Technical Impacts of Photovoltaic Distributed Generation on a Rural Feeder: A Multi-Scenario OpenDSS Analysis

Pedro Ricardo Nery Nunes Silva[1,2*], Leonardo Jaime Machado Simões[2], Gustavo Tavares Pereira dos Santos[2], Danilo Pinchemel Cardoso Filho[2], Thamiles Rodrigues de Melo[1], Rodrigo Santiago Coelho[1]

[1] *SENAI CIMATEC University, Graduate Program in Industrial Management and Technology (PPG GETEC), Salvador, Bahia, Brazil*

[2] *SENAI CIMATEC, Power Generation, Transmission and Distribution Department, Salvador, Bahia, Brazil*

**Corresponding author: SENAI CIMATEC; Av. Orlando Gomes, nº 1845, Piatã, CEP: 41650-010; pedro.nunes@fieb.org.br*

Abstract: The integration of distributed generators into power systems has notable impacts on the behavior of electrical variables, especially due to bidirectional power flow and component overloading. In this context, the evaluation of distributed generation penetration levels is important to enhance the operation of distribution networks, which includes the investigation of power quality limits. This research proposes the study of a real rural distribution feeder, located in Brazil's Northeast, in the presence of photovoltaic micro distributed generators. The OpenDSS software was utilized to model the system and to simulate three different operational conditions. These scenarios are then compared to verify the feeder's behavior in terms of voltage deviation, reverse power flow, and transformer overloading.

Keywords: Distributed Generation; Rural Distribution Feeder; Reverse Power Flow; Photovoltaic Solar Generation.

1.Introduction

Electric Power Systems (EPS) are undergoing significant transitions in their energy, operational, and institutional structures. Historically, their expansion has been geared toward operating in unidirectional flows, with power plants based on rotating machines and distant from passive loads, such as hydroelectric and thermoelectric plants.

However, the use of renewable sources, mainly in distribution networks, has been changing this traditional architecture, bringing about the decentralization of generation by the insertion of distributed energy resources (DERs), such as photovoltaic systems, hydroelectric plants, and wind generators connected directly to the distribution network. This new configuration allows the exploitation of bidirectional energy flow in some circumstances, breaking with the conventional paradigm in the electricity sector[1].

Following the global trend, Brazil has seen continuous increases in the use and production of renewable energy. According to the 2025 National Energy Balance, the Brazilian electricity matrix is composed of 88.2% renewable sources, having the fastest growing of the solar photovoltaic energy between 2023 and 2024, with 39.6% in generation and 28.1% in installed capacity [2].

Solar photovoltaic energy is predominant in Distributed Generation (DG), accounting for 97% of production. One of the main factors for this prominence is the regulatory consolidation brought about by Law No. 14,300/2022, the legal framework for Micro and Mini Distributed Generation (MMDG). Proof of this is the 36.6% growth in installed capacity in MMDG between 2023 and 2024 [2], [3].

However, the massive growth of MMDG leads to increased complexity in the operation of electrical systems. Originally designed to operate with centralized generation, distribution networks filled with DG can present a number of technical and operational challenges that affect their stability, quality, and safety. This scenario is driven by the rapid expansion of photovoltaic generation, which introduces new variables into grid management. Among these impacts, the intermittency of this type of generation source stands out, in addition to overvoltage and reverse flow [4], [5].

These challenges are especially pronounced in rural distribution networks. Such networks are characterized by their large size, predominantly radial topology, and low load density. This configuration makes them inherently more susceptible to voltage variations. Power injection by Distributed Microgeneration (MicroDG), even on a small scale, can easily reverse the power flow and cause more severe voltage elevations along the extensive feeders. Therefore, analyzing the impacts of MicroDG on these specific systems is crucial to ensure the quality of supply and the safe integration of new generators [6].

Thus, this article aims to analyze the technical impacts of inserting solar photovoltaic MicroDG into a rural distribution network using specialized tools and a multi-scenario methodology.

