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Use of Artificial Intelligence in The Control of Electric Power Transmission and Distribution Networks in Brazil

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ABSTRACT
This article addresses the application of artificial intelligence (AI) technologies to optimize the management and operation of the Brazilian electric power sector. With the increasing complexity of energy networks, AI emerges as an essential tool to enhance efficiency, reduce costs, and improve the safety of generation and transmission operations. The research followed a qualitative approach and employed a bibliographic review procedure. The primary objective of this scientific article is to explore the intersections between electrical engineering and computer science, aiming to initiate a discussion on the feasibility of implementing AI to manage Brazil's power generation and transmission networks using the existing infrastructure of the National Interconnected System (SIN). At the end of the study, it is recommended that academia, together with the government and private sector, invest in research on how to apply AI in the control of the SIN, considering global studies on the subject and adapting them to the Brazilian context.

Keywords*: Artificial Intelligence; National Interconnected System; Energy Networks; Optimizing Management and Operation.*

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I. INTRODUCTION

The introduction of artificial intelligence (AI) in the Brazilian electrical sector marks a significant advancement in how energy is generated, distributed, and utilized. Brazil, with its robust National Interconnected System (Sistema Interligado Nacional - SIN), faces challenges associated with the efficient management of its extensive electrical grid, composed primarily of hydroelectric plants and, more recently, renewable sources such as solar and wind energy.

AI enables not only real-time monitoring of operations but also energy demand forecasting, predictive maintenance, and fault identification. These innovations are crucial in the context of growing energy demand, requiring solutions that ensure supply security and reliability. The use of AI has the potential to transform the electrical sector by enabling more efficient allocation of energy resources, reducing supply interruptions, and promoting more sustainable consumption. The implementation of these technologies not only enhances the operational efficiency of companies in the sector but also supports environmental sustainability by facilitating the integration of renewable sources into the energy matrix.

This research followed a qualitative approach and used a bibliographic review method. The general objective of this scientific article is to explore the intersections between the disciplines of electrical and computer engineering, seeking to spark a discussion on the feasibility of implementing Artificial Intelligence (AI) to manage energy generation and transmission networks in Brazil, using the existing infrastructure of the National Interconnected System (SIN). The specific objectives planned are as follows: to present the aspects of Artificial Intelligence; to discuss the National Interconnected System; and to explore the connection between AI and the SIN.

This article is structured into four sections. The first is the introduction, which explains the research objectives. The second section details the methodology, describing the methodological procedures employed in this study. The third section provides the theoretical foundation, constituting a discussion among authors addressing the same topic covered here. The fourth section presents the final considerations.

II. MATERIAL AND METHODS

The research followed a qualitative approach and employed a bibliographic review procedure. This methodology was chosen as it allows for an in-depth analysis of the studied phenomena, considering the complexity and subjectivity of the data. Sousa and Santos (2020, p. 03) understand that:

> In the context of the qualitative approach, there is a unique recognition of the various ways of investigating phenomena that involve human subjectivities and their complex social relations within society. From this perspective, the qualitative approach contrasts with a uniform research model applicable to all sciences, as each discipline has its specificities that vary according to the case under analysis, implying the need for a specific methodology.

The theoretical foundation of the research was based on scientific articles and doctoral theses, providing a broad view of the subject in question. The bibliographic review is a crucial stage, as it allows the researcher to gather and analyze existing information, contributing to knowledge building. As Gil (2019, p. 45) states, "the bibliographic review is a systematic and critical survey of relevant publications on a given topic." Thus, the combination of the qualitative approach with the bibliographic review enabled a deeper understanding of the studied context, as well as offering robust theoretical support for the analyses performed.

The main authors who contributed most to this research were Zhao and Zhang (2016), Sozontov, Ivanova, and Gibadullin (2019), Fikri, Sabri, and Cheddadi (2020), Yousuf et al. (2021), Nath and Balaji (2023), and Santillán and Barzola (2024).

III. THEORETICAL FRAMEWORK

This theoretical foundation was organized into three subtopics. The first discussed aspects of artificial intelligence (AI). The second addressed the National Interconnected System (SIN). The final subtopic explored the intersection, or the link, between AI and SIN.

