



Analysis of the Droop Control Method in DC Microgrids with Regard to the Types of Loads

M. Mahdavyfakhr^{1,*}, M. Hamzeh², E. Afjei³

^{1,2,3} Department of Electrical Engineering, Shahid Beheshti University, Tehran, Iran

ARTICLE INFO	ABSTRACT
<p>Article History: Received 29 November 2019 Received in revised form 4 January 2020 Accepted 11 March 2020 Available online 12 March 2020</p>	<p>The droop control method enables decentralized load sharing among voltage source converters (VSCs) in microgrids, eliminating the need for centralized control or communication. However, the accuracy of power sharing under droop control can be significantly affected by various factors, including the configuration of the microgrid and the nature of the connected loads. This study presents a comprehensive evaluation of the power-sharing accuracy of the droop control method, specifically examining its performance with three distinct types of electrical loads: constant impedance (CI), constant current (CC), and constant power (CP). Each load type introduces unique challenges that influence the proportional power distribution among converters. Furthermore, the effect of the microgrid's topology and line impedance variations on the power-sharing capability of droop control is systematically investigated. The research also explores how different DC microgrid configurations affect the reliability and fairness of power distribution. To validate the theoretical findings, detailed simulations are conducted in the MATLAB/Simulink environment. The simulation results confirm the sensitivity of the droop control approach to load type and network structure, offering insights into optimizing controller parameters for enhanced performance and robust load sharing in practical DC microgrid applications.</p>
<p>Keywords: Constant Current Load, Constant Impedance Load, Constant Power Load, Droop Method, Power Sharing Accuracy.</p>	

1. INTRODUCTION

With the incremental consumption of electricity, the needs for higher reliability, efficiency, power quality and lower carbon dioxide emission are felt more and more. To satisfy these challenges, the microgrid (MG) concept has been proposed. In general, the MGs are small scale power grids which incorporate renewable resources and advanced control schemes as their key features. Not only are they capable of working in the autonomous mode and supplying the loads independently but also they can operate in the grid-connected mode and inject the surplus of generated power to the main grid. Many researches are carried to extend the MGs' application and also to deal with the relevant challenges.

* Corresponding Author: M. Mahdavyfakhr
 Department of Electrical Engineering, Shahid Beheshti University, Tehran, Iran



The MGs are divided into two main groups of AC and DC MGs. It can be claimed that the major parts of future MGs are DC MGs. The reasons for such prediction are that the DC MGs are much reliable than their counterparts, the efficiency of power conversion is higher due to reduced required step of conversion, the majority of the renewable resources produce DC power and simpler control of DC MGs compared to AC MGs. Therefore, using an effective method to control the DC MG is of paramount importance [1].

There are different control methods for power sharing among DG units in DC MGs. Some of these methods (including master slave and average power sharing methods) rely on communication links. Hence, with the loss of communication links, the power sharing strategy is failed. On the contrary, the droop method is independent of communication links and it results in plug and play feature of DG units. In this method, all the sources operate in voltage source mode but the reference signal of each DG unit is modified according to the desired power flow requirements [2,3].

Some shortcomings, however, can be found in the droop procedure, which is the voltage drop on the MG buses, high error of power sharing in high impedance systems, instability and dynamic problems. In [4], an adaptive method, and in [5,6] efficient solutions for voltage drop compensation are proposed. The authors in [7] present an effective control scheme in DC MG to precisely share the load current oscillatory and DC components among DG units. The dynamic problems in droop procedure are discussed in [8] and the proposed control strategy can effectively improve the dynamic response of DC MGs under various load changes. In [9,10], a virtual impedance based method, and in [11] a novel technique are recommended for improvement of the MG stability. In [12], in order to improve the performance of the dc microgrid operation, a low-bandwidth communication (LBC)-based improved droop control method is proposed. The control system uses local controllers and the LBC network to exchange information between converter units.

In this paper, the load types' effect on the power sharing accuracy is thoroughly investigated in a DC MG. For this purpose, a DC MG containing two DG units and a common load is considered. Then, the DGs' power ratio is calculated in different cases. It will be shown that the DG units' power ratio is dependent on the load types. To validate the findings, the simulation is performed in a DC MG. The simulation results reveal that the load types can have significant effect on the power sharing accuracy.

