Tapan Kumar Basu
Swapan Kumar Goswami
Nandita Sanyal   *Editors*

Advances in Control, Signal Processing and Energy Systems

Select Proceedings of CSPES 2018

Springer

Lecture Notes in Electrical Engineering

Volume 591

The book series *Lecture Notes in Electrical Engineering* (LNEE) publishes the latest developments in Electrical Engineering - quickly, informally and in high quality. While original research reported in proceedings and monographs has traditionally formed the core of LNEE, we also encourage authors to submit books devoted to supporting student education and professional training in the various fields and applications areas of electrical engineering. The series cover classical and emerging topics concerning:

- Communication Engineering, Information Theory and Networks
- Electronics Engineering and Microelectronics
- Signal, Image and Speech Processing
- Wireless and Mobile Communication
- Circuits and Systems
- Energy Systems, Power Electronics and Electrical Machines
- Electro-optical Engineering
- Instrumentation Engineering
- Avionics Engineering
- Control Systems
- Internet-of-Things and Cybersecurity
- Biomedical Devices, MEMS and NEMS

For general information about this book series, comments or suggestions, please contact leontina. dicecco@springer.com.

To submit a proposal or request further information, please contact the Publishing Editor in your country:

China

Jasmine Dou, Associate Editor (jasmine.dou@springer.com)

India

Swati Meherishi, Executive Editor (swati.meherishi@springer.com)
Aninda Bose, Senior Editor (aninda.bose@springer.com)

Japan

Takeyuki Yonezawa, Editorial Director (takeyuki.yonezawa@springer.com)

South Korea

Smith (Ahram) Chae, Editor (smith.chae@springer.com)

Southeast Asia

Ramesh Nath Premnath, Editor (ramesh.premnath@springer.com)

USA, Canada:

Michael Luby, Senior Editor (michael.luby@springer.com)

All other Countries:

Leontina Di Cecco, Senior Editor (leontina.dicecco@springer.com)
Christoph Baumann, Executive Editor (christoph.baumann@springer.com)

** Indexing: The books of this series are submitted to ISI Proceedings, EI-Compendex, SCOPUS, MetaPress, Web of Science and Springerlink **

More information about this series at http://www.springer.com/series/7818

Tapan Kumar Basu · Swapan Kumar Goswami ·
Nandita Sanyal
Editors

Advances in Control, Signal Processing and Energy Systems

Select Proceedings of CSPES 2018

Editors
Tapan Kumar Basu
Indian Institute of Technology Kharagpur
Kharagpur, West Bengal, India

Swapan Kumar Goswami
Jadavpur University
Kolkata, West Bengal, India

Nandita Sanyal
B.P. Poddar Institute of Management
and Technology
Kolkata, West Bengal, India

Committees

Chief Patrons

Shri Arun Poddar, Chairman, B.P. Poddar Foundation for Education and B.P. Poddar Group

Patrons

Shri Ayush Poddar, Vice-Chairman, B.P. Poddar Foundation for Education and B.P. Poddar Group

Dr. Subir Choudhury, Founder Trustee and Chief Mentor, B.P. Poddar Foundation for Education

Prof. (Dr.) Sutapa Mukherjee, Principal, B.P. Poddar Institute of Management & Technology

Prof. (Dr.) B. N. Chatterjee, Dean (Academics), B.P. Poddar Institute of Management & Technology

Advisory and Technical Programme Committee

Dr. Siddhartha Sen, IIT Kharagpur
Dr. N.K. Kishor, IIT Kharagpur
Dr. Amitava Chatterjee, Jadavpur University
Dr. Abhijit Lahiri, Supreme knowledge Foundation
Dr. Samarjit Sengupta, University of Calcutta
Dr. Jitendra Nath Bera, University of Calcutta
Prof. Sugata Munshi, Jadavpur University
Prof. Pranab Kumar Dutta, IIT Kharagpur

