Automatica 61 (2015) 18–26

Contents lists available at ScienceDirect

Automatica

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

Distributed control and optimization in DC microgrids☆

Jinxin Zhao[a], Florian Dörfler[b]

[a] Department of Mechanical and Aerospace Engineering, University of California, Los Angeles, CA, 90024, United States

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

ARTICLE INFO

Article history:
Received 9 October 2014
Received in revised form
26 March 2015
Accepted 29 June 2015
Available online 11 August 2015

Keywords:
DC microgrids
Load sharing
Distributed control
Optimal control
Stability analysis

ABSTRACT

Due to their compatibility with renewable and distributed generation, microgrids are a promising operational architecture for future power systems. Here we consider the operation of DC microgrids that arise in many applications. We adopt a linear circuit model and propose a decentralized voltage droop control strategy that is inspired by frequency droop control in AC networks. We demonstrate that our primary droop control strategy is able to achieve fair and stable load sharing (even in presence of actuation constraints) or an economic dispatch of the generation formulated as a quadratic and linearly-constrained optimization problem on the source injections. Similar to frequency droop control, voltage droop control induces a steady-state voltage drift depending on the imbalance of load and generation in the microgrid. To compensate for this steady-state error, we consider two secondary control strategies. A purely decentralized secondary integral control strategy successfully compensates for the steady-state voltage drifts yet it fails to achieve the desired optimal steady-state injections. Next, we propose a consensus filter that requires communication among the controllers, that regulates the voltage drift, and that recovers the desired optimal injections. The performance and robustness of our controllers are illustrated through simulations.

1. Introduction

Driven by environmental concerns, renewable energy sources are rapidly deployed, such as photovoltaic and wind generation. These sources will, for the most part, be deployed as small-scale generation units in low-voltage distribution networks. As a natural consequence, the conventional centralized and hierarchical operation of power grids is advancing towards distributed and flat architectures, and so-called microgrids have been proposed as conceptual solutions. Microgrids are low-voltage electrical distribution networks, composed of distributed generations, storages and loads. The advantages of microgrids are as follows: first, microgrids are capable of connecting to the power transmission grid, but they are also able to island themselves and operate independently, e.g., in case of an outage. Second, microgrids can be deployed as stand-alone small-footprint power systems (possibly in remote locations) while providing high quality power supply, e.g., in hospitals, research facilities, and school campuses. Third and finally, microgrids are naturally designed to integrate small-scale distributed generation, i.e., power is generated where it is needed without transmission losses.

Microgrids have been proposed based on either alternative current (AC) or direct current (DC) paradigms. AC power grids have been in service for many decades, and their components and operation are well understood. The operational paradigms from conventional AC power transmission networks have been inherited in AC microgrids (Guerrero, Vasquez, Matas, de Vicuna, & Castilla, 2011). However, using DC microgrids has the following advantages: there is an increasing number of DC sources and storages (e.g., solar cells and Li-ion batteries), end-user equipment (e.g., electric vehicles), and most of the contemporary electronic appliances. In Nilsson and Sannino (2004) it is demonstrated that many daily loads supplied by AC nowadays can operate also with a DC supply. In comparison to AC microgrids with DC sources, the efficiency is raised since conversion losses of DC-to-AC inverters are removed—though conversion losses arise in DC-to-DC converters for sources with different voltage levels. Finally, DC microgrids are widely deployed in aircrafts and spacecrafts (Justo, Mwasilu, Lee, & Jung, 2013). In summary, DC microgrids are a promising technology that has already attracted much research attention.

☆ A preliminary version of part of this paper's results is Zhao and Dörfler (2015). This work was supported by ETH Zürich startup funds. The material in this paper was presented at the 2015 American Control Conference, July 1–3, 2015, Chicago, IL, USA. 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: jinxinzh@ucla.edu (J. Zhao), dorfler@ethz.ch (F. Dörfler).