Section 2 details this methodology, presenting the logical flow and the assumptions and tools defined for performing the simulations. Section 3 addresses and shows the main results of the impact analysis of solar photovoltaic DG and the main discussions about it. Finally, Section 4 shows the conclusions and final considerations regarding the studies carried out.

2.Methodology

This section aims to define the scope and assumptions established for simulating the impacts of solar photovoltaic MicroDG on distribution networks. In addition, it describes the logical flow of the simulations and the scenarios defined. Section 2.1 presents the generalized methodology, while Section 2.2 describes the tools and simulation environment used to apply the methods.

2.1. Generalized approach

To assess the impact of solar photovoltaic MicroDG on distribution networks, we propose using network models based on real rural feeders. The electrical data from the model must be converted to the standard established by the power flow calculation software.

The simulations should cover a one-year period, with hourly sampling and multiple DG injection scenarios. Load curves with seasonal characteristics and local irradiance data are required as input data.

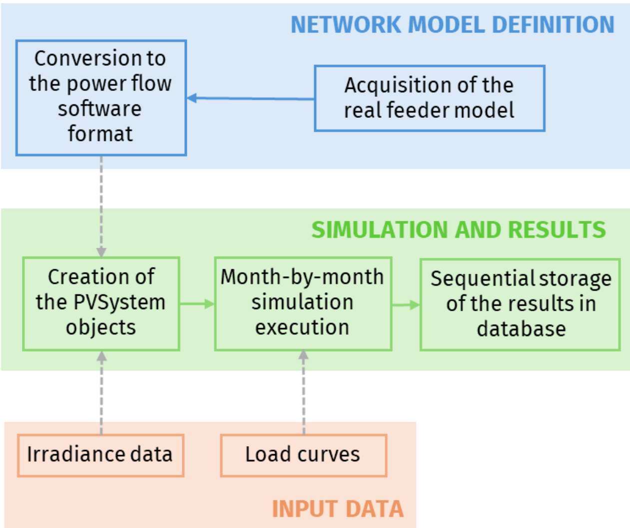
Thus, the logical flow of the simulations for each of the scenarios will proceed in steps as follows:

- Step 1: Creation of objects representing solar photovoltaic MicroDG systems in the grid model, with an installed capacity of 75 kW, which receive the irradiance input data to obtain the solar photovoltaic generation for each moment in time;

- Step 2: Execution of simulations month by month, applying the seasonal load curve and calculating the power flow of the entire system at each moment in time;
- Step 3: Sequential storage of the results obtained (i.e., power balance, voltage profiles) in auxiliary databases.

In summary, Figure 1 shows the generalized flowchart representing the methodology for simulating the impacts of MicroDGs on distribution networks.

Figure 1. Generalized methodology for simulating the impacts of MicroDGs on distribution networks



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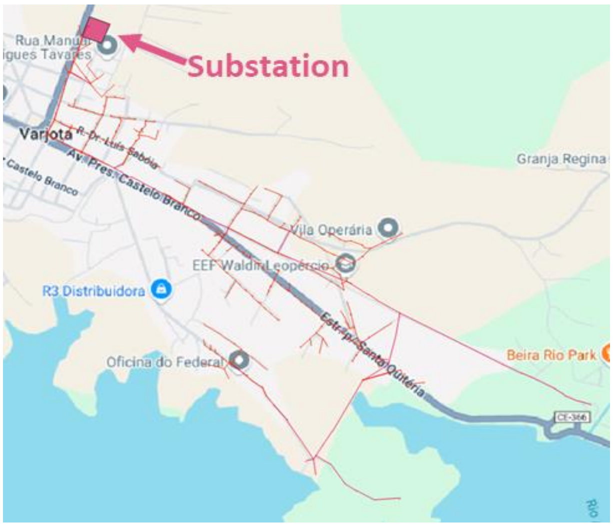
2.2. Simulation tools and environment

To apply the methodology, a real network model was used, extracted from ANEEL's Geographic Database (BDGD). In accordance with the assumptions established in the previous subtopic, the ARU01Y8 model was chosen, from the energy distributor Enel in the state of Ceará, Brazil, located in the municipality of Varjota [7]. Figure 2 shows the geographical extent of the feeder.

