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Adaptive Droop Control Method for Suppressing Circulating Currents in DC Microgrids

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ABSTRACT DC microgrids are introduced to reduce the conversion stages needed for connection of DC sources to the DC loads. They employ the droop control algorithm for managing the power flow from sources to the loads. However, the droop control functionality is affected by circuit parameters, especially line resistances. As a consequence, load sharing as the primary objective of the droop controller lacks accuracy. Parallel-connected converters have mismatched output voltages, resulting in circulating currents. This paper proposes an adaptive droop control algorithm for suppressing circulating currents in a low voltage DC microgrid. Line resistances are estimated through mathematical calculations and droop parameters are adjusted accordingly. Moreover, a distributed secondary controller is proposed to improve the load sharing accuracy and eliminate the effect of line resistances. The secondary controller shifts the droop controller voltage setpoint according to the converter current. Both of the proposed methods result in an accurate load sharing; Each of the participating converters has the rated current and consequently circulating current is suppressed. The effectiveness of the proposed method is verified through simulation and hardware-in-the-loop (HIL) setup.

INDEX TERMS Circulating current, dc microgrid, distributed control, droop control, hardware-in-the-loop (HIL).

I. INTRODUCTION

RENEWABLE resources are scattered geographically to maximize the energy harness [1]. Microgrid concept is introduced for the utilization of such renewable resources [2]. Microgrids also provide platforms for connecting the renewable resources to an AC or DC network through power electronic converters.

Various types of distributed generations and renewable resources, e.g., photovoltaic (PV), offer DC powers. Moreover, DC loads usage expands in different microgrid applications [3]. Therefore, employing DC microgrids is an efficient method of connecting DC sources to the DC loads. The advantages of DC microgrids are derived from the reduction of conversion chains and reduced number of DC-AC or AC-DC inverters. Hence, higher efficiency and reliability are among the primary results of such network simplicity [4].

A simple structure of a DC microgrid is shown in Fig. 1. All sources provide DC power, except the utility grid which produces AC power and is connected to the common DC bus through an AC-DC inverter. As the arrows show, loads and PV arrays have unidirectional power flow, while battery energy storage systems (BESSs) and the utility grid have bidirectional power flow means they can supply or absorb power.

Different control issues exist in DC microgrids. Accurate current sharing is one of the primary matters in DC microgrids with parallel-connected sources [5]. Therefore, the existence of a comprehensive control platform is of great interest. An appropriate control method should be capable of maintaining the stability of the system as well as achieving the desired objectives. The droop control method is a traditional strategy that is widely implemented in DC microgrids [6]. In this control method, converter output currents and voltages are defined according to droop parameters. Droop functionality depends on droop parameters to be set sufficiently large with respect to the line resistances. However, large values of droop parameters result in unacceptable voltage drops. Therefore, there is a trad-off between these objectives [7].

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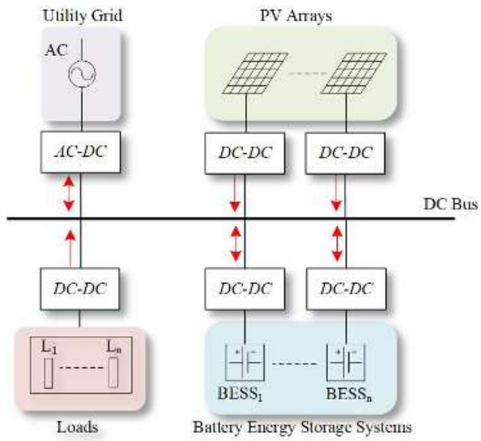


FIGURE 1. **A simple structure of a DC microgrid.**

Droop parameters are defined according to the acceptable voltage drop [8]. However, line resistances affect the functionality of droop controllers, especially when the droop parameters are chosen to be small. The accuracy of the currents shared among sources is reduced with the existence of these uncontrollable and unknown variables. As a result, there is a mismatch between converter output voltages, and circulating currents arise. Circulating currents are generated from some of the converters and pass the others without feeding the load. Therefore, the currents exceed the desired ratings of the converters and reduce their lifetimes [9].

There are some research items which introduce new adoptions to the droop controllers to achieve accurate load sharing between parallel-connected converters. They suppress the circulating current by either adjusting the droop parameter or establishing a secondary controller.

In [10], a method of decoupling droop control is proposed considering both line resistances and load characteristics. However, obtaining the accurate value of line resistances through the proposed method is difficult. This method also depends highly on the load characteristics. Another adaptive droop method is proposed in [11]. The proposed method changes the droop resistance to follow any variation in the load current. It doesn't improve the current sharing among converters which is deteriorated by line resistances. In [12], a generic method of particle swarm optimization is introduced for tuning the virtual resistance of the droop controller. This method does not calculate line impedance and achieves the current sharing through heuristic methods. In [13], the droop parameters are calculated based on a proposed indicator called droop index. Although this method results in an accurate load sharing, it suffers from the huge computational effort. Authors of [14] propose a new virtual parameter by passing the converter's power to a low pass filter. Utilizing a low pass filter adds latency and complexity to the design stage. Authors of [15] present modified droop parameters for reducing the circulating currents. The proposed parameters are defined according to the maximum allowed voltage deviation. In this method, the circulating current is reduced from the initial amount. However, it is not completely suppressed.

The secondary controller is another method of regulating the load sharing. This method shifts the droop controller voltage setpoint according to data gathered through the communication links. All methods of employing secondary controllers can compensate for the voltage regulation and improve the load sharing with the help of a low bandwidth communication network. In [16], a spread secondary control is utilized with the dynamic current averaging. It gets the information only from adjacent converters instead of all converters to achieve equal load sharing. Communication stress is highly reduced in this method. However, unequal load sharing is not investigated.

