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An internal model approach to (optimal) frequency regulation in power grids with time-varying voltages[☆]

Sebastian Trip[a,1], Mathias Bürger[b], Claudio De Persis[a]

[a] ENTEG, Faculty of Mathematics and Natural Sciences, University of Groningen, Nijenborgh 4, 9747 AG Groningen, The Netherlands
[b] Cognitive Systems, Corporate Research, Robert Bosch GmbH, Robert Bosch Campus 1, 71272 Renningen, Germany

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ABSTRACT

This paper studies the problem of frequency regulation in power grids under unknown and possible time-varying load changes, while minimizing the generation costs. We formulate this problem as an output agreement problem for distribution networks and address it using incremental passivity and distributed internal-model-based controllers. Incremental passivity enables a systematic approach to study convergence to the steady state with zero frequency deviation and to design the controller in the presence of time-varying voltages, whereas the internal-model principle is applied to tackle the uncertain nature of the loads.

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1. Introduction

The power grid can be regarded as a large interconnected network of different subsystems, called control area's. In order to guarantee reliable operation, the frequency is tightly regulated around its nominal value, e.g. 60 Hz. Automatic regulation of the frequency in power grids is traditionally achieved by primary proportional control (droop-control) and a secondary PI-control. In this secondary control, commonly known as automatic generation control (AGC), each control area determines its "Area Control Error" (ACE) and changes its production accordingly to compensate for local load changes in order to regulate the frequency back to its nominal value and to maintain the scheduled power flows between different area's.

By requiring each control area to compensate for their local load changes the possibility to achieve economic efficiency is lost. Indeed, the scheduled production in the different control area's is currently determined by economic criteria relatively long in advance. To be economically efficient an accurate prediction of load changes is necessary. Large scale introduction of volatile renewable energy sources and the use of electrical vehicles will however make accurate prediction difficult as the net load (demand minus renewable generation) will change on faster time scales and by larger amounts.

Due to the difficulty of precisely predicting the load, the problem of designing algorithms for power generation able to maintain the network at nominal operating conditions despite the effect of unmeasured power demand and while retaining economic efficiency has attracted considerable attention and a vast literature is already available. The aim of this paper is to provide a different framework in which the problem can be tackled exploiting the incremental passive nature of the dynamical system adopted to model the power network and internal-model-based controllers (Bürger & De Persis, 2015; Pavlov & Marconi, 2008) able to achieve an economically efficient power generation control in the presence of possibly time-varying power demand. We focus on a third-order model with time-varying voltages known as "flux-decay model" (Chiang, Chu, & Cauley, 1995; Machowski, Bialek, & Bumby, 2008), which, although simplistic, is tractable and meaningful.

Literature review. An up-to-date review of current research on AGC can be found in Ibraheem, Kumar, and Kothari (2005). The economic efficiency of AGC has attracted considerable attention and the vast literature available makes the task of providing an exhaustive survey very difficult. Relevant results which are close to

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[☆] An abridged version of the paper has appeared in Bürger et al. (2014). The material in this paper was partially presented at the 21th International Symposium on Mathematical Theory of Networks and Systems (MTNS), July 7–11, 2014, Groningen, The Netherlands. This paper was recommended for publication in revised form by Associate Editor Jun-ichi Imura under the direction of Editor Toshiharu Sugie.

E-mail addresses: s.trip@rug.nl (S. Trip), mathias.buerger@de.bosch.com (M. Bürger), c.de.persis@rug.nl (C. De Persis).

[1] Tel.: +31 50 363 3077.

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the present paper are briefly discussed below to better emphasize our contribution.

In Andreasson, Dimarogonas, Johansson, and Sandberg (2013), distributed and centralized controllers that require the knowledge of the frequency deviations at the bus and its neighbors are proposed for the linearized version of the swing equation and shown to achieve frequency regulation while minimizing a quadratic cost function under a suitable matrix condition. An economically efficient, discrete time AGC algorithm incorporating generator constraints is proposed in Apostolopoulou, Sauer, and Domínguez-García (2014) and investigated numerically. The use of distributed proportional and proportional–integral controllers for microgrids has been studied in Guerrero, Vasquez, Matas, de Vicuña, and Castilla (2011), Simpson-Porco, Dörfler, and Bullo (2013) with additional economic insights provided in Dörfler, Simpson-Porco, and Bullo (2014), where, among other contributions, decentralized tertiary control strategies have been proposed. Investigation of stability conditions for droop controllers in a port-Hamiltonian framework and in the presence of time-varying voltages was pursued in Schiffer, Ortega, Astolfi, Raisch, and Sezi (2013). In Li, Chen, Zhao, and Low (2014), Zhang and Papachristodoulou (2013), the problem of optimal frequency regulation was tackled by formulating suitable optimal power flow problems, characterizing their solutions and then providing gradient-like algorithms that asymptotically converge to the optimum. While Zhang and Papachristodoulou (2013) focused on power networks with star topology, quadratic cost functions and including equality and inequality constraints, the paper (Li et al., 2014) does not assume any specific topology for the network and considers convex cost functions, but assumes the knowledge of the power flows at the buses to guarantee the achievement of the desired steady state solution. Work relating automatic generation control and optimal load control has appeared in Zhao and Low (2014), Zhao, Topcu, and Low (2013), with the former focusing on linearized power flows and without generator-side control and the latter removing these assumptions.

