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Assessment Of The Impacts Of Integrating Renewable Sources Into Distribution Networks

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Abstract:
Background: *This study conducts a comparative analysis of the impacts of integrating distributed generation (DG) into medium-voltage distribution networks, with a specific focus on photovoltaic systems.*
Materials and Methods: *Simulations were performed using Interplan software, considering a conventional distribution network as the baseline and three alternative scenarios with different levels of photovoltaic generation power injection.*
Results: *The findings revealed that while small-scale generation does not pose significant challenges, higher levels exceeding the feeder's load capacity can result in reverse power flow, overvoltage, power factor degradation, and increased technical losses. The absence of detailed and robust preliminary feasibility studies has been identified as a key factor behind the rejection of DG connection requests by electric power distribution companies. This scenario has led to operational difficulties and financial losses for all stakeholders, creating conditions that fail to align with minimum global cost criteria.*
Conclusion: *To address these challenges, this study recommends the adoption of advanced simulation tools by utilities and industry stakeholders to identify optimal connection points. This approach aims to enhance the technical and economic sustainability of the electrical system, thereby supporting the feasibility of this essential requirement for the energy transition.*
Keywords: *Distributed Generation (DG); Reverse Power Flow; Photovoltaic Solar Energy; Distribution Networks; Feasibility Studies.*

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I. Introduction

In recent years, the search for renewable energy sources has intensified globally, driven by concerns about climate change and the environmental impacts of non-renewable sources that have dominated the world's electrical matrix. Although cleaner options, such as nuclear energy, natural gas, and biofuels, were already available, these sources are also finite and could lead to serious consequences due to their future scarcity. In light of this scenario, scientists around the world have dedicated themselves to developing new technologies and sustainable solutions to mitigate these challenges and ensure a safer and more balanced energy future.

In Brazil, the transition to renewable energy sources began with the expansion of wind energy, followed by biofuels, biomass, and more recently, photovoltaic solar energy. It was only in 2012, with the publication of Normative Resolution 482/2012, that captive consumers began to adopt solar energy through the model now known as Distributed Generation (DG). Currently, DG, especially photovoltaic solar energy, holds a prominent position among electricity sources in Brazil, second only to hydropower. However, this decentralized growth, while bringing numerous benefits, also presents significant challenges, particularly regarding the integration and operation of the distribution network[1].

The distribution network was originally designed to operate with unidirectional power flow, starting from generating sources, passing through transmission lines, following into distribution networks, and finally reaching consumer loads. However, in order to encourage self-generation of energy, Normative Resolution 482/2012 introduced a credit compensation system. This mechanism allows excess energy generated by

Distributed Generation (DG) systems to be converted into credits that can later be used to offset consumption recorded on electricity bills[1].

Initially, electricity distributors were concerned only with adapting the network standards for bidirectional flow, allowing energy generated by consumers to flow back into the grid. However, with the exponential growth of Distributed Generation (DG) over the years, significant challenges emerged for the infrastructure of distribution networks. This growth has become financially burdensome for utilities since many self-generating consumers paid only the availability fee while using the grid as support without bearing the full costs of its maintenance.

In response to these issues, the Legal Framework for Distributed Generation was established by Law 14.300/2022, which set new parameters and guidelines for the distribution and compensation of generated energy, seeking to balance the interests of consumers and utilities while ensuring the sustainability of the national electrical system[2].

Law 14.300/2022 provided significant relief for electric utilities regarding the operation and maintenance of distribution networks. Prior to regulation, utilities transported energy in both directions—generation and consumption—without additional costs for consumers. However, implementing charges related to wire usage on electricity bills presents considerable challenges, especially due to over a decade-long history of power injection into the distribution network without adequate financial compensation[2].

To quantify the magnitude of this scenario, Brazil currently has 2,921,470 installed Distributed Generation (DG) systems, with most of these systems being residential—totaling 2,316,959 units. This corresponds to 79.31% of all DG in the country according to data from ABSOLAR (2024). These numbers highlight the relevance and impact of DG on the national electrical system, emphasizing the importance of balanced regulation to ensure sector sustainability[3].

In addition to the challenge of appropriately pricing wire usage charges, another growing issue is reverse power flow, which has generated significant impacts on the electrical system. This reversal has contributed to overvoltages, increased levels of technical losses, and distortions in load curves with significant reductions in power factor at installations, further complicating the operation of distribution networks.

