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A generalized droop control approach for islanded DC microgrids hosting parallel-connected DERs

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ABSTRACT

A great attention is dedicated to design a generalized droop control approach contributing to proper load current sharing and voltage regulation in DC microgrids (MGs). The established approach is based on fundamental principles of parallel-connected distributed energy resources (DERs) equivalent circuit ending in a general method effective for different interconnection schemes. Accordingly, proper load sharing and voltage regulation are pursued in DERs with different power ratings and different cable impedances. Moreover, the proposed approach is apt to be operated in both load current and power sharing modes. Comparative studies are conducted to evaluate performance of the proposed approach regarding these two control strategies and highlighting the possible differences. Accordingly, the desired control and technical requirements could be accommodated, effectively. Detailed simulation studies are conducted and compared with each other to interrogate performance of the proposed approach. Results are discussed in depth.

1. Introduction

The concept of microgrid (MG) is an expediting factor in swift deployment of small-scale distributed energy resources (DERs), more specifically in islanded and remote areas (Hatziargyriou, Asano, Iravani, & Marnay, 2007). Besides the traditional power resources, renewable-based DERs are one of the main elements of MGs and are widely deployed in cities and rural environments. For instance, rooftype PVs are now a common seen at these areas (Sasidharan & Singh, 2017). By developing a suitable and well-defined control system, these resources could be easily integrated into the energy grid and contributing to reduce emissions and environmental pollutions (Ahmad & Alam, 2017). Besides, the energy grid of sustainable cities mainly depends on MG concept which outlines the great importance of this notion to be explored more (Chan, Cameron, & Yoon, 2017; Wouters, 2015). On the other hand, if different types of consumers in a particular boundary interact with each other, they could attain further mutual benefits. This notice also adds to the merits of MG concept in real-case applications (Reynolds, Rezgui, & Hippolyte, 2017). As clarified, all of these features enable the swift progress and the final transition towards the sustainable cities through MG implementations (Hussain, Muhammad Arif, Aslam, & Danial Ali Shah, 2017).

Technically speaking, MG is defined as a single entity accommodating a cluster of loads and generating units inside a particular boundaries being operated in a grid-connected or an autonomous mode. It also provides seamless transitions between grid-connected and islanded modes of operation. MGs fall in two main categories including alternative current (AC) and direct current (DC) types. The latter type manifests competitive features over the former (Planas et al., 2015; John Justo, Mwasilu, Lee, & Jung, 2013). Annihilating the skin effect and power quality issues, absence of frequency control, and an easy power flow are some of the main features of DC MGs over their AC counterparts. Accordingly, DC MGs offer higher figures of merit say as efficiency, reliability, safety, redundancy, and reduced cost (Chehardeh, Lesani, Zadeh, & Siavashi, 2009; Jian, He, Jia, & Xie, 2013). Taking a look from consumption requirements, many of the loads in MG premises demand a DC power emphasizing the superiority of DC electrification (Boeke & Wendt, 2015; Fregosi et al., 2015). Computers and data centers, variable-speed drives, and light emitting diodes are to be named, but a few. Dealing with generation shape of DERs in DC MGs, they produce power inherently in DC form or it is converted to DC through power electronics converters. Photovoltaics (PVs), fuel cells (FCs), and energy storage systems (ESSs) are in touch with DC power. In contradiction, wind turbines (WTs) and the main grid provide an AC power being converted to an equivalent DC. In recent attempts, DC and AC MGs are coupled together through an interfacing converter introducing the concept of hybrid MGs (Mortezapour & Lesani, 2017). This type of MG provokes opportunities

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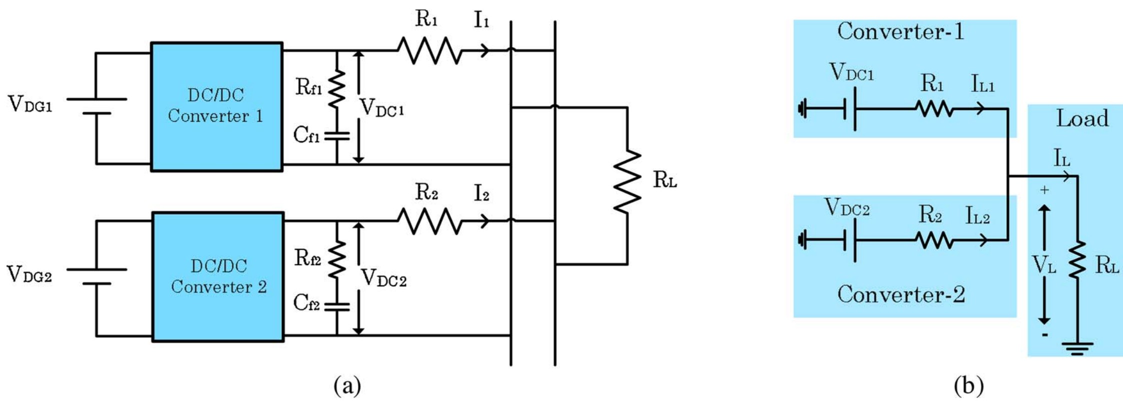

Fig. 1. (a) Two parallel-connected DC/DC converters, (b) equivalent circuit.

of both AC and DC MGs. However, it is not the main focus of the present study and accordingly is not tailored here. On the main side, the ongoing study looks into the efficient DC MGs.

