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Research Paper

Transformer Winding Deformation Detection and Modeling Based on Frequency Response Method

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Abstract: *Power transformer is one of the key equipment of the power system, and its reliable operation is an important factor for the safety of the whole power grid and even national power. With the increasing scale of the power grid, the probability of transformer failure due to winding deformation is on the rise. When using online frequency response method to detect winding deformation, it needs to be verified with simulation, the experiment provides a scientific basis for simulation, and simulation verifies the correctness of the experimental method. At present, the field experiment affects the accuracy of winding deformation detection mainly because of the signal injection and extraction, power system noise and the analysis of the experimental results; in the simulation analysis, the error mainly exists in the establishment of the transformer winding model, and the frequency response curve obtained from the simulation of different precision models is not consistent. This paper summarizes the research results in recent years from several aspects such as signal injection and measurement methods and different winding modelling structures. Firstly, the advantages and disadvantages of the frequency response method, which is the most widely used method in the detection of winding deformation, are compared between offline and online, and several new detection methods are analyzed; afterwards, several measurement techniques are introduced according to the signal injection and extraction problems encountered in the experiments; finally, the method of constructing the winding model of transformers is proposed, and there is an urgent need to obtain a more accurate winding model. Comprehensively, the above three aspects of improving the accuracy of winding deformation detection are outlined, and the next research direction will be gradually transferred to the construction of a digital twin model of winding wide-band electromagnetic characteristics, revealing the precise quantitative mapping mathematical equation from the winding structure to the electromagnetic characteristics of its ports, and promoting the development of transformer digitalization.*

Keywords: *frequency response; transformer; winding modelling; detection accuracy; digital twin*

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Ⅰ. INTRODUCTION

The transformer is a key equipment in the power grid, and its operating status directly affects the stability and reliability of the power grid. If the transformer windings are deformed, it may lead to problems such as transformer short circuits and faults, which in turn affect the operation of the entire power grid. Through the study of transformer winding deformation, potential problems can be found and dealt with in time, and the stability and reliability of the power grid can be improved. The research of power transformers is of great significance for improving energy utilization, improving power quality, enhancing grid controllability, supporting energy development, and extending equipment life.

Ⅱ. TRANSFORMER WINDING DEFORMATION MONITORING METHOD

At present, there are two main winding deformation monitoring methods: offline monitoring and online monitoring, the offline monitoring method includes the short-circuit impedance method [1-3], the frequency response method [4], the low-voltage pulse method [5-6], etc., and the online monitoring method includes the vibration method [7], the ultrasonic testing method [8], the online short-circuit impedance method [9] and the online frequency response method [10].

2.1 Offline frequency response method

The detection principle of the frequency response method is to treat the transformer winding as a passive multi-port electrical network with the high-voltage outlet end of the winding and the neutral point as the port, apply an excitation signal from a certain port of the winding, and measure the response current signal at each port, and diagnose the structural characteristics of the winding by analyzing the change of the frequency response curve corresponding to the network function of the port signal construction winding. If the windings are deformed, the capacitance and inductance of the windings will change, and the amplitude and frequency characteristics reflected in the port will also change. The calculation formula of the offline frequency response method is shown in equation (1), which requires the transformer to be disconnected from the system and the input and output signals to be measured independently.

$$|H(jw)| = 20\lg\left(\left|\frac{I_{out}(jw)}{I_{in}(jw)}\right|\right) \qquad （1）$$

where I_{out} is the response current at the outgoing end and I_{in} is the current at the incoming end of the signal.

