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Stable current sharing and voltage balancing in DC microgrids: A consensus-based secondary control layer☆

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ABSTRACT

In this paper, we propose a secondary consensus-based control layer for current sharing and voltage balancing in DC microGrids (mGs). To this purpose, we assume that Distributed Generation Units (DGUs) are equipped with decentralized primary controllers guaranteeing voltage stability. This goal can be achieved using, for instance, Plug-and-Play (PnP) regulators, which allow one to analyze the behavior of the closed-loop mG by approximating local primary control loops with either unitary gains or first-order transfer functions. Besides proving exponential stability, current sharing, and voltage balancing, we describe how to design secondary controllers in a PnP fashion when DGUs are added or removed. Theoretical results are complemented by simulations, using a 7-DGUs mG implemented in Simulink/PLECS, and experiments on a 3-DGUs mG.

1. Introduction

Power generation and distribution are rapidly changing due to the increasing diffusion of renewable energy sources, advances in energy storage, and active participation of consumers to the energy market (Hu, Zou, & Yang, 2016; Ipakchi & Albuyeh, 2009; Justo, Mwasilu, Lee, & Jung, 2013). This shift of paradigm has motivated the development of microgrids (mGs), commonly recognized as small-scale power systems integrating Distributed Generation Units (DGUs), storage devices and loads. Since AC power generation is the standard for commercial, residential, and industrial utilization, several studies focused on the control of AC mGs (Bolognani & Zampieri, 2013; Guerrero, Chandorkar, Lee, & Loh, 2013; Riverso, Sarzo, & Ferrari-Trecate, 2015; Schiffer, Seel, Raisch, & Sezi, 2016; Simpson-Porco, Dörfler, & Bullo, 2017). However, nowadays, DC energy systems are gaining interest (Dragicevic, Lu, Vasquez, & Guerrero, 2016; Elsayed, Mohamed, & Mohammed, 2015) because of the increasing number of DC loads, the availability of efficient converters, and the need of interfacing DC energy sources and batteries with minimal power losses (Elsayed et al., 2015; Fairley, 2012; Justo et al., 2013). As reviewed in Elsayed et al. (2015), DC mGs are becoming more and more popular in several application domains, such as avionics, automotive, marine and residential systems (Elsayed et al., 2015).

The basic problems in control of DC mGs are voltage stabilization (Cezar, Rajagopal, & Zhang, 2015; Dragicevic et al., 2016; Hamzeh, Ghafouri, Karimi, Sheshyekani, & Guerrero, 2016; Persis, Weitenberg, & Dörfler; Tucci, Riverso, Vasquez, Guerrero, & Ferrari-Trecate, 2016; Zhao & Dörfler, 2015; Zonetti, Ortega, & Benchaib, 2014) and current sharing (or, equivalently, load sharing), the latter meaning that DGUs must compensate constant load currents proportionally to given parameters (for example, the converter ratings) and independently of the mG topology and line impedances. Current sharing is crucial for preserving the safety of the system, as unregulated currents may overload generators and eventually lead to failures or system blackout (Han et al., 2016). An additional desirable goal is voltage balancing, i.e. to keep the average output voltage of DGUs close to a prescribed level. Indeed, load devices are designed to be supplied by a nominal reference voltage: it is therefore important to ensure that the voltages at the load buses are spread around this value.

These objectives can be realized using hierarchical control structures. In particular, current sharing is often realized by coupling secondary-layer consensus algorithms with primary voltage