Figure 2. Actual rural distribution feeder.



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The power flow calculation software chosen was OpenDSS, due to the existence of tools that perform the conversion of BDGD network models in an automated manner. To perform this conversion, the Python library *bdgd2opendss* was used [8], [9].

The simulation scenarios were characterized based on different levels of solar photovoltaic MicroDG penetration. The installed power of the plants for each scenario was sized according to the total demand of the network, resulting in three case studies: 1) low penetration and marginal impact on the system; 2) intermediate penetration; and 3) high penetration, designed to cause severe impacts on the feeder. Table 1 quantifies the operating conditions of the simulation.

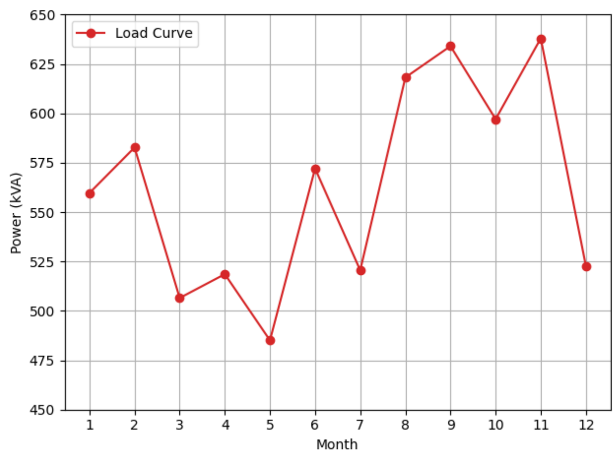
Table 1. Definition of Simulation Scenarios

Scenario	Penetration Level	Number of DGs	Installed Capacity (kW)
20 DG	High	20	1500
15 DG	Intermediate	15	1125
10 DG	Low	5	375

As defined in Figure 1, scenario simulations require two main sets of input data: load curves and irradiance.

The load curves applied were imported from the BDGD. The database provides characteristic consumption profiles for typical working days of each month of the year, reflecting seasonal variations in demand. For the annual simulation, a representative load curve was used for each month of the year. Figure 3 shows the average monthly load characteristic.

Figure 3. Monthly system load curve.



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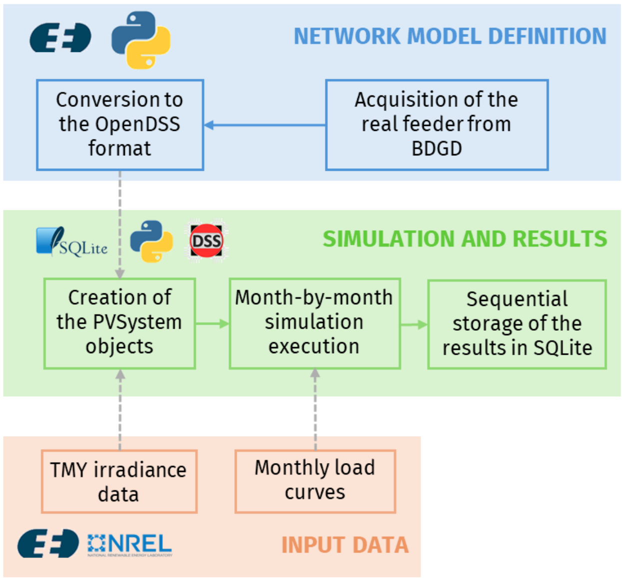
The irradiance data were extracted from the National Solar Radiation Database (NSRDB) belonging to the National Renewable Energy Laboratory (NREL). This is an hourly database referring to Global Horizontal Irradiance (GHI) for the locality of Varjota. The horizon covered refers to a Typical Meteorological Year (TMY), a methodology developed by NREL to consider the historical characteristics of irradiance in a single year [10], [11].

