Intelligent Control for Electric Power Systems and Electric Vehicles

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First Edition

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In memory of my mother
Diamantina Rigatou (1939-2018)
Gerasimos Rigatos

To my wife Elham
and my sons, Arman and Ario
Masoud Abbaszadeh

To my family, wife and children
Mohamed-Assaad Hamida

To my family, wife and children
Pierluigi Siano

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Foreword

Overview:

The monograph presents advances in nonlinear control and nonlinear estimation for electric machines with particular use in the traction system of electric vehicles. The topics noted above are important because energy consumption grows at a galloping pace worldwide while the capacity of the electric power generation, transmission and distribution system gets at its limits, with the risk of energy shortages to be now apparent. The functioning of the power grid remains suboptimal thus raising the cost of energy production while also resulting into unnecessary energy dispersion. It is thus clear that there is need for developing and implementing nonlinear control, estimation and fault diagnosis methods that will optimize the functioning of the electricity grid.

Furthermore, in the transportation sector there is progressive transition to electric vehicles. Actually, all developed countries pursue to substitute progressively combustion engine vehicles with electric vehicles. Reducing the use of fossil fuel in transportation is anticipated to contribute significantly to the Net Zero objective that aims at eliminating the emission of harmful exhaust gases coming from human activities. Most known manufacturers of vehicles have shifted to the production of all-electric cars, and the announced plan by several car industries is to suspend progressively combustion engine vehicles' production and to get completely substituted these vehicles by electric ones. It is thus clear that there is need for developing and implementing nonlinear control, estimation and fault diagnosis methods that will optimize the traction system of electric vehicles.

The monograph is addressed to engineers and to the academic community. Engineers working in the design and development of electric power systems, and electric vehicle traction and propulsion systems may come against nonlinear control, estimation and fault diagnosis problems which can be solved using the monograph's methods. Additionally. the manuscript is suitable for teaching nonlinear control, estimation and fault diagnosis topics with emphasis to electric power systems and to electric vehicle traction and propulsion systems both at late undergraduate and at postgraduate level. Such courses can be part of the curriculum of several university departments, such as Electrical Engineering, Computer Science, Informatics etc. The proposed book contains teaching material which can be also used in a supplementary manner to the content of various other courses on control systems (e.g. control systems design, nonlinear control systems, nonlinear estimation and filtering, systems identification etc.). The book can also serve perfectly the needs of postgraduate courses on the aforementioned topics.

Foreward by Dr. N. Zervos:

The new monograph on ”Intelligent Control for Electric Power Systems and Electric Vehicles”, is the outcome of a many year research effort in a topic of major technological and societal importance. The aim of Green Development has fostered the deployment of renewable energy sources as a mean for covering the continuously growing energy demand worldwide. It has also imposed electromotion and electrification of transportation systems as the solution towards drastically reducing polluting gases emission. The results and methods of the new monograph come to address the above noted objectives and are certainly a valuable contribution towards optimizing electric power generation, traction and propulsion systems and towards bringing this technology in the service of sustainable and environmentally friendly development.

Dr. Nikolaos Zervos
Emeritus Research Professor
Industrial Systems Institute
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March 2024, Athens, Greece

