Adaptive Droop Control Strategy for Load Sharing and Circulating Current Minimization in Low-Voltage Standalone DC Microgrid

Sijo Augustine, *Student Member, IEEE*, Mahesh K. Mishra, *Senior Member, IEEE*,
and N. Lakshminarasamma, *Member, IEEE*

***Abstract*—This paper addresses load current sharing and circulating current issues of parallel-connected dc–dc converters in low-voltage dc microgrid. Droop control is the popular technique for load current sharing in dc microgrid. The main drawbacks of the conventional droop method are poor current sharing and drop in dc grid voltage due to the droop action. Circulating current issue will also arise due to mismatch in the converters output voltages. In this work, a figure of merit called droop index (DI) is introduced in order to improve the performance of dc microgrid, which is a function of normalized current sharing difference and losses in the output side of the converters. This proposed adaptive droop control method minimizes the circulating current and current sharing difference between the converters based on instantaneous virtual resistance R_{droop}. Using R_{droop} shifting, the proposed method also eliminates the tradeoff between current sharing difference and voltage regulation. The detailed analysis and design procedure are explained for two dc–dc boost converters connected in parallel. The effectiveness of the proposed method is verified by detailed simulation and experimental studies.**

***Index Terms*—Circulating current, droop index (DI), droop method, load sharing, microgrid, parallel converters, voltage deviation.**

I. INTRODUCTION

THE CONCEPT of microgrid has been introduced for sustainable energy generation and proper utilization of small-scale distributed energy resources (DERs). When DERs such as solar, wind, and fuel cell are connected together, its energy management becomes important [1]. It is not necessary that these energy sources exist in the same site but can be scattered depending upon the ease of energy harness. Integrating DERs to a common ac or dc grid through power electronic interfaces gives flexibility in conversion and power level.

One of the main advantages of microgrid is that, it can be operated in islanded or grid-connected mode [2]. Several effective control strategies have been developed and implemented to integrate DERs to existing power grid [3]–[5]. The control of ac microgrid deals with the power flow, load sharing, voltage regulation and mitigation of various kinds of power quality issues [6]; whereas, in dc microgrid, power quality issues such as reactive power and skin effect are not present. Therefore, compared to ac, dc microgrids are highly efficient, reliable, easy to control, and economic [7], [8].

The basic architecture of low-voltage dc microgrid is shown in Fig. 1. There are several control issues related to the microgrid, including interconnection schemes between DERs and common dc grid, voltage control among parallel converters, load sharing, maximum power point tracking, and energy storage [9], [10]. Among these, this paper focuses on the voltage control and load sharing between different DERs connected through dc–dc converters to a common dc microgrid. There are several advantages of parallel-connected converters such as: 1) expandability of output power, 2) reliability, 3) efficiency, and 4) ease of maintenance [11].

The problems associated with voltage control are poor load sharing and circulating current between converters [12]. The reasons for variations from the constant output voltage are sudden changes in the input power, load, parametric variations, and error in voltage and current feedback. The circulating current issue will arise if there is a mismatch in the converters output voltages.

Several load sharing methods have been proposed in literature in which, most popular schemes are active current sharing [13], [14] and droop control [15]–[26] methods. Droop control method is a decentralized voltage control method in which each converter output voltage reference is controlled based on its output current [15]. The major limitation of this scheme is poor voltage regulation. The central limit current sharing control for parallel dc–dc converter is reported in [16] based on independent voltage feedback loops. This paper also discusses the importance of cable resistance in load current sharing. A droop current sharing method without any communication link between converters is explained in [17]. In this paper, the calculation of maximum droop range for parallel-connected converters is explained. A novel droop method for converters parallel operation is reported in [18], in which peak output current is compared with current set value to control the reference voltage of each converter. This algorithm gives better performance only when the source supplies rated power because the droop gain values are calculated based on rated power. A dc bus signaling method (DBS) [19] can also be used for parallel

Manuscript received February 21, 2014; revised May 23, 2014 and July 28, 2014; accepted September 02, 2014. This work was supported by Renault Nissan Technology & Business India Pvt. Ltd., under Research Support Program at IIT Madras. Paper no. TSTE-00077-2014.

The authors are with the Department of Electrical Engineering, Indian Institute of Technology Madras, Chennai, India. (e-mail: sijomundackal@outlook.com; mahesh@ee.iitm.ac.in; lakshmin@ee.iitm.ac.in).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TSTE.2014.2360628

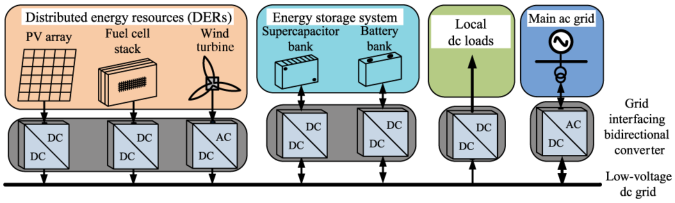


Fig. 1. Architecture of low-voltage dc microgrid.

