Luenberger Observer-based PCC voltage Estimation for Load Sharing in Islanded DC Microgrids

Mulualem YESHALEM, Abdelhakim SAIM, Azeddine HOUARI, Mohamed MACHMOUM
Nantes Université, Institut de Recherche en Énergie Électrique de Nantes Atlantique, IREENA, UR 4642, Saint-Nazaire F-44600, France

ABSTRACT – The increasing integration of DC loads, Distributed Energy Resources (DERs), and Energy Storage Systems (ESSs) has heightened interest in DC Microgrid. This paper proposes a Luenberger observer-based control method for parallel-connected DG units in islanded DC microgrids. The method addresses challenges arising from unmatched line impedances and load variations by using an observer to accurately estimate the voltage at the Point of Common Coupling (PCC). This estimation enables precise and equal load power sharing among DG units. The performance of the proposed method was evaluated under various operating conditions using MATLAB/Simulink simulations and compared with conventional droop control approaches. Results validate that the proposed control method achieves superior load power sharing and enhanced robustness against system parameter mismatches and load variations.

Keywords—DC Microgrid, Power sharing, Luenberger Observer, Line Impedance mismatch, Droop Control, PCC Voltage Estimation

1. INTRODUCTION

A Microgrid is a localized power system that operates in grid-connected or autonomous mode, supplying local loads using Distributed Generation (DG) units and ESSs [1]. Microgrids are classified into three types based on architecture and voltage: AC, DC, and hybrid AC/DC. DC microgrids (DCMGs) are advantageous due to their efficient integration of DC-based renewable energy sources (RESs) and energy storage systems (ESSs), minimizing conversion losses and eliminating harmonics [1]. Even-though parallel connected DG units in DC Microgrids offer numerous benefits, they also introduce several challenges related to load sharing and power flow control in presence of multiple DG units; voltage regulation, and protection [2]. The general configuration of an islanded DC microgrid along with its main components is shown in Fig. 1.

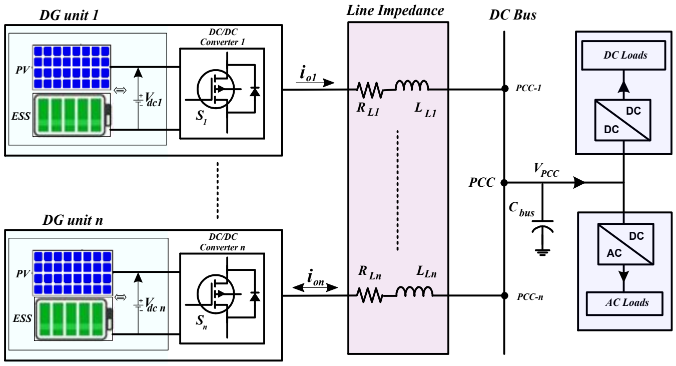


Fig. 1. Typical Islanded DC Microgrid Configuration

Distributed generation (DG) units are small, modular power systems located near end users [3], utilizing locally available energy sources such as solar, wind, and hydropower. This makes them particularly suitable for Ethiopia and other African nations. DG systems can range in capacity from a few kilowatts to several megawatts.

In the context of DC Microgrid operation, various control strategies have been employed to improve conventional droop control techniques performances in regulating power sharing and maintaining voltage stability[4], [5]. In [6], an adaptive droop control scheme is proposed to enhance load power sharing and voltage stability in DC microgrids. Unlike conventional fixed droop control, this approach adjusts droop control gains based on voltage deviations, addressing limitations of fixed-gain droop control. In the research article [7], a distributed two-layer control method is introduced. This method combines droop control for load power sharing with voltage regulation to ensure voltage stability at the Point of Common Coupling (PCC). Additionally, the paper leverages the advantages of dynamic consensus algorithms to enable accurate voltage estimation at different points within the microgrid before compensating for voltage deviations.

In paper [8], a control scheme based on a disturbance observer is proposed to achieve accurate voltage control and load sharing in a DC islanded Microgrid. The scheme employs a nonlinear decentralized back-stepping control strategy, ensuring robust performance against load variations and uncertainties in microgrid parameters. In research article [9], a Luenberger observer is utilized alongside a modified adaptive sliding mode controller to estimate unknown parameters, specifically the input voltage and load resistance in a photovoltaic system.

In this paper, an observer-based control method is proposed for load sharing and PCC voltage regulation in presence of uneven line impedances and load variations. To address the issue of inaccurate power sharing among parallel-connected DG units, this study proposes a Luenberger observer-based power-sharing control method, ensuring effective load sharing while minimizing voltage deviations in islanded DC microgrids. The main contributions of this study are:

1. Design of a Luenberger observer-based control method for accurate power sharing among parallel DG units in islanded DC microgrids.
2. Estimation of PCC voltage at the DC bus using locally available voltage and current measurements without communication links.