In [17], a precise method of power sharing is proposed with the introduction of the voltage observer and the frequency controller. However, this scheme requires high speed communication links to achieve accurate power sharing. Furthermore, designing the voltage observer makes the computation complex. The average of all converters currents is calculated to restore the compensation signal of the secondary controller in [18]. However, this method does not consider unequal droop parameters and load sharing.

To have complete elimination of the circulating current through adjusting the droop parameters, the knowledge of line resistances is beneficial. Some research studies focus on estimating the line resistances, especially in the remote connection of voltage sources to the DC bus [19]. Their main intention is to estimate the line resistances to help power flow optimization. Therefore, they need big data and huge computational efforts. For example in [20], the authors address a method for estimating the line resistances through trial and error algorithms. The method needs both active and reactive power measurements to estimate the line impedance.

In some other research studies, the circulating currents between converters are suppressed with different control strategies. The circulating current is minimized through heuristic methods in [21]. However, droop control is not considered as the main control algorithm for power sharing. A low pass filter is another method of suppressing the circulating current. In [22], feedback from the difference between the converters' currents is passed through a filter. In [23] the same input is passed through a PID filter. The problem in these methods is the introduction of latency and instability. The circulating current is reduced and is not completely eliminated in [24], due to the estimation of voltage drop according to the maximum output voltage deviation.

Studied methods do not address the complete suppression of circulating currents. Moreover, the line resistances are not estimated accurately, which have great influences on the functionality of droop controllers and deteriorate the objective of accurate current sharing. The proposed secondary controllers are appropriate for equal load sharing. However, any other desired load sharing is not investigated. In this paper, an adaptive droop control method is proposed to overcome the drawbacks of the existing methods. The main contributions of this paper are summarized as follows:

1) A new method for estimating the line resistances is proposed by only knowledge of the DC bus voltage and converters currents.
2) The estimated line resistances are used in adjusting droop parameters. The proposed method operates accurately for any desired current sharing.
3) A secondary controller is proposed for achieving the desired current sharing. Fewer signals are needed with respect to the studied methods. No filter design is required. Therefore, the controller design has fewer complications and is easy to be implemented.

The rest of the paper is organized as follows. In Section II, the distributed control platform containing the droop controller is reviewed. Circulating current is defined and possible methods of its suppression are discussed. Section III proposes the droop parameter adjusting method for different case studies. Section IV presents the voltage shifting method in different operating modes. Section V presents HIL results and compares two proposed methods. Finally, Section VI concludes the paper.

II. DROOP CONTROLLER AND CIRCULATING CURRENT

Droop control is one of the well-known control methods in DC microgrids which defines power sharing among sources. The load current is shared among parallel-connected sources according to their droop parameters. Droop parameters are defined in the design stage according to the desired objectives. Then the converters are connected to the DC bus and their output voltages and currents deviate from the desired ones. In fact, line resistances affect droop functionality in satisfying the desired objectives. They change the line currents and output voltages of the converters. Therefore, what is defined in the design stage cannot be achieved. If there is any slight mismatch in the voltage feedback of two converters, their currents are not the same as what is defined. The difference between the predefined current and the current generated by the converter passes through the other converters. This leads to the circulating current between the converters.

Fig. 2 shows three sources and their controllers communicating with each other. Controllers get measured data through the communication link, calculate the gating signals and send the PWM signals to the converters' switches. The DC/DC converters are buck converters connecting the voltage sources to the DC bus. R_{c_i} is an unknown line resistance connecting the i^{th} converter to the DC bus. I_{cir} is the circulating current that flows from one converter to the other one. Estimating line resistances is necessary to modify droop parameters in order to suppress the circulating current. For all sources with droop controllers, the corresponding line resistances should be calculated and the droop parameters should be modified accordingly. All the voltage sources of the DC microgrid have their own droop controllers. Therefore, the proposed

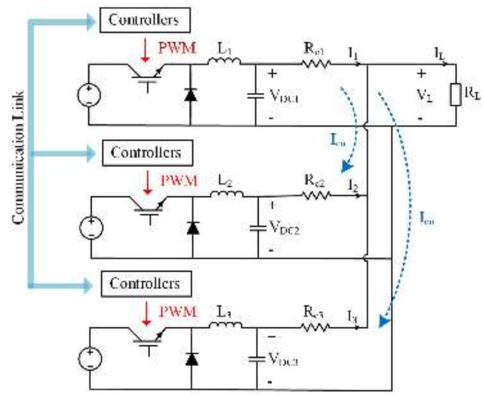


FIGURE 2. Parallel-connected sources and their DC-DC converters in a DC microgrid.

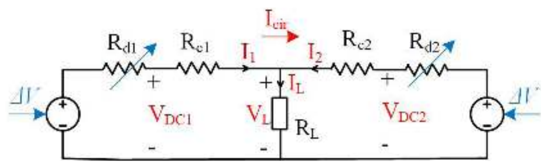


FIGURE 3. Circuit modeling of two parallel-connected sources.

method of accurate power sharing can be applied to all of the parallel voltage sources of the system, like BESSs or grid-tied inverter.

Circulating currents should be avoided for several reasons. First, it degrades the converter components. Converters' components are selected according to the desired values of currents and voltages. In the existence of the circulating current, extra currents flow from one converter to the other, resulting to higher current ratings of some converters. Higher current ratings affect selected converter's components and decrease their reliability. Second, total system losses are higher as there are excess amounts of currents flowing among converters. In a DC microgrid, the sources are parallel to each other through short cables. Therefore, the line resistances are small. Although, they can have great impacts on the converters' currents, especially when the droop parameters are small. The typical value for line resistances is 0.1Ω which is large with respect to droop parameters [25].

