

Sensitivity analysis of voltage limit in radial AC microgrids considering the loading condition and line length

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ABSTRACT

A sensitivity analysis of voltage compliance in radial AC microgrids linked to a low-voltage main grid is presented in this paper, with an emphasis on the combined effects of feeder length and load-generation balance. Three loading scenarios: demand exceeding generation, demand matching generation, and generation exceeding demand are used to apply a Newton-Raphson power flow algorithm to a radial network with five distributed generators (DGs) and five loads. Feeder lengths, both long and short, are assessed for every condition. The findings indicate that voltage falls below the IEEE 1547 lower limit of 207 V when demand exceeds generation with long feeders (200 m line sections), falling as low as 166.9 V at the farthest load, potentially causing load shedding and DG disconnection. On the other hand, even in extended feeder situations, voltages stay within the acceptable $\pm 10\%$ range when generation matches or surpasses demand. These results offer useful recommendations for feeder design and DG placement in grid-connected microgrids, as well as quantitative insights into worst-case operation scenarios.

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1. INTRODUCTION

The transition from conventional distribution systems to microgrid-based architectures is accelerated due to the growing utilization of distributed energy resources (DERs) [1]-[4]. Microgrids, particularly radial AC configurations, have attained massive attention due to their agreement with existing low-voltage distribution networks and their potential to strengthen system resilience, performance, and flexibility [5], [6]. However, ensuring a voltage boundary within permissible limits in grid-connected microgrids remains a persistent challenge, especially when the loading conditions are varied. Voltage regulation in radial AC microgrids is greatly impacted by network operating conditions and feeder characteristics [7]-[9]. Feeder impedance may increase due to longer distribution lines, resulting in more noticeable voltage drops or rises [10], [11]. Similarly, bus voltages are directly impacted by the balance between generation and demand, possibly pushing them beyond the acceptable boundary set by international standards like IEEE 1547 and EN 50160 [12], [13]. These restrictions are critical in low-voltage microgrids, where there is more sensitivity to load and line fluctuations and a comparatively high R/X ratio.

Although optimization methods, control systems, stability assessments, real and reactive power sharing of AC microgrids have been the subject of several research [14]-[18], the combined impact of line lengths and loading circumstances on the allowable voltage border in AC microgrids has received

comparatively little attention in previous studies. Hence, these factors motivate the need for a systematic evaluation of how network loading and line lengths interact to specify the range of safe operating voltages in realistic microgrid architectures. Most existing works consider these factors separately or examine them in the context of optimization frameworks, sizing the distributed generator (DG), voltage compensators installment, without clearly quantifying their influence on the operational feasibility of radial AC microgrids. For example, Muttaqi *et al.* [19] addresses the issues of improving the network voltage profile in distribution system by installing a DG of the most suitable size, at a suitable location. Voltage stability analysis is carried out in [20] where two novel voltage stability indices based on real-time measured voltage data are considered. Ghaffari and Aly [21], imperialist competitive algorithm (ICA) and genetic algorithm (GA), as well as their hybrid application are used to significantly enhance the voltage regulation in microgrids. Passive utilization of voltage control is tested in [22] on a sample section of radial distribution network to reduce the impact on system voltages and overcome the distribution voltage rise barrier such that more DGs can connect.

The explicit sensitivity of voltage boundaries to the relationship between feeder length and load-generation balance has not been extensively evaluated, despite the fact that previous research has addressed voltage regulation through optimization frameworks [19], control techniques [16], and DG sizing [21]. The majority of earlier studies either tackle these elements independently or incorporate them into more general optimization problems without separating their individual and combined effects. This research closes this gap by:

- Measuring the combined effects of load-generation balance (demand $>$, $=$, $<$ generation) and feeder length (short versus long) on voltage compliance.
- Determining the essential thresholds under IEEE 1547 limits when voltage breaches take place.
- Supplying a framework for power flow that is repeatable and has clear parameters to direct microgrid design.

