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A New Current Sharing Method for Circulating Current Mitigation in Meshed Microgrid

***Abstract**. In AC microgrids, droop control is widely employed for active and reactive power sharing due to its decentralized nature. However, when dealing with microgrids where the impedance of feeder lines is mismatched, droop control's objectives may not be effectively achieved. Specifically, accurate sharing of reactive power is compromised, thereby impacting the overall microgrid performance. In response to these challenges, numerous researchers have explored alternative techniques to achieve precise current or power sharing, taking into account impedance disparities among feeder lines. Despite meeting these objectives, the presence of considerable circulating current within the microgrid remains, which could potentially threaten the system stability. To address these issues, this paper introduces a novel current sharing method designed for meshed microgrids. This method is designed not only to ensure accurate current sharing among distributed generations but also to mitigate circulating current to very low values. The effectiveness of the proposed approach is rigorously evaluated through software simulations employing MATLAB/SIMULINK. A comparison of circulating current values is conducted between two methods from the literature and the presented approach in this paper. The results demonstrate the effectiveness of the proposed method in achieving current sharing and reducing circulating current to minimal levels in challenging conditions.*

***Streszczenie.** W mikrosieciach prądu przemiennego powszechnie stosuje się regulację nachyleniową w celu podziału mocy czynnej i biernej ze względu na jej zdecentralizowany charakter. Jednakże, przy mikrosieciach, gdzie impedancje linii zasilających są niezrównoważone, cele regulacji nachyleniowej mogą nie być skutecznie osiągnięte. W szczególności dokładny podział mocy biernej może być utrudniony, co wpływa negatywnie na ogólną wydajność mikrosieci. W odpowiedzi na te wyzwania, liczni badacze eksplorują alternatywne techniki osiągania precyzyjnego podziału prądu lub mocy, uwzględniając nierówności impedancji między liniami zasilającymi. Pomimo spełnienia tych celów, w mikrosieci pozostaje znaczny prąd krążący, który potencjalnie może zagrażać stabilności systemu. W celu rozwiązania tych problemów, niniejsza praca przedstawia nową metodę podziału prądu zaprojektowaną dla splecionych mikrosieci. Ta metoda ma na celu nie tylko zapewnienie dokładnego podziału prądu między rozproszonymi źródłami generacji, ale także zminimalizowanie prądu krążącego do bardzo niskich wartości. Skuteczność zaproponowanego podejścia jest rygorystycznie oceniana za pomocą symulacji komputerowych przy użyciu programu MATLAB/SIMULINK. Porównanie wartości prądu krążącego jest przeprowadzone między dwiema metodami z literatury a przedstawionym podejściem w tej pracy. Wyniki demonstrują skuteczność zaproponowanej metody w osiąganiu podziału prądu i redukcji prądu krążącego do minimalnych poziomów w trudnych warunkach. (**Nowa metoda współdzielenia prądu w celu ograniczenia prądu obiegowego w mikrosieci siatkowej**)*

Keywords: Microgrids, Circulating Current, Current Sharing, Power Sharing.
Słowa kluczowe: Mikrosieci, prąd krążący, podział prądu, podział mocy.

1. Introduction

The emergence of the microgrid concept has been driven by the growing need for sustainable development [1]-[2]. Microgrids, incorporating renewable energy sources such as solar photovoltaics, wind turbines, and hydroelectric power, have gained significant recognition recently due to their numerous benefits in different areas [3]. These benefits take the form of a notable reduction in carbon emissions, considerable savings in energy costs, enhanced energy independence, and more [2]. The flexibility of microgrids enables a strategic allocation of the distributed energy sources in different places, generating power based on the available renewable resources in the area, such as solar, wind, water, and others.

The seamless adaptability and strategic positioning of microgrids are complemented by the reliability achieved through the parallel operation of multiple inverters. This configuration ensures that even if one inverter were to fail, the remaining inverter can collectively provide uninterrupted power to the loads, thereby maintaining continuous operation [4]. To facilitate this parallel operation, the most prevalent primary control method employed is the droop control. This control mechanism ensures efficient power sharing without necessitating communication between the parallel distributed generation sources [5]. Despite its widespread use, this control method is not free from serious constraints. One of the key issues arises when the impedances of feeders are mismatched, a scenario frequently encountered in real-world applications. Consequently, the precise sharing of reactive power being compromised can result in some DGs being overloaded while others are underutilized [6]. This imbalance in power distribution can lead to premature wear and tear, reduced equipment lifespan, and increased maintenance costs.

Hence, numerous researchers have focused on developing enhanced control methods which are mainly improved power sharing methods or active current sharing strategies.

In their work [7], the researchers introduced an enhanced power sharing approach utilizing virtual impedance control. The method involves the injection of minor AC signals to mitigate any disparities in power sharing. Notably, this approach does not necessitate communication or prior knowledge of the lines' impedances. In the study described in [8], the authors combined virtual impedance and virtual power controls to achieve precise power sharing among components. Additionally, this approach led to an improvement in the voltage at the point of common coupling (PCC). The control system developed by researchers in [9] utilizes a comprehensive consensus-based nonlinear methodology at both primary and secondary levels within AC mesh microgrids. This ensures resilient sharing of active and reactive power while effectively restoring voltage and frequency. In [10], researchers discuss the implementation of enhanced droop controllers with virtual output impedance, aimed at enhancing the performance of active and reactive power decoupling. The study in [11] presents an improved droop control for islanded DC microgrids, using a virtual voltage derived from the average values of individual DG output voltages. While this method guarantees accurate power sharing among converters, it necessitates complete information on all DC–DC converters within the microgrids, including their respective quantities and output voltages, to determine the virtual voltage. The method introduced in [12] outperforms conventional droop control in sharing active and reactive power. However, its execution necessitates inter-VSI communication. Furthermore, a dedicated control for harmonic circulating current is not taken into consideration. In [13], the paper suggests a control strategy for a three-phase four-wire microgrid employing three-level neutral point clamped inverters. This approach effectively maintains voltage and frequency within acceptable limits, leading to an enhanced power sharing. Paper [14] introduces a distributed Proportional Reactive Power Sharing (PRPS) controller designed for AC microgrids. Precise proportional sharing of reactive power is achieved, even when the microgrid contains sources of varying capacities and mismatched interconnecting lines. This is achieved by adjusting the Q − E droop characteristics accordingly, allowing each source to supply power in proportion to its rated capacity.