2. DESCRIPTION OF THE DG UNITS' CONTROL SYSTEM

As mentioned earlier, the droop procedure is a reliable method for power sharing among DG units. In this method, the DG units produce voltage in different magnitude by synthesizing different virtual resistance, which results in desired power sharing. Fig. 1 illustrates a DC MG of two DG units supplying a common load. RD1 and RD2 are the synthesized resistances of DG1 and DG2, respectively. In such system, the ratio of DG units' current is as following equation.

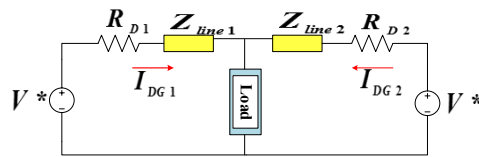


Fig. 1. A DC MG with two DG units.

$$\frac{I_{DG2}}{I_{DG1}} = \frac{R_{D1} + Z_{line1}}{R_{D2} + Z_{line2}} \quad (1)$$

Equation (1) indicates that the synthesized resistances have to be designed much greater than the line impedances in order for proper power sharing accuracy, otherwise they will have non-trivial effects on power sharing accuracy. Hence, the virtual resistance is often designed according to (2), where ΔV_{max} is the maximum MG's voltage variation and I_{DGmax} is the maximum DG unit's current.

$$R_{DG} = \frac{\Delta V_{max}}{I_{DG_{max}}} \quad (2)$$

The droop characteristic is depicted in Fig. 2. When DG units are operating in no-load condition, the output voltage of them is V_0 and when they are full loaded, the output voltage is decreased to the minimum permissible MG voltage. Moreover, the line slope is inversely related to the DG units' output current. In other words, the sheer slope of a DG unit's droop characteristic, the lower share of the load is produced. Furthermore, the voltage drop in the droop scheme can be compensated by equally shifting all droop characteristics. In such case, the no-load voltage of DG units is maximum permissible network MG voltage and the mentioned principles are still valid. The droop control signals are derived from the (3-5), where V_{ref} is the reference voltage signal and R_D is the synthesized resistance (droop gain) [3].

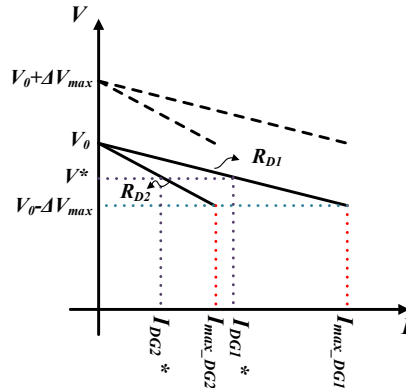


Fig. 2. The characteristics of the droop procedure.

$$V_{ref} = V_0 - R_D \times I_{out-ave} \quad (3)$$

$$I_{out-ave} = LPF(s) \times I_{out} \quad (4)$$

$$LPF(s) = \frac{\omega_c}{s + \omega_c} \quad (5)$$

where $LPF(s)$ is a low-pass filter with a cutoff frequency of f_c .

The droop procedure provides the reference signal of voltage source units, which leads to synthesis of a specific virtual resistance or impedance (often inductive term is added to improve the dynamic performance of DG units [7]). The control loop of DG units is presented in Fig. 3, where R_D and L_D are virtual resistance and inductance synthesized by the droop procedure. Also, $G_c(s)$, PWM , $G_{vd}(s)$, $G_{vg}(s)$ and $Z_{out}(s)$ are voltage controller, pulse width modulation transfer function, duty cycle to output transfer function and output impedance, respectively.

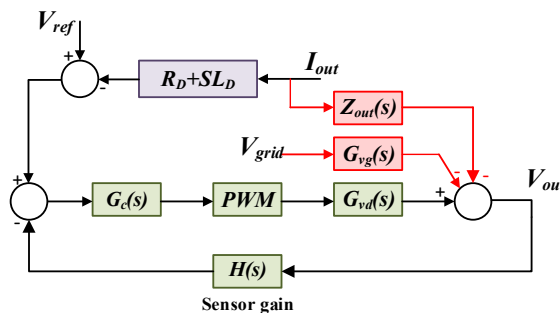


Fig. 3. The control structure of each DG unit.

