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Fault Location in HVDC Systems Using Multilayer Perceptron and Wavelet Packet Transform: A Sustainable Approach to Renewable Energy Integration

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Localização de Faltas em Sistemas HVDC Utilizando Perceptron Multicamadas e Transformada Wavelet Packet: Uma Abordagem Sustentável para a Integração de Energias Renováveis

RESUMO

Objetivo: O estudo tem como objetivo desenvolver e avaliar um modelo baseado em redes neurais, especificamente o Perceptron Multicamadas (MLP) em conjunto com a Transformada Wavelet Packet (TWP), para aprimorar a localização de faltas em sistemas de transmissão de energia em corrente contínua de alta tensão (HVDC), visando contribuir para a sustentabilidade ambiental ao aumentar a eficiência e a confiabilidade desses sistemas.

Metodologia: A pesquisa utiliza dados de corrente medidos na linha HVDC como entradas para treinar o modelo MLP, avaliando seu desempenho por meio de métricas como Erro Absoluto Médio (MAE) e Erro Quadrático Médio (MSE). O estudo simula diferentes condições operacionais para testar a eficácia do modelo.

Originalidade/relevância: O trabalho se insere no gap teórico relacionado à necessidade de técnicas mais eficientes e precisas para localização de faltas em sistemas HVDC, destacando a relevância acadêmica e prática de soluções que minimizem o tempo de resposta e maximizem a eficiência energética, contribuindo para a redução do impacto ambiental.

Resultados: O modelo proposto demonstra alta precisão na localização de faltas, reduzindo significativamente o erro de estimação e eventualmente a redução do tempo de inatividade da linha de transmissão.

Contribuições teóricas/metodológicas: O estudo contribui com uma abordagem que combina MLP e TWP, oferecendo um método robusto para a localização de faltas em sistemas HVDC, com aplicações potenciais em outros sistemas de transmissão de energia.

Contribuições sociais e ambientais: A pesquisa reforça os benefícios ambientais das linhas HVDC, como a eficiência energética e o menor impacto ambiental, ao propor uma solução que reduz o tempo de inatividade e aumenta a confiabilidade do sistema, promovendo a sustentabilidade na transmissão de energia.

PALAVRAS-CHAVE: HVDC. Localicazação de faltas. Sustentabilidade.

Fault Location in HVDC Systems Using Multilayer Perceptron and Wavelet Packet Transform: A Sustainable Approach for Renewable Energy Integration

ABSTRACT

Objective: The study aims to develop and evaluate a model based on neural networks, specifically the Multilayer Perceptron (MLP) combined with the Wavelet Packet Transform (WPT), to improve fault location in High-Voltage Direct Current (HVDC) transmission systems, contributing to environmental sustainability by enhancing the efficiency and reliability of these systems.

Methodology: The research uses current data measured from the HVDC line as inputs to train the MLP model, evaluating its performance through metrics such as Mean Absolute Error (MAE) and Mean Squared Error (MSE). The study simulates different operational conditions to test the model's effectiveness.

Originality/relevance: This work addresses a theoretical gap concerning the need for more efficient and accurate techniques for fault location in HVDC systems. It highlights both the academic and practical relevance of solutions that minimize response time and maximize energy efficiency, thereby contributing to the reduction of environmental impact.

Results: The proposed model exhibits high accuracy in fault location, significantly reducing estimation errors and, consequently, transmission line downtime.

Theoretical/methodological contributions: The study contributes with an innovative approach combining MLP and WPT, offering a robust method for fault location in HVDC systems, with potential applications in other energy transmission systems.

Social and environmental contributions: The research highlights the environmental benefits of HVDC lines, including energy efficiency and reduced environmental impact, by proposing a solution that minimizes downtime and enhances system reliability, thereby promoting sustainability in power transmission.

KEYWORDS: HVDC. Fault Location. Sustainability.

Localización de Fallas en Sistemas HVDC Utilizando Perceptrón Multicapa y Transformación de Paquetes Wavelet: Un Enfoque Sostenible para la Integración de Energías Renovables

