Automatica 94 (2018) 102–111

Contents lists available at ScienceDirect

Automatica

journal homepage: www.elsevier.com/locate/automatica

Brief paper

Real-time power sharing: Dynamic control allocation and VPP aggregation☆

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ARTICLE INFO

Article history:
Received 30 December 2016
Received in revised form 30 September 2017
Accepted 11 March 2018
Available online 3 May 2018

Keywords:
Power generation
Distributed control
Control allocation
Redundant control systems
H_2-optimization

ABSTRACT

This paper studies the problem of the dynamic coordination of power generation by Distributed Energy Resource (DER) networks. The problem is posed as minimizing the fuel consumption by the whole network under prespecified overall power generation. Two technical challenges toward this end addressed in the paper are how to exploit control redundancy and how to account for limitations on available communication infrastructure. To fully exploit control redundancy, a state-space characterization of all stable right inverses of right-invertible systems is derived. Demands on the information exchange are alleviated via the proposed split of DERs into Virtual Power Plants (VPPs), which contain DERs with equal dynamics. It is demonstrated that this approach can substantially reduce both computational complexity and amount of information exchange in the system.

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1. Introduction

Recent years have witnessed a growing demand for electricity, which has led to increasing generation of energy by Distributed Energy Resources (DERs) (Pudjianto, Ramsay, & Strbac, 2007). As part of this trend, nuclear and fossil fuel based power plants are now supported or even replaced by small and autonomous generators, such as renewable sources. This ongoing change creates many challenges concerning the design and operation of power systems, and especially raises questions regarding the grid stability, reliability, and efficiency (Bouhafs, Mackay, & Merabti, 2012).

Distributed sources should be coordinated to supply power demands of loads, while maintaining efficient and reliable energy production. One challenge is to cope with problem dimensions and communication constraints. An approach for coordinating DERs in real-time is investigated by Prodanović and Green (2006). The DERs are assumed to have identical dynamics, up to scaling, and are optimally controlled to provide high power quality. Several studies suggest hierarchical control schemes (Bidram & Davoudi, 2012; Vandoorn, Vasquez, Kooning, Guerrero, & Vandevelde, 2013; Vasquez, Guerrero, Miret, Castilla, & de Vicuña, 2010) to overcome some of the obstacles that arise from implementing real-time power-sharing controllers in large-scale systems.

In this paper we put forward an alternative approach, which is based on aggregating generators with identical dynamics into Virtual Power Plants (VPPs), with the need to coordinate only between VPPs, not each individual generator. This may be viewed as a generalization of the approach of Madjidian and Mirkin (2014) (and, to some extent, that of Prodanović and Green (2006)) to the case of several groups of agents. As the number of generators is normally much higher than the number of different generator types, this approach can yield a substantial reduction in communication demands to coordinate DERs.

Another challenge, which may also be seen as an opportunity, is that the power distribution among DERs is not unique. Namely, the same total power can be produced by different combinations of power generation at individual DERs (Zhao & Dörfler, 2015). This degree of freedom could be exploited to reduce the overall costs of operation, since at every given moment the most efficient combination of DERs can be dispatched. Such problems have been extensively studied in the context of optimal *steady-state* power flow problems (Grainger & Stevenson, 1994), however exploiting this opportunity under changing loads conditions and in transient regimes is currently an open challenge (Olivares et al., 2014). One of our main contributions in this paper is an extension of

☆ Supported by the Grand Technion Energy Program, grant 2020938 and by the Israel Science Foundation (grant no. 2000/17). The material in this paper was not presented at any conference. This paper was recommended for publication in revised form by Associate Editor Giancarlo Ferrari-Trecate under the direction of Editor Ian R. Petersen.

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https://doi.org/10.1016/j.automatica.2018.04.020
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the approach of Grainger and Stevenson (1994) to account for *dynamic* properties of DERs and demonstrate that the gain of doing this is worthwhile. We demonstrate that operation costs can be substantially reduced if power generation during transients is done by small DERs having low inertia, while the bulk of the steady-state load is carried by high-inertia powerful generators.

To this end, we develop new technical tools for characterizing the degree of freedom available in redundant control problems. These tools may be of a general interest, as issues related to actuation redundancies arise in a wide spectrum of control problems, like multi-arm cooperating robots (Hayati, 1986), dual-stage actuators (Zheng, Su, & Fu, 2010), fault tolerant control (Zhao & Jiang, 1998), multi-rate sampled-data systems (Francis & Georgiou, 1988), et cetera (Johansen & Fossen, 2013). To the best of our knowledge, there is still no *exhaustive* characterization of the freedom of choice in general output feedback problems with redundant control action. Redundancy is commonly exploited via some special structure of state-space realizations, like the right invertibility of the system "B" matrix or special state-space realizations. The only dynamic characterizations appear to be those in Serrani (2012), where state feedback is studied in geometric framework, and Cristofaro and Galeani (2014), which considers the output-feedback case and exploits the Smith form decomposition of the system. But even these studies do not investigate the completeness of derived characterizations, which is important in our context.

The paper is organized as follows. Section 2 introduces the problem setup, technical assumptions, and the formulation of the problem, whose solution is provided in Section 3. The next two sections are devoted to the proof. First, in Section 4 we present general results on parametrizing all stable right inverses of a class of LTI systems, which are of independent interest. These results are then used in Section 5 to prove the main result. The generalization to the case of unstable systems are outlined in Section 6. Section 7 then explains how to aggregate DERs with identical dynamics to reduce computational and communication burden. Section 8 contains simulation results, showing advantages of the proposed approach over the conventional static power sharing.