Droop controller offers two flexible parameters in suppressing circulating currents: the droop parameter and the voltage setpoint. Fig. 3 shows the circuit modeling of two parallel-connected sources and these two flexible parameters: R_{d_1}, R_{d_2}, and ΔV. As droop parameters act as virtual resistances, they are considered series to line resistances. Without line resistances, converters output voltages, V_{DC1} and V_{DC2}, are the same. However, the existence of R_{c1} and R_{c2} introduces mismatches to the converters output voltages:

$$\begin{cases} V_{DC_1} = V_{DC_2} = V_L, & \text{No line resistances} \\ V_{DC_1} \neq V_{DC_2} \neq V_L, & R_{c1} \neq R_{c2} \end{cases} \tag{1}$$

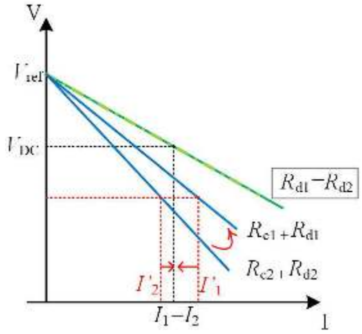


FIGURE 4. **Droop parameter adjustment method.**

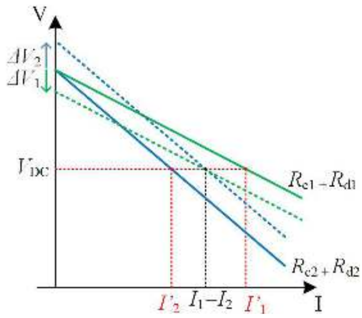


FIGURE 5. **Voltage setpoint shifting method.**

According to Fig. 3, line resistances change the load voltage, V_L and the load current, I_L. As a result, converters' currents change. Moreover, their contribution is also changed according to the droop parameters as well as line resistances.

The mismatch in output voltages results in currents deviations. By changing droop parameters or shifting voltage setpoints, the currents can be restored. Droop curves of two voltage sources having equal droop parameters are shown in Fig. 4 and 5. Line resistances change the droop slopes to two different values which results in two different currents. The droop parameter adjustment method is shown in Fig. 4. In this approach, the slopes of the curves are changed to restore the desired values. The currents are changed from I_1' and I_2' to I_1 and I_2. In Fig. 5, solid lines show the droop curves that are affected by line resistances. In this approach, the curves slopes are maintained, however, the voltage setpoints are shifted up and down to restore the initial currents.

The implementation of these methods is shown in Fig. 6. The converters have the primary control algorithm consisting of current controllers, voltage controllers, and droop controllers. The voltage and current controllers are PI controllers generating signals to PWM blocks. Fig. 6(a) shows the droop parameter adjustment method and Fig. 6(b) shows the voltage setpoint shifting method. The proposed controllers change the droop parameters or voltage setpoints to achieve the current sharing objective. In the following section, the droop parameter adjustment method is explained in detail. Then, the next section discusses the voltage setpoint shifting method.

III. DROOP PARAMETER ADJUSTMENT

The adaptive philosophy of the proposed method is the modification of droop parameters according to the DC microgrid data, instead of having certain values for these parameters. Therefore, droop parameters are changed according to the circuit data to satisfy the power sharing objective. In this section, two comprehensive case studies are investigated to estimate line resistances and modify droop parameters accordingly.

A. VOLTAGE SOURCES WITH EQUAL LOAD SHARING

In this case study, a DC microgrid consisting of PV arrays, a grid-tied converter and *n* number of BESSs as the system voltage sources is considered. The objective is to have equal load sharing among all BESSs and the grid-tied converter. Therefore, their droop parameters are set the same initially. It is expected that the load current is equally shared among sources. However, line resistances change the converters' currents and don't allow them to follow their initial droop parameters. To equalize the converters' currents, droop parameters should be modified according to the actual currents.

In this paper, in order to focus on the circulating current, it is assumed that PV arrays have fixed currents controlled by maximum power point tracking (MPPT) controllers. Moreover, the DC bus is considered right at the output of the grid-tied converter and there is no line resistances in between. Therefore, both of these sources have fixed currents and are not affected by the circulating currents that flow between BESSs.

The i^{th} BESS is connected to the load through a line with an unknown R_{c_i} resistance. Line resistances cannot be estimated in the design stage, as they are dependent on the converters locations and their distances to the common DC bus. On the other hand, the converter's droop parameter is selected based on the desired output voltage and current sharing, regardless of cable parameters. The droop formula for the i^{th} BESS is:

$$V_{DC_i} = V_{\text{ref}} - R_{d_i} I_i \tag{2}$$

where, V_{ref} is the voltage setpoint, V_{DC_i} is the converter output voltage, and R_{d_i} is the converter initial droop parameter. With no line resistances, all the converters' output voltages are the same as the DC bus voltage, V_L, and the droop control method works as desired.