In this paper, a power flow algorithm is implemented based on the well-known Newton–Raphson method and is applied to a network system comprising radial AC microgrid connected to a low-voltage main grid. Three network loading conditions are investigated: i) demand exceeding generation, ii) demand matches generation, and iii) generation exceeding demand. For each condition, both long and shorter feeder lengths are presumed to examine their impact on the DG and load voltages. The results prove that the most critical condition arises when the demand exceeds the generation, as the voltages of DGs and loads deviate beyond the acceptable voltage range. By contrast, when the demand meets or exceeds the generation, the system voltages operate within the permissible voltage boundaries even under variations in feeder or line lengths. Thus, the contributions of this work can be summarized as follows:

- Quantifying how feeder length (short versus long) and load-generation balance jointly affect voltage compliance in grid-connected radial AC microgrids.
- Identifying critical voltage thresholds under IEEE 1547 limits, including specific voltage values where violations trigger DG disconnection or load shedding.
- Providing a reproducible power flow framework with explicit parameters (convergence criteria, line data, and bus specifications) to guide microgrid planning and feeder design.

The remainder of this paper is organized as follows: section 2 presents the configuration of a radial AC microgrid. Section 3 describes the power flow algorithm including the analysis and the flowchart. Section 4 discusses the results including the previously-mentioned three conditions. Finally, section 5 concludes the paper and outlines potential directions for future research.

2. CONFIGURATION OF THE AC MICROGRID

The network system includes an AC microgrid connected to a fixed AC main grid via point of common coupling (PCC). The AC microgrid contains 5 DG systems and 5 local loads. The DG is represented as a PQ bus where the known quantities are the real and reactive power and the unknown quantities are the voltage magnitude and phase angle. The same logic is extended to the local loads. However, the difference here is that the real and reactive power values of the DG are specified as $+ve$ values, contrary to the local loads which are specified as $-ve$ values. The main grid is considered the slack bus (reference) with a fixed voltage and frequency. Three-line sections are forming the network connections; in which line x , L_x is the branch connecting two nodes, line Y , L_Y connects the DG, or load to the system node. These lines will be varied in order to test the AC microgrid performance and will be discussed further in the section of results. The resistance and reactance of all line sections are adjusted to $R = 0.722 \Omega/\text{km}$ and $X = 0.086 \Omega/\text{km}$ which reflect near practice values of low voltage lines in the distribution network. The network system under study which covers the info mentioned above is depicted in Figure 1 where the dotted red line is forming the AC microgrid structure.

A power flow algorithm will be applied to the network system under study taking into consideration different loading conditions for the DGs and local loads, as well as short and long line lengths. In this way, the voltage of DGs and local loads will judge either if the DG will remain grid-connected and if the local load will

be shed or still fed by either the DG or the main grid. Thus, the performance of the AC microgrid will be directly influenced by the loading status and the line sections length discussed before.