The close loop transfer function of DG units' output voltage is provided in (6). For stable performance of DG units, it is essential for their loop gain $T(s)$ –defined in (7)- to have positive phase margin and gain margin, which are achieved by properly designing of controller, $G_c(s)$. In addition, the loop gain should have high magnitude in the vicinity of 0 Hz to ensure both the tracking of the reference signal and the attenuation of the disturbance signal. The general form of $G_c(s)$ meeting the above requirement is given in (8).

$$V(s) = \frac{1}{H} \times \frac{T}{T+1} \times d(s) + \frac{G_{vg}(s)}{1+T} \times V_g(s) - \frac{Z_{out}(s)}{1+T} \times i_{out}(s) \tag{6}$$

$$T(s) = H \cdot G_{vd} \cdot G_c \cdot PWM \tag{7}$$

$$G_c(s) = G_{cm} \times \frac{(1 + \omega_L/s)(1 + s/\omega_z)}{(1 + s/\omega_p)} \tag{8}$$

3. ACCURACY OF THE POWER SHARING CONSIDERING THE LOAD TYPES

Fig. 4 shows a DC MG of two DG units supplying different types of load. The DG units are controlled with the droop procedure. Z_{D1} and Z_{D2} are the virtual impedance synthesized by DG1 and DG2. Assuming that the DG units have an equal reference voltage, the ratio of DG units' power is obtained as (9).

$$\frac{P_{DG2}}{P_{DG1}} = \frac{V_{DG2}}{V_{DG1}} \times \frac{I_{DG2}}{I_{DG1}} = \frac{V_{DG2}}{V_{DG1}} \times \frac{Z_{D1} + Z_{line1}}{Z_{D2} + Z_{line2}} \tag{9}$$

It can be seen that the DG units' power ratio is dependent on their voltages. The DG units' voltage when supplying CI loads, CC loads and CP loads are calculated from (10), (11) and (12), respectively (the set of equations are obtained by applying the KVL law in each circuit). In fact, as the load type changes, the DG units output voltage is also changed and consequently, different DG units' power ratio are obtained in these three cases. Therefore, it can be concluded that the load sharing accuracy is dependent on the load types and can differ widely.

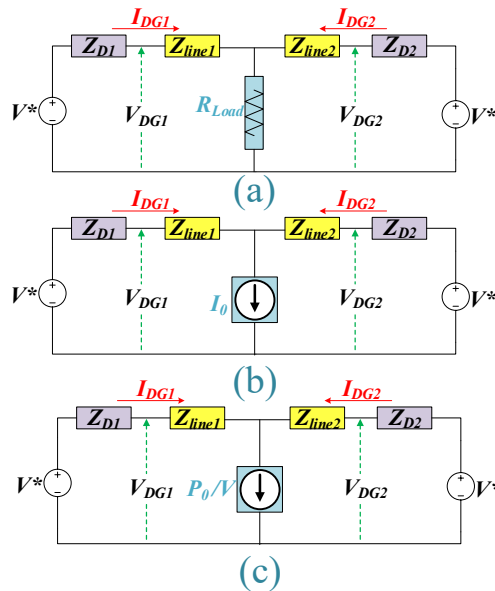


Fig. 4. Equivalent circuit of a DC MG with two voltage source DGs supplying (a) constant impedance, (b) constant current, and (c) constant power load.

