Design and Control for Linear Machines, Drives, and MAGLEVs—Part I

ROTATING electric machines have existed for more than 150 years. Their linear counterpart, called linear electric (electromagnetic) machines (LEMs), were introduced at the turn of the last century. They have been conceived to convert electrical energy into mechanical energy (or vice versa) as a direct linear motion through electromagnetic forces. LEMs are reversible devices, meaning that they can work as both motors and generators. Although feasible, linear alternators are currently explored for limited applications (e.g., Stirling motor). On the contrary, linear motors or actuators are electromagnetic devices capable of producing direct (without any link or interposition) linear motions of the following types: in a unique direction, short-stroke motion, oscillatory motion, and step-by-step motion. Correspondingly, exactly as in the rotating counterpart, different types of linear motors have been devised: linear synchronous motors (LSMs) in its versions with excitation winding, with permanent magnets (PMs) LSMs or without both (linear reluctance motor = LRM), linear induction motors (LIMs), and linear stepper motors.

The first industrial applications of LEMs date back the beginning of last century. In 1937, Kemper in Germany proposed a magnetically levitated linear motor propelled vehicle. In 1945, Electropult in the USA developed an LIM to assist the takeoff of aircraft from aircraft carriers. Despite their early introduction, studies on LEMs basically stopped until the 1960s, when a resurgence of their study occurred. During the period from 1970 to1980, there was an extraordinary effort to develop full-scale people movers propelled by linear induction or synchronous motors, either wheeled or with magnetic [magnetically levitated vehicle (MAGLEV)] suspension, especially in Germany, Japan, USA, Canada, U.K., and Romania. Today, vehicle people movers with LIMs have been installed and work in large international airports such as Chicago, Dallas/Fort Worth, Atlanta, Toronto, Vancouver, Tokyo, and Birmingham.

In general, typical industrial applications of LEMs are as follows.

1) MAGLEVs (see Shanghai Transrapid).
2) Urban people movers (see Dallas/Forth Worth's Airline Commuter).
3) Vessel rudders, bow thrusters.
4) Linear oscillatory PM motor-driven refrigerators/compressors.
5) Espresso cafe steamer drives.
6) Digital camera zoomers.
7) Clean room industrial transporters.
8) Linear electric generators for deep space missions or for wave energy conversion.
9) Hotel door locker solenoids.
10) Electric power switch solenoids.
11) Microphones and loudspeakers in cellular phones.

LEMs are characterized by the following features:

1) Low initial cost (especially in small excursion applications).
2) High reliability.
3) Low energy consumption per job done.
4) Adhesion-free propulsion (lighter vehicles: lower Wh/passenger/km).
5) Better position tracking (no backlash) in industrial positioning.

One major difference between a linear and a rotating motor is that the linear motor presents a beginning and an end, in the direction of the motion, whereas the rotating one does not.

Such a characteristic produces so-called end effects, which negatively influence the performance of the linear motor in the electromechanical conversion (sometimes such effects can be considered negligible, especially at high speeds). Another major difference between rotating and linear motors is that the latter present very large air-gaps, as such effect is inherent to their construction. A further difference is that most LEMs present a secondary, which is invariably wider than the core of the primary. Such a feature results in the presence of transverse edge effects. All these peculiarities of LEMs make their design certainly more difficult, calling for specific design criteria, their modeling more complex, calling for specific models accounting for both the end and transversal edge effects, and the controllability of their electromechanical variables (e.g., magnetic flux, thrust, and speed) poorer, calling for specific control techniques, both linear and nonlinear ones. All these issues still have not been successfully treated in the scientific literature, which is the basis of this "Special Section on Design and Control for Linear Machines, Drives, and MAGLEVs" of the IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS.

All the accepted papers for this Special Section will be published in different issues of the journal. In this issue, the first 18 papers are presented. The subjects of these papers embrace all the subjects of interest of the scientific community related to LEMs, ranging from innovative procedures for the optimal design of such machines, to their analysis with finite elements, to advanced control techniques, suitably devised for specific applications.

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Item 1) in the Appendix, written by the guest editors of this Special Section, attempts an overview on recent progress of LEMs, from innovative topologies to advanced modeling, design, and control, with case studies and examples related to specific industrial applications from people movers to small compressors, solenoids, speakers, and microphones.

As for the design methodologies, item 2) in the Appendix studies several PM configurations employed to realize the magnetic screw and proposes a new structure, well-approximating the helical magnetic poles. Item 3) in the Appendix presents a new design of flux-switching PM linear generators in which the translator has been clipped off and split into two separate portions to minimize its weight. Item 4) in the Appendix proposes one novel stator-magnet moving-iron transversal-flux linear machine, with magnets inserted into the stator yoke (rather than mounted on stator poles) and a mover composed of iron core only, which has merits of lower fabrication cost and weight, much higher reliability, thrust density, material utilization ratio, etc. Item 5) in the Appendix deals with the design of a transverse flux linear motor using the superconductor aluminum hybrid as the secondary, to explore the potentials of integrating the propulsion with the levitation and the guidance. Item 6) in the Appendix proposes a new design method for superconducting linear motor (SLM), adopting stacks of second generation superconducting tapes, responsible for replacing high-temperature superconductor bulks. Item 7) in the Appendix proposes a modular flux-reversal linear generator for low-speed reciprocating power generation adopting a short-primary and a long-secondary structure.