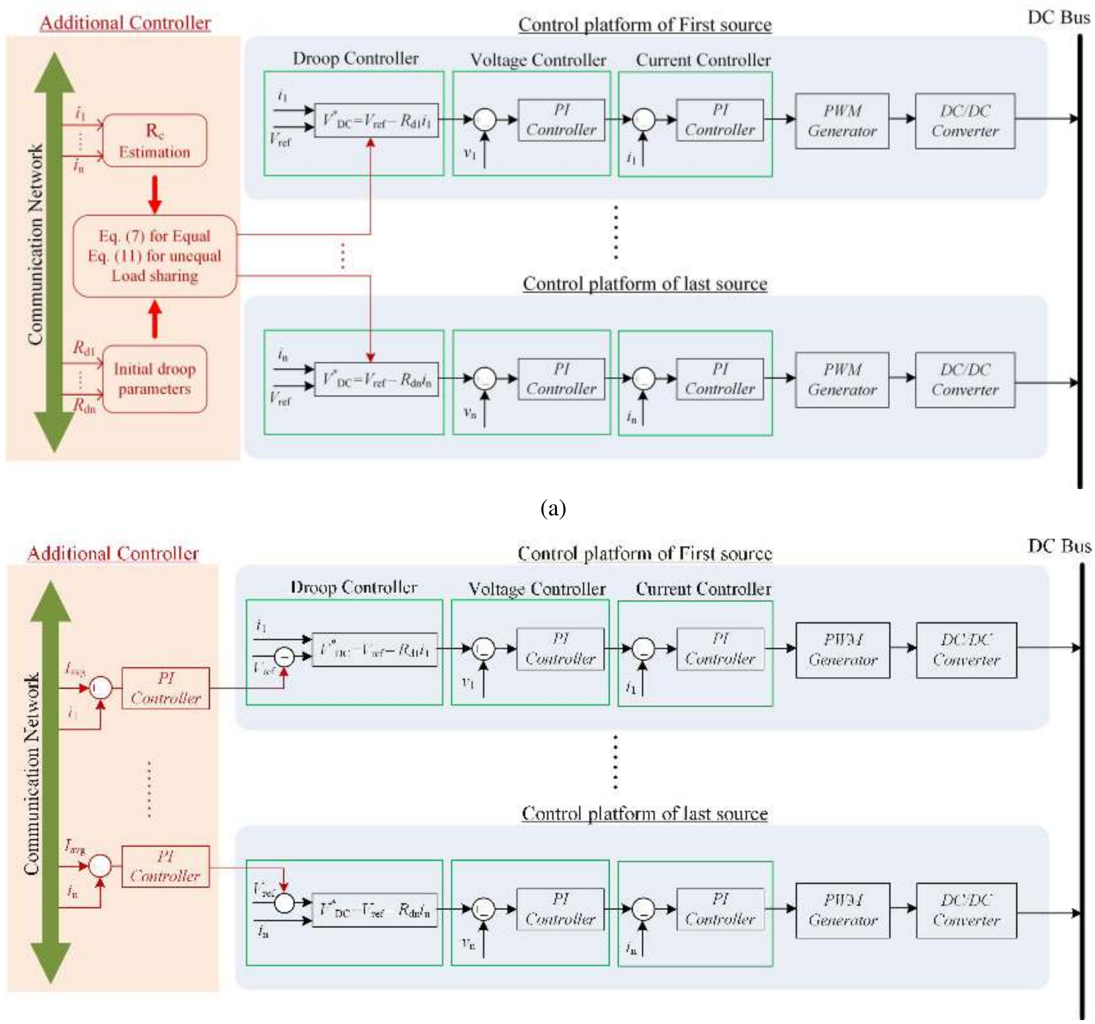
$$\begin{aligned} R_{d_1} = R_{d_2} = \cdots = R_{d_n} \rightarrow I_1 = I_2 = \cdots = I_n \\ V_{DC_1} = \cdots = V_{DC_n} = V_L \end{aligned} \tag{3}$$

With line resistances, another stage of voltage drop is introduced to the droop formula. Then, V_L is:

$$V_L = V_{DC_i} - R_{c_i} I_i = V_{\text{ref}} - (R_{c_i} + R_{d_i}) I_i \tag{4}$$

Therefore, all the voltage drops resulted from line resistances and droop parameters are equal:

$$(R_{c_1} + R_{d_1}) I_1 = (R_{c_2} + R_{d_2}) I_2 = \cdots = (R_{c_n} + R_{d_n}) I_n \tag{5}$$



(a)

(b)

FIGURE 6. Block diagram of the control platform. (a) Droop parameter adjustment method; (b) Voltage setpoint shifting method.

As the line resistances are not the same, the resulting I_is are different:

$$I_i = \frac{R_{c_j} + R_{d_j}}{R_{c_i} + R_{d_i}} I_j \tag{6}$$

In order to have the same currents, line resistances should be estimated and droop parameters are modified accordingly:

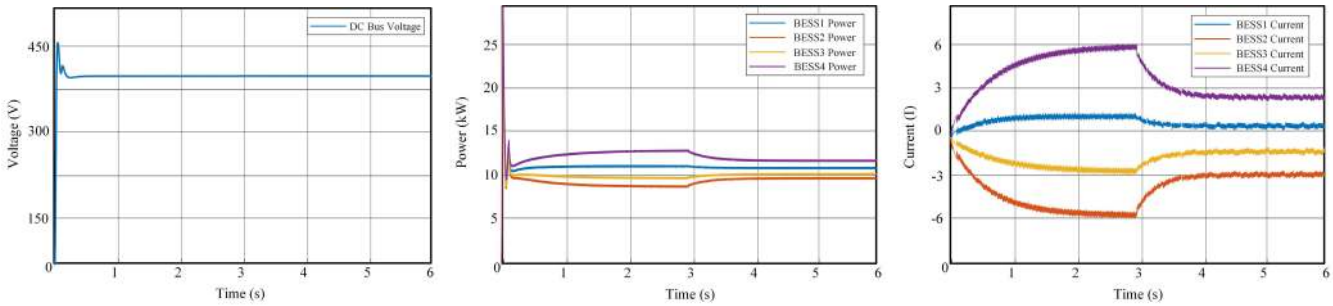
$$R'_{c_i} + R^{new}_{d_i} = R'_{c_j} + R^{new}_{d_j} \tag{7}$$

R'_{c_i} and R'_{c_j} are the estimated line resistances and $R^{new}_{d_i}$ and $R^{new}_{d_j}$ are the i^{th} and j^{th} converters modified droop parameters, respectively. To estimate the line resistances, the following equations are obtained from Fig. 3:

$$V_{\text{ref}} = (R_{c_i} + R_{d_i}) I_i + V_L \Rightarrow R'_{c_i} = \frac{V_{\text{ref}} - V_L}{I_i} - R_{d_i} \tag{8}$$

By measuring I_i, V_L, and having information about the initial droop parameters, line resistances can be estimated. Then, by replacing R'_{c_i} and R'_{c_j} in (7), the ratio of new droop parameters are defined. One of the droop parameters can be set to its initial value. Then, all other converters' droop parameters are calculated. The new currents' ratios become equal by means of slight changes in droop parameters. Circulating current is suppressed, while the initial objective of accurate current sharing is achieved. The simple method used in (8) overcomes the existing methods of the line resistance estimation, since all the parameters used in this equation have already been measured for control purposes and there is no need for extra data. Fig. 6(a) shows the implementation of this adaptive method. The droop parameters are modified according to the estimated line resistances. Then, droop controllers get the updated parameters and force the converters to operate at the same current sharing.