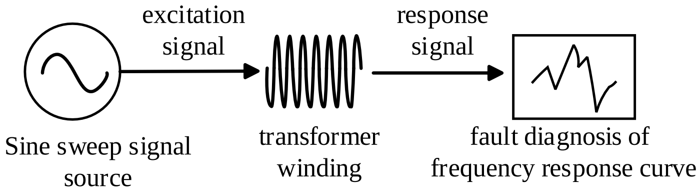

Fig.1 The test principle of the frequency response method

Early scholars' research on winding deformation detection methods mainly focused on the low-voltage pulse method, and in 1978, Canadian scholar E.P. Dick proposed for the first time that the frequency response method (FRA) could be used to detect winding deformation, and the FRA results obtained through multiple experiments can be used to model transformer windings [11]. In 1999, Huang Hua et al. from the Shanghai Electric Power Laboratory demonstrated that the frequency response method has higher sensitivity than the short-circuit impedance method through transformer fault simulation tests, but the understanding of the frequency response method is still based on the analysis of physical concepts and the summary of practical experience in testing, and lacks strict norms and standards [12]. In May of the same year, Liu Lianrui et al. preliminarily formed a set of judgment standards for detecting transformer winding deformation using the frequency response method on the basis of field tests of 470 transformers across the country [13]. J.R. Secue et al. proposed that the swept response analysis (SFRA) method used to evaluate the winding state by combining offline measurement and data analysis has higher sensitivity than the low-pressure pulse method, but due to the lack of testing and documentation guidelines, it can only be evaluated by expert visual or with the help of correlation coefficients [14]. In order to improve the practicability of the frequency response analysis method and further standardize the performance indicators of the continuously developing frequency response analysis method detection device, the power industry standard DL/T911-2016 "Frequency Response Analysis Method for Power Transformer Winding Deformation" puts forward new requirements and ideas for testing instruments, performance indicators, and new data curve analysis and diagnosis methods [15].

2.2 Online frequency response method

Mehdi Bagheri and other scholars from the University of New South Wales introduced the basic concept of online measurement method, combined with field experiments to inject 20Hz-2MHz signals into 400 MVA step-up transformers, and improved the winding deformation fault identification method from offline to online [16]. In recent years, most of the research on frequency response method has focused on the comparison of other detection methods with frequency response method. In 2018, Wang et al. proposed a frequency response method to detect transformer winding deformation considering phase characteristics, which added phase characteristics to the previous frequency response amplitude characteristics to obtain higher detection sensitivity [17]. In 2023, Iranian scholar Kakolaki proposed a transformer modeling method at different frequencies in order to locate transformer faults more accurately, introduced and discussed various methods for analyzing frequency response results, and tried to solve the limitations of the frequency response method with more advanced methods [18]. A single detection technology will have its own disadvantages to some extent: for example, the spectrum presented by the frequency response method is relatively abstract, and the criterion of the test results is relatively vague, which requires O&M personnel to have high experience in spectrum analysis. Field practice has found that the deformed windings found directly by using the frequency response curve of the winding port are basically windings with severe deformation, while slight or even moderate deformation are not easy to find, and the detection methods need to be further improved [19]. In order to make up for this shortcoming, a multi-dimensional comprehensive evaluation technology of transformer winding deformation combining impedance method and frequency response method was proposed, which improved the accuracy of winding deformation diagnosis technology [20].

Zhao Xiaozhen from Hebei University of Technology proposed a frequency response coordinate reconstruction method, which integrates the frequency, amplitude, and phase characteristics of the frequency response curve into a three-dimensional coordinate system, and the texture analysis technology can better identify the fault type than the correlation coefficient method, which provides a new idea for detecting winding deformation by online frequency response method [21].

In recent years, digital technologies such as artificial intelligence, machine learning, big data, cloud computing, and digital twins have developed rapidly, and the State Grid Corporation of China has proposed to build a ubiquitous Internet of Things (IoT) and traditional power grids to form a powerful value creation platform [22-23]. Digital twin technology is a system that integrates many cutting-edge information technologies, which is an effective way to improve the sensitivity and accuracy of transformer defect diagnosis, and has broad development prospects.

Ⅲ. MEASUREMENT TECHNIQUES FOR EXCITATION AND OUTPUT SIGNALS

There are two problems in diagnosing winding deformation by using the frequency response method: in the live state, the signal cannot be injected from the high-voltage port like offline detection, and the obtained frequency response curve is not completely accurate; The existing state of the art cannot fully understand and apply the information contained in the frequency response curve, and only individual numerical indicators are used to represent the frequency response curve, so a large amount of information is discarded. How to inject the excitation signal into the winding at high potential and obtain the response signal from the winding has been solved in a limited range, and there are currently three main solutions.