As for the control techniques, item 8) in the Appendix treats a robust cooperative positioning control of networked linear switched reluctance machines with network-induced sensor-to-controller and controller-to-actuator time delays. Item 9) in the Appendix proposes an adaptive robust control algorithm applied to dual-linear-motor-driven gantry systems to obtain a robust performance in the presence of both parametric uncertainties and uncertain nonlinearities. Item 10) in the Appendix deals with the 5-DOF control of an electrodynamic Maglev suspension with active control of the levitation coil. Item 11) in the Appendix presents a methodology for the design and analysis of a magnetic levitation hyperloop system, adopting PMs and electromagnets to levitate, propel, and control a pod. Item 12) in the Appendix deals with a new fault-tolerant direct thrust force control of a dual inverter fed open-end winding linear vernier PM motor. Item 13) in the Appendix deals with a position measurement method of linear motor movers based on machine vision, aiming at the detection of the linear motor mover position on the basis of an image processing algorithm and a phase correlation algorithm. Item 14) in the Appendix presents a new control method to suppress current harmonics for a PM synchronous linear motor SLM that is applied in the microsecond laser cutting system.

As for the modeling, item 15) in the Appendix, starting from the analysis of the longitudinal distribution of the air-gap flux density and its relationship with the slip, develops an advanced equivalent circuit model for the LIM.

As for the analysis techniques, item 16) in the Appendix proposes a methodology for the closed-loop identification problem of the space-periodic force ripple in PM linear synchronous motor systems. Item 17) in the Appendix faces a methodology for reducing the influence of the transverse force on the stability of the vehicle guidance system, with a special construction of the ladder-slit secondary. Item 18) in the Appendix treats a new long primary double-sided linear flux-switching PM motor that is quantitatively compared with LIMs for the electromagnetic launch systems.

The guest editors hope that this Special Section could be of interest for people coming from both the academia and the industry who work in the area of LEMs. They are grateful to all the authors who have contributed to this Special Section, making it possible, and to all the reviewers who have spent their time studying and commenting on these contributions. We would also like to thank Prof. L. Franquelo, Editor-in-Chief of the IEEE Transactions on Industrial Electronics, for his support.

I. Boldea, *Guest Editor*
Department of Electrical Machines and Drives
Politehnica University of Timisoara
300006 Timisoara, Romania

M. Pucci, *Guest Editor*
National Research Council of Italy (CNR-ISSIA)
Institute on Intelligent Systems for Automation
90145, Palermo, Italy

W. Xu, *Guest Editor*
State Key Laboratory of Advanced Electromagnetic Engineering and Technology
Huazhong University of Science and Technology
Wuhan 430074, China

Appendix
Related Work

1) I. Boldea, L. N. Tutelea, W. Xu, and M. Pucci, "Linear electric machines, drives and MAGLEVs: An overview," *IEEE Trans. Ind. Electron.*, vol. 65, no. 9, pp. 7504–7515, Sep. 2018.
2) Z. Ling, J. Ji, J. Wang, and W. Zhao, "Design optimization and test of a radially magnetized magnetic screw with discretized PMs," *IEEE Trans. Ind. Electron.*, vol. 65, no. 9, pp. 7536–7547, Sep. 2018.
3) O. Farrok, M. R. Islam, M. R. I. Sheikh, Y. Guo, and J. G. Zhu, "A split translator secondary stator permanent magnet linear generator for oceanic wave energy conversion," *IEEE Trans. Ind. Electron.*, vol. 65, no. 9, pp. 7600–7608, Sep. 2018.
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5) G.-T. Ma, Z.-T. Wang, K. Liu, H.-Y. Qian, and C. Wang, "Potentials of an integrated levitation, guidance, and propulsion system by a superconducting transverse flux linear motor," *IEEE Trans. Ind. Electron.*, vol. 65, no. 9, pp. 7548–7557, Sep. 2018.