Preface

The present monograph has been based on (a) research and teaching work which has been carried out at the Ecole Centrale de Nantes as part of the 2021-2022 European Commission Project ”E-Pico: Electric Vehicles Propulsion and Control Project”, (b) work which has been carried out at the Unit of Industrial Automation of the Industrial Systems as part of the unit's long-term research and development plan. The monograph proposes systematic methods for the solution of the nonlinear control, nonlinear estimation and fault diagnosis problems in electric power systems as well as in electric traction and propulsion systems. The monograph presents advances in nonlinear control and nonlinear estimation for electric machines (with particular use in the traction system of electric vehicles). The topics noted above are important because (1) energy consumption grows at a galloping pace worldwide while the capacity of the electric power generation, transmission and distribution system gets at its limits, with the risk of energy shortages to be now apparent. The functioning of the power grid remains suboptimal thus raising the cost of energy production while also resulting into unnecessary energy dispersion. It is thus clear that there is need for developing and implementing nonlinear control, estimation and fault diagnosis methods that will optimize the functioning of the electricity grid, (2) On the other side, in the transportation sector there is progressive transition to electric vehicles. Actually, all developed countries pursue to substitute progressively combustion engine vehicles with electric vehicles. Reducing the use of fossil fuel in transportation is anticipated to contribute significantly to the Net Zero objective that aims at eliminating the emission of harmful exhaust gases coming from human activities. Most known manufacturers of vehicles have shifted to the production of all-electric cars, and the announced plan by several car industries is to suspend combustion engine vehicles' production by 2030 and to substitute completely these vehicles by electric ones by 2035. It is thus clear that there is need for developing and implementing nonlinear control, estimation and fault diagnosis methods that will optimize the traction system of electric vehicles.

The contents of the current monograph on "Intelligent control for electric power systems and electric vehicles" demonstrate in more detail the unique contribution of this research work and are outlined as follows: (1) Fault tolerant control (nonlinear flatness-based control, nonlinear optimal control, Lie algebra-based control, sliding-mode control, multi-loop backstepping-type control, multi-model fuzzy control, flatness-based adaptive control) (2) Control of electric machines (control of AC motors such as three-phase PMSMs, three-phase induction motors, synchronous reluctance motors and permanent magnet brushless DC motors, switched reluctance motors, and control of multi-phase PMSMs or multi-phase IMs), as well as control of the associated power electronics (that is converters and inverters), control of the powertrains of electric vehicles and control of electric propulsion systems (3) Nonlinear control for synchronisation of the electricity grid (control and synchronisation of distributed AC power units, coordination of AC and DC power units in hybrid microgrids, control of wind power units and marine power units, control of DC power units such as photovoltaics and fuel cells).

With reference to (1) the aim is to analyse nonlinear control and estimation techniques that exhibit fault tolerance (a) control and filtering based on differential flatness theory. The significance of differential flatness theory is explained regarding diffeomorphisms, transformations of a system's dynamics into equivalent state-space representations and the associated design of stabilizing feedback controllers and of convergent state estimators. Several application examples will be analyzed focusing on distributed electric power generators, voltage source inverters and converters, synchronous and asynchronous electric machines both in the electric motor and in the power generator functioning mode, voltage source converters and inverters, conventional AC power generation units and renewable power sources (b) control based on Lie-algebra and the associated transformations into linear state-space forms. Several application examples will be given about electric vehicle traction systems, conventional AC power generation units, as well as renewable energy sources (c) nonlinear optimal control based on approximate linearization with the use of Taylor-series expansion and subsequent application of H-infinity optimal control methods. Several application examples will be given on electric traction with the use of synchronous and asynchronous motors, integrated traction systems comprising electric motors and the associated power electronics, as well as conventional AC power units and renewable energy power units (d) sliding-mode control associated with prior transformation of the system's dynamics into input-output linearized forms. Several application examples will be given about electric vehicle traction systems and renewable power generation.

With reference to topic (2) the aim is to analyse modelling issues in the dynamics of electric machines, particularly when these are used for traction in electric vehicles jointly with power electronics such as converters or jointly with motion transmission systems. Nonlinear control and estimation methods are proposed about (a) voltage source inverter-fed three-phase PMSMs, (ii) induction motors used for electric vehicles' traction and motion transmission through drivetrains, (iii) voltage-source inverter-fed three-phase induction motors, (iv) inverter-fed multi-phase permanent magnet synchronous motors, (v) power-chains in electric and hybrid vehicles. Besides control issues are analyzed about traction systems which are based on DC actuators driven by DC-DC converters, on switched reluctance motors as well on three-phase BLDC motors.