These anomalies not only increase costs and complexity for utility operations but also pose direct risks to consumers. Elevated voltages caused by overvoltages can damage electronic equipment in consumer units, resulting in financial losses and dissatisfaction with service quality. These challenges reinforce the need for investments in technological infrastructure and regulatory strategies to adapt the distribution network to the accelerated growth of Distributed Generation (DG), ensuring greater security and reliability in energy supply[4].

Based on this context, this article aims to demonstrate how the distribution network operates in light of power injection from decentralized renewable sources, focusing on the impacts caused by Distributed Generation (DG). To achieve this objective, two simulations were conducted using Interplan software: one with conventional power flow without DG representing the traditional operational model of distribution networks; and another considering power injection from photovoltaic solar systems. The simulations allow for an analysis of changes in power flows as well as challenges and opportunities associated with integrating DG into electrical networks.

The specific objectives are: to demonstrate the importance of preliminary technical feasibility studies in connection requests for distributed generation; and to corroborate issues caused by reverse flow in the distribution network. This scientific article is structured into five sections.

The first section is the introduction. The second section is reserved for methodology. The third section presents the theoretical framework. The fourth section analyzes results; and in the fifth and final section discusses conclusions drawn from this research.

II. Material And Methods

The approach adopted for this study is characterized as qualitative. This research was conducted through simulations aimed at comparing how the distribution network behaves with the integration of photovoltaic solar energy. A bibliographic review was developed to enrich the theoretical framework of this work, consisting of references from regulatory resolutions, scientific articles, and master's theses.

Regarding the qualitative approach, González (2020, p. 02) states: "The qualitative approach refers to a variety of perspectives, methods, approaches, and techniques used in the planning, execution, and evaluation of research[5]."

On the topic of bibliographic research, Lunetta and Guerra (2023, p. 03) express the following opinion: "The bibliographic review is a research procedure that relies on existing documents, such as books and scientific articles. In some studies, it is common to focus solely on bibliographic sources[6]." The primary authors who contributed to this study include: Veríssimo (2018), Neiva et al. (2021), and Silva (2023).

III. Literature Review

This article was developed based on power flow simulations, using the Interplan software (2024), and is divided into four chapters: - The first subtopic presents a reference distribution network without distributed generation. - The second subtopic introduces a generating unit with an injected power of 1 MW (unit power factor) into the reference distribution network. - The third subtopic introduces a generating unit with an injected power of 2.5 MW (unit power factor) into the reference distribution network. - The fourth subtopic introduces a generating unit with an injected power of 5 MW (unit power factor) into the reference distribution network.

A distribution network (medium voltage feeder) was created with the following parameters: a 69/13.8 kV substation with a capacity of 10 MVA, using a 1/0 CAA cable type over a 5.39 km route, with 15 intermediate network sections and 16 busbars. For load modeling, three transformer stations (TSs) were inserted, with rated powers of 300, 500, and 2500 kVA, all connected with 1/0 CAA cables. For simulations with distributed generation (DG), a photovoltaic solar generating unit was added at the end of the network, with the following generation curve (1 p.u. of maximum power during morning and afternoon hours, and 0 p.u. during early morning and night hours).

Normative Resolution No. 1.059, of February 7, 2023, specifies:

Energy surplus: the positive difference between the active electrical energy injected and the active electrical energy consumed by a consumer unit with microgeneration or minigeneration, determined by the tariff rate at each billing cycle, except in the case of an enterprise with multiple consumer units with microgeneration or minigeneration or shared generation, in which the energy surplus may be all the energy generated or injected into the distribution network by the consumer unit, at the discretion of the consumer unit owner with microgeneration or minigeneration[7]. Table 1 presents the load data modeled for this study:

Table 1 - Load data modeled for this study

LOAD 01: DEMAND			LOAD 02: DEMAND			LOAD 03: DEMAND		
PERIOD	S (KVA)	fp	PERIOD	S (KVA)	fp	PERIOD	S (KVA)	fp
Early morning	90,00	0,92	Early morning	50,00	0,92	Early morning	700,00	0,92
Morning	170,00	0,92	Morning	370,00	0,92	Morning	1600,00	0,92
Afternoon	180,00	0,92	Afternoon	420,00	0,92	Afternoon	1800,00	0,92
Evening	230,00	0,92	Evening	100,00	0,92	Evening	2200,00	0,92

Source: Interplan (2024, modified by the authors).