It should be noted that the above calculations can be applied to both charging and discharging operations of BESSs. In other words, regardless of currents flowing



(a) (b) (c)

FIGURE 7. Results of simulation for voltage sources with equal load sharing. (a) DC bus voltage; (b) Power sharing among sources; (c) Circulating currents among sources.

TABLE 1. DC microgrid and controllers parameters.

Parameter	Amount	Parameter	Amount
Output inductor	$L = 5\text{mH}$	Output capacitor	$C = 500\mu$ F
Nominal voltage	$V_{\text{ref}} = 380V_{\text{dc}}$	Switching Freq.	$F_{sw} = 20$ kHz
First BESS line resistance	$R_{c_1} = 0.1\Omega$	Second BESS line resistance	$R_{c_2} = 0.14\Omega$
Third BESS line resistance	$R_{c_3} = 0.12\Omega$	Forth BESS line resistance	$R_{c_4} = 0.08$
Grid-tied converter droop parameter	$R_{d_g} = 0.057\Omega$	Load power	$P_{\text{load}} = 65$ kW
Voltage controller proportional gain	$K_{p_v} = 0.4$	Voltage controller integral gain	$K_{i_v} = 10$
Current controller proportional gain	$K_{p_i} = 0.5$	Current controller integral gain	$K_{i_i} = 4$
Secondary controller proportional gain	$K_p = 0.3$	Secondary controller integral gain	$K_i = 0.2$

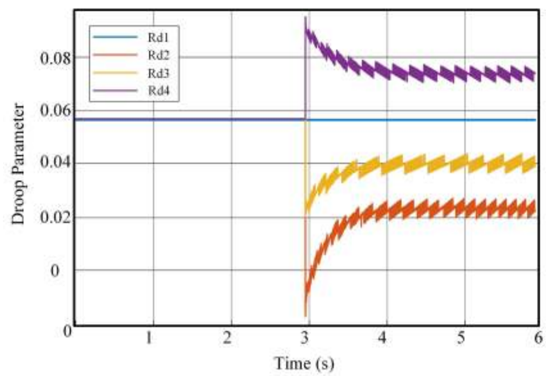


FIGURE 8. BESSs' Droop parameters.

to or from BESSs, the equations remain valid and line resistances are estimated.

A DC microgrid with PV arrays, a grid-tied converter, and four BESSs as the voltage sources of the system is simulated in MATLAB/Simulink. The BESSs and the grid-tied converter have the same droop parameters of 0.057 for equal load sharing. The selection of droop parameters is carried out in [26] according to the desired range of the DC bus voltage and converters' ratings. It should be noted that the converters' ratings are different in the practice. Therefore, the load sharing among them can be considered to be equal or unequal. Droop parameters are also selected according to these ratings; Different droop parameters demonstrate different ratings of the converters.

PV arrays are controlled to be in the MPPT mode with a fixed current of 40 A. The parameters of the studied DC microgrid and the controllers' settings are summarized in Table 1. The DC microgrid feeds a constant power load of 65 kW. Fig. 7 shows simulation results for this case study. As it is seen the DC bus voltage is independent of the adaptive method and is kept stable for the whole period of simulation. Fig. 7(b), demonstrates the power sharing among BESSs. At the beginning of the simulation, droop parameters are according to their initial values. The converters' powers are different due to the existence of line resistances. At $t = 3$s, line resistances are estimated and the adaptive droop control method is utilized. BESSs powers start getting equalized afterward. The current sharing and the power sharing curves are similar, except for their amounts, due to the constant value of the DC bus voltage. The circulating currents that pass from the converters are shown in Fig. 7(c). It is seen how the circulating currents are suppressed by modifying the droop parameters that are shown in Fig. 8. As it is seen, the first converter's droop parameter is fixed as the basis for all other droop parameters. Then, other BESSs' droop parameters are modified to force the power sharing to get equalized.

B. VOLTAGE SOURCES WITH UNEQUAL LOAD SHARING

This case study discusses unequal load sharing between n converters having different ratings and droop parameters. The currents are desired to be according to the ratio of droop parameters. However, in the existence of line resistances, the currents ratios are different. Without line resistances, the currents are derived based on the droop parameters ratios:

$$I_1 = \frac{R_{d_2}}{R_{d_1}} I_2 = \frac{R_{d_3}}{R_{d_1}} I_3 = \cdots = \frac{R_{d_n}}{R_{d_1}} I_n \tag{9}$$

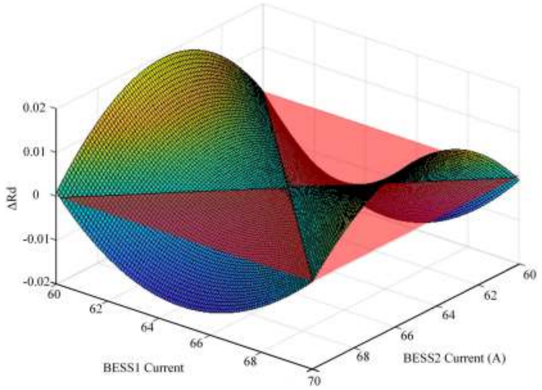


FIGURE 9. Droop parameters difference according to the currents.

