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Research on Grid Fault Diagnosis Algorithm Based on Real-Time Feedback

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Abstract. With the rapid advancement of global energy storage technologies, surging electricity demand, and the escalating penetration of renewable energy, microgrids have become pivotal in energy supply and resource management, while Electrical Power Grid Systems face growing complexity, diversified fault patterns, and accelerated fault propagation. Conventional methods of data analysis and periodic examination cannot satisfy the immediate requirements of providing quick fault localization, isolation and prevention of further spread which limits the capability of power utilities to recover grid safety and efficiency. The most common algorithms that are being researched include data-driven and intelligent algorithms including Neuromorphic Analytics, Variational Mode Decomposition (VMD) and Convolutional Neural Networks (CNN). These analyses are limited by a lack of flexibility to realistic grid-conditions, cross scenario generalizability, engineering feasibility, and the problem of large scale, accurately labelled data that limits the applications of real-time diagnosis efficacy. To deal with these issues, this paper will present an extensive review and outlook of intelligent real-time feedback based grid fault diagnostics, with perspective of moving away the individual algorithm approaches to an engineering based closed-circuit autonomous technical system. It presents the systematic examination of the data processing in real time (such as the technique of feature extracting and adaptive learning diagnostic model) and evaluates five important system structures, as well as examines their operations on the basis of practical application cases. The research should maximize the efficiency, flexibility, and robustness of grid diagnostic algorithms, provide technical advice on future research, and establish the basis of next generation high reliability and self healed power grid.

Keywords: Power grid, fault diagnosis, real-time feedback, adaptive learning

1. Introduction

Microgrids have occupied a key position in electricity provision and resource management because of the rapid advancement of energy storage technologies across the world and the increased energy consumption levels [1]. Moreover, Electrical Power Grid Systems (EPGSs) have become more complex as the fault patterns became more diverse, and the velocity of the fault patterns transmission grew exponentially. The conventional approaches to fault diagnosis including the

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analysis of data about power utilities in the offline mode or an electrical utility carrying out inspection at the periodical terms are already not sufficient to satisfy the urgent task of determining the location of faults and isolate the damaged areas and the undamaged ones and avoiding the further development of the incident. Consequently, capacity of power utilities to restore power grid systems to a safe status and have high degree of efficiency has been highly limited. The real-time feedback-based intelligent grid fault diagnosis technology has become one of the key research priorities to enhance the operational security and resiliency of power grid systems, based on these challenges and needs.

Most of the current studies in this field currently focus on the application of data-driven and intelligence algorithms. Neuromorphic Analytics (NN-based) is already being tested to diagnose the faults in the linear circuits by researchers and a combination of Variational Mode Decomposition (VMD) and Convolutional Neural Networks (CNN) is being used to treat grid fault signals [2,3]. Nevertheless, even the existing research has serious flaws in measures such as the adaptation to the complex grid conditions, cross-scenario generalization, the ability to integrate the system and engineer implementation, or adaptability to the new high-renewable-energy-penetration grid paradigms. Furthermore, nearly all existing diagnostics processes use significant copious quantities of correctly-tagged data [4]. Electric utility companies actually do not have clean, complete, and properly annotated actual operational data because of the nature in which they work [5].

As a result, even in real-time diagnostics, all these constraints will continue to reduce the effectiveness of the whole system. Hence, this paper aims at offering an extensive overview and insight into the field of smart real-time fault-based grid diagnostics with feedback. Despite significant progress in this field, as the amount of literature devoted to this problem increases, both academic and technical types of literature are too concentrated on the search of a breakthrough model design and the deficiency of attention to the architectural structure of the model and processes required to implement the models in practice. Model design focus has introduced a bottleneck in capability to respond to dynamic and continually growing complexities of present grid systems, in addition to disrupting conventional constructs related to data quality.

This paper aims chiefly to attempt to transcend the discussion of isolated algorithms and attempt to develop and conceive of an engineering-based and practice-based, closed-loop, autonomous technical framework. The goal of this paper is to find and define an integrated system of combining real time data perception, dynamic feature extraction, online intelligent diagnostics, and fast self-healing control to optimally propose the efficiency of optimization, flexibility and overall robustness of grid diagnostic algorithm. The purpose of the systematic review will be to give a summary of newer and more traditional approach to grid fault diagnostics within the past several years coupled with the focus on the developing design principles and conventional reasoning to address the underlying problems. The general aim behind this structure is to offer a very scalable architecture of the ability to promptly respond and address faults in the firmly bound cyber-physical systems. The paper shall endeavor to discuss the determinant factors that are significant to the current ability of intelligent diagnostic systems to perform in real time, derive a comprehensive notion of the potential optimization tightfits of an intelligent diagnostic system, and offer the imminent and concise technical advice to the further scientists so that they do not go astray easily and rather concentrate on breakthroughs that will lead to subsequent enhancement of the systems security and operation efficiencies.