In [15], the paper introduces a controller for a DC microgrid, ensuring both current sharing and voltage regulation. It requires minimal data and proves effective in various scenarios, despite small voltage errors. In [16], A simplified discrete model of paralleled modules was used to design an optimal current control strategy, with a focus on the Buck converter system. The control error was adjusted based on the difference between the real module and the simplified model, employing a digital PI controller for precise adjustments. Authors in [17] introduces a Modified Droop-based secondary controller for DC Microgrids. The proposed control algorithm aims to achieve precise load current sharing and improved voltage regulation. It uses an average voltage controller, an average current controller, and a droop controller for each converter, allowing for effective regulation even under varying line and load impedances and sudden load changes. In [18], the method employs a central controller, communication network, and PI controllers to regulate the distributed battery systems (DBS) output currents. It combines variable virtual resistances with static ones through a Differential Evolution (DE) algorithm, ensuring precise current sharing. In [19], researchers introduce a Current Weighting Distribution Control (CWDC) strategy for parallel inverters, aiming to achieve accurate current distribution. Each inverter in the system is equipped with a voltage controller for stability, a current controller for swift dynamic response, and a weighting current controller for achieving current sharing among the inverters.

In [20], accurate current sharing is ensured by calculating the droop resistance values in response to alterations in the source voltage, thereby influencing the converter's output voltage. By ensuring load sharing, the proposed algorithm achieves the mitigation of circulating current as well. In [21], The paper proposes an adaptive droop control algorithm aimed at mitigating circulating currents in a low voltage DC microgrid. Line resistances are estimated using mathematical calculations, leading to the adjustment of droop parameters. Furthermore, a distributed secondary controller is suggested to enhance the accuracy of load sharing and counteract the influence of line resistances. In [22], a 3 DG DC microgrid is introduced, featuring a distributed architecture-based SMC technique. This method ensures precise current distribution among the 3 DGs, effectively reducing circulating current and minimizing voltage deviation. In reference [23], the approach relies on voltage and phase droop schemes for accurate current sharing among inverters. It also employs a DC offset droop scheme to eliminate DC circulating current, while the AC component is divided into active (Ip) and reactive (Iq) parts to counteract AC circulating current. In [24], the integration of an adaptive virtual impedance into the DG output compensates for the divergence in feeder impedance among DGs. Consequently, this improves the precision of reactive power sharing and minimizes circulating current for AC microgrids.

This paper introduces a novel approach aimed at ensuring accurate current sharing and minimizing circulating current in AC islanded microgrids. The proposed strategy is designed for a meshed microgrid, inspired by the IEEE 9 bus configuration. It takes into account mismatched impedances in the interconnecting lines, recognized as the principal culprit behind inaccurate current sharing and the amplification of circulating current among parallel DGs.

The subsequent sections of this paper are structured as follows: Section II provides an analysis of load sharing and circulating current issues. Section III outlines the details of the proposed method. In Section IV, simulation results are presented, including a comparison of circulating current between two methods from the literature and the proposed method in this paper. Finally, Section V concludes this research paper.

2. Load sharing and circulating current issues

2.1. Conventional droop control

A comprehensive analysis of droop control falls beyond the scope of this paper; thus, we present a concise overview.

An islanded microgrid consists of multiple inverters that are linked together in parallel. Fig. 1 illustrates a block diagram of n inverters. Each inverter is connected to a Point of Common Coupling (PCC) via the line impedance.

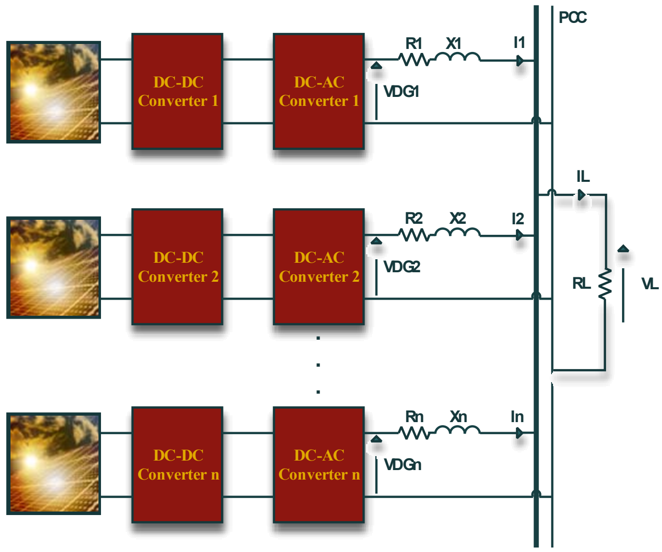


Fig. 1. AC Islanded Microgrid with n converter

Active and reactive powers, Pi and Qi, supplied by Distributed Generator DGi connected to the PCC bus through inductive lines with reactance Xi (Xi>>Ri) [25], with i taking values from the set {1, 2, …, n}:

(1) $$P_i = \frac{U_{PCC} U_i}{X_i} \delta_i$$

(2) $$Q_i = \frac{U_{PCC}}{X_i}(U_i - U_{PCC})$$

These findings constitute the fundamental basis for the droop control equations which are presented in eqs. (3) and (4):

(3) $$w_i = w_{in} - m_i (P_i - P_{in})$$

(4) $$U_i = U_{in} - n_i (Q_i - Q_{in})$$

The primary objective of conventional droop control is to stabilize the network and achieve an equitable distribution of the load among the Distributed Generators (DGs). Achieving this goal necessitates the establishment of a comprehensive framework of control loops dedicated to the regulation of both frequency and voltage.