http://dx.doi.org/10.1016/j.automatica.2015.07.015
0005-1098/

Literature review: The articles (Guerrero et al., 2011; Ito, Zhongqing, & Akagi, 2004; Salomonsson & Sannino, 2007) focus on the hardware implementation of DC microgrids. A hierarchical control layout for DC microgrids is proposed in Guerrero et al. (2011): a primary controller rapidly stabilizes the grid, and a secondary controller (on a slower time scale) corrects for the steady-state error induced by primary control. An experimental system involving solar-cell, wind turbine and power storage is designed and constructed in Ito et al. (2004). A low-voltage DC distribution system for sensitive loads is described in Salomonsson and Sannino (2007). In Shafiee, Dragicevic, Vasquez, and Guerrero (2014), a modeling method of DC microgrid clusters is described. A scenario-based operation strategy for a DC microgrid is developed in Xu and Chen (2011), emphasizing the detailed model and control of wind turbine and battery. Feasibility conditions for DC microgrids with constant power loads were proposed in Simpson-Porco, Dörfler, and Bullo (2015). A cooperative control paradigm is proposed in Nasirian, Moayedi, Davoudi, and Lewis (2015) to establish a distributed primary/secondary control framework for DC microgrids with communication capabilities. Distributed controllers have been studied to regulate multi-terminal DC transmission systems which share similar problem aspects with DC microgrids. The controller proposed in Andreasson, Dimarogonas, Sandberg, and Johansson (2014) achieves fair power sharing and asymptotically minimizes the cost of the power injections. Distributed controllers focusing on voltage control are studied in Tucci, Riverso, Vasquez, Guerrero, and Ferrari-Trecate (2015) and Morstyn, Hredzak, Demetriades, and Agelidis (2015). In Zonetti, Ortega, and Benchaib (2014) a unified port-Hamiltonian system model is proposed, and the performance of decentralized PI control is discussed for a multi-terminal DC transmission system. For AC microgrids a flat and distributed operation architecture has been proposed in Dörfler, Simpson-Porco, and Bullo (2014) and Simpson-Porco, Dörfler, and Bullo (2013), consisting of simultaneous (without time-scale separation) primary, secondary, and tertiary controls. Inspired by these AC operation strategies we seek similar solutions for DC microgrids.

Contribution and contents: In this article, we propose a comprehensive operational control strategy for DC microgrids in order to achieve multiple objectives.

In Section 2, we introduce the considered DC microgrid model. Inspired by the shortcomings of conventional DC droop control and the merits of frequency droop control in AC systems, we propose a novel primary voltage droop control strategy in Section 3. Our proposed primary control strategy is fully decentralized, and we demonstrate that it is capable of stabilizing the grid while achieving load sharing and avoiding actuator saturation. As base scenario we consider a purely resistive network with constant current loads, but we also discuss extensions to other load and network models. In Section 4, we consider the economic dispatch of multiple generating units and formulate it as a convex optimization problem. We demonstrate that the set of minimizers of the economic dispatch are in one-to-one correspondence with the steady states achieved by our primary voltage droop control with appropriately chosen control gains. As a result, we propose a selection of control gains (droop coefficients) to achieve economic optimality in a decentralized way and without a model of the network or the loads. In Section 5, we discuss the limitations of droop control causing steady-state voltage drifts, and we study secondary control strategies to compensate for it. First, we consider fully decentralized integral controllers and illustrate their limitations. Next, we propose a distributed consensus filter that relies on communication between local controllers. We show that this distributed control strategy is capable of regulating the voltage drifts while simultaneously achieving tertiary-level objectives such as load sharing or economic dispatch. In Section 6, we present simulation results to illustrate the performance and robustness of our primary and secondary controllers. Finally Section 7 concludes the paper.

Aside from the importance of DC microgrids in their own right, we sincerely believe that the considered DC scenario also serves as valuable and accessible introduction to many power system operational paradigms that have nonlinear and complex parallels in AC networks. A preliminary version of part of this paper's results is Zhao and Dörfler (2015).

Preliminaries and notation

Vectors and matrices: Let $\mathbb{1}_n$ and $\mathbb{0}_n$ be the n-dimensional vectors of unit and zero entries, respectively. Let $\mathbf{I_n} \in \mathbb{R}^{n\times n}$ be the n-dimensional identity. Let $\mathbf{diag}(v)$ represent a diagonal matrix with the elements of v on the diagonal. For a symmetric matrix $A = A^T$, the notation $A > 0, A \geq 0, A < 0$, and $A \leq 0$ means that A is positive definite, positive semidefinite, and negative definite and negative semidefinite, respectively.

