facilitate an in-depth survey of the published papers, their contributions are examined below by highlighting the most noteworthy investigations and findings.

In item 1) in the Appendix, written by the guest editors of this Special Section, a comprehensive overview of the existing multiport topologies, from fundamental characteristics to advanced modeling, analysis, and control, is presented, with emphasis on the brushless doubly fed machines for highly reliable wind turbines and the power split devices for hybrid electric vehicles. A qualitative approach is mainly adopted, but efforts are made to quantitatively highlight the electromagnetic and control performance of the topologies. Research challenges are identified, and future trends are discussed.

In item 2) in the Appendix, a new multiport magnetic-planetary-gear permanent magnet (MPG-PM) machine is proposed by incorporating the new concept of the noncontact MPG into a PM brushless machine. To achieve flexible combination and split of the power and torque among different electrical or mechanical ports in the machine, a multiobjective optimization design method considering multioperational modes is proposed and investigated. In order to obtain the high optimization design efficiency, the whole optimization procedure is divided into three steps based on various driving modes. In each step, the multiobjective genetic algorithm, response surface method, and direct screening method are utilized, respectively.

In item 3) in the Appendix, a segmented-rotor high temperature superconducting (HTS) flux-switching generator with dual

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electrical ports for offshore wind power generation is presented. Since both the armature and field windings are placed in the stator, the stationary seal of the cryogenic cooling system can be realized. A new racetrack-shaped Dewar with a vacuum-sandwich was proposed and fabricated, to accommodate and cool the HTS coils. Based on this racetrack-shaped Dewar, a cryogenic cooling system of the generator was built to secure the superconducting properties of HTS wires.

In item 4) in the Appendix, a novel parallel-hybrid-excited vernier reluctance machine with improved torque density and enhanced bidirectional field regulation capacity is proposed. By introducing an auxiliary PM excitation, to make full use of the redundant airgap harmonics of the single-layer concentrated armature winding, the torque density is boosted. In addition, this auxiliary stator-slot PM excitation produces a flux return path parallel to that of the dc excitation and the two excitation sources interact with each other by different airgap field harmonics, yielding an effective bidirectional field regulation.

In item 5) in the Appendix, a general modeling technique based on a four-dimensional (4-D) loop-up table is proposed for a triple redundant 3×3-phase PM-assisted synchronous reluctance machine. The magnetomotive force (MMF) of the machine is divided into three parts, each associated with one 3-phase set. The MMF of each 3-phase set can be described by four variables: d- and q-axis components of the currents, the rotor angle, and an MMF offset component, which implicates the mutual coupling between three 3-phase sets. As a result, the complete machine behavior in all operating conditions can be predicted by 4-D tables storing the flux linkage and torque information. Finite-element (FE) analysis for one 3-phase set is used to construct the 4-D tables to take into account the magnetic saturation. The proposed model has a high fidelity and is capable of representing healthy and fault operations, including unequal current operation in three 3-phase sets, and offers great flexibility for performance assessment, post-fault control and fault detection.

In item 6) in the Appendix, a simplified model predictive torque control for an asymmetrical dual three-phase PM synchronous motor (PMSM) is presented. By preselecting the appropriate voltage vectors in α-β and x-y subspace according to a flux position and torque deviation based switching table, the proposed method not only greatly reduces the computation burden but also effectively suppresses the undesired harmonic currents.

In item 7) in the Appendix, an adaptive sliding mode (ASM) fault tolerant coordination control is proposed by combining the ASM control and the fault tolerant control allocation to address the multimotor coordinate operation, against the actuator faults in the 4-wheel independent drive system. A new vehicle dynamic model with driving motor fault is set up. In the control layer, an adaptive variable exponential reaching law is used in the ASM to alleviate the chattering and improve the reaching speed, precision, and robustness. The fault tolerant control allocation based on the quadratic programming is then designed to properly coordinate the four in-wheel motors in the presence of the motor fault.

In item 8) in the Appendix, a predictive direct torque control strategy for torque and stator flux regulations of a two-PMSM series-connection system considering winding faults is proposed. The optimal voltage vector is selected to minimize the errors of torque, stator flux, and zero-sequence current. To achieve continuous torque control during an open-phase fault, the open-phase winding is taken into account in the prediction of the stator flux and the construction of inverter voltage vectors in the open-phase control strategy. Reduced ripples in steady-state torque and stator flux of the series-connected drive system are demonstrated, and the drive system proves to be able to operate without interruption from healthy to fault operation.

In item 9) in the Appendix, a novel fault-tolerant scheme is proposed for an open-winding linear PM vernier motor, fed by a floating-capacitor bridge dual-inverter structure to achieve continuous operation in case of the breakdown of one bridge arm. The unity power factor operation is considered in this fault-tolerant control, where the main inverter is only in charge of the active power and all the reactive components are compensated by the capacitor inverter to solve the voltage limit problem.