To evaluate line voltage variations, Table 2 of PRODIST module 8 was used. This module establishes parameters for electrical energy quality (QEE)[8].

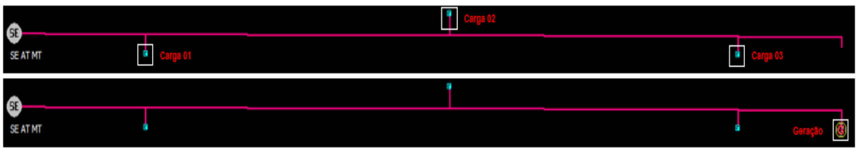
Table 2 - Connection points at Nominal Voltage above 2.3 kV and below 69 kV

Service Voltage	Voltage Reading (VR) Variation Range in Relation to Reference Voltage (RV)
Adequate	$0.93RV \leq VR \leq 1.05RV$
Precarious	$0.90RV \leq VR < 0.93RV$
Critical	$VR < 0.90RV$ or $VR > 1.05RV$

Source: Module 8 of PRODIST (2021)[8]

In the network connection bars with loads and generation bars, 1/0 ACSR cables were used from the feeder to the end of the network.

Figure 1 - Networks with and without DG

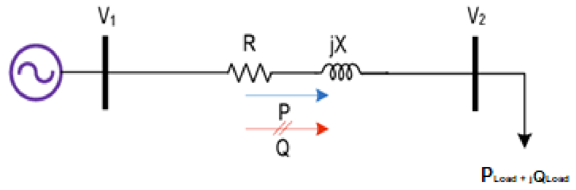


Source: Interplan (2024, modified by the authors).

Reference Distribution Network Without Distributed Generation

For this simulation, a conventional network (Figure 2) was created, following a single flow: centralized generation towards the load.

Figure 2 - Conventional Flow of a Distribution Network



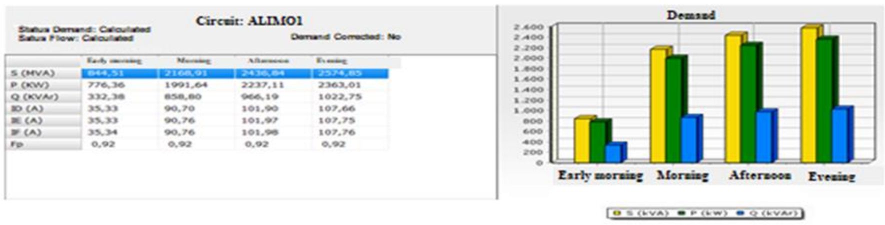
Source: Souza et al. (2017)[9]

Veríssimo (2018, p. 13) explains that:

Distribution networks are designed to deliver energy to domestic or industrial consumers at three respective voltage levels: low voltage, where devices should be directly connected; medium voltage, which should supply all transformation stations; and high voltage, which should exclusively supply substations. These networks can also receive energy produced by independent producers using renewable sources such as solar energy, small hydroelectric power, wind energy, among others. Additionally, they can receive energy generated through cogeneration plants[10].

Graph 1 shows the levels of apparent, active, and reactive power, as well as line currents and power factor. The load curve modeled for this study represents a typical mixed curve with both commercial and residential characteristics, justified by their respective consumption patterns. It is observed that the maximum demand level (peak) of the simulated feeder corresponds to the nighttime level (contribution from public lighting combined with other residential consumption habits).

Graph 1 - Network Power Without DG



Circuit: ALIMO1

Status Demand: Calculated
Satus Flow: Calculated
Demand Corrected: No

	Early morning	Morning	Afternoon	Evening
S (MVA)	844,51	2168,91	2436,84	2574,85
P (KW)	776,36	1991,64	2237,11	2363,01
Q (KVAr)	332,38	858,80	966,19	1022,75
ID (A)	35,33	90,70	101,90	107,66
IE (A)	35,33	90,76	101,97	107,75
IF (A)	35,34	90,76	101,98	107,76
Fp	0,92	0,92	0,92	0,92

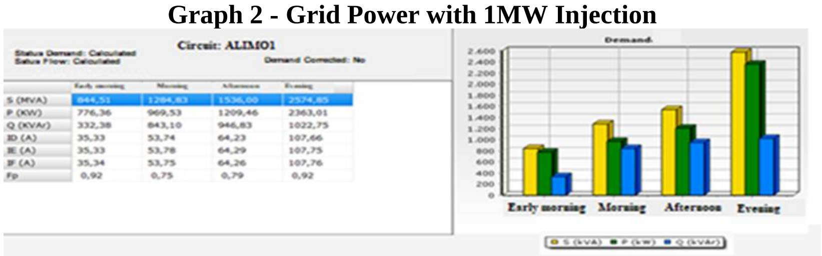
Source: Interplan (2024).