Dr. Ashoke Sutradhar, IIEST Shibpur
Dr. Sanjoy Saha, Jadavpur University
Dr. Debasis Chatterjee, Jadavpur University
Dr. Kamalika Ghosh, Jadavpur University
Dr. Kalyan Chatterjee, IIT(ISM) Dhanbad
Dr. Sovan Dalai, Jadavpur University
Dr. Diganta Saha, Jadavpur University
Dr. Biswendu Chatterjee, Jadavpur University
Dr. Debangshu Dey, Jadavpur University
Dr. Ranjit Kr. Barai, Jadavpur University
Dr. Parimal Acharjee, NIT Durgapur
Dr. Somnath Pan, IIT(ISM) Dhanbad
Dr. Sanjoy Mondal, IIT(ISM) Dhanbad
Dr. Saikat Mookherjee, Jadavpur University
Dr. Arghya Mitra, VNIT Nagpur
Dr. Kaushik Das Sharma, University of Calcutta
Dr. Chandan Kr. Chanda, IIEST Shibpur
Dr. Biswarup Basak, IIEST Shibpur
Dr. Rajarshi Gupta, University of Calcutta
Dr. Jayanta Kumar Chanda, Purulia Government Engineering College
Dr. Madhubanti Mitra, Jadavpur University
Dr. Subrata Chatterjee, NITTTR
Dr. Ranjan Kr. Behera, IITP

Organizing Committee

General Chair

Prof. Dr. Tapan Kumar Basu, IIT Kharagpur (Retired)

Organizing Chair

Dr. Nandita Sanyal, Head, Department of EE

Technical Programme Chairs

Dr. Krishnendu Chakraborty, Principal, Government College of Engineering and Ceramic Technology
Dr. Sudipta Chakraborty, Associate Professor, B.P. Poddar Institute of Management & Technology

Finance Committee

Dr. Subhasish Pradhan, Registrar, BPPIMT
Mr. Amlan Roy Choudhury, BPPIMT
Ms. Chandrani Das, BPPIMT
Mr. Aritra Ghosh, BPPIMT

Publication Committee

Dr. Ivy Majumdar, BPPIMT
Dr. Sutapa Mukherjee, BPPIMT
Dr. Indrakanta Maitra, BPPIMT
Mr. Argha Kamal Pal, BPPIMT

Industry Relations, Registration and Publicity

Ms. Anushree Roy, BPPIMT
Ms. Susmita Dey, BPPIMT
Ms. Madhumita Kundu (Mondal), BPPIMT
Ms. Sujata Saha, BPPIMT

Website Committee

Mr. Subhadip Chandra, BPPIMT
Mr. Subhasish Das, BPPIMT

Preface

It was a great pleasure with which we released the proceedings of National Conference on Control, Signal Processing & Energy Systems (CSPES 2018) organized by the Department of Electrical Engineering, B.P. Poddar Institute of Management and Technology, Kolkata, India, on 16–18 November 2018. This conference was technically supported by IEEE CSS IMS Joint Chapter Kolkata, WEBREDA, Department of Power and N. E. S West Bengal, and the Institution of Engineering and Technology (IET), Kolkata Network.

This conference was a modest effort to assemble academicians, researchers, engineers and technocrats under a tutelage to facilitate the exchange of ideas, thoughts, and research outcomes which would inspire students for higher studies and research and also to find the gaps between existing curriculum and industry requirements.

We like to thank all the authors for contributing their manuscripts and all the reviewers whose effort and hard work contributed towards the quality of submissions. The editors wholeheartedly like to acknowledge the constant encouragement and support from the institute management. Our sincere thanks extend to Dr. Akash Chakraborty, Associate Editor, Applied Science and Engineering, Springer.

We also like to thank our sponsors for extending their financial support to hold the conference. We are indebted to Dr. Debanshu Dey and his team from Jadavpur University and Dr. Kaushik Das Sharma from the Department of Applied Physics, University of Calcutta, for constant technical support. Last but not least, we are sincerely thankful to all the faculty members, staffs and students for their tireless effort with which the publication of CSPES 2018 Proceedings came true.

