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Studies on applications of Artificial Intelligence in medium and high voltage circuit breakers

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ABSTRACT

Artificial Intelligence (AI) has played an important role in contributing to various engineering applications, including preventive maintenance and fault detection in high-voltage electrical equipment. Among them, medium and high voltage circuit breakers stand out, which are strategic components, used not only in maneuvers, but also in protection against overcurrents and short circuits in electrical power systems. The failures of this equipment can lead to significant interruptions in the power supply, sometimes causing great economic and social damage, as well as risks to the safety of the facilities. In this sense, the objective of this work is to present different scientific studies on AI applied to medium and high voltage circuit breakers, aiming at the analysis and comparisons between them. The justification of these studies is evidenced by the need to identify mechanical and electrical failures early, minimizing unplanned downtime and costs associated with corrective maintenance of this equipment. The methodology adopted is based on available scientific studies with selection and analysis of cases on the application of AI in diagnosing incipient faults of medium and high voltage circuit breakers. The results highlight the efficiency of integrating AI algorithms. They feature different methods, such as signal processing techniques, for example: *Wavelet* Transform and Entropy of Decomposition Energy in Enhanced Empirical Mode; Machine Learning, namely: *Principal Component Analysis* (PCA), *K-means*, Random Forest and *Support Vector Machine* (SVM); and Deep Learning, such as: *AlexNet Network* and *Autoencoder,* to extract relevant characteristics from the vibration and voltage signals of these equipment. Therefore, this work highlights the importance of the application of Artificial Intelligence aiming at innovations in the area of Maintenance Engineering. In view of the challenges and perspectives in the area, we propose complements with studies that use methods that deal well with few data and can be used for more constant monitoring of the operating status of medium and high voltage circuit breakers. In addition, these tools must be able to identify when the equipment has been able to intervene and if its condition has improved, as well as to provide failure predictions based on its history, since the application of AI techniques shows promise in the early detection of failures, preventive maintenance and improvement of the operational efficiency of these important equipment for the electrical power system.

Keywords: Medium and high voltage circuit breaker, Artificial Intelligence, Maintenance, Signal processing, Predictive techniques.

INTRODUCTION

Artificial Intelligence (AI) has played an important and growing role in various scientific applications, including applications in high-voltage electrical equipment. In particular, medium and high voltage circuit breakers are essential components in electrical power systems, responsible for protecting networks against failures resulting from current surges, such as short circuits. The failure of this

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equipment itself can lead to significant interruptions in the power supply, causing economic losses and safety risks. Traditionally, the maintenance of this equipment has been carried out in a preventive or corrective manner, based on periodic inspections and the history of occurrences with the circuit breakers.

With the advancement of AI tools, such as deep and machine learning, new opportunities arise to improve the detection of incipient faults in medium and high voltage circuit breakers. These newer methods can analyze large volumes of data coming from sensors and maintenance histories, identifying patterns and categories. Thus, AI-based preventive maintenance can potentially contribute to reducing the downtime of medium and high voltage circuit breakers, minimizing operating costs and improving the reliability of electric power systems.

OBJECTIVE

This paper aims to present studies on the application of artificial intelligence (AI) in medium and high voltage circuit breakers, aiming to contextualize the existing applications in the literature, highlighting the main methods, algorithms, approaches, challenges and perspectives of the maintenance area of this equipment. The motivation for this study is to understand how AI can be applied in the maintenance of medium and high voltage circuit breakers, which is fundamental for technological advances in the electric power sector.

METHODOLOGY

The methodology used was based on the literature review, through analysis of studies on the application of artificial intelligence (AI) in medium and high voltage circuit breakers, investigating and clarifying the mechanisms by which AI techniques can identify incipient failures in these equipment, in order to gather the existing developments on preventive maintenance and identify gaps and necessary complementations in the research area.

CHARACTERIZATION OF MEDIUM AND HIGH VOLTAGE CIRCUIT BREAKERS

Medium and high voltage circuit breakers are essential assets for the safe and reliable operation of electrical systems. Such equipment must interrupt current surges, especially those from short circuits, and cease overload currents, as well as section parts of circuits to allow maintenance work, as well as maneuvering transmission lines and switching capacitor and reactor banks [1-8]. When they are exposed to great mechanical and electromagnetic stresses, they can suffer degradation, leading to a decrease in their performance. They consist of three main modules [5]:

- **Extinguishing chamber**: sealed compartment that surrounds the electrical contacts, the extinguishing and insulating medium. This is where the electric arc extinguishing occurs, which is formed through the gases and ionized materials between the already separated contacts. Thus, the re-establishment of the dielectric condition of the insulating medium must occur as soon as possible.

