Automatica 90 (2018) 62–72

Contents lists available at ScienceDirect

Automatica

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

Stability analysis of DC microgrids with constant power load under distributed control methods[☆]

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A R T I C L E I N F O

Article history:
Received 28 October 2016
Received in revised form 26 September 2017
Accepted 16 November 2017
Available online 15 February 2018

Keywords:
Constant power load (CPL)
DC microgrid
Distributed control
Inertia theorem
Current sharing
Stability

A B S T R A C T

Constant power loads (CPLs) often cause instability due to its negative impedance characteristics. In this study, the stability of a DC microgrid with CPLs under a distributed control that aims at current sharing and voltage recovery is analyzed. The effect of the negative impedance on the behavior of distributed controller is investigated. The small-signal model is established to predict the system qualitative behavior around equilibrium. The stability conditions of the system with time delay are derived based on the equivalent linearized model. Additionally, eigenvalue analysis based on inertia theorem provides analytical sufficient conditions as a function of the system parameters, and thus it leads to a design guideline to build reliable microgrids. Simulations are performed to confirm the effectiveness and validity of the proposed method.

1. Introduction

Driven by environmental concerns, renewable energy sources, such as photovoltaics and wind generation, are being rapidly deployed (Bidram1, Lewis, & Davoudi, 2014; George, Zhong, Ren, & Krstic, 2015; Schiffer, Zonetti, Ortega, Stanković, & TevfikSezi, 2016; Simpson-Porco, Dörfler, & Bullo, 2013; Song et al., 2017). Microgrids have been identified as key components of modern electrical systems for facilitating the integration of renewable distributed generation units (Chang & Zhang, 2016; Schiffer, Zonetti, Ortega, Stanković, & TevfikSezi, 2014). Microgrids can be divided into two types: alternating-current (AC) and direct-current (DC) microgrid (Sun et al., 2017). Recently, DC microgrids have attracted increasing attentions owing to their advantages, including their reliability and efficiency, simple control, robustness and natural interface for renewable source (Kakigano, Miura, & Ise, 2010). As a result, DC microgrid consisting of multiple converters is increasingly used in applications such as aircrafts, space crafts, electric vehicles (Maknouninejad, Qu, Lewis, & Davoudi, 2014).

Usually, the main control objectives of a DC microgrid include sharing current, regulating voltage and maintaining stability (Han, Wang, Sun, Yang, & Liu, 2017). There are mainly three methods for current sharing and voltage regulation: decentralized control, centralized control and distributed control.

The traditional V–I droop is a typical decentralized control which is convenient, inexpensive and efficient, however, with the drawbacks: voltage sag and biased power sharing (Augustine, Mishra, & Lakshminarasamma, 2015). For this situation, several improved decentralized methods are proposed (Huang, Liu, Xiao, & Moursi, 2015). Although the performance has improved, the shortcomings are not completely overcome.

The centralized control method has been widely used in DC microgrids. All distributed generators (DGs) can realize the targets of current sharing and voltage recovery via commands from the central controller unit, which collects the global information (Guo, Feng, Li, & Wang, 2014). Despite its satisfactory performance, centralized control requires complex communication networks and is thus vulnerable to link failures.

To overcome these drawbacks, distributed control strategies have been proposed. The key feature of the distributed control method is the consensus algorithm, which just needs the neighbor information (Moayedi, Student, & Davoudi, 2016; Nasirian, Davoudi, Lewis, & Guerrero, 2014; Nasirian, Moayedi, Davoudi, &

☆ This work is supported by the National Natural Science Foundation of China under Grants 51677195, 61622311, 61573384, Fundamental Research Funds for the Central Universities of Central South University under Grant 2016zzts052, and the Project of Innovation-driven Plan in Central South University. The material in this paper was not presented at any conference. This paper was recommended for publication in revised form by Associate Editor Jun-ichi Imura under the direction of Editor Thomas Parisini.

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https://doi.org/10.1016/j.automatica.2017.12.051
0005-1098/

Lewis, 2015; Shafiee, Dragicevic, Vasquez, & Guerrero, 2014; Zhao & Dörfler, 2015). Thus, highly accurate current sharing and voltage regulation can be realized via a sparse communication network (Behjati, Davoudi, & Lewis, 2014; Meng, Dragicevic, Roldán-Pérez, Vasquez, & Guerrero, 2016).

However, the DC microgrid with CPL tends to be unstable when traditional decentralized control or distributed control is implemented independently. Stability issues of the DC microgrid with CPL under decentralized control have been investigated. In order to realize current sharing, the small-signal stability of a system with CPLs under droop control has been analyzed in Sandeep and Fernandes (2013), Su, Liu, Sun, Han, and Hou (2018) and Tahim, Pagano, Lenz, and Stramosk (2015). A reduced-order linearized model is derived, wherein the transient process is ignored (Sandeep & Fernandes, 2013; Tahim et al., 2015). These studies show that if the droop coefficient is larger than the equivalent negative impedance of the CPL, the system would be stable. A high-dimensional model has been proposed for analyzing the transient processes of the converter (Su et al., 2018). By using the quadratic eigenvalue problem theories (Tisseur & Meerbergen, 2001), the stability of the linearized system is analyzed, and a wide stability solution is obtained.