The paper will be divided into four parts. Section 1 provides the state of the research and the background of the article. Section 2 is concerned with ways of processing data on-the-fly. Another subject that will be discussed in this part is the problem linked to the real-time perception of faults,

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specifically, methods of contemporary extraction of features, and the creation of adaptive learning-based diagnostic frameworks. Section 3 is based on the general architectural structure of the diagnostic system, which includes; system integration structure, performance assessment models, and use cases of application in a realistic grid environment. Section 4 ends the paper with a conclusion by summarizing key findings as well as future research directions and the future research trends.

2. Analysis of real-time data processing methods

In order to resolve the main problem of fault characteristics perception in real-time, data processing in real-time becomes the basic connection in power grid fault diagnostics. It entails deriving discriminative characteristics on the huge, high-dimensional, and time-varying power grid operational data and on minimizing redundancy of data, thus creating the basis of swift and accurate fault diagnosis. This segment dwells on the extraction of the information feature in real-time monitoring and adaptive learning diagnostic model with the systematic investigation of the real time data processing mechanisms.

2.1. Information extraction for real-time monitoring

The power grid real-time data feature extraction, which is part of the background of feature extraction and data processing, involves transformation of raw monitoring data (voltage, current, frequency, and phase angle) measured by sensors, Phosphor Measurement Units (PMUs) and smart meters into a low-dimensional, representative feature vectors, which can be used to characterize the operating state of the power grid. The ultimate objective is to minimize the redundant information, decrease the complexity of computations, and emphasize the discrepancies between the normal operating conditions and the fault conditions, thus, it allows identifying the faults very fast and precisely. The environment of operation in the contemporary power grid with high renewable energy penetration is becoming more complicated, and the characteristics of the faults tend to be non-stationary, nonlinear, and transient. Conventional approaches in data processing which is based on steady-state signal processing systems find it hard to satisfy the demands of real-time fault diagnosis. Thus, both advanced signal processing and dimensionality reduction techniques have been extensively used to get features of the fault.

Wavelet Transform (WT), Discrete Wavelet Transform (DWT), Wavelet Packet Transform (WPT), Fourier Transform (FT), Hilbert-Huang Transform (HHT) and Principal Component Analysis (PCA) are common methods of data processing and feature extraction in the current research. The wavelet-based transform methods are especially applicable in the processing of transient and non-stationary fault signals among others because of their high time-frequency localization abilities. It is worth noting that PCA, a traditional method of dimensionality reduction, is capable of eliminating interrelations between the variables, as well as reducing the amount of data, based on its ability to keep the most noticeable information, which is highly relevant to ensuring the real-time performance of the diagnostics programs. As an example, in the fault diagnosis of transmission lines, DWT can be used to calculate the fault transient current and voltage signal in multiple frequency band to obtain high-frequency fault information, and the dimensionality of the extracted multi-dimensional information can be reduced by PCA to achieve high diagnostic accuracy and reduce the computational burden of the diagnostic model.

Chen et al. Proposed an online fault diagnosis method based on fuzzy directed graph models, extracting fault features through signal amplitude and phase variation analysis. In terms of the

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experimental results obtained from those tests, the diagnostic accuracy for single and multiple faults exceeded 90% (verified in a 10-bus power system). It is also worth mentioning that the research realized online monitoring and diagnosis, strong interpretability, but the feature extraction process was overly dependent on expert experience [6]. Jiang et al. Proposed a fault detection and phase selection method based on Haar wavelet transform, using dyadic wavelet transform to extract transient features of transmission line faults. When used on the diagnosis of transmission line faults, the rate of correct phase selection in this method was more than 95% in a short list of fault types, and also had a high fault resistance selection rate [7]. Liang et al. presented a multi-scale approximate entropy feature extraction approach that uses the Dempser-Shafer (DS) theory and Deng entropy that combines multi-scale characteristics to describe fault states. This technique was experimentally validated to achieve a mean diagnostic error of 99.74 percent of 22 fault modes obtained when the technique was used to diagnose wind power converter faults when the wind speed varied. To its effects, it is able to capture multi-scale fault information and is very robust to changes in operating conditions, though the feature extraction process involves numerous parameters (such as embedding dimension and tolerance) to be set. In their article, Thomas et al. used 1D deep Convolutional Neural Networks (CNNs) as an automatic feature extractor, and combined them with transformer encoders to discover sequence features of fault data. In experimental validation, used on the IEEE 14-bus system fault diagnosis this method was more than 98 percent accurate on the High-Impedance Faults (HIFs). In terms of its impacts, it allows to extract features and diagnose end-to-end and minimizes the utilization of manual feature engineering, albeit with a substantial amount of labeled data to train models [8].