- **Drive mechanism and energy accumulator**: mechanical system consisting of springs, mechanical transmission, pneumatic or hydraulic mechanism, or pneumo-hydraulic. It provides the power and motion transmission needed to close and open the contacts and can be operated either manually or by means of electric actuators.
- **Control circuit**: electrical system, interconnected with protection relays, of local and/or remote activation, responsible for the command actions for the operations of closing and opening the contacts.
- Regarding the extinguishing medium, circuit breakers can be subdivided into: small and large volume oil, compressed air, vacuum or SF6. As for the drive mechanism: mechanical, pneumatic or hydraulic [1]. As for energy accumulators: spring or pneumatic.

MAINTENANCE OF MEDIUM AND HIGH VOLTAGE CIRCUIT BREAKERS

The maintenance of medium and high voltage circuit breakers aims to extend the useful life of these equipment and keep them in good operating condition in order to reduce the probability of their failure [9, 10]. In general, maintenance strategies can be classified as corrective or preventive [11]. The second, due to its impact on the reliability and service life of circuit breakers, can reduce failure costs and postpone investment to replace old equipment [12].

Statistical data from around the world indicate that mechanical failures represent the majority of cases of failure in high-voltage circuit breakers, justifying preventive maintenance practices in these equipment [13-15], although periodic mechanical reviews are considered effective, despite the high costs, representing a large expenditure on labor [16]. Thus, maintenance based on preventive actions is necessary.

In this sense, knowledge of the operating conditions of circuit breakers is essential to make decisions about maintenance [12, 17]. Thus, the concept of performance index is used, being a numerical representation of the operating state of the medium and high voltage circuit breaker, considering specific data related to predictive techniques, such as [18, 19]:

A. Electrical insulation resistance tests;
B. Electrical tests of resistance of contacts;
C. Oscillography tests (operating times);
D. Maintenance History:

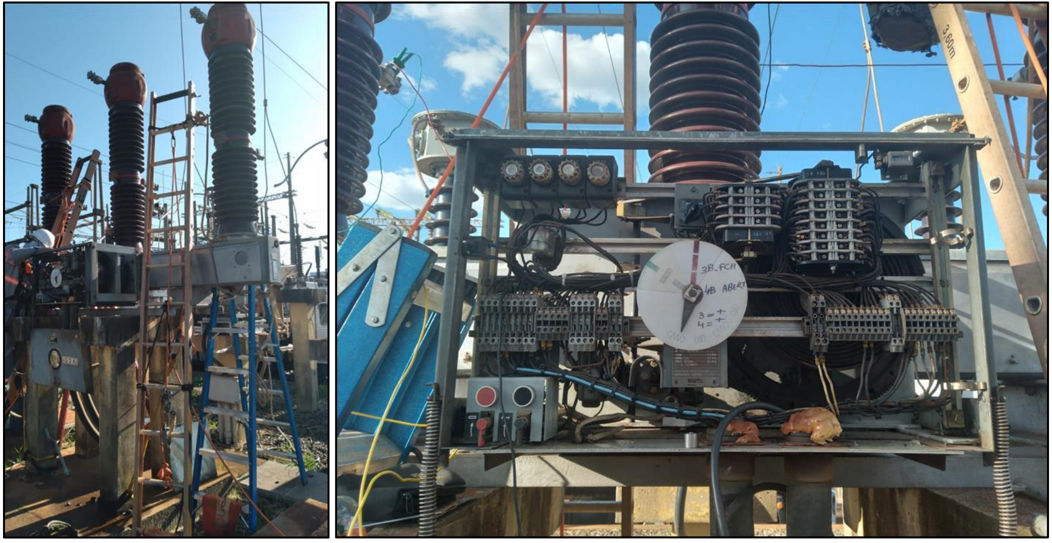
- time elapsed since the last maintenance;
- number of manoeuvres with a current equal to or less than the nominal current; and
- number of short-circuit manoeuvres.

E. Visual inspections and on-site checks; and

F. Thermography.

Figure 1 [19] illustrates the field maintenance of a 40-year-old circuit breaker with a nominal voltage of 69 kV, small oil volume type (PVO), spring-loaded with a nominal current of 2000 A and a nominal interrupting capacity of 31.5 kA, which presented mechanical problems in its control mechanism.