RESUMEN

Objetivo: El estudio tiene como objetivo desarrollar y evaluar un modelo basado en redes neuronales, específicamente el Perceptrón Multicapa (MLP) combinado con la Transformada de Paquetes de Wavelets (TPW), para mejorar la localización de fallas en sistemas de transmisión de energía de corriente continua de alta tensión (HVDC), contribuyendo a la sostenibilidad ambiental al aumentar la eficiencia y confiabilidad de estos sistemas.
Metodología: La investigación utiliza datos de corriente medidos en la línea HVDC como entradas para entrenar el modelo MLP, evaluando su desempeño mediante métricas como el Error Absoluto Medio (MAE) y el Error Cuadrático Medio (MSE). El estudio simula diferentes condiciones operativas para probar la eficacia del modelo.
Originalidad/relevancia: El trabajo aborda la brecha teórica relacionada con la necesidad de técnicas más eficientes y precisas para la localización de fallas en sistemas HVDC, destacando la relevancia académica y práctica de soluciones que minimicen el tiempo de respuesta y maximicen la eficiencia energética, contribuyendo a la reducción del impacto ambiental.
Resultados: El modelo propuesto demuestra una alta precisión en la localización de fallas, reduciendo significativamente los errores de estimación y, eventualmente, el tiempo de inactividad de la línea de transmisión.
Contribuciones teóricas/metodológicas: El estudio contribuye con un enfoque innovador que combina MLP y TPW, ofreciendo un método robusto para la localización de fallas en sistemas HVDC, con aplicaciones potenciales en otros sistemas de transmisión de energía.
Contribuciones sociales y ambientales: La investigación refuerza los beneficios ambientales de las líneas HVDC, como la eficiencia energética y el menor impacto ambiental, al proponer una solución que reduce el tiempo de inactividad y aumenta la confiabilidad del sistema, promoviendo la sostenibilidad en la transmisión de energía.

PALABRAS CLAVE: HVDC. Localización de fallas. Sostenibilidad.

1. INTRODUCTION

High Voltage Direct Current (HVDC) transmission lines are a viable solution for long-distance energy transmission, overcoming many limitations of High Voltage Alternating Current (HVAC) systems. While HVAC systems suffer significant energy losses over long distances, HVDC technology offers higher efficiency, reducing these losses considerably (NGUYEN; ETINGOV; ELIZONDO, 2023). Studies indicate that, depending on the transmission distance and line conditions, HVDC systems can reduce losses by 30-50% compared to AC lines (YOUSAF et al., 2024). Additionally, HVDC transmission enhances operational stability and facilitates grid interconnections across different regions and countries (MERZAH; ABBAS; TUAIMAH, 2024).

In the context of sustainable development, as outlined in the United Nations (UN) 2030 Agenda, adopting energy-efficient technologies is crucial for minimizing environmental impact. HVDC aligns with multiple Sustainable Development Goals (SDGs) by contributing to carbon emission reduction and improving the reliability of electrical grids through renewable energy integration (Purificação, Ramos, & Kniess, 2020). Therefore, beyond optimizing electricity transmission, HVDC strengthens global sustainability initiatives and promotes responsible resource utilization.

A key advantage of HVDC technology is its compatibility with renewable energy sources such as photovoltaic and wind power. Unlike AC systems, direct current facilitates the efficient transmission and storage of intermittent energy sources—critical for a more sustainable energy matrix (HUSIN et al., 2021). In regions with high renewable energy potential, HVDC systems mitigate stability issues and physical constraints caused by the variability of these sources.

Moreover, HVDC systems require less installation space, as they utilize narrower easement strips compared to HVAC lines. This is particularly beneficial in ecologically sensitive areas or regions where land acquisition is challenging, such as conservation zones. By reducing environmental impact and facilitating projects in areas with land acquisition challenges (ANDERSEN, 2023). HVDC technology is also essential for offshore wind energy integration. The use of HVDC in offshore wind farms enables the efficient transmission of large power capacities to the mainland while reducing the number of required cables, thereby minimizing environmental disruption (RAHMAN et al., 2021). Thus, HVDC lines offer significant economic and environmental benefits. Its lower territorial invasiveness and reduced impact on ecosystems make it a sustainable option. However, ensuring the continuous and reliable transmission of power remains a critical challenge. Efficient fault detection and location systems are essential to maintaining uninterrupted operation.

Fault location in HVDC systems is particularly challenging due to the absence of natural current commutation current (which occurs in AC networks) and the rapid propagation of electrical transients. Traditional impedance-based fault detection methods often struggle with the complexity of direct current transmission (PRAGATI et al., 2023). To overcome these limitations, Rohani and Koochaki (2020) have explored artificial intelligence (AI)-driven approaches and advanced signal analysis techniques, reducing response time and enabling more reliable fault identification while maximizing HVDC technology benefits.

This study proposes the application of a Multilayer Perceptron (MLP) artificial neural

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network combined with the Wavelet Packet Transform (WPT) technique for accurate fault location in HVDC systems. WPT enables the extraction of time-domain information from transient waves generated during fault events, enabling accurate fault location. This approach improves fault detection, accelerates operation restoration, and ensures the continuity of transmission while maintaining HVDC's environmental benefits.

