IUST
Iran University of
Science and Technology

Iranian Journal of Electrical and Electronic Engineering

Journal Homepage: ijeee.iust.ac.ir

Advanced Control Strategies for Managing Circulating Currents in Islanded Microgrid Inverters

Nurul Husna Abd Wahab*(C.A.), Mohd Hafizuddin Mat **, Norezmi Md Jamal *** and Nur Hidayah Ramli **

Abstract: In islanded microgrids, circulating currents among parallel inverters pose significant challenges to system stability and efficient power distribution. Traditional droop control methods often struggle to manage these currents effectively, leading to inefficiencies and potential system damage. This study introduces an advanced fuzzy-robust droop control strategy that integrates fuzzy logic with robust droop control to address these challenges. By incorporating fuzzy logic, the proposed strategy enhances the adaptability of droop control to varying system conditions, improving the management of circulating currents and ensuring more accurate power sharing among inverters. Comprehensive mathematical modeling and extensive simulation analyses validate the performance of this control strategy. The results show that the fuzzy-robust droop control method significantly outperforms conventional approaches, achieving up to a 70% reduction in circulating currents. This improvement leads to a substantial reduction in power losses and enhances the dynamic response under varying load conditions. Additionally, the strategy improves voltage and frequency regulation, contributing to the overall stability and reliability of the microgrid. The findings provide a robust solution to the longstanding issue of circulating currents, optimizing microgrid operations, and paving the way for more efficient and resilient distributed energy systems. The advanced control strategy presented in this study not only addresses critical challenges but also demonstrates the potential for innovative methodologies to meet the growing demands of future energy infrastructures, where reliability and efficiency are essential.

Keywords: Circulating current; Fuzzy-Robust control; islanded microgrid; power-sharing; fuzzy logic; robust droop

1 Introduction

ISLANDED microgrids are gaining prominence as a viable solution for delivering reliable and sustainable energy, especially in remote and off-grid areas. These autonomous systems operate independently of the main utility grid, integrating local energy generation, consumption, and often storage. Their ability to function in both grid-connected and isolated modes not only enhances energy reliability but also offers significant economic benefits by optimizing the use of distributed energy resources (DERs) [1], [2]. Effective power-sharing is essential for the stable and efficient operation of islanded microgrids. A key component in this process is the DC-DC converter, which plays a crucial role in integrating and controlling DERs such as solar photovoltaic systems, wind turbines, and energy storage units. Beyond basic energy conversion, DC-DC converters are integral to managing power flow, regulating voltage and frequency, and ensuring microgrid stability under both grid-connected and

---

Iranian Journal of Electrical & Electronic Engineering, 2025.
Paper first received 24 Dec. 2024 and accepted 20 Feb. 2025.

* The author is with the Faculty of Electrical Engineering & Technology, Universiti Malaysia Perlis (UniMAP), 02600 Arau, Perlis, Malaysia.
E-mail: husnawahab@unimap.edu.my.
** The authors are with the Faculty of Electronic Engineering & Technology Advanced Communication Engineering Centre of Excellence, Universiti Malaysia Perlis, Perlis, Malaysia.
E-mails: hafizuddinmat@unimap.edu.my,
hidayahramli@unimap.edu.my
*** The author is with the Department of Electrical Engineering Technology, Faculty of Engineering Technology, Universiti Tun Hussein Onn Malaysia (UTHM), Malaysia.
E-mail: norezmi@uthm.edu.my.
Corresponding Author: Nurul Husna Abd Wahab.

islanded conditions [3]–[6].

Recent studies have provided extensive insights into the technical challenges and technological advancements in AC-DC microgrids [7]. The role of DC-DC converters has been particularly emphasized, as they are critical in addressing issues such as power quality, real-time power management, and voltage and frequency control [8]–[10]. As microgrids increasingly integrate renewable energy sources (RES), the need for advanced DC-DC converter technology becomes even more critical. These advancements are vital for the broader adoption and successful implementation of islanded microgrids, which are poised to become a significant part of the future energy landscape [11], [12]. However, the integration of RES and the operation of microgrids under varying load conditions present considerable challenges, particularly in power flow management and control. Among these challenges, the issue of circulating currents—undesirable currents that arise due to differences in line impedances—emerges as a critical concern. Circulating currents can lead to unbalanced power sharing, decreased efficiency, and potential damage to system components, thereby undermining the stability and reliability of the microgrid [3], [13]–[15]. To mitigate the adverse effects of circulating currents, various strategies have been proposed, including the use of virtual impedance loops and secondary control mechanisms. These methods aim to balance power output among DERs, ensuring accurate power-sharing and minimizing the impact of line impedance mismatches [16]–[18]. Despite these efforts, conventional control approaches, such as the widely used droop control method, have limitations, particularly in low-voltage microgrids where line impedances are more resistive than inductive [19]. In such environments, achieving precise reactive power sharing is challenging, necessitating the development of more sophisticated control strategies.

