



**ESTUDOS SOBRE OS IMPACTOS DO FLUXO REVERSO DE POTÊNCIA NA PROTEÇÃO
DE SISTEMAS ELÉTRICOS COM ALTA INSERÇÃO DE GERAÇÃO DISTRIBUÍDA
STUDIES ON THE IMPACTS OF REVERSE POWER FLOW ON PROTECTION OF
ELECTRIC SYSTEMS WITH HIGH PENETRATION OF DISTRIBUTED GENERATION**

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RESUMO

Os estudos sobre os impactos gerados pela geração distribuída são importantes porque visam propor adequações e melhorias à operação do Sistema Elétrico de Potência, uma vez que esse tipo de geração está se tornando cada vez mais comum. O sistema elétrico tradicional é projetado levando em consideração o planejamento dos centros geradores e sentido unidirecional da corrente, dessa forma o fluxo de potência apresenta um sentido convencional e previsível. Com a alta inserção de geração distribuída, o fluxo de potência se torna mais complexo, apresentando mais de uma direção e diversas fontes distribuídas na rede elétrica. Neste sentido, este trabalho tem como objetivo apresentar a revisão da literatura sobre o fluxo reverso diante da alta inserção de geração distribuída e seus impactos na operação, principalmente na proteção do sistema elétrico de potência. Os resultados destacam os principais impactos na proteção como: disparo indevido, zonas cegas de proteção e perda de alcance em relé de distância. Portanto, constata-se a importância dessas pesquisas em relação aos principais impactos na coordenação e seletividade dos dispositivos de proteção e aos estudos sobre estratégias para mitigação dos efeitos de fluxo reverso em rede de distribuição com alta inserção de fontes renováveis, visando maior confiabilidade e melhorias nas instalações de geração distribuída.

Palavras-chave: Geração Distribuída, Fluxo Reverso de Potência, Sistema Elétrico de Potência, Sistemas de Proteção.

ABSTRACT

Studies on the impacts generated by distributed generation are important because they aim to provide adjustments and improvements to the operation of the Electric Power System, since this type of generation is becoming increasingly common. The traditional electrical system is designed taking into account the planning of generating centers and the unidirectional direction of the current, thus the power flow presents a conventional and predictable direction. With the high insertion of distributed generation, the power flow becomes more complex, presenting more than one direction and several sources distributed in the electrical grid. This work aims to present a review of the literature on the reverse flow in the face of the high insertion of distributed generation and its impacts on the operation, mainly protection of the electrical power system. The results highlight the main impacts on protection such as: improper tripping, protection blind zones and loss of range in distance relays. Therefore, the importance of this research is evident in relation to the main impacts on the coordination and selectivity of protection devices and studies on strategies to mitigate the effects of reverse flow in distribution networks with high insertion of renewable sources, aiming at greater reliability and improvements in distributed generation facilities.

Keywords: Distributed Generation, Electrical Power System, Protection Systems, Reverse Power Flow.



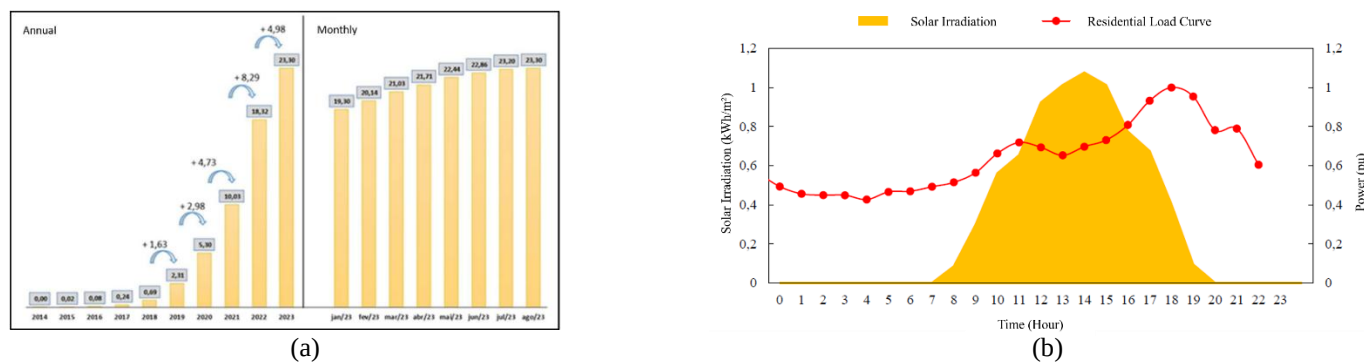
1 INTRODUCTION

The use of alternative energy sources for electricity generation has increased significantly in recent years. Renewable sources such as photovoltaic solar and wind power are driving the expansion of Distributed Generation (DG), enabling the production of electricity close to the point of consumer and directly connecting it to the Distribution Network (DN).