$$\left\{ \begin{aligned} V_{DG1} \left(\frac{Z_{line1} + R_{load}}{Z_{D1}} \right) + V_{DG2} \left(\frac{R_{load}}{Z_{D2}} \right) &= V_0 \left(\frac{R_{load}}{Z_{D1}} + \frac{R_{load}}{Z_{D2}} + \frac{Z_{line1}}{Z_{D1}} - I \right) \\ V_{DG1} \left(\frac{R_{load}}{Z_{D1}} \right) + V_{DG2} \left(\frac{Z_{line2} + R_{load}}{Z_{D2}} \right) &= V_0 \left(\frac{R_{load}}{Z_{D1}} + \frac{R_{load}}{Z_{D2}} + \frac{Z_{line2}}{Z_{D2}} - I \right) \end{aligned} \right. \quad (10)$$

$$\left\{ \begin{aligned} V_{DG1} \left(\frac{Z_{line1}}{Z_{D1}} + I \right) + V_{DG2} \left(-I - \frac{Z_{line2}}{Z_{D2}} \right) &= V_0 \left(\frac{Z_{line1}}{Z_{D1}} - \frac{Z_{line2}}{Z_{D2}} \right) \\ V_{DG1} \left(\frac{I}{Z_{D1}} \right) + V_{DG2} \left(\frac{I}{Z_{D2}} \right) &= V_0 \left(\frac{I}{Z_{D1}} + \frac{I}{Z_{D2}} - I_0 \right) \end{aligned} \right. \quad (11)$$

$$\left\{ \begin{aligned} V_{DG1} \left(\frac{Z_{line1}}{Z_{D1}} + I \right) + V_{DG2} \left(-I - \frac{Z_{line2}}{Z_{D2}} \right) &= V_0 \left(\frac{Z_{line1}}{Z_{D1}} - \frac{Z_{line2}}{Z_{D2}} \right) \\ V_{DG1} \left(\frac{I}{Z_{D1}} \right) + V_{DG2} \left(\frac{I}{Z_{D2}} \right) &= V_0 \left(\frac{I}{Z_{D1}} + \frac{I}{Z_{D2}} - \frac{P_0 \times Z_{D1}}{V_0 \times Z_{D1} - (Z_{D1} + Z_{line1})(V_0 - V_{DG1})} \right) \end{aligned} \right. \quad (12)$$

4. SIMULATION RESULTS

In this section, a DC MG whose DG units are controlled with droop controller is simulated for three types of load (CI, CC and CP). The understudy DC MGs are depicted in Fig. 5. To investigate the effect of the MGs' configuration on the accuracy of power sharing, the simulation is also performed on a non-radial DC MG (b). Moreover, different load change scenarios are introduced to see their effects on the power sharing accuracy. The parameters of the DC MGs and the loads and also the load change scenarios are provided in table 1 and table 2, respectively. To clarify the difference of the power sharing accuracy in the different cases, the linear model of buck converter is used for simulation. The controller of DG units and the droop coefficients are provided in table 3. Moreover, Matlab/Simulink software and Otb23 solver is used for performing simulation.

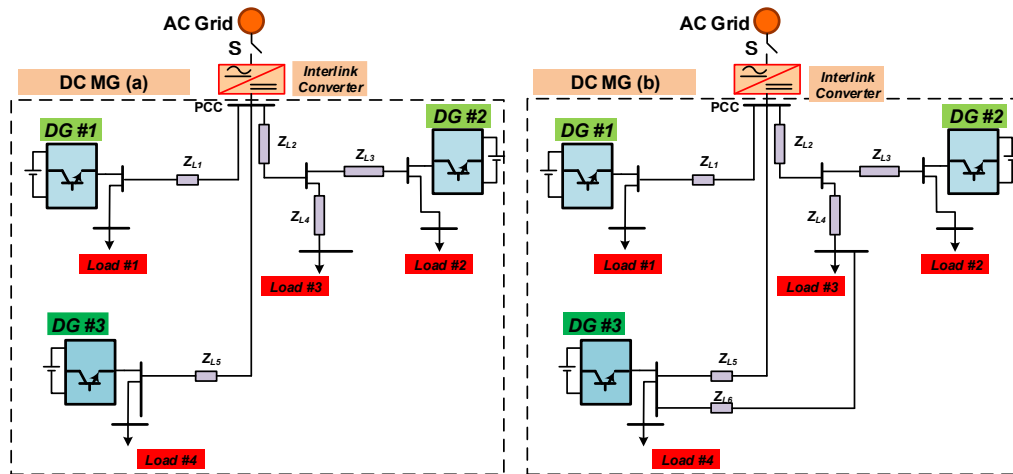


Fig. 5. Understudy radial DC MG (a) and non-radial DC MG (b).