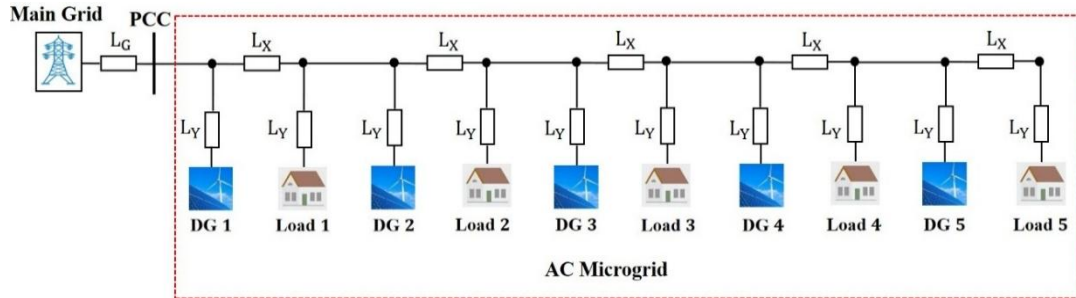


Figure 1. Network system under study

3. POWER FLOW ALGORITHM

Extracting the unknown quantities of the network system under study necessitates building a power flow algorithm to solve the non-linear system of equations introduced by the system. Newton–Raphson method is used to solve such a nonlinear system due to its better convergence speed relative to other load flow methods [23]. Another advantage is that whatever the number of buses involved, the number of iterations needed to reach a solution is independent. The numerical analysis and flowchart of the algorithm is explained in subsequent sections.

3.1. Numerical analysis

The real and reactive power for a typical power network considering Newton–Raphson method is given as (1) and (2):

$$P_i = \sum_{j=1}^n |V_i| |V_j| |Y_{ij}| \cos(\theta_{ij} - \delta_i + \delta_j) \quad (1)$$

$$Q_i = \sum_{j=1}^n |V_i| |V_j| |Y_{ij}| \sin(\theta_{ij} - \delta_i + \delta_j) \quad (2)$$

In (1) and (2) results in a nonlinear system of equations. Thus, partial derivatives of these equations are performed to provide the Jacobian matrix elements in which linearized relationship between small changes in voltage magnitude and phase angle is obtained. Thus, the equation is introduced in matrix form as (3):

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_3 \\ J_2 & J_4 \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta |V| \end{bmatrix} \quad (3)$$

where, $J_1 \dots J_4$ represents the elements of the Jacobian matrix. More analytical details can be found in [24], [25]. The power residuals (mismatches) which are the difference between the scheduled and calculated power values are introduced as (4) and (5):

$$\Delta P_i^{(k)} = P_i^{sch} - P_i^{(k)} \quad (4)$$

$$\Delta Q_i^{(k)} = Q_i^{sch} - Q_i^{(k)} \quad (5)$$

where, k is the iteration number.

The updated estimates for each node/bus voltage in the AC microgrid are then given as (6):

$$\delta^{(k+1)} = \delta_i^{(k)} + \Delta \delta_i^{(k)} \quad (6)$$

$$|V^{(k+1)}| = |V_i^{(k)}| + \Delta |V_i^{(k)}| \quad (7)$$

3.2. Flowchart of the algorithm

The flowchart of the power flow algorithm which employs the well-known Newton–Raphson method is presented in Figure 2. This flowchart is a reflection of the pseudo code implemented in MATLAB environment taking into consideration all the needed data of the AC microgrid and main grid. The algorithm begins with loading the parameters of the local loads and the DGs at each node/bus in addition to the data of the line sections mentioned in the previous subsection. It is worth mentioning that the length of line sections

and the loading condition of the DGs and loads are specified according to each condition, which will be discussed in the next section. The main grid is identified as the slack or reference node/bus where the voltage magnitude and phase angle are specified as $230\angle 0^\circ$ V. A tolerance value for the power residuals and a maximum iteration number are set for the sake of algorithm convergence. As the system data are loaded, the Y-bus matrix of the system is extracted to allow execution of the power flow solution. The power flow is initialized at iteration $k = 1$ where the calculated values of P_i and Q_i in (1) and (2) is accomplished. Subsequently, the elements of the Jacobian matrix and system linearization is established according to (3). In this way, the updated variables of the voltage magnitude and phase angle are extracted according to (6) and (7). Once the specified tolerance for the power residuals in (4) and (5) or the maximum iterations are reached; that means the algorithm is converged to a solution. Thus, the voltages of all system nodes and the power transferred to the main grid via PCC can be obtained.