Figure 1 – Circuit breaker being opened for corrective maintenance purposes [19].



Source: Dias, Y.A. (2023) [19]

ARTIFICIAL INTELLIGENCE FOR MAINTENANCE OF MEDIUM AND HIGH VOLTAGE CIRCUIT BREAKERS

There are several Artificial Intelligence algorithms used in the maintenance of medium and high voltage circuit breakers. For example, the mass loss (erosion) of the contacts of SF 6 gas-insulated circuit breakers could be evaluated, proposing a mathematical model for this, as a function of three parameters: maximum short-circuit current, arc-electric duration time and energy of the phenomenon [20]. The weaknesses of the mechanical contact resistance test are discussed, concluding that it is proportional to the opening speed [21]. In addition, an original methodology for performing the dynamic contact resistance test is presented, using not only SF6 gas insulated circuit breakers, as well as compressed air circuit breakers [22, 23], while it is possible to evaluate the correlation between various levels of contact degradation and the waveforms obtained in the tests [24].

In addition, it is possible to use statistical metrics to monitor the operation of medium and high voltage circuit breakers. Analysis of variance to identify anomalies in SF6 gas-insulated circuit breakers is used [25], while in [26], it was concluded that the opening and closing times of the equipment obey the normal distribution, allowing the execution of hypothesis tests to identify the acceptable deviation between phases of the circuit breaker. In addition, multivariate models are proposed [27, 28], using Decision Tree Analysis (FTA) to evaluate the probability of circuit breaker failure, and Markov Chain to construct the overall reliability model of the substation.

In addition, a ranking method based on regressions using SF6 temperature and pressure data is proposed [29], aiming to predict when the circuit breaker pressure is close to the limit established by the manufacturer, creating a prioritization of maintenance. Another aspect addressed by traditional methods is the ability to monitor circuit breaker opening times by means of a radiometric system, in order to determine various parameters, such as the duration and energy of the electric arc [5, 30, 31].

Thus, the main advantage of AI-based tools is to be able to apply multivariate classification algorithms, which is a complex activity. As medium and high voltage circuit breakers behave dependently on the mechanical characteristics of the asset and, consequently, on the model and manufacturer, this task becomes even more onerous [1, 5, 8, 13-15, 20, 32, 33]. In view of this, the diagnosis of medium and high voltage circuit breaker failures uses AI techniques, such as: Random Forest (RF); Back *Propagation Neural Network* (BPNN); Extreme *Learning Machine* (ELM); and Generalized *Regression Neural Network (GRNN*) [31, 34-37].

Another benefit of AI-based diagnostic methods is that they provide a quick solution for automating the diagnosis of medium and high voltage circuit breakers, even if the technology is applied remotely. From AI, diagnostic models are developed, which learn from characteristics related to the state of medium and high voltage circuit breakers, extracted from various monitoring signals – such as coil current and contact displacement curve and vibration – to find the correlation between them and the operating condition of the equipment [27-31].

In this sense, monitoring for fault diagnosis of these circuit breakers is essential in order to provide safe and reliable operation of the power grid [43-45]. Currently, the diagnosis mainly includes three processes:

A. Advanced use of signal processing methods to construct models that characterize failures in these equipment, including Fourier transform, *wavelet transform*, empirical mode decomposition, and variational mode decomposition [34, 35, 46].
B. Use of the dimension reduction method to extract parameters from key features. The most typical method is Principal Component Analysis (PCA), the *autoencoder* and its improved algorithms [46].

C. The pattern recognition method is used to classify the characteristics of the aforementioned structures. The most popular methods are Support Vector Machine (SVM), Random Forests (RF), and Artificial Neural Networks [37, 40-42, 46].

MAIN AI ALGORITHMS APPLIED TO THE TESTING OF MEDIUM AND HIGH VOLTAGE CIRCUIT BREAKERS FOR INCIPIENT FAULT DIAGNOSIS

Deep learning methods have achieved good results in the diagnosis of incipient medium and high voltage circuit breakers, with recent advances in Artificial Intelligence. In addition, an imperative step towards implementing an effective operating state assessment approach is to identify failure modes and the source of failures over time [47]. This provides a comprehensive analysis of key concerns that deserve more attention and additional research to identify effective diagnostic signs.

In the literature, failure statistics have been published, considering various historical data [12, 14, 48-52]. [49], for example, presents an extensive study of SF6 and oil-fired circuit breaker failures in Swedish and Finnish transmission systems, including 1,546 circuit breakers with a total operating history of 16,384 years, concluding that circuit breakers with a higher operating frequency, i.e. more than 50 operations per year, are more vulnerable to failure.

