

Nonconvex and Nonsmooth Optimization for Robust Control and Power Systems



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Declaration

I, Ye Shi, declare that except where specific reference is made to the work of others, the contents of this dissertation are original and have not been submitted in whole or in part for consideration for any other degree or qualification in this, or any other university. This dissertation is my own work and contains nothing which is the outcome of work done in collaboration with others, except as specified in the text and Acknowledgements.

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Abstract

There is considerable interest in structured \mathcal{H}_∞ control in linear parameter varying (LPV) systems and Takagi-Sugeno (T-S) fuzzy systems. The optimal power flow (OPF) problem, Electrical vehicles (EVs) charging problem and optimal placement of phasor measurement unit (PMU) have emerged as promising areas in power systems. This dissertation focuses on nonconvex and nonsmooth optimization for the structured \mathcal{H}_∞ control problem in LPV systems and T-S fuzzy systems and the OPF problem, the EV charging problem and the PMU placement problem in power systems.

We first consider reduced order LPV-LFT (linear parameter varying-linear fractional transformational) control synthesis. The reduced order control synthesis can be reformulated as a linear matrix inequality (LMI) optimization subject to a rank constraint on a matrix-valued affine function of the Lyapunov matrix variables. Finding a good reduced-order stabilizing controller is not an easy task because its computation is a NP-hard problem. A novel approach proposed in this thesis is to equivalently express the rank constraints on a positive semi-definite matrix-valued affine function by spectral nonlinear functions. We then show a simple but effective nonsmooth optimization technique leading to a path-following optimization procedure for these problems. An intensive simulation shows the clear advantage of the proposed method over the state-of-the-art nonlinear matrix inequality solvers.

In the second part of the dissertation, we investigate the \mathcal{H}_∞ Proportional-integral-derivative (PID) control design in fuzzy systems. To gain the practicability and tractability of fuzzy systems, this thesis develops a parameterized bilinear matrix inequality characterization for the \mathcal{H}_∞ fuzzy PID control design, which is then relaxed into a bilinear matrix inequality optimization problem of nonconvex optimization.

Several computational procedures are then developed for its solution. The merit of the developed algorithms is shown through the benchmark examples.

Thirdly, we consider the optimal power flow (OPF) problem over transmission networks. The OPF problem is to locate a steady state operating point such that the cost of electric power generation is minimized subject to operating constraints and meeting demand. Due to the highly nonlinear operation constraints, the OPF problem has been known as an NP-hard problem. The existing nonlinear solvers may fail in yielding a feasible point. Semi-definite relaxation (SDR) could provide the global solution only when the matrix solution of the relaxed semidefinite program (SDP) is of rank-one, which does not hold in general. We develop a nonsmooth optimization approach to address this difficult OPF problem, which is an iterative process to generate a sequence of improved points. We also develop an efficient decomposition for the large-scale OPF problem, which involves reduced numbers of the rank-one constraints on matrices of moderate size for expressing the network nonlinear constraints. Simulations for OPF problems and large-scale OPF problems demonstrate the efficiency of our approaches.

In the fourth section of this dissertation, we study the charging scheduling of plug-in electric vehicles (PEVs) and power control in smart grid. PEV charging scheduling aims at minimizing the potential impact of the massive integration of PEVs into smart grid to save service costs to customers while power control aims at minimizing the cost of power generation subject to operating constraints and meeting demand. A model predictive control (MPC)-based approach is proposed to address the joint PEV charging scheduling and power control to minimize both PEV charging cost and energy generation cost in meeting both residence and PEV power demands. Unlike in related works, no assumptions are made about the probability distribution of PEVs' arrivals, the known PEVs' future demand, or the unlimited charging capacity of PEVs. The proposed approach is shown to achieve a globally optimal solution. Numerical results for IEEE benchmark power grids serving Tesla Model S PEVs show the merit of this approach.

Finally, we consider the PMU placement problem for power grid state estimation under different degrees of observability. Observability degree is the depth of the buses'

reachability by the placed PMUs and thus constitutes an important characteristic for PMU placement. However, the sole observability as addressed in many works still does not guarantee a good estimate for the grid state. Some existing works also considered the PMU placement for minimizing the mean squared error or maximizing the mutual information between the measurement output and grid state. However, they ignore the observability requirements for computational tractability and thus potentially lead to artificial results such as acceptance of the estimate for an unobserved state component as its unconditional mean. In this dissertation, the PMU placement optimization problem is considered by minimizing the mean squared error or maximizing the mutual information between the measurement output and grid state, under grid observability constraints. The provided solution is free from the mentioned fundamental drawbacks in the existing PMU placement designs. The problems are posed as binary nonlinear optimization problems, for which this paper develops efficient algorithms for computational solutions. The performance of the proposed algorithms is analyzed in detail through numerical examples on large scale IEEE power networks.

Publications

The contents of this thesis are based on the following papers that have been published, accepted, or submitted to peer-reviewed journals and conferences.