In Brazil, the National Electric Energy Agency (ANEEL) initiated the regulation of DG through Normative Resolution No. 482/2012, which established the general conditions for grid access and the electricity credit compensation system. This regulation has since undergone revisions, and the current applicable standard is Normative Resolution No. 1098/2024. Since then, there has been a remarkable and continuous growth in the number of DG installations, mainly dominated by photovoltaic (PV) solar energy. Figure 1a illustrates the growth of distributed generation in terms of installed capacity (GW), both annually and monthly, as recorded in 2023, according to Rangel (2024).

The popularization of DG in residential increases the complexity of controlling the Electric Power System (EPS), since PV generation does not coincide with peak load hours (Stecanella, 2020). Figure 1b shows a typical residential load curve for the state of Goiás (Brazil) and the average solar irradiation throughout the day (Stecanella, 2020).

Figure 1 – Distributed generation: a) Growth in installed capacity (GW), annual and monthly values recorded in 2023 in Brazil; and b) Typical residential load curve and average solar irradiation in the state of Goiás/Brazil.



Fonte: a) Rangel, 2024; b) Stecanella, 2020.

DG structure differs from the traditional centralized generation model, which relies on large generation centers located far from the end consumer and is designed based on unidirectional and predictable power flow, while DG allows power to be injected directly into the low-voltage DN. Power flow reversal in the distribution network occurs when the amount of electricity injected from DG exceeds the demand of consumers connected to the same network, which can generate overloading, voltage imbalance, and interruptions in power supply. In Pereira (2019), a comparison is made between the positive and negative aspects of distributed and centralized photovoltaic generation. These negative aspects directly affect the control and protection systems of the electrical grid.

Usually, the power flow reversal in the distribution transformers can be associated with short circuits in the medium-voltage segment of the grid, triggering protection devices. A study conducted in Neiva et al. (2021) analyzes simulations using the



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OpenDSS software involving short circuits and DG in meshed networks, aiming to distinguish between the power flow reversals caused by each.

In Makine, Akinyele and Amole (2021) are discussed the problems related to voltage rise caused by the Reverse Power Flow (RPF), along with an overview of the approaches used to mitigate such issues. The approaches presented are based on methodologies for strengthening the grid infrastructure and actively managing the DN.

A DG can be installed at random points along the DN causing overvoltage at various points in the grid. Holguin, Rodriguez and Ramos (2020) proposed a tool to identify the occurrence of RPF indicated by overvoltage at the distribution network nodes and to use the overvoltage protection function 59 to limit the maximum installed DG capacity.

Transformers are the main equipment used to regulate voltage in the network and are also affected by reverse power flow, which compromises their performance and lifespan. In Majeed and Nwulu (2022), it is analyzed how the penetration level of photovoltaic sources results in overloading conditions for the equipment. Simulation results using the ETAP software for a low-voltage radial DN in an urban area of Ghana were analyzed, and it was observed that the transformer's load capacity decreases as photovoltaic DG is integrated. Therefore, the authors proposed limiting PV penetration to 88.3% in order to prevent transformer overloading (Majeed and Nwulu, 2022).

Therefore, this work aims to present a literature review on the impacts of high penetration of DG in the EPS and its implications for protection philosophy, contributing to the theoretical foundation regarding the need to adapt protection systems to ensure greater reliability and operational safety.

2 METHODOLOGY

The methodology of this work is based on a literature review on the impacts of high DG penetration in the DN and the consequences of RPF on protection systems. The theoretical basis is presented, along with a discussion of the impact of high DG penetration and analyze of methods proposed in the literature to mitigate its effects, aiming to improve the reliability and selectivity of protection device operation.