With the development of the communication technology, distributed control becomes more and more popular in DC microgrid. Nevertheless, stability of the system with CPL under distributed control has never been studied concretely. What is worse, possible time delay would further deteriorate the stability problem. So, it is vital to develop the stability analysis of the system under distributed control.

In this paper, we propose a distributed control method that not only overcomes the instability of the CPL, but also realizes current sharing and voltage regulation. This method can be treated as a combination of V–I droop (inherently virtual resistance) and distributed control. Moreover, the stability condition of the system with time delay is also obtained. The main contributions of this study are summarized as follows.

- A distributed control method is proposed that not only overcomes the instability of the CPL, but also realizes current sharing and voltage regulation.
- The small-signal stability of the system with a CPL under distributed control is analyzed, and the analytic sufficient conditions are obtained. The relation among the line resistances, control parameters, reference voltage and the maximum load that keep the system stable is obtained.
- This paper provides an efficient method for stability analysis of two typical matrices (see Theorems 1 and 3). These problems can be effectively solved using the proposed method.
- The stability condition of the system with time delay is obtained, and the validity of the proposed method is tested by simulations.

The paper is organized as follows. Section 2 introduces the distributed control framework. The stability analysis and the sufficient conditions are introduced in Section 3. The simulation results are presented in Section 4. The conclusions are drawn in Section 5.

2. Distributed control framework

2.1. Basic model and assumptions

The DC microgrid, which comprises multiple parallel DC/DC converters with a CPL, is shown in Fig. 1(a). It contains a physical network and a communication network and is modeled according to the following assumptions:

(1) The response of the buck converter is sufficiently fast that dynamics can be neglected. That is, the DC/DC converters can be treated as ideal controllable voltage sources.
(2) The loads are ideal CPLs. In fact, because the response of the output regulating controllers of the point of load (POL) converters is fast enough, all the POL converters attached to the load could be regarded as CPLs (Su et al., 2018).
(3) The resistance of the common bus is zero; hence, all loads are regarded as one common CPL.
(4) The cable is purely resistive. In low-voltage DC microgrid, the cable inductance can be neglected.

For constant power loads, the power balance equation should be satisfied.

$$\begin{cases} u_L \sum_{i=1}^{n} i_i = P \\ u_i = i_i r_i + u_L \end{cases} \tag{1}$$

where u_L represents the voltage of the DC bus, P is the power of the load, and r_i represents the resistance of the cable between the ith DG to loads.

2.2. Graph theory

Fig. 1(b) shows the mapping of a cyber network to a physical DC microgrid. The nodes represent converters, and the edges represent the communication links for data exchange. In distributed control, all agents exchange information only with their neighbors.

A graph is usually represented as a set of nodes $V_G = \{v_1, v_2, \dots, v_n\}$ connected by a set of edges $E_G \subset V_G \times V_G$, along with an associated adjacency matrix $A_G = [a_{ij}] \in R^{n\times n}$. n is the number of nodes. The elements of A_G represent the communication weights, where $a_{ij} > 0$ if the edge $(v_j, v_i) \in E_G$; otherwise, $a_{ij} = 0$. Here, the matrix A_G is assumed to be time-invariant. The in-degree matrix $D_G = diag\ \{d_i\}$ is a diagonal matrix with $d_i = \sum a_{ij}$. The Laplacian matrix is defined as $L = D_G - A_G$, and its eigenvalues determine the global dynamics. For a connected graph, there is at least one spanning tree, and $\ker(L) = \mathrm{span}(1_n)$, where $1_n = [1\,1\ldots 1]^T$ (Olfati-Saber & Murray, 2004).

2.3. Stabilizing distributed control

To realize proportional current sharing and excellent load voltage regulation, a distributed control method is proposed. To overcome the instability of the CPL, stabilization measures are necessary. Because damping can mitigate oscillation, virtual resistances are employed for auxiliary stabilization and improving the transient performance. The control diagram is illustrated in Fig. 2. The output voltage for each converter can be expressed as

$$u_i = v_{ref} + \delta i_i + \delta u_i - c_i i_i \tag{2}$$

where u_i, i_i, δi_i , and δu_i represent the output voltage, output current, current-correction terms and the voltage-correction terms, respectively, for the ith converter. v_{ref} represents the rated point of the DC bus voltage; and c_i represents the virtual resistance (or droop gain of V–I droop).

The current correction term is designed as follows:

$$\delta i_i = \frac{b_1}{k_i} \int \sum a_{ij} \left(\frac{i_j}{k_j} - \frac{i_i}{k_i} \right) dt \tag{3}$$

where $k_i\,(k_i > 0)$ is the current-sharing proportionality coefficient, b_1 is a positive gain coefficient, and a_{ij} represents the communication weight. If there is a communication link between nodes i and