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Artificial intelligence techniques for modeling wind behavior: innovations in wind forecasting

Técnicas de inteligência artificial para a modelagem do comportamento do vento: inovações na previsão eólica

Técnicas de inteligencia artificial para modelar el comportamiento del viento: innovaciones en el pronóstico eólico

Lucas Emanuel Almeida Barboza

Abstract:
The stochastic and chaotic nature of wind is one of the greatest challenges to safely integrating wind energy into modern power grids. This article presents a qualitative literature review aimed at analyzing the application of artificial-intelligence (AI) and machine-learning techniques to modeling and forecasting wind behavior. The methodology is based on an integrative literature review selecting recent articles and reference works on data science applied to renewable energy. The results indicate that traditional physical and statistical models have limitations over very short time horizons, a setting in which artificial neural networks (ANNs) and deep-learning algorithms stand out for their ability to map complex nonlinear patterns. It is concluded that the systemic adoption of AI not only reduces forecasting errors and minimizes regulatory penalties but also drives sector digitalization through advanced predictive technologies.

Keywords:
Artificial intelligence. Machine learning. Wind forecasting. Artificial neural networks. Time series.

Resumo:
A natureza estocástica e caótica do vento representa um dos maiores desafios para a integração segura da energia eólica às redes elétricas modernas. O presente artigo apresenta uma revisão bibliográfica qualitativa com o objetivo de analisar a aplicação de técnicas de Inteligência Artificial (IA) e Aprendizado de Máquina (Machine Learning) na modelagem e previsão do comportamento do vento. A metodologia fundamenta-se em uma revisão integrativa da literatura, selecionando artigos recentes e obras de referência sobre ciências de dados aplicadas a energias renováveis. Os resultados indicam que modelos tradicionais físicos e estatísticos apresentam limitações em horizontes de curtíssimo prazo, cenário onde as Redes Neurais Artificiais (RNAs) e algoritmos de Deep Learning se destacam pela capacidade de mapear padrões não lineares complexos. Conclui-se que a adoção sistêmica da IA não apenas reduz os erros de previsão (minimizando penalidades regulatórias), mas também impulsiona a digitalização do setor por meio de tecnologias preditivas avançadas.

Palavras-chave:
Inteligência artificial. Machine Learning. Previsão eólica. Redes neurais artificiais. Séries temporais.

Resumen:
La naturaleza estocástica y caótica del viento representa uno de los mayores desafíos para integrar de forma segura la energía eólica en las redes eléctricas modernas. Este artículo presenta una revisión bibliográfica cualitativa cuyo objetivo es analizar la aplicación de técnicas de inteligencia artificial (IA) y aprendizaje automático (Machine Learning) al modelado y pronóstico del comportamiento del viento. La metodología se fundamenta en una revisión integradora de la literatura que selecciona artículos recientes y obras de referencia sobre ciencia

de datos aplicada a energías renovables. Los resultados indican que los modelos físicos y estadísticos tradicionales presentan limitaciones en horizontes de muy corto plazo, contexto en el que las redes neuronales artificiales (RNA) y los algoritmos de Deep Learning destacan por su capacidad para mapear patrones no lineales complejos. Se concluye que la adopción sistémica de la IA no solo reduce los errores de pronóstico y minimiza penalizaciones regulatorias, sino que también impulsa la digitalización del sector mediante tecnologías predictivas avanzadas.

Palabras clave:
Inteligencia artificial. Machine Learning. Pronóstico eólico. Redes neuronales artificiales. Series temporales.

1. Introduction

The growing penetration of wind energy into global energy mixes brings a significant operational challenge: intermittency. The inability to dispatch wind energy on demand requires highly accurate weather and generation forecasts so that national system operators can balance the power grid by turning other energy sources on or off in real time (SOMAN et al., 2010). Historically, wind forecasting has relied on mesoscale numerical weather prediction (NWP) models and traditional statistical methods such as ARIMA. However, the fluid-dynamic complexity of the atmosphere makes these models less accurate at very fine spatial resolutions or for very-short-term forecasts (nowcasting) (KUSIAK; ZHENG, 2010). Therefore, this article analyzes how artificial intelligence and machine learning are emerging as transformative tools for modeling wind behavior and overcoming the limitations of classical methods.

2. Theoretical framework

2.1. Traditional limitations and the rise of machine learning

Physical models (NWP) rely on supercomputers to solve complex thermodynamic equations. Although effective for long-term projections measured in days, they are computationally expensive and often fail to capture abrupt wind variations caused by microscale topography. Purely statistical models, in turn, assume linearity in time series, an inadequate premise for the chaotic nature of weather. According to Zufferey et al. (2017), machine learning has emerged to fill this gap through a data-driven learning paradigm. Instead of programming rigid physical rules, algorithms such as support vector machines (SVMs) and decision trees (random forests) are trained on large historical volumes of anemometric data

(SCADA) to identify intricate patterns and map the nonlinear correlation between weather conditions and wind speed at the turbine site.

2.2. Deep neural networks in time series

The state of the art in computational atmospheric modeling has shifted from traditional machine learning toward deep learning. The architecture of artificial neural networks (ANNs) mimics brain function and comprises multiple hidden layers capable of abstracting high-level features from raw data (GOODFELLOW; BENGIO; COURVILLE, 2016). In wind modeling, recurrent neural networks (RNNs), particularly the long short-term memory (LSTM) variant, stand out. Unlike traditional networks, LSTMs have "memory", which allows them to retain information about past winds to forecast future winds, making them an ideal architecture for processing complex atmospheric time series (WANG et al., 2019).

3. Materials and method

This study is characterized as qualitative research conducted through an integrative literature review. To capture the field's rapid technological advance, the search prioritized scientific articles and conference proceedings published during the last decade (2014-2024) in IEEE Xplore, ScienceDirect, and Google Scholar. Selection criteria included texts addressing the transition from linear statistical methods to artificial-intelligence techniques in atmospheric science. Data analysis used a categorization technique, organizing the findings according to gains in accuracy and computational limitations of AI applications in the sector.

4. Results and discussion

The literature analysis shows that AI-based models significantly reduce error metrics such as RMSE (root mean square error) and MAE (mean absolute error) in short- and very-short-term wind forecasts (0 to 6 hours). AI does not eliminate the need for classical meteorology; on the contrary, the current trend is toward "hybrid models", in which neural networks correct bias and refine results generated by physical NWP models (KUSIAK; ZHENG, 2010). Despite excellent predictive results, the literature identifies important operational bottlenecks. The main challenge is the "black-box" nature of deep neural networks, which makes it difficult for meteorologists to physically interpret forecasts. Effective model

training also requires big-data infrastructure, compelling wind farms to invest heavily in the quality of observational data, including telemetry and high-quality sensors, to avoid the garbage-in, garbage-out phenomenon.

5. Final considerations

The research achieved its objective by demonstrating that artificial intelligence is an indispensable driver of innovation in modeling wind behavior. It is concluded that machine-learning algorithms, especially LSTM neural networks, provide the mathematical agility needed to manage the volatility inherent in wind energy. As a theoretical contribution, this article systematized the technological transition of wind forecasting into the domain of data science. Future research should investigate digital twins integrated with artificial intelligence and assess how virtual models synchronized in real time with physical wind farms can optimize fault diagnosis, aerodynamic-wake prediction, and active control of plant power.

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