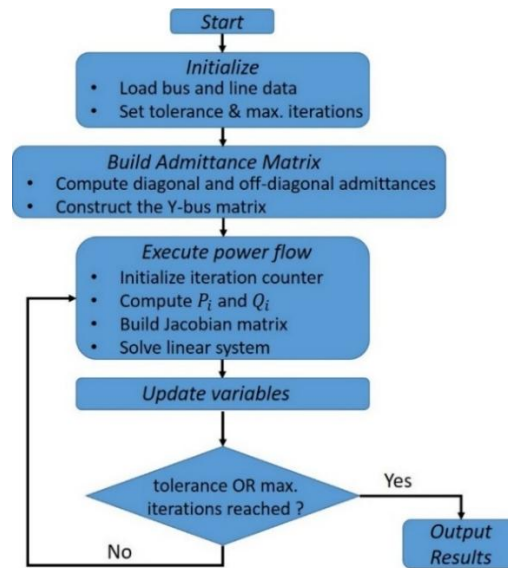


Figure 2. Flowchart of the proposed power flow algorithm

3.3. Algorithm setup and convergence criterion

The Newton–Raphson power flow algorithm was implemented in MATLAB with the following parameters:

- Tolerance: 10^{-6} for maximum power mismatch.
- Maximum iterations: 10^3 .
- Initialization: flat start ($1\angle 0^\circ$ for all PQ buses).
- System parameters: main grid (slack bus) set to $230\angle 0^\circ$ Vrms.

The operational mode of DG inverters without reactive power regulation was reflected by modelling all DGs as PQ buses with just active power injection. Constant active power consumption was used to model loads. Reactive power and power factor issues are mentioned as expansions for future work; this simplification was used to isolate the impacts of active power balance on voltage behaviour. For low-voltage distribution lines, line resistance and reactance were set to $R = 0.722 \Omega/\text{km}$ and $X = 0.086 \Omega/\text{km}$. Section 4 specifies the line lengths for both short and long configurations.

4. RESULTS AND DISCUSSION

In this section, the network system under study presented previously in Figure 1 is tested considering three loading conditions of the AC microgrid. For each loading condition, only active power is considered to be injected by the DG to mimic the behavior of PV systems as they don't inject reactive power. The local loads are also considered to consume only active power. Short and long line lengths are considered in each loading condition to examine the performance of the AC microgrid, particularly the voltage magnitude at each DG and local load. The power flow algorithm considers the maximum power mismatch or the tolerance as 10^{-6} and the maximum number of iterations as 10^3 . Thus, the three conditions are performed as follows: i) Case 1: Demand > Generation; ii) Case 2: Generation = Demand; iii) and Case 3: Generation > Demand.

First, when the demand is greater than the generation, two sets are considered for the line section lengths: long and short. When they considered long, this will result in noticeable impedance and resistive losses. However, for shorter line lengths, the voltage drop will be minimized, reducing the resistive losses. Hence, for long lengths, L_X length is adjusted to 200 m, while L_Y length is adjusted to 100 m. For short lengths, L_X length is reduced to 100 m, while L_Y length is reduced to 50 m. L_G is fixed always at 100 m length in all cases. Either if the length of lines is long or short, each load is considered to consume 5 kW and each DG is considered to produce only 3 kW. No reactive power generation or consumption is considered. Second, when the demand matches the generation, the line lengths are considered as the previous case too. Here, the generation and demand are perfectly matched where each load is considered to consume 5 kW and each DG is considered to produce only 5 kW. No power is needed from the main grid to compensate the shortage. Long and shorter line lengths are presumed as in case 1. Hence, again for long lengths, L_X length is adjusted to 200 m, while L_Y length is adjusted to 100 m. For short lengths, L_X length is reduced to 100 m, while L_Y length is reduced to 50 m. L_G is fixed always at 100 m length in all cases. Third, when the generation exceeds the demand, the line lengths are considered as in the previous two cases for the long and short line sections. Here, the generation is made greater than the demand resulting in reverse power flow. Each load is considered to consume 3 kW and each DG is considered to produce only 5 kW. Similar to other cases, L_X length is adjusted to 200 m, while L_Y length is adjusted to 100 m for long lines. For short lengths, L_X length is reduced to 100 m, while L_Y length is reduced to 50 m. L_G is fixed always at 100 m length in all cases.