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7) W. Li, K. T. Chau, T. W. Ching, and C. Liu, “A phase-decoupled flux-reversal linear generator for low-speed oscillatory energy conversion using impedance matching strategy,” *IEEE Trans. Ind. Electron.*, vol. 65, no. 9, pp. 7590–7599, Sep. 2018.
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9) C. Li, C. Li, Z. Chen, and B. Yao, “Advanced synchronization control of a dual-linear-motor-driven gantry with rotational dynamics,” *IEEE Trans. Ind. Electron.*, vol. 65, no. 9, pp. 7526–7535, Sep. 2018.
10) H. M. Gutierrez and H. Luijten, “5-DOF real-time control of active electrodynamic MAGLEV,” *IEEE Trans. Ind. Electron.*, vol. 65, no. 9, pp. 7468–7476, Sep. 2018.
11) A. S. Abdelrahman, J. Sayeed, and M. Z. Youssef, “Hyperloop transportation system: Analysis, design, control, and implementation,” *IEEE Trans. Ind. Electron.*, vol. 65, no. 9, pp. 7427–7436, Sep. 2018.
12) W. Zhao, B. Wu, Q. Chen, and J. Zhu, “Fault-tolerant direct thrust force control for dual inverter fed open-end winding linear vernier permanent-magnet motor using improved SVPWM,” *IEEE Trans. Ind. Electron.*, vol. 65, no. 9, pp. 7458–7467, Sep. 2018.
13) H. Wang, J. Zhao, J. Zhao, J. Song, Z. Pan, and X. Jiang, “A new rapid-precision position measurement method for a linear motor mover based on 1-D EPCA,” *IEEE Trans. Ind. Electron.*, vol. 65, no. 9, pp. 7485–7494, Sep. 2018.
14) Z. Pan, F. Dong, J. Zhao, L. Wang, H. Wang, and Y. Feng, “Combined resonant controller and two-degree-of-freedom PID controller for PMSLM current harmonics suppression,” *IEEE Trans. Ind. Electron.*, vol. 65, no. 9, pp. 7558–7568, Sep. 2018.
15) G. Lv, D. Zeng, and T. Zhou, “An advanced equivalent circuit model for linear induction motors,” *IEEE Trans. Ind. Electron.*, vol. 65, no. 9, pp. 7495–7503, Sep. 2018.
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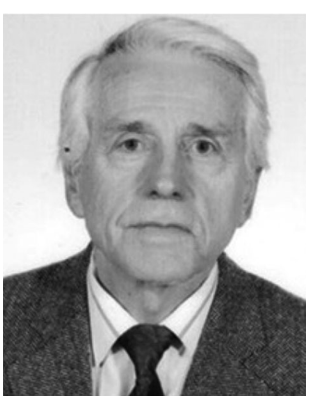
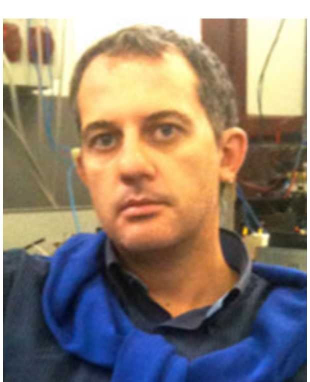


Ion Boldea (M’77–SM’81–F’96–LF’14) received the M.S. and Ph.D. degrees in electrical engineering from the Politehnica University of Timisoara, Timisoara, Romania, in 1967 and 1973, respectively.

He is currently a Full Professor with the Politehnica University of Timisoara, Timisoara, Romania. He has worked and authored or coauthored extensively in linear and rotary electric machines, drives, and magnetic levitation vehicles. He has authored or coauthored numerous books, with 6000 entrances in libraries worldwide.

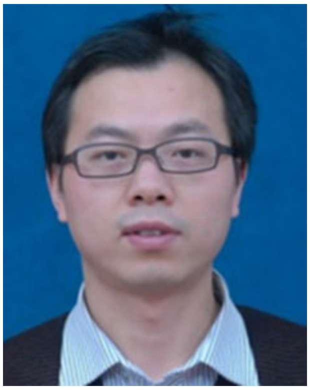
Dr. Boldea is a member of the Industrial Drives Committee and the Electric Machines Committee of the IEEE Industry Applications Society (IAS). Since 1996, he has been the Chairman of the OPTIM International Conferences (IEEE IAS sponsored). He was the recipient of the 2015 IEEE Nikola Tesla Award.



Marcello Pucci (M’03–SM’11) received the Laurea and Ph.D. degrees in electrical engineering from the University of Palermo, Palermo, Italy, in 1997 and 2002, respectively.

From 2001 to 2007, he was a Researcher, and since 2008 he has been a Senior Researcher with the National Research Council of Italy (CNR-ISSIA), Institute on Intelligent Systems for Automation, Genova, Italy. His current research interests include electrical machines, control, diagnosis and identification techniques of electrical drives, intelligent control, and power converters.

Dr. Pucci is an Associate Editor for the IEEE Transactions on Industrial Electronics and IEEE Transactions on Industry Applications. He is a member of the Editorial Board of the *Journal of Electrical Systems*.



Wei Xu (M’09–SM’13) received the double B.E. and M.E. degrees from Tianjin University, Tianjin, China, in 2002 and 2005, and the Ph.D. degree from the Institute of Electrical Engineering, Chinese Academy of Sciences, Beijing, China, in 2008, all in electrical engineering.

From 2008 to 2012, he held several academic positions in both Australian and Japanese universities and companies. Since 2013, he has been a Full Professor with the State Key Laboratory of Advanced Electromagnetic Engineering and Technology, Huazhong University of Science and Technology, Wuhan, China. His research interests include electromagnetic design and control algorithm of linear/rotary machines.