3.1 Aspects of Artificial Intelligence

Artificial intelligence (AI) represents an interdisciplinary area of computer science aimed at creating systems capable of performing tasks that traditionally require human intelligence. The term "Artificial Intelligence" has several definitions, including the one by Russell and Norvig (2010, p. 2): "The automation of activities associated with human thinking, such as decision-making, problem-solving, and learning; the study of mental faculties through computational models; the study of how to build computers to perform tasks that, so far, humans perform better."

The term "AI" was initially defined in 1955 by Professor John McCarthy, the first faculty member in AI at Stanford University, as "the science and engineering of making intelligent machines" (apud Manning, 2022, p. 01). Given certain constraints in data processing capabilities, AI qualifies as a technology that can offer higher quality and efficiency, often yielding better results than human specialists (Bughin & Hazan et al., 2018).

AI has become significant across various scientific fields and has gained prominence in public debate, as it can emulate human intelligence, supporting or, in some cases, even surpassing human abilities (Mueller & Massaron, 2021).

3.2 The National Interconnected System

The National Interconnected System (SIN) is a large-scale hydro-thermal-wind system for electricity generation and transmission in Brazil, comprising four subsystems: South, Southeast/Central-West, Northeast, and most of the Northern region (ONS, 2024a).

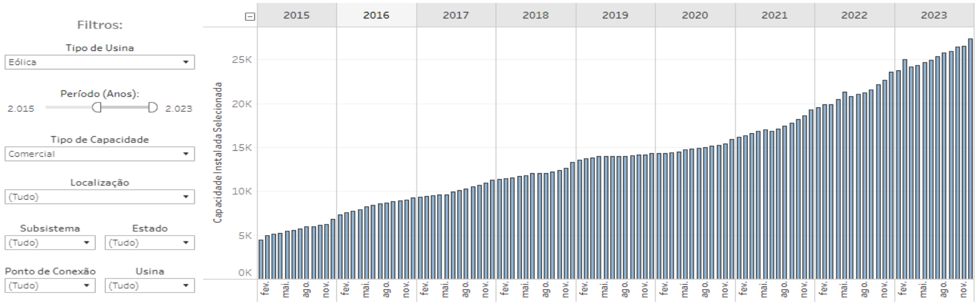
The interconnection of these subsystems is achieved through a complex transmission network, enabling the transfer of electricity across all regions of Brazil and allowing for a secure and economical energy supply. The energy generation of SIN predominantly comes from hydroelectric plants, which are distributed across sixteen river basins throughout Brazil, though generally located far from consumer centers. In contrast, thermoelectric plants are situated closer to major consumer hubs and play a critical role in SIN’s reliability. Given Brazil's vast size, river basins experience different hydrological cycles, and thermoelectric plants can be activated to manage the water reserves in the reservoirs, ensuring future energy supply (ONS, 2024a).

3.1.1 Impacts of the Introduction of Renewable Energy Sources in SIN

The installed capacity of wind energy increased from 6,850 MW in 2015 to 27,354 MW in 2023, representing a substantial growth of 299.33%, as illustrated in Figure 1.

On the other hand, solar energy experienced even more remarkable growth, rising from 10 MW in 2015 to 10,132 MW in 2023—a staggering increase of 101,220%, as shown in Figure 2.

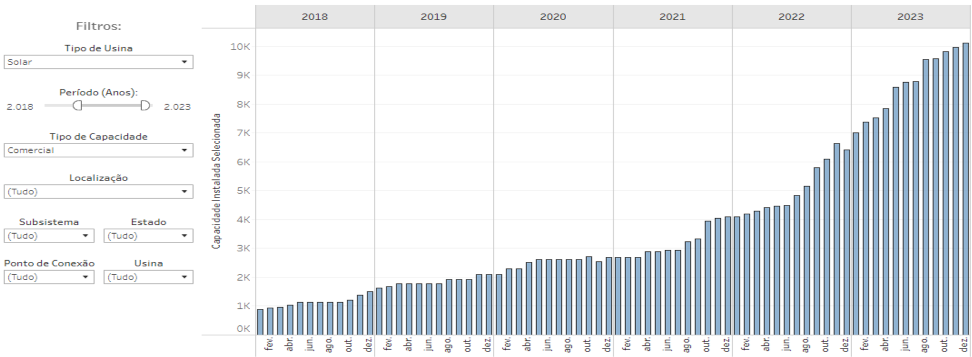
Figure 1 - Evolution of Installed Wind Capacity