Table 1 shows the RMS voltage at each bus for all loading conditions considering long and shorter line lengths. When the demand exceeds generation, the RMS voltage for long line lengths is significantly reduced moving from the main grid (slack bus) to the farthest DG or load. This behavior is consistent with voltage drop analyses in radial distribution systems, where cumulative feeder impedance causes progressive voltage decay [20], [24]. However, the reduction rate of RMS voltage for shorter lines is apparently less in comparison to long line lengths either for the DGs or the loads, as reduced impedance minimizes the voltage drop per section [11]. However, when the demand matches generation, the RMS voltage for long and shorter line lengths are also reduced. The voltage drop for long line lengths is seen to be higher than the shorter line lengths. However, it can be seen that the voltage levels remain within acceptable limits according to IEEE 1547-2003 standard where the main grid experiences minimal loading. This finding aligns with previous studies showing that balanced power flow minimizes voltage deviations and reduces the need for reactive compensation [16], [22]. All DGs and loads are functioning efficiently without overvoltage or under voltage risk. This confirms that the balanced local generation and consumption enhances the overall AC microgrid performance.

Table 1. RMS voltage at each bus considering all 3 loading conditions for long and shorter line lengths

Bus	V_{rms} for long lines	V_{rms} for shorter lines	V_{rms} for long lines	V_{rms} for shorter lines	V_{rms} for long lines	V_{rms} for shorter lines
	Demand>Gen	Demand>Gen	Demand=Gen	Demand=Gen	Gen>Demand	Gen>Demand
Grid	230.00	230.00	230.00	230.00	230.00	230.00
DG 1	226.76	226.94	231.33	230.68	234.50	233.80
DG 2	209.21	219.47	226.99	228.80	241.58	237.53
DG 3	194.59	213.34	222.82	226.96	246.38	240.07
DG 4	183.14	208.61	218.82	225.17	248.93	241.44
DG 5	175.07	205.29	215.01	223.41	249.26	241.63
Load 1	213.37	220.97	224.13	227.25	234.45	233.86
Load 2	196.90	214.10	219.78	225.38	240.48	237.02
Load 3	183.50	208.61	215.60	223.54	244.21	238.99
Load 4	173.43	204.54	211.60	221.74	245.67	239.78
Load 5	166.93	201.91	207.79	219.98	244.87	239.38

Finally, when the generation exceeds the demand, note that a voltage rise phenomenon is noticed here due to the reverse power flow from the AC microgrid back to the main grid. This voltage rise is a well-documented effect in distribution systems with high DG penetration, where excess power injected upstream causes voltage elevation across feeder impedances [19], [25]. The RMS voltage for long and shorter line lengths as noticed is increased moving from the main grid (slack bus) to the farthest DG or local load. The voltage rise for long line lengths is seen to be higher than the shorter line lengths. However, notice how the voltage levels remain within permissible voltage range according to IEEE 1547-2003 standard. All DGs and loads are functioning efficiently with overvoltage risk, especially the farthest DG 5. Thus, despite reverse power flow, the system remains stable and converges quickly, confirming the robust performance of the AC microgrid during reverse power flow conditions.

Figure 3 depicts the relationship between RMS voltage of DGs/loads versus the cumulative line length when the demand exceeds generation in which Figures 3(a) and (b) reflect long and shorter line lengths, respectively. The cumulative line length is simply the cumulative distance between each DG/load and the main grid. It is an indicator which shows how the RMS voltage of the DG/load is affected as long as the distance from