3. Achieving equal power sharing among the two DG units despite unmatched line impedances while maintaining acceptable voltage regulation.

This paper is organized as follows: Section 2 presents the modeling of islanded DC microgrids, covering both line impedance dynamics and the state-space formulation of parallel DG units operating within the islanded DC microgrid. Section 3 provides an overview of the conventional droop control method. Section 4 introduces the proposed Luenberger observer-based control mechanism. In Section 5, simulation results are presented to validate the performance of the proposed method. Finally, Section 6 concludes the study.

2. Modeling of the Islanded DC Microgrid

The islanded DC microgrid model under study, illustrated in Fig. 2, comprises two parallel-connected distributed generator (DG) units. Each DG unit includes a DC voltage source, a boost converter, and an LC filter, all connected to a common DC bus at the point of common coupling (PCC) through unmatched line impedances (Z_{Li}).

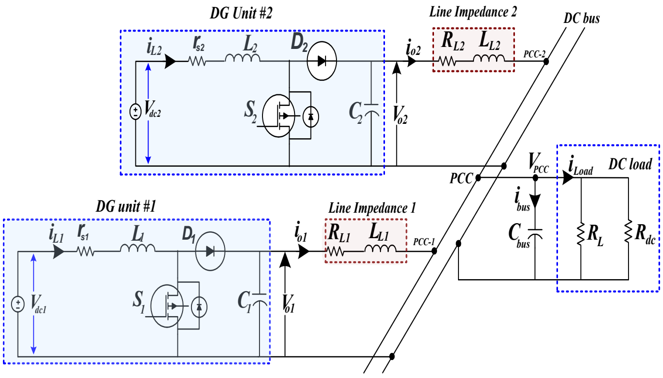


Fig. 2. Islanded DC microgrid Model with parallel DG unit

A. Line Impedance Dynamics

In the DC microgrid, the line impedance between each DG unit and the common DC bus is represented by the line resistance R_{Li} and inductance L_{Li}. By applying Kirchhoff's Voltage Law (KVL) to the circuit shown in Fig. 2, the differential equation governing the line current i_{oi} can be formulated as:

$$L_{Li}\frac{di_{oi}}{dt} = V_{oi} - V_{PCC} - (i_{oi}R_{Li}) \tag{1}$$

B. DC Bus Voltage Equation

The DC bus voltage at the point of common coupling (PCC) can be characterized by analyzing the dynamics of the DC link capacitor C_{bus} as follows.

$$C_{bus}\frac{dV_{PCC}}{dt} = \sum_{i=1}^{n} i_{oi} - i_{Load} \tag{2}$$

The total load current, i_{Load} is given as the sum of the individual line currents, i_{oi}:

$$i_{Load} = \sum_{i=1}^{2} i_{oi} = i_{o1} + i_{o2} \tag{3}$$

where, i_{oi} is the line current between the i^{th} DG and the common bus, V_{oi} is the output voltage of the i^{th} DG unit and V_{PCC} is the voltage at the PCC on the DC bus. The parameters R_{Li} *and* L_{Li} are the line resistance and inductance between the i^{th} DG and the common bus respectively, and C_{bus} is capacitance of the DC bus. i ranging from 1 to n, where n represents the total number of DG units in the DC microgrid system. In this study, n = 2.

C. State space representation of the studied DC Microgrid

The dynamic differential equations (1) and (2), which describe the interconnection model of DG units with the common DC bus, form the basis for deriving the state-space representation of the islanded DC microgrid model with two parallel-connected DG units [10], and are expressed as follows:

$$\frac{di_{oi}}{dt} = \left(\frac{-R_{Li}}{L_{Li}}\right) i_{oi} + \left(\frac{-1}{L_{Li}}\right) V_{PCC} + \left(\frac{1}{L_{Li}}\right) V_{oi} \tag{4}$$

$$\frac{dV_{PCC}}{dt} = \left(\frac{1}{C_{bus}}\right) \sum_{i=1}^{n} i_{oi} + \left(\frac{-1}{C_{bus}}\right) i_{Load} \tag{5}$$

The voltage at the PCC, V_{PCC}, is observed to change very slowly compared to the dynamic variations of the line currents. This slow change is typically attributed to the relatively large capacitance at the DC bus, C_{bus}, which serves to buffer voltage fluctuations. Therefore, for the purpose of observer design, we assume that $dV_{PCC}/dt = 0$, effectively treating the PCC voltage as a constant over the time scale.