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controllers. Secondary regulators, however, can have a detrimental effect and closed-loop stability of the mG must be carefully analyzed. In order to guarantee stability, several existing approaches focus on specific mG topologies or provide centralized control design algorithms, i.e. the synthesis of a local controller for a DGU requires knowledge about all other DGUs and lines. For instance, in Behjati, Davoudi, and Lewis (2014); Moayedi, Nasirian, Lewis, and Davoudi (2015) only mG with a bus topology is considered and local control design is performed in a centralized fashion. The synthesis procedures proposed in Han, Meng, Guerrero, and Vasquez (2018); Nasirian, Moayedi, Davoudi, and Lewis (2015) suffer from similar limitations. Indeed, in these works, the computation of local controllers guaranteeing collective stability uses a global closed-loop transfer function matrix, and the largest eigenvalue of the Laplacian matrix associated with the communication network. Consensus-based secondary controllers for mG with general topologies have been presented in Shafiee, Dragicevic, Andrade, Vasquez, and Guerrero (2014); also in this case, however, stability of the closed-loop mG equipped with primary and secondary control layers is studied through centralized analysis (i.e. the root locus), or via simulations (Dragicevic et al., 2016). Similar drawbacks affect the approach in Meng, Dragicevic, Roldan Perez, Vasquez, and Guerrero (2016), whereas, in Setiawan, Abu-Siada, and Shahnia (2018), current sharing is achieved by means of a centralized controller, which receives informations from all the DGUs in the mG.

All the synthesis algorithms mentioned above become prohibitive for large mGs. Moreover, they are unsuitable for mGs with flexible structure because, to preserve voltage stability, the plugging-in or -out of DGUs might require to update all local controllers in the mG. This motivated the development of *scalable* design procedures for local controllers as in Tucci, Riverso, and Ferrari-Trecate (2018); Tucci et al. (2016); Zhao and Dörfler (2015). In Tucci et al. (2018, 2016), the aim is to stabilize the voltage only via primary decentralized controllers. These regulators, termed Plug-and-Play (PnP) have the following features: (*i*) the existence of a local controller for a DGU can be tested on local hardware, and control design is cast into an optimization problem, (*ii*) each optimization problem exploits information about the DGU only (Tucci et al., 2018) or, at most, the power lines connected to it (Tucci et al., 2016), and (*iii*) when a DGU is plugged-in, no other DGUs (Tucci et al., 2018), or at most neighboring DGUs (Tucci et al., 2016), must update their local controllers.

Paper contributions. In this paper, we present a secondary regulation scheme for achieving stable current sharing and voltage balancing in DC mGs. We assume that the proposed higher-level scheme is build on top of a primary stabilizing voltage control layer; moreover, similar to Zhao and Dörfler (2015), at the secondary level we exploit consensus filters requiring DGUs to communicate in real-time over a connected network. There is, however, a key difference between our approach and the one presented in Zhao and Dörfler (2015). In the latter work, the authors assume DGUs to be controllable *current* sources; on the contrary, we consider primary-controlled DGUs behaving as *voltage* generators. In this setting, by properly choosing the reference values for the output voltages of each DGU, one can always regulate the currents that flow through the power lines, even when load conditions change. In this way, unwanted circulating currents (which may open the safety breakers in order to prevent damages on the devices) can be avoided. Instead, if all the DGUs in the mG are ideal current sources, the primary regulation scheme alone cannot guarantee such control on the flowing currents (Zhao & Dörfler, 2015).

At the modeling level, we propose two abstractions for the DGUs controlled with primary voltage regulators: unit gain and first-order transfer function approximation. The first one is used only for tutorial purposes and for developing basic mathematical tools that will allow us to extend the key results to the second (more realistic) approximation of the primary loops.

Another contribution of this paper is the study of the eigenstructure of the product of three matrices ($\mathbb{L}D\mathbb{M}$), where (*i*) $\mathbb{L}$ and $\mathbb{M}$ are the graph Laplacians associated with the electrical and the communication graphs, respectively, and (*ii*) D is a diagonal positive definite matrix defining the desired ratios between balanced currents. While several studies focused on the properties of the product of stochastic matrices (see e.g. Jadbabaie, Lin, & Morse, 2003), which are central in discrete-time consensus, to our knowledge weighted products of Laplacians received much less attention. In particular, we show that, under two different conditions, $\mathbb{L}D\mathbb{M}$ preserves some key features of Laplacian matrices. In this case, the asymptotic achievement of current sharing and voltage balancing in a globally exponentially stable fashion is proved.

Finally, we provide an experimental validation of our approach using a lab-size DC mG. The results show the robustness of the proposed controllers to non-idealities that are unavoidably present in a real mG.