	jan.	fev.	mar.	abr.	mai.	jun.	jul.	ago.	set.	out.	nov.	dez.
2015	4.488	4.942	5.151	5.239	5.477	5.587	5.763	5.963	5.974	6.153	6.197	6.850
2016	7.337	7.611	7.780	7.950	8.261	8.421	8.604	8.672	8.816	8.962	9.025	9.304
2017	9.375	9.447	9.543	9.573	9.643	9.924	10.131	10.283	10.526	10.709	10.911	11.314
2018	11.384	11.438	11.499	11.704	11.823	12.035	12.065	12.037	12.213	12.417	12.663	13.326
2019	13.520	13.696	13.831	13.994	13.994	13.994	13.994	14.023	14.049	14.121	14.190	14.282
2020	14.302	14.322	14.410	14.482	14.715	14.833	14.946	15.001	15.125	15.256	15.432	15.943
2021	16.209	16.342	16.605	16.810	17.054	16.860	17.118	17.439	17.758	18.169	18.607	19.268
2022	19.581	19.853	19.905	20.496	21.334	20.800	21.035	21.248	21.565	22.151	22.647	23.583
2023	23.749	25.016	24.157	24.329	24.657	24.891	25.325	25.777	25.963	26.425	26.567	27.354

Source: ONS (2024b)

Figure 2 - Evolution of Installed Solar Capacity



	jan.	fev.	mar.	abr.	mai.	jun.	jul.	ago.	set.	out.	nov.	dez.
2018	892	926	961	1.029	1.142	1.142	1.142	1.142	1.142	1.203	1.389	1.513
2019	1.628	1.688	1.769	1.769	1.769	1.769	1.769	1.920	1.920	1.920	2.090	2.090
2020	2.090	2.286	2.286	2.518	2.618	2.618	2.618	2.618	2.618	2.714	2.555	2.693
2021	2.693	2.693	2.693	2.879	2.879	2.942	2.942	3.226	3.321	3.944	4.042	4.090
2022	4.090	4.190	4.297	4.418	4.458	4.502	4.832	5.163	5.798	6.093	6.635	6.430
2023	6.999	7.369	7.519	7.842	8.585	8.753	8.792	9.558	9.587	9.827	9.977	10.132

Source: ONS (2024b)

It is noteworthy that these data refer only to the generation from plants under the centralized dispatch and scheduling control of the National System Operator (ONS), considering commercial operations only. Thus, they do not account for the impact of self-generation, such as that by residential or small business and commercial installations. Over an 8-year period, there has been a significant increase in electricity generation from the main renewable sources, reaching 30,626 MW.

This amount of energy, approaching 31 GW, must be precisely managed by the National System Operator (ONS), considering consumption demand as well as climatological and market factors. However, it is important to emphasize that these energy sources are not fully dispatchable. For instance, during excessive nighttime demand, solar plants cannot immediately meet this demand for obvious reasons.

Similarly, unexpected overproduction at a given time by one or more wind farms could exceed demand, causing other generation sources to shut down. This would occur without direct consent or intervention from the ONS, but rather through automatic curtailment systems. Therefore, effective management of these energy sources is crucial to maintaining the balance between supply and demand. A clear example of the massive introduction of new renewable energy sources without proper ONS oversight occurred during the blackout on August 15, 2023, at 8:30 AM, when the automatic disconnection of the 500 kV transmission line between Quixadá and Fortaleza II took place.

According to ONS analyses presented in this document, the abrupt voltage drop observed in the field after the loss of a single transmission line was due to the unexpected performance of wind and photovoltaic plants in the field, which was much lower than that expected by ONS based on their studies. These studies are conducted using mathematical models provided to ONS by the agents involved (ONS, 2023).

To control this sudden voltage drop, the Regional Load Relief Scheme (ERAC) was activated, resulting in the disconnection of 23,368 MW of load from the National Interconnected System (SIN). Of this total, 12,689 MW pertained to the North/Northeast macro-region, and 10,680 MW to the South/Southeast/Central-West macro-region. This situation culminated in a blackout (ONS, 2023).