In addition, in [50], the failures of 8,600 high-voltage circuit breakers (with rated voltages greater than 100 kV), including oil, vacuum and SF6 circuit breakers, with about 6800 failures, were investigated to identify the failure rate trend and the optimal maintenance time. It has been reported that a large part of the origin of the failures is related to the operating mechanism, high voltage, and secondary and auxiliary circuits of the circuit breakers. In addition, it was analyzed that the aging problem may not be detectable until 15 years of operation.

Therefore, several diagnostic tests can be used to assess the condition of circuit breakers in *offline/online* conditions. Regarding coil current, numerous studies have addressed this signal to identify the appropriate diagnostic characteristics, establish a relationship between faults and these characteristics, and use this signal in fault detection algorithms [47].

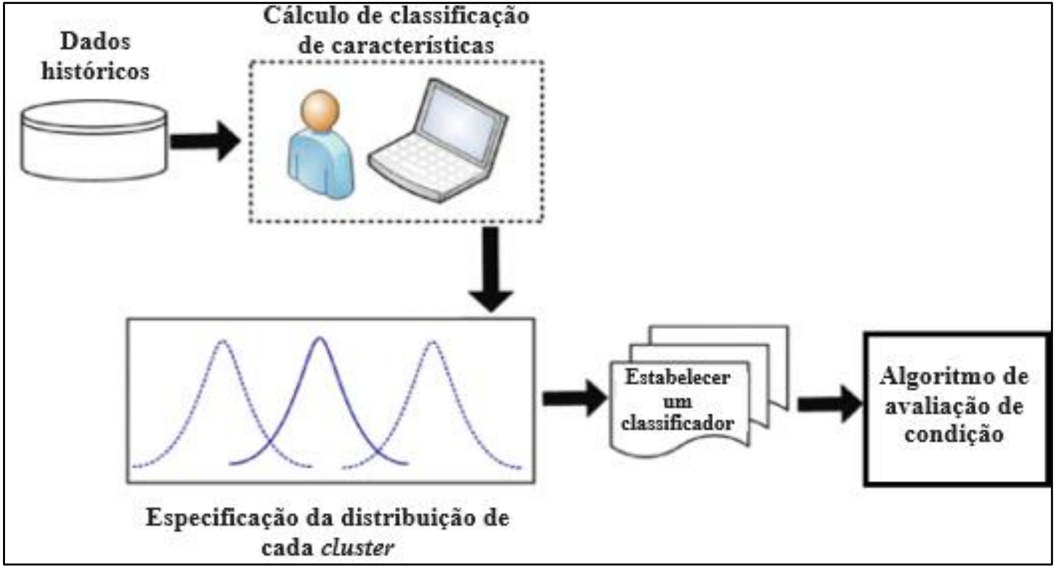
In [34, 53], the interaction between various faults resulting from malfunctions in the latch, control voltage, and coil was investigated. Whereas, in [15, 54], the appropriate diagnostic characteristics of the coil current were identified for application in fault prediction. This signal, along with the displacement curve, was employed for the detection of faults in high-voltage circuit breakers in [55].

In addition, problems of degraded contacts, coil, and friction were diagnosed using coil current (DC) at [54, 56]. In [57], the coil current signal is used to detect coil aging, core blockage, and lack of space for core displacement. More than that, one of the important challenges in diagnosis is the identification of the threshold level of the characteristics from the normal (healthy) state to the defective state [47], which was addressed in [15, 58], applying data mining and probabilistic approach. Figure 2 [15] shows the sequence of processes involved in the classification.

For the displacement of contacts over time, another methodology used the displacement curve. It is captured by means of a transducer and indicates a close-open duration time characteristic [47]. The operating speed is calculated based on two predefined points on the curve. Thus, the methodology is applied to evaluate the operating time of circuit breakers (timing test), as well as to detect failures in the operating mechanism [34, 59, 60].

