2 Loop Pairing Analysis

Despite the availability of sophisticated methods for designing multivariable control systems, decentralized control remains dominant in industry applications, because of its simplicity in design and ease of implementation, tuning, and maintenance with less cost \[29, 30\]:

(i) Hardware simplicity: The cost of implementation of a decentralized control system is significantly lower than that of a centralized controller. A centralized control system for an $n \times n$ plant consists of $n!$ individual single-input single-output transfer functions, which significantly increases the complexity of the controller hardware. Furthermore, if the controlled and/or manipulated variables are physically far apart, a full controller could require numerous expensive communication links.

(ii) Design and tuning simplicity: Decentralized controllers involve far fewer parameters, resulting in a significant reduction in the time and cost of tuning.

(iii) Flexibility in operation: A decentralized structure allows operating personnel to restructure the control system by bringing subsystems in and out of service individually, which allows the system to handle changing control objectives during different operating conditions.

However, the potential disadvantage of using the limited control structure is the deteriorated closed-loop performance caused by interactions among loops as a result of the existence of nonzero off-diagonal elements in the transfer function matrix. Therefore, the primary task in the design of decentralized control systems is to determine loop pairings that have minimum cross interactions among individual loops. Consequently, the resulting multiple control loops mostly resemble their SISO counterparts such that controller tuning can be facilitated by SISO design techniques \[31\]. This chapter aims to obtain a new loop pairing criterion which may result in minimum loop interactions.

2.1 Introduction

Since the pioneering work of Bristol \[32\], the relative gain array (RGA) based techniques for control-loop configuration have found widespread industry applications, including blending, energy conservation, and distillation columns, etc \[13, 33, 34, 35\].
RGA-based techniques have many important advantages, such as very simple calculation because it is the only process steady-state gain matrix involved and independent scaling due to its ratio nature, etc \[36\]. To simultaneously consider the closed-loop properties, the RGA-based pairing rules are often used in conjunction with the Niederlinski index (NI) \[37\] to guarantee the system stability \[31, 13, 36, 38, 39, 40\]. However, it has been pointed out that this RGA- and NI-based loop-pairing criterion is a necessary and sufficient condition only for a 2 × 2 system; it becomes a necessary condition for 3 × 3 and higher dimensional systems \[36, 41\]. Moreover, it is very difficult to determine which pairing has less interaction between loops when the RGA values of feasible pairings have similar deviations from unity.

To overcome the limitations of a RGA-based loop-pairing criterion, several pairing methods have later been proposed. Witcher and McAvoy \[42\], as well as other authors \[43, 44\], defined the dynamic RGA (DRGA) to consider the effects of process dynamics and used a transfer function model instead of the steady-state gain matrix to calculate RGA, of which the denominator involved achieving perfect control at all frequencies, while the numerator was simply the open-loop transfer function. The \(\mu\)-interaction measurement \[45, 46, 47\] is another measurement for multivariable systems under diagonal or block-diagonal feedback controllers. By employment of structured singular value (SSV) techniques, it can be used not only to predict the stability of decentralized control systems but also to determine the performance loss caused by these control structures. In particular, its steady-state value provides a sufficient condition for achieving offset-free performance with the closed-loop system. Hovd and Skogestad \[41, 48\] introduced performance RGA (PRGA) to solve the problem that the RGA cannot indicate the significant one-way interactions in the case in which the process transfer function matrix is triangular.

Even though some excellent techniques based on the RGA and NI principles have been proposed to measure loop interactions, there is a lack of a systematic method to treat the control structure configuration problem effectively for high-dimensional processes. To solve this problem, the following questions must be addressed: (1) What are the interaction effects to a particular loop when all other loops work together or individually? (2) What are the reverse interaction effects from a particular loop open and closed to other open and closed loops? (3) What is the feasible definition of the minimal interactions?

The flexibility to bring subsystems in and out of service is very important also for the situations when actuators or sensors in some subsystems fail. The characteristic of failure tolerance is that without readjustment to the other parts of the control system, stability can be preserved in the case of any sensor failure and/or actuator failure \[49\]. The RGA \[32, 38\], NI \[37\] and block relative gain (BRG) \[50\] are widely used for eliminating pairing that produce unstable closed-loop systems under failure conditions \[36, 51, 52, 53\]. Chiu and Arkun \[30\] introduced the concept of decentralized closed-loop integrity (DCLI) which requires that the decentralized control structure should be stabilized by a controller having integral action and should maintain its nominal stability in the face of failures in its sensors and/or actuators. A number of necessary or sufficient conditions for DCLI were also developed \[30, 54\]. However, the necessary and sufficient conditions for DCLI are still not available. Morari and co-workers \[52, 55\]