According to (6), line resistances change the currents ratio:

$$I_1 = \frac{R_{d_2} + R_{c_2}}{R_{d_1} + R_{c_1}} I_2 = \frac{R_{d_3} + R_{c_3}}{R_{d_1} + R_{c_1}} I_3 = \cdots = \frac{R_{d_n} + R_{c_n}}{R_{d_1} + R_{c_1}} I_n \quad (10)$$

However, the desired ratios of currents are shown in (9). Thus, the droop parameters should be adjusted accordingly:

$$\frac{R_{d_i}^{new} + R'_{c_i}}{R_{d_j}^{new} + R'_{c_j}} = \frac{R_{d_i}}{R_{d_j}} \quad (11)$$

Without loss of generality, the first converter is considered to have a fixed droop parameter. Then, R'_{c_i}s are estimated from (8) and new droop parameters are obtained. By simplifying (11), the following equation is derived that shows how the droop parameter is changed according to the line resistances:

$$R_{d_i}^{new} + R'_{c_i} = \frac{R_{d_i}}{R_{d_1}} (R_{d_1} + R_{c_1}) \rightarrow \Delta R_{d_i} = \frac{R_{d_i}}{R_{d_1}} R_{c_1} - R_{c_i} \quad (12)$$

This equation shows that if the initial droop parameters are the same, each converter's droop parameter deviates from R_{d_1} according to the difference between the line resistances:

$$\Delta R_{d_i} = -\Delta R_{c_i} \quad (13)$$

Otherwise, each line resistances need to be scaled with the scaling factor according to the ratio of droop parameters. To investigate how the droop parameter is changed according to the difference in the converters' currents, R'_{c_i} is replaced in (7) with the related voltage and current:

$$R_{d_i}^{new} = R_{d_1} + \frac{V_{\text{ref}} - V_L}{I_1} - \frac{V_{\text{ref}} - V_L}{I_i} \quad (14)$$

Fig. 9 shows the difference between $R_{d_i}^{new}$ and R_{d_1}. It is seen that their difference increases as the difference in the currents increases. The red surface shows zero deviation which happens only if the converter currents are the same and equal current sharing happens. The red surface is also met when the two converters' currents summation is exactly the same as the load current. In this case, there is no circulating current between converters, since all currents should supply the load. This case cannot happen in real-world with line resistances between converters.

A DC microgrid with three BESSs having droop parameters of 0.057, 0.115, and 0.173 is simulated. The grid-tied converter has the droop parameter of 0.057. In theory, the second BESS's current should be half and the third BESS's current should be one-third of the first BESS's current according to their droop parameters. Simulation results for the converters' currents are shown in Fig. 10(a). It can be seen that in the first three seconds of the simulation, BESSs' currents are not according to the desired ratios. At $t = 3$s, the adaptive droop control method is utilized. The currents are adjusted to the desired ratios, with the steady state amounts of 46.44 A, 23.22 A, and 15.48 A, respectively. After the adjustment, BESS1 has twice the current of BESS2 and thrice current of BESS3. The circulating currents are shown in Fig. 11(a). They diverge before the adaption method is employed. However, after the modification of droop parameters, the circulating currents converge.

IV. VOLTAGE SETPOINT SHIFTING

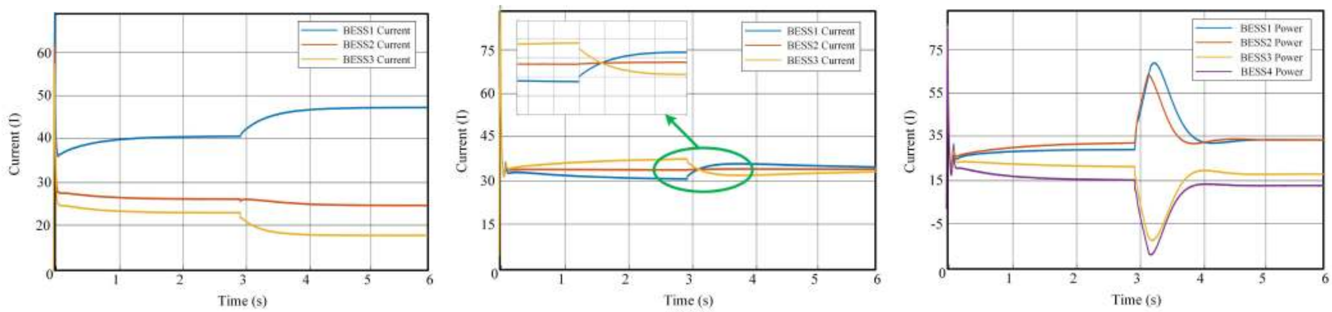
As mentioned earlier, the main control algorithm for the power sharing is the droop controller. This controller provides two parameters to be modified in order to suppress the circulating current: the droop parameter, R_d and the voltage setpoint, V_{ref}. In the previous section, a new method is proposed to estimate line resistances and adjust droop parameters accordingly.

Estimating line resistances depends on the knowledge of V_L which can be far from converters and requires an additional measurement. Moreover, although changing the droop parameter helps in suppressing the circulating current, it can deteriorate other objectives such as keeping the voltage drop as low as possible. Therefore, the voltage setpoint can be manipulated to suppress the circulating current. Similar to the last section, the analysis can be done for two different case studies, considering equal or unequal load sharing.

A. VOLTAGE SOURCES WITH EQUAL LOAD SHARING

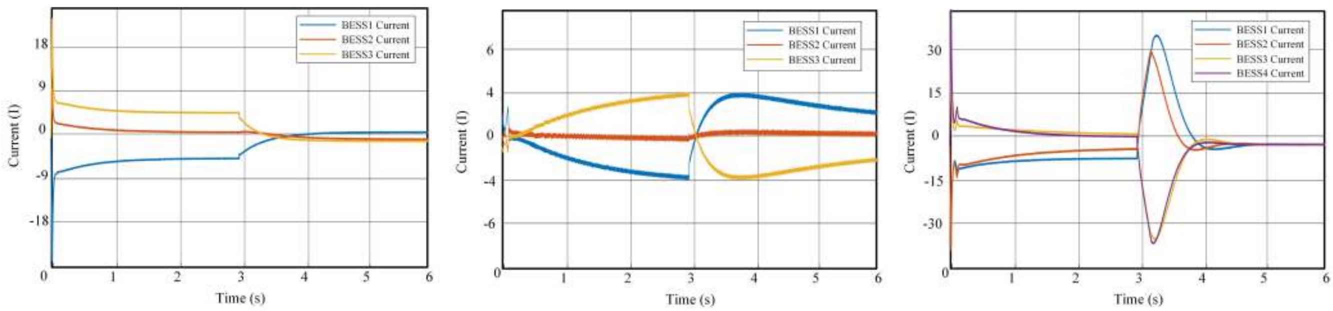
In this case study, a DC microgrid with n number of voltage sources having equal droop parameters is considered. The currents are desired to be the same. However, due to line resistances, currents are different. To address this issue, a secondary controller is utilized in order to manipulate the voltage setpoint of the droop controller.

