

University of Groningen

Control of electrical networks: robustness and power sharing

Weitenberg, Erik

IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.

Document Version

Publisher's PDF, also known as Version of record

Publication date:

2018

[Link to publication in University of Groningen/UMCG research database](#)

Citation for published version (APA):

Weitenberg, E. (2018). Control of electrical networks: robustness and power sharing [Groningen]: Rijksuniversiteit Groningen

Copyright

Other than for strictly personal use, it is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license (like Creative Commons).

Take-down policy

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Downloaded from the University of Groningen/UMCG research database (Pure): <http://www.rug.nl/research/portal>. For technical reasons the number of authors shown on this cover page is limited to 10 maximum.

Control of Electrical Networks: Robustness and Power Sharing

ERIK WEITENBERG



university of
 groningen

The research described in this dissertation has been carried out at the Faculty of Mathematics and Natural Sciences, University of Groningen, the Netherlands.

disc

The research reported in this dissertation is part of the research program of the Dutch Institute of Systems and Control (DISC). The author has successfully completed the educational program of DISC.

Cover: David McEachan

Printed by *Studio

ISBN 978-94-034-0582-7 (printed version)

ISBN 978-94-034-0581-0 (electronic version)



**rijksuniversiteit
 groningen**

Control of Electrical Networks: Robustness and Power Sharing

Proefschrift

ter verkrijging van de graad van doctor aan de
Rijksuniversiteit Groningen
op gezag van de
rector magnificus prof. dr. E. Sterken
en volgens besluit van het College voor Promoties.

De openbare verdediging zal plaatsvinden op

dinsdag 10 juli 2018 om 11:00 uur

door

Erik Roelf Arjen Weitenberg

geboren op 10 mei 1987
te Smalingerland

Promotor

Prof. dr. C. De Persis

Copromotor

Dr. P. Tesi

Beoordelingscommissie

Prof. dr. G. Ferrari Trecate

Prof. dr. B. Jayawardhana

Prof. dr. K.H. Johansson

Acknowledgements

Being a PhD candidate has been a wonderful time, and certainly, this book would not exist without the formidable support I have enjoyed from my colleagues, friends and family. My deepest gratitude goes out to Claudio De Persis, my supervisor, for his guidance, patience, wisdom and sharp wit. Your passion and dedication are unmatched, and have been a great source of inspiration for me during the past years.

My gratitude also to my office-mates and neighbours, Tjardo, Sebastian, Tobias, Danial and Mingming: thank you for our many fruitful and fun discussions. I much enjoyed building the Smart Grid Game with you, and teaching the Keuzecollege, and of course our late-night logistics optimization sessions, which I trust are far from over. I would also like to thank my many current and previous colleagues at SMS, DTPA and JBI, Martin and Sietse, for being an awesome and very supportive group. Frederika, thank you too for always being there for us guppies, and organizing many of the outings and movie nights. I would also like to thank Jaap Top, my supervisor during my master's and bachelor's research, for introducing me to research and showing me how much fun it can be.

I am very lucky to have many awesome friends. Everyone at Serious Talk, in #brak and the festival crowd, thank you for our many great moments, weekend trips, festivals, endless banter, and of course for keeping me sufficiently distracted from research when I needed the extra motivation only an imminent deadline can provide. Monique, Jana, and of course my Muppet friends, René, Wouter and Nynke, thank you for our many years of (board) games, delicious food and our adventurous vacations. Many of my best memories during my time at university involve you, and much of the support I needed during these years has come from you.

Finally, endless thanks to my family, André, Jantine and Leo, for always being there when I needed you and supporting my choices. I am ever grateful for your wisdom and love.

Countless more people have directly or indirectly helped and supported me

during this time. Though it is impossible to mention everyone, thank you all so much.

Erik Weitenberg
Groningen
25th of May, 2018

Contents

1	INTRODUCTION	1
1.1	Robustness	2
1.2	Power sharing	3
1.3	Outline of this thesis	3
1.4	List of publications	4
1.5	Notation	5
1.6	Preliminaries	6
I	Strict Lyapunov functions for the swing equations	9
	Contributions	12
	Outline	13
2	EXPONENTIAL CONVERGENCE UNDER DAI FREQUENCY CONTROL	15
2.1	Introduction	16
2.2	Setting	18
2.3	Strictly decreasing Lyapunov function	23
2.4	Convergence bounds under DoS	31
2.5	Simulations	34
2.6	Conclusions	35
2.7	Proofs and technical lemmas	36
3	INPUT-TO-STATE STABILITY WITH RESTRICTIONS OF THE DAI CONTROLLER	43
3.1	Introduction	44
3.2	Setting	44
3.3	Lyapunov function	47
3.4	ISS of the closed-loop system	52
3.5	Conclusions	56
4	INPUT-TO-STATE STABILITY WITH RESTRICTIONS OF THE LEAKY INTEGRAL CONTROLLER	61
4.1	Introduction	62

4.2	Power System Frequency Control	63
4.3	Fully Decentralized Frequency Control	66
4.4	Properties of the Leaky Integral Controller	69
4.5	Case Study: IEEE 39 New England System	79
4.6	Summary and Discussion	84
4.7	Technical lemmas	85
II Consensus algorithms for DC microgrids		87
	Contributions	90
	Outline	91
5	A POWER CONSENSUS ALGORITHM FOR DC GRIDS	93
5.1	DC resistive microgrid	94
5.2	Power consensus controllers	94
5.3	Power consensus algorithm with ZIP loads	99
5.4	Simulations	114
5.5	Conclusions	115
6	A POWER CONSENSUS ALGORITHM FOR DC GRIDS WITH RL LINES	121
6.1	The RL network	122
6.2	Power consensus controllers	124
6.3	Lyapunov function	127
6.4	Stability of the closed-loop system	129
6.5	Simulation study	131
6.6	Summary and discussion	134
7	CONCLUSIONS	135
7.1	Research suggestions	136
	BIBLIOGRAPHY	139
	SUMMARY	149
	SAMENVATTING	151