Table 1. Network and Load Parameters.

Parameters	Value
$P_{DG1}, P_{DG2}, P_{DG3} [kW]$	10, 5, 7.5
$P_{load1}, P_{load2}, P_{load3}, P_{load4} [kW]$	2.4, 4, 3.6, 5
$P_{base} [kW]$	20
$Z_{L1}, Z_{L2}, Z_{L3}, Z_{L4}, Z_{L5}, Z_{L6} [\%]$	$[1, 0.5, 0.3, 0.5, 1, 1] \cdot (1+0.3j)$
DC grid voltage [V]	400
$L_{DG1}, L_{DG2}, L_{DG3} [mH]$	1, 2, 1.5
$C_{DG1}, C_{DG2}, C_{DG3} [\mu F]$	50, 25, 37.5

Table 2. Load Change Scenarios.

Time	Description
2 [sec]	3 kW load is added to load1
4 [sec]	0.4 kW load is added to load4
6 [sec]	Load3 is disconnected

Table 3. Controller Parameters Of Dg Units.

Parameters	Value
$R_{D1}, R_{D2}, R_{D3} [\Omega]$	0.8, 1.6, 1.066
$L_{D1}, L_{D2}, L_{D3} [mH]$	1.5, 3, 2.25
$f_c [Hz]$	10
PWM, H	1, 1/4
$G_{c_DG1}(s)$	$(2107 s^2 + 9.652 s + 8.802e9) / (3324 s^2 + 3.553e08 s)$
$G_{c_DG2}(s)$	$(1187 s^2 + 3.272e06 s + 2.255e9) / (1374 s^2 + 2.467e8 s)$
$G_{c_DG3}(s)$	$(1819 s^2 + 6.539e06 s + 5.461e9) / (2275 s^2 + 2.986e8 s)$

Figs. 6-8 illustrate the power of CI, CC and CP loads in the radial DC MG. As it can be seen, the load profile for CI and CC loads are very similar, however, the CP loads' response to the load change scenarios are the fastest one compared to the others.

The error of the power sharing for simulation of CI and CC loads are depicted in Fig. 9. As it can be seen, in both cases, the DG3 has lowest power sharing error since it supplies the largest local load. On the other hand, as DG2 supplies the smallest local load, it has the highest power sharing error. Moreover, by comparing the power sharing error of two cases, it can be found that all the DG units have higher power sharing error when they supply CC loads. The difference in power sharing error is very small as the CC loads are simulated as ideal current source. In real cases, however, this difference can be much higher.

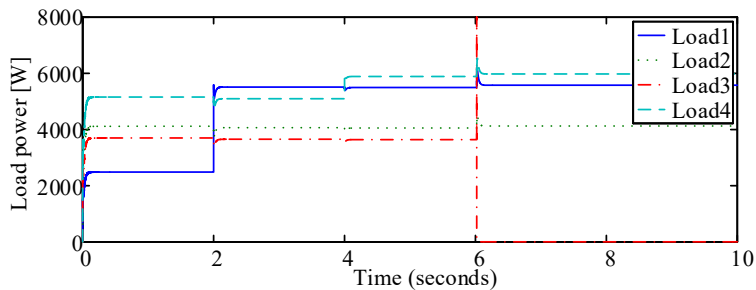


Fig. 6. Resultant CI loads' power in the understudy radial DC MG (a).

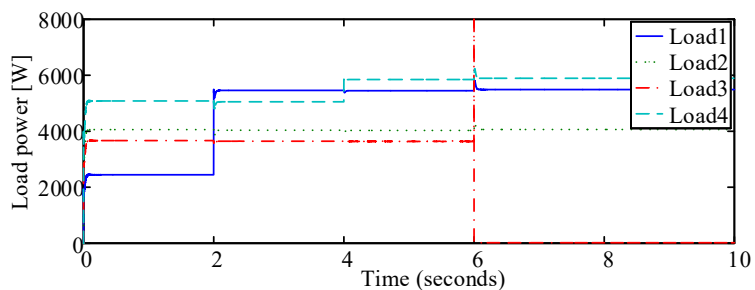


Fig. 7. Resultant CC loads' power in the understudy radial DC MG.