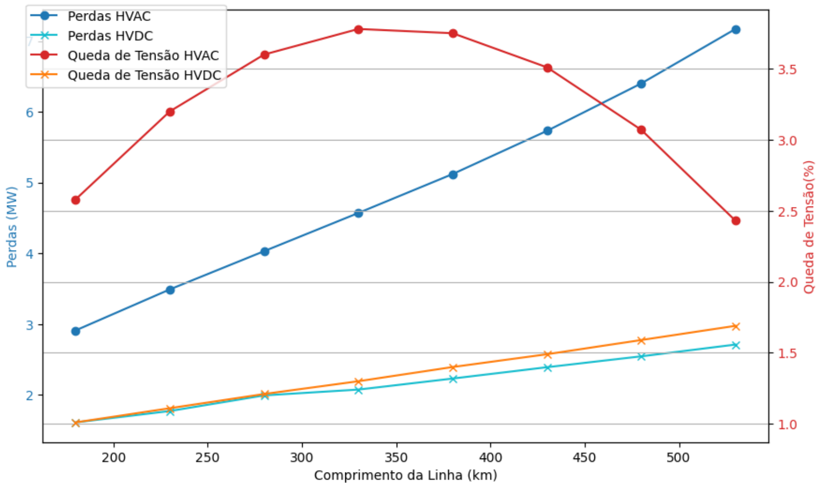
2 LITERATURE REVIEW

The promotion of renewable energy sources has become a key policy strategy for mitigating climate change and enhancing energy security (RIBEIRO & BRAGHINI JUNIOR, 2023). In this context, the demand for low-impact energy solutions has driven the adoption of HVDC power transmission, a technology that significantly reduces energy losses over long distances.

In HVAC systems, Joule effect losses are substantial, requiring intermediate substations to compensate for energy dissipation (NGUYEN, ETINGOV, & ELIZONDO, 2023). In contrast, HVDC transmission minimizes these losses and reduces the need for additional infrastructure, such as substations and extra transmission cables (WANG, LI, & GUO, 2022). Studies indicate that an HVDC transmission line can exhibit up to 56% lower energy losses and a 58% lower voltage drop compared to an equivalent HVAC system (ALAM et al., 2022). Beyond its technical efficiency, HVDC aligns with global climate strategies for mitigation and energy security as its lower energy losses contribute to more efficient use of electricity generation. This lowers CO_2 emissions.

Figure 1 illustrates the relationship between transmission losses and distance for a 400 kV transmission line over distances ranging from 180 km to 700 km. The figure highlights the significantly higher energy and voltage losses associated with increasing HVAC transmission distances compared to HVDC (ALAM et al., 2022).

Figure 1 - Comparison of Power Losses and Voltage as a function of line length.



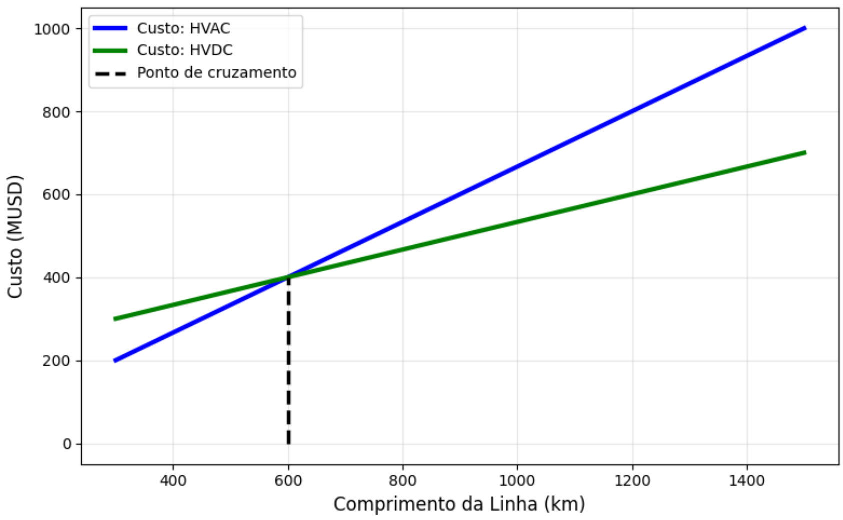
Source: Adapted from table 3 (ALAM et al., 2022).

The sustainable technology adoption in power transmission is fundamental to boosting the transition to renewable sources and meeting international decarbonization commitments, ensuring a safer and more economically viable electricity system.

Figure 2 illustrates the general costs associated with HVAC transmission lines, showing that not only do these lines have higher losses, but their costs also tend to increase significantly as the line length extends. Additionally, long-distance AC transmission incurs extra costs related to the need for reactive compensation.