3. Conventional Droop Control Method

The primary control layer of a DC microgrid comprises inner control loops and droop control, the latter being a commonly employed technique to achieve power sharing among parallel-connected DG units [11]. As illustrated in Fig. 3, droop control generates the voltage reference for the inner control loops, facilitating the parallel operation of DG units.

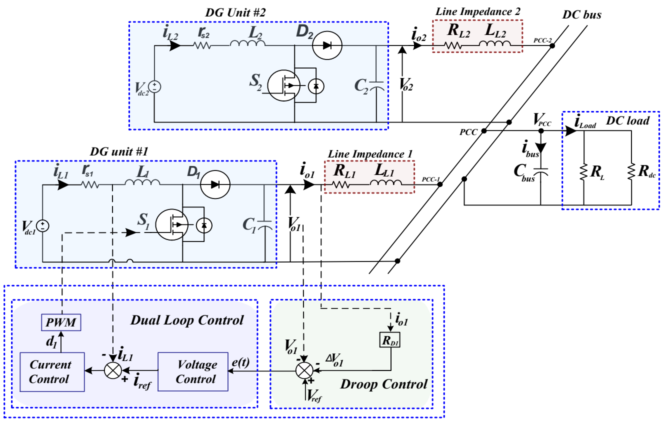


Fig. 3. Parallel connected DG units with Droop Control method

In the conventional droop control method, the voltage reference is dynamically modified according to the output current, ensuring load sharing among parallel DG units, as defined by:

$$V_{ref}^{*} = V_{ref} - i_{oi}R_{Di} \tag{6}$$

where, V_{oi} is the output voltage of ith DG unit; V_{ref} is the reference voltage under no load condition; i_{oi} is output current from ith DG unit; R_{Di} represents droop coefficients. The droop control mechanism facilitates proportional load sharing among parallel DG units by allowing the output voltage to decrease (droop) as the output current increases as described in Fig. 4.

There is a tradeoff between accurate load power sharing and bus voltage regulation, making it challenging to achieve equal load current sharing while maintaining the DC bus voltage at the reference value [12], [13].

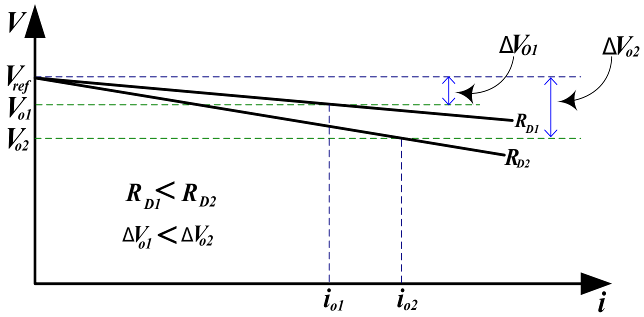


Fig. 4. Droop Characteristic Curves for unequal droop gain

4. Improved Control Method using Luenberger Observer

In DC microgrid, the influence of line impedance on power sharing and voltage regulation is significant [14], [15]. In practical DC Microgrid systems, some states are challenging to measure directly due to different factors such as the long distances between the local DG units and the load, sensor limitations, noise, or disturbances.

To address these challenges, this study proposes an observer to estimate the output voltage at the PCC for each DG unit without relying on additional sensors or communication infrastructure. The PCC voltage estimation compensates for the effects of unknown line impedances, enabling improved power sharing among the microgrid's DG units.

A. *Proposed Control Method Based on a Luenberger Observer*

The proposed control strategy utilizes a Luenberger observer technique to estimate the PCC voltage of parallel-connected DG units, as depicted in Fig. 5. The Luenberger observer technique is used to estimate the unknown state, which is the voltage after line impedances, (V_{PCC}). After-that, a local voltage correction term is calculated at the level of each DG units to adapt voltage references, maintaining the DC bus voltage at the PCC to its nominal value (48 V) while achieving balanced power sharing between the two DG units.

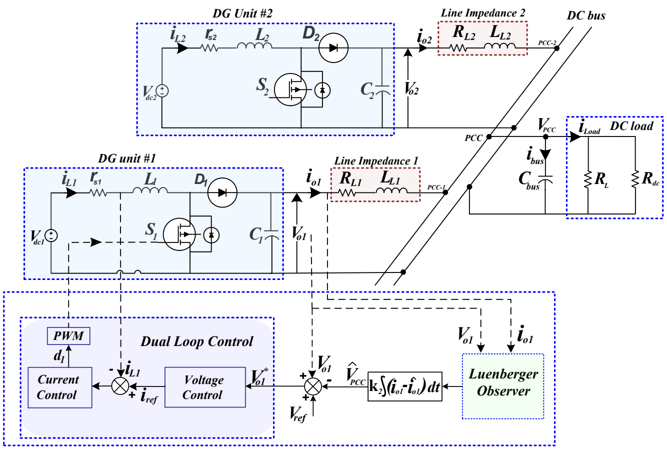


Fig. 5. Proposed Control Method based Luenberger observer

The reference output voltage of each DG unit can be expressed:

$$V_{oi}^{*} = V_{ref} + V_{oi} — \hat{V}_{PCC} \quad (7)$$

where, V_{oi}^{*} is the new reference voltage calculated after the PCC voltage is estimated and set as input to the voltage control loop.