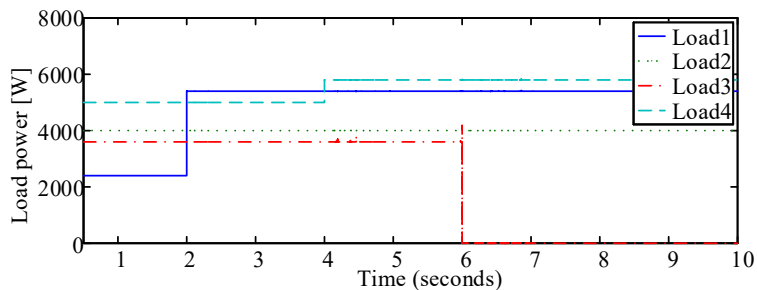


Fig. 8. Resultant CP loads' power in the understudy radial DC MG.

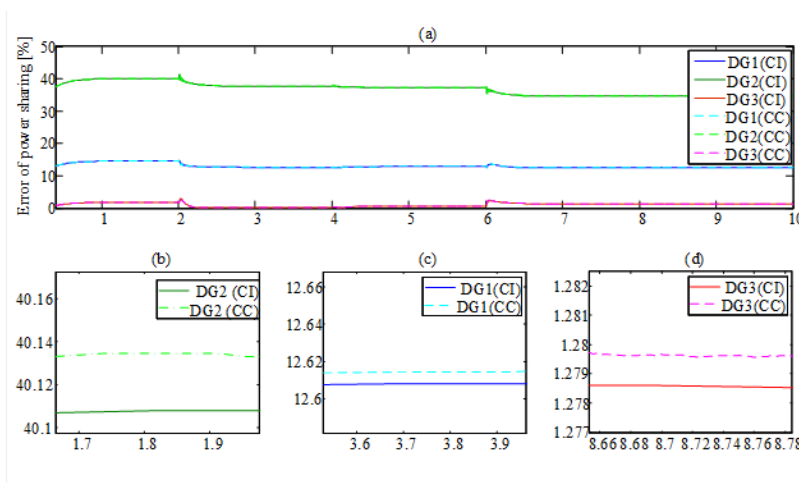


Fig. 9. Comparison of the power sharing error for simulation of CI and CC loads, and (b,c,d) zoom in of plot (a) in radial DC MG.

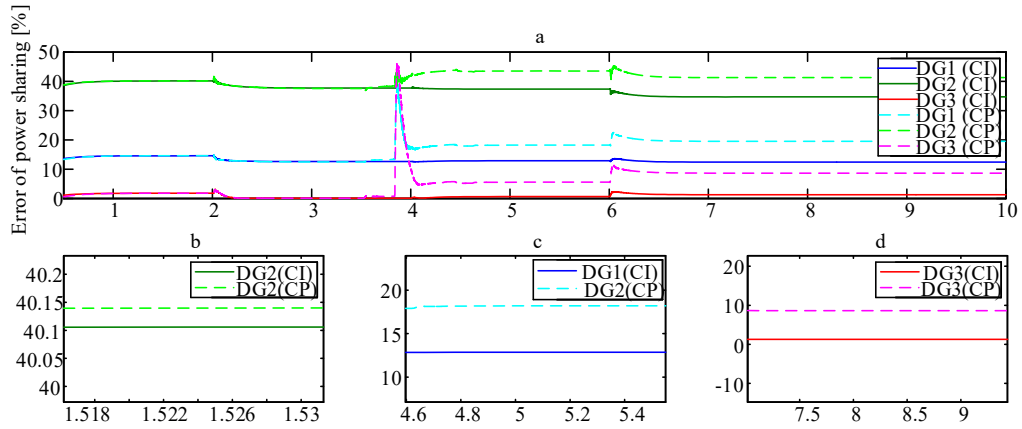


Fig. 10. Comparison of the power sharing error for simulation of CI and CP loads, and (b,c,d) zoom in of plot (a) in radial DC MG.