Nonetheless, it is extensively documented in the literature that when mismatched impedance lines are present, precise sharing of reactive power becomes unattainable. Additionally, the occurrence of circulating currents within the system can stem from this issue. The presence of these circulating currents can have detrimental effects on the network's overall efficiency and stability, resulting in increased losses and potential damage of sensitive equipment. Mitigating this problem often requires the implementation of efficient control strategies aimed at reducing the occurrence of circulating currents and upholding the system's optimal performance (load sharing).

2.2 Circulating Current Analysis

The load sharing in microgrids is significantly impacted by converts' terminal voltage. Even a slight deviation in the converter voltage can lead to a substantial fluctuation in load sharing. Achieving precise control over load distribution necessitates the implementation of an accurate control method. However, before delving into control methods, it is crucial to understand the concept of circulation and the factors that influence it.

To facilitate this understanding, let's consider fig. 2 which is the equivalent circuit of fig. 1 under the assumption that the microgrid is composed of three DGs and the transmission lines are resistive. In this depiction, the symbols VDGi, IDGi, RDGi, and LDGi represent the output voltage, output current, cable resistance of the converters, respectively, with i taking values from the set {1, 2, 3}. The impedance is connected in series with the DG, as indicated in this figure.

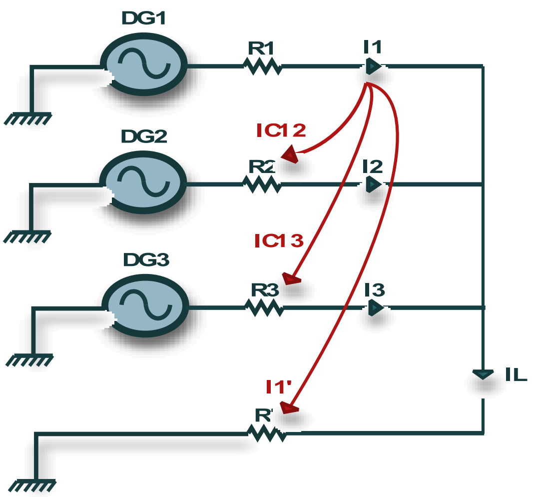


Fig. 2. Equivalent circuit of AC islanded microgrid with 3 DGs

By applying Kirchhoff's voltage law (KVL) to the circuit illustrated in Fig. 2:

(5) $$V_{DG1} - R_1 I_1 - R_L I_L = 0$$

(6) $$V_{DG2} - R_2 I_2 - R_L I_L = 0$$

(7) $$V_{DG3} - R_3 I_3 - R_3 I_3 = 0$$

Equations (1) through (3) allow us to determine the output currents IDG1, IDG2 and IDG3:

(8) $$I_1 = \underbrace{\frac{R_2R_3}{R_1R_2R_L + R_1R_3R_L + R_2R_3R_L}}_{\text{IL1}} V_{DG1} + \frac{R_3R_L}{R_1R_2R_L + R_1R_3R_L + R_2R_3R_L}(V_{DG1} - V_{DG3}) + \frac{R_2R_L}{R_1R_2R_L + R_1R_3R_L + R_2R_3R_L}(V_{DG1} - V_{DG3})$$

(9) $$I_2 = \underbrace{\frac{R_1R_3}{R_1R_2R_L + R_1R_3R_L + R_2R_3R_L}}_{\text{IL2}} V_{DG2} + \frac{R_3R_L}{R_1R_2R_L + R_1R_3R_L + R_2R_3R_L}(V_{DG2} - V_{DG1}) + \frac{R_1R_L}{R_1R_2R_L + R_1R_3R_L + R_2R_3R_L}(V_{DG2} - V_{DG3})$$

(10) $$I_2 = \underbrace{\frac{R_1R_2}{R_1R_2R_L + R_1R_3R_L + R_2R_3R_L}}_{\text{IL3}} V_{DG3} + \frac{R_2R_L}{R_1R_2R_L + R_1R_3R_L + R_2R_3R_L}(V_{DG3} - V_{DG1}) + \frac{R_1R_L}{R_1R_2R_L + R_1R_3R_L + R_2R_3R_L}(V_{DG3} - V_{DG2})$$

The expressions obtained from equations (8) to (10) demonstrate that the initial terms, denoted as IL1, IL2 and IL3, are the load current provided by respective DGs. Meanwhile, the subsequent terms, namely IC12, IC13 and IC23, signify the circulating current within the system which are expressed separately in equations (11) to (13)

(11) $$I_{C12} = \frac{R_3R_L}{R_1R_2R_3 + R_1R_2R_L + R_1R_3R_L + R_2R_3R_L}(V_{DG1} - V_{DG2})$$

(12) $$I_{C13} = \frac{R_2R_L}{R_1R_2R_3 + R_1R_2R_L + R_1R_3R_L + R_2R_3R_L}(V_{DG1} - V_{DG2})$$

(13) $$I_{C23} = \frac{R_1R_L}{R_1R_2R_3 + R_1R_2R_L + R_1R_3R_L + R_2R_3R_L}(V_{DG2} - V_{DG3})$$

This mathematical analysis is applicable as well to a system with n converters, leading to a generalized expression for the circulating current as follows:

(14) $$I_{Cij} = \frac{\prod_{k \neq i,j}^{n} R_i R_L}{\prod_{k=1}^{n} R_i + \sum_{i=1}^{n}\left(\prod_{j \neq i}^{n} R_i R_L\right)}(V_{DGi} - V_{DGj})$$

The earlier analysis demonstrates that when there is a difference in the output voltage of converters, circulating currents are introduced alongside the load current. Therefore, according to equation (14), the primary parameter for mitigating the circulating current is the output voltage of converters.