Here, a Luenberger observer estimates the PCC output voltage ($\hat{V}_{PCC}$), as expressed in (9), through integrating the error between the measured output line current (i_{oi}) and the estimates the line current ($\hat{i}_{oi}$) of each DG units.

$$\frac{d\hat{V}_{PCC}}{dt} = K_2(i_{oi} — \hat{i}_{oi}) \quad (8)$$

where, $K = [K_1\ K_2]^T$ represents the observer gain vector.

Then, the estimated PCC voltage ($\hat{V}_{PCC}$) is defined as follows:

$$\hat{V}_{PCC} = K_2 \int (i_{oi} - \hat{i}_{oi})dt \quad (9)$$

B. *Luenberger Observer Design*

The state space representation of the DG units in islanded DC microgrid is analyzed as follow:

$$\frac{d}{dt}x(t) = Ax(t) + Bu(t) \quad (10)$$

Then system output $y(t)$ is the measurable and can be written as:

$$y(t) = Cx(t) \quad (11)$$

Thus, the differential equation (4) is used as the real model in the Luenberger observer to estimate the V_{PCC} of the DC microgrid, as shown in Fig. 6.

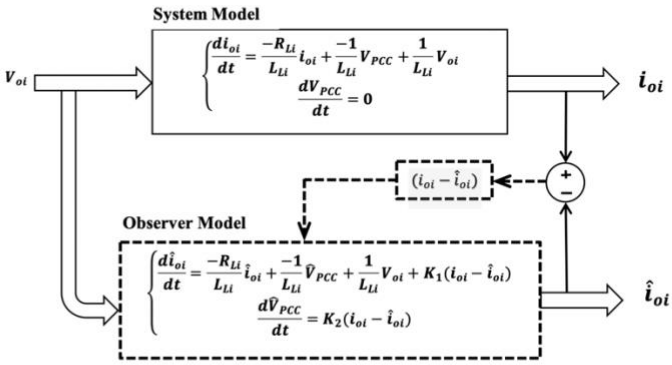


Fig. 6. Block diagram of Luenberger Observer

Here we consider that the DC bus voltage V_{PCC} changes very slowly compared with the load current; therefore, the voltage derivation is assumed equal to zero in (12).

$$\frac{d}{dt}\begin{bmatrix} i_{oi} \\ V_{PCC} \end{bmatrix} = \begin{bmatrix} \frac{-R_{Li}}{L_{Li}} & \frac{-1}{L_{Li}} \\ 0 & 0 \end{bmatrix}\begin{bmatrix} i_{oi} \\ V_{PCC} \end{bmatrix} + \begin{bmatrix} \frac{1}{L_{Li}} \\ 0 \end{bmatrix}[V_{oi} \quad 0] \quad (12)$$

where, $x(t) = [x_1 \quad x_2]^T = [i_{o1} \quad V_{PCC}]^T$ is state variables, $u(t) = [V_{oi} \quad 0]$ is the control input vector of the system and *y(t)* is the output vector of the system.

The observer model's state estimation equation can be defined as follows:

$$\frac{d}{dt}\hat{x}(t) = A\hat{x}(t) + Bu(t) + K\big(y(t) - \hat{y}(t)\big) \quad (13)$$

$$\hat{y}(t) = C\hat{x}(t) \quad (14)$$

Substituting (11) & (14) into (13) then:

$$\frac{d}{dt}\hat{x}(t) = (A - KC)\hat{x}(t) + Bu(t) + Ky(t) \qquad (15)$$

The observer model can be expressed as:

$$\begin{cases} \frac{d\hat{i}_{oi}}{dt} = \frac{-R_{Li}}{L_{Li}}\hat{i}_{oi} + \frac{-1}{L_{Li}}\hat{V}_{PCC} + \frac{1}{L_{Li}}V_{oi} + K_1(i_{oi} - \hat{i}_{oi}) \\ \frac{d\hat{V}_{PCC}}{dt} = K_2(i_{oi} - \hat{i}_{oi}) \end{cases} \qquad (16)$$

