454f A Hierachical Approach to the Control of Integrated Process Networks

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Process networks, consisting of reaction and separation sequences connected through material and energy recycle streams, represent the rule, rather than an exception, in the modern process industry.

While offering significant economic benefits, integrated process networks pose distinct analysis and control challenges, as the presence of recycle streams leads to feedback interactions among the process units. These interactions are weak when the streams connecting the units are small compared to the network throughput or when ``low-pass filters'' (surge tanks) are built into the network. However, modern plant design favors leaner plants, that feature tight integration (\eg through large recycle flow rates), fewer units and diminished material inventory. In this latter case, interactions between units are significant, and have been shown to give rise to more complex, overall network dynamics, in addition to the dynamics of the individual units.

Strong interactions and the consequent presence of an overall network dynamic behavior lead to a strong coupling between the control loops of the process units. Control loop coupling due to plant-wide interactions has been recognized by many researchers as a major issue, that must be addressed within a plant-wide control setting. Yet, the majority of the studies concerning the control of process networks with material and energy recycle have been within a multi-loop linear control framework. In general, the implementation of advanced, model-based, control strategies for process networks is hindered by the often overwhelming size and complexity of their dynamic models. In most cases, the design of fully centralized controllers on the basis of entire network models is impractical, such controllers being almost invariably ill conditioned, difficult to tune, expensive to implement and maintain, and sensitive to measurement errors and noise. The need for finding a rational and transparent paradigm for synthesizing model-based control structures for entire networks has thus emerged as a key issue in modern process control.

In our previous work [1,2], we have investigated the dynamics of process networks with large recycle streams and of process networks with purge streams. We have demonstrated that the presence of flowrates of vastly different magnitudes induces a time scale separation in the material and energy dynamics of such process networks, their behavior featuring two time scales. Using singular perturbation tools, we derived reduced order models for the dynamics in each of the time scales, and proposed a controller design framework that accounts for the time scale separation.

In the present work, we consider generic integrated process networks, featuring significant material recycling and impurities present in the feed stream removed by a small purge stream. We show that such networks exhibit a dynamic behavior featuring three time scales. Employing singular perturbation arguments, we identify the process parameters that are at the origin of this behavior, thereby establishing a connection between steady state design and the network dynamics. Also, following a nested application of singular perturbations, we derive reduced-order, nonlinear models for the dynamics in each time scale. Subsequently, we reveal the implications of the integrated network design on the selection of control structures and on controller synthesis. Specifically, our analysis provides a rational means for selecting the manipulated inputs that act in each time scale and can thus be used to address the regulatory and supervisory control objectives of the network. Moreover, we propose a hierarchical controller design framework that takes advantage of the identified time scale multiplicity, by relying on the derived reduced order models for the synthesis of well-conditioned supervisory controllers.

The developed concepts are exemplified through a case study on the dynamics and control of a reactor-single-stage separator network core. Such structures lie at the heart of benchmark industrial plant wide control examples, their rigorous analysis thus representing an important step in tackling the dynamic and control challenges posed by integrated chemical plants. In this study, we perform a dynamic analysis of the class of networks considered, and develop a hierarchical control system that accounts for their multiple time scale behavior. Illustrative numerical simulation results are then provided.

[1] A. Kumar and P. Daoutidis, J. Proc Contr, 12 (2002) 475–484.

[2] M. Baldea, P. Daoutidis and A. Kumar, AIChE J., submitted.