Due to the Ferranti effect, the voltage along the line can increase considerably, particularly in high-voltage systems operating under light or no load. This phenomenon occurs due to the predominance of the capacitive effect over the inductive effect of th e line, leading to a rise in voltage towards the middle and end of the line. Consequently, the transferred power can be limited, requiring corrective measures to maintain the stability of the system. To mitigate the Ferranti effect and ensure optimal power transmission, Static Reactive Compensators are typically installed at strategic points along the line. This requirement further raises the cost of HVAC lines (MUSHI, SUWI & JUSTO, 2024), making HVDC technology a more economically viable alternative for long-distance transmission beyond the point identified in the graph.

Figure 2 – HVDC vs HVAC: Cost comparison as a function of line length.



Source: Adapted from Arcuri et al.(2022)

Another benefit of HVDC systems is their ability to support underground transmission lines, which reduces their visual impact and helps preserve natural landscapes, particularly in tourist and rural areas (HUSIN et al., 2021). This feature minimizes conflicts with local communities, reduces the need for expropriation, and is less invasive in environmentally sensitive regions.

Furthermore, HVDC lines generate lower electromagnetic interference compared to HVAC systems, making them an attractive option. Research shows that the electromagnetic fields produced by HVDC lines are more stable and less intense, reducing potential impacts on local fauna and flora (WATSON & WATSON, 2020). This characteristic is particularly important in areas of high biodiversity, where projects must balance energy efficiency with environmental conservation (ANDERSEN, 2023).

The integration of HVDC technology with renewable energy sources, such as solar and wind, is a key factor in developing sustainable energy systems. HVDC's ability to handle the intermittency of these energy sources without compromising grid stability is vital for transitioning to a low-carbon economy. Additionally, the interconnection of networks across different countries and regions using HVDC maximizes the exchange and use of renewable energy, helping to reduce reliance on fossil fuels (HUSIN et al., 2021).

Lastly, the literature highlights the need for efficient fault location systems in HVDC lines. Traditional methods often fall short when addressing the complexities of DC transmission, particularly in long-distance scenarios (PRAGATI et al., 2023). Advanced algorithms, such as the multilayer perceptron combined with WPT, provide enhanced accuracy and speed in fault detection. This ensures the continuity of operations and the sustained benefits of HVDC technology (ROHANI & KOOCHAKI, 2020).

3 OBJECTIVES AND MAIN CONTRIBUTIONS

With the growing demand for efficient and sustainable transmission systems, HVDC lines have emerged as a leading solution. However, fault location remains a technical challenge, particularly in long-distance transmission lines. This study aims to develop and evaluate a neural network model, specifically the MLP, to enhance fault location accuracy in HVDC systems. The speed and accuracy of fault detection have a direct impact on the response time of teams tasked with repairing the fault, ultimately affecting the time it takes to restore power transmission after a failure.

To achieve precise fault location, the study uses the current values measured along the HVDC line as inputs to the neural network. Through proper training, the neural network will be able to identify the fault location by analyzing the current variation profile along the transmission line.

Among the specific objectives, this work aims to analyze the environmental benefits of HVDC lines, emphasizing their energy efficiency and reduced environmental impact, while also exploring the benefits of accurate fault detection in HVDC systems.

The main contribution of this work is the evaluation of the MLP model's performance in fault location accuracy. This is measured using metrics like Mean Absolute Error (MAE) and Mean Squared Error (MSE) under different operating conditions. The goal is to minimize maintenance downtime, preserving the environmental advantages associated with HVDC technology. In doing so, the study contributes to both innovation in electrical engineering and the global pursuit of sustainability in power transmission.

4 HVDC TRANSMISSION LINES: DEFINITION, OPERATION AND IMPORTANCE

HVDC transmission lines represent a significant innovation in electric power transmission, especially in long-distance scenarios and for intercontinental systems. Unlike HVAC systems, which operate with alternating current, HVDC lines use high voltage direct current to transport electricity from one point to another (KALAIR; ABAS; KHAN, 2016). Direct current transmission minimizes resistive losses, improving efficiency, especially when it comes to connecting electrical networks that are geographically distant and with different frequencies or network topologies (FARGHALI et al., 2023).