Thus, the state-space model becomes:

$$\frac{d}{dt}\begin{bmatrix}\hat{i}_{oi} \\ \hat{V}_{PCC}\end{bmatrix} = \begin{bmatrix}\frac{-R_{Li}}{L_{Li}} - K_1 & \frac{-1}{L_{Li}} \\ -K_2 & 0\end{bmatrix}\begin{bmatrix}\hat{i}_{oi} \\ \hat{V}_{PCC}\end{bmatrix} + \begin{bmatrix}\frac{1}{L_{Li}} \\ 0\end{bmatrix}\begin{bmatrix}V_{oi} & 0\end{bmatrix} + \begin{bmatrix}K_1 \\ K_2\end{bmatrix}\begin{bmatrix}i_{oi}\end{bmatrix} \qquad (17)$$

where, $\hat{x}(t) = [\hat{x}_1 \quad \hat{x}_2]^T = [\hat{\imath}_{o1} \quad \hat{V}_{PCC}]^T$ is the estimated state vector of the order of 2×1;

The estimated output vector of the system is given as:

$$\hat{y}(t) = \hat{i}_{oi}$$

The state estimation error of the system can be written as:

$$e(t) = x(t) - \hat{x}(t) \qquad (18)$$

The error $e(t)$ dynamics can be express as follows:

$$\frac{d}{dt}e(t) = (A - KC)e(t) \qquad (19)$$

To ensure the stability of the observer, the gain must be chosen in a manner that the real parts of the eigenvalues of the matrix $(A - KC)$ given bellow is negative.

$$A - KC = \begin{bmatrix}\frac{-R_{Li}}{L_{Li}} - K_1 & \frac{-1}{L_{Li}} \\ -K_2 & 0\end{bmatrix} \qquad (20)$$

Through reasonable configuration of pole position, the system will be gradually stabilized. The estimation will converge if the error tends to zero. Trial-and-error method used to determine the Luenberger observer gain in this research study.

5. Simulation Results

The studied system consists of an islanded DC Microgrid with two DG units interconnected to a common DC bus through unbalanced line impedances, as illustrated in Fig. 2. The simulation model was developed in MATLAB/Simulink to analyze load sharing between parallel DG units and assess voltage deviations from the nominal value. The results validate the proposed Luenberger observer–based control for accurate load sharing and PCC voltage regulation, comparing its performance with conventional droop control.

We assess system performance under three scenarios to test the proposed model. Scenario 1 applies conventional droop control to a DC microgrid with identical power ratings and line impedances, providing an ideal case to examine load variation effects under uniform line resistance. Scenario 2 maintains equal power ratings for both DG units but introduces unequal line impedances, with the second line impedance (RL2) set five times higher than the first (RL1), allowing the evaluation of conventional droop control under mismatched conditions. Finally, Scenario 3 validates the proposed control strategy under both unequal line impedances and load variations, maintaining the same impedance ratio as in Scenario 2, as shown in Table I.

The DC microgrid system parameters are summarized in Table I, while the control parameters are detailed in Table II. Both DG units have identical power ratings, and the DC load (PLoad) is connected at the PCC, varying across different time intervals as shown in Table I.

Table I. System parameters

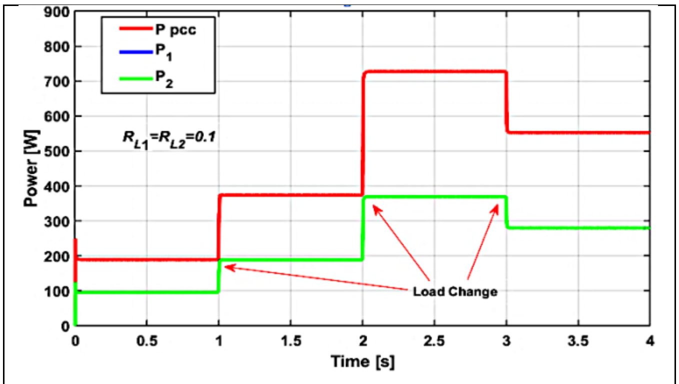
Parameters	*Symbols*	*Values*
Input DC Voltage	V_{dci}	36 V
Reference Voltage	V_{ref}	48 V
DC Boost Converter parameters	L_i	1000 µH
	C_i	1000 µF
	r_{si}	0.1 Ω
Switching frequency	f_{sw}	10000 Hz
DC bus capacitor	C_{bus}	3000 µF
Line Resistance	R_{L1}	0.1 Ω (All Scenario)
		0.3 Ω (Scenario 4)
	R_{L2}	0.5 Ω (All Scenario)
Load profile		
Load power at PCC	*(P_{Load})*	*Time*
	192 W	0 < t < 1s
	384 W	1s < t < 2s
	768 W	2s < t < 3s
	576 W	3s < t < 4s