3. Proposed method: current sharing with circulating current mitigation

In this section, we present a distributed control strategy designed for a 3 DGs meshed AC multi-PCC microgrid inspired from the IEEE 9 bus test feeder. The primary goals of this approach are to achieve precise load current sharing while minimizing circulating currents to very low values. The microgrid scheme is illustrated in Fig. 3.

Given the dynamic conditions in microgrids, affected by load fluctuations and DGs connections/disconnections, it is essential for the proposed method to adapt to these changes and sustain microgrid stability. This is why we focused on preserving the P-W (Active Power – Frequency) equation used in droop control, as it remains unaffected by microgrid operating conditions, even under aggressive scenarios.

Yet, in order to meet the defined objectives, certain adjustments have been implemented: The second equation in the proposed method now features the I-V (RMS Current – RMS Voltage) equation, deviating from the initial Q-V (Reactive Power – RMS Voltage) equation. In fact, instead of relying on reactive power measurement, the proposed method uses the RMS values of DGs output voltage and RMS values of the circulating currents. This involves the integration of PI regulators as well.

The equations for the proposed method are expressed in the following forms as (15) and (16):

(15) $$w_i = w_{in} - m_i(P_i - P_{in})$$

(16) $$V_i = F_i \int (U_{in} - V_{DG1})dt + M_i \int I_{Ci} dt$$

(17) Where: $$I_{Ci} = \sum_{\substack{j=1 \\ j \neq i}}^{3} I_{Cij}$$

The symbols win and Uin represent the power system's nominal frequency and voltage, with Pin and Qin denoting the rated values of active and reactive powers. Pi stands for the measurement of active power, while Vi and wi are the calculated references for voltage and frequency, respectively. The parameters Fi and Mi represent the proportional and integral gains. mi is the coefficient associated with the droop control. Finally, ICi is the total RMS circulating current generated from DGi to the other microgrid's DGs.

In the initial equation, we derived the P-W relationship (active power-frequency) from droop control. Its purpose is to define the microgrid's frequency. Moving on to the second equation, it consists of two blocks. The first block operates as a Proportional-Integral (PI) regulator with a dual function. Firstly, it establishes and compensates the voltage to match the rated value at the output of the (DG). Secondly, it ensures that there is no deviation in voltage from the set reference. The second block in this equation serves a distinct purpose: it introduces slight variations to the voltage reference values, aiming to gradually reducing the circulating current over the time. Significantly, the first regulator is designed to prevent any deviations in voltage from the rated value that could potentially result from the operations of the second regulator.

4. Simulation results

This section is dedicated to validating the efficiency of the proposed method using MATLAB/SIMULINK software. A comparative analysis will be conducted among three methods with a specific focus on the circulating current value in each case:

1. Droop control: The equations for droop control are already specified in eqs. (3) and (4), but it does not account for circulating current mitigation.
2. Power sharing technique from [26]: This technique, outlined in [26], also lacks consideration for circulating current mitigation.
3. Current sharing method proposed in this paper: The equations for this method are given in eqs. (9) and (11) and specifically address circulating current mitigation.

The purpose is measuring the circulating current in each scenario. To fulfill the objectives set in this section, the meshed multi-PCC microgrid illustrated in Fig. 3 is considered and implemented in MATLAB/Simulink. The microgrid's parameters are presented in tables 1 to 3. The equations corresponding to each of the three methods are incorporated into the model to enable a comprehensive comparison of results.

Table 1. First microgrid's lines' parameters

Lines	Resistance (Ω)	Inductance (mH)	Capacitance (μF)
Line 1	0.069	0.714	50
Line 2	0.069	0.714	50
Line 3	0.069	0.714	50
Line 4	0.069	0.714	50
Line 5	0.069	0.714	50
Line 6	0.069	0.714	50

Table 2. Second microgrid's lines' parameters

Lines	Resistance (Ω)	Inductance (mH)	Capacitance (μF)
Line 1	0.069	0.714	50
Line 2	0.069*2	0.714*2	50
Line 3	0.069*3	0.714*1.5	50
Line 4	0.069*4	0.714*0.5	50
Line 5	0.069*1.5	0.714*1.2	50
Line 6	0.069*2.5	0.714*3	50

Table 3. Microgrid's loads parameters

	P (W)	Q (VAR)
Load 1	29000	13500
Load 2	4000	2300
Load 3	9000	4000

4.1 Scenario 1: Conventional Droop Control

4.1.1 Droop control: Power sharing test

The performance results of the droop control are depicted in Fig. 4. Both DG1 and DG2 remain operational throughout the entire simulation duration. As anticipated, the method ensures active power sharing fig. 4.a but falls short in ensuring reactive power sharing fig. 4.b. Fig. 4.c is to show the DGs output voltage.