Kharagpur, India   Tapan Kumar Basu
Kolkata, India   Swapan Kumar Goswami
Kolkata, India   Nandita Sanyal

About the Institute

In 1999, B.P. Poddar Institute of Management and Technology (BPPIMT) was set up as a tribute to late B.P. Poddar, a visionary philanthropist, educationist and founding father of the group. Supported by the B.P. Poddar Foundation for Education, a trust dedicated to enriching the quality of technical education in the country, the institute is affiliated to the Maulana Abul Kalam Azad University of Technology (MAKAUT), West Bengal, and approved by the All India Council for Technical Education (AICTE). B.P. Poddar Institute of Management and Technology aims for a better society by bettering the education system. Its ambition resets on its unique learning culture that encourages collaboration and communication and the dedication of its experienced faculty picked from diverse fields.

The courses are offered in the disciplines of computer science and engineering, electronics and communication engineering, electrical engineering and information technology. The institute blends a dynamic and progressive approach towards outcome-based education teaching–learning with a vision to emerge as a progressive and premier institute for engineering and technology education with ethical values for creative engineering solutions commensurate with global changes.

The mission of the institute is to offer quality education through modern, accessible, comprehensive and research-oriented teaching–learning process; create opportunities for students and faculty members in acquiring knowledge through research and development; provide an effective interface with the industry by strengthening industry–institute interaction and develop entrepreneurial skills; and meet ever-changing needs for the nation through rational evolution towards sustainable and environment-friendly technologies.

The institute management also always encourages to create a platform for professional development activities in the institute in association with professional engineering societies/chapters and to help students to organize and participate in invited lectures, workshops, seminars and other technical events to improve

technical skills. The institute also tries to bridge the gap between the institute and the industry, thus enhancing the relationship among each other. The aim of the institute is to make an effective contribution to the educational system by identifying the gap between academic curriculum and need of the industry.

Keynote Speakers

Prof. (Dr.) Sutapa Mukherjee, Patron

It is my pleasure to inform that Electrical Engineering department of B.P. Poddar Institute of Management and Technology is organizing a National Conference on Control, Signal Processing and Energy System during 16th to 18th November, 2018 which will provide a platform for the researchers and students to share their ideas and to enrich the knowledge through interaction with the experts in their respective domains. As Head of the Institute, I welcome you all to this Conference to make it a grand success.

Prof. (Dr.) Sutapa Mukherjee, Patron, CSPES 2018

Prof. Dr. Tapan Kumar Basu, General Chair

Respected Chief Guest Mr. Samar Roy and Today's Guest of Honour & Keynote Speaker in the morning session Prof. Shivaji Chakraborty, Principal Prof. Dr. Sutapa Mukherjee, our Ex-Dean Prof. Biswanath Chatterji my, dear faculty colleagues of BPPIMT, and members of the staff, delegates from different institutions, my dear student friends, ladies and gentlemen, A very Good Morning to all of you!

On behalf of the organizing committee of CSPES2018 and on my personal behalf, I extend a Hearty Welcome to all of you to this 3-day National event. The idea of holding a conference is to create an opportunity for young scholars for intellectual discourse and exchange notes in their professional areas and get exposed to newer ideas through brain storming sessions.

I am confident that the young researchers will get a platform here to interact with other scholars and at the end will get immensely enriched when they go back.

I thank all of you for coming over here to participate in this modest programme; though it is being the third technical conference organized by the Department of Electrical Engineering. I hope you will excuse us for any lapse on our part.