3.1 Capacitive bushing end screen lead wire based on the principle of voltage division

In order to solve the problem of signal injection, Canadian scholar Tom De Rybel et al. [24] proposed a high-power signal generator using casing injection. In 2014, Zhan Huamao of North China Electric Power University also tried to inject an input signal from the end screen of the bushing, and verified the consistency of the measured frequency response curve and the simulated frequency response curve on a 110 kV transformer, proving its feasibility [25]. However, this signal injection method has not been widely used in practice, and there are some shortcomings: firstly, according to the characteristic that the ratio of the main capacitance to the grounding capacitance at the end of the bushing is a fixed value, the current value that can be injected into the bushing is a fixed value, and because the main capacitance is much smaller than the ground capacitance, the actual injected signal is generally less than 1/10 of the signal source, which has a certain impact on the measurement accuracy [26]; Secondly, due to the characteristics of the lead wire at the end of the casing, there is a certain uncertainty in the signal injection, which may affect the accuracy of the measurement results. In addition, only one 650 kV transformer was experimentally verified in this study, and further research is needed on the suitability of transformers of other sizes.

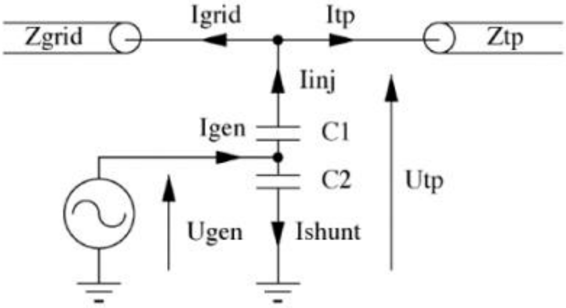

Fig 2: Casing tap injection into the equivalent circuit

3.2 A live detection method based on neutral point casing injection

Compared with the conventional live detection method, the difference between the live detection method of neutral point bushing injection is that the excitation signal is injected into the transformer from the neutral point bushing, the excitation signal is the input current of the coupling capacitor, and the output signal is the grounding current of the end screen of the high-voltage bushing. The frequency response curve obtained by the test method on a 110 kV transformer is very close to the offline test results, which proves that the method of casing injection at the neutral point can effectively improve the signal-to-noise ratio of the injected signal [26].

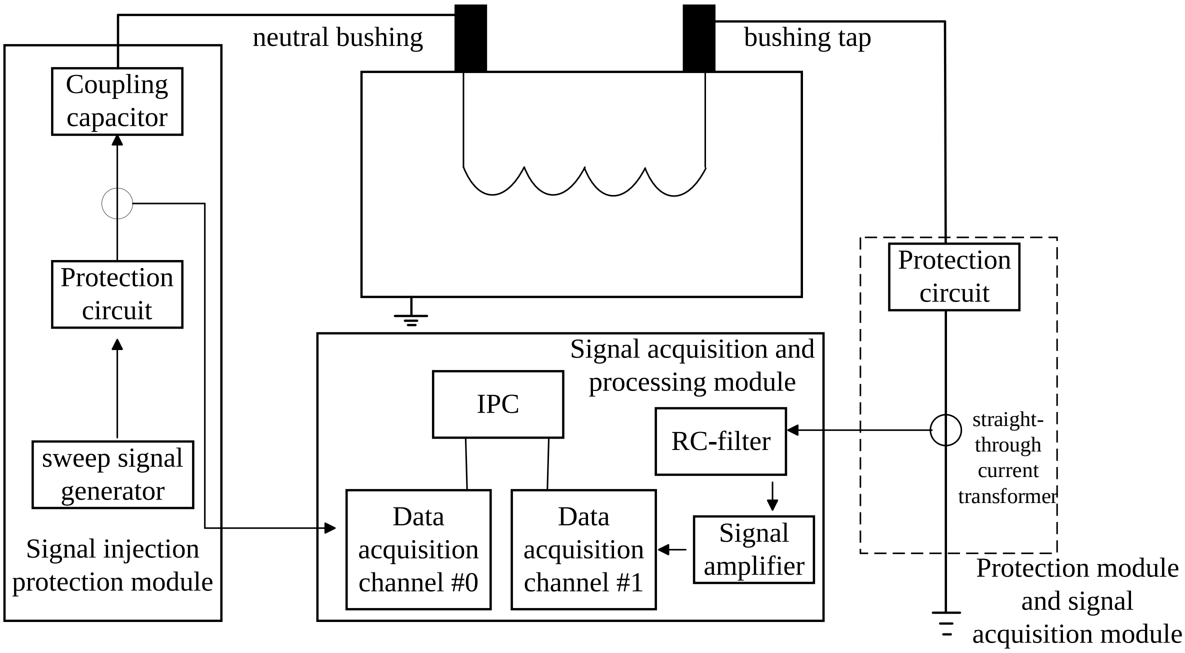

Fig 3: Injection current of neutral point casing[26]