3 RESULTS AND DISCUSSION

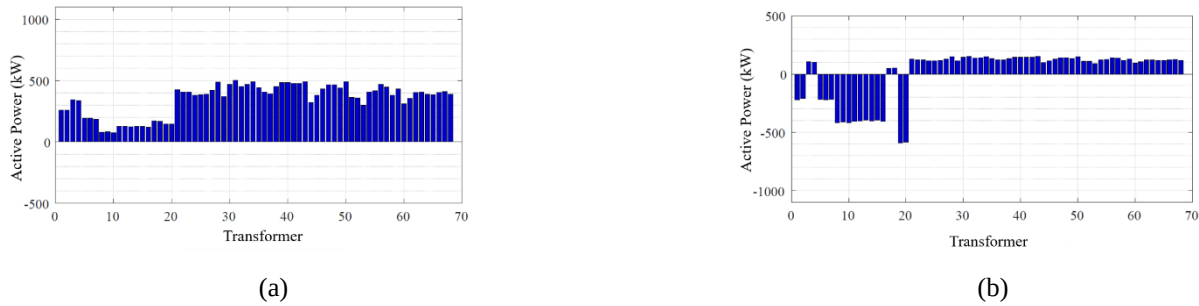
Typically, radial DN consider only the highest fault current from a single source, which simplifies short-circuit analysis (Norshahrani et al., 2017). However, with the presence of DGs, the system becomes more complex, involving multiple sources and more than one direction of fault current (Norshahrani et al., 2017; Ates et al., 2016). The unplanned current contribution from DGs to system faults alters the sensitivity of the protection system and may exceeding the fault interruption capacity of equipment such as circuit breakers and fuses.

In Dias (2018), simulations were carried out on a 390-bus meshed network to analyze the response of protection devices and the amount of active power in each transformer branch under both high and low loading conditions, according to different levels of photovoltaic generation. Figure 2 illustrates the amount of active power in the system with a 70% level of photovoltaic DG penetration for (a) high and (b) low loading. It is observed that for the same DG penetration level, RPF occurs under low loading conditions, whereas it does not under high loading. It was also observed that the number of protection devices triggered varies



significantly with transformer loading. Therefore, DGs can cause cascading tripping of protection devices, potentially leading to complete de-energization of the meshed network (Dias, 2018).

Figure 2 – Active power in the transformers of the 390-bus meshed network under 70% photovoltaic generation for: (a) high loading; and (b) low loading.

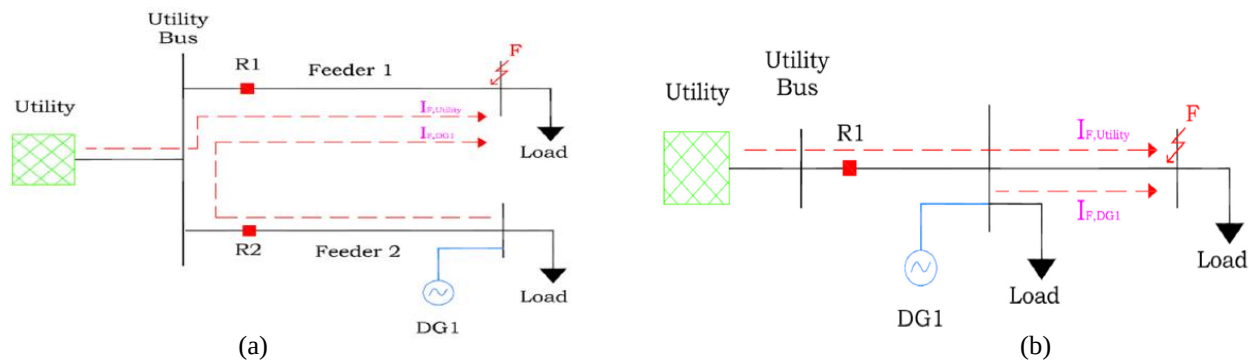


Fonte: Dias, 2018.

The main objective of the protection system is to ensure coordination and selectivity of the electrical system in the event of a fault. Selectivity ensures that only the faulty section is isolated, while coordination guarantees the correct sequence of relay operations, starting with the protection relays closest to the fault, followed by those farther away. In Filho et al. (2022), simulations were performed using Matlab/Simulink on a 13-bus test system to evaluate the behavior and verify the performance of overcurrent protection after DG integration. The results showed that the effectiveness of protection vary depending on the fault location and the DG connection point. Additionally, unintended tripping was observed due to faults occurring in the reverse direction relative to the relay.

Two fault scenarios are presented in Agwa and El-Fergany (2023) to demonstrate the impacts of DG integration on the protection system. Figure 3a illustrates a possible scenario of false tripping in a system with DG. The system consists of two feeders protected by relays R1 and R2, with a fault located on feeder 1. In this situation, feeder 2, where DG is present, contributes to the fault current. The reverse current flowing through R2 may trigger its protection before R1, leading to the unintended de-energization of feeder 2 and compromising the system's selectivity (Agwa and El-Fergany, 2023).