In our previous research [4], we developed a robust droop control method augmented with fuzzy logic to address key challenges in the operation of islanded microgrids, particularly focusing on enhancing frequency stability and ensuring equitable power-sharing among parallel-connected inverters. The conventional droop control approach, widely utilized due to its simplicity and decentralized nature, adjusts the power output of inverters based on deviations in frequency and voltage. However, in low-voltage microgrids, where line impedances are more resistive than inductive, this traditional method encounters significant limitations. Our earlier work introduced fuzzy logic into the droop control framework, which provided an adaptive mechanism to better handle the inherent variability and uncertainties of real-world microgrid environments. This integration allowed the system to maintain a stable frequency reference of 50 Hz across parallel inverters, even under challenging conditions such as varying inductive line impedances. The results showed a marked improvement in both frequency stability and the distribution of power among inverters, reducing the risks of instability and inefficiency within the microgrid.

Despite these advancements, the issue of circulating currents—unintended currents that flow between inverters due to slight mismatches in output voltages—remained a persistent challenge. These circulating currents can lead to significant power losses, increased harmonic distortion, and even potential damage to system components if not adequately managed [15], [20]–[23]. Building upon the foundation of our previous research, this study introduces a more advanced fuzzy-robust droop control strategy specifically designed to mitigate the issue of circulating currents. By further refining the integration of fuzzy logic with the robust droop control framework, this new approach enhances the system's adaptability to dynamic operational conditions. It achieves this by dynamically fine-tuning control parameters in real time, effectively responding to changes in load conditions, line impedances, and other critical variables within the microgrid. The proposed strategy has demonstrated a significant reduction in circulating currents—up to 70%—compared to conventional methods, leading to enhanced power efficiency, greater system stability, and improved overall reliability of the microgrid. This innovation not only addresses a long-standing challenge in microgrid operations but also underscores the importance of continuous advancements in control methodologies to meet the evolving demands of modern energy infrastructures [17], [20], [24]–[29].

The outcomes of this study underscore the critical importance of addressing circulating currents in islanded microgrids and highlight the effectiveness of advanced control methodologies in optimizing microgrid performance. By overcoming these long-standing challenges, the proposed fuzzy-robust droop control strategy offers a pathway to more resilient, efficient, and adaptable distributed energy systems. As the demand for sustainable energy solutions continues to rise, the innovations presented in this study contribute significantly to the evolution of energy infrastructure, paving the way for future microgrid deployments.

2 Methodology

2.1 Process flow

As this work is extended from our previous work, therefore, Stage I, Stage II, and Stage III as shown in Fig. 1, are already presented and discussed in [4]. Stage IV will be presented in this work. A parallel multi-inverter system is illustrated in Fig. 2. Each inverter in this model is considered a voltage source connected in series with line impedance. All parameter variations, including the closed-loop voltage gain (G_j), the output impedance of the inverter (Z_j), and line impedance (Z_{lj}), are taken into consideration. they are unavoidable.

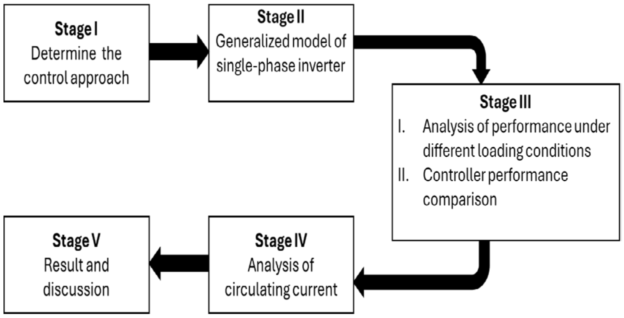


Fig 1. Fig. 1 Research flow and process.

Z_L represents the load impedance, while V_O is the load voltage. The parallel system of this model can be defined as in Eq. (1):

$$\sum_{j=1}^{N} i_j = i_1 + i_2 + \cdots + i_N = \frac{V_O}{Z_L} \tag{1}$$

The parallel-connected inverters are assumed to be identical, and only the line impedance differs. Thus,

$$G_1 = G_2 = G_N = G$$
$$Z_1 = Z_2 = Z_N = Z \tag{2}$$

Using this assumption, Eq. (1) and Eq. (2) simplifies to

$$G\sum_{j=1}^{N} V^*{}_{ij} - NV_O = Z\sum_{J=1}^{N} i_j + \sum_{j=1}^{N} i_j Z_{lj} \tag{3}$$

By substituting Eq. (10) from the previous work [3], into Eq. (3) and solving for VO, as presented in Eq. (4).