Based solely on the feeder load curve, it would be justifiable to inject a generation power of approximately 2200 kW, as under this condition there would be no reversal of flow, since the active power during the afternoon period (solar generation peak) averages 2200 kW. However, other factors such as power factor, overvoltage, and technical energy losses must be considered in order to assess the optimal point for the integration of distributed generation into the feeder.

Insertion of the Generation Unit with Injected Power of 1MW

For this simulation, a 1MW generation unit was inserted, as shown in Graph 2. A reduction in the power flow from the original source (substation) was observed due to the net injection of active power downstream of the grid, as evidenced by the reduction in active demand levels during the morning and afternoon periods (solar generation peak).

Graph 2 - Grid Power with 1MW Injection



Circuit: ALIMO1

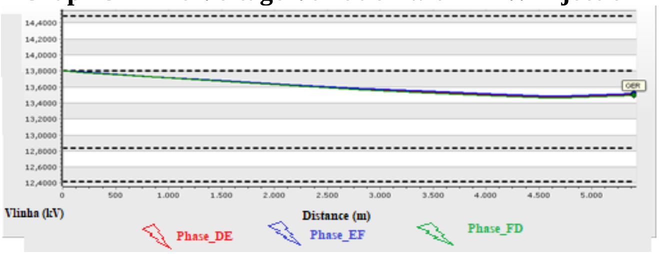
Status Demand: Calculated
Satus Flow: Calculated
Demand Corrected: No

	Early morning	Morning	Afternoon	Evening
S (MVA)	844,51	1284,83	1536,00	2574,85
P (KW)	776,36	969,53	1209,46	2363,01
Q (KVAr)	332,38	843,10	946,83	1022,75
ID (A)	35,33	53,74	64,23	107,66
IE (A)	35,33	53,78	64,29	107,75
IF (A)	35,34	53,75	64,26	107,76
Fp	0,92	0,75	0,79	0,92

Source: Interplan (2024).

In this situation, there was no reversal of flow; however, there was a reduction in the power factor on the feeder from 0.92 to 0.75 and 0.79 (respectively during the morning and afternoon periods, corresponding to the solar generation peak). The line voltage resulted in a value of 13.5 kV (0.978 p.u.), which is close to the network voltage level in the scenario without distributed generation (13.2 kV), further reinforcing the viability of this scenario. See Graph 3.

Graph 3 - Line Voltage Variation with 1MW Injection



Source: Interplan (2024).

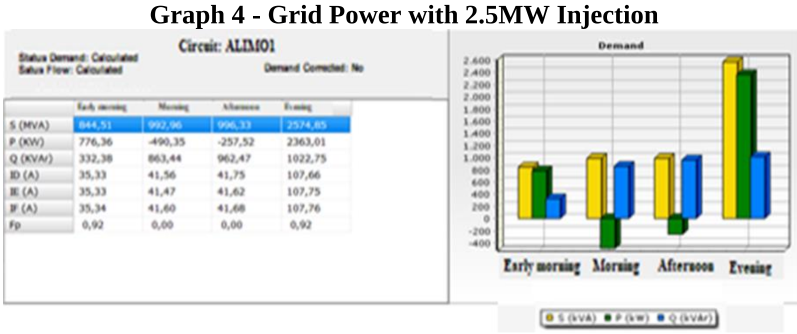
Insertion of the Generation Unit with Injected Power of 2.5MW

For this simulation, a 2.5MW generation unit was inserted, as shown in Graph 4. A slight reversal of power flow in the load-to-source direction was observed, justified by the level of power injected by the generation unit being higher than the peak demand during the morning and afternoon periods. This indicates that, in this scenario, the existing loads on the feeder are insufficient to accommodate the injected active power flow, resulting in a reversal of flow in the GD-Substation direction during the morning and afternoon periods (solar generation peak).

