Design and application research of a device for effectively simulating arc-type turn-to-turn short-circuit faults in dry-type reactors

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Keywords: dry-type reactor, arc-type turn-to-turn short-circuit, fault simulation, device design, application research

Abstract: In order to effectively simulate the arc-type turn-to-turn short-circuit fault that may occur in dry-type reactors during actual operation, and to study its impact on the performance of the reactor and the stability of the power system, this paper designs a simulation device that can accurately reproduce this type of fault. Through in-depth analysis of the formation mechanism and characteristics of the arc-type turn-to-turn short-circuit fault, the key influencing factors are clarified, and on this basis, the overall design scheme of the device and the optimization strategy of the key modules are proposed. The device integrates an arc generator, a reactor model and an intelligent control unit, and has high precision, high controllability and good experimental adaptability. In the experimental verification, the device successfully reproduced the turn-to-turn short-circuit fault under various working conditions, and the obtained data was highly consistent with the theoretical analysis, further revealing the fault evolution process and its characteristics. The research results show that the simulation device has important application value in the research of power equipment maintenance and fault diagnosis, and provides a scientific basis for the reliability design and fault prevention and control of dry-type reactors.

1. Introduction

As the power system develops towards large-scale and high reliability, the operational stability of dry-type reactors, as a key piece of equipment, is directly related to the safety of the entire power system. However, in long-term operation, due to environmental factors, overloads and other reasons, dry-type reactors may experience turn-to-turn short-circuit faults, of which arc-type turn-to-turn short-circuit faults are particularly complex and harmful[1]. Such faults not only cause a significant decrease in the performance of the reactor, but may also induce instability in the power system, and even cause serious equipment damage and power grid accidents[2].

Research on reactor faults has mainly focused on the detection and diagnosis of traditional short-circuit faults, while the mechanism analysis and simulation reproduction of arcing turn-to-turn short-circuit faults has received relatively little attention[3]. On the one hand, arc-type turn-to-turn short-circuits have complex nonlinear characteristics, and their formation process and evolution mechanism are difficult to completely describe through theoretical models. On the other hand, the lack of effective experimental devices makes it a huge challenge to reproduce and study such faults in depth[4]. Therefore, designing a simulation device with high precision and strong controllability is of great significance for in-depth understanding of the characteristics and impact mechanism of arc-type turn-to-turn short-circuit faults.

In this paper, based on an in-depth analysis of the mechanism and characteristics of arcing turn-to-turn short-circuit faults, a simulation device is designed that can effectively reproduce the fault process[5]. The accuracy and reliability of the device are verified through experimental tests. This paper systematically analyzes the impact characteristics of the fault and its performance under different operating conditions, providing new ideas and technical support for power equipment fault diagnosis research and reactor optimization design[6].

2. Analysis of the mechanism and characteristics of arcing turn-to-turn short-circuit faults

Arcing turn-to-turn short-circuit faults are mainly caused by local breakdown or aging of the insulation layer of the dry-type reactor[7]. In a high-voltage and high-temperature environment during long-term operation, the dielectric properties of the insulation material gradually degrade. When the turn-to-turn electric field strength exceeds a critical value, partial discharge will occur. Initial discharges are mostly transient partial breakdowns. As the arc continues to act, the high temperature causes further ablation of the insulation material, gradually forming a stable turn-to-turn short-circuit loop[8]. The entire process exhibits significant nonlinear characteristics and is affected by multiple random factors.

The formation and development of the arc is affected by a combination of factors such as the turn-to-turn voltage, the characteristics of the insulating material, the operating ambient temperature and humidity. The relationship between voltage and current is not linear, but a complex process of dynamic change. Changes in the length of the arc, differences in the degree of ionization and fluctuations in the state of the medium can cause the arc to exhibit strong non-stationary characteristics. Changes in the operating conditions of the reactor can significantly interfere with the stability of the arc. This complexity increases the difficulty of fault prediction and analysis. Ohm's Law for the short-circuit current:

$$I=VR \tag{1}$$

Arc-type turn-to-turn short-circuit faults have a significant impact on the performance of the reactor. The immediate consequence is a rapid decrease in inductance, which seriously affects the normal operation of the reactor[9]. Fault-induced local overheating and arc oscillation may exert mechanical stress on the coil structure, further accelerating physical damage to the device. Turn-to-turn short-circuits may also cause a significant increase in the harmonic content of the power system, reducing power quality and having a knock-on effect on the operational stability of other equipment[10]. Arc-type turn-to-turn short-circuit faults have obvious dynamic evolution characteristics. The initial fault is dominated by partial discharge and transient short-circuit. As the arc gradually expands, the short-circuit state changes from intermittent to continuous. Thermal effects and electrical effects superimpose on each other in this dynamic process, which continuously aggravates the deterioration of the insulation layer and forms a vicious circle. This dynamic characteristic makes the fault show great randomness and complexity, which puts forward higher technical requirements for its monitoring and diagnosis, showed in Figure 1:

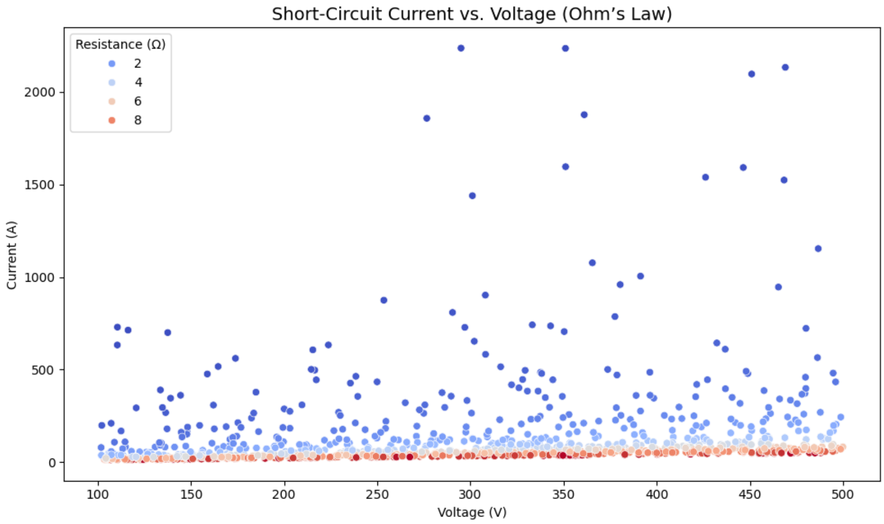

Figure 1 Short-Circuit Current vs. Voltage (Ohm's Law)

3. Design and implementation of simulation device

To effectively simulate an arcing turn-to-turn short-circuit fault, this paper designs an integrated, high-precision experimental device. The device design is based on fault mechanism analysis. By integrating an arc generator, a reactor model and an intelligent control unit, the entire process of a turn-to-turn short-circuit fault can be accurately reproduced. By optimizing the device performance and establishing a reliable experimental environment, the controllability of the simulation and the accuracy of the data can be ensured.

3.1. Overall design concept

In order to accurately reproduce the dynamic characteristics of an arcing turn-to-turn short-circuit fault, the design of the simulation device aims to achieve high reproducibility and reliability, taking into account the nonlinear characteristics of the arc generation process and its multidimensional impact on the performance of the reactor. The device is designed in a modular way to ensure a simple structure while being sufficiently expandable to adapt to the needs of different experimental scenarios.

The core design of the device is based on the analysis of arc characteristics, and a high-precision arc generator is built. The generator can dynamically adjust the arc length, voltage and current to simulate the formation and development process of the turn-to-turn short circuit arc under actual working conditions. By introducing intelligent control algorithms, real-time monitoring and parameter adjustment of arc behavior are realized to ensure the accuracy and safety of the experiment. In order to realistically simulate the impact of turn-to-turn short circuits on reactors, the device is equipped with an adjustable reactor model. This model, with its multi-layer winding and variable gap design, can flexibly adjust the turn-to-turn voltage and insulation degradation, so as to study the changes in reactor characteristics under different fault conditions. The model is closely coupled with the arc generator to form a complete experimental circuit. Inductive reactance of a coil:

$$XL=2\pi fL \tag{2}$$

The device integrates a variety of sensing and data acquisition modules to record the electrical, thermal and mechanical responses in real time when a fault occurs. All the collected data is stored and analyzed by a central processing unit and compared with the theoretical model to provide a scientific basis for further optimizing the device and studying the characteristics of arcing faults.