In item 10) in the Appendix, an optimization method for determination of the injected third-harmonic current is proposed for a five-phase dual-stator winding induction generator. By smoothing the flat top of the airgap flux density waveform, the iron core is better utilized and the power density is improved. The detailed implementation and experimental results based on the control-winding flux oriented control, under different loading conditions, are presented to verify the validity of the proposed optimization method.

In item 11) in the Appendix, a new control strategy to improve the output voltage quality of a dual-stator brushless doubly fed induction generator (BDFIG) in stand-alone operation with non-ideal loads is presented. The control target is to eliminate the unbalanced, fifth and seventh voltage harmonics, so that a sinusoidal voltage can be obtained at the point of common coupling. Considering the fact that both dc and ac components appear in the current reference of control winding, a proportional-integral dual frequency resonance current regulator is used to achieve satisfactory steady-state and dynamic performance.

In item 12) in the Appendix, a super-twisting sliding mode direct power control (SSM-DPC) strategy for the BDFIG is proposed. The SSM-DPC strategy controls active and reactive power directly, without the need of a phase-locked loop. The achieved transient response is similar to the DPC and its steady-state performance is just the same as with vector control. The proposed controller is robust to uncertainties in parameter variations and has a constant converter switching frequency by using space vector modulation. Simulations of a 2-MW BDFIG and experimental results of a 3 kW scaled-down prototype are provided and compared with those of the integral-sliding mode and DPC to validate the effectiveness, correctness, and the robustness of the proposed strategy.

In item 13) in the Appendix, a comprehensive comparison of the dual-three-phase hybrid-excited flux-switching machines and their PM counterparts based on the general airgap field modulation theory is presented, revealing the underlying theoretical mechanism that causes the differences in electromagnetic behavior of the six flux-switching machine topologies.

In item 14) in the Appendix, a comparative study is conducted between the switched flux memory machines with

single-stator and dual-stator structures in terms of flux regulation, torque characteristic, demagnetization withstand capability, flux-weakening performance, losses, and efficiency, showing the superiority of the dual-stator switched flux memory machines.

In item 15) in the Appendix, a brushless electrically excited synchronous reluctance generator is fully presented from the fundamental operating principle, FE-based design, and optimization to experimental tests under different load conditions.

In item 16) in the Appendix, a spherical-motor-based motion platform (SMP) is presented to provide a high performance nozzle-substrate negotiation in conformal printing of curved electronics. Unlike conventional motion systems using serially/parallel mechanisms for multi-DOF rotations, a ball-joint-like spherical motor that can realize continuous 3-DOF rotations in one joint is designed to meet the special needs of conformal printing process. Both the kinematic and dynamic models of the SMP are developed and a prototype has been developed to demonstrate the improved negotiation capability of the SMP.

Overall, we feel extremely delighted and privileged to have run the Special Section on "Emerging Multiport Electrical Machines and Systems" in the IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS. We are also confident that this Special Section will contribute to the advancements of research works and applications on multiport electrical machines and systems, and more importantly, will stimulate new exploration endeavors in an area that is likely to see a further increase of importance in forthcoming years.

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APPENDIX
RELATED WORK

1) M. Cheng, P. Han, G. Buja, and G. M. Jovanović, "Emerging multiport electrical machines and systems: Past developments, current challenges, and future prospects," *IEEE Trans. Ind. Electron.*, vol. 65, no. 7, pp. 5422–5435, Jul. 2018.
2) X. Zhu, Z. Xiang, L. Quan, Y. Chen, and L. Mo, "Multimode optimization research on a multiport magnetic planetary gear permanent magnet machine for hybrid electric vehicles," *IEEE Trans. Ind. Electron.*, vol. 65, no. 11, pp. 9035–9046, Nov. 2018.
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12) R. Sadeghi, S. M. Madani, M. Ataei, M. R. Kashkooli, and S. Ademi, "Super-twisting sliding mode direct power control of brushless doubly fed induction generator," *IEEE Trans. Ind. Electron*., vol. 65, no. 11, pp. 9147–9156, Nov. 2018.
13) G. Zhang, W. Hua, and P. Han, "Quantitative evaluation of the topologies and electromagnetic performances of dual-three-phase flux-switching machines," *IEEE Trans. Ind. Electron*., vol. 65, no. 11, pp. 9157–9167, Nov. 2018.
14) H. Yang, Z. Q. Zhu, H. Lin, and S. Lyu, "Comparative study of hybrid PM memory machines having single- and dual-stator configurations," *IEEE Trans. Ind. Electron*., vol. 65, no. 11, pp. 9168–9178, Nov. 2018.
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