4.1.2 Droop control: Circulating current test

In this examination, the impact of variations in both loads and transmission line impedances is assessed through the analysis of three case studies. Fig. 5.a, Fig. 5.b, and Fig. 5.c illustrate the results of circulating current for droop control in scenarios involving transmission lines with equal impedances values tab. 1, transmission lines with mismatched impedances tab. 2 (with increasing impedance values), and mismatched impedances tab. 2 considering load variations, respectively. Fig. 5.a indicates that under conventional droop control, the average circulating current value is notably high IC=1.03A. However, with mismatched lines impedances (increase in impedance values), as anticipated by eq. (14), this value decreases significantly to IC=0.36A, as depicted in Fig. 5.b. When load variation is introduced, as shown in Fig. 5.c, circulating current increases to IC = 0.66A in t=15s compared to the scenario with a constant load demand in Fig. 5.b.

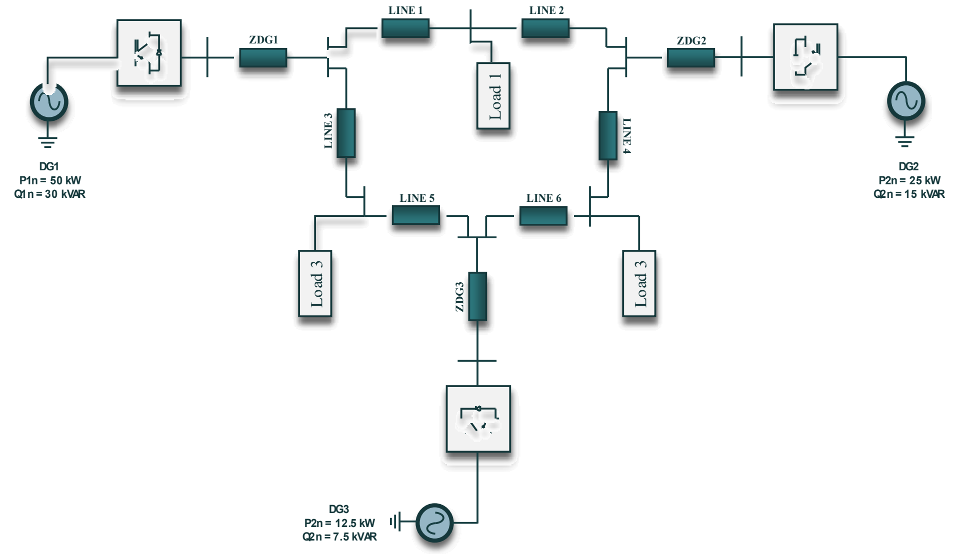


Fig. 3. (3) DGs meshed AC microgrid inspired from IEEE 9 bus test feeder

4.2 Scenario 2: Power sharing method from [26]

4.2.1 Power sharing method [26]: power sharing test

Performance results of the power sharing method in [26] are illustrated in Fig. 6. Throughout the entire simulation duration, both DG1 and DG2 remain operational. The method successfully maintains accurate sharing of both active and reactive power as illustrated in fig. 6.a and fig. 6.b, respectively. Fig. 6.c illustrates the output voltage of the distributed generation sources. A comprehensive examination of the power sharing methodology outlined in [26] is beyond the scope of this paper.

4.2.2 Power sharing method [26]: Circulating current test

In this examination, the impact of variations in both loads and transmission line impedances on the average circulating current value is assessed through the analysis of three case studies. Fig. 7.a, Fig. 7.b, and Fig. 7.c illustrate the results of circulating current for the power sharing method [26] in scenarios involving transmission lines with equal impedances tab. 1, transmission lines with mismatched impedances tab. 2 (with increasing impedance values), and mismatched impedances tab. 2 considering load variations, respectively. Fig. 7.a indicates that under the power sharing method, the average circulating current value is notably high IC=0.84A. However, with mismatched lines impedances (increase in impedance values), as anticipated by eq. (14), this value decreases to IC=0.79A, as depicted in Fig. 7.b. When load variation is introduced, as shown in Fig. 7.c, circulating current increases remarkably to IC = 1.66A in t=15s compared to the scenario with a constant load demand in Fig. 7.b.

4.3 Scenario 3: Proposed current sharing method

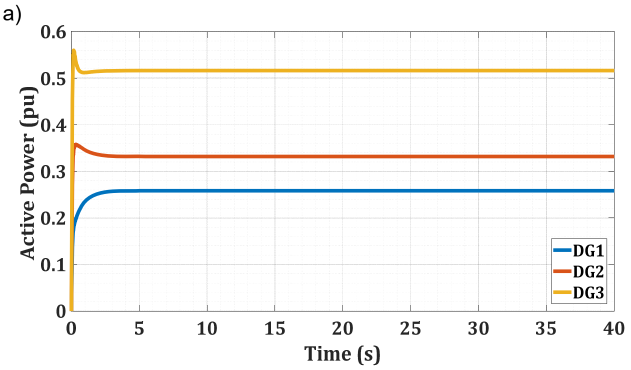
4.3.1 Current sharing method: Current sharing test

The performance results of the proposed current sharing method are depicted in fig. 8. Throughout the entire simulation duration, all three DGs remain operational. The method successfully maintains accurate sharing of current among the three DGs as illustrated in fig. 8.a. Furthermore, the current sharing is unaffected even in the presence of load variations as shown in fig. 8.b. Fig. 8.c is to show the DGs output voltage.