3.2. Core module design

The core module design of the simulation device is intended to achieve accurate reproduction of arcing turn-to-turn short-circuit faults and ensure the reliability and controllability of experimental results. The core module mainly includes an arc generator, a reactor model and an intelligent control unit. These modules work together to accurately simulate the entire process of an arcing turn-to-turn short-circuit fault. The following provides a detailed design description of each module.

The arc generator is a key component of the simulation device. This module uses a high-voltage DC power supply combined with pulse modulation technology to precisely regulate the voltage and current of the arc generator. The arc generator can simulate the characteristics of arcs under different fault conditions, including the initial discharge, growth process and steady-state characteristics of the arc. By monitoring the voltage, current and temperature of the arc in real time, the control system can dynamically adjust the behavior of the arc as needed to ensure a high degree of consistency with actual faults.

The reactor model is designed to accurately simulate the electromagnetic characteristics and temperature response of a dry-type reactor under an interturn short-circuit fault. The module achieves adjustable control of the inductance change, thermal effect and electric field distribution of the reactor through a multi-layer winding structure and adjustable inductive components. In particular, the voltage and current distribution between the windings can be adjusted according to experimental requirements to reproduce different degrees of insulation degradation and electric field changes, thereby simulating the fault evolution process of the reactor when an interturn short circuit occurs.

The intelligent control unit is the “brain” of the entire simulation device. It uses real-time control technology, combined with sensor data and feedback mechanisms, to precisely control the arc generator, reactor model and other auxiliary modules. The control system can automatically adjust the operating state of each module according to the set experimental conditions and fault types, ensuring the consistency and accuracy of the entire fault simulation process. The intelligent control unit is also responsible for the collection and analysis of experimental data, real-time monitoring of the evolution of arc faults, and ensuring the safety and efficiency of the experimental process.

3.3. Device performance optimization

In order to ensure the high accuracy and stability of the simulation device in the reproduction of arcing turn-to-turn short-circuit faults, the device performance optimization has been designed and improved in depth from multiple dimensions. The optimization scheme focuses on improving the system response speed, enhancing the controllability of fault simulation, improving the accuracy of data collection, and ensuring the stability of the experimental process. The following are specific strategies for device performance optimization. To improve the response speed of the simulation process, the control system of the arc generator was optimized. By using high-frequency pulse modulation technology and more advanced feedback control algorithms, the arc generator can respond faster to changes in external parameters and adjust the voltage, current and temperature of the arc in real time. This optimization ensures that the device can maintain high simulation accuracy under transient operating conditions and meet the dynamic response requirements of different interturn short-circuit fault conditions, showed in Figure 2 :