Journal Papers:

1. Y. Shi, H. D. Tuan and P. Apkarian, "Nonconvex Spectral Optimization Algorithms for Reduced-Order H_∞ LPV-LFT controllers", *International Journal of Robust and Nonlinear Control*, vol. 27, pp. 4421-4442, 2017.
2. Y. Shi, H. D. Tuan, H. Tuy and S. W. Su, "Global Optimization for Optimal Power Flow over Transmission Networks", *Journal of Global Optimization*, vol. 69, pp. 745-760, 2017.
3. Y. Shi, H. D. Tuan, A. V. Savkin, S. W. Su, "Optimal Power Flow over Large-Scale Transmission Networks", *Systems & Control Letters*, vol. 118, pp. 16-21, 2018.
4. Y. Shi, H. D. Tuan, A. V. Savkin, T. Q. Duong and H. V. Poor, "Model Predictive Control for Smart Grids with Multiple Electric-Vehicle Charging Stations", accepted by *IEEE Transaction on smart grid*, 2017.
5. Y. Shi, H. D. Tuan, "Parameterized Bilinear Matrix Inequality Techniques in Fuzzy PID Control Design", under submission to *IEEE Transactions on Fuzzy System*, 2018.
6. Y. Shi, H. D. Tuan, A. V. Savkin, T. Q. Duong and H. V. Poor, "On-off Charging of Electrical Vehicles in Smart Grids", under submission to *IEEE Transaction on smart grid*, 2018.

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7. Y. Shi, H. D. Tuan, A. A. Nasir, T. Q. Duong, and H. V. Poor, "PMU Placement Optimization for Smart Grid Observability and State Estimation", under submission to IEEE Transaction on smart grid, 2018.

Conference Papers:

1. Y. Shi, H. D. Tuan, S. W. Su and H. H. M. Tam, "Nonsmooth Optimization for Optimal Power Flow over Transmission Networks", the 3rd IEEE Global Conference on Signal and Information Processing, pp. 1141-1144, 2015, Orlando, America.
2. Y. Shi, H. D. Tuan, S. W. Su, and A. V. Savkin, "Multiple Matrix Rank Constrained Optimization for Optimal Power Flow over Large Scale Transmission Networks", proceedings of the 5th International Conference on Smart Cities and Green ICT Systems, vol. 1, pp. 384-389, 2016, Rome, Italy.
3. Y. Shi, H. D. Tuan, and S. W. Su, "Nonconvex Spectral Algorithm for Solving BMI on the Reduced Order H_∞ Control", the 6th IEEE International Conference on Control Systems, Computing and Engineering, 2016, Penang, Malaysia.
4. Y. Shi, H. D. Tuan, and A.V. Savkin, "Three-phase Optimal Power Flow for Smart Grids by Iterative Nonsmooth Optimization", the 6th International Conference on Smart Cities and Green ICT Systems, 2017, Porto, Portugal.

Table of contents

List of figures

List of tables

1	Introduction	1
1.1	Motivation and Scope	1
1.2	Structured \mathcal{H}_∞ control in LPV system and OPF in power system	2
1.2.1	Reduced order \mathcal{H}_∞ control	3
1.2.2	\mathcal{H}_∞ fuzzy PID control	4
1.2.3	OPF problem in power system	5
1.2.4	Joint OPF-PEV charging problem in smart grid	7
1.2.5	Optimal PMU Placement in smart grid	8
1.3	Dissertation Outline	9
2	Background	15
2.1	H_∞ Control for Linear time varying system	15
2.2	H_∞ Control for Linear parameter varying system	16
2.3	Linear matrix inequality and bilinear matrix inequality	18
2.3.1	Linear matrix inequality	18
2.3.2	Bilinear matrix inequality	19

2.4	Optimization Theory	19
2.4.1	Convex Optimization	19
2.4.2	D.C. optimization	20
3	Nonconvex Spectral Optimization Algorithms for Reduced-Order \mathcal{H}_∞	
	LPV-LFT controllers	23
3.1	Introduction	23
3.2	Dynamic reduced order \mathcal{H}_∞ LPV control synthesis	26
3.3	Static output feedback LPV-LFT \mathcal{H}_∞ controller	36
3.4	Simulation results	39
3.4.1	RTAC control	39
3.4.2	Reduced order LPV-LFT controllers	41
3.4.3	Static output feedback LPV-LFT controller	42
3.4.4	LTI systems	43
3.5	Conclusions	45
4	Parameterized Bilinear Matrix Inequality Techniques in \mathcal{H}_∞ Fuzzy	
	PID Control Design	55
4.1	Introduction	55
4.2	H_∞ fuzzy PID PDS for T-S systems	57
4.3	Nonconvex spectral optimization techniques for solving BMIs	63
4.4	Simulation results	70
4.4.1	Inverted pendulum control	72
4.4.2	Duffing forced-oscillation	73
4.4.3	TORA	75
4.5	Conclusions	78

