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Design of wide-area damping controllers using the block relative gain

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ABSTRACT

A novel technique to determine the best pairing of inputs and outputs for the design of wide-area damping controllers (WADCs) is proposed. The method extends the conventional use of the relative gain array (RGA) for interacting control systems, to the block relative gain (BRG) to analyze interactions among multi-input multi-output (MIMO) controllers. First, geometric measures of controllability and observability are used to screen the most effective stabilizing signals for partially centralized control of large interconnected power systems. Then, the BRG analysis is used to quantify the potential for adverse interactions between a given set of controllers or subsystems. This gives candidate sets for supplementary controllers which are solved using linear matrix inequality (LMI) techniques and are evaluated in closed-loop mode to detect and quantify process interactions. In general, this approach also allows better coordination of control capabilities and the use of interaction measures to help in the choice of control location and structure. The effectiveness of the proposed control scheme on system behavior is tested on a realistic 5-area model of the Mexican interconnected power system.

1. Introduction

With the advent of distributed renewable generation and more complex system configurations, there has been a surge of interest in utilizing hierarchically structured, distributed control systems for enhancing global system behavior. At the heart of these techniques are the problems of selecting pairings of input and output variables, and the associated design of control structures for decentralized power system control.

The use of wide-area measurement system (WAMS)-based power system stabilizers (PSSs) and flexible AC transmission system (FACTS) has been suggested as a mean to enhance the dynamic performance of large interconnected power systems [1–3]. Robust control theories such as $\mathcal{H}_\infty$ and μ, which incorporate robust properties and different characteristics of uncertainty, have been used to design feedback controllers [4,5].

In recent years, the development of synchrophasor technology and robust control theory has made possible to design wide-area power system controllers that guarantee robustness and performance of the system over a large range of operating conditions. The performance of centralized controllers, however, may be affected by communication delays and result in highly complex high dimensional control structures. Modern block-decentralized (partially centralized) control techniques, on the other hand, offer the possibility to design efficient, partially decentralized controllers using LMI $\mathcal{H}_\infty$ techniques [6].

WADCs require wide-area signals which have the potential to enhance system dynamic performance, but the size and complexity of modern power systems may lead to undesirable interactions among controllers that can limit their ability to achieve good performance and improve the stability of the system [34].

RGA-based selection of input–output pairings has been studied in the control and power systems literature [7,8,10,11]. Originally, the RGA was introduced to design decentralized controllers assuming that the control has a proportional integral (PI) feedback [9]. The method is particularly well suited to the analysis and detection of relationships between control loops, but is conservative and empirical; it uses knowledge of the steady-state process and lacks dynamic information, which may result in wrong pairings and inaccurate quantification of the amount of control loop interactions.

In order to evaluate dynamic control loop interactions, the RGA was extended to include frequency evaluations; this method was called the dynamic relative gain array (DRGA). To avoid the RGA constraints arising from the use of integral feedback, the generalized dynamic relative gain (GDRG) was proposed to generalize the concept of RGA to dynamic decentralized control of general closed-loop systems [12,13]. Other similar methodologies derived from decentralized control theory have been proposed, but their use has been constrained to specific control structures which limits their applicability [14–17]. The BRG concept and their properties were originally proposed in [18] to extend the relative gain concept from

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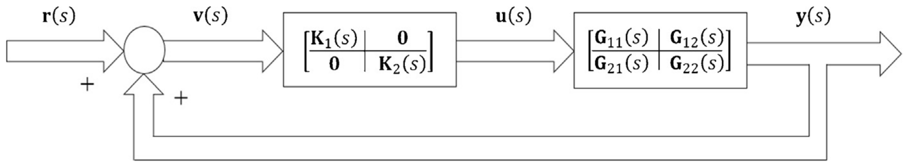

Fig. 1. General block-decentralized control configuration.

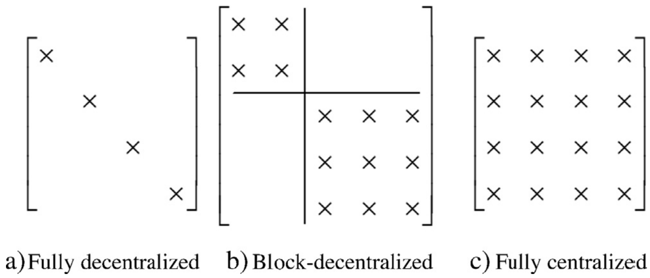

Fig. 2. Comparison of control structures: (a) fully decentralized, (b) block decentralized and (c) fully centralized control.

a scalar to a block matrix representation. In [19–21] the properties of the BRG were studied in a formal context.