Figure 3 – Impacts of DG integration on the protection system: a) False trip; and b) Blinding of Protection.



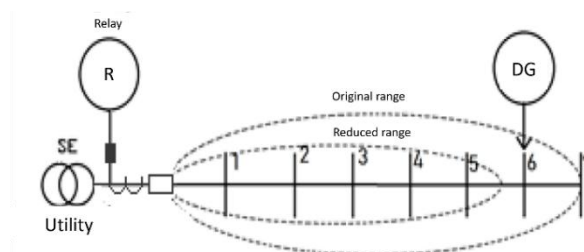
Fonte: Agwa and El-Fergany, 2023.



Another possible scenario is the emergence of unprotected zones in the system. Figure 3b shows a feeder system with DG presence, in which a fault occurs in the section protected by relay R1. The system fails to interrupt the fault current due to the contribution from the DG, which may also lead to unintentional islanding and asynchronous reclosing (Agwa and El-Fergany, 2023).

Distance protection relays use impedance calculation to determine whether the current exceeds the short-circuit current for the protected section. High penetration of DG alters the system, making impedance calculation more difficult and compromising the protection of the analyzed section. Figure 4 illustrates the reduction in protection reach showing that the original system adequately protects up to bus 7, but , with DG integrated at bus 6, the current measured by the relay decreases, and the reach of the protected zone is reduced to bus 5.

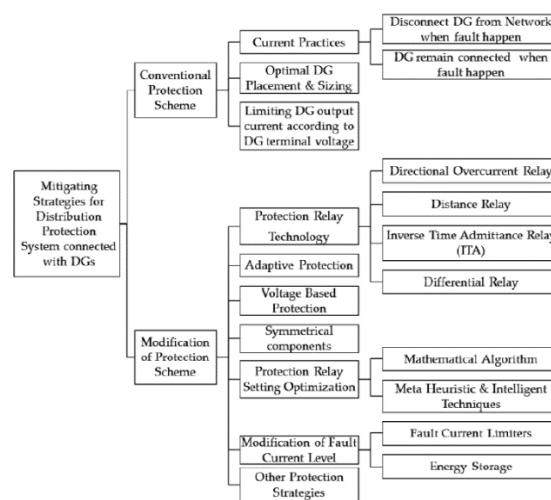
Figure 4 – Distance Protection zone scheme.



Fonte: Translated of Garcias, Leão and Barradas, 2021.

Different mitigation strategies for protecting systems with high DG penetration are summarized in Figure 5, where they are categorized into two approaches. The first approach is based on the conventional protection scheme with minimal modifications, which reduces implementation costs and operational disruptions, but they impose limitations on DG generation capacity. The other approach involves modifying the conventional distribution system through the introduction of additional components related to the protection system.

Figure 5 – Protection strategies to mitigate the impact of DGs.



Fonte: Norshahrani et al., 2017.



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Among the strategies for protection systems with high DG penetration presented in Norshahrani et al. (2017), Table 1 provides a comparison of main technical advantages and disadvantages of protection relay technologies (directional relay, distance relay, admittance relay, and differential relay) that can be applied on DN.

Table 1 - Comparison of Protection Relay Technology.

Protection Strategy	Advantages	Disadvantage
1. Protection Relay Technology		
a. Directional Over Current Relay	Able to sense current for both directions effectively to solve the bidirectional power flow impact. Good selectivity and able to avoid adjacent feeders tripping effects.	Capital cost is high with double cost of relays, CT, and CB required. Difficulty to set for all contingencies scenario.
b. Distance Relay	Relay setting is constant for a wide variety of changes to the protected line. Suitable for closed-loop and mesh due to its directional element. Faster relay operation time.	Small range of parameter for relay characteristics. Required a voltage transformer which contributes to additional cost. Setting procedure of distance relay could be more difficult than conventional OC relay.
c. Inverse Time Admittance Relay	Capable to distinguish and isolate the faults in both grid-connected and autonomous micro-grids. Capable to sense multiple fault levels in DN. Provides backup protection to its immediate downstream relay. Able to isolate the faulty section on the upstream feeder and downstream region without affecting DG based on admittance measurement. Does not require safety margin to cover the protection zones.	Risk of miscalculations in the measured admittance due to fault resistance. The effectiveness of the scheme has not been validated.
d. Differential Relay	Capable to protect DN either in radial or looped feeders. Not sensitive to bidirectional current flow effects.	Difficult and expensive to be applied due to too many distribution lines and the needs of a communication link between relays. Has not been experimentally validated. Effective only for line protection and had not the ability to protect buses connected to DGs or loads.