the main grid is varied. It's obvious from Figure 3(a) that the RMS voltage is decreasing either for the DGs and loads when the cumulative line length is increased. According to IEEE standard for interconnecting distributed resources with electric power systems (IEEE 1547-2003 standard), the permissible voltage limits in low-voltage distribution network should be between $\pm 10\%$ of the network voltage which corresponds to ($207 V_{RMS} \leq V \leq 253 V_{RMS}$) such that the DG remains grid-connected. Based on this, only DG 1 and DG 2 can remain grid-connected and the others may disconnect to operate in islanded mode. Besides, load 1 can remain grid-connected and the other loads should be shed off as they deviate beyond the permissible voltage limits. This scenario demonstrates significant voltage violations, indicating that without reinforcement or compensation, the interconnection may not be feasible. As a result, the main grid becomes heavily loaded to maintain system balance, which can strain system stability. The RMS voltage in Figure 3(b) is decreasing too. However, it can be seen that they remain higher than the previous case for long lines. For example, the final load voltage is 201.91 V while it was 166.93 V in the long lines case. Thus, DG1-DG4 can remain grid-connected as they oscillate within permissible voltage limits and DG5 may disconnect and operate in islanded mode. Besides, Load 1-Load 3 may still be supplied by the DGs while Load 4 and 5 may shed off. This confirms the benefit of shorter lines in reducing both the voltage drop and line losses when the demand is greater than the generation of the DG units.

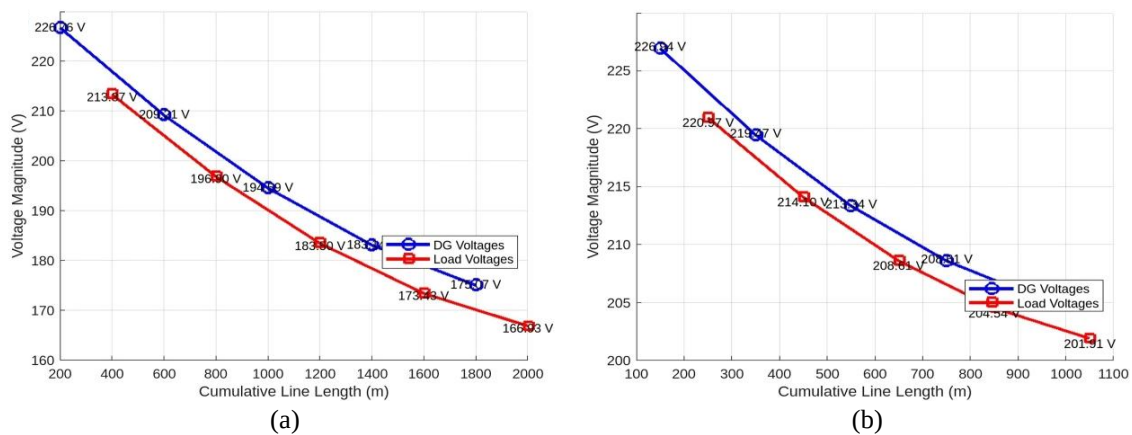


Figure 3. Relationship between RMS voltage of DGs/loads versus the cumulative line length when the demand exceeds generation; (a) long lines and (b) shorter lines

The voltage drop observed in long feeders (Case 1) is attributed to the cumulative impedance along the line sections. With $L_X = 200 \text{ m}$ and $L_Y = 100 \text{ m}$, the total resistance per branch reaches approximately $R = 0.216 \Omega/\text{km}$, causing a voltage drop proportional to the current drawn by downstream loads. When demand exceeds generation, the main grid supplies the deficit, increasing current flow and exacerbating the voltage drop along the feeder. This explains why the farthest DG5 and Load 5 experience the most severe violations, with voltages dropping to 175.07 V and 166.93 V respectively under long-line conditions.

Conversely, the voltage rise phenomenon in Case 3 (generation exceeding demand) occurs when local generation exceeds consumption, causing power to flow from the microgrid toward the main grid. This reverse current creates a voltage rise across feeder impedances, with the magnitude of rise proportional to the distance from the PCC. Although voltages in Case 3 remain within IEEE 1547 limits (below 253 V), the trend indicates that further increases in generation or feeder length could push voltages above the upper bound, consistent with reverse power flow analyses reported in the literature [13], [16].