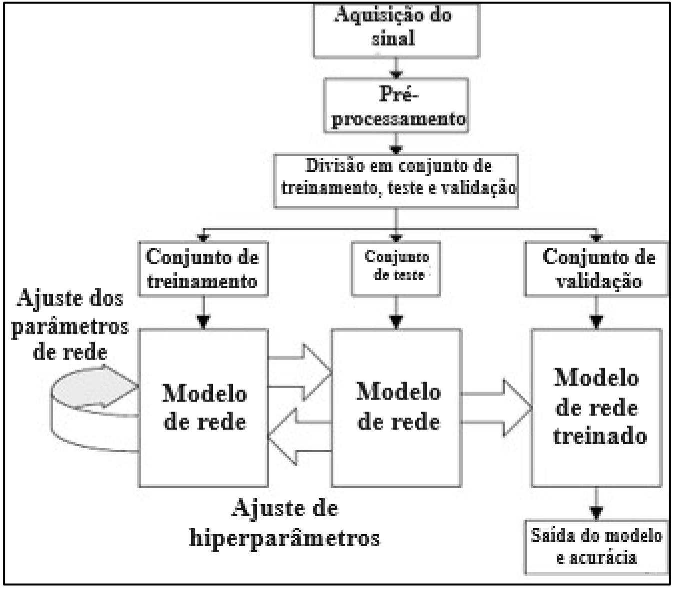
In [61], a new U-Net *with* CapsNet is proposed for fault diagnosis in high-voltage circuit breakers to solve problems with little data, achieving a robust and *high-precision diagnosis of low-tripping high-voltage* circuit breakers, as shown in Figure 3 [61]. The experimental results show that, using the proposed architecture, it is possible to quickly and accurately diagnose incipient faults of high voltage circuit breakers, with an accuracy of 93.25%.

Figure 2 – Sequence of processes involved in the classification.



Source: Translated from RAZI-KAZEMI, A. A. et al (2015) [15].

Figure 3 – Diagnostic process



Source: YE, X. et al (2022) [61]

Furthermore, based on samples collected from the Yunnan Power Grid in China [62], a new system of performance indicators is constructed using Bayesian probability to measure the correlation between the individual indicators and the comprehensive indicators at the same status level to weigh the individual indicators. The following properties were used: mechanical, such as speed and time of opening of the contacts; aperture coil current; insulation, e.g. SF6 gas density and partial discharges; and electrical performance, such as main electrical circuit resistance and relative electrical wear. The proposed method had the following advantages [62]:

A. An effective system of estimation indicators, built by extracting association rules from many real data from operational samples;
B. the calculation of the weight of all individual indicators based on the highest confidence, which exceeds the limit of the number of samples;
C. The weights of the comprehensive indicators are adjusted and determined by an *adaptive perceptron* that can reflect the different effects of the same failure on equipment in different operating states; and
D. Based on the calculated scores of all the estimates of the performance indexes, one can diagnose the potential failure of the equipment to some extent.

In addition, it should be noted that determining when the circuit breaker needs maintenance is an important and non-trivial problem, since this equipment is used for long periods. Thus, it is proposed in [63] the use of data mining techniques to predict the need for maintenance. In the corresponding data, one class (minority, or positive class) is significantly less represented than the other (majority, or negative class). Table 1 [63] shows the descriptive variables used in the study.

Table 1 – Descriptive variables used to determine performance in [63]

Name	Kind
Isolation Camera	Real
Isolation support	Real
Contact Resistance	Real
SF6 Gas Pressure	Real
Resistance of coils	Real
Number of operations	Whole
Main Terminals	Nominal {1-10}
Porcelain	Nominal {1-10}
Temperature Compensator	Nominal {1-10}
Cabinets	Nominal {1-10}
Grounding	Nominal {1-10}
Connections	Nominal {1-10}
Overall control	Nominal {1-10}
Operational criticality	Nominal {High, Normal, or Low}
Electrical wear	Nominal {High, Normal, or Low}
Circuit breaker wear	Nominal {High, Normal, or Low}

Source: translated from RAMENTOL, E. (2016) [63]

Next, a new unbalanced learning preprocessing algorithm called SMOTE-FRST2T is introduced. It combines the Synthetic Minority Oversampling Technique (TSMS) with an instance selection strategy based on *fuzzy* approximate set theory. Experimental analysis shows better results than a number of state-of-the-art algorithms.

Still using *fuzzy logic*, in [64], the calculation of the reliability between the uncertainties is determined, with the objective of classifying the degree of criticality in the maintenance of the circuit breakers in the imminence of technical problems, performing a preventive maintenance, comparing with the method already used by the company. The results, obtained from the maintenance history of the equipment, demonstrate greater precision of the proposed methodology in relation to the model presented by the concessionaire.

