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A Review Paper on the Fault Diagnosis and Detection of Transformer

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ABSTRACT:

The transformer plays a critical role in maintaining the stability and smooth operation of the entire power system, particularly in power transmission and distribution. The paper begins by providing an overview of traditional fault diagnosis methods for transformers, including dissolved gas analysis and vibration analysis techniques, elucidating their developmental trajectory. Building upon these traditional methods, numerous researchers have aimed to enhance and optimize them through intelligent technologies such as neural networks, machine learning, and support vector machines. These researchers have addressed common issues in traditional fault diagnosis methods, such as the low correlation between characteristic parameters and faults, ambiguous fault descriptions, and the complexity of feature analysis. However, due to the complexity of transformer structures and the uncertainties in operating environments, the collection and analysis of characteristic parameters becomes highly intricate. Researchers have further refined algorithms a feature values based on intelligent diagnostic algorithms for transformers. The goal is to improve diagnostic speed, mitigate the impact of measurement noise, and further advance the adaptability of artificial intelligence technology in the field of transformers. On the other hand, the excellent multi-parameter analysis capability of artificial intelligence technology is more suitable for transformer diagnostic techniques that involve the fusion of multiple information sources. Through the powerful data acquisition, processing, and decision-making capabilities provided by intelligent algorithms, it can comprehensively analyze non-electrical parameters such as oil and gas characteristics, vibration signals, temperature, along with electrical parameters like short-circuit reactance and load ratio. Moreover, it can automatically analyze the inherent relationship between faults and characteristic quantities and provide decision-making suggestions. This technique plays a pivotal role in ensuring transformer safety and power network security, emerging as a prominent direction in transformer fault diagnosis research.

Introduction

Power transformers are critical components in electrical power systems, facilitating efficient voltage regulation and energy transfer across generation, transmission, and distribution networks. Due to their pivotal role, even minor faults in transformers can lead to significant operational disruptions, economic losses, and safety hazards. Therefore, accurate and timely fault detection is essential to ensure system reliability, minimize downtime, and enable predictive maintenance.

Traditionally, transformer fault detection has relied on techniques such as Dissolved Gas Analysis (DGA), oil analysis, thermal imaging, and electrical testing. While these methods have proven effective to a certain extent, they often require manual interpretation, have limited sensitivity to early-stage faults, and are inadequate for real-time monitoring. To overcome these limitations, recent research has focused on integrating intelligent systems and data-driven models to enhance the accuracy, speed, and automation of transformer fault diagnosis.

This review paper presents an overview of various modern approaches to transformer fault detection, including machine learning algorithms (such as Random Forest, CatBoost, GBDT), fuzzy logic, neural networks, and hybrid techniques that combine traditional methods with advanced data analytics. Additionally, emerging tools like SMOTE for sample balancing, optimization algorithms (e.g., DBSO and NGO), and distributed monitoring systems based on Rich Internet Applications (RIA) are discussed. The objective is to highlight the evolution of diagnostic methods, evaluate their effectiveness, and emphasize the need for intelligent, real-time, and robust fault detection systems in modern power grids.

Previous works

In research paper [1, it is mentioned that power transformers are critical components in the generation and distribution of electrical energy, and maintaining their optimal operational state remains a key priority for industry professionals. The overall health of a power transformer is largely governed by the condition of its composite insulation system, which includes both solid cellulose-based paper and liquid insulating oil. To support early fault detection, the Three Ratio Technique (TRT) has proven to be an effective diagnostic tool. In this study, the diagnostic ratios defined by the TRT method are utilized as input features to train a machine learning classifier. Specifically, ensemble learning methods and the Random Forest algorithm are employed to enhance fault identification accuracy. The effectiveness of the proposed approach is validated through an experimental evaluation of a fault identification software application developed based on the method.

In research paper [2], it is mentioned that Transformers are vital components in both industrial and societal infrastructures due to their essential role in power distribution, enabling the delivery of electricity across various loads and geographic locations. Given their critical importance, ensuring high operational reliability is imperative to avoid unplanned outages and economic losses. Within a transformer, the primary and secondary windings are insulated using oil, and analysis of this insulating oil serves as a key diagnostic tool for assessing the transformer's health and identifying potential faults. This study presents a hybrid approach combining Fuzzy Logic and Neural Network methodologies for fault detection and, where possible, fault prediction. The primary aim is to assist maintenance personnel in making timely and informed decisions. Experimental results demonstrated a fault detection accuracy of up to 95%, underscoring the effectiveness of the proposed technique. Additionally, the research emphasizes the value of predictive maintenance strategies and offers a novel framework to enhance decision-making in transformer management.

In research paper [3], it is mentioned that the power transformer is one of the most critical components in an electrical power system. Consequently, its condition monitoring is essential to ensure reliable operation and maintain the quality of power supply within the grid. Traditionally, Dissolved Gas Analysis (DGA) has been widely employed for fault detection and diagnosis in power transformers. However, DGA methods exhibit certain limitations in precision and applicability for online fault detection.

To address these shortcomings, this study proposes a novel approach based on the analysis of metallic elements dissolved in transformer oil for real-time fault diagnosis. Initially, extensive datasets comprising metal element concentrations in transformer oil were collected and analyzed. A Back Propagation (BP) neural network model was then developed to perform fault classification and diagnosis. The model was trained using the collected sample data, and its performance was evaluated by comparing the predicted results with the expected fault conditions.

The findings indicate that metal element analysis, when integrated with BP neural networks, provides an effective and reliable means for transformer fault detection. This method enhances diagnostic accuracy and is well-suited for real-time monitoring applications.