Prof. Dr. Tapan Kumar Basu, General Chair, CSPES 2018

Dr. Nandita Sanyal, Organizing Chair

It is a great pleasure for me to be a part of organising Committee of the National Conference on Control, Signal Processing and Energy Systems CSPES2018 and to welcome the participants from all over India, to exchange experience and share new ideas for these three days. It is worth mentioning that Joseph Maria Roselle from Spain is also participating in this conference. I verily welcome all participants of CSPES 2018 and wish to thank our Chief Mentor and founder Trustee Dr. Subir Chowdhury, Principal Dr. Sutapa Mukherjee, Former Dean academics Prof. B. N. Chatterjee, and Registrar Dr. Subhasis Pradhan for their patronage and active support. I am also thankful to Prof. Tapan kumar Basu, Prof. Krishnendu Chakraborty and Prof. Sudipta Chakraborty who kindly consented to become General and Program Chairs. I am also thankful to Dr. Ivy Majumdar from Department of ECE and Amlan Roy Chowdhury from Department of CSE. We have the privilege of having Prof. Sivaji Chakravorti Director NIT Calicut as the Guest of Honour and Keynote Speaker in the Conference. I am also thankful to Mr. Samarendra nath Roy former Director BHEL India as Chief Guest. All the Invited Speakers, Session Chairs from renowned Universities have showed their honour to me for giving consent to participate in the conference in spite of their busy schedule. Team work of all the Faculty members from Department of Electrical Engineering make this Dream come true. I am thankful to them.

We have got immense support from IET Kolkata network, Globsyn on financial aspects and WEBREDA, CSS IMS Joint Chapter IEEE Kolkata section in technical aspects. This conference proceedings will be published by Springer LNEE series.

Finally, this conference is for the Students. If outcome of this conference can inspire them for higher studies, Research and to become successful professional the purpose will be served.

"Na chor haryam, Na cha raj haryam Na bhratu bhajyam Na cha bharkariVyaye krute vardhart ev nityaamVidya dhanam sarva dhane pradhanam".

No one can steal it, not authority can snatch, Not divided in brothers, not heavy to carry, As you consume or spend, it increases; as you share, it expands, Knowledge (Vidhya) is the best wealth among all the wealth anyone can have.

Hope CSPES 2018 will be a grand Success.

Dr. Nandita Sanyal, Organizing Chair, CSPES 2018

Prof. K. Chakrabarty, Program Chair

On behalf of the Program Committee, it is my great pleasure to welcome you to the National Conference on Control, Signal processing and Energy system (CSPES 2018) organized by the Electrical Engineering Department of B.P. Poddar institute of management and technology, Kolkata. CSPES 2018 brings together researchers to discuss the latest advances in Control, Signal processing and Energy system. This will also throw light on the direction of research and development in those areas that are very essential for the development of the civilization.

The Technical Program of CSPES 2018 consists of tutorials, symposia, keynote addresses, industry sessions and exhibitions. The keynote speakers will highlight the state-of-the art advancements in control, signal processing and other emerging topics in energy systems. Together, all these forums present cutting-edge advances of both the scientific and industrial developments in modern engineering.

The main symposia of CSPES 2018 received many paper submissions from the country and abroad, out of which 20 papers have been accepted. All papers have undergone a rigorous peer review process—every symposium paper was reviewed by at least 3 independent experts, with many receiving even more reviews. In addition to the main symposia, CSPES 2018 features tutorial on emerging and important topics in the field, which will be held on the first day of the conference. A large number of proposals for the tutorials were carefully scrutinized with only half of submitted proposals were finally accepted. Most of the technical symposia papers will be presented in lecture style, while some papers will be presented in interactive sessions for in-depth discussions among respective authors and the conference attendees. The quality of papers in lecture-style and interactive sessions is the same. The only criterion to assign a paper to an interactive session is topic homogeneity. Under the current policy of the conference, all papers must be presented by their authors, which will increase the discussions and lead to fruitful technical exchanges.

I would like to especially thank the General Chair-Prof. Tapan Kumar Basu, Organising Chair-Prof. Nandita Sanyal, Technical Program Chair-Prof. Sudipta Chakraborty, Track Chairs-Prof. Aparajita Sengupta, Prof. Kumardeb Banerjee, Prof. Swapan Kumar Goswami, Prof. Tapan Kumar Basu, Prof. Gautam Bandyopadhyay and as well as the all members of the advisory and technical program committee and the external reviewers for their dedication. Without their help, this conference would not be possible. I would also like to thank the Keynote Speakers for contributing to this important part of the program.

I look forward to welcome you all in Kolkata, the city of Joy.

