Temperature Measuring-Based Decision-Making Prognostic Approach in Electric Power Transformers Winding Failures

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Abstract—The electric power transformer is a vital apparatus in power systems, and failure prognostics is significant for the protection of this asset. In addition to the asset damage, its unexpected failure would interrupt power delivery and jeopardize the stability of the system. There are several fault diagnosis methods introduced for the detection of this kind of fault; however, their functionality is for the postfault condition when the asset is already damaged, and the operation of the system is interrupted. Electric insulation deteriorations make the transformers susceptible to faults due to thermal and electrical stresses. In this article, the impact of early stages insulation deteriorations on the temperature inside the transformer is studied using a finite-element electromagnetic–thermofluid method and based on the observations an online sensor-based decision-making predictive fault diagnosis approach is proposed. Finally, the results are experimentally verified.

Index Terms—Internal fault, power transformer, prognostic, thermos-fluid, winding fault.

I. INTRODUCTION

POWER transformers are essential elements of electric power systems. Unexpected failures of power transformers can cause substantial economic loss due to unscheduled electrical outages. Furthermore, power transformers are expensive equipment, and their repair or replacement is too costly. Therefore, it is important to detect faults in the early stages to disconnect the equipment and prevent prospective catastrophic damages and losses [1].

The winding fault is one of the most common faults in power transformers. Electromechanical forces and insulation deterioration can make the winding of the transformer vulnerable to different kinds of faults. When the deterioration is in severe stages, with external short circuit, overvolt-

age, or any other stresses to the winding, an electrical fault is inevitable [2].

Several fault diagnosis methods have been proposed so far. One of the first introduced methods is dissolved gas analysis, in which the ratios or concentrations of different gases dissolved in the oil of transformers are used to detect the fault [3]. However, this method is not useful enough for interturn fault detection, because, in the early stages, this fault cannot generate enough gases for fault detection. Also, for applying this method, many samples are required. Differential protection can be used for high power transformers; however, this method does not provide enough sensitivity to detect the fault in the incipient stages. In spite of the dangerously high current in the faulty turns, the change in the terminal currents is relatively low. Negative sequence differential protection is the other method proposed to overcome this issue. In fact, an interturn fault causes asymmetry current, which leads to the presence of negative sequence current. This negative sequence current is employed to detect the fault [4]. The main issue of deploying this method is that it is applicable after the occurrence of the fault. Furthermore, in incipient stages of fault, this method might not be effective. An