Algebraic graph theory: Consider a connected, undirected, and weighted graph $G = (\mathcal{V}, \mathcal{E}, W)$, where $\mathcal{V} = \{1, \ldots, n\}$ is the set of nodes, $\mathcal{E} \subset \mathcal{V} \times \mathcal{V}$ is the set of undirected edges, and $W = W^T \in \mathbb{R}^{n\times n}$ is the adjacency matrix with entries $w_{ij} > 0$, if $(i, j) \in \mathcal{E}$ and $w_{ij} = 0$ otherwise. The degree matrix $D \in \mathbb{R}^{n\times n}$ is the diagonal matrix with elements $d_{ii} = \sum_{j=1,j\neq i}^{n} w_{ij}$. The Laplacian matrix $L = L^T \in \mathbb{R}^{n\times n}$ is defined by $L = D - W$, and it satisfies $L \geq 0$ and $L\mathbf{1_n} = \mathbf{0_n}$. If the graph is connected, then the null space of L is spanned by $\mathbf{1_n}$, and all the other $n - 1$ eigenvalues of L are strictly positive.

2. DC microgrid model

For our purposes, a microgrid is a linear connected circuit with associated undirected graph $G(\mathcal{V}, \mathcal{E}, W)$, nodes $\mathcal{V} = \{1, \ldots, n\}$, and edges $\mathcal{E} \subset \mathcal{V} \times \mathcal{V}$. We assume that all lines in the DC microgrid are purely resistive, and refer to Remark 3.1 for an extension of our results of more general line impedances. The adjacency matrix W is defined with nonzero entries $w_{ij} = w_{ji} = 1/R_{ij}$ for $(i, j) \in \mathcal{E}$, where R_{ij} is the resistance of the line connecting nodes $i, j \in \mathcal{V}$. The diagonal degree matrix $D \in \mathbb{R}^{n\times n}$ has elements $d_{ii} = \sum_{j=1,j\neq i}^{n} w_{ij}$. The admittance matrix Y is defined as $Y = D - W$. Thus, $Y = Y^T \in \mathbb{R}^{n\times n}$ is a real-valued Laplacian matrix satisfying $\mathbb{1}_n^T Y = \mathbb{0}_n^T$.

We partition the set of nodes into m sources and $n - m$ loads: $\mathcal{V} = \mathcal{V}_S \cup \mathcal{V}_L$. Throughout this paper we denote sources and loads by the superscripts S and L, respectively. The sources are assumed to be controllable current sources with positive current injections $I_i^S \geq 0$ and are assembled in the vector I^S. Each source is constrained by its output current capacity $\bar{I}_i$, i.e., $I_i^S \in [0, \bar{I}_i]$. The loads are assumed to be constant-current loads with negative current injections $I_i^L \leq 0$ and are assembled in the vector I^L. Following Kirchhoff's and Ohm's laws, the network model is built as[1]

$$\begin{bmatrix} I^S \\ I^L \end{bmatrix} = \begin{bmatrix} Y_{SS} & Y_{SL} \\ Y_{SL}^T & Y_{LL} \end{bmatrix} \begin{bmatrix} V^S \\ V^L \end{bmatrix} \tag{1}$$

where the admittance matrix Y is partitioned according to sources and loads, and V^S and V^L represent the nodal voltages (potentials) of sources and loads, respectively. Since Y is a Laplacian matrix, $\mathbb{1}_n^T Y = \mathbb{0}_n^T$ and a necessary feasibility condition for Eq. (1) is

[1] Loads in DC power systems are conventionally modeled as constant-current, constant-impedance, constant-voltage or constant-power loads (Nilsson & Sannino, 2004). Often loads do not belong to a single category but display a combination of the above properties. We mainly focus on pure constant-current loads which arise primarily in electronic loads and also in some conventional loads such as LED lighting. We find that these loads are the mathematically most challenging linear loads. In Remarks 3.2 and 3.3 we show how all our results extend to constant-impedance loads and constant-voltage buses.