Prof. K. Chakrabarty, Program Chair, CSPES 2018

Dr. Sudipta Chakraborty, Technical Programme Chair

CSPES 2018, National Conference on Control, Signal Processing and Energy Systems is a humble endeavour to amass scientists, academicians, researchers, engineers and technocrats under an aegis to facilitate exchange of novel ideas, thoughts, research outcomes which would provide impetus to stalwarts and amateurs equally to contribute in innovative breakthroughs in science, technology, engineering and mathematics. This forum will not only be a knowledge hub for veterans but it will equally benefit the entire scientific fraternity and inspire students for higher studies and research.

Research papers in three broad domains of Electrical Engineering, namely Control Systems, Signal Processing and Energy systems have been accepted. Since the first two areas are extensively interdisciplinary ones, there has been ample scope for researchers involved in allied arenas to contribute significantly. All the papers have undergone blind peer review before acceptance, based on quality, originality, technical content and relevance. All accepted papers presented at the Conference will be included in Proceedings to be published by Springer.

This Conference is hosted jointly by the parent Institute, BPPIMT, in collaboration with **IET** (The Institution of Engineering and Technology). We are honoured to have **IEEE Joint CSS-IMS**, Kolkata Chapter as our Technical Co-Sponsor. The esteemed association of **WEBREDA**, Department of Power and NES, Govt. of West Bengal as technical collaborator, has added further value to this technical meet.

Besides technical paper presentation in the three tracks mentioned, the Conference will witness invaluable technical deliberations and addresses by distinguished Professors as well as dedicated research scientists. The programme will be graced by **Dr. Sivaji Chakravorti**, Director, National Institute of Technology, Calicut and **Dr. Shrabani Ghosh**, DRDO Lab, Balasore as well as **Dr. Kuntal Ghosh**, Indian Statistical Institute, Kolkata as Key-note speakers.

The first day of the Conference has been reserved for pre-Conference tutorial when renowned personnel from WEBREDA, Department of Power and N. E. S. West Bengal will enlighten the students with their practical knowledge garnered through hands on experience. A plant visit has also been organised to provide the students a feel and insight into the intricate work field where they would venture in near future.

Hope the success of the Conference will be replicated in the form of quality research and publications.

Welcoming everyone to the knowledge fiesta and wishing a great time ahead.

With warm regards, **Dr. Sudipta Chakraborty, Technical Programme Chair**

Reviewers

Prof. Anirban Mukherjee, IIT Kharagpur
Prof. Tapan Basu, IIT Kharagpur (retired) and Visiting Faculty, B.P. Poddar Institute of Management and Technology, Kolkata
Dr. R. V Sarvadnya, Shri Guru Gobind Singhji Institute of Engineering and Technology, Nanded
Prof. Jaya Sil, IIEST Shibpur
Dr. S. S Gajre, Shri Guru Gobind Singhji Institute of Engineering and Technology, Nanded
Dr. Debaprasad Kastha, IIT Kharagpur
Dr. Aurobinda Rout Roy, IIT Kharagpur
Dr. Siddhartha Sen, IIT Kharagpur
Dr. L. M. Waghmare, Shri Guru Gobind Singhji Institute of Engineering and Technology, Nanded
Dr. S. V. Bonde, Shri Guru Gobind Singhji Institute of Engineering and Technology, Nanded
Dr. R. R. Manthalkar, Shri Guru Gobind Singhji Institute of Engineering and Technology, Nanded
Dr. Balasaheb Patre, Shri Guru Gobind Singhji Institute of Engineering and Technology, Nanded
Dr. Kaushik Das Sharma, University of Calcutta, Kolkata
Dr. Rakesh Misra, IIT(BHU) Varanasi
Dr. Parthasarathi Bera, Kalyani Government Engineering College, Kalyani
Prof. Sanjay Talbar, Shri Guru Gobind Singhji Institute of Engineering and Technology, Nanded
Prof. Arun Ghosh, IIT Kharagpur
Dr. Sudipta Chakraborty, B.P. Poddar Institute of Management and Technology, Kolkata
Prof. Raghunath Holambe, Shri Guru Gobind Singhji Institute of Engineering and Technology, Nanded
Prof. Amitava Chatterjee, Jadavpur University, Kolkata