Notation. The transpose of a matrix A is denoted by A'. By $\operatorname{diag}\{A_i\}$ we denote the block-diagonal matrix with A_i on its diagonal. If a is a vector, $\|a\|$ means its Euclidean norm. The closed right-half plane $\overline{\mathbb{C}}_0 := \{s \mid \operatorname{Re} s \geq 0\}$. The conjugate transfer function $G^{\sim}(s) := [G(-s)]'$. The space $H_2^{n\times m}$, or just H_2, comprises causal $n \times m$ systems, whose impulse responses are square integrable in $[0, \infty)$. By RH_2 we denote a subset of systems in H_2 whose transfer functions are rational. It is the set of all strictly proper rational transfer functions with no poles in $\overline{\mathbb{C}}_0$. The space $H_\infty^{n\times m}$, or just H_∞, comprises stable and causal $n \times m$ systems, whose transfer functions are holomorphic and bounded in $\{s \mid \operatorname{Re} s > 0\}$. Its subset RH_∞ comprises all systems with proper and rational transfer functions having no poles in $\overline{\mathbb{C}}_0$. We thus use RH_∞ to denote the set of all causal and stable finite-dimensional systems.

2. Problem formulation

2.1. Problem setup

The setup in Fig. 1 outlines the logic of a distributed power system with ν distributed energy resources (DERs) and κ loads, interconnected via a transmission and distribution system. It is common to assume that the bus is infinite, which can be done for large grids, see Fitzgerald, Kingsley, and Umans (1983). This assumption facilitates the separation of dynamics of individual DERs from each other and from the loads, so that the effect of interconnections could be accounted via exogenous disturbances, denoted d_i in Fig. 1.

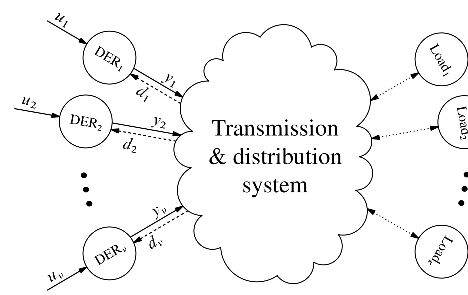

Fig. 1. Schematic diagram of a power grid.

Let $u_i(t)$ denote the deviation of the power reference signal of DER_i from its chosen equilibrium. It is related to the mechanical power, or the amount of fuel, supplied to it. Let $y_i(t)$ denote the deviation of the generated real electrical power by DER_i from the corresponding equilibrium. We think of the ith DER as a system connecting $u_i(t)$ and $y_i(t)$. In describing this connections, we use the so-called *average-value* or *quasi-static* models, like those presented in Anderson and Fouad (2002, Ch. 6) or Fitzgerald et al. (1983, Ch. 8). In this framework, signals are represented as time-varying phasors and the results are accurate as long as the phasors vary slowly in comparison to the systems frequency (Miller, Cibulka, Brown, & von Meier, 2013). Although such models effectively disregard fast parts of DERs dynamics, their effect on the grid behavior is of minor importance, so the approach is plausible. What we gain is the *linearity* and *time invariance* of the mappings $(u_i, d_i) \mapsto y_i$. Namely, we model DER_i as

$$y_i = P_i u_i + d_i, \tag{1}$$

where P_i is an LTI system with the transfer function $P_i(s)$.

The ultimate goal of the whole system is to maintain required power supply balanced with load consumption (Sarlette, Dai, Phulpin, & Ernst, 2012). This goal can be expressed as the requirement to follow a given power reference trajectory $r(t)$ as

$$\sum_{i=1}^{\nu} y_i(t) = r(t), \quad \forall t > 0. \tag{2}$$

As (2) can be attained by various combinations of y_i's, we have redundancy. The question then is how to exploit it.

A possible approach, which we adopt in this paper, is to endeavor to minimize the fuel consumption of the whole grid. The effect of the control input on the *fuel consumption rate* of an individual DER may be taken to be of the form Grainger and Stevenson (1994)

$$f_i(t) = a_i u_i^2(t) + b_i u_i(t) + c_i \tag{3}$$

for some constants $a_i > 0$, b_i, and c_i determining the efficiency of transforming the fuel energy into control effort. The minimization of (3) under a fixed power production is a well-exploited approach in the *static* setting, when the dynamics of DERs are neglected and disturbances d_i are not accounted for, see Grainger and Stevenson (1994). It can be verified that if $y_i(t) = P_i(0)u_i(t)$, where $P_i(0)$ is the static gain of P_i, the total fuel consumption rate $\sum_i f_i(t)$ is minimized at every t by

$$u_i(t) = \frac{P_i(0)/a_i}{\sum_j [P_j(0)]^2/a_j}\left(r(t) + \sum_{j=1}^{\nu} \frac{P_j(0)b_j}{2a_j}\right) - \frac{b_i}{2a_i}, \tag{4}$$

which is the most efficient steady-state distribution of fuel consumptions guaranteeing (2). Yet this solution does not account for/exploit dynamical properties of DERs and thus might miss some

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