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Robustness of distributed averaging control in power systems: Time delays & dynamic communication topology ☆

Johannes Schiffer [a], Florian Dörfler [b], Emilia Fridman [c,d]

[a] School of Electronic & Electrical Engineering, University of Leeds, LS2 9JT, United Kingdom

[b] Automatic Control Laboratory, Swiss Federal Institute of Technology (ETH) Zürich, 8092, Switzerland

[c] Tel Aviv University, Tel Aviv 69978, Israel

[d] ITMO University, 49 Avenue Kronverkskiy, 197101 Saint Petersburg, Russia

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ABSTRACT

Distributed averaging-based integral (DAI) controllers are becoming increasingly popular in power system applications. The literature has thus far primarily focused on disturbance rejection, steady-state optimality and adaption to complex physical system models without considering uncertainties on the cyber and communication layer nor their effect on robustness and performance. In this paper, we derive sufficient delay-dependent conditions for robust stability of a secondary-frequency-DAI-controlled power system with respect to heterogeneous communication delays, link failures and packet losses. Our analysis takes into account both constant as well as fast-varying delays, and it is based on a common strictly decreasing Lyapunov–Krasovskii functional. The conditions illustrate an inherent trade-off between robustness and performance of DAI controllers. The effectiveness and tightness of our stability certificates are illustrated via a numerical example based on Kundur's four-machine-two-area test system.

1. Introduction

1.1. Motivation

Power systems worldwide are currently experiencing drastic changes and challenges. One of the main driving factors for this development is the increasing penetration of distributed and volatile renewable generation interfaced to the network with power electronics accompanied by a reduction in synchronous generation. This results in power systems being operated under more and more stressed conditions (Winter, Elkington, Bareux, & Kostevc, 2015). In order to successfully cope with these changes, the control and operation paradigms of today's power systems have to be adjusted. Thereby, the increasing complexity in terms of network dynamics and number of active network elements renders centralized and inflexible approaches inappropriate creating a clear need for robust and distributed solutions with plug-and-play capabilities (Strbac et al., 2015). The latter approaches require a combination of advanced control techniques with adequate communication technologies.

Multi-agent systems (MAS) represent a promising framework to address these challenges (McArthur et al., 2007). A popular distributed control strategy for MAS are distributed averaging-based integral (DAI) algorithms, also known as consensus filters (Freeman, Yang, & Lynch, 2006; Olfati-Saber, Fax, & Murray, 2007) that rely on averaging of integral actions through a communication network. The distributed character of this type of protocol has the advantage that no central computation unit is needed and the individual agents, i.e., generation units, only have to exchange information with their neighbors (Bidram, Lewis, & Davoudi, 2014).

One of the most relevant control applications in power systems is frequency control which is typically divided into three hierarchical layers: primary, secondary and tertiary control (Kundur, 1994). In the present paper, we focus on secondary control which is tasked with the regulation of the frequency to a nominal value in an economically efficient way and subject to maintaining the net area power balance. The literature on secondary DAI frequency controllers addressing these tasks is reviewed in the following.

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E-mail addresses: j.schiffer@leeds.ac.uk (J. Schiffer), dorfler@control.ee.ethz.ch (F. Dörfler), emilia@eng.tau.ac.il (E. Fridman).

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1.2. Literature review on DAI frequency control