According to Falcão (2023, p. 02):

The reversal of flow in the electricity distribution network occurs when the amount of electrical energy injected from distributed generation exceeds the demand of consumers connected to the same network, which can lead to overloading, voltage imbalance, and interruptions in the electricity supply[11].

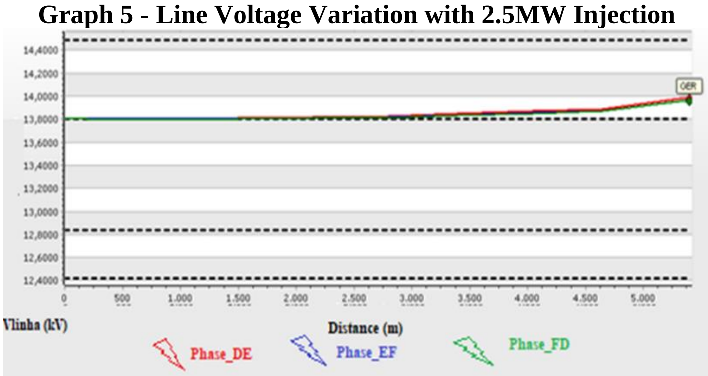
Graph 4 - Grid Power with 2.5MW Injection



Source: Interplan (2024).

In this condition, where the substation supplies only the reactive component to the loads during the morning and afternoon periods, and the surplus active power returns from the grid to the source, it was observed that the power factor reached its minimum value. The voltage in this case was 13.98 kV (1.013 p.u.), slightly above the nominal value but still within the established standards. See Graph 5.

Graph 5 - Line Voltage Variation with 2.5MW Injection

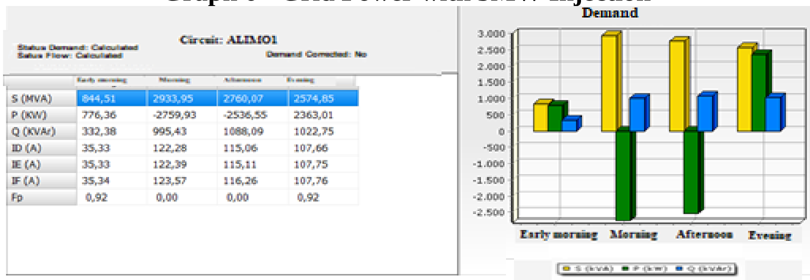


Source: Interplan (2024).

Insertion of the Generation Unit with Injected Power of 5MW

For this simulation with a 5MW generation unit (See Graph 6), a significant imbalance was observed between the power injected by the distributed generation (DG) and the network demand, resulting in a high reverse power flow, from load to source, of approximately 2.8MW in the morning period and 2.5MW in the afternoon period.

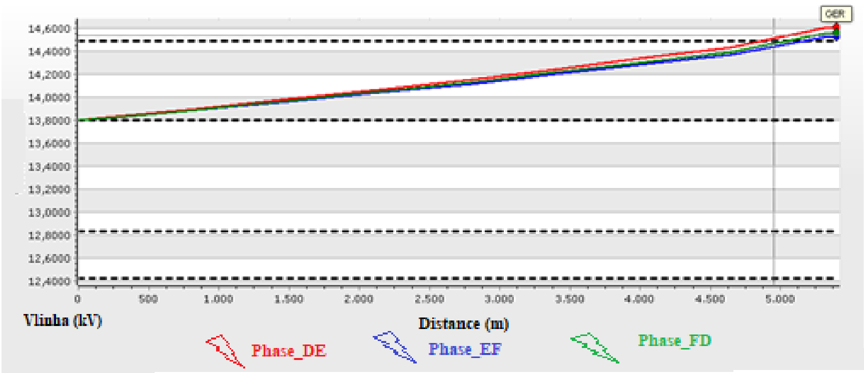
Graph 6 - Grid Power with 5MW Injection



Source: Interplan (2024).

Similar to the previous case, the power factor remained zero due to the injection of only reactive power in the source-to-load direction along the grid during the operation of the solar power plant. The voltage in this case was 14.61 kV (1.059 p.u.), a level above the limit and the established standards.