4.3.2 Current Sharing method: Circulating current test

In this examination, the impact of variations in both loads and transmission line impedances on the average circulating current value is assessed through the analysis of three case studies. Fig. 9.a, Fig. 9.b, and Fig. 9.c illustrate the results of circulating current for the proposed current sharing method in scenarios involving transmission lines with equal impedances tab. 1, transmission lines with mismatched impedances tab. 2 (with increasing impedance values), and mismatched impedances tab. 2 considering load variations, respectively. Fig. 9.a indicates that under the current sharing method, the average circulating current value is very low IC=8.46e-07A at t=15s. Furthermore, even with mismatched impedances (increase in impedance values), the value of the circulating current remains very low IC=9.26e-08A at t=15s, as depicted in Fig. 9.b. Finally, when load variation is introduced, as shown in Fig. 9.c, circulating current value remains very low IC = 6.01e-06A at t=30s. Therefore, effectiveness of the proposed current sharing method with consideration of circulating current mitigation is demonstred accross all these various simulations scenarios.

a)



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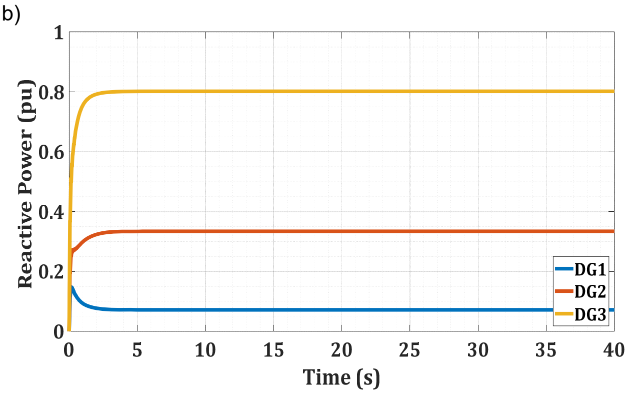

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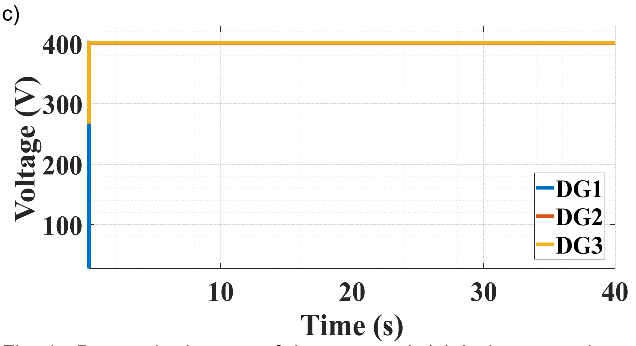
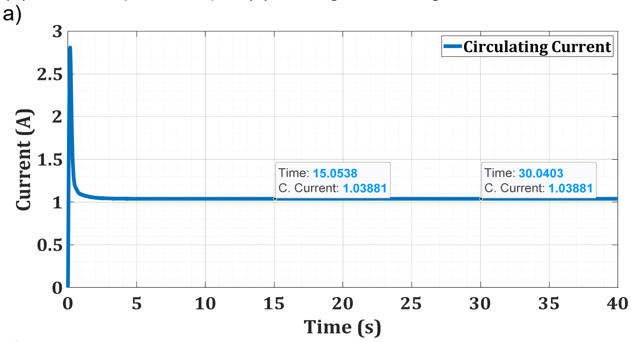


Fig. 4. Power sharing test of droop control. (a) Active power in pu. (b) Reactive power in pu. (c) Microgrid's voltage.

a)



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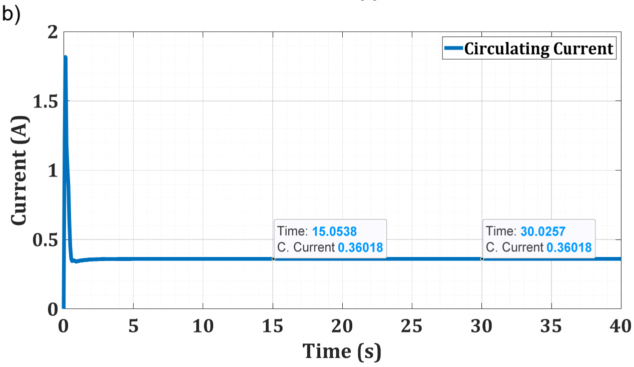

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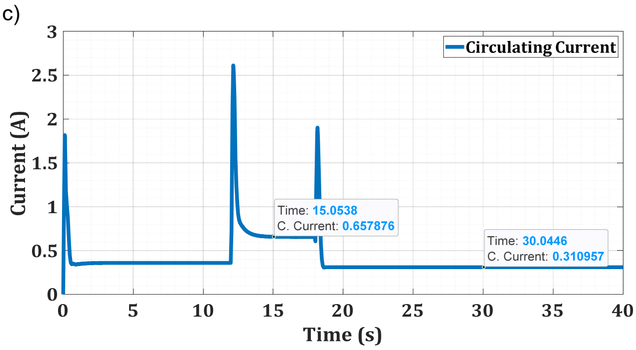
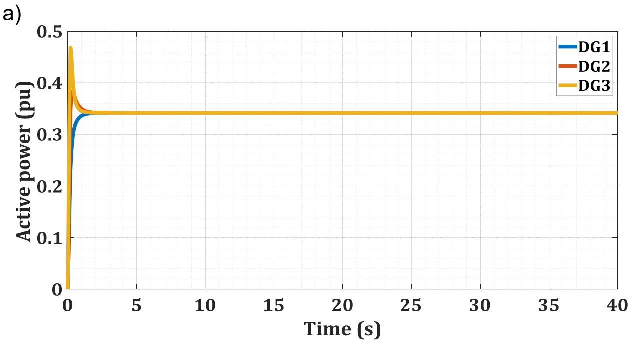