A wavelet transform-based approach suggested by Jiang can effectively make use of transient faults and its calculation speed can be rapid, although it requires enhancement in noise resilience. Chen incorporated expert knowledge in feature extraction, which increases the intelligibility of the diagnostic procedure but because the expert experience is subjective, it could influence diagnostic accuracy. The concept of multi-scale feature fusion was proposed by Liang, and this makes the fault information richer and the robustness against changes in operating conditions much better, however, the procedure of setting the parameter is rather complicated. Thomas also employed a deep learning-based automatic feature extraction system that does not require the use of manual feature engineering and is thus very accurate on data-intensive complex faults such as HIFs, however the expensive training of the model does require massive labelled data and high computational power.

Overall, the current feature extraction algorithms are not without their benefits, but they continue to be problematic, including, though not limited to, lack of noise resistance, too much expert experience or labeled data, and over-parameterization. Thus, the further investigations must be aimed to balance feature discriminability and computational efficiency, make them more adaptable to complicated operating conditions and noise levels, and less reliant on manual intervention and computational means.

2.2. Adaptive learning diagnostic model

Along with the further penetration of renewable sources of energy and the constant growth of the scale of the power grid, the nature of power grid faults is becoming increasingly multifaceted. It is with this context that adaptive learning models are aligned with their background. Classical models of fault diagnosis tend to be trained on offline historical data and their parameters cannot be changed. They will fail to detect the faults as they do when operating under new conditions, new types of faults or when they are not aware of the noise interference they are likely to have. To overcome this problem, there have risen adaptive learning diagnostic models. These models are

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capable of modifying their parameters and structures in real time based on the new data and feedback information and this allows them to keep learning and optimizing as they proceed online.

There are two varieties of adaptive learning diagnostic models online learning models and reinforcement learning models. Online learning models are able to rapidly update model parameters to new fault data without completely retraining the model which allows them to adapt to new fault characteristics. The models of reinforcement learning exceed the typical diagnostic roles. They do the fault diagnosis and disposal as a sequential decision making process trying various control actions, e.g. relays settings adjustment, isolation of fault sections etc. By exposure to the power grid environment, and coming to understand the most appropriate fault disposal plan, depending on the outcome of the feedback. This is not only crucial in raising diagnostic accuracy, but also in increasing the fault tolerance as well as self-healing property of the power grid.

Shahriar et al. suggested the Deep Belief Network (DBN) model developed by relying on dropout strategy and online learning and optimizes model weights during the incremental learning process under the condition of receiving the new fault data. The accuracy of the diagnostic was more than 95 percent in experimental testing of microgrid fault diagnosis with 50 rounds of online update. For its effects, this method shows strong adaptability to new fault types and reduces overfitting via the dropout strategy, but the incremental learning process may accumulate errors [9]. Liu et al. put forward a reinforcement learning-based fault diagnosis and disposal optimization model, which applies Q-learning to optimize fault section isolation and load restoration strategies. When applied in a distribution network with distributed generation, this model reduced the fault recovery time by 30% compared with traditional methods. Its effects include integrated diagnosis and disposal, which improves the self-healing capability of the power grid, yet the reward function design is complex and relies on accurate environment modelling [10]. Wang & Zhao proposed a hierarchical adaptive fault diagnosis model based on multi-source information: this model uses the NSGA-II algorithm to optimize the switching information layer, and constructs electrical criteria in the electrical information layer for online adjustment. In experimental verification on the IEEE 14-bus system, this method achieved a diagnostic accuracy of 98% for faults involving protective relay or circuit breaker malfunctions. Regarding its effects, the model realizes layered adaptive adjustment and has strong fault tolerance, but its hierarchical structure increases the complexity of the model [11]. Brahma & Girgis proposed an adaptive protection scheme for distribution systems with high distributed generation penetration, which adjusts relay settings online based on communication and network device data. Tested in a 33-bus distribution system, the protection coordination success rate reached 92% under different DG penetration rates. Its effects include adaptability to changes in power grid topology and DG output, as well as improved protection reliability, but it relies heavily on communication infrastructure [12].