As the objective is to have the same currents for all converters, the currents are compared together and passed through a PI controller as the secondary controller. The output is the amount that the voltage setpoint should be increased or decreased. Fig. 6(b) shows how the voltage setpoint shifting method operates. The average current of all converters is taken as the reference that each converter current is compared to. The difference between them feeds a PI controller and shifts the reference voltage of the droop controller. Therefore, the voltages are shifted up for the sources that have higher currents and shifted down for the remaining. When each converter's current is compared to the average current, their difference is decayed and they get equalized.



(a) (b) (c)

FIGURE 10. Converters' waveform from simulation results: (a) Droop adjustment method with unequal load sharing; (b) Voltage setpoint shifting method with equal load sharing; (c) Voltage setpoint shifting method with unequal load sharing.



(a) (b) (c)

FIGURE 11. Circulating currents: (a) Droop adjustment method with unequal load sharing; (b) Voltage setpoint shifting method with equal load sharing; (c) Voltage setpoint shifting method with unequal load sharing.

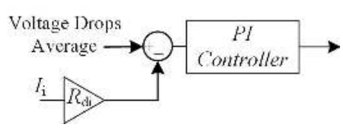


FIGURE 12. Block diagram of the secondary controller implementation for the unequal load sharing.

A DC microgrid with PV arrays, three BESSs, and a grid-tied converter is considered for the simulation. Fig. 10(b) shows the BESSs' currents. In the first three seconds of simulation time, the currents are diverging from each other. Line resistances deteriorate the functionality of the droop controllers and the objective of equal current sharing. Then, the currents get equalized after employing the secondary controller at $t = 3$s. The suppression of circulating currents is shown in Fig. 11(b).

B. VOLTAGE SOURCES WITH UNEQUAL LOAD SHARING

In this case study, the droop parameters are set different to meet any desired load sharing. Without line resistances, the currents are desired to be according to the ratios of droop parameters. Therefore, the voltage drops of all converters due to droop controllers are the same:

$$\text{Voltage Drop:} R_{d_1} I_1 = R_{d_2} I_2 = \cdots = R_{d_n} I_n \tag{15}$$

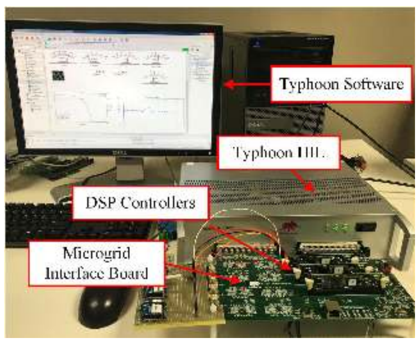
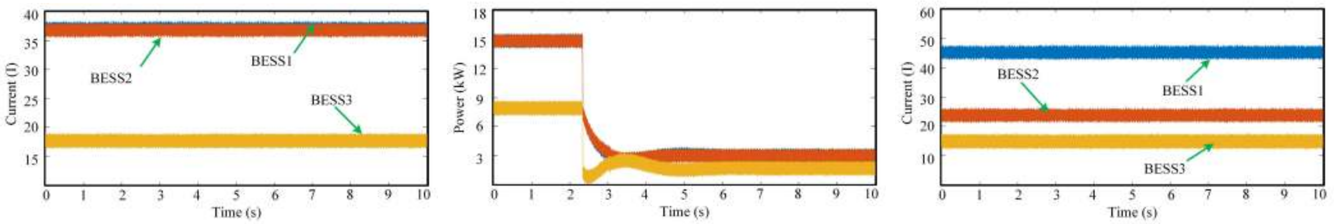


FIGURE 13. HIL setup.

In order to restore converters currents to be according to (15), each converter voltage drop, $R_{d_i} I_i$, should be compared to other converters voltage drops and passed through a PI controller. Through PI controllers, the input differences decay and all voltage drops are equalized. To equalize all converters voltage drops simultaneously, each converter voltage drop can be compared to the average of all converters voltage drops:

$$\text{Voltage Drops Average} = \frac{\sum_{i=1}^{n} R_{d_i} I_i}{n} \tag{16}$$

Fig. 12 shows the secondary controller that generates the signal to shift the voltage setpoint of the droop controller.



(a) (b) (c)

FIGURE 14. HIL results of the BESSs' currents and powers for the unequal load sharing: (a) Droop parameter adjustment method; (b) Load changes from 65kW to 22.8 kW; (c) Voltage setpoint shifting method.

TABLE 2. Circulating currents and voltage drops values.

Case Studies	I_{CC_1}	I_{CC_2}	ΔI_{CC}	Voltage Drop	V_d percentage
Section III-A	6.35	1.46	23 %	374.6	1.42 %
Section III-B	9.3	1.76	18.9 %	368.6	3 %
Section IV-A	3.97	0.933	23.5 %	376.6	0.89 %
Section IV-B	3.75	0.1743	2.7 %	376.6	0.89 %

With this method, any deviation in the converter current from the desired amount is suppressed by the PI controller.

A DC microgrid with PV arrays, a grid-tied converter, and four BESSs with droop parameters of 0.0577, 0.0577, 0.11, and 0.17 is simulated. The grid-tied converter is considered to have droop parameter of 0.0577 connected to the DC bus with no line resistance. Therefore, the PV arrays and grid currents are fixed.