Main contribution. The contribution of this paper is to propose a new approach to the problem that differs substantially from the aforementioned works. We move along the lines of Bürger and De Persis (2013, 2015), where a framework to deal with nonlinear output agreement and optimal flow problems for dynamical networks has been proposed. In those papers internal-model-based dynamic controllers have been designed to solve output agreement problems for networks of incrementally passive systems (Pavlov & Marconi, 2008) in the presence of time-varying perturbations. In this paper we build upon (Bürger, De Persis, & Trip, 2014). After showing that the dynamical model adopted to describe the power network is an incrementally passive system with respect to solutions that are of interest (solutions for which the frequency deviation is zero), we provide a systematic method to design internal-model-based power generation controllers that are able to balance power loads while minimizing the generation costs at steady state.

This design is carried out first by solving the regulator equations (Bürger & De Persis, 2015; Pavlov & Marconi, 2008) associated with the frequency regulation problem. Among the feedforward power generation inputs that solve the regulator equations, we single out the one for which the static optimal generation problem is solved. Then, following Bürger and De Persis (2013, 2015), an internal-model-based incrementally passive controller is proposed which is able to generate in open-loop the desired feedforward input and stabilize the closed-loop system in such a way that all the solutions converge to the desired synchronous solution and to the optimal generation control.

Although the proposed incrementally passive controllers share similarities with others presented in the literature, the way in which they are derived is to the best of our knowledge new. Moreover, they show a few advantages.

(i) If we allow for time-varying power demand in the model, our internal-model controllers can deal with this scenario and it turns out that proportional–integral controllers that are more often found in the literature are a special instance of these controllers.

(ii) Being based on output regulation theory for systems over networks (Bürger & De Persis, 2013, 2015; De Persis & Jayawardhana, 2014; Isidori, Marconi, & Casadei, 2014; Wieland, Sepulchre, & Allgöwer, 2011), our approach has the potential to deal with fairly rich classes of external perturbations (Cox, Marconi, & Teel, 2012; Serrani, Isidori, & Marconi, 2001), thus paving the way towards frequency regulators in the presence of a large variety of consumption patterns. Furthermore, other extensions of Bürger and De Persis (2015) considered the presence of non-quadratic cost functions and flow capacity constraints (Bürger, De Persis, & Allgöwer, 2014a,b) that could turn out to be useful also for the problem considered here. See Li et al. (2014), Zhao and Low (2014), Zhao et al. (2013) for a different approach to deal with non-quadratic cost functions and constraints.

(iii) Passivity is an important feature shared by more accurate models of the power network, as already recognized in Caliskan and Tabuada (2014), Shaik, Zonetti, Ortega, Scherpen, and van der Schaft (2013), and in Schiffer et al. (2013) in the context of microgrids, implying that the methods that are employed in this paper might be used to deal with more complex (and more realistic) dynamical models. Although this level of generality is not pursued in this paper, the passivity framework allows us to include voltage dynamics in our model, a feature that is usually neglected in other approaches (Andreasson et al., 2013; Li et al., 2014; Zhang & Papachristodoulou, 2013), but see Schiffer et al. (2013) for the inclusion of time-varying voltages in the case of microgrids, and also (Simpson-Porco et al., 2013). Furthermore, passivity is a very powerful tool in the analysis and design of dynamical control networks (Bai, Arcak, & Wen, 2011; van der Schaft & Maschke, 2013).

(iv) To show incremental passivity we introduce storage functions that interestingly can be interpreted as energy functions, thus establishing a connection with classical work in the field (see e.g. Bergen & Hill, 1981 and Chiang et al., 1995 and references therein) that can guide a further investigation of the problem. For instance, it can lead to the inclusion of automatic voltage regulators (Chiang et al., 1995; Miyagi & Bergen, 1986) in the analysis, a study that is not explored in this paper.

The paper is organized as follows. In Section 2, we introduce the dynamical model adopted to describe the power grid. In Section 3, we analyze the dynamical model assuming constant generation, and show that it leads to a nonzero frequency deviation. In Section 4, we characterize the optimum generation to minimize the generation costs. In Section 5, we propose a distributed controller which ensures frequency regulation and at the same time minimizes the generation costs under the assumption of constant demand. In Section 6, the restriction of constant demand is relaxed and we extend results to the case of a certain class of time-varying demands. In Section 7, we test our controllers for an academic case study using simulations. In Section 8, conclusions are given and an outline for future research is provided.

2. System model

The history of power grid modeling is rich and the models we adopt can be found in most textbooks on power systems such as (Machowski et al., 2008). We focus on swing equations to take into account the frequency dynamics and, comparing to recent work which also concerns optimal frequency regulation (Bürger et al., 2014; Dörfler et al., 2014; Li et al., 2014; Zhao & Low, 2014), we do

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