With reference to topic (3) the aim is to analyse modelling issues in interconnected electric power systems of various power generation sources (DC and AC power units) and in different configurations, and to provide an insight of the associated nonlinear control, stabilization and synchronization methods. Nonlinear control and estimation methods are developed about distributed and interconnected (i) synchronous power generators used in conventional AC power units and in wind power generation, (ii) multi-rotor wind power units, (iii) wind-power units based on multiphase synchronous and asynchronous generators (iv) marine power generation units

(v) microgrids consisting of wind-power units, hydro-power units and photovoltaics and of the associated power electronics such as AC/DC and DC/ DC converters.

The contents of the present monograph on *Intelligent Control for Electric Power Systems and Electric Vehicles*, are outlined as follows: Chapter 1 is on Nonlinear optimal control and Lie algebra-based control (Control based on approximate linearization and Global linearization-based control concepts). Chapter 2 is on Differential flatness theory and flatness-based control methods (Global linearization-based control with the use of differential flatness theory and Flatness-based control of nonlinear dynamical systems in cascading loops). Chapter 3 is on Control of DC and PMBLDC electric motors (Control of DC motors through a DC-DC converter and Control of Permanent Magnet Brushless DC motors). Chapter 4 is on Control of VSI-fed three-phase and multi-phase PMSMs (Nonlinear optimal control VSI-fed three-phase PMSMs and Nonlinear optimal control VSI-fed six-phase PMSMs). Chapter 5 is on Control of energy conversion chains based on PMSMs (Control of wind-turbine and PMSM-based electric power unit and Control of a PMSM-driven gas-compression unit).Chapter 6 is on Control of energy conversion chains based on Induction Machines (Control of the VSI-fed three-phase induction motor, Control of an induction motor-driven gas compressor and Control of induction generator-based shipboard microgrids). Chapter 7 is on Control of multi-phase machines in gas processing and power units (Control of gas-compressors actuated by 5-phase PMSMs and Control of 6-phase induction generators in renewable energy units). Chapter 8 is on Control of Spherical Permanent Magnet Synchronous Motors and Switched Reluctance Motors (Control of spherical permanent magnet synchronous motors, Control of switched reluctance motors for electric traction and Adaptive control for switched reluctance motors). Chapter 9 is on Control of traction and powertrains in Electric Vehicles and Hybrid Electric Vehicles (Control of multi-phase motors in the traction system in electric vehicles and Control of synchronous machines and converters in power-chains of hybrid electric vehicles). Chapter 10 is on Control of renewable power units and heat management units (Control of residential microgrids with Wind Generators, Fuel Cells and PVs and Control of heat pumps for thermal management in electric vehicles).

Through the detailed and in depth treatment of the aforementioned topics, the monograph is expected to have a meaningful contribution to the members of the research, academic and engineering community. It is anticipated that the monograph will be particularly useful to researchers and university tutors working on nonlinear control, nonlinear estimation and fault diagnosis problems of electric power systems and of electric traction and propulsion systems.

Gerasimos Rigatos	Masoud Abbaszadeh	Mohamed Hamida	Pierluigi Siano
Athens, Greece	New York, USA	Nantes, France	Salerno, Italy
March, 2024	March, 2024	March, 2024	March, 2024

About the authors

Dr. Gerasimos Rigatos obtained his diploma (1995) and his Ph.D. (2000) both from the Department of Electrical and Computer Engineering, of the National Technical University of Athens (NTUA), Greece. In 2001 he was a post-doctoral researcher at IRISA-INRIA, Rennes, France. He is currently a Research Director (Researcher Grade A') at the Industrial Systems Institute, Greece. He is a Senior Member of IEEE, and a Member and CEng of IET. He has led several research cooperation agreements and projects which have given accredited results in the areas of nonlinear control, nonlinear filtering and control of distributed parameter systems. His results appear in 8 research monographs and in several journal articles. According to Elsevier Scopus his research comprising 135 journal articles where he is the first or sole author, has received more than 3000 citations with an H-index of 26. Since 2007, he has been awarded visiting professor positions at several academic institutions (University Paris XI, France, Harper-Adams University College, UK, University of Northumbria, UK, University of Salerno, Italy, Ecole Centrale de Nantes, France). He is an editor of the Journal of Advanced Robotic Systems and of the SAE Journal of Electrified Vehicles.

