The Development of Systematic Controllability Assessment for Process Control Designs

This thesis is presented for the degree of
Doctor Philosophy in Engineering

by

Estiyanti Ekawati
B. Eng, M. Eng

School of Engineering Science
Murdoch University
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Declaration

I declare that this thesis is my own account of my research and contains as its main content work, which has not previously been submitted for a degree at any tertiary educational institution.

Estiyanti Ekawati

Abstract

Chemical process industries are constantly challenged to operate profitably and efficiently, despite the presence of significant uncertainties and disturbances on the operational conditions, and various operational limitations. The capability to meet the challenge relies on the quality of process control design, which should integrate the dynamic controllability characteristics in addition to the traditional economic considerations.

The focus of this thesis is the development of a systematic controllability assessment framework for process control design. The framework addresses the controllability aspects in process and controller structures, as well as in time-domain dynamic performances. The aim is to provide clearer relationships between process profitability, controllability, and operational switching strategies in response to variations in the operating conditions.

The skeleton of the framework is a mathematical optimisation algorithm. This algorithm considers the structural, operational and economic problems arising in process control design as a progressive, dynamic, and uncertain semi-infinite mixed integer nonlinear programming problem. The algorithm is an iterative, two-level optimisation, which determines the optimum process design and the associated controllability index within an optimisation window. The window progresses along a time horizon, ensuring optimal process design within the window while accommodating the design switching during the course of load variations in a larger time horizon.

The controllability index quantifies the design capability to satisfy a given economic objective. Unique to other existing approaches, the process controllability index is computed based on the multi-dimensional geometric representation of the disturbances and uncertainties, measured process dynamics, and feasible operating spaces. These representations account for variable interactions existing in a multivariable process operation, in contrast to separate quantification in traditional single variable assessments.

The geometric computation of the index requires the analysis and elimination of redundant measurement variables, which occur in different combinations at different process and controller structures. The redundancy is detected and eliminated based on statistical collinearity among the process data, allowing the assessment to focus on the retained functional variables and the associated critical disturbances and uncertainties.

The redundancy analysis is tailored with a dynamic mixed integer nonlinear programming (MINLP) solver, which is dedicated to select the optimum process and controller structure within the design. The solver is developed based on the branch and bound strategy over the design tree, which consists of alternative nonlinear programming (NLP) sub-problems. In addition to the redundancy analysis, the solver is equipped with a compact MINLP formulation, an alternating depth-first and breadth-first search strategy, and the rapid pruning of inferior NLP sub-problems. The tailored strategy ensures fast and efficient convergence of convex problems, as well as superior optimum of non-convex counterparts.

Finally, the framework is performed within a time window, which progresses along the time horizon. This strategy provides realistic responses to major variations along greater length of time, by switching between optimum operational modes, while maintaining the optimum process controllability.

The performance of the framework is illustrated through several case studies. Each case demonstrates the novelty of addressing various computational features in a concise algorithm. These include the industrial case, which involves the systematic controllability assessment of an industrial five-effect liquor-burning evaporator within an Alumina refinery, which highlights the contribution of this framework in bridging the process design methodologies with the industrial implementation.

The thesis consists of eight chapters, presenting the systematic development of the framework. The numerical implementations have been organised in a MATLAB Toolbox, accompanied with the relevant case studies.

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