Thus, the logical flow per scenario for the application of the generalized methodology developed in the previous subsection was as follows:

- Step 1: OpenDSS PVSystem objects were created to calculate solar photovoltaic generation over time based on irradiance input data. Each system was configured with a 75 kW power limit, a unity power factor (PF=1), an efficiency curve, and a fixed operating temperature of 25°C;
- Step 2: Execution of simulations month by month, applying the seasonal load curve and calculating the power flow of the entire system at each moment in time, for each scenario;
- Step 3: Sequential storage of the results obtained (i.e., power balance, voltage profiles) for each scenario in auxiliary SQLite databases.

Figure 4 shows a detailed flowchart of the methodology applied in conducting the simulations.

Figure 4. Methodology applied to simulate the impacts of MicroDGs on distribution networks



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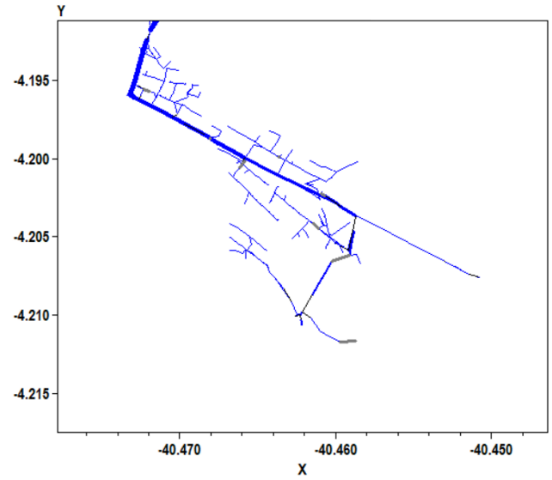
3.Results and Discussion

This section presents the results of the proposed methodology under various operational conditions of the real rural distribution feeder introduced in Section 2. Firstly, in Subsection 3.1, the original feeder is presented and modeled in OpenDSS to analyze its behavior without distributed generation. Subsequently, three DG penetration scenarios are defined in Subsection 3.2 to assess their impact on the rural distribution network.

3.1. Original Distribution Feeder Analysis

The ARU01Y8 distribution feeder (Figure 2) was modeled in OpenDSS using the *bdgd2opendss* tool, as shown in Figure 5.

Figure 5. Rural distribution feeder modeled in OpenDSS.



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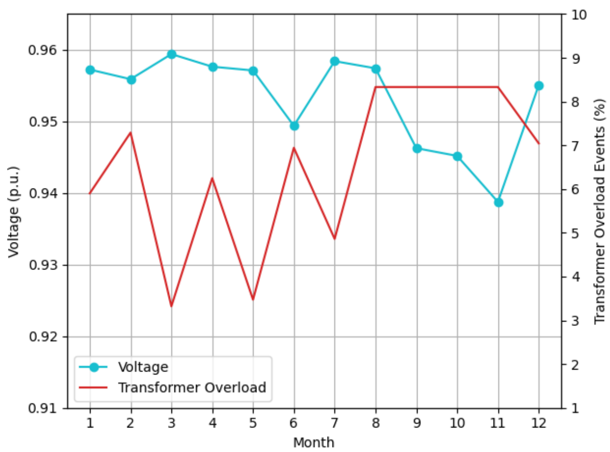
The system was simulated over a one-year scenario based on the load curve depicted in Figure 3. As a result, no reverse power flow events were observed, which is expected given the absence of DG. Moreover, the mean voltage for the medium voltage buses and the percentage of transformer overload events were obtained for each month, as depicted in Figure 6.

Figure 6. Monthly profile of average voltage and transformer overload events.



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During periods of higher demand, which occur from August to November, a peak of 8.33% in monthly transformer overload events is observed. This dynamic results in higher system losses, leading to a minimum voltage level of 0.938 p.u. in the 11th month.

