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 $\mathcal{H}_\infty$ control in linear parameter varying (LPV) systems and Tagaki-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 noncovex and nonsmooth optimization for the structured $\mathcal{H}_\infty$ 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 $\mathcal{H}_\infty$ 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 $\mathcal{H}_\infty$ 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 obsvervability requirements for computational tractibility 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.

7. Y. Shi, H. D. Tuan, A. A. Nasir, T. Q. Duong, and H. V. Poor, "PMU Placement Optimization for Smart Grid Obvervability 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