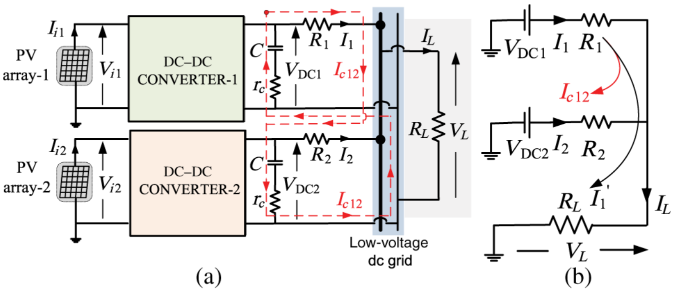
operation of converters. In this method, the source and storage converters operate autonomously based on the voltage level of the dc bus. A three-level hierarchical control algorithm is proposed in [20] which uses low bandwidth communication (LBC). This algorithm minimizes the mismatch in the converters output voltages due to droop method; however, the effect of cable resistance was not considered. A decentralized circulating current control method is proposed in [21], which is based on no-load circulating current values. This algorithm is inefficient for parallel operation of conventional boost converter in microgrid because no load operation is not possible. In order to improve voltage regulation, droop control with voltage shifting is reported in [22]. The advantage of this method is that the magnitude of droop does not affect the output voltage of the converters. An improved droop control method is also discussed in [23]. In this method, conventional droop control with LBC and local controllers are used to achieve load current sharing and dc bus voltage restoration.

An adaptive droop resistance (ADR) technique is proposed in [24] for adaptive voltage positioning (AVP) control in dc–dc converters. The proposed ADR technique can vary the droop resistance to track the variation of the load current. Load sharing issues of an autonomous hybrid microgrid is explained based on ac and dc subgrids in [25]. In this method, the active power flows within subgrids is brought to a common per-unit range for power sharing. A co-operative algorithm with a voltage regulator and current regulator is presented in [26]. In this algorithm, the current regulator compares local per-unit current with the neighbours per-unit currents and, accordingly, adjusts the droop virtual impedance to balance the per-unit supplied currents. In literature, there are methods based on gain scheduling and fuzzy logic [27], [28] to implement droop method. In these methods, load sharing is possible with calculation of membership value from the membership function.

The major drawbacks of the existing droop control methods used in dc microgrid are poor voltage regulation, use of fixed droop value irrespective of the instantaneous voltage deviation, and unequal load sharing. To overcome these limitations, an instantaneous droop calculation method is proposed in this paper. The calculation of droop values are based on a figure of merit called droop index (DI). This method gives better control over circulating current and proper load sharing in both transient and steady-state conditions.

II. LOAD SHARING AND CIRCULATING CURRENT ISSUES

In this section, load current sharing and circulating current issues for parallel dc–dc converters connected to a low-voltage dc microgrid are discussed. Fig. 2(a) shows two parallel-connected dc–dc converters, which interface PV arrays and dc grid. In this figure, $V_{\mathrm{DC}1}$, $V_{\mathrm{DC}2}$, I_1, I_2, and R_1, R_2 represent output voltages, output currents, and cable resistances of converter-1 (Conv-1) and converter-2 (Conv-2), respectively. The output side of the converter can be represented as a voltage source in series with the cable resistance and its equivalent circuit is shown in Fig. 2(b) [12]. If $V_{\mathrm{DC}1} > V_{\mathrm{DC}2}$, I_{C12} is the circulating current component from Conv-1 to Conv-2 and I_1' is the load component from Conv-1. Case studies for current sharing and circulating current based on the converters output voltages and cable resistances are listed in Table I.



(a) (b)

Fig. 2. (a) Parallel dc–dc converters with different output voltages. (b) Steady-state equivalent circuit for the dc output side.

TABLE I
CASE STUDIES FOR LOAD SHARING AND CIRCULATING CURRENT

Case	V_{DC1}, V_{DC2}	R_1, R_2	I_1, I_2	I_{C12} / I_{C21}
1	equal	equal	equal	zero
2	equal	different	different	zero
3	different	equal	different	not zero
4	different	different	different	not zero

A. Analysis of Circulating Current for Two-Converter System

By applying kirchoff's voltage law (KVL) in Fig. 2(b)

$$V_{\mathrm{DC}1} - I_1 R_1 - I_L R_L = 0 \tag{1}$$

$$V_{\mathrm{DC}2} - I_2 R_2 - I_L R_L = 0. \tag{2}$$

The expression for converters output current I_1 and I_2 can be derived from (1) and (2) and is given as

$$I_1 = \frac{(R_2 + R_L)V_{\mathrm{DC}1} - R_L V_{\mathrm{DC}2}}{R_1 R_2 + R_1 R_L + R_2 R_L} \tag{3}$$

$$I_2 = \frac{(R_1 + R_L)V_{\mathrm{DC}2} - R_L V_{\mathrm{DC}1}}{R_1 R_2 + R_1 R_L + R_2 R_L}. \tag{4}$$

Further, the circulating current can be expressed as

$$\begin{aligned} I_{C12} = -I_{C21} &= \frac{V_{\mathrm{DC}1} - V_{\mathrm{DC}2}}{R_1 + R_2} \\ &= \frac{I_1 - I_2}{2} \quad (\text{if } R_1 = R_2) \\ &= \frac{I_1 R_1 - I_2 R_2}{R_1 + R_2} \quad (\text{if } R_1 \neq R_2). \end{aligned} \tag{5}$$