Fig. 5. Circulating current test of droop control. (a) Same transmission lines' impedance value. (b) Different transmission lines' impedance values. (c) Different transmission lines' impedance values with consideration of load variations

a)



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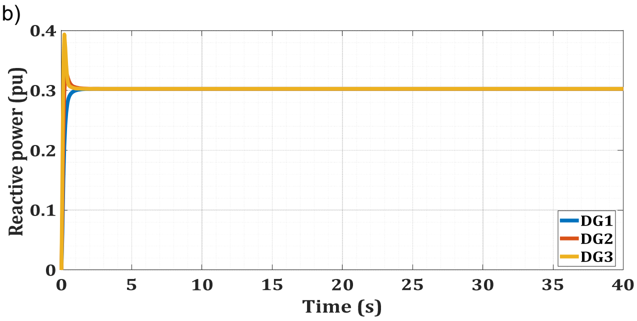


c)

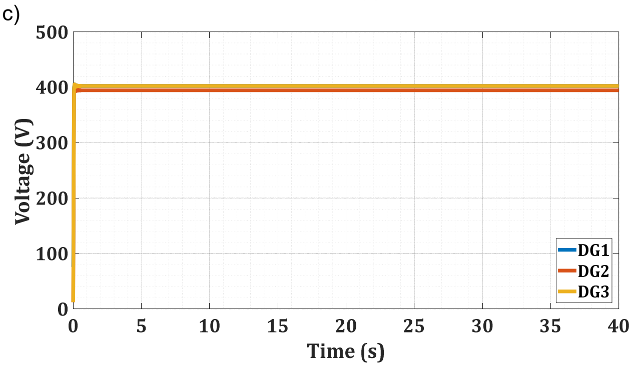
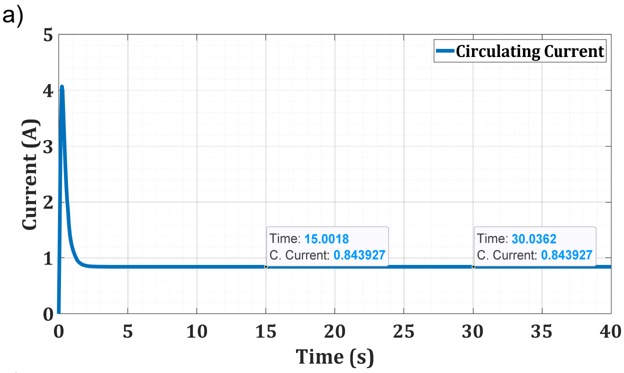
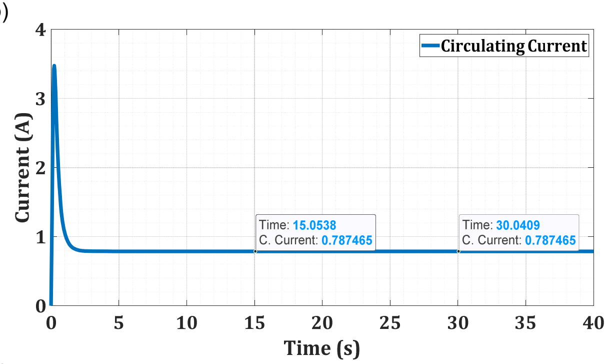


Fig. 6. Power sharing test of the power sharing method in [26]. (a) Active power in pu. (b) Reactive power in pu. (c) Microgrid's voltage

a)



b)



c)

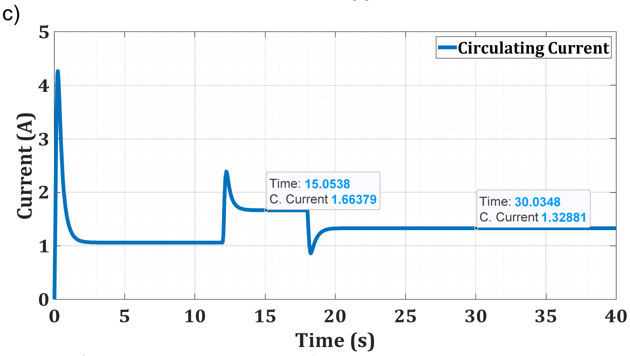


Fig. 7. Circulating current test of the power sharing method in [26]. (a) Same transmission lines' impedance value. (b) Different transmission lines' impedance values. (c) Different transmission lines' impedance values with consideration of load variations