Table II. Control parameters

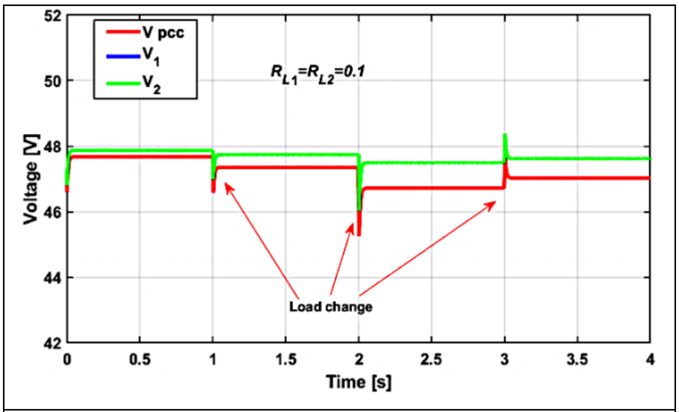
	Parameters	*Symbols*	*Values*
Voltage and Current control	*Voltage controller gains*	*Kp,v*	2
		Ki, v	450
	Current controller gains	*Kp, c*	10
		Ki, c	1000
Droop control	*Droop coefficient*	*d*	0.065
Luenberger Observer	*Observer gain*	K_1	3000
		K_2	3000

I. Scenario 1: DG units with identical power ratings and line impedances.

The conventional droop control results are presented in Fig. 7. Fig. 7(a) depicts the total power at the PCC alongside each DG unit's contribution, demonstrating coordinated operation under the test conditions. With equal line impedances ($R_{L1} = R_{L2} = 0.1$ Ω), both units share the load power equally. Fig. 7(b) illustrates the output voltages of each DG unit under conventional droop control, revealing that the PCC voltage on the DC bus deviates from its 48 V nominal value.



(a)



(b)

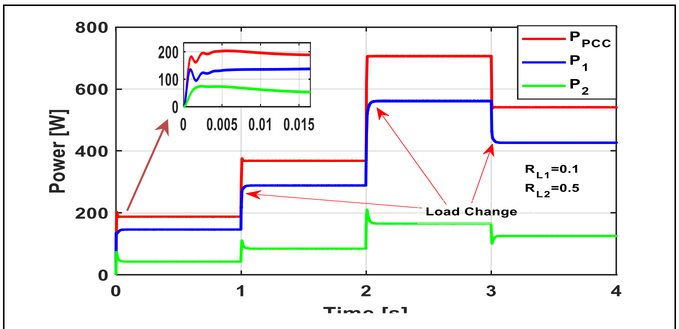
Fig. 7. Conventional droop control method: (a) Load power sharing between the two DG units and total load consumption. (b) Output voltage of each DG unit and PCC voltage at the DC bus.

Despite equal load sharing under varying demand, conventional droop control induces significant DC bus voltage deviations and transient fluctuations with load changes, as shown in Fig. 7 (b), revealing its inability to maintain stable voltage regulation and the need for a secondary control layer to correct these voltage deviations.

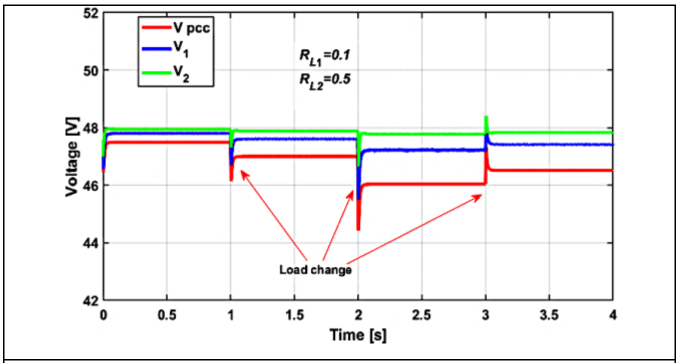
II. Scenario 2: DG units with identical power ratings and unequal line impedances.

This case analyzes the conventional droop control's power-sharing performance under line impedance mismatch and load variations, with both DGs using the same droop coefficient. Fig. 8 (a) shows total DC load consumption alongside each DG unit's contribution under conventional droop control. although load demand is met, unequal line impedances cause uneven power sharing, yielding suboptimal distribution. The Fig. 8 (b) illustrates the DC microgrid voltage profile under conventional control, showing DG2's output exceeding DG1's (i.e., Vo2>Vo1) due to its higher line impedance (R_{L2}= 0.5 Ω vs. R_{L1} = 0.1 Ω), which produces a larger voltage drop across the second line and an approximately 8.3% imbalance between the units.