3.3 Measurement scheme based on non-intrusive capacitive sensors

For transformers without bushing taps, a non-invasive capacitive sensor (NICS) can be used, a concept first proposed in 2006 by Hossein Borsi and others at the University of Hannover, Germany [27]. The NICS is a thin layer of conductor that is mounted on the ceramic surface of the bushing close to the ground potential and forms a capacitor with the last ungrounded bushing layer that can detect the bushing behavior. They conducted a NICS study on a 132kV/400kV, 500MVA off-line transformer and measured the frequency response curve. With the further development of the technology, in 2011, Vahid Behjat et al. used this method as a theoretical basis to realize the on-line test analysis of different degrees of inter-turn faults on the windings of a 35 kV/400 V, 100 kVA oil-immersed distribution transformer, and the results showed that the newly developed on-line monitoring system has reduced sensitivity compared with the off-line detection method, but provides sufficient information about the occurrence of faults to accurately detect inter-turn faults in windings [28].

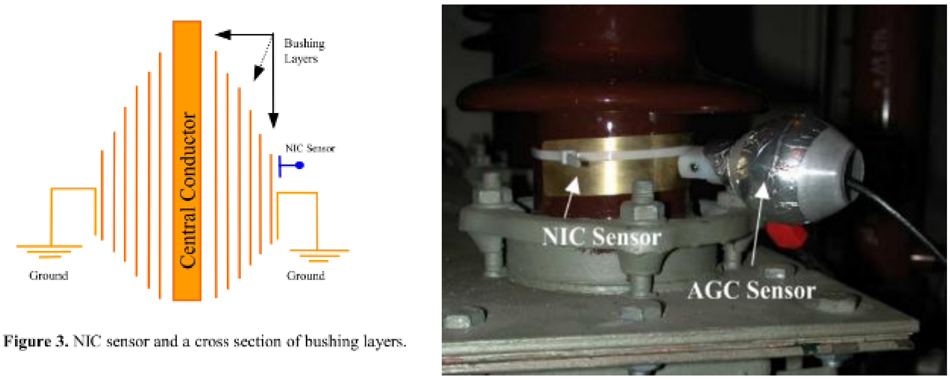

Fig 4: Schematic diagram and physical diagram of NICS

In 2014, Shen Ming, a scholar from Shanghai Jiao Tong University [29], and Zhang Chongyuan, a scholar from North China Electric Power University [30] in 2015, also used NICS to inject pulse signals into the transformer to improve the on-line test device for transformer winding deformation. The test signal is injected into the transformer winding through the high-voltage bushing through the non-intrusive capacitive sensor (NICS) installed on the surface of the transformer bushing, which avoids direct connection with the high-voltage side bus and provides a safer solution for frequency response signal detection.