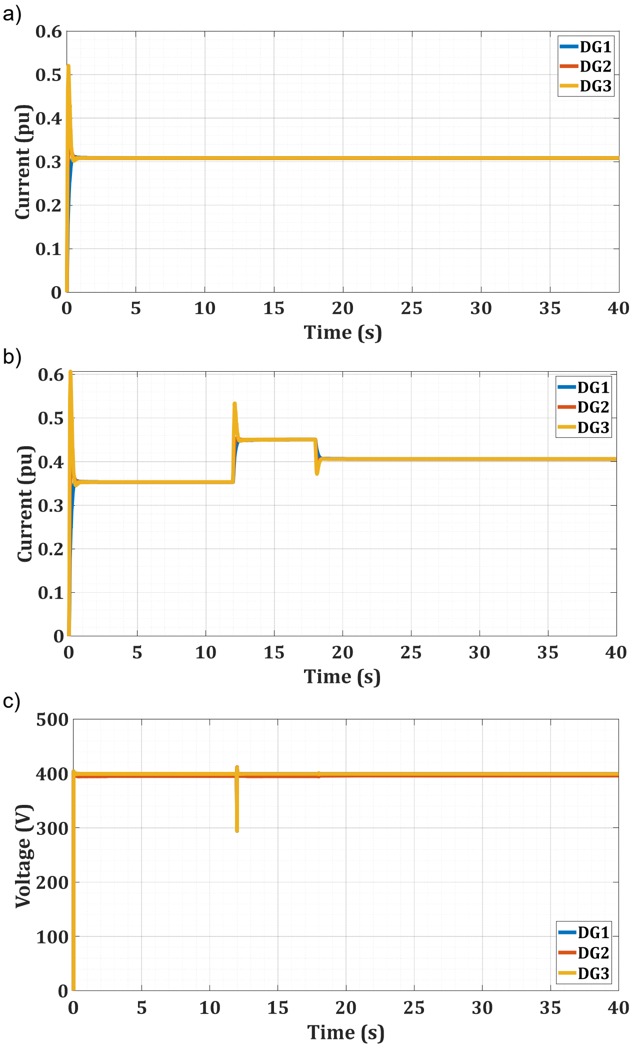
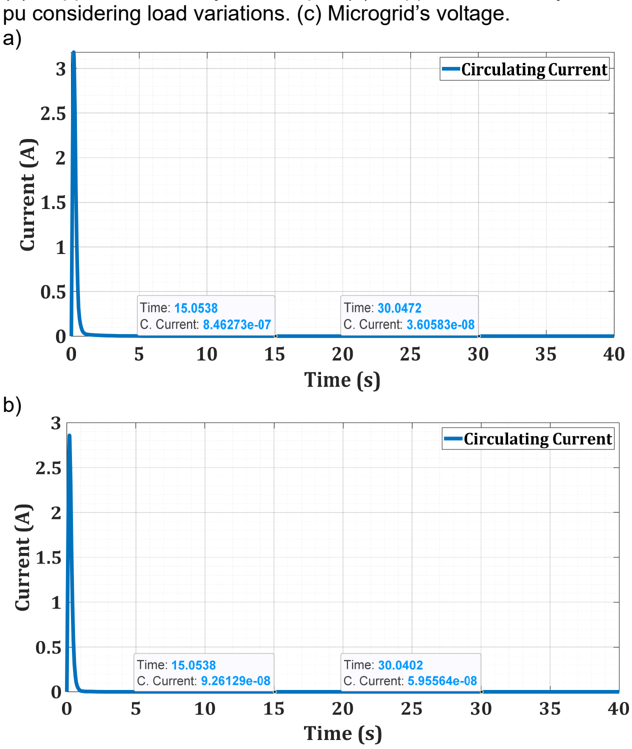


Fig. 8. Power sharing test of the proposed current sharing method. (a) Supplied current by DGs in pu. (b) Supplied current by DGs in pu considering load variations. (c) Microgrid's voltage.



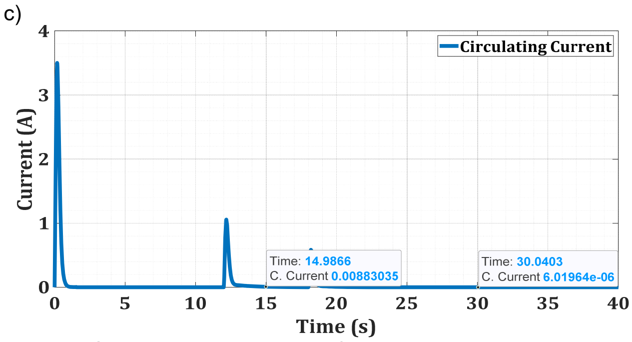


Fig. 9. Circulating current test of the proposed current sharing method. (a) Same transmission lines' impedance value. (b) Different transmission lines' impedance values. (c) Different transmission lines' impedance values with consideration of load variations

Table 3 summarizes the results obtained from simulations of circulating current in the three considered scenarios. The key observations are as follows:
1. Implementing a droop control or a power sharing method without addressing circulating current mitigation leads to high circulating current values.
2. In cases with varied impedance, particularly with increased transmission lines' impedance, circulating current values decrease, yet they remain significant in the absence of an improved method such as the one suggested in this paper.
3. Variations in load result in an increase in circulating current values. However, the proposed method current sharing method effectively maintains these values at very low levels.

Table 4. Summary of the results obtained from Mtalab/Simulink simulations

Scenarios	Droop Control	Power sharing method [26]	Current sharing method (Proposed method)
Equal transmission lines impedance without Load variation	Ic = 1,03 A	Ic = 0,84 A	Ic = 8,46e-07
Different (increase) impedance with constant load demand	Ic = 0,36 A	Ic = 0,78 A	Ic = 9,26e-08
Different impedance with load variation demand	Ic = 0,66 A	Ic = 1,66 A	Ic = 6,01e-06

5. Conclusion

In this paper, we present a straightforward and reliable approach to address circulating current issues in a meshed multi-PCC microgrid with three Distributed Generators (DGs). The method relies on the real-time measurements of DGs' output current and voltage. It dynamically computes the voltage reference for each DG, responding instantly to changes in transmission lines' impedances and load demand without requiring prior knowledge of microgrid parameters.

Notably, the proposed method not only ensures proper load sharing but also effectively mitigates circulating current under diverse scenarios. To underscore its robustness and efficacy, we conducted simulations comparing our method with two others from the literature: conventional droop control and a power-sharing method that neglects circulating current mitigation. Utilizing MATLAB/Simulink, we observed consistently high circulating current values in all scenarios when an enhanced mitigation method was not employed.

The results underscore the necessity of an improved method for circulating current mitigation. Our proposed approach, in contrast, successfully achieves a significant reduction in circulating current, demonstrating its effectiveness and robustness across various simulation scenarios.

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