Considering data exchange between the embedded elements, DC MGs could be operated in two main configurations. In one type, there are communication links to establish bilateral data transfers between specific DERs and the control center. Centralized control approaches (Yang, Paire, Gao, Miraoui, & Liu, 2015; Farhadi & Mohammed, 2015) and master/slave methods (Mazumder, Tahir, & Acharya, 2008; Ferreira, Braga, Ferreira, & Barbosa, 2012) require such connections. Although beneficial for small-scale MGs, communication links are not judged as economic and reliable solutions for real-scale MGs. The second scheme excludes the need for high bandwidth communication links wherein each DER deploys its local variables for control purposes. Accordingly, DERs are operated in a decentralized manner without any data transfer. Droop control method is a popular decentralized approach which controls the converter output voltage based on its output current (Bouzid et al., 2015).

Different droop control strategies have been proposed for DC MGs. In (Gu, Xiang, Li, & He, 2014), considering the presence of ESSs, the droop control strategy is evaluated in three different modes. Based on the output power level, one of the three modes is selected for droop strategy. Proper responses are attained based on the proposed strategy; however, it does not accommodate parallel operation of DERs and the cable impedance is not considered in the proposed approach. Authors in (Augustine, Mishra, & Lakshminarasamma, 2015) have developed a figure of merit called as droop index to assign the minimum power losses and circulating current between the parallel-connected DERs converters. To this end, droop resistance is determined and then based on V–I droop mechanism, proper load current sharing is performed. A similar approach is adopted in (Niyitegeka, Choi, & Ok, 2016) which deploys a different form of droop index. Targeting the minimization of generation cost, appropriate droop gains are determined in (Moayedi & Davoudi, 2017). The proposed approach improves load current sharing of parallel converters. A variable droop gain is developed in (Lu et al., 2014) in which by increasing the droop gain, load current sharing gets better. On the other side, any decrement in droop gain ameliorates the voltage regulation with reduced voltage deviations. A variable droop gain is also established in (Tahim, Pagano, Lenz, & Stramosk, 2015) which hinges on ESS state of charge. A virtual capacitance is deployed in (Xu et al., 2017) to improve dynamic response of voltage and current signals. Evidently, significant attempts have been made to design efficient droop strategies for proper control requirements of DC MGs. Meanwhile, some influencing issues such as load current sharing in DERs with different rated powers, appropriate power sharing instead of current sharing, and the effect of cable resistance are still under question.

This manuscript establishes an efficient droop control strategy for DC MGs which affords a proper load current and power sharing in parallel-connected DERs. The proposed approach is a generalized one established based on fundamental principles of DERs equivalent circuit which could contribute to proper load current sharing and a proper power sharing among them. Moreover, the proposed droop strategy demonstrates satisfactory results in DERs with different rated powers and different interconnection cable impedance. Detailed simulation studies are evolved to assess performance of the proposed approach and come into a comparison platform.

The remainder of this manuscript is organized as follows: Section 2 addresses the principle formulation of the proposed approach. Based on these equations, Section 3 extends V–I droop characteristics to achieve two individual objectives say as proper sharing of load current and proper power sharing. Some technical considerations regarding the proposed approach are discussed in Section 4. Simulation studies are provided in Section 5 and detailed comparative studies are conducted to portray the merits of the proposed approach. Concluding remarks and general discussions are unveiled in the last section.

2. Proposed load sharing approach

The proposed approach for a proper load sharing in an islanded DC MG is developed in this section. The investigated test system is shown in Fig. 1(a) whereas its equivalent circuit is illustrated in Fig. 1(b). In this figure, V_{DC1}, V_{DC2}, I_1, I_2, and R_1, R_2 signify the output voltages and the output currents of converters 1 and 2, respectively. The cables resistance is also denoted by R.

To establish the load voltage (V_L) expression, kirchoff's voltage law (KVL) is applied in Fig. 1(b). The compact representation of this parameter is as follows.

$$V_L = \frac{R_L(R_2 V_{DC1} + R_1 V_{DC2})}{R_1 R_L + R_2 R_L + R_1 R_2} \quad (1)$$

In this equation, R_L models the load resistance. Solving the equivalent circuit for converters currents, I_1 and I_2 are expressed based on (2) and (3).

$$I_1 = \frac{R_2 V_{DC1} + (V_{DC1} - V_{DC2})R_L}{R_1 R_L + R_2 R_L + R_1 R_2} \quad (2)$$

$$I_2 = \frac{R_1 V_{DC2} - (V_{DC1} - V_{DC2})R_L}{R_1 R_L + R_2 R_L + R_1 R_2} \quad (3)$$

Two different outlooks could be applied in load sharing. In the first view, load current sharing is the aim of the implemented droop strategy. This notion is the running trend in majority of the conducted studies. The second one fulfills this mission by a proper power sharing among the DERs converters. The proposed approach is explored on the basis of these two notions and a thorough comparison is performed. It is worth mentioning that in both of the cases; the converters power ratings could be equal or unequal with each other. Dealing with the