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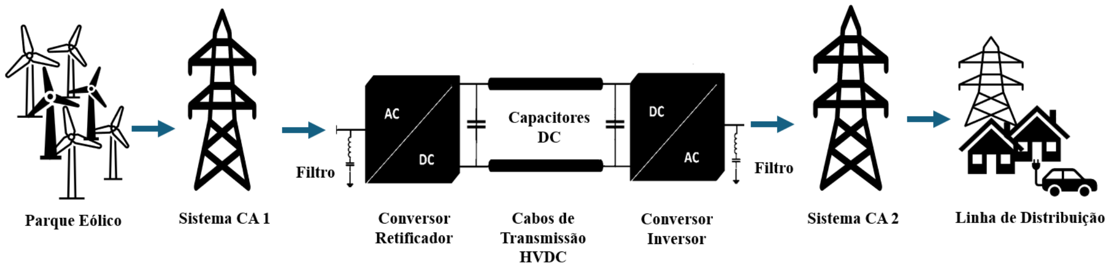
2.6 4.1 HVDC Lines Operation

The figure below illustrates an HVDC grid system that interconnects a wind farm to an electric power distribution network, highlighting the direct current transmission process. The system consists of a rectifier converter station, a direct current (DC) transmission line, an inverter converter station, and alternating current (AC) systems at the ends for integration with the conventional grid.

Figure 3 - Interconnection between Wind Farm and Distribution Network via HVDC.



Source: Prepared by the author.

The integration of the HVDC system with AC networks takes place through converter stations located at the ends of the transmission line. These stations aim to convert electrical power from AC to DC and vice versa, ensuring compatibility between HVDC and AC networks.

At the rectifier converter station, located near the power generation source, such as the wind farm, the electric energy in AC is converted to DC, allowing transmission with lower losses and greater efficiency. The direct current transmission line has two conductors, the positive and negative poles, in contrast to the three conductors required by three-phase alternating current systems. This configuration reduces costs and simplifies infrastructure.

Moreover, the use of DC effectively eliminates the skin effect, a phenomenon that limits the full utilization of conductors in AC systems, further enhancing transmission efficiency (MATHELUBA; MBULI, 2024).

At the receiving end, the inverter converter station performs the reverse process, converting DC power back to AC. This allows seamless integration into the conventional distribution network. This setup enables an efficient connection between renewable energy sources and AC systems, enhancing grid flexibility and stability, while also providing greater transmission capacity and precise power flow control.

4.2 Applications and Favorable Scenarios to the Use of HVDC

HVDC technology is particularly beneficial for long-distance power transmission, intercontinental interconnections, and offshore environments like wind farms (RAHMAN et al., 2021). For transmission distances exceeding 600 km, such as those connecting remote regions to urban centers, HVDC lines become economically viable. This is because resistive losses are significantly lower compared to HVAC systems, even over extreme distances (ALAM et al., 2022).

Moreover, HVDC transmission is an ideal solution for interconnecting networks operating at different frequencies, such as the North American (60 Hz) and European (50 Hz) grids. Another example is the interconnection between Brazil and Paraguay, where HVDC technology links Brazil's 60 Hz system with Paraguay's 50 Hz system. This interconnection enhances the integration of international networks, improving the security and stability of the energy supply. Additionally, in regions with environmental and territorial constraints, HVDC stands out due to its smaller easement strips and reduced visual impact, as it requires fewer supporting structures for the transmission line.

4.3 Importance and Benefits of HVDC Lines

HVDC transmission lines play a crucial role in energy systems seeking the decarbonization and integration of renewable energies. The technology allows connecting remote wind and solar farms directly to consumption centers, minimizing energy losses and promoting the use of renewable sources. With the growing demand for renewable energy, HVDC's ability to carry out energy transmission in high efficiency and stability assists in the transition to a more sustainable and resilient electrical system.

Additionally, HVDC lines allow for greater control over power flow, reducing the risk of fluctuations and imbalances in the power grid. Unlike HVAC lines, where synchronization between different regions must be strictly maintained, HVDC lines offer a more flexible solution actively controlled by electronic systems. This facilitates the integration of large blocks of energy into complex grids, where control over the direction and amount of energy can be adjusted with greater precision.

The growing demand for HVDC transmission systems reflects the importance of this technology in a global energy transition scenario. Its use expands transmission capability between countries and continents, meets energy efficiency needs, and offers a more environmentally viable alternative to HVAC systems.

5 ENVIRONMENTAL IMPACTS OF HVDC TRANSMISSION LINES

HVDC transmission lines have been shown to be an environmentally advantageous alternative compared to conventional alternating current (HVAC) transmission lines. In addition to reducing transmission losses over long distances, HVDC reduces physical and visual impacts on the natural environment and contributes to the mitigation of carbon emissions (HUSIN et al., 2021). With the growing need to expand power grids to support renewable energy sources, such as wind and solar, HVDC transmission emerges as an efficient solution that meets the demand for more sustainable systems with less environmental impact (KALAIR; ABAS; KHAN, 2016).