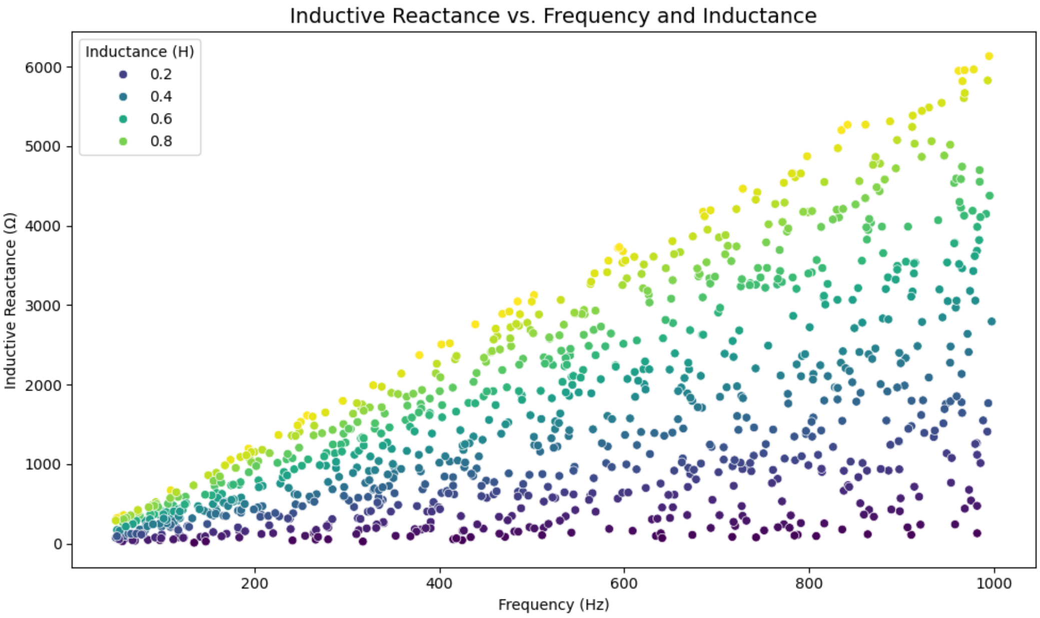

Figure 2 Inductive Reactance vs. Frequency and Inductance

Another important direction of optimization is to enhance the controllability of fault simulation. The device introduces an intelligent adaptive control algorithm, which makes the interaction between the arc generator and the reactor model more refined and adjustable. By precisely adjusting the power of the arc generator and the inductance of the reactor, various fault scenarios can be accurately simulated. The system has the function of customizing the type, duration and degree of fault. Users can adjust the relevant parameters according to the needs of the experiment to achieve diversified fault simulation. The device's data collection accuracy has been significantly improved. The optimized sensor system uses high-precision voltage, current, temperature and other measurement devices, and a real-time data acquisition module accurately records all data during the experiment. This data is directly transmitted to the central processing unit for analysis and storage to ensure data integrity and accuracy. The data analysis module also further corrects experimental errors by comparing with theoretical models to improve data reliability.

The stability of the device is optimized, and the continuity of fault recurrence and experimental safety are greatly enhanced. Improvements in system thermal management, the power supply system and mechanical stability ensure that the device can continue to work stably for long periods of time, avoiding faults caused by overheating or power fluctuations. The system is also equipped with multiple protection mechanisms, such as overcurrent protection, overheating protection and voltage protection, to ensure safety and repeatability during the experiment.

4. Simulation of device failure recurrence and data analysis

The process of failure recurrence is accomplished through the coordinated operation of an arc generator and a reactor model. At the beginning of the experiment, the initial discharge phase of an arcing turn-to-turn short-circuit fault is simulated by adjusting the voltage and current of the arc generator. As the experiment progresses, the turn-to-turn voltage in the reactor model gradually increases, the length and temperature of the arc continue to change, and a stable short-circuit loop is eventually formed. By precisely controlling the operating conditions of each module, the entire process of the turn-to-turn short-circuit fault, from the initial discharge to the evolution of the fault steady state, was successfully reproduced. During the experiment, the dynamic characteristics of the arc, the duration of the fault, and its impact on the performance of the reactor were accurately simulated.

The experimental data obtained during the fault recurrence process provides a rich basis for subsequent analysis. The data acquisition module uses high-precision sensors to monitor the voltage, current, temperature and other parameters of the arc in real time, and transmits this data to the central processing unit for real-time analysis. At different stages of the fault, the system can accurately record and store various data, providing a basis for analyzing the characteristics of the fault. This data not only helps to verify the simulation accuracy of the device, but also provides a reliable basis for further optimizing the performance of the device.

The data analysis process revealed the dynamic characteristics of an arcing turn-to-turn short-circuit fault through in-depth mining of the collected data. Analysis of key parameters such as the arcing current waveform, temperature distribution, and coil losses revealed that the current fluctuation during the fault has strong nonlinear characteristics, and the fault process shows a significant lag effect. The data analysis also revealed the mechanism by which an interturn short-circuit affects the inductance of the reactor. The inductance decreased significantly at the beginning of the fault, but as the fault continued, the change in inductance tended to stabilize, indicating that the effect of an arc-type short-circuit fault on the reactor is a gradual process.

In order to ensure the accuracy and reliability of the data analysis, the device was also compared with a theoretical model. By comparing the experimental data with a theoretical model based on an arc-type interturn short-circuit fault, the accuracy of the device design and fault reproduction process was verified. The data analysis results show that the experimental data is highly consistent with theoretical expectations, which further proves the effectiveness of the device in reproducing arcing turn-to-turn short-circuit faults. The nonlinear dynamic characteristics captured during the experiment provide new ideas for the study of arcing turn-to-turn short-circuit faults and help to better understand the evolution of the fault and its potential impact on the power system.