Dr. A. V. Nandedkar, Shri Guru Gobind Singhji Institute of Engineering and Technology, Nanded

Prof. Manesh Kokare, Shri Guru Gobind Singhji Institute of Engineering and Technology, Nanded

Prof. Sanjoy Kumar Saha, Jadavpur University, Kolkata

Prof. Binoy Kumar Roy, NIT Silchar

Contents

About the Editors

Prof. Tapan Kumar Basu obtained his B.Tech (Hons.) in Electrical Engineering and M.Tech in Power System Engineering in 1968 and 1970 respectively from IIT Kharagpur. Subsequently he joined IIT Delhi as a research Scholar and obtained his Ph.D. in Power System Stability. He joined NIT, Kurukshetra (Formerly known as Regional Engineering College) in Nov. 1973 as a lecturer and later as an Astt. Prof. in the Electrical Engg. Deptt. In July 1976 he joined IIT Bombay as an Astt. Prof. in the Electrical Engg. Deptt. and then moved to IIT Kharagpur in April 1980. He became a Professor in July 1985 and retired from IIT in August 2009 to join the Aliah University, Kolkata as the Dean in Sept. 2009. In October 2010 he joined the Institute of Technology and Marine Engg (ITME) near Diamond Harbour as the Director. After completing his term as the Director, he left ITME and joined Academy of Technology (AOT), Adisaptagram, Dt. Hooghly in Feb. 2013 where he served as a senior Professor in Electrical Engineering till July 2017.

Prof. Basu served on the Board of Directors of West Bengal State Electricity Transmission Company Limited (WBSETCL) during 2008–2014. Currently he is an Adjunct Professor at AOT and B.P. PODDAR Institute of Management & Technology (BPPIMT), Kolkata. He has been appointed as an Advisor to the Speech and Image Processing Group of CDAC (Centre for Development of Advance Computing), Kolkata.

Prof. Basu guided 13 Ph.D. scholars and several M.tech students in areas of Power system Stability and Forecasting, Signal and Image Processing and Speech Processing and taught a large number of subjects to undergraduate and postgraduate classes during his long teaching career. He has developed two video courses on Networks, Signals and Systems and Digital Signal Processing under NPTEL National Project for Technology Enhanced Learning. He has published more than 150 papers in many national and international journals and conferences. He has obtained many awards He is a Life Fellow of the Institution of Engineers (I), System Society of India and Indian Society for Theoretical and Applied Mathematics.

Swapan Kumar Goswami is a Professor in Electrical Engineering, Jadavpur University, Kolkata. He has published more than one hundred research papers. Since 2013 his papers were cited 1860 occasions as per report of Google Scholar amongst which 22 h indexed. His area of research interest includes Power System analysis, Optimization, Distribution System, Restructuring and Smart Grid, Distribution planning, analysis and automation, optimum operation and planning of Power System. AI applications Deregulation Development of an OPF based Power System Simulator.

He has guided a good number of Doctoral students for the award of Ph.D. degree. He has several IEEE transactions.

Nandita Sanyal obtained her BE (Hons.) in Electrical Engineering, ME Electrical in Measurement and instrumentation and Ph.D. in Engg in 1993, 2003 and 2015 respectively from Jadavpur University. Her Research topic is Development of Image processing algorithm using Bacterial Foraging Optimization. She is presently Head of the Department of Electrical Engineering B.P. Poddar Institute of Management and Technology Kolkata. She has few International Journal Publication in Elsevier and has a chapter in book of Computational Intelligence in Image processing Applications by Springer Germany.

Nandita worked in Swedish Multinational ESAB India Limited for eight years. Where she was engaged in design and development of Welding Transformers and Rectifiers. She does consultancy in small scale industries. She is Executive Committee member of IEEE CSS IMS joint Chapter Kolkata Section.