Shahriar adopted the DBN model with dropout strategy, which realizes incremental learning and reduces overfitting, but the error accumulation in the online update process may affect long-term diagnostic accuracy. Liu integrated reinforcement learning into fault diagnosis and disposal, improving the power grid's self-healing capability, but the reward function design and environment modelling are difficult and require rich expert knowledge. The hierarchical adaptive model put across by Wang and Zhao is very effective in incorporating multi-source information and highly fault tolerant to complex faults, at the same time, the framework of the model is very complex and consumes high computational costs. Brahma & Girgis paid attention to adaptive adjustment of the settings in the relay, to the adaptation to the changes in the DG penetration rates, however, the use of communication infrastructure makes the likelihood of system failures higher.

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Generally, adaptive learning diagnostic models have been demonstrated as exhaustively beneficial in their adaptation of the constantly changing and demanding power grid faults. But they still have to deal with such problems as an error accumulation in the online update, the multidimensional optimization of model parameters, and excessive dependence on communication and computing resources. The future study must concern the improvement of the online update mechanism to save the errors, the simplification of the model structure with an enhanced computer demand, and the flexibility and high-quality performance of the model under the varied environments of operation and failures.

3. System architecture analysis and application

Having analyzed in some detail the major functions and technical issues involved in the real-time data processing methods and adaptive learning methods applied in the process of fault diagnosis of the power systems, this chapter will now critically assess how the two theoretical methods can be operationalized into a solid and seamless process of developing deployable and practical methods of fault diagnosis. The system architecture design is a key aspect of the relationship between the algorithmic model and the engineering in that, it directly determines the overall real-time performance, reliability, scalability and efficacy of the fault diagnosis system. In this way, this chapter goes beyond individual algorithms performances, and broadly considers the combination of the algorithmic model and engineering starting with the top and then carefully examines the way to construct a system that is characterized by a synergistic operational framework and includes many streams of data, processing units, decision modules, and feedback control loops. It offers a channel on quantitative measures of system performance across the system of operation and gives a step by step account of practical application and situations in reality. The chapter lays out the foundation and instruction on the way of engineering optimisation and progressive development of the findings of theoretical studies. To begin with it will be structured based on the organisational structure of the diagnostic systems in terms of their operation and utilisation of real-time feedback systems and how this translates into the systems of architectural design. It will then be narrowed down on performance appraisals and uses of the systems as established in a series of experiments and case studies. The performance, relative effectiveness, and operational constraints of the different architectures will be shown throughout the chapter using the power systems fault diagnosis applications. Lastly, It will create a complete technical closed-loop in approach to methodology till implementation of the system to eventual demonstration of results.

3.1. Analysis of the control framework based on the diagnostic system

This sub-section provides a brief description of five different intelligent fault diagnosis system architectures that were developed to overcome the above challenges in the power grid fault diagnosis context, which are: integrated information across the multiple sources, uncertain information to be processed, faults in new power electronics equipment and faults in analog circuit at an early stage.

The architecture, as described by the first one, is developed upon multi-objective optimization that integrates the approach to hierarchical diagnosis of the switching information as well as the electrical one. In the first layer, switching information is evaluated with information available in a multi-objective way, whereas the second layer of the architecture builds criteria of a set of target components. On the whole, this architecture can significantly enhance the effectiveness of diagnosis and the quality of diagnosis in relation to possible failures.

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The second is an end-to-end pure deep-learning network and is composed of CNN and transformer networks. CNN is applied to automatically detect features related to faults in fault current signals and the transformer is applied to learn the time sequence of the signals by taking advantage of the attention mechanism. This allows the symmetric/asymmetric faults, the high-impedance faults in the distribution system to be accurately and promptly detected.

Also, an intuitionistic fuzzy Petri net architecture is proposed to be used to deal with the information uncertainty [13]. The degree of certainty and uncertainty of the alarm information is ascertained with the help of the intuitionistic fuzzy sets. This is presented by the Petri net construct-based matrix reasoning methodology. The architectures enable the systems to handle complicated situations like faults of protection schemes (circuit breakers), continuously failing to trip or malfunction, and information loss because of a deficit of reaction to alarm communications.