5.1 Reduced Space Occupancy and Reduced Easement Range

HVDC lines require fewer conductive cables compared to HVAC lines to transmit the same amount of power. In HVAC systems, three phases of cable (three-phase) are required, while in HVDC only one or two conductive lines are required. This significantly decreases the width of the easement strip required for the installation of the towers and transmission line, reducing the physical space occupied on the ground. This spatial economy allows HVDC lines to occupy less land, an especially important advantage in densely populated regions or ecologically sensitive such as forests and environmental protection areas (RAMESH; LAXMI, 2012).

5.2 Reduced Visual Impact and Greater Social Acceptance

Due to the nature of direct current, HVDC towers can be spaced further apart than HVAC towers. This reduces the total number of towers required along the transmission line path. In addition, due to the smaller number of conductors, when compared to the HVAC system, the infrastructure required to support the conductors is also reduced. This results in a lower visual impact of the HVDC lines. This can be crucial for projects that cross inhabited areas, where the aesthetic impact of transmission infrastructures can be a concern. In areas with high landscape value, the social acceptance of HVDC transmission projects tends to be higher since the visual impact is less intrusive. This factor is also important to minimize the resistance of local communities and make it feasible to expand transmission infrastructure with less social opposition (PILLAY; KABEYA; DAVIDSON, 2020).

In the context of large metropolises, an alternative is underground HVDC transmission lines, an effective solution for reinforcing electrical grids in densely populated urban areas, where the installation of overhead towers is unfeasible due to space constraints and aesthetic concerns. In the United States, projects such as SOO Green HVDC Link exemplify this approach. This project envisages the installation of a 2,100 MW underground transmission line along existing railway easements, connecting significant energy markets and minimizing visual and environmental impact (FRENKEL, 2020). As reported by Scenic America, in 2023, the project obtained approval from Iowa state regulatory agencies and is expected to go live in mid-2029 (SCENIC AMERICA, 2024).

5.3 Emission Reduction and Compatibility with Renewable Energies

In addition to being more efficient over long distances, the HVDC system has a significant environmental benefit by minimizing energy losses. These losses in the HVAC transmission lines increase with distance due to factors such as reactance and capacitance, which implies additional energy consumption to compensate for it. On the other hand, HVDC lines do not face these same limitations, which results in a cleaner transmission with less need for compensatory power generation. This factor is even more relevant for renewable energy integration, where wind and solar farms are usually located in remote areas and require efficient transmission to urban consumption centers (FARGHALI et al., 2023).

5.4 Less Magnetic and Electric Field Effect

HVDC lines also present an advantage by minimizing the effects of magnetic and electric fields in areas adjacent to the transmission line. While HVAC lines produce alternating electromagnetic fields that can impact the health and behavior of animals and humans, HVDC lines generate constant fields, reducing these possible adverse effects. In environmental conservation areas, this characteristic makes HVDC lines less invasive to local fauna and flora, increasing their environmental and ecological value (MATHEBULA; MBULI, 2024).

6 LOCATION OF FAULTS IN HVDC LINES

Despite its environmental benefits, HVDC presents technical challenges, particularly in protection systems and fault locations. The unidirectional nature of direct current makes it difficult to develop protection systems that identify and isolate faults as effectively as those in HVAC systems. This is partly due to the absence of an alternating cycle, which facilitates pinpointing the exact point of the fault. In HVAC systems, fault location methods rely on current and voltage oscillations, but in HVDC, the absence of these oscillations complicates the application of these same techniques. According to the Muniappan study (2021), failures in HVDC systems tend to spread rapidly, requiring specialized sensors and algorithms for effective detection.

However, advances in power electronics and digital control have made these systems increasingly effective. Additionally, artificial intelligence and neural networks for fault location offer a promising solution to overcome these challenges, further enhancing HVDC's environmental appeal as a sustainable and technically viable transmission system (RAMESH; LAXMI, 2012).

Recent research has focused on developing dedicated protection systems for HVDC networks, incorporating localization methods that combine digital measurement and signal analysis technologies. Studies such as Farkhani et al. (2024) indicate that improving protection systems can significantly enhance the safety and reliability of HVDC networks. However, technical challenges must still be addressed to achieve an efficiency level comparable to that of HVAC networks.

7 NEURAL NETWORKS APPLIED TO FAULT FINDING IN HVDC SYSTEMS

The use of artificial neural networks has shown promising results in accurately locating faults in HVDC lines. MLP networks, trained with historical fault data, enable algorithms to identify specific patterns and predict fault locations based on current and voltage signal characteristics (ALPSALAZ et al., 2024). This approach enhances fault detection accuracy in HVDC systems, addressing some limitations of traditional methods.