3.3 The Link between AI and the SIN

Given that the ONS uses mathematical models to simulate the SIN, enabling system operators to make crucial national decisions with significant economic and environmental impacts, and considering that AI is a technology that automates activities simulating human thought—such as decision-making, problem-solving, and learning—while also offering increased quality and efficiency, why not explore the potential of this link? This question regarding the interaction between the mathematical models used in modeling the National Interconnected System (SIN) by the National System Operator (ONS) and the increasing presence of artificial intelligence (AI) in the sector is essential. Traditionally, SIN modeling employs complex mathematical models that are key to making decisions that impact the economy and the environment, influencing energy resource allocation and the reliability of energy supply (Castro, Borges, & Simone, 2023).

Given the importance of these decisions, it raises the question of why AI's potential to enhance these processes is not explored more broadly. AI can automate processes that mimic human reasoning, offering greater efficiency and accuracy in managing the SIN. Unlike conventional mathematical models, which rely on fixed parameters and human interpretation, AI learns from real-time data, adapting automatically to new patterns. This approach not only optimizes routine operations but also enables the prediction of energy crises and the identification of potential failures before they occur, providing solutions that traditional models might not reach with the same effectiveness (Artaxo, Rizzo, & Machado, 2024).

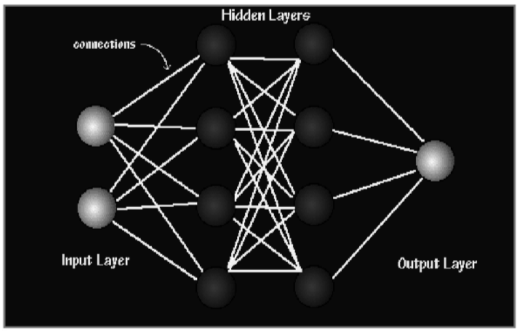
A central aspect of this discussion is the synergy between the mathematical models used by the ONS and AI. While mathematical models provide a robust foundation, AI can evolve with data and optimize processes in real-time. Combining these approaches could result in a hybrid system in which AI complements existing models, automating analyses and forecasting future scenarios with greater precision (Meneses, 2012). Artificial Neural Networks (ANNs) are particularly noted for their ability to model nonlinear problems and learn from data, making them suitable for tasks like rainfall estimation and flow forecasting (Fikri, Sabri, & Cheddadi, 2018; Bordin, 2020).

A comparison of different AI methodologies shows that, although ANNs are effective for specific forecasting tasks, other models, such as Adaptive Neuro-Fuzzy Inference Systems (ANFIS) and Support Vector Machines (SVM), may outperform them in certain scenarios (Bordin, 2020).

3.3.1 Artificial Neural Networks (ANNs)

An artificial neural network (ANN) is a computing system inspired by the biological neural networks found in animal brains. It is designed to simulate how the human brain analyzes and processes information (Fikri, 2020). The basic structure of an ANN consists of artificial neurons grouped into layers. Typically, an ANN includes an input layer, one or more hidden layers, and an output layer, as shown in Figure 3. This layered structure enables the network to learn and make decisions by adjusting the connections between neurons (Fikri, 2020).

Figure 3 – Artificial Neuron Model



Source: NATH (2023)

3.4 Adaptive Neuro-Fuzzy Inference Systems (ANFIS)

The Adaptive Neuro-Fuzzy Inference System (ANFIS) is a hybrid intelligent system that merges the strengths of artificial neural networks (ANNs) with fuzzy logic principles to model complex systems. This integration allows ANFIS to utilize the learning capabilities of neural networks and the interpretability of fuzzy systems (Fikri, 2020).

ANFIS is structured into five layers, each corresponding to a step in a Takagi-Sugeno type fuzzy inference system. The structure of ANFIS is critical to its performance, making it essential to select the appropriate type, number, and parameters of the membership functions for effective learning and adaptation (Fikri, 2020).