Figure 4 presents the relationship between RMS voltage of DGs/loads versus the cumulative line length when the demand matches generation in which Figures 4(a) and (b) reflect long and shorter line lengths, respectively. long and shorter line lengths when demand matches generation. Notice how the RMS voltage is decreasing either for the DGs and loads when the cumulative line length is increased. All DGs and loads can remain grid-connected either for long or shorter line lengths according to the IEEE 1547-2003 standard. This makes this interconnection optimal since very small voltage drops occurred. As a result, the AC microgrid maintain system balance, which can improve the system stability. Figure 5 also depicts the relationship between RMS voltage of DGs/loads versus the cumulative line length when the generation exceeds demand in which Figures 5(a) and (b) reflect long and shorter line lengths, respectively. It can be seen that the RMS voltage is increasing either for the DGs and loads when the cumulative line length is increased. This voltage rise occurs due to the reverse power flow. However, it is notable that the existed overvoltage did not cause the voltage of DGs and loads to operate beyond the acceptable limits either if the line lengths are long or shorter.

Consequently, according to the IEEE 1547-2003 standard, they can still operate in grid-connected mode and the DGs can still transfer the excess power to the main grid.

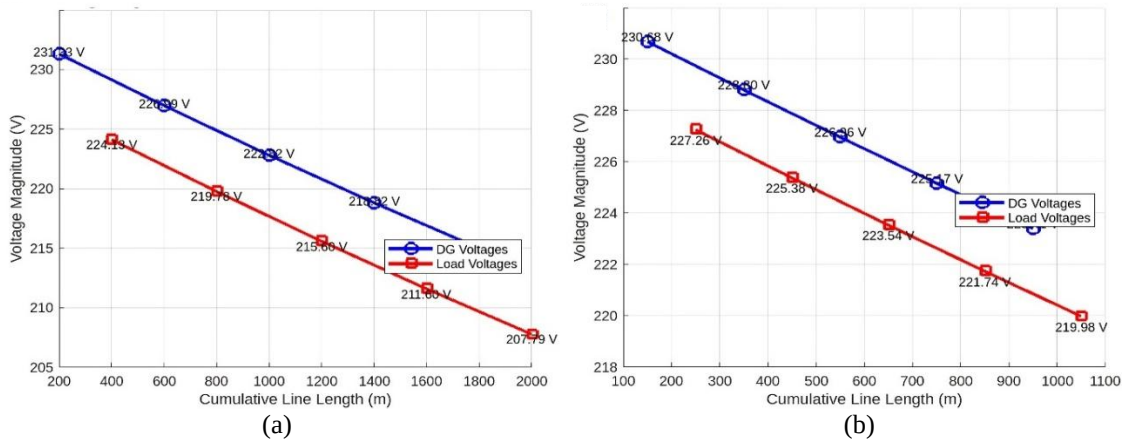


Figure 4. Relationship between RMS voltage of DGs/loads versus the cumulative line length when the demand matches generation; (a) long lines and (b) shorter lines