BESS1 and BESS2 are supposed to have the same currents, while BESS3 and BESS4 are supposed to have half and one-third of BESS1 current, respectively. It is seen in Fig. 10(c) that currents are not as desired, initially. By employing the proposed method at $t = 3$s, the currents are set back to the desired values. First and second BESS have currents of 34.3 A, third BESS has the current of 17.15 A, and fourth BESS has the current of 11.44 A. The circulating currents convergence is shown in Fig. 11(c).

The quantitative indices extracted from simulation results are shown in Table 2. It is seen for all four case studies, the circulating currents are decreased significantly. Voltage drops for these case studies are also shown. It is seen that the voltage setpoint shifting method operates better in reducing the voltage drop across the DC bus. Also, from the figures, it can be concluded that both methods have a higher speed in circulating current suppression when there is unequal load sharing. The references in the literature review proposed some methods to suppress circulating currents. However, they need huge computational efforts and their design procedures are complex [12]. On the other hand, they focus on suppressing circulating currents for equal rating converters. Unequal power sharing is not considered in most of them, like [14]. In the following section, HIL results are presented to verify the effectiveness of the proposed methods.

V. HIL RESULTS

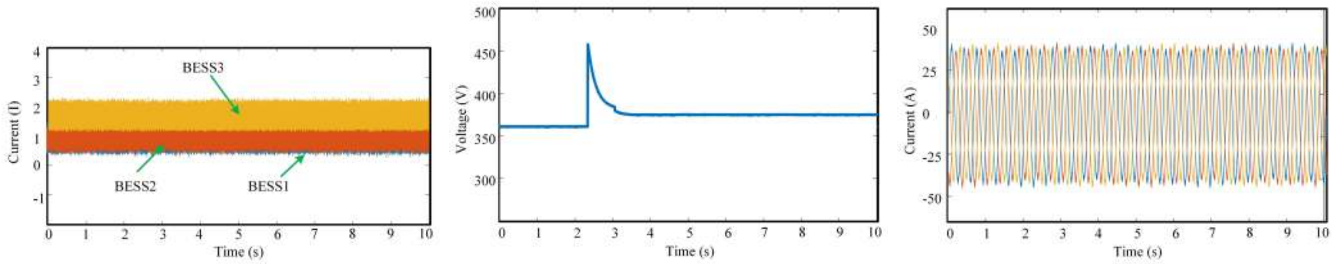
A HIL real-time simulator is used to show the proposed control methods effectiveness and feasibility in suppressing circulating currents. Fig. 13 shows the HIL setup. PV arrays, BESSs, the utility grid and all buck converters are modeled in Typhoon HIL 602 through Typhoon software.

Texas Instruments DSP boards are used for implementing the control part and generating gating signals. The control platform is programmed to the DSP boards. DSP controllers communicate with Typhoon HIL through the microgrid interface board as the low bandwidth communication network.

HIL results of the converters' waveform for the droop parameter adjusting and the voltage setpoint shifting methods are summarized in Fig. 14. Droop parameter adjusting method is employed in Fig. 14(a), (b). In this case study, R_{d_1} and R_{d_2} are set to 0.057, while R_{d_3} is set to 0.11. It is seen that BESS1 and BESS2 have the same currents which are twice BESS3 current. Fig. 14(b), shows the BESSs' powers when the load is changing. The load current is supplied by PV arrays, the utility grid, and three BESSs. PV arrays produce a fixed current of 40 A. The utility grid has also a fixed droop parameter and considered to be connected to the DC bus with no line resistances. In the beginning, the load power is 65 kW and drops at $t = 2.5$ to 22.8 kW. It is seen that BESSs' powers keep having the same ratio and circulating currents are suppressed automatically. Fig. 14(c) shows the BESSs' currents for the voltage setpoint shifting method. In this case study, the BESSs' droop parameters are set to 0.057, 0.11, and 0.17, respectively. It is seen that BESS1 current is twice BESS2 current and thrice BESS3 current. The HIL results verify the effectiveness of both proposed methods in achieving any desired current sharing.

Fig. 15(a) shows how the circulating currents are minimized. Fig. 15(b) and Fig. 15(c) demonstrate the DC bus voltage and the utility grid currents, respectively. It is seen that the DC bus voltage is kept in the desired range of operation which is [360 V, 380 V] and the load change doesn't have an affect on the voltage level. Fig. 15(c) shows the three phase utility grid currents. As it is seen, they are independent of line resistances as the utility grid is considered to be connected to the DC bus directly.

Both proposed methods have their own advantages and disadvantages. The droop parameter adjusting method doesn't



(a) (b) (c)

FIGURE 15. HIL results for unequal load sharing: (a) Circulating currents; (b) DC bus voltage; (c) The utility grid current.

add any controller stage. Therefore, there is no need to deal with the controlling design. However, in voltage setpoint shifting method, another controller is added which introduces complexity and latency. This method changes the voltage reference and as a result, reduces the voltage drop. It sets the output voltage around the nominal value. However, the droop parameter adjusting method results in more voltage drop as the droop slopes change.

VI. CONCLUSION

The traditional droop control is affected by line resistances. As a consequence, the load sharing has lacks accuracy. Parallel-connected converters have mismatches in their output voltages and circulating currents arise as the result. This paper proposes an adaptive droop control algorithm for a DC microgrid by incorporating estimated line resistances. Line resistances are defined through mathematical calculations and droop parameters are adjusted accordingly. The proposed method eliminates the effect of line resistances and is feasible for both equal and unequal load sharing. Moreover, a distributed secondary controller is proposed to suppress circulating currents. The proposed scheme results in accurate load sharing in the utilization of converters with different ratings. Each participating converter has the predefined current and circulating current is suppressed. The success of the proposed methods is verified through simulation and HIL results. Observing the stability of the system in employing both of the proposed methods is considered as the future work.

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