$$G\sum_{j=1}^{N} V_{ij}{}^* - NV_O = Z\frac{V_O}{Z_L} + \sum_{j=1}^{N} i_j Z_{lj}$$

$$Z\frac{V_O}{Z_L} + NV_O = G\sum_{j=1}^{N} V_{ij}{}^* - \sum_{j=1}^{N} i_j Z_{lj} \tag{4}$$

$$V_O\left[\frac{V_O}{Z_L} + N\right] = G\sum_{j=1}^{N} V_{ij}{}^* - \sum_{j=1}^{N} i_j Z_{lj} G \sum_{j=1}^{N} V_g{}^*$$

$$-NVo$$

$$= Z\frac{V_O}{Z_L} + \sum_{j=1}^{N} i_j Z_{lj}$$

$$V_O = \frac{\frac{1}{N} G \sum_{j=1}^{N} V_{ij}{}^* - \frac{1}{N}\sum_{j=1}^{N} i_j Z_{lj}}{1 + \frac{Z}{NZ_L}}$$

The stability of the output voltage of the parallel multi-inverter only depends on the denominator as in Eq. (4), in which the characteristic equation is

$$1 + \frac{Z}{NZ_L} = 0 \tag{5}$$

The effect of the proportional and resonant gains on the stability of the voltage control loop, as implemented in this study, must comply with Eq. (5).

The results presented in [4], demonstrate the occurrence and persistence of circulating currents when using either the robust droop controller or the fuzzy-robust droop controller in parallel inverter systems. These findings underscore the challenges in achieving effective control over circulating currents, which remain a significant issue even with advanced control strategies. Circulating currents, as highlighted in the previous study, are problematic because they can lead to inefficiencies such as power losses, increased harmonic distortion, and potential damage to the inverters. Despite the enhancements offered by fuzzy logic integration in the robust droop controller, the simulation results indicate that circulating currents continue to exist, thus necessitating further investigation and refinement of control strategies to mitigate these effects more effectively.

To delve deeper into this issue, the present study conducts a series of simulations to thoroughly investigate circulating currents within a system of three parallel inverters. Each simulation is carried out over a period of 0.1 seconds, with all inverters configured to have the same power rating, set according to the S_{base} value. These simulations are crucial for understanding the behaviour of circulating currents under various conditions and for evaluating the performance of different control strategies in real-world scenarios. By maintaining consistent power ratings and simulation parameters, this study aims to provide a clear comparison of how different control approaches handle circulating currents and to identify potential improvements that could be made to enhance the stability and efficiency of islanded microgrid operations.

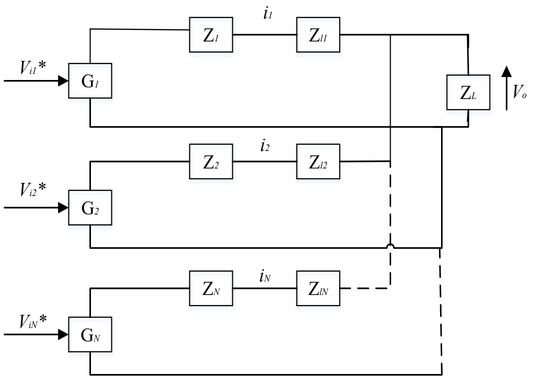


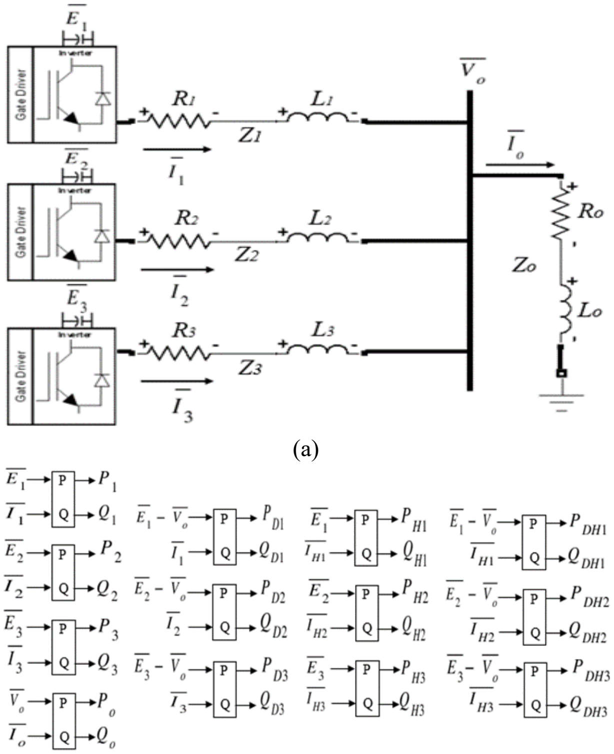
Fig 2. The model of the parallel multi-inverter system.