Control Systems

Anti-windup Control of Nonlinear Cascade Systems with Particle Swarm Optimization Parameter Tuning

Fernando Serrano and Josep M. Rossell

Abstract Assuming that many physical models can be decoupled, an anti-windup control scheme for nonlinear cascade systems is proposed. Taking into account that saturation appears frequently, in order to overcome this difficulty, an efficient control approach is developed. The paper is divided into two parts; First, the design of a cascade control system with dynamic controllers in the inner and outer loops, considering the closed-loop stability in the controller design with a suitable anti-windup compensator; Secondly, a PID cascade controller design in the inner and outer loop is presented, when the parameter tuning in both control schemes is done by particle swarm optimization (PSO). However, in this case, the implementation of an anti-windup compensator is not needed. Apart from the theoretical background, two numerical examples are shown to corroborate the provided results.

1 Introduction

Cascade control systems have been investigated since several decades. In the SISO linear case, as it is known, the controllers are tuned in sequence, first by tuning the inner loop and then the outer loop. Usually, the kind of controllers implemented are proportional–integral–derivative (PID). In recent years, the research about cascade control systems has been extended to the nonlinear case, considering that many physical systems such as mechanical, electrical, power systems, and chemical systems can be controlled and stabilized by means of this approach. The design is possi-

F. Serrano
Central American Technical University (UNITEC), Zona Jacaleapa, Tegucigalpa, Honduras
e-mail: serranofer@eclipso.eu

J. M. Rossell (✉)
Department of Mathematics, Univ. Politècnica de Catalunya (UPC), Avda. Bases de Manresa 61-73, 08242 Manresa, Spain
e-mail: josep.maria.rossell@upc.edu

ble because a decoupled system can be divided into an inner and an outer loop, improving the performance in comparison with single loop control techniques. In the literature, the research about this topic is limited but an example can be found in [1] where a cascade control system is designed for the stabilization of underactuated mechanical systems. Although the anti-windup control problem for cascade control systems has not been investigated extensively, there are interesting results in single loop anti-windup design. In [2], an anti-windup control design is developed for the control of Takagi–Sugeno systems and a reliable state feedback control of Takagi—Sugeno fuzzy systems with sensor faults can be seen in [3]. A control scheme for disturbance observer systems is provided in [4], dealing with the saturation torque. Other theoretical and applied studies have been presented in [5], where the results are implemented in single-loop linear systems and the gain matrices are computed by using linear matrix inequalities (LMIs). Based on a linear approach, an anti-windup control scheme for an underwater vehicle is given in [6] and an anti-windup approach for nonlinear systems can be found in [7]. Other interesting works related to this topic are given in [8–10].

In this paper, an anti-windup control scheme is proposed for the stabilization of cascade nonlinear systems, which is developed in two parts. The first one is a dynamic controller implemented in the inner and outer loop. The closed-loop stability of the system is based on the theory stability of Lyapunov [11]. An anti-windup compensator is designed in order to reduce the unwanted effects of windup such as poor performance or even instability. The second part is done by implementing PID controllers in the inner and outer loop but now without anti-windup compensation. In the first and second part of this study, the gain matrices are tuned by particle swarm optimization [12–15].

The paper is organized as follows: In Sect. 2, the design of an anti-windup control scheme for cascade control systems, implementing dynamic controllers in the inner and outer loop, is developed. In Sect. 3, a PID cascade control system design is presented by considering input saturation but without the anti-windup compensator. In Sect. 4, a PSO algorithm is supplied in order to tune the gain matrices for both approaches. Two numerical examples are given in Sect. 5 and the conclusions can be found in Sect. 6.

2   Anti-windup Cascade Dynamic Controller Design

This section is devoted to designing an anti-windup controller for nonlinear cascade systems. This strategy implements dynamic controllers in the inner and outer loops with gain matrices that help to improve the system performance. The controllers are tuned, as explained in Sect. 4, by a particle swarm optimization algorithm to reduce the integral square error, i.e., the difference between the reference variable and the output of the outer system. The same applies to the inner system. The main idea of this first approach is to design an appropriate anti-windup compensator to deal with the unwanted effects when saturation appears in the inner loop. Even when the gain