DAI algorithms have been proposed previously to address the objectives of secondary frequency control in bulk power systems (Andreasson, Sandberg, Dimarogonas, & Johansson, 2012; Monshizadeh & De Persis, 2017; Schiffer & Dörfler, 2016; Trip, Bürger, & De Persis, 2016) and also in microgrids (i.e., small-footprint power systems on the low and medium voltage level) (Anon, 2016; Bidram et al., 2014; Simpson-Porco, Dörfler, & Bullo, 2013). They have been extended to achieve asymptotically optimal injections (Stegink, De Persis, & van der Schaft, 2016a; Zhao, Mallada, & Dörfler, 2015), and have also been adapted to increasingly complex physical system models (Persis, Monshizadeh, Schiffer, & Dörfler, 2016; Stegink, De Persis, & van der Schaft, 2016b). The closed-loop DAI-controlled power system is a cyber–physical system whose stability and performance crucially relies on nearest-neighbor communication. Despite all recent advances, communication-based controllers (in power systems) are subject to considerable uncertainties such as message delays, message losses, and link failures (Strbac et al., 2015; Yang, Barria, & Green, 2011) that can severely reduce the performance – or even affect the stability – of the overall cyber–physical system. Such cyber–physical phenomena and uncertainties have not been considered thus far in DAI-controlled power systems.

For microgrids, the effect of communication delays on secondary controllers has been considered in Liu, Wang, and Liu (2015) for the case of a centralized PI controller, in Ahumada, Crdenas, Sez, and Guerrero (2016) for a centralized PI controller with a Smith predictor as well as a model predictive controller and in Coelho et al. (2016) for a DAI-controlled microgrid with fixed communication topology. In all three papers, a small-signal (i.e., linearization-based) analysis of a model with constant delays is performed.

In Lai, Zhou, Lu, and Liu (2016) and Lai, Zhou, Lu, Yu, and Hu (2016) distributed control schemes for microgrids are proposed, and conditions for stability under time-varying delays as well as a dynamic communication topology are derived. However, both approaches are based on the pinning-based controllers requiring a master–slave architecture. Compared to the DAI controller in the present paper, this introduces an additional uncertainty as the leader may fail (see also Remark 1 in Lai, Zhou, Lu, Yu, & Hu, 2016). In addition, the analysis in Lai, Zhou, Lu, and Liu (2016) and Lai, Zhou, Lu, Yu, and Hu (2016) is restricted to the distributed control scheme on the cyber layer and neglects the physical dynamics. Moreover, the control in Lai, Zhou, Lu, and Liu (2016) is limited to power sharing strategies, and secondary frequency regulation is not considered.

The delay robustness of alternative distributed secondary control strategies (based on primal–dual decomposition approaches) has been investigated for constant delays and a linearized power system model in Zhang, Kang, McCulloch, and Papachristodoulou (2016) and Zhang and Papachristodoulou (2014).

1.3. Contributions

The present paper addresses both the cyber and the physical aspects of DAI frequency control by deriving conditions for robust stability of nonlinear DAI-controlled power systems under communication uncertainties. With regard to delays, we consider constant as well as fast-varying delays. The latter are a common phenomenon in sampled data networked control systems, due to digital control (Fridman, 2014a,b; Liu & Fridman, 2012) and as the network access and transmission delays depend on the actual network conditions, e.g., in terms of congestion and channel quality (Hespanha, Naghshtabrizi, & Xu, 2007). In addition to delays, in practical applications the topology of the communication network can be time-varying due to message losses and link failures (Lin & Jia, 2008; Olfati-Saber et al., 2007; Olfati-Saber & Murray, 2004). This can be modeled by a switching communication network (Olfati-Saber et al., 2007; Olfati-Saber & Murray, 2004). Thus, the explicit consideration of communication uncertainties leads to a *switched nonlinear power system model with (time-varying) delays* the stability of which is investigated in this paper.

More precisely, our main contributions are as follows. First, we derive a strict Lyapunov function for a nominal DAI-controlled power system model without communication uncertainties, which may also be of independent interest. Second, we extend this strict Lyapunov function to a common Lyapunov–Krasovskii functional (LKF) to provide sufficient delay-dependent conditions for robust stability of a DAI-controlled power system with dynamic communication topology as well as heterogeneous constant and fast-varying delays. Our stability conditions can be verified without exact knowledge of the operating state and reflect a fundamental trade-off between robustness and performance of DAI control. Third and finally, we illustrate the effectiveness of the derived approach on a numerical benchmark example, namely Kundur's four-machine-two-area test system (Kundur, 1994, Example 12.6).