In addition, real cases are addressed in which circuit breaker shutdowns were avoided based on the analysis of the lists of events and oscillographs of the intelligent electronic devices, which make up the protection system of the Eletronorte substations, in Pará [65]. The data analysis technique allowed the company to perform preventive maintenance, anticipating the problem. Useful information for better decision-making, as well as a significant reduction in financial losses in the process of operation and maintenance of your electrical system, are advantages of the proposed methodology. Similarly, in [66], the behaviour of the protection systems was assessed, treated and analysed by oscillography records generated during the occurrence of faults, as shown in Figure 4 [66]. The specification made it possible to conclude that the development of an automatic system for the acquisition and treatment of oscillography is a complex process, which, however, can bring benefits to the concessionaires, not only in terms of maintenance of protection systems, but also as an aid to the rapid reestablishment of the electric power service.

Figure 4 – Characteristics of an oscillography record

Source: adapted from GUERRA, M. M (2014) [66]

In this way, intelligent fault detection methods and life estimation algorithms are established based on data and reference curves. The steps for fault detection comprise the obtaining of the diagnostic features and the correlation between those features and the defective and healthy cases in order to provide a condition assessment algorithm or, one step further, a fault prediction approach.

In addition, in general, these methods deal extensively with vibration signals. Therefore, the waveform characteristics of signals resulting from various faults can exist in different frequency components. Consideration of noise in real-time evaluation increases the complexity of vibration signal processing.

VIBRATION SIGNAL OF MEDIUM AND HIGH VOLTAGE CIRCUIT BREAKERS

To analyze the vibration signal of medium and high voltage circuit breakers, the *Principal Component Analysis* (PCA) algorithm is used, being a dimension reduction technique, which consists of transforming an initial set of correlated variables into a new one, composed of uncorrelated variables [1, 38, 39, 43, 44]. The process produces an output set with descending order of importance, so that the first vector accounts for most of the variance. Thus, it is possible to reduce the size without generating loss of information. Table 2 [1] represents the step-by-step process for implementing the algorithm.

Table 2 – Principal *Component Analysis* (PCA) Algorithm

Step	**Description**
1	Get Database () with n samples and dimensionsXd
2	Calculate the average of each vector (sample)
3	Calculate the database covariance matrix
4	Calculate the eigenvalues and eigenvectors of the covariance matrix
5	Sort eigenvectors by eigenvalues in descending order
6	Transform the original database using the chosen eigenvectors

Source: PEREIRA, L. D. N. (2023) [1]

Another algorithm used is *k-means,* shown in Table 3 [1].

Table 3 – Basic *k-means algorithm*

Step	Description
1	Input: The number of *clusters* k and a sample base n
2	Choose points k in the database as index centroids
3	Allocate each sample n to the nearest centroid
4	Calculate the distance from each n sample to the nearest centroid
5	Recalculating o centroide cada *cluster*
6	Repeat the process until the centroids converge

Source: PEREIRA, L. D. N. (2023) [1]

The main application of *k-means* is to distinguish data, which makes it possible to use it for anomaly detection [1, 34]. It is an iterative distance-based method for segregating a data set. On the other hand, as the number of input variables increases, the algorithm converges to a constant value, thus requiring a pretreatment to reduce the dimension [1].

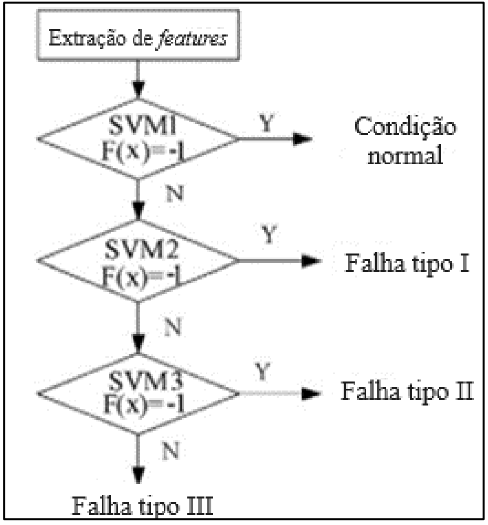
Analysis of the vibration signals generated during circuit breaker closing or opening operations shows that it is possible to obtain detailed information about the operation, transmission and interrupting mechanism [67]. Due to the very complicated mechanical system and the extremely short operating time of the circuit breaker, the vibration signal is non-linear and non-stationary, which makes it difficult to characterize the equipment for fault diagnosis. Thus, the chaotic nonlinear dynamical technique is proposed, offering a new way to study complex vibration signals [67]. In addition, nonlinear time series analysis is applied, with the objective of detecting mechanical anomalies in the equipment.