Dr. Masoud Abbaszadeh obtained a B.Sc and a M.Sc in Electrical Engineering from Amirkabir University of Technology and Sharif University of Technology, in Iran, respectively. Next, he received a Ph.D. degree in Electrical Engineering (Controls) in 2008 from the University of Alberta, Canada. From 2008 to 2011, he was with Maplesoft, Waterloo, Ontario, Canada, as a Research Engineer. He was the principal developer of MapleSim Control Design Toolbox and was a member of a research team working on the Maplesoft-Toyota joint projects. From 2011 to 2013, he was a Senior Research Engineer at United Technologies Research Center, East Hartford, CT, USA, working on advanced control systems, and complex systems modeling and simulation. Currently he is a Principal Research Engineer at GE Research Center, Niskayuna, NY, USA. He has also held an Adjunct Professor position at Rensselaer Polytechnic Institute, NY, USA. He has over 150 peer-reviewed papers, 9 book chapters, and holds 39 issued US patents, with over 40 more patents pending.. His research interests include estimation and detection theory, robust and nonlinear control, and machine learning with applications in diagnostics, cyber-physical resilience and autonomous systems. He serves as an Associate Editor of IEEE Transactions on Control Systems Technology, and a member of IEEE CSS Conference Editorial Board.

Dr. Mohamed-Assaad Hamida was born in El Oued, Algeria, in 1985. He received the B.Sc . degree in electrical engineering from the University of Batna, Batna, Algeria, in 2009, the M.Sc. degree in automatic control from Ecole Nationale Superieure d'Ingenieurs de Poitiers (ENSIP), Poitiers, France, in 2010, and the Ph.D degree in automatic control and electrical engineering from Ecole centrale de Nantes, Nantes, France, in 2013. From 2013 to 2017, he was an Associate Professor of Electrical Engineering with the University of Ouargla, Algeria. In 2017, he joined the Ecole Centrale de Nantes and the Laboratory of Digital Sciences of Nantes (LS2N), as an Associate Professor. Dr. Hamida is the local coordinator of the European project E-PiCo on Electric Vehicles Propulsion and Control at Ecole Centrale of Nantes and the head of the real-time systems unit in the same university. His research interests include robust nonlinear control (higher order sliding mode, backstepping, adaptive control, optimal control), theoretical aspects of nonlinear observer design, control and fault diagnosis of electrical systems and renewable energy applications. His current research interests include robust nonlinear control, theoretical aspects of nonlinear observer design, control, and fault diagnosis of electrical systems and renewable energy applications.

Dr. Pierluigi Siano received the M.Sc. degree in electronic engineering and the Ph.D. degree in information and electrical engineering from the University of Salerno, Salerno, Italy, in 2001 and 2006, respectively. He is Full Professor of Electrical Power Systems and Scientific Director of the Smart Grids and Smart Cities Laboratory with the Department of Management and Innovation Systems, University of Salerno. Since 2021 he has been a Distinguished Visiting Professor in the Department of Electrical and Electronic Engineering Science, University of Johannesburg. His research activities are centered on demand response, energy management, the integration of distributed energy resources in smart grids, electricity markets, and planning and management of power systems. In these research fields, he has co-authored more than 700 articles including more than 410 international journals that received in Scopus more than 19200 citations with an H-index equal to 66. Since 2019 he has been awarded as a Highly Cited Researcher in Engineering by Web of Science Group. He has been the Chair of the IES TC on Smart Grids. He is Editor for the Power & Energy Society Section of IEEE Access, IEEE Transactions on Power Systems, IEEE Transactions on Industrial Informatics, IEEE Transactions on Industrial Electronics, and IEEE Systems.

Acknowledgement

The authors of the monograph appreciate the review remarks and comments of colleagues working in the research area of nonlinear control, estimation and fault diagnosis of complex dynamical systems and particularly of electric power systems and of electric traction and propulsion systems. Through their feedback, the necessity for further elaboration on specific topics of the monograph has become apparent and the related presentation has been updated accordingly.