There are three voltage sources (E_1, E_2, E_3) are used in representing the output voltage of three inverters after LC filtering. These voltage sources are connected to a load, Z_O, through their respective line impedances (Z_1, Z_2, Z_3). Fig. 3 (a) illustrates the system configuration used for analysis in this section. The calculation blocks of the active and reactive powers used to calculate the output power (P_1, Q_1, P_2, Q_2, P_3, Q_3), power absorbed by line impedance (P_{D1}, Q_{D1}, P_{D2}, Q_{D2}, P_{D3}, Q_{D3}), circulating power (P_{H1}, Q_{H1}, P_{H2}, Q_{H2}, P_{H3}, Q_{H3}), power absorbed by line impedance due to circulating current (P_{DH1}, Q_{DH1}, P_{DH2}, Q_{DH2}, P_{DH3}, Q_{DH3}), and load power (P_o, Q_o). The circulating current (I_{H1}, I_{H2}, I_{H3}) is seen by voltage sources 1, 2, and 3 respectively as shown in Fig. 3 (b). The importance of understanding circulating current in various electrical systems cannot be overstated. Therefore, through a series of six in-depth case studies, this research paper aims to examine the existence and characteristics of circulating current. The parameters for each case are outlined in the accompanying Table 1, providing a comprehensive overview of the factors considered in this investigation.

2.2 Analysis Methods

The ideal condition of parallel operation is simulated in Case 1. The system parameters in the first column from Table 1 are used. The voltage sources and line impedances for the three parallel voltage sources are identical within the distance of 0.25 km. All of them are connected to the RL load. The effect of the voltage amplitude difference of parallel connected voltage sources on the circulating current is investigated in Case 2. In this analysis, the amplitude of the second and third voltage sources are changed as referred to in Case 2 in Table 1, while the other parameters remain the same as in Case 1. While, Case 3 is the same as Case 2, but the testing is done with the load disconnected from the system as referred to in column Case 3.

In Case 4, the purpose is to determine whether the voltage frequency difference of the parallel voltage sources compromises the circulating current while the load is still connected, thus, this analysis was carried out to investigate this issue. In this work, the frequency of the second and third voltage sources are changed as referred to in the column of Case 4, while the other parameters are the same as in Case 1. Same as in Case 4, the analysis in Case 5 is investigated with the load disconnected from the system as stated in the column of Case 5 in Table 1. In order to identify whether the different line impedance of the parallel voltage sources contributes to the circulating current, Case 6 is performed to investigate the effect of line impedance.



(a)

(b)

Fig 3. Circulating current simulation for three parallel-connected inverters (a) output voltage of three inverters (b) calculation blocks of the active and reactive powers

3 Results and Discussion

The simulation results for circulating currents in a system of three parallel-connected inverters are presented in this section. For comparative analysis, simulations using the conventional robust droop controller, as referenced in [30], are also included. Table 2 summarizes the current measurements from each scenario, comparing the performance of the proposed fuzzy-robust droop control method with the robust droop control. The analyses were conducted using RL loads, with identical distances for each inverter, under various operational conditions to evaluate the effectiveness of the proposed strategy in mitigating circulating currents. The results, complemented by corresponding figures and tables, provide a comprehensive assessment of the control strategy's performance in enhancing system stability and reducing circulating currents.

The initial simulation scenario was designed to evaluate the system under ideal parallel operations, where all parallel-connected inverters were configured with identical voltage sources and line impedances, as specified in Case 1 of Table 2. The results, illustrated in Fig. 4 (a) and 4 (b), showed that the output voltages of the inverters perfectly synchronized in both amplitude and phase, resulting in the absence of circulating currents.

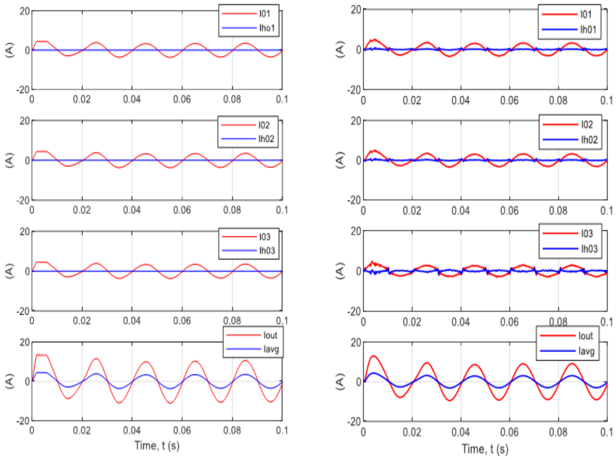
Table 1 System parameters of circulating current simulation for three parallel-connected inverters.

		Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
E_1	A_1(V)	230	230	230	230	230	230
	f_1(Hz)	50	50	50	50	50	50
E_2	A_2(V)	230	240	240	230	230	230
	f_2(Hz)	50	50	50	50.02	50.02	50.02
E_3	A_3(V)	230	220	220	230	230	230
	f_3(Hz)	50	50	50	49.96	49.96	49.96
Z_1	R_1	0.135	0.135	0.135	0.135	0.135	0.068
	X_1	0.024	0.024	0.024	0.024	0.024	0.012
Z_2	R_2	0.135	0.135	0.135	0.135	0.135	0.135
	X_2	0.024	0.024	0.024	0.024	0.024	0.024
Z_3	R_3	0.135	0.135	0.135	0.135	0.135	0.203
	X_3	0.024	0.024	0.024	0.024	0.024	0.036
Z_o	R_o	30Ω	30Ω	∞	30Ω	∞	30Ω
	X_o	1.57Ω	1.57Ω		1.57Ω		1.57Ω

The output current I_o curve is in red and the current I_{ho} curve is in blue. This outcome confirms the effectiveness of the proposed fuzzy-robust droop control strategy under ideal conditions. The strategy ensures stable operation without the emergence of circulating currents, establishing a benchmark for comparing performance under more challenging, non-ideal conditions.

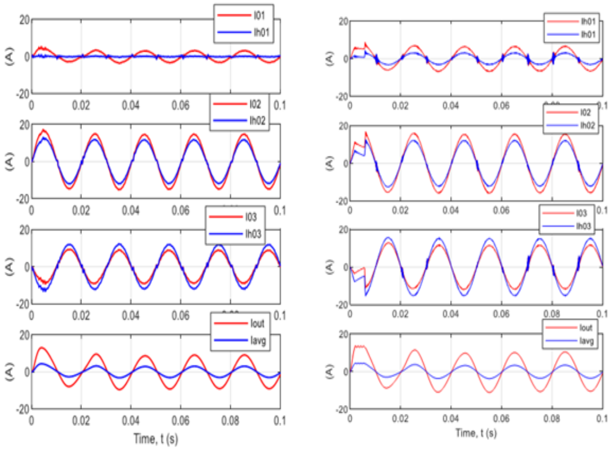
To explore the impact of voltage amplitude discrepancies between the inverters, simulations were conducted with varying conditions both with and without load, as detailed in Cases 2 and 3 of Table 1. In the presence of a load (Case 2), varying the voltage amplitudes of the second and third inverters led to the emergence of circulating currents, as shown in Fig. 5 (a) and 5 (b). However, the proposed fuzzy-robust droop control strategy significantly mitigated these currents, achieving a reduction of 43.83% compared to the conventional robust droop control method.

When the load was disconnected (Case 3), circulating currents persisted, as illustrated in Fig. 6 (a) and 6 (b), indicating that these currents are primarily driven by voltage differences rather than by the load conditions. The proposed control method continued to perform effectively, significantly reducing circulating currents even in the absence of a load. This combined outcome highlights the robustness of the fuzzy-robust droop control strategy in managing circulating currents across different load scenarios, underscoring its capability to maintain system stability regardless of the load condition.



(a) (b)

Fig 4. Simulation results for Case 1 (a) output current using the proposed controller (b) output current using the robust droop control.



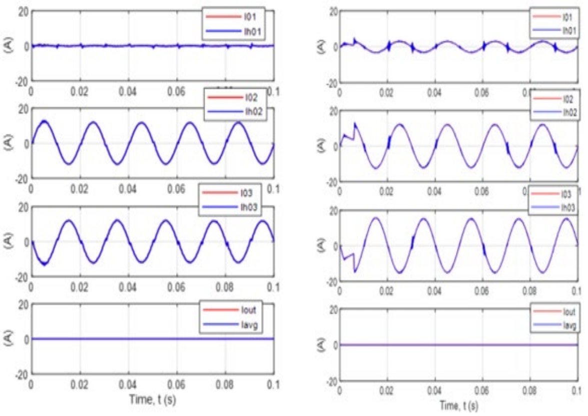
(a) (b)

Fig 5. Simulation results for Case 2 (a) output current using the proposed controller (b) output current using the robust droop control.

The next set of simulations focused on the effects of frequency differences between the inverters, both with and without load, as described in Cases 4 and 5 of Table 1. When slight frequency variations were introduced among the inverters, the conventional robust droop control method resulted in significant circulating currents, as depicted in Fig. 7 (a) and 7 (b). In contrast, the fuzzy-robust droop control strategy successfully eliminated these currents, preventing additional power losses and enhancing overall system efficiency.