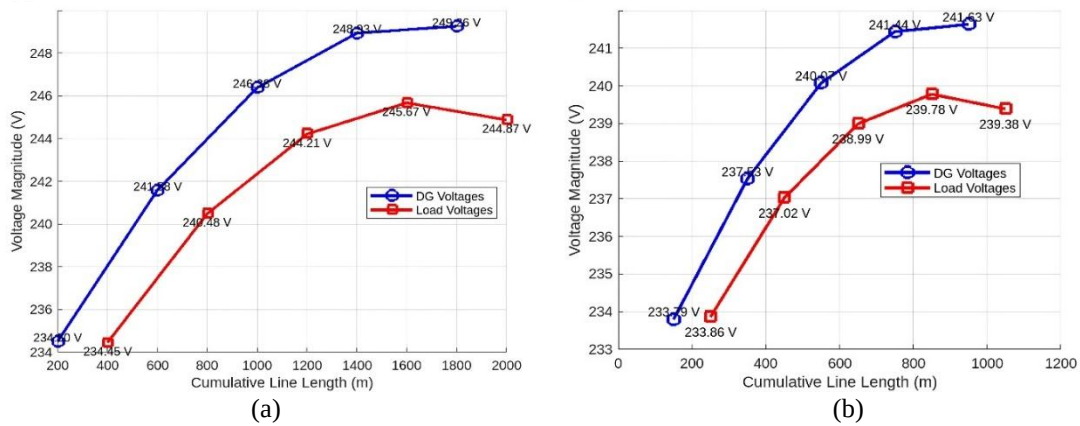


Figure 5. Relationship between RMS voltage of DGs/loads versus the cumulative line length when the generation exceeds demand; (a) long lines and (b) shorter lines

The practical implications for microgrid planning in response to the sensitivity analysis discussed above can be summarized as follows:

- DG placement: locating DGs closer to loads or at the far end of long feeders can mitigate voltage drops during demand-dominated conditions. In Case 1, moving DGs downstream reduced the voltage drop at Load 5 by approximately 8 V compared to upstream placement scenarios (based on comparative simulations not shown for brevity).
- Feeder design: shorter feeders (≤ 100 m per section) significantly reduces voltage violations. In Case 1, reducing L_X from 200 m to 100 m and L_Y from 100 m to 50 m improved the minimum load voltage from 166.93 V to 201.91 V—a 21% improvement. This suggests that compact microgrid layouts are preferable for voltage stability when demand exceeds generation.
- Control strategies: when demand exceeds generation by more than 40% (as in Case 1, where 5 kW loads exceed 3 kW DG output), active voltage control or reactive power support may be necessary to maintain compliance. Modern inverter-based DGs can provide reactive power support even during active power injection [10], [16], which could mitigate voltage drops without requiring feeder redesign.
- Operational limits: for system operators, the results define safe operating envelopes. In microgrids with long feeders, the generation-to-demand ratio should be maintained above 0.6 to avoid voltage violations below the IEEE 1547 lower bound of 207 V.

5. CONCLUSION

Using Newton-Raphson power flow analysis, this study measured the sensitivity of voltage compliance in radial AC microgrids to feeder length and load-generation balance. The primary contributions are: i) quantitative voltage limits: voltages fell to 166.9 V—29% below the IEEE 1547 lower limit—when demand exceeded generation with long lines (200 m sections), indicating that such configurations need active regulation or strengthening, ii) safe operating circumstances: voltages stayed within $\pm 10\%$ of nominal (207–253 V) even under lengthy feeder situations where generation met or exceeded demand, demonstrating that balanced power flow improves voltage stability, iii) feeder length sensitivity: in demand-dominated scenarios, shorter feeders (100 m sections) reduced voltage dips by up to 20%, underscoring the need of compact microgrid design, and iv) limitations: only active power and steady-state conditions were taken into account in this investigation. Islanded operation, transient events, and reactive power dynamics were not modelled.

Future research will expand this framework to include: i) reactive power regulation from inverter-based distributed generation (DGs), ii) dynamic simulations that capture load variations and fault conditions, iii) validation using real-world actual microgrid data, building on existing constraints, and iv) the effect of varying R/X ratio on the voltage of DGs and loads.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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Rafat Aljarrah		✓				✓		✓	✓	✓	✓	✓		

C : Conceptualization

M : Methodology

So : Software

Va : Validation

Fo : Formal analysis

I : Investigation

R : Resources

D : Data Curation

O : Writing - Original Draft

E : Writing - Review & Editing

Vi : Visualization

Su : Supervision

P : Project administration

Fu : Funding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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