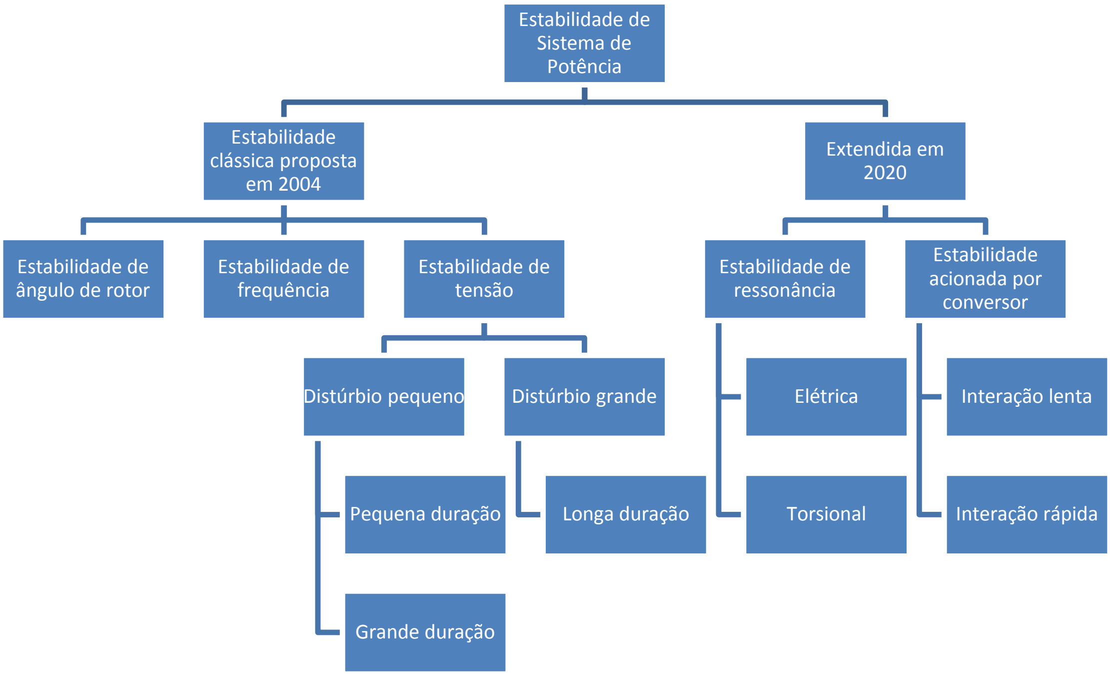
The learning process in ANFIS involves a two-pass cycle: forward propagation and backpropagation. During training, the parameters of the membership functions are adjusted using the backpropagation algorithm, sometimes in combination with other methods, such as the least squares method, to achieve optimal prediction results (Fikri, 2020).

ANFIS's capacity to combine neural network adaptability with fuzzy system interpretability makes it especially valuable for tasks that require handling uncertainty and complexity, such as energy load forecasting and dynamic system modeling in power systems.

3.4.1 Stability in Power Electric Systems (PES)

Stability is a fundamental property of any system, such as a Power Electric System (PES), referring to its ability to operate in a stable state under normal conditions and to return to that state after experiencing a disturbance. There are different types of stability, as illustrated in Figure 4 (Barzola, 2024).

Figure 4 – Classification of Stability in Power Electric Systems



Source: Barzola (2024)

There are various factors that cause instability in Power Systems, such as increased load, operation at the maximum limits of machines, the distance from the generation source to the consumption center, and excessively high inductive reactive power (Barzola, 2024).

The introduction of renewable energy sources into the Power System can also lead to instability, as discussed in Section 3.2.1. In a scenario of growing energy demand and transition to renewable sources, this collaboration would bring significant benefits. The integration of artificial intelligence would facilitate faster and more informed decision-making, particularly in critical situations, thereby enhancing operational efficiency and promoting more effective environmental management by prioritizing sustainable solutions.

IV. DISCUSSION AND CONCLUSION

The research fully met the proposed objectives, highlighting the fundamental aspects of Artificial Intelligence (AI), discussing the National Interconnected System (SIN), and establishing the connection between them. The study demonstrated that Brazil needs to treat AI as a crucial component in the control of the SIN.

AI should be a vital tool in the context of SIN management, considering that the recurring introduction of new renewable energy plants into the system exponentially increases its complexity, thereby complicating human actions in the control of the SIN.

Finally, it is recommended that academia, in collaboration with the government and the private sector, invest in research on how to apply AI in the control of the SIN, taking into account globally developed articles on the subject and adapting them to the Brazilian context.

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