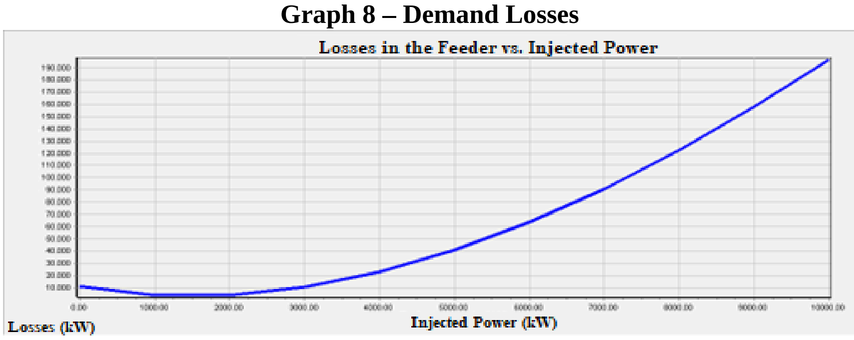
Graph 7 - Line Voltage Variation with 5MW Injection



Source: Interplan (2024).

The analysis of this type of graph is useful for evaluating the performance of transmission lines in renewable energy supply scenarios or distribution systems. It is essential to ensure that the voltage increase stays within operational limits to avoid power spikes or damage to equipment[12].

Graph 8 – Demand Losses



Source: Interplan (2024).

It was demonstrated, as shown in Graph 8, that for this simulated feeder, the level of active power injection from distributed generation (solar photovoltaic) corresponds to approximately 2,000 kW (2.0 MW), which represents the inflection point of the curve showing the reduction of technical losses versus the increase in active power from solar photovoltaic distributed generation.

IV. Analysis Of Results

To obtain the expected results, the analyses were conducted only in cases where power injection from distributed generation (DG) was present, using the conventional grid solely as a reference for parameters such as voltage variation, power factor, and technical losses. A brief analysis of the three scenarios reveals that, in the case of the 1MW plant installation, no flow reversal occurred. The line voltage remained close to the level of the grid without distributed generation, and although the power factor was below the regulated value, this imbalance in power was observed only at the substation, which can be easily solved using capacitor banks near the load center of the feeder. The power factor remained at 0.92 at the load delivery point, without causing any issues for the consumers supplied by the network[13].

In the case of the 2.5MW plant, there was a flow reversal. The generation unit was supplying the entire demand during the operation periods (morning and afternoon) and still returned a portion of this active power to the source (represented by the power substation). Although there was an increase in line voltage, its level remained within the upper limit of 5%, as shown in Table 3 of module 8 of PRODIST (2021)[8].

The substation feeder was injecting only reactive power, as the entire network demand was supplied by the DG, with the excess active power returning as reverse flow to the substation. This imbalance between the powers caused the power factor at the concessionaire's substation to reach zero. In this case, the concessionaire would need to conduct a technical feasibility study to assess possible solutions for the installation of this plant[14].

In the case of the 5MW plant, flow reversal also occurred, with more than 100% of the active power returning to the feeder. Overvoltage was observed in the section where the plant was installed, clearly demonstrating the infeasibility of connecting this power level under these network conditions. This final scenario highlighted the importance of conducting preliminary feasibility studies for connecting distributed generation to the distribution system to avoid situations where there is a significant mismatch between the network's characteristics (such as conductor type, length, demand level, load level, power factor, technical losses, and voltage level) and the desired generation level[15].

It is in the interest of all parties involved to seek the minimum global cost, in order to avoid unnecessary investments, technical conditions that may jeopardize assets and human lives, as well as additional tariff or regulatory costs.

V. Conclusion

Based on the results obtained in this study, the importance of conducting a proper technical feasibility analysis for connecting distributed generation, particularly solar photovoltaic, to distribution systems is highlighted. Depending on the chosen connection point, the network characteristics, and the level of generated power, the viability of the connection can vary dramatically, ranging from a scenario where there is no impact on the network and DG even contributes to improving the power flow, to an extreme scenario where the connection of the generation unit becomes entirely unfeasible due to technical criteria for minimum global cost.

As a contribution of this work, it is recommended that the technical feasibility analysis process, conducted by distribution utilities, be more transparent to the market. Additionally, the market, represented by energy traders, consultants, and end consumers, should strive to optimize their prospecting and improve their preliminary connection analysis through simulations that identify optimal points for integrating distributed generation into the medium-voltage grid.

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