The conventional control method induces DC bus voltage deviations and transient disturbances at startup and during load changes, causing the PCC voltage to stray from its 48 V nominal value with each load increment producing a noticeable drop. Additionally, its sensitivity to line impedance mismatches and dynamic loading prevents accurate power sharing between the two DERs.



(a)

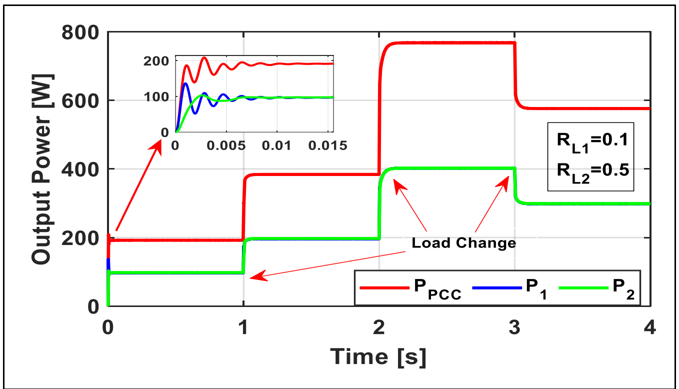


(b)

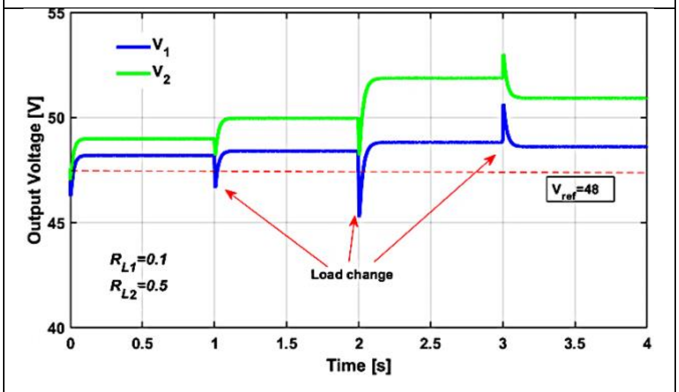
Fig. 8. Conventional Droop control methods (a) Load power sharing among the two DG units and total Load Power consumed (b) Output voltage of each DG unit and PCC voltage at the DC bus

III. Scenario 3: Identical DG power ratings with unequal line impedances under the proposed control method.

Fig. 9 demonstrates the performance of the proposed Luenberger observer–based control under unmatched line impedances and varying loads. As shown in Fig. 9 (a), the observer compensates for impedance disparities to maintain equal power sharing between the two DG units across all load conditions. In contrast to conventional droop control, which yields unequal output when line impedances differ, the proposed strategy reliably enforces balanced power contribution, fulfilling its primary objective of accurate load sharing.



(a)



(b)

Fig. 9. The Proposed control method (a) Load sharing among the two DG units and total power consumed b) Output voltages of the two DG units and the DC bus voltage of the load

Fig. 9 (b) show the PCC voltage, and each DG unit's output voltage; despite dynamic load changes, the proposed control holds the PCC voltage at its 48 V nominal value and keeps each

DG unit's voltage within allowable deviation limits, demonstrating robust voltage regulation under varying conditions.

Simulation results demonstrate that the Luenberger observer–based control achieves equal power sharing and maintains the PCC voltage at 48 V under unequal line impedances and dynamic load changes, outperforming conventional droop control in both accuracy and stability.

However, transient fluctuations in individual DG outputs and bus voltage during startup and load transitions persist, indicating the need for a secondary control layer to fully suppress these voltage disturbances and fully stabilize the DC bus and suppress transient effects.

6. Conclusions

This work introduces an enhanced control scheme based on the Luenberger observer technique for accurate load power sharing in an islanded DC microgrid, effectively addressing the challenges of unmatched line impedance and load variations. The proposed strategy, implemented locally in each DG unit, the observer estimates PCC voltage and compensates for unequal line conditions. Simulation results using MATLAB/Simulink confirmed that the proposed method outperforms conventional droop control by ensuring equal power sharing and maintaining the DC bus voltage near its nominal value across varying operating scenarios. These findings validate the method's robustness to impedance uncertainties and load disturbances. Further research is needed to extend the method to multi-DG configurations and optimize observer gain.

Data Availability Statement: Data available from the author upon request.

Acknowledgments: This research was partially supported by the Ethiopian Ministry of Education and the Embassy of France in Ethiopia, and the National Research Agency (ANR), LEAP RE "MiDiNA—Microgrids Development in North Africa - ANR-23-LERE-0002–01".