Fonte: Norshahrani et al., 2017.

The high variability and uncertainty in DG source generation can affect the stability and supply of electric power, posing significant challenges for protection and control systems in the grid. Therefore, proper coordination of protection relays is necessary, and optimization methods are used to calculate relay settings. Optimal coordination of overcurrent relays can be formulated as a mixed-integer nonlinear programming problem, and due to its combinatorial nature, such problems are better handled through metaheuristic approaches (Serna-Montoya et al., 2024). In Serna-Montoya et al. (2024), a methodology is proposed to optimize the selection of the most suitable time-current characteristic curves for overcurrent relay coordination in microgrids. The methodology considers both the American standard (IEEE) and European standard (IEC) curve models, and its performance is compared using four optimization techniques: Imperialist Competitive Algorithm (ICA), Firefly Algorithm (FA), Genetic Algorithms (GAs), and Harmony Search (HS).

The adaptive overcurrent protection is a strategy that dynamically adjusts relay settings based on real-time system conditions, including load variations, changes in network topology, and fault characteristics. This approach ensures optimal coordination among protection devices, reducing the risk of incorrect operations and enhancing system robustness against disturbances (Serna-Montoya et al., 2025). In this way, the protection system can employ computational logic and intelligent algorithms to increase the reliability and flexibility of the distribution network.

Sampaio et al. (2023) proposed an adaptive protection system that employs fuzzy logic to calculate new relay settings in a microgrid, based on network components, topology changes and operating mode. The system shows a significant contribution



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in eliminating miscoordination when compared to systems with fixed optimized settings. The proposed algorithms have proven to be efficient in adjusting multiple directional relay settings, although it requires a robust communication infrastructure. The implementation of equipment with new technologies, such as Smart Transformers, is being studied as a means of mitigating RPF, even though modernizing all equipment in the network is currently commercially unfeasible. In Couto and Mendes (2018), the use of Smart Transformers is proposed to prevent excess power generated by DG from propagating to the transmission system. The control strategy consists of reducing the active power injected by the DG whenever the grid frequency increases. Upon detecting the occurrence of RPF, the Smart Transformer slightly raises the frequency on the distribution side, to which the DGs are connected. As a result, the inverters detect the frequency variation and automatically reduce the injected power due to their droop or P/f control (Couto and Mendes, 2018). The frequency continues to increase until the power flow perceived by the Smart Transformer is approximately zero, remaining off the nominal value as long as the forward power flow stays below a pre-established reference.

Several mitigation strategies have been proposed to address the effects of high DG penetration and support its effective integration on DN. In Meskin, Domijan and Grinberg (2020), solutions are reviewed that involve reformulating the protection system as well as those that consider the capacity and characteristics of DG. The study highlights that the proposed alternatives cannot be generalized to all distribution networks. Suggested mitigation strategies include inverter control, multi-agent methods, network matrix algorithms, the use of neural networks for fault detection, among others.

Srivastava et al. (2021), in another review of mitigation solutions for the effects of RPF, presents additional strategies such as synchrophasor-assisted protection, traveling wave techniques, and protection schemes based on machine learning and Wavelet Transform. Additionally, in this study, several research gaps were identified, including how to design a communication-assisted protection system that is both cost-effective and robust against communication delays and link failures; how to improve the practical and field validation of newly proposed techniques; and how to address data quality and communication latency issues in synchrophasor-based protection schemes.

4 CONCLUSION

This study contributes to existing research by reviewing the impacts of high DG penetration on protection systems in DN, with emphasis on RPF. DG integration can compromise relay performance, leading to unintended tripping, blind zones, and loss of selectivity. To address these challenges, the proposed mitigation strategies in the literature can be divided into two categories: limiting DG penetration to maintain system stability, and modernizing protection schemes to support DG integration.

BIBLIOGRAPHIC REFERENCES

- AGWA, A. M.; EL-FERGANY, A. A.. Protective Relaying Coordination in Power Systems Comprising Renewable Sources: Challenges and Future Insights. **Sustainability**, v. 15, n. 9, p. 7279, 2023.
- ATES, Y. et al.. Adaptive Protection Scheme for a Distribution System Considering Grid-Connected and Islanded Modes of Operation. **Energies**, v. 9, n. 5, p. 378, 2016.