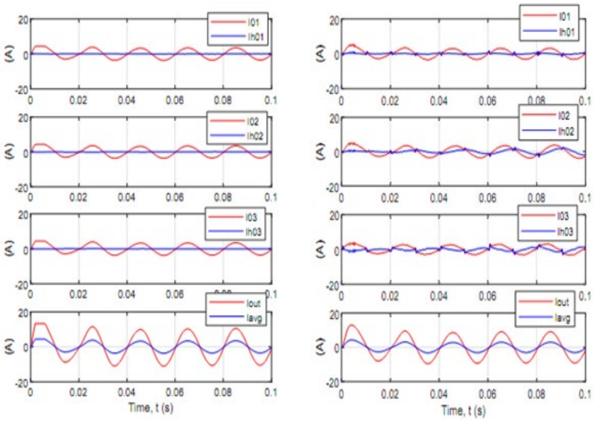
In the scenario where the load was disconnected (Case 5), the proposed control method maintained its effectiveness, continuing to eliminate circulating currents despite the absence of a load, as shown in Fig. 8 (a) and 8 (b). This combined outcome emphasizes the adaptability of the proposed method to dynamic changes in system frequency, ensuring stable and efficient microgrid operations even under varying load conditions. The ability to maintain system stability during periods of low or no load is particularly valuable for real-world microgrid applications.

The final scenario explored the impact of varying line impedances by altering the impedances of the lines connected to the first and third inverters, as detailed in Case 6 of Table 1. The simulation results, displayed in Fig. 9 (a) and 9 (b), indicated that differences in line impedance led to observable circulating currents. Despite these variations, the fuzzy-robust droop control strategy effectively minimized these currents, showcasing its ability to adapt to changes in the physical parameters of the system. This outcome is critical for real-world microgrid applications, where line impedances may vary due to external factors. The proposed method's adaptability in maintaining stability and reducing inefficiencies under varying line impedance conditions further demonstrates its robustness and practical utility.



(a) (b)

Fig 6. Simulation results for Case 3 (a) output current using the proposed controller (b) output current using the robust droop control.



(a) (b)

Fig 7. Simulation results for Case 4 (a) output current using the proposed controller (b) output current using the robust droop control.

Table 2 Simulation results of current measurements using the proposed controller and robust droop controller.

	Case 1		Case 2		Case 3		Case 4		Case 5		Case 6	
	Fuzzy-robust	Robust	Fuzzy-robust	Robust	Fuzzy-robust	Robust	Fuzzy-robust	Robust	Fuzzy-robust	Robust	Fuzzy-robust	Robust
I_{01} rms (p.u)	0.33333	0.34569	0.37387	0.35195	0.14609	0.19521	0.25463	0.35977	0.0001	0.03754	0.2644	0.34882
I_{02} rms (p.u)	0.33333	0.34569	0.9535	1.62678	0.84609	1.30142	0.25103	0.37072	0.0001	0.17988	0.25	0.37697
I_{03} rms (p.u)	0.33333	0.34569	0.63467	1.31863	0.98981	1.51885	0.25823	0.39105	0.00004	0.31441	0.23354	0.30659
$I_{01}+I_{02}+I_{03}$ rms (p.u)	1	1.03707	1.96204	3.29736	1.982	3.01549	0.76389	1.12154	0.00031	0.53183	0.74794	0.99015
I_o rms (p.u)	1	1	0.67315	1.00266	0	0	0.76389	1.00422	0	0	0.75617	1.00422
$I_{01}+I_{02}+I_{03}-I_o$ rms (p.u)	0	0.03707	1.28889	2.2947	1.982	3.01549	0	0.11732	0.00031	0.53183	0.00823	0.02816
% of Reduction in Circulating Current using Proposed Scheme	100		43.83		34.27		100		99.94		70.77	

The results from these simulations, summarized in Table 2, clearly indicate that the fuzzy-robust droop control strategy consistently outperforms the conventional robust droop control method across all scenarios. The proposed strategy achieves up to a 70% reduction in circulating currents, which not only minimizes power losses but also significantly enhances the overall stability, efficiency, and reliability of the microgrid.

4 Conclusion

This research presents a significant advancement in microgrid control by introducing a fuzzy-robust droop control strategy designed to effectively mitigate circulating currents in parallel inverter systems. Through comprehensive simulations, the proposed strategy demonstrated its superiority over the conventional robust droop control method, achieving up to a 70% reduction in circulating currents. This substantial improvement not only minimizes power losses but also enhances the overall stability, efficiency, and reliability of microgrid operations. The integration of fuzzy logic with robust droop control represents a key contribution of this work, providing an adaptive mechanism that dynamically adjusts control parameters in real-time to respond to changes in voltage amplitude, frequency, and line impedance. This adaptability ensures more accurate power sharing among inverters, addressing the limitations of traditional control approaches and significantly contributing to the resilience and longevity of islanded microgrids.

Looking forward, the practical implementation of this fuzzy-robust droop control strategy in operational microgrids is a critical next step. Future research should focus on testing the strategy under diverse environmental conditions and scaling it to accommodate larger, more complex microgrid systems. Additionally, integrating this control strategy with advanced technologies, such as machine learning algorithms, could further enhance its real-time predictive capabilities and optimize system performance. The development of hybrid control systems that combine the fuzzy-robust droop method with other advanced techniques offers another promising avenue for future exploration, potentially leading to even greater improvements in microgrid resilience and efficiency. Moreover, examining the impact of this strategy on other critical aspects of microgrid performance, such as harmonic distortion and voltage stability, could provide a more comprehensive understanding of its benefits and broaden its applicability in the optimization of distributed energy systems.