Another approach uses *wavelet* and SVM packet decomposition [68]. In this way, a support vector machine model with particle swarm optimization is developed. The validity of this fault diagnosis model is determined with a set of actual data from the operation experiment.

Additionally, to ensure that the signals generated by the models are identical to the real ones, a stochastic optimization algorithm is proposed [69]. Based on the data produced by the optimized models, two methods are proposed: one based on fast model matching, which adopts the *k-means* clustering algorithm to group the data and form a model library, and the other combines a deep network and a *Softmax* classifier, to extract not only high-level information from the characteristic signals, but also a but avoid the negative impact of large size on ranking results [69]. In simulation studies, both methods are tested in various scenarios and the latter shows superior performance over the former.

Another proposed method is based on empirically enhanced mode (EMD) decomposition energy entropy and multiclass SVM (MSVM) to diagnose faults in high-voltage circuit breakers [70]. A new multi-layer classification of SVM, called the "one against the other" algorithm approach, is proposed and applied to the fault diagnosis of high-voltage circuit breaker machines. Compared to the backpropagation network (BPN), the test results of the MSVM demonstrate that the application of enhanced EMD energy entropy to vibration signals is superior to that based on *wavelet packet analysis* (WPT). Therefore, the type of failure under high-voltage machine conditions is accurately and quickly estimated [70]. Then, based on the Darwinian principle of survival of the fittest, the genetic algorithm (GA) obtains the optimal solution after a series of iterative computations and searches for a better match of the SVM kernel parameters. The proposed classification scheme is shown in Figure 5 [70].

Figure 5 – SVM-Based Classification Framework



Source: translated from HUANG, J.; HU, X.; GENG, X (2011) [70]

Another approach, based on the time-frequency analysis of the transient electric fields (E-fields) radiated due to switching operations outside the envelope (transient switching electric fields), is presented in [71]. Based on the comparison and analysis of the main characteristics, STEFs can reflect the operating states and serve as an indicator of the early insulation defect of high-voltage circuit breakers. The proposed flaw detection method has been experimentally validated, taking full advantage of the high rate of change of the induced current in the circuit breaker housing, which in itself is a weak signal and difficult to capture by traditionally adopted means. This method can be an even more useful reference for diagnosing defects or failures in switching equipment in operation.

In addition, a methodology is developed to use the vibration signal from the operating system of high-voltage circuit breakers, by collecting the amplitudes of normal vibration signals, segmented by a time scale [72]. Through joint learning, features can be extracted from each part of the split signal and used to construct a vector from GR [72]. Next, forward sequential selection (SFS) is applied to determine the optimal subset, while Regularized Fisher Criterion (RFC) is used to analyze classification ability [72]. Finally, the known fault types are identified using RF, and the identification results are related to a specific fault type.

New approaches use *wavelet* packet decomposition and RF [73]. The process of diagnosing high-voltage circuit breakers faults based on vibration signals includes three parts: data acquisition under variable faults, feature extraction using the wavelet packet transform (WPT) for time-frequency analysis, and RF-based optimal identification model [73]. The results of the comparative experiment show that the classification accuracy of the proposed method with the original feature space reached 93.33% and reached 95.56% with the optimized classifier input feature vector [73].

Regarding noise reduction, the stacked *autoencoder* is used to perform automatic feature extraction and pattern recognition classification on the pre-processed data [74]. As the number of samples increases, the recognition accuracy of the stacked *autoencoder* for noise reduction surpasses the traditional method.

In [75], the assessment and diagnosis of the severity of mechanical failures in 12 kV circuit breakers is studied. A deep learning-based diagnostic approach is presented to overcome the shortcomings of traditional diagnostic models [75]. Simple and compound faults are diagnosed with a high detection rate and a low error rate, as the proposed method is purely data-based and implemented directly using only time-frequency images of the raw vibration data [75]. Validation is conducted on a 12 kV switchgear with circuit breaker inside, demonstrating the effectiveness of the proposed approach [75]. The *AlexNet architecture* is the one adopted as the diagnostic model.

Another method of diagnosing mechanical failures for high-voltage circuit breakers is through hybrid feature extraction and the integrated extreme learning machine (IELM) [76]. First, complete empirical mode decomposition of ensemble with adaptive noise (CEEMDAN) is used to decompose the vibration signal and obtain intrinsically mode functions (IMF) [76]. Then, the reconstruction of subranges of each order IMF component is performed by combining the Hilbert transform and the bandpass filter to obtain the time-frequency matrix [76]. The advantages of the proposed scheme are: in combination with bandpass filtering, it can eliminate modal *aliasing*, reduce the number of auxiliary noise additions, and improve decomposition efficiency [76].