In the fourth architecture, open circuit fault diagnosis and fault-tolerant control are combined in grid-connected Neutral-Point-Clamped (NPC) inversers [14]. The faults are observed based on the distortion nature of the output current and by injecting reactive power. This enables coordination of the modulation strategies to sustain system operation, or fault-detection services in the process of mitigating the impact of fault conditions.

The final architecture is geared towards dimensionality reduction and feature generalization to perform fault detection at early stages of analog electrical circuit systems [15]. Discrete Wavelet Transform (DWT) is used together with statistical techniques to generate high dimensional features. The dimensionality reduction algorithm applies Kernel Local Linear Discriminant Analysis (KLDLA) to radically reduce the time needed to complete fault pattern recognition with the help of an Extreme Learning Machine (ELM).

Together, these five fault diagnosis architectures constitute a multilevel intelligent fault diagnosis solution system representing various aspects of the above-described problems, including systems that process information through fusion strategies and deep learning models, employs techniques to account for uncertainty in reasoning about faults of power electronics, and constructs a multilayered framework for feature engineering, systems, networks and even components. Table 1 summarizes the characteristics and feedback mechanisms of the five grid system architectures mentioned in the previous text.

Table 1. Summary of system architecture

System architecture	Core algorithm	Information source and feedback mechanism
Hierarchical Multi-source Information Fusion Diagnosis System	NSGA-II, Fuzzy Theory, Electrical Criteria Construction	Switch & Electrical Information to Hierarchical Fusion Diagnosis
CNN-Transformer End-to-End Deep Learning Diagnostic System	1D CNN, Transformer Encoder, Multi-head Attention	Collect the three-phase current signals from multiple fixed monitoring points, input them into the model for automatic feature extraction and sequence learning. Directly output the classification results of fault type, phase and position.
Intuitionistic Fuzzy Petri Net Diagnostic System	Intuitionistic Fuzzy Petri Nets, Matrix Reasoning	The input includes protection information for both certainty and uncertainty as well as circuit breaker action alarm information. The reasoning is conducted through matrix operations of the intuitive fuzzy Petri net, and the failure probabilities of each component are calculated.
NPC Inverter Open-Circuit Fault Diagnosis & Fault-Tolerant System	Current Normalization, Reactive Power Injection Detection, SVM Reconstruction	Real-time monitoring of the output phase current of the inverter and the DC-side capacitor voltage is carried out. Fault detection and classification are conducted by analyzing the average current and distortion characteristics. After diagnosis, the corresponding fault-tolerant modulation strategy is automatically switched.

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Table 1. (continued)

Analog Circuit Fault Diagnosis System	Wavelet Analysis, KLLDA, ELM	Obtain the output response signal of the tested circuit, extract the initial high-dimensional features through wavelet transformation and statistical analysis.

3.2. Performance evaluation and main applications

To advance the theoretical design of a fault diagnosis system into engineering applications, the next important step is to assess the system's performance quantitatively and determine how effectively it will work in complex real-life situations. Therefore, this section focuses on "Performance Assessment and Major Application Areas." To meet this goal, this section proposes scientific experiments together with empirical investigation of representative application environments that provide objective data and reliable evidence of the system architecture's theoretical benefit.

For example, a study by Shou-Peng Wang proposed a multi-source information-based hierarchical fault diagnosis method. Simulation was used to validate the method's robustness using a model developed within the IEEE 14-bus system environment by PSCAD/EMTDC. For the experiment, simultaneous A-phase grounding faults occurring at both T1 and between lines L6 and L12 were simulated, as well as various abnormal PR and CB operations such as failure to trip and incorrect operations, in addition to distorted alarm messages. The experiment was divided into two stages. The first stage is building a multi-objective model only using switching information and optimizing with NSGA-II; for the second stage, if multiple candidate faults existed, developing an electrical criterion only relative to each candidate part (lines, buses, transformers).

The study used several electrical parameters, including modal components of fault current and voltage, Kirchhoff's current law, positive-sequence phase angles, source-resistance calculations, and zero-sequence current relationships to distinguish between candidates. As a result, the verification demonstrates the potential for future implementation of fast, efficient, and effective methods to analyse faults in dispatch systems when protection devices are malfunctioning and the available data for analysis are severely limited.