Acknowledgment

The authors acknowledge the financial support provided by the Faculty of Electrical Engineering & Technology, Universiti Malaysia Perlis (UniMAP) under FKTE research fund.

References

[1] G. Invernizzi and G. Vielmini, “Challenges in Microgrid Control Systems Design. An application case,” in *2018 AEIT International Annual Conference*, 2018, pp. 1–6.

[2] J. VAISH, A. K. Tiwari, and S. K., “Cost Optimization and Battery Sizing of Grid-Connected Microgrid with Distributed Energy Resources Using Random Forest Technique,” *Iran. J. Electr. Electron. Eng.*, vol. 19, no. 4, 2023.

[3] R. Sabzehgar, “Overview of Technical Challenges, Available Technologies and Ongoing Developments of AC/DC Microgrids,” in *Development and Integration of Microgrids*, W.-P. Cao and J. Yang, Eds. Rijeka: InTech, 2017.

[4] A. W. N. Husna, M. A. Roslan, and M. H. Mat, “Droop control technique for equal power sharing in islanded microgrid,” *Int. J. Power Electron. Drive Syst.*, vol. 10, no. 1, 2019.

[5] M. Syahril, M. A. Roslan, and B. Ismail, “Microgrid synchronization using power offset through a central controller,” in *Journal of Physics: Conference Series*, 2020, vol. 1432, no. 1.

[6] A. Karimpour, A. M. Amani, M. Karimpour, and M. Jalili, “Enhancing Voltage Regulation in DC Microgrids Using a Price Incentive Load Management Approach,” *Iran. J. Electr. Electron. Eng.*, vol. 17, no. 4, 2021.

[7] S. P. Tiwari, “A Dependable Protection Scheme for Electrical Vehicle Integrated Microgrid Considering Stressed Fault Scenarios and Dissimilar Fault Inceptions,” *Iran. J. Electr. Electron. Eng.*, vol. 20, no. 1, 2024.

[8] A. W. N. Husna, S. F. Siraj, and M. H. Mat, “Effect of load variations in DC-DC converter,” in *Proceedings - CIMSim 2011: 3rd International Conference on Computational Intelligence, Modelling and Simulation*, 2011.

[9] N. H. A.W., S. S.F., and M. Z. Ab Muin, “Modeling of DC-DC converter for solar energy system applications,” in *2012 IEEE Symposium on Computers & Informatics (ISCI)*, 2012, pp. 125–129.

[10] V.-H. Bui, A. Hussain, and H.-M. Kim, “A Strategy for Flexible Frequency Operation of Stand-Alone Multimicrogrids,” *IEEE Trans. Sustain. Energy*, vol. 9, no. 4, pp. 1636–1647, 2018.

[11] Q. Liu, T. Caldognetto, and S. Buso, “Review and Comparison of Grid-Tied Inverter Controllers in Microgrids,” *IEEE Trans. Power*

Electron., vol. 35, no. 7, pp. 7624–7639, 2020.

[12] N. H. A. Wahab, M. H. Mat, and M. A. Roslan, “A Review on Optimization of Control Strategy on Paralleled Connected Inverters in an Islanded Microgrid,” *Adv. Sci. Lett.*, vol. 23, no. 6, pp. 5406–5409, Jun. 2017.

[13] R. WANG, Q. SUN, Y. GUI, and D. MA, “Exponential-function-based droop control for islanded microgrids,” *J. Mod. Power Syst. Clean Energy*, vol. 7, no. 4, pp. 899–912, 2019.

[14] E. De Santis, A. Rizzi, and A. Sadeghian, “A Hierarchical Genetic Optimization of a Fuzzy Logic System for Flow Control in Micro Grids,” Apr. 2016.

[15] Y. Xia, Y. Peng, P. Yang, M. Yu, and W. Wei, “Distributed Coordination Control for Multiple Bidirectional Power Converters in a Hybrid AC/DC Microgrid,” *IEEE Trans. Power Electron.*, vol. 32, no. 6, pp. 4949–4959, 2017.

[16] S. Gholami, S. Saha, and M. Aldeen, “Robust multiobjective control method for power sharing among distributed energy resources in islanded microgrids with unbalanced and nonlinear loads,” *Int. J. Electr. Power Energy Syst.*, vol. 94, pp. 321–338, Jan. 2018.

[17] K. Wang, X. Huang, B. Fan, Q. Yang, G. Li, and M. L. Crow, “Decentralized Power Sharing Control for Parallel-Connected Inverters in Islanded Single-Phase Micro-Grids,” *IEEE Trans. Smart Grid*, vol. 9, no. 6, pp. 6721–6730, Nov. 2018.