5	Global Optimization for Optimal Power Flow over Transmission Networks	87
5.1	Introduction	87
5.2	Optimal power flow problem and challenges	90
5.3	Nonsmooth optimization algorithm for OPF	95
5.4	Decomposed nonsmooth optimization for large-scale OPF	100
5.5	Simulation results	106
5.5.1	Simulation results for OPF problem	106
5.5.2	Simulation results for large-scale OPF problem	112
5.6	Conclusions	115
6	Model Predictive Control for Smart Grids with Multiple Electric-Vehicle Charging Stations	117
6.1	Introduction	117
6.2	Problem statement and computational challenges	119
6.3	Model predictive control (MPC)-based computational solution	123
6.4	Lower bound by off-line optimization	128
6.5	Simulation results	130
6.5.1	Simulation setup	130
6.5.2	MPC-based online computational results	132
6.5.3	Off-line computation and comparison with MPC-based online computation	135
6.6	Conclusions	140
7	PMU Placement Optimization for Smart Grid Observability and State Estimation	143
7.1	Introduction	143

7.2	Problem statement	145
7.3	Scalable Penalty algorithms for optimal PMU selection	149
7.4	Tailored path-following discrete optimization algorithms	154
7.5	Simulation results	155
7.6	Conclusions	159
8	Conclusions and Future Work	165
8.1	Conclusions	165
8.2	Future work	166
	References	169

List of figures

3.1	Closed-loop LPV-LFT system	27
3.2	Tracking performance of the first-order LPV-LFT controller in the absence of disturbance	40
3.3	Tracking performance of the first-order LPV-LFT controller with the disturbance $w = 0.1 \sin(5\pi t)$	41
3.4	The behaviour of the first-order LPV-LFT controller in the absence of disturbance (dot) and with disturbance $w = 0.1 \sin(5\pi t)$ (solid).	41
4.1	The state behaviour with and without disturbance	73
4.2	PID PDC behaviour with and without the disturbance	74
4.3	Convergence performance by Algorithm 10 and Algorithm 11 for the inverted pendulum system	79
4.4	The system state behavior without control	80
4.5	The system state under PID PDC control	80
4.6	The state and PID PDC behavior of the Duffing forced-oscillation system	81
4.7	Convergence performance by Algorithm 10 and Algorithm 11 for the Duffing forced-oscillation system	82
4.8	The state behaviour with and without disturbance	83
4.9	The PID PDC behaviour with and without the disturbance	84

4.10	Convergence performance by Algorithm 10 and Algorithm 11 for the TORA system	85
5.1	Case39mod1 [1]	109
6.1	System architecture of PEV charging in smart grid	120
6.2	The probability density of PEVs' arrivals	131
6.3	Residential load demands of four profiles	132
6.4	Energy prices for four profiles	133
6.5	Voltage profile for four networks during the charging period	135
6.6	Aggregated active power of online charging for Case30 under four residential profiles	136
6.7	Voltage profile of online charging for Case30 under four residential profiles	137
6.8	The SOC of PEVs during the charging period	138
6.9	Power generation under MPC-based (online) and offline computation for Case30 with four residential profiles	139
6.10	PEVs charging load under MPC-based and offline computation for Case30 with four residential profiles	140
6.11	SOC of PEVs randomly taken from Case30 with profile 2	141
7.1	MMSE by different methods	157
7.2	MI by different methods	158
7.3	MMSE found by Algorithm 3 and by [2]	160
7.4	MMSE found by Algorithm 10 under depth-of-one unobservability condition and Algorithm 12 without any observability constraints	161
7.5	Number of buses left unobserved by Algorithm 10 under depth-of-one unobservability condition and Algorithm 12 without any observability constraints for IEEE 30-bus network	162
7.6	Number of iterations required for the convergence of Algorithm 3	163

List of figures

7.7	Minimum number of PMUs required versus different values of tolerance level ϵ for MMSE	164
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List of tables

3.1	Computational results for reduced-order LPV-LFT controllers by Algorithm 1	42
3.2	Computational results for static LPV-LFT controllers by Algorithm 3	42
3.3	Numerical results by Algorithms 1 and 3 compared with [3]	44
3.4	Distillation tower case with γ fixed by Algorithm 4 compared with [3]	44
3.5	Numerical results of static output feedback controllers by Algorithm 3 compared with [4]	52
3.6	Numerical results of static output feedback controllers by Algorithm 4 compared with [4]	53
5.1	WB2mod [5]	107
5.2	WB5 [1] and WB5mod [5]	108
5.3	Case39mod1 and Case118mod [1]	108
5.4	Case9, 14, 30, 57 [6]	109
5.5	SDR feasibility check for Case57	110
5.6	Case14, 30, 57mod [7]	111
5.7	Results compared with Matpower6.0 [6]	111
5.8	Comparison of bags number \mathcal{I} , largest bag size M_i and number of variables	113
5.9	Performance comparison	113

6.1	Information on four networks	133
6.2	MPC results	134
6.3	MPC results for Case30 with four different residential profiles	134
6.4	Offline results of optimal PEV charging for four networks	136
6.5	Performance comparison under MPC-based and off-line computations .	138
7.1	The minimum number of PMUs needed for two observability conditions	156
7.2	Numerical details of Algorithm 10, Algorithm 11 and Algorithm 12 . .	159