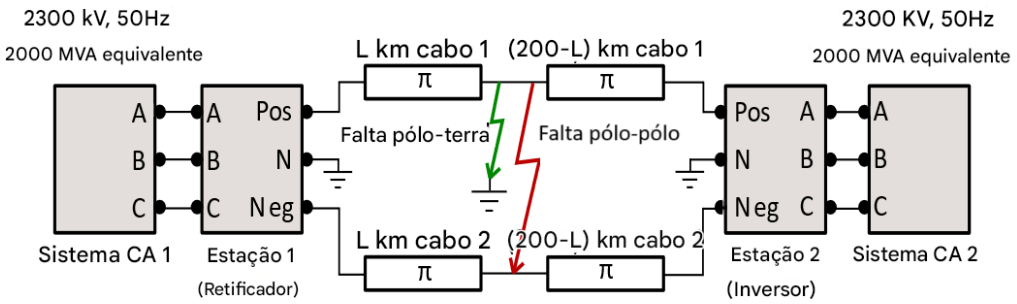
Neural networks can generalize complex and rapidly propagating fault patterns, which is essential for the success of HVDC systems. A study by Zhang and Yu (2024) explores the application of neural networks for fault identification and location in HVDC lines, concluding that this approach can reduce response time and improve overall system reliability. While promising, implementing neural networks for HVDC protection requires a robust dataset and adequate training to handle variations in operating conditions.

8 APPLICATION SCENARIO

To evaluate the performance of a neural network applied to fault location in transmission systems, a two-terminal HVDC system, modeled from a test system available in MathWorks Simulink, was used. The analyzed system considered two types of faults: pole-to-ground and pole-to-pole.

The test system, illustrated in Figure 4, consists of two AC systems operating at 50 Hz, connected to two converter stations, which are eventually interconnected by an HVDC transmission line. The AC systems have voltages of 230 kV and a power rating of 200 MVA, while the transmission line is 200 km long and operates at ±100 kV. This configuration represents an ideal HVDC transmission scenario for evaluating the effectiveness of the proposed approach.

Figure 4 - VSC-based HVDC transmission line.



Source: adapted from (BERTHO JUNIOR et al., 2014).

For the tests, failure condition simulations were conducted to generate a representative dataset for the subsequent training of the neural network. Fault resistances were varied in 2-ohm increments, ranging from 1 to 299 ohms. The fault application point along the transmission line was adjusted in 5 km increments, covering distances from 5 to 195 km from the rectifier. A total of 11,720 simulations were performed, during which current values at the poles were recorded with a sampling frequency of 135 kHz.

The current signals generated by the simulations were captured in windows of 512 samples, corresponding to a period of 3.792 ms. To extract features from these signals, the WPT was applied to the positive pole current signal recorded in the fault oscillography. Wavelet decomposition was performed using the Daubechies (DB1) function up to the fourth level, generating 16 sets of coefficients representing distinct frequency bands. The maximum coefficient from each set was extracted and used as input for the MLP neural network.

Regarding the MLP network, training was performed using the Levenberg-Marquardt backpropagation algorithm, known for its efficiency in regression problems. After a series of preliminary tests, the network architecture that produced the best results consisted of:

- An input layer with 16 neurons, corresponding to the extracted wavelet coefficients.
- Two hidden layers, with 60 neurons in the first layer and 30 in the second.
- An output layer with a single neuron, whose linear activation function directly returns the fault distance in kilometers.

The training parameters were optimized through multiple tests to achieve the best performance. Five iterations of 2,500 epochs were conducted, with a learning rate of 0.001. The activation function used was ReLU, the optimizer was RMSprop, and the loss function was Mean

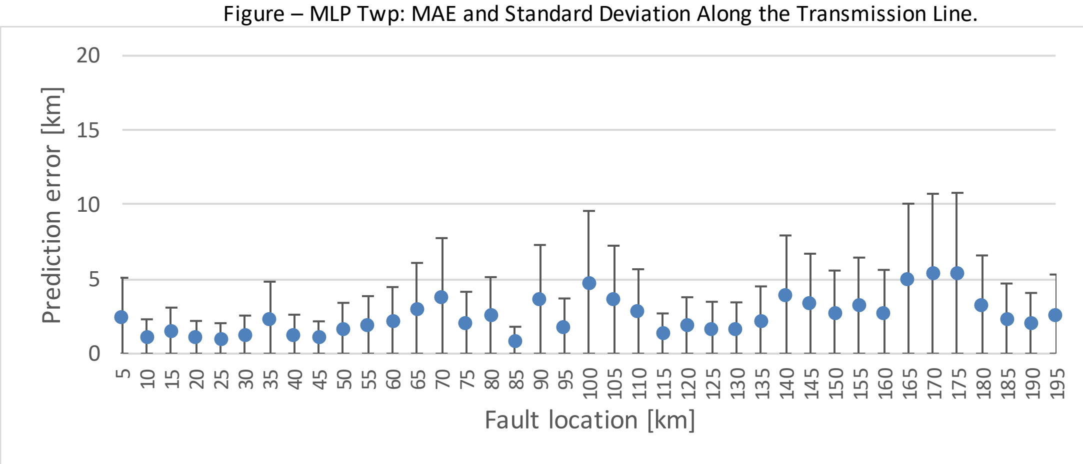
Square Error (MSE). As an evaluation metric, Mean Absolute Error (MAE) was adopted to directly assess the accuracy of the results.