[18] F. Deng, A. Petucco, P. Mattavelli, and X. Zhang, “An enhanced current sharing strategy for islanded ac microgrids based on adaptive virtual impedance regulation,” *Int. J. Electr. Power Energy Syst.*, vol. 134, p. 107402, 2022.

[19] Q. C. Zhong, Y. Wang, and B. Ren, “UDE-Based Robust Droop Control of Inverters in Parallel Operation,” *IEEE Trans. Ind. Electron.*, vol. 64, no. 9, pp. 7552–7562, 2017.

[20] Z. Peng *et al.*, “Droop control strategy incorporating coupling compensation and virtual impedance for microgrid application,” *IEEE Trans. Energy Convers.*, vol. 34, no. 1, pp. 277–291, 2019.

[21] A. Villalon, C. Munoz, R. Aliaga, J. Munoz, M. Rivera, and P. Zanchetta, “Power sharing control of islanded ac microgrid considering droop control and virtual impedance,” *Proc. IEEE Int. Conf. Ind. Technol.*, vol. 2020-Febru, pp. 1139–1144, 2020.

[22] J. Niu *et al.*, “Analysis of circulating harmonic currents in paralleled three level ANPC inverters using SVM,” *Conf. Proc. - IEEE Appl. Power Electron. Conf. Expo. - APEC*, vol. 2019-March, pp. 2481–2487, 2019.

[23] B. Wei, J. M. Guerrero, J. C. Vasquez, and X. Guo, “A circulating current suppression method for parallel connected voltage-source-inverters (VSI) with common DC and AC buses,” in *2016 IEEE Energy Conversion Congress and Exposition (ECCE)*, 2016, pp. 1–6.

[24] A. Karaarslan and M. E. Seker, “Distributed Control of Microgrids,” *Power Syst.*, no. February, pp. 403–422, 2020.

[25] Q. C. Zhong and D. Boroyevich, “Structural Resemblance between Droop Controllers and Phase-Locked Loops,” *IEEE Access*, vol. 4, pp. 5733–5741, 2016.

[26] X. Wang, H. Lv, Q. Sun, Y. Mi, and P. Gao, “A proportional resonant control strategy for efficiency improvement in extended range electric vehicles,” *Energies*, vol. 10, no. 2, 2017.

[27] Asian Development Bank, *Handbook on Microgrids for Power Quality and Connectivity*, no. July. 2020.

[28] A. Kaur, J. Kaushal, and P. Basak, “Areview on microgrid central controller,” *Renew. Sustain. Energy Rev.*, vol. 55, pp. 338–345, Mar. 2016.

[29] M. U. Safder, M. J. Sanjari, A. Hamza, R. Garmabdari, M. A. Hossain, and J. Lu, “Enhancing Microgrid Stability and Energy Management: Techniques, Challenges, and Future Directions,” *Energies*, vol. 16, no. 18, 2023.

[30] Q.-C. Zhong, “Robust Droop Controller for Accurate Proportional Load Sharing Among Inverters Operated in Parallel,” *IEEE Trans. Ind. Electron.*, vol. 60, no. 4, pp. 1281–1290, Apr. 2013.

Biographies

Dr. Nurul Husna Binti Abd Wahab is a Senior Lecturer at the Faculty of Electrical Engineering and Technology, Universiti Malaysia Perlis (UniMAP), specialising in electrical systems engineering, power electronics, renewable energy integration, and microgrid technologies. Her academic journey includes a PhD and Master of Science in Electrical Systems Engineering from UniMAP, where she focused on robust control strategies for microgrids and DC-DC converters for renewable energy sources. She also holds a Bachelor’s degree in Industrial Electronic Engineering and a Diploma in Telecommunication Engineering. Dr. Husna’s research expertise encompasses adaptive PID controllers, fuzzy logic, DC-DC converter design, and microgrid frequency regulation

Dr. Mohd Hafizuddin Mat currently works at the Faculty of Electronic Engineering Technology, Universiti Malaysia Perlis. Mohd Hafizuddin does research in Communication Engineering, Electronic Engineering and Electrical Engineering. Their current project is Specific Absorption Rate (SAR) between metal object and antennas performance.

Dr. Norezmi Md Jamal is a Senior Lecturer at the Faculty of Engineering Technology, Universiti Tun Hussein Onn Malaysia (UTHM). She holds a PhD in Electrical Engineering from UTHM, with research interests in power electronics, energy storage, wireless power transfer, and IoT-based control systems. She has published in indexed journals, led national research grants, and actively supervised postgraduate students. Her work focuses on developing intelligent and robust energy conversion systems for renewable energy applications.

Dr. Nur Hidayah Ramli is a Senior Lecturer and currently works at the Faculty of Electronic Engineering Technology, Universiti Malaysia Perlis. She has been conferred as a Professional Technologist by the Malaysia Board of Technologists (MBOT). Her current project is related to antenna propagation, RF, and microwave engineering.