In research paper [4], it is mentioned that to overcome the limitations of low diagnostic accuracy in conventional power transformer fault identification methods, this study introduces a novel transformer fault diagnosis approach based on the DBSO-CatBoost model. The proposed method integrates advanced data preprocessing, feature extraction, dimensionality reduction, and model optimization techniques to improve fault classification performance. Initially, a data preprocessing pipeline was implemented where feature engineering was performed using the ratio method to enrich the original dataset. Feature importance was further enhanced using SHAP (Shapley Additive Explanations), and dimensionality reduction was achieved through the application of Kernel Principal Component Analysis (KPCA). The refined dataset was subsequently used to train a CatBoost model, a gradient boosting algorithm known for its high efficiency and handling of categorical features. To optimize the CatBoost model parameters, the Difference-mutation Brain Storm Optimization (DBSO) algorithm was employed, resulting in an enhanced diagnostic model referred to as the DBSO-CatBoost model. This model was then applied to classify transformer faults and predict corresponding fault types. Experimental results demonstrated that the proposed DBSO-CatBoost model achieved a diagnostic accuracy of 93.71%, representing a 3.958% improvement over the standard CatBoost model and outperforming several other conventional approaches. Additionally, the tailored data preprocessing strategy adopted in this study contributed significantly to the improvement in diagnostic performance, highlighting the effectiveness of the integrated methodology for accurate and reliable transformer fault diagnosis.

In research paper [5], it is mentions a novel method for diagnosing transformer insulation faults using a decision tree-based approach. Leveraging a historical fault sample library, the method employs entropy-based information gain as a heuristic criterion for selecting test attributes, and constructs the decision tree using the ID3 (Iterative Dichotomiser 3) algorithm. To enhance the model’s generalization capability and reduce overfitting, post-processing techniques such as tree pruning are applied to eliminate noise, followed by the extraction of interpretable classification rules. The proposed approach demonstrates several advantages: it provides rapid inductive learning, offers high classification speed, and is capable of efficient data compression, thereby saving memory resources. The effectiveness of this diagnostic method is validated through practical application, confirming its reliability and utility for transformer insulation fault identification.

In research paper [6], it is mentioned that traditional transformer monitoring systems suffer from limitations such as centralized architecture, geographic constraints, and reduced scalability. To overcome these challenges, a distributed remote insulation condition monitoring and fault diagnosis system based on the Rich Internet Applications (RIA) model is proposed. This system integrates multiple diagnostic techniques, including ultra-high frequency (UHF) partial discharge (PD) detection and core grounding current analysis, to enable comprehensive monitoring of transformer insulation.

The proposed approach establishes correlations between discharge events and insulation defects, enabling the identification of discharge locations and associated failure causes. A fusion-based methodology combining pulse waveform analysis with statistical operators is employed for discharge pattern recognition and fault classification. Furthermore, the system supports remote online monitoring of insulation conditions and facilitates distributed, multi-expert collaborative diagnosis. This distributed architecture enhances scalability, improves fault detection accuracy, and enables timely maintenance interventions, ultimately contributing to increased transformer reliability and reduced risk of failure.

In research paper [7], it is mentioned that a novel diagnostic approach for power transformer insulation faults based on fuzzy normal partitioning and logical reasoning. The method begins by applying fuzzy processing to both insulation diagnostic parameters and diagnostic conclusions using normal distribution functions, which allows for more accurate representation of uncertainty in the data. Subsequently, diagnostic knowledge is formalized, and corresponding reasoning rules are established. Fuzzy reasoning is then applied to interpret test results and derive diagnostic conclusions. This technique effectively addresses the challenge of describing complex relationships between measured data and fault outcomes. It enhances reasoning efficiency, improves diagnostic accuracy, and increases practical applicability. Actual computational results validate the method’s capability to deliver accurate and efficient insulation fault detection, making it a viable tool for real-world power transformer monitoring systems.

In research paper [8], it is mentioned that to address the challenge of imbalanced datasets and improve the accuracy of transformer fault diagnosis, this study proposes a hybrid diagnostic model based on Synthetic Minority Over-sampling Technique (SMOTE) and an optimized Gradient Boosting Decision Tree (GBDT) algorithm using Northern Goshawk Optimization (NGO). Initially, SMOTE is employed to augment minority class samples, thereby mitigating the effects of class imbalance and enhancing model generalization. Subsequently, a non-coding ratio method is utilized to construct multi-dimensional feature parameters, and an embedded Light Gradient Boosting Machine (LightGBM) strategy is applied for optimal feature subset selection.

Finally, the NGO algorithm is used to fine-tune the hyperparameters of the GBDT model. Experimental results demonstrate that this integrated approach significantly reduces misclassification of minority samples and enhances overall fault identification accuracy. Compared to conventional ensemble models, the SMOTE and NGO-GBDT framework exhibits superior performance in terms of diagnostic accuracy, reduced error rates, and operational stability, making it a robust solution for real-world transformer condition monitoring.

Conclusion

The reliable operation of power transformers is vital for ensuring the stability and efficiency of electrical power systems. This review has explored a wide range of techniques and recent advancements in transformer fault detection and diagnosis, including traditional methods like Dissolved Gas Analysis (DGA), advanced machine learning models such as Random Forest, CatBoost, GBDT, and hybrid approaches incorporating neural networks, fuzzy logic, and optimization algorithms. The integration of intelligent systems and real-time monitoring frameworks has significantly enhanced fault prediction accuracy and decision-making capabilities. Moreover, emerging technologies like SMOTE for data balancing, SHAP for feature selection, and distributed monitoring based on Rich Internet Applications (RIA) further emphasize the shift toward smart and adaptive transformer health assessment systems. Overall, the reviewed literature indicates a strong trend toward data-driven, automated, and accurate fault detection methods that not only ensure timely maintenance but also prolong transformer lifespan and reduce operational risks.

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