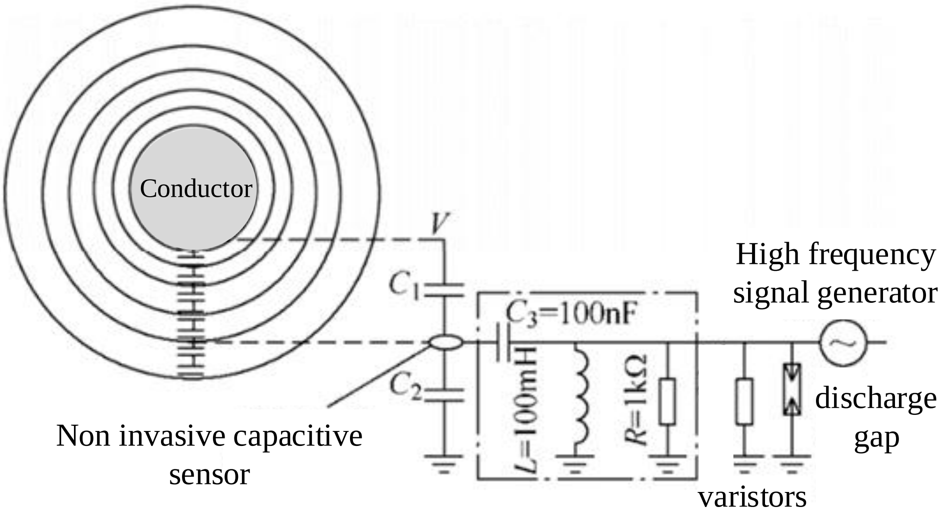

Figure 5: Schematic diagram of the signal coupling circuit [30]

3.4 The output signal is measured by a sensor based on Rogowski coil coupling

In 2016, Cheng Yangchun of North China Electric Power University first proposed that the signal could be injected into the transformer from the neutral ground wire through the magnetic coupling principle of the Rogowski coil, and the response current was extracted at the root of the bushing, which not only verified the feasibility of the scheme in the network of two 110/35/10 kV transformers, but also carried out experiments in the operating 35 kV working transformer [31-32]. However, there is a strong noise electromagnetic signal in this way, and although the signal can be measured, there is still a certain distance to obtain an accurate frequency response signal. Therefore, in 2019, Cheng Yangchun of North China Electric Power University cooperated with the Chinese Academy of Electric Power Sciences to conduct research on the problems of core saturation of Rogowski coil sensors and excessive current power frequency interference in the measurement response at the root of the high-voltage bushing, and proposed an improved dual-coil anti-power frequency magnetic saturation method, which has been shown by theoretical analysis and laboratory verification to significantly reduce the problem of excessive power frequency interference and improve the accuracy of the measurement signal [33]. In 2024, North China Electric Power University and Beijing Tongzhou Power Supply Company jointly proposed a three-phase parallel sensing system [34], which realizes the function of measuring microampere-level high-frequency current in the context of power frequency and high current, and compresses power frequency interference by 100 times through field measurement, which is of great significance for live diagnosis of transformer winding defects.

Ⅳ. Modeling methods for transformer windings

In order to obtain a more accurate frequency response curve when the signal propagates in the transformer network, it is necessary to accurately model the internal structure of the transformer, and the establishment of common winding models is divided into three types: lumped parameter model, multi-conductor transmission line model and mixed parameter model.

4.1 Lumped parametric model

The lumped parameter model is a chain circuit (also known as a trapezoidal circuit) composed of a few inductors, capacitors, and resistive elements, or n groups of circuits of similar structure in series. Zhongdong Wang, University of Manchester, V. V. Wang, Russia Larin, Australia N. Hashemnia et al. [35-37] have been establishing lumped parameter models for windings since 2000. The electrical components in the lumped parameter model represent the total electrical parameters of the whole winding or a part of the winding, and the parameter solution is simple, but because the number of components can not be too much, the model is generally modeled according to the pie, and the established model is relatively rough, it is difficult to reflect the details inside the pie coil, and it is difficult to accurately locate the fault point when the fault occurs. For the problem of rough winding modeling, A. Abu-Siada et al. [38] combined an artificial intelligence algorithm to estimate the parameters of the transformer's high-frequency electrical model using the transformer's frequency response characteristics. From the given reference dataset, different fault types can be identified based on the physical significance of the varying model parameters. However, in the case of high-frequency signals, the lumped parameter model does not meet the applicable conditions, and the circuit parameters cannot be solved.