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- COUTO, H. P.; MENDES, V. F.. Simulação do Uso de Smart Transformers para Mitigação da Inversão do Fluxo de Potência em Redes de Distribuição. **Anais Congresso Brasileiro de Energia Solar-CBENS**. 2018.
- DIAS, Leandro Rosa. **Análise a Influência de Elevados Níveis de Geração Fotovoltaica na Operação das Redes Reticuladas de Distribuição de Energia Elétrica**. Dissertação de mestrado. Universidade de São Paulo, São Carlos, 2018.
- FILHO, C. P. S.. et al.. Impacto da Geração Distribuída por Fonte Fotovoltaica em uma Rede de Distribuição e seu Sistema de Proteção de Sobrecorrente. **Simpósio Brasileiro de Sistemas Elétricos-SBSE**, v. 2, n. 1, 2022.
- GARCIA, T. R.; LEÃO, F. B.; BARRADAS, H. M.. Metodologia para Reparametrização Adaptativa do Sistema de Proteção Considerando a Inserção de Geração Distribuída. **Simpósio Brasileiro de Sistemas Elétricos-SBSE**, v. 1, n. 1, 2020.
- HOLGUIN, J. P.; RODRIGUEZ, D. C.; RAMOS, G.. Reverse Power Flow (RPF) Detection and Impact on Protection Coordination of Distribution Systems. **IEEE Transactions on Industry Applications**, v. 56, n. 3, p. 2393-2401, 2020.
- MAJEED, I. B.; NWULU, N. I.. Impact of Reverse Power Flow on Distributed Transformers in a Solar-Photovoltaic-Integrated Low-Voltage Network. **Energies**, v. 15, n. 23, p. 9238, 2022.
- MAKINDE, K. A.; AKINYELE, D. O.; AMOLE, A. O.. Voltage Rise Problem in Distribution Networks with Distributed Generation: A Review of Technologies, Impact and Mitigation Approaches. **Indonesian Journal of Electrical Engineering and Informatics (IJEI)**, v. 9, n. 3, p. 575-600, 2021.
- MESKIN, M.; DOMIJAN, A.; GRINBERG, I.. Impact of Distributed Generation on the Protection Systems of Distribution Networks: Analysis and Remedies–Review Paper. **IET Generation, Transmission & Distribution**, v. 14, n. 24, 2020.
- NEIVA, L. J. R. et al.. Análise da Inversão no Sentido do Fluxo de Potência Devido à Falta na Média Tensão e Geração Distribuída no Secundário Reticulado. **Simpósio Brasileiro de Sistemas Elétricos-SBSE**, v. 1, n. 1, 2020.
- NORSHAHRANI et al.. Progress on Protection Strategies to Mitigate the Impact of Renewable Distributed Generation on Distribution Systems. **Energies**, v. 10, n. 11, p. 1864, 2017.
- PEREIRA, N. X.. **Desafios e Perspectivas da Energia Solar Fotovoltaica no Brasil: Geração Distribuída Vs Geração Centralizada**. Tese de mestrado. Universidade Estadual Paulista Julio de Mesquita Filho, Sorocaba, 2019.
- RANGEL, H. L. T.. **Análise de Impactos da Integração de Geração Distribuída em Consumidores Conectados à Rede de Energia Elétrica**. Tese de mestrado. Centro Federal de Educação Tecnológica de Minas Gerais, Belo Horizonte, 2024.
- SAMPAIO, F. C. et al.. Smart Protection System for Microgrids with Grid-Connected and Islanded Capabilities Based on an Adaptive Algorithm. **Energies**, v. 16, n. 5, p. 2273, 2023.
- SERNA-MONTOYA, L. F. et al.. Optimal Coordination of Directional Overcurrent Relays in Microgrids Considering European and North American Curves. **Energies**, v. 17, n. 23, 2024.
- SERNA-MONTOYA, L. F. et al.. Optimal Microgrid Protection Coordination for Directional Overcurrent Relays Through Mixed-Integer Linear Optimization. **Energies**, v. 18, n. 8, p. 2035, 2025.
- SRIVASTAVA, A. et al.. A Review on Challenges and Solutions in Microgrid Protection. **2021 IEEE Madrid PowerTech**, 2021.
- STECANELLA, P. A. J.. **Metodologia para a Determinação dos Impactos Técnicos e Financeiros Provocados pela Instalação de Geração Distribuída Fotovoltaica em um Sistema de Distribuição**. Tese de doutorado. Universidade de Brasília, Brasília, 2020.