The use of RGA was introduced in the power systems literature in [22–24] to coordinate static VAR compensators (SVCs) and PSSs. In [25,26], a general method, to select signals for FACTS devices and locate controllers was examined. In [27,28], the RGA was used to evaluate the capability, control structure and the bifurcation subsystems of a μ-synthesis power system stabilizer design. At present, RGA research focuses on the design of WAMS-based PSSs and FACTS controllers to damp inter-area oscillations [30,36]. In most cases, the selection of the input–output variables for the design of WADCs has been based on single-input single-output (SISO) models [29].

In this paper, a common mathematical framework for decentralized, and quasi-decentralized control of large interconnected power systems is provided. A systematic analytical procedure based on the concept of the BRG and block GDRG is used to design block-decentralized controllers or WADCs to damp out electromechanical oscillations. The method allows to identify the most suitable pairing loops for MIMO WADCs and avoids degradation of performance and stability among designed controllers. In addition, the proposed methodology incorporates the use of LMI techniques to synthesize MIMO controllers. Finally, the design procedure is tested on a 5-area, 46-generator test power system.

2. Preliminaries: system modeling and control structure

Consider a MIMO linear dynamical system described by the state space equations:

$$\begin{aligned} \dot{\mathbf{x}}(t) &= \mathbf{A}\mathbf{x}(t) + \mathbf{B}\mathbf{u}(t), \quad \mathbf{x}(t_0) = \mathbf{x}_0 \\ \mathbf{y}(t) &= \mathbf{C}\mathbf{x}(t) + \mathbf{D}\mathbf{u}(t) \end{aligned} \tag{1}$$

where $\mathbf{x}(t) \in \mathbb{R}^n$ is the vector of states, $\mathbf{x}(t_0)$ is the vector of initial condition of the system, $\mathbf{u}(t) \in \mathbb{R}^p$ is the input vector related to the output signals of WADCs and PSSs to be designed, and $\mathbf{y}(t) \in \mathbb{R}^q$ is the output vector related to the input signals of phasor measurement units (PMU) and speeds of generators. Matrices $\mathbf{A} \in \mathbb{R}^{n\times n}$, $\mathbf{B} \in \mathbb{R}^{n\times p}$, $\mathbf{C} \in \mathbb{R}^{q\times n}$, and $\mathbf{D} \in \mathbb{R}^{q\times p}$ are the state, input, and output matrices, respectively.

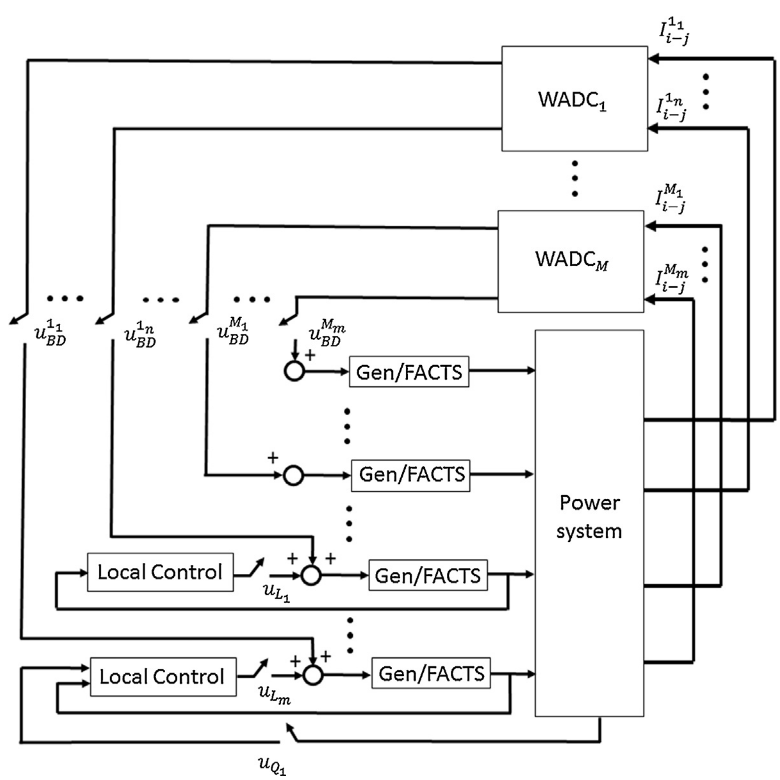

Fig. 3. General control structure.