Furthermore, Da-Zhang You has also conducted research on general fault diagnosis of analog circuits using the IWOA-ELM (Improved Whale Optimization Algorithm-Extreme Learning Machine) method [16]. This research has examined the challenges associated with identifying faults within nonlinear and higher dimensional feature spaces and refined the existing approach to diagnosis using IWOA and ELM. As part of the validation of this method, two standard test circuits were used, including a Sallen-Key bandpass filter and a CSTV filter. The experiment carried out voltage measurement waveforms analysis depending on diverse fault scenarios through Monte Carlo analysis and transient simulation. Wavelet packet decomposition was then applied to the outputs to obtain 32 dimensional representations and methodology was applied through Principal Component Analysis (PCA) of the data sets above to identify principal components that, on average, had a cumulative contribution rate of at least 85 per cent.

The IWOA is better than the classical WOA in several aspects including Tent chaotic mapping in the beginning part, using non-linear time dependent factors to adjust weights, the introduction of a random-differential mutation approach within the optimization process and others. With this optimized technique, optimum values of input weights and hidden-layer bias values were particularly obtained in an ELM as fitness measures that were optimized through an iterative procedure. Accuracy rates of 99.41% and 98.46% of the IWOA-ELM method were the highest and could be obtained with the Sallen-Key and CSTV circuits, respectively, and there was the ability of the best convergence without the local optima. Intelligent optimization and PCA-based dimensionality reduction of features offered a practical way of significantly enhancing the discriminating capability of several fault state instances of analog circuits as well as offering a good diagnostic remedy of IC testing and anticipatory maintenance of electronic devices.

The section critically discusses the important role played by a system architecture, which is defined by strong hierarchy, modular synergies and responsiveness with regard to the real-time performance and thus establishes a fundamental foundation towards improving the accuracy and reliability of fault diagnosis in high-performance power systems. In-depth performance analysis offers factual affirmation of the logic of optimally implementing such systems in real-time process and also aids in subsequent development to maintain its growth.

4. Conclusion

In the background of high rates of renewable energy penetration, growing power grid scale, and faults with varied modes, the customary offline and steady-state-based fault diagnosis strategies have turned out not to be efficient enough to manage the non-stationary, nonlinear, and transient fault characteristics of modern power grids. Recent studies have addressed three overlapping fundamental directions namely real time data processing, adaptive learning models and integrated system architectures to provide a connection between the theoretical algorithm and engineering practice that forms the basis of effective and reliable fault diagnosis.

Fault diagnosis is based on real-time data processing which aims at deriving low-dimensional, discriminative features of high volume monitoring data with reduced redundancy. The most important ones are wavelet-based transforms (WT, DWT, WPT) in the context of transient signal processing, dimensionality reduction algorithms (PCA and KLLDA), and automatic extraction of features implemented with the help of deep learning. Examples of representative studies are the Haar wavelet transform method by Jiang et al, 1D CNN-Transformer framework by Thomas et al and multi-scale fusion method by Liang et al. Nevertheless, these approaches are limited in number: wavelet based approaches lacks robustness to noise, expert knowledge methods are subjective and deep learning models are resource intensive in terms of both data with labels, and computation.

The model Adaptive learning models overcome the inflexibility of classical fixed-parameter models, which fall into the online learning and reinforcement learning paradigms. The dropout-based DBN model by Shahriar et al. preserves at least 95% accuracy with 50 online updates but accumulates errors whereas the Q-learning framework proposed by Liu et al. reduces the time needed to recover a fault by 30% but has difficulty with the design of reward functions. Some complementary architectures, such as hierarchical multi-source fusion, end-to-end deep learning and intuitionistic fuzzy Petri nets, NPC inverter fault-tolerant control and KLLDA-ELM analog circuit diagnosis, address certain challenges such as uncertainty of information and malfunctions of protection. All these architectures enhance the effectiveness of diagnostics but have shared problems: inadequate resistance to noise, excessive dependence on specialist knowledge or annotated data, and resource consumption.

Continuing on the latest achievements in the field of research and on the existing problems in the field, the further investigations in the area of power grid fault diagnostics will be focused on the combination of different technological directions in order to enhance the level of diagnostic accuracy, operating efficiency, system reflexibility, generalization ability and cooperative functioning with complex grid operating conditions. Moreover, the creation of common evaluation frameworks and open and high-quality datasets will serve as a complementary part and parcel to rigorous comparison of methods, as well as to practical engineering use, the frameworks will bundle the assessment standards, thereby ensuring fair performance verification, whereas the open datasets will open the data scarcity bottleneck in model training and verification. In general, the next

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generation fault diagnosis systems will be developed further as intelligent, tougher and even more efficient in terms of performance through cross-domain technological integration and systematic innovative design approach to create the highly reliable and self-intercompeting next-generation power grids.

Authors' contributions

These authors contributed equally and their names were listed in alphabetical order.

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