As a challenge, when the amount of data decreases, fault diagnosis performance drops severely. To solve these problems, a few-sample transfer learning (FSTL) method with attention mechanism (AM) is proposed to perform the diagnosis of mechanical failures in high-voltage circuit breakers [77]. Experimental results show that the proposed method can achieve highly accurate and robust fault diagnosis with few samples in place [77].

Finally, a condition evaluation algorithm based on the arc model of the high-voltage circuit breaker is developed. The arc voltage initiated after the circuit breaker has been operated contains vital information about the condition of the equipment's mechanism. After the arc episode, the voltage generated includes two significant sections [78]. Both are characterized according to the operating mechanism of the circuit breaker. Therefore, the operating condition of the equipment can be well monitored through the analysis of the voltage generated through it due to the opening operation within a real-time condition monitoring algorithm. Table 4 [47] presents the various applications of AI in medium and high voltage circuit breakers.

Table 4 – Artificial Intelligence in Medium and High Voltage Circuit Breakers

Object	**Methods**
Vibration	Energy entropy [70], *Autoencoder* [74] and *AlexNet* [75]
Coil vibration and current	Package *wavelet* and *multi-mapping* [57]
Prediction using displacement curve	Multi-Model Interaction [32]
Displacement curve and auxiliary contact	Neuro-Inference System*Fuzzy* [59]
Coil current	Agglomerative Hierarchical Grouping and Data Mining [15]
Coil displacement curve and current	Neural network and SVM [55]

Source: adaptado de RAZI-KAZEMI, A. A.; NIAYESH, K. (2021) [47]

Therefore, the applications of AI in medium and high voltage circuit breakers represent significant innovations in the field of electrical engineering, as advanced methods related to machine learning and predictive analysis are incorporated. In this way, the integration of AI into this equipment has the potential to improve the reliability and preventive maintenance practices in this equipment.

CONCLUSION

This work presented the studies on the application of artificial intelligence in medium and high voltage circuit breakers, with the main predictive techniques, the performance index, and in general, it was found that the deep learning methods have achieved promising results in the diagnosis of incipient faults in medium and high voltage circuit breakers, benefiting from recent advances in AI. Thus, the identification of the modes and origins of failures over time is essential to implement an effective approach to evaluate the operating states of these equipments.

Studies have indicated that circuit breakers with higher operating frequency are more vulnerable to failures, and several diagnostic tests are used to evaluate their condition, such as coil current and displacement curve. Other approaches have utilized algorithms, such as *U-Net* with *CapsNet*, Bayesian probability, and *fuzzy* logic, providing high success rates. In addition, data mining techniques were used to predict the need for maintenance, dealing with the unequal representation of classes in the data. Also, the analysis of events and oscillographs were useful in preventive maintenance and reduction of financial losses of electric power utilities.

The analysis of vibration signals has been widely used in AI applied to medium and high voltage circuit breakers, to obtain accurate information about the operating mechanism of the circuit breakers.

Some algorithms, such as *Principal Component Analysis* (PCA), *k-means*, wavelet packet decomposition, and SVM have been employed to characterize and diagnose failures. In addition, deep learning models, such as the stacked *autoencoder* and the *AlexNet* architecture, were used for classification and noise reduction in the data.

In view of the analyses, the restricted availability of monitoring and information on diagnostics and maintenance in the real circuit breakers stands out as limitations, for the application of data processing resources, with a significant number of samples and predictive techniques, optimizing and providing accurate validation with the application of AI.

Thus, the contribution of this work is concluded in presenting the existing studies on this equipment and highlighting the importance of the application of artificial intelligence aiming at innovations in the area of Maintenance Engineering. Therefore, in view of the challenges and perspectives in the area, we propose complements with studies that use methods that deal well with little data and can be used for more constant monitoring of the operating status of medium and high voltage circuit breakers. In addition, these tools must be able to identify when the equipment has been able to intervene and if its condition has improved, that is, if there was effectiveness in the maintenance action, as well as to present predictions of future failures based on its history, since the application of AI techniques shows promise in the early detection of failures, in preventive maintenance and in the improvement of the operational efficiency of this important equipment for the electrical power system.

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