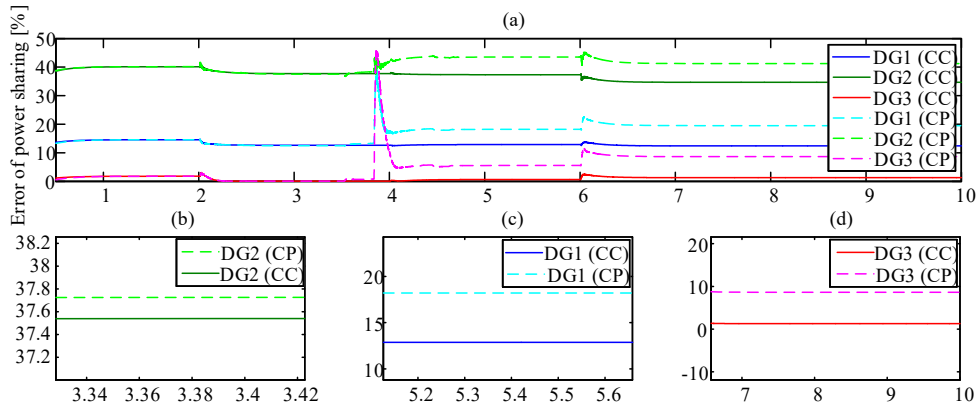


Fig. 11. Comparison of the power sharing error for simulation of CP and CC loads, and (b,c,d) zoom in of plot (a) in radial DC MG.

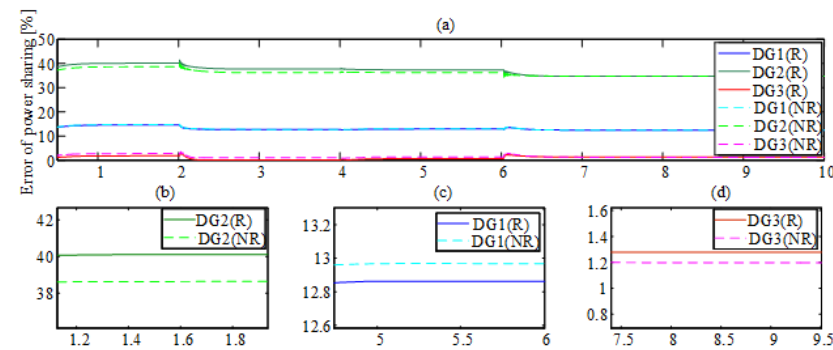


Fig. 12. Comparison of the power sharing error for simulation of CI loads in radial (R) and non-radial (NR) DC MG

The error of power sharing for simulation of CP loads compared to CI and CC loads are also depicted in Figs. 10 and 11. The same reason can be given for highest power sharing error of DG2 and lowest power sharing error in DG3. Furthermore, the difference of power sharing error for CI and CP loads in Fig. 10 and for CC and CP loads in Fig. 11 are dramatically increased at around $t=4$ sec. The reason for such difference is that the control loop of CP loads synthesizes another virtual impedance in parallel to CP load. This new virtual impedance can deteriorate the error of power sharing.

The comparison power sharing error simulating CI loads in two DC MGs is also provide in Fig. 12. Until $t=6$ sec, the error for DG1 is higher in the radial (R) DC MG rather than in non-radial (NR) DC MG but then the opposite occurs. The similar observation can be found for DG2 and DG3. Therefore, it can be concluded that the power sharing error is dependent on the DC MG configuration and it varies with load changes.

5. SUMMARY AND CONCLUSION

In this paper, the load type's effect on the power sharing accuracy is thoroughly discussed. Based on the selected parameters, the CP loads led to highest power sharing error in the droop procedure. However, this error is highly dependent on DC MG's configuration and the synthesized virtual impedance. In fact, the synthesized impedance can deteriorate the power sharing error when it is added to line impedance. On the other hand, the power sharing error can be mitigated when the synthesized impedance is negative and it decreases the line impedance effect on power sharing accuracy. Therefore, a general conclusion cannot be made as the power sharing error is dependent on DC MG's parameters.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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