The remainder of the paper is structured as follows. In Section 2 we recall some preliminaries on algebraic graph theory and introduce the power system model employed for the analysis. The DAI control is motivated and introduced in Section 3, where we also derive a suitable error system. A strict Lyapunov function for the closed-loop DAI-controlled power system is derived in Section 4. Based on this Lyapunov function, we then construct a common LKF for DAI-controlled power systems with constant and fast-varying delays in Section 5. A numerical example is provided in Section 6. The paper is concluded with a brief summary and outlook on future work in Section 7.

Notation. We define the sets $\mathbb{R}_{\geq 0} := \{x \in \mathbb{R} | x \geq 0\}$, $\mathbb{R}_{>0} := \{x \in \mathbb{R} | x > 0\}$ and $\mathbb{R}_{<0} := \{x \in \mathbb{R} | x < 0\}$. For a set $\mathcal{V}$, $|\mathcal{V}|$ denotes its cardinality and $[\mathcal{V}]^k$ denotes the set of all subsets of $\mathcal{V}$ that contain k elements. Let $x = \mathrm{col}(x_i) \in \mathbb{R}^n$ denote a vector with entries x_i for $i \in \{1, \dots, n\}$, $\mathbb{0}_n$ the zero vector, $\mathbb{1}_n$ the vector with all entries equal to one, I_n the $n \times n$ identity matrix, $\mathbb{0}_{n\times n}$ the $n \times n$ matrix with all entries equal to zero and $\mathrm{diag}(a_i)$ an $n \times n$ diagonal matrix with diagonal entries $a_i \in \mathbb{R}$. Likewise, $A = \mathrm{blkdiag}(A_i)$ denotes a block-diagonal matrix with block-diagonal matrix entries A_i. For $A \in \mathbb{R}^{n\times n}$, $A > 0$ means that A is symmetric positive definite. The elements below the diagonal of a symmetric matrix are denoted by $*$. We denote by $W[-h, 0]$, $h \in \mathbb{R}_{>0}$, the Banach space of absolutely continuous functions $\phi : [-h, 0] \to \mathbb{R}^n$, $h \in \mathbb{R}_{>0}$, with $\dot{\phi} \in L_2(-h, 0)^n$ and with the norm $\|\phi\|_W = \max_{\theta\in[a,b]} |\phi(\theta)| + \left(\int_{-h}^{0} \dot{\phi}^2 d\theta\right)^{0.5}$. Also, ∇f denotes the gradient of a function $f : \mathbb{R}^n \to \mathbb{R}$.

2. Preliminaries

2.1. Algebraic graph theory

An undirected graph of order n is a tuple $\mathcal{G} = (\mathcal{N}, \mathcal{E})$, where $\mathcal{N} = \{1, \dots, n\}$ is the set of nodes and $\mathcal{E} \subseteq [\mathcal{N}]^2$, $\mathcal{E} = \{e_1, \dots, e_m\}$, is the set of undirected edges, i.e., the elements of $\mathcal{E}$ are subsets of $\mathcal{N}$ that contain two elements. In the context of the present work, each node in the graph represents a generation unit. The adjacency matrix $\mathcal{A} \in \mathbb{R}^{|\mathcal{N}|\times|\mathcal{N}|}$ has entries $a_{ik} = a_{ki} = 1$ if an edge between i and k exists and $a_{ik} = 0$ otherwise. The degree of a node i is defined as $d_i = \sum_{k=1}^{|\mathcal{N}|} a_{ik}$. The Laplacian matrix of an undirected graph is given by $\mathcal{L} = \mathcal{D} - \mathcal{A}$, where $\mathcal{D} = \mathrm{diag}(d_i) \in \mathbb{R}^{|\mathcal{N}|\times|\mathcal{N}|}$. An ordered sequence of nodes such that any pair of consecutive nodes in the sequence is connected by an edge is called a path. A graph $\mathcal{G}$ is called connected if for all pairs