Conflicts of Interest: The authors declare no conflicts of interest

7. References

[1] G. Mirzaeva and D. Miller, "DC and AC Microgrids for Standalone Applications," *IEEE Trans Ind Appl*, vol. 59, no. 6, 2023, doi: 10.1109/TIA.2023.3299906.

[2] O. Azeem *et al.*, "A comprehensive review on integration challenges, optimization techniques and control strategies of hybrid ac/dc microgrid," *Applied Sciences (Switzerland)*, vol. 11, no. 14, 2021, doi: 10.3390/app11146242.

[3] I. S. Association, *IEEE 1547-2018. Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces*, no. February. 2018.

[4] Y. Han, X. Ning, L. Li, P. Yang, and F. Blaabjerg, "Droop coefficient correction control for power sharing and voltage restoration in hierarchical controlled DC microgrids," *International Journal of Electrical Power and Energy Systems*, vol. 133, 2021, doi: 10.1016/j.ijepes.2021.107277.

[5] M. Jafari, S. Peyghami, H. Mokhtari, and F. Blaabjerg, "Enhanced Frequency Droop Method for Decentralized Power Sharing Control in dc Microgrids," *IEEE J Emerg Sel Top Power Electron*, vol. 9, no. 2, 2021, doi: 10.1109/JESTPE.2020.2969144.

[6] W. Wang, X. Lei, B. Wei, K. He, and P. Yang, "Research on Adaptive Droop Control Strategy of DC Active Power and Voltage in DC Microgrid," in *2023 International Conference on Power Energy Systems and Applications, ICoPESA 2023*, 2023. doi: 10.1109/ICoPESA56898.2023.10140308.

[7] A. Calpbinici, E. Irmak, and E. Kabalci, "Distributed Hierarchical Control for Voltage Stability and Proportional Current Sharing in Island-Mode DC Microgrids," in *Proceedings - 2023 IEEE 5th Global Power, Energy and Communication Conference, GPECOM 2023*, 2023. doi: 10.1109/GPECOM58364.2023.10175733.

[8] H. Amiri, G. A. Markadeh, and N. M. Dehkordi, "Voltage Control and Load Sharing in a DC Islanded Microgrid based on Disturbance Observer," in *ICEE 2019 - 27th Iranian Conference on Electrical Engineering*, 2019. doi: 10.1109/IranianCEE.2019.8786488.

[9] R. K. Subroto, L. Ardhenta, and E. Maulana, "A novel of adaptive sliding mode controller with observer for DC/DC boost converters in photovoltaic system," in *Proceeding - 2017 5th International Conference on Electrical, Electronics and Information Engineering: Smart Innovations for Bridging Future Technologies, ICEEIE 2017*, 2017. doi: 10.1109/ICEEIE.2017.8328754.

[10] M. Tucci, S. Riverso, J. C. Vasquez, J. M. Guerrero, and G. Ferrari-Trecate, "A Decentralized Scalable Approach to Voltage Control of DC Islanded Microgrids," *IEEE Transactions on Control Systems Technology*, vol. 24, no. 6, pp. 1965–1979, Nov. 2016, doi: 10.1109/TCST.2016.2525001.

[11] F. Gao, R. Kang, J. Cao, and T. Yang, "Primary and secondary control in DC microgrids: a review," 2019. doi: 10.1007/s40565-018-0466-5.

[12] Y. Han, X. Ning, P. Yang, and L. Xu, "Review of Power Sharing, Voltage Restoration and Stabilization Techniques in Hierarchical Controlled DC Microgrids," *IEEE Access*, vol. 7, 2019, doi: 10.1109/ACCESS.2019.2946706.

[13] X. Lu, J. M. Guerrero, K. Sun, and J. C. Vasquez, "An improved droop control method for dc microgrids based on low bandwidth communication with dc bus voltage restoration and enhanced current sharing accuracy," *IEEE Trans Power Electron*, vol. 29, no. 4, 2014, doi: 10.1109/TPEL.2013.2266419.

[14] N. Mohammed, L. Callegaro, M. Ciobotaru, and J. M. Guerrero, "Accurate power sharing for islanded DC microgrids considering mismatched feeder resistances," *Appl Energy*, vol. 340, p. 121060, Jun. 2023, doi: 10.1016/j.apenergy.2023.121060.

[15] Y. Mi *et al.*, "A Power Sharing Strategy for Islanded DC Microgrid with Unmatched Line Impedance and Local Load," *Electric Power Systems Research*, vol. 192, 2021, doi: 10.1016/j.epsr.2020.106983.