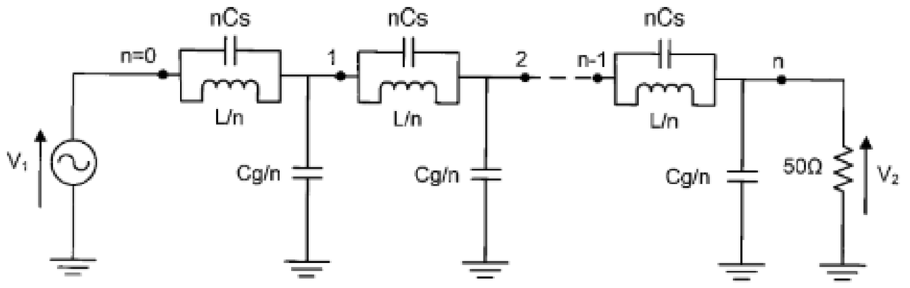

Fig 6: Lumped parametric circuit model

4.2 Multi-conductor transmission line model

Therefore, Zhongdong Wang, M. Bagheri, Fangcheng Li, Guishu Liang et al. [39-42] established and studied the multi-conductor transmission line model of transformer windings, and regarded the windings as many turns transmission lines connected from end to end, and characterized the port characteristics of the windings with accurate analytical expressions. The advantage of the multi-conductor transmission line model is that the transfer function of the winding can be directly derived through the operation of inductance, capacitance, resistance and conductivity matrix, especially the characterization of the mutual inductance and mutual capacitance between the line turns is more convenient, so it can reflect the winding structure in more detail, and is suitable for the process of high-frequency modeling. However, the transformer winding turns are large, the multi-conductor transmission line model is very computational, the computer requirements are high, the workload is large, and the winding equivalent model parameters are difficult to solve. In order to solve this problem, Tang Zhiguo [43] proposed an improved solution model for transformer multi-conductor transmission lines, using Active-X technology and using MATLAB to control ANSYS according to the winding size information to achieve automatic modeling, so as to provide capacitance parameters for MTL program operation, and the capacitance parameters can be obtained by simply changing the size parameters for different transformers, which improves adaptability and reduces manual intervention. The original asymmetric complex matrix diagonal decoupling problem is transformed into a sparse solid symmetric matrix diagonal decoupling problem by mathematical derivation, which shortens the program running time by 49.919% and improves the computational efficiency. However, this method is only in the stage of theoretical simulation and has not been verified in the field.

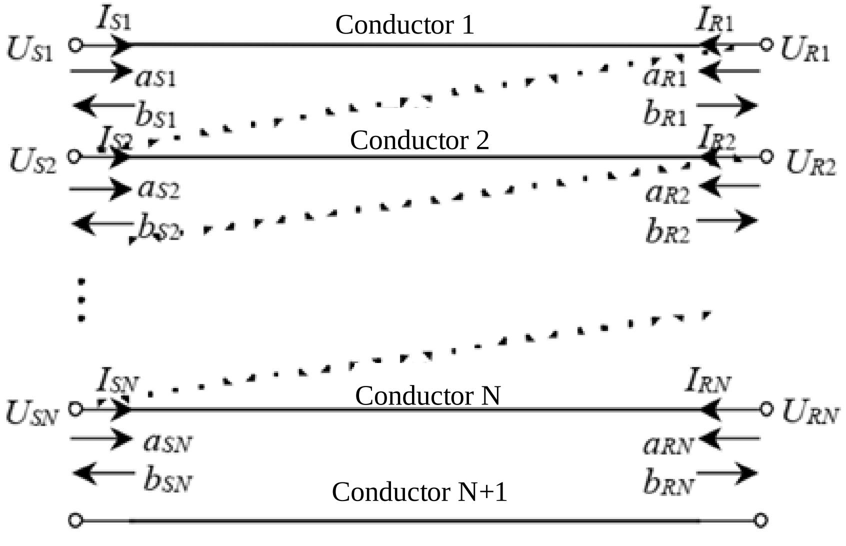

Fig 7: Multi-conductor transmission line model

4.3 Mixed-parameter models

In addition to the above two methods, in 2006, A. Shintemirov[44]、T.Y. Ji; W.H [45] et al. also proposed a compromise scheme, that is, a mixed-parameter model, in which the turns of the same line cake are bundled together and modeled by transmission line theory, and the connections between line cakes are characterized by a chain circuit similar to a lumped parameter circuit. The windings are designed as continuous disc type windings, where each disc consists of multiple turns wound radially. Continuous disc windings have interdisc connections on the inside and outside of the winding, so the wave propagates in the opposite direction along the next disc to the previous one. The model takes advantage of the simplicity of the lumped parameter model and the accuracy of the multi-conductor transmission line model, and the order in the calculation process is lower than that of the multi-conductor transmission line theory, which can reduce the workload of the computer. However, the transformer core, which may affect the parameters of the circuit model, is not taken into account in this structure, so the simulation results may deviate from the actual transformer frequency response curve.