This configuration proved effective in handling the complexity of the data and ensuring consistent model convergence. The combination of WPT and the neural network architecture enabled a detailed and accurate analysis of fault conditions in the HVDC system, providing a solid foundation for the discussion of results.

9 RESULTS

The MLP neural network model, combined with WPT as a feature extraction technique, demonstrated promising performance in locating faults in HVDC transmission lines, reinforcing its applicability in real-world systems. As illustrated in Figure 2, the MAE ranged between 2 and 3 km along the 200 km transmission line. This level of accuracy is remarkable given the total line length and the complexity of the simulated scenarios.

Figure – MLP Twp: MAE and Standard Deviation Along the Transmission Line.



Source: Prepared by the author.

A detailed analysis of the results revealed that approximately 32.4% of the fault location predictions had errors in the range of -1 to 1 km, corresponding to an absolute error of less than 0.5% of the total line length. This level of accuracy highlights the robustness of the model, even when subjected to variations in fault characteristics, such as differences in fault resistance and location along the line.

In terms of overall performance metrics, the model achieved an average absolute error of 2.57 km, equivalent to 1.29% of the total line length, with a standard deviation of 2.7 km. This performance demonstrates consistent and adaptable accuracy, particularly under fault conditions with higher resistances, where the model exhibited remarkable stability. Additionally, the average error remained steady, underscoring the practical applicability of the solution under real operating conditions.

Another key aspect is the contribution of the model to the stability and reliability of power supply in HVDC networks, particularly considering that these lines are often used to integrate renewable energy sources, such as wind farms and solar plants. By mitigating transmission disruptions, the MLP-WPT model enhances the feasibility of sustainable and resilient networks, supporting a cleaner and more efficient energy transition.

Although the model demonstrated robust performance, there is still room for improvement, especially in critical scenarios such as short-distance faults and low-resistance faults. Fine-tuning the model for these cases could further enhance system reliability and expand its applicability to even more demanding environments. An effective fault location system enables the solidification of HVDC systems as reliable power transmission solutions.

10 CONCLUSION

From a technical perspective, the proposed architecture combines precision and robustness in an efficient computational system, significantly reducing costs and response times in fault scenarios. Additionally, the use of advanced pre-processing techniques, such as WPT, highlights how modern signal processing tools enhance the analysis of complex waveforms, enabling machine learning models to achieve high performance.

In an environmental context, the benefits of the proposed solution are equally significant. By enabling fast and accurate fault identification, the model minimizes power supply interruptions, reducing the impact of unexpected outages on systems integrating renewable energy sources. This operational efficiency not only increases the reliability of transmission networks but also contributes to reducing greenhouse gas emissions associated with corrective actions and the use of less sustainable backup power sources. Furthermore, automated and remote monitoring reduces the need for frequent on-site interventions, thereby reducing the carbon footprint of maintenance operations.

Despite the promising results, the study identifies clear opportunities for future improvements. Targeted adjustments to optimize performance in critical scenarios—such as short-distance faults or low-resistance conditions—could further improve model accuracy and reliability. Additionally, integrating the model with real-time monitoring systems and expanding its application to larger networks could unlock new possibilities for practical deployment.

In conclusion, the MLP-WPT not only represents a viable and efficient solution for fault location in HVDC transmission systems but also underscores the importance of technological advancements in driving sustainable solutions for the power sector. By combining high technical performance with environmental benefits, this work serves as a reference for developing innovative methods that address both operational reliability and environmental sustainability—essential for a more sustainable and resilient energy future.

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REPRESENTATIONS

CONTRIBUTION OF EACH AUTHOR

When describing each author's participation in the manuscript, use the following criteria. The distribution of the specific contribution of each author to this work will be presented below, highlighting their respective responsibilities and participation throughout the research and development process of the study.

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Statement of Conflicts of Interest

We, **Messias Silva de Melo, Guilherme Alexandre Lopes Neto, Hermes Manoel Galvão Castelo Branco and Rui Bertho Junior**, declare that the manuscript entitled "**Fault Location in HVDC Systems Using Multilayer Perceptron and *Wavelet Packet* Transform: A Sustainable Approach to the Integration of Renewable Energies**":

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