5. Conclusion

In this study, an experimental device for simulating arcing turn-to-turn short-circuit faults was designed and implemented, and its performance was optimized. By precisely controlling the coordinated operation of the arc generator, reactor model and intelligent control unit, the entire process of an arc-type turn-to-turn short-circuit fault was successfully reproduced, and the dynamic characteristics of the fault and its impact on the performance of the reactor were thoroughly analyzed. The experimental results show that the device can accurately reproduce the nonlinear characteristics of an arc-type turn-to-turn short-circuit fault, especially key parameters such as current fluctuations, temperature changes, and the dynamic changes in inductance. This provides a reliable experimental platform for further research on the failure mechanism of reactors.

Through data analysis, the research revealed the typical characteristics of an arc-type turn-to-turn short-circuit fault, including the nonlinear dynamic behavior of the arc, the sharp decrease in inductance value during the initial stage of the fault, and the gradual recovery of inductance during the sustained stage of the fault. These findings not only verified the accuracy of the device simulation, but also provided theoretical support for the development of reactor fault diagnosis technology. The optimization of the device performance, especially the improvement in the response speed of the arc generator, the controllability of fault simulation, and the accuracy of data acquisition, further ensured the reliability and repeatability of the experimental results.

Acknowledgements

The authors acknowledge the Research on Precise Sensing Technology and Application of High-Voltage Dry-Type Air-Core Reactor (Project Number: 5500-202119131A-0-0-00).

References

[1] Ahn H M , Oh Y H , Kim J K ,et al.Experimental Verification and Finite Element Analysis of Short-Circuit Electromagnetic Force for Dry-Type Transformer[J].IEEE Transactions on Magnetics, 2012, 48(2):819-822.DOI:10.1109/TMAG.2011.2174212.

[2] L,A, Mackie-Dawson C ,et al.Seasonal changes in the structure of clay soils in relation to soil management and crop type. I: Effects of crop rotation at Cruden Bay, NE Scotland[J].European Journal of Soil Science, 1989, 40(2):269-281.DOI:10.1111/j.1365-2389.1989.tb01272.x.

[3] Hoi M , Hrgeti M , Kranjevi N ,et al.Design of a Disc-on-disc-type CNC Tribometer Targeted at Dry Clutch Friction Plate Wear Characterization[J].International Journal of Automotive Technology, 2022, 23(1):55-71.DOI:10.1007/s12239-022-0005-2.

[4] Smolka J, Nowak A J. Shape Optimization of Coils and Cooling Ducts in Dry-Type Transformers Using Computational Fluid Dynamics and Genetic Algorithm[J].IEEE Transactions on Magnetics, 2011, 47(6):1726-1731.DOI:10.1109/TMAG.2011.2109731.

[5] En T , Harada K , Nakano T .On the combined effect of AC and DC magnetic fields in a dry-type magnetic Separator[J].Magnetics IEEE Transactions on, 1982, 18(6):1701-1703. DOI:10.1109/TMAG.1982.1062002.

[6] Lee M , Abdullah H A , Jofriet J C ,et al.Thermal modeling of disc-type winding for ventilated dry-type transformers[J].ELECTRIC POWER SYSTEMS RESEARCH, 2010, 80(1):121-129. DOI:10.1016/j.epsr.2009.08.007.

[7] Tseng Y S , Wang J R , Tsai F P ,et al.Thermal design investigation of a new tube-type dry-storage system through CFD simulations[J].Annals of Nuclear Energy, 2011, 38(5):1088-1097. DOI:10.1016/j.anucene.2011.01.001.

[8] Kusy R P , Whitley J Q , Prewitt M J .Comparison of the Frictional Coefficients for Selected Arch Wire-Bracket Slot Combinations in the Dry and Wet States[J].The Angle Orthodontist, 1991, 61(4):293-302. DOI:10.1043/0003-3219(1991)0612.0.CO;2.

[9] Pfuntner R A , Franck R E , D" Entremont F R .A new dry-type insulation for instrument transformers[J].Electrical Engineering, 1950, 69(7):594-599.DOI:10.1109/ee.1950.6433952.

[10] Hirai T , Kano M .Adaptive Virtual Metrology Design for Semiconductor Dry Etching Process Through Locally Weighted Partial Least Squares[J].IEEE Transactions on Semiconductor Manufacturing, 2015, 28(2):137-144.DOI:10.1109/TSM.2015.2409299.