Paper organization. The paper is organized as follows. Section 2 summarizes the electrical model of DGUs and PnP controllers. The secondary control layer is developed and analyzed in Sections 3 and 4. In particular, Section 4.4 shows that, similarly to the regulators in Tucci et al. (2018, 2016), secondary controllers can be designed in a PnP fashion. Section 5.1 demonstrates current sharing and voltage balancing through simulations in Simulink/PLECS (Allmeling & Hammer, 2013), where non-idealities of real converters and lines have been taken into account. Finally, in Section 5.2 we present experimental tests performed on a real DC mG.

A preliminary version of the paper will be presented at the 20th IFAC World Congress. Different from the conference version, the present paper includes (*i*) the proofs of Propositions 2–5 and Theorem 1, (*ii*) the more realistic case where primary control loops are approximated with first-order transfer functions, and (*iii*) experimental results and more detailed simulations.

Notation and basic definitions. The cardinality of the finite set S will be denoted with $|S|$. A weighted directed graph (*digraph*) $\mathcal{G} = (\mathcal{V}, \mathcal{E}, W)$ is defined by the set of nodes $\mathcal{V} = \{1, \dots, n\}$, the set of edges $\mathcal{E} \subseteq \mathcal{V} \times \mathcal{V}$ and the diagonal matrix $W \in \mathbb{R}^{|\mathcal{E}|\times|\mathcal{E}|}$ with $W_{ii} = w_i$, where $w_i \in \mathbb{R}$ is the weight associated with the edge $e_i \in \mathcal{E}$. The set of neighbors of node $i \in \mathcal{V}$ is $\mathcal{N}_i = \{j : (i,j) \in \mathcal{E} \text{ or } (j,i) \in \mathcal{E}\}$. A digraph $\mathcal{G}$ is *weakly connected* if its undirected version is connected (Bullo, 2016). $Q(\mathcal{G}) \in \mathbb{R}^{|\mathcal{V}|\times|\mathcal{E}|}$ is the incidence matrix of $\mathcal{G}$ (Grone, Merris, & Sunder, 1990). The Laplacian matrix of $\mathcal{G}$ is $\mathcal{L}(\mathcal{G}) = Q(\mathcal{G})WQ(\mathcal{G})^T$, and it is independent of the orientation of edges.

The average of a vector $v \in \mathbb{R}^n$ is $\langle v\rangle = \frac{1}{n}\sum_{i=1}^n v_i$. We denote with H^1 the subspace composed by all vectors with zero average (Bensoussan & Menaldi, 2005; Ferrari-Trecate, Buffa, & Gati, 2006) i.e. $H^1 = \{v \in \mathbb{R}^n : \langle v\rangle = 0\}$. The space orthogonal to H^1 is $H^1_\perp$. It holds $H^1_\perp = \{\alpha\mathbf{1}_n,\ \alpha \in \mathbb{R}\}$ and $\dim(H^1_\perp) = 1$. Moreover, the decomposition $\mathbb{R}^n = H^1 \oplus H^1_\perp$ is direct, i.e. each vector $v \in \mathbb{R}^n$ can always be written in a unique way as

$$v = \hat{v} + \bar{v} \quad \text{with } \hat{v} \in H^1 \text{ and } \bar{v} \in H^1_\perp. \tag{1}$$

Consider the matrix $A \in \mathbb{R}^{n\times n}$. With $A(H^1|H^1)$ we indicate the linear map $A : H^1 \to H^1$ (i.e. the restriction of the map $A : \mathbb{R}^n \to \mathbb{R}^n$ to the subspace H^1). For a subspace $\mathcal{V} \subset \mathbb{R}^n$, we denote with $P_{\mathcal{V}}(v)$ the projection of $v \in \mathbb{R}^n$ on $\mathcal{V}$. The subspace $\mathcal{V} \subset \mathbb{R}^n$ is said to be *A-invariant* if $v \in \mathcal{V} \Rightarrow Av \in \mathcal{V}$. Moreover, with $\lambda_i(A)$, $i = 1, \dots, n$, we denote the eigenvalues of A.

Let $A \in \mathbb{R}^{n\times n}$ be a matrix with real eigenvalues. The *inertia* of A is the triple $i(A) = (i_+(A), i_-(A), i_0(A))$, where $i_+(A)$ is the