When modeling the transformer winding, the finite element analysis method is often used to obtain the equivalent circuit parameters of the winding, which builds a three-dimensional model by inputting the geometric size, shape and relative position of the transformer winding, and obtains the parameter matrix of capacitance and inductance through the finite element calculation inside the software. However, when modeling transformers, it is often considered that the transformer core is directly grounded, ignoring the influence of transformer shells, bushings and other components on the electromagnetic field of the windings.

4.4 The inverse problem solves the transformer winding model

All the above forward modeling methods are based on the transformer winding structure, and the complex electromagnetic characteristics between the components inside the transformer cannot be directly established, so the internal model of the transformer is considered to be reversed through the measured data.

In solving the inverse problem of electromagnetic characteristics of transformer windings, scholars such as Deng Xiangli of Shanghai Electric Power University and Xiong Xiaofu of Chongqing University [46] used the parameter identification method to obtain the component parameters in the simplified electromagnetic transient model of transformers, and then used the physical relationship between the power frequency leakage inductance and the winding structure parameters to realize the diagnosis of winding deformation defects. Ref. [47] proposes a new method that uses artificial neural networks and genetic algorithms to synthesize a frequency-response-based lumped parameter network of power transformers, which can distinguish the parameters of the core and each winding without understanding the internal structure of the transformer, and obtain the lumped parameter values with the least cost and time. Future work could also use actual power transformer parameter values to train artificial neural networks to improve results.

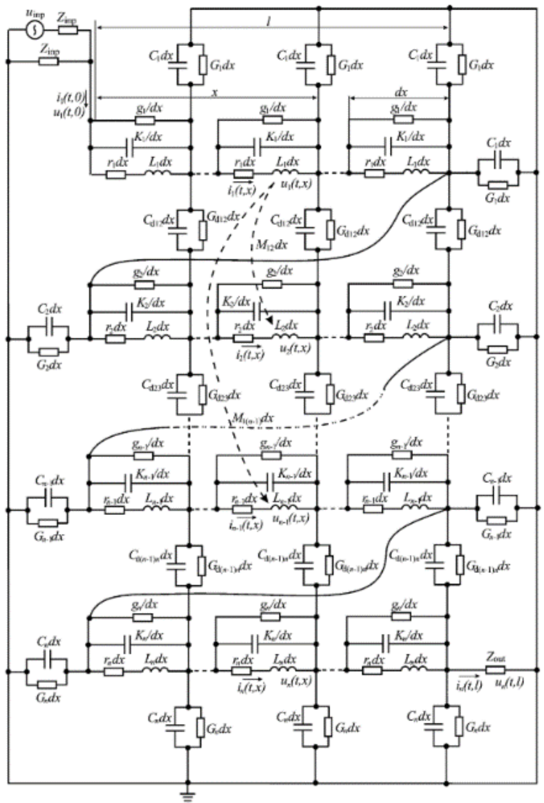

Fig 8: Mixed-parameter model

V. CONCLUSION

In this paper, the application of the online frequency response method in the deformation detection of transformer windings is introduced, and its development process is analyzed from two aspects: the signal injection method of field test and the transformer winding model of simulation experiment, and the differences are compared. The results show that artificial intelligence algorithms have great potential to solve complex inverse problems, but the existing achievements do not have an inversion method for the transformer multi-conductor transmission line model, and the future development mainly focuses on intelligent algorithms and digital twins.

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Supporting Project Introduction:
Applicant: Guangdong Power Grid Co., Ltd., Guangzhou Power Supply Bureau Electric Power Test Research Institute
Project Name: Research on Online Monitoring Method of Transformer Winding Deformation and Trial Production of Device GDKJXM20222322 (030100KK52222017)
Project Overview: The main research content is the high-sensitivity and strong anti-interference detection technology of the frequency response signal of the live operating transformer; Explain the propagation characteristics of frequency response signals in substation networks, establish a frequency response network function suitable for transformers in operation, and propose a high-sensitivity diagnosis method for winding deformation. A highly reliable online monitoring device for transformer winding deformation was developed and the on-site pilot application was completed.