3.2. Modified Distribution Feeder with DG Penetration Analysis

As previously discussed, three penetration levels of MicroDG were defined, as shown in Table 1. These plants were strategically placed at buses with the lowest voltage levels, yielding the conditions detailed in Figure 7.

After the integration of the MicroDG plants into the distribution network model, various scenarios were simulated in accordance with the methodology presented in Section 2. Initially, the monthly average voltage profile of the system was obtained, as illustrated in Figure 8.

It has been observed that an increase in DG penetration results in higher voltage levels, which is expected due to the reduction in losses promoted by distributed generators, particularly at the feeder's end buses. Therefore, it is evident that voltage variations throughout the year are smaller with high DG penetration, even during months of higher demand, reaching a minimum value of 0.951 p.u.

Furthermore, the inclusion of 5 extra plants in the 15-generator scenario (resulting in the 20-generator scenario) has no significant impact on voltage deviation. Hence, from a voltage regulation perspective, this increase in installed capacity leads to higher project and operational costs but does not provide practical advantages for the technical operation of the grid.

Figure 7. DG Penetration scenarios: a) 20-generator scenario; b) 15-generator scenario; c) 10-generator scenario.

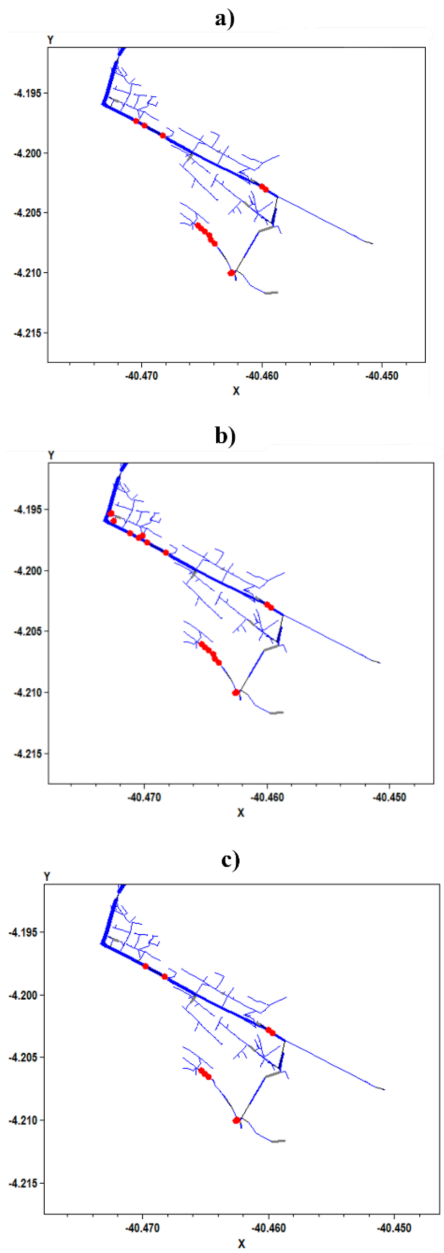

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Figure 8. Monthly profile of average voltage for DG penetration levels.

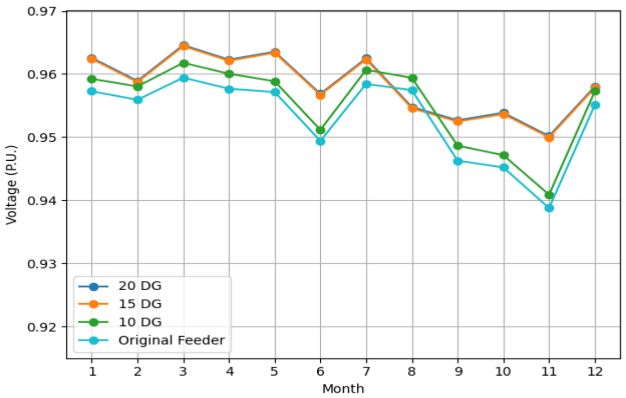

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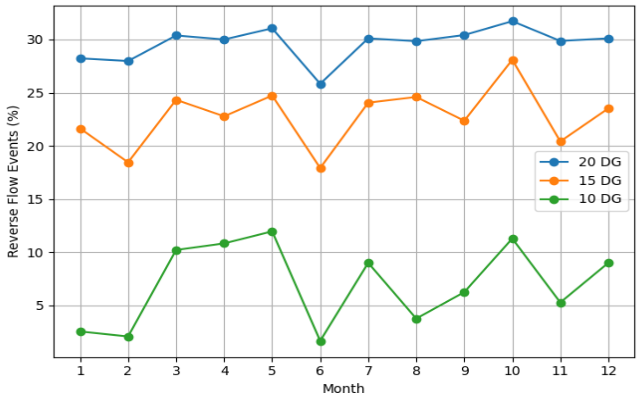
Figure 9. Monthly reverse flow events for different DG penetration levels.



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The monthly reverse power flow conditions, acquired from OpenDSS, are presented in Figure 9. The scenarios with higher distributed generation levels exhibit a greater number of reverse power flow events, which also leads to increased transformer overloading, as demonstrated in Figure 10.

A comparison of the two conditions reveals that the impact of MicroDG penetration on reverse power flow events is more pronounced than its impact on transformer overload. Thus, the photovoltaic generation from the MicroDG plants is sufficient to meet the total load, with the remaining energy being absorbed by the substation's grid equivalent.

Additionally, the influence of DG presented earlier is corroborated by the annual averages of voltage, photovoltaic generation, reverse power flow events, and transformer overload events, as detailed in Table 2.

Figure 10. Monthly transformer overload events for different DG penetration levels.

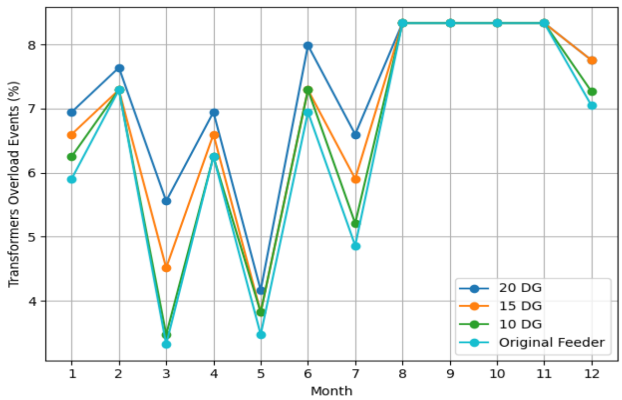

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Table 2. Annual average values for different DG penetration levels.

Scenario	Mean Voltage	Mean Photovoltaic Output Power	Reverse Power Flow Events	Transformer Overload Events
20 DG	0.9584 p.u.	454.23 kW	29.626 %	7.243 %
15 DG	0.9582 p.u.	427.85 kW	22.741 %	6.925 %
10 DG	0.9552 p.u.	401.62 kW	6.992 %	6.682 %
Original Feeder	0.9532 p.u.	0 kW	0 %	6.535 %

4. Conclusion

This work analyzes the impacts of integrating MicroDG plants into a real rural feeder by simulating three operational scenarios in OpenDSS. The observed behavior and the results indicate that increasing DG penetration leads to higher system voltage levels. This is beneficial for minimizing voltage sags and for meeting power quality standards, particularly at buses located at the end of the feeder.

However, at increased DG installed capacity, a greater number of reverse power flow events have been observed, which causes the utility's substation to absorb part of the system's power. Consequently, high transformer overloading is observed, resulting in elevated network losses.

Future work will aim to analyze the insertion of MicroDG in the context of emerging power system paradigms. This includes the incorporation of virtual power plants (VPPs) to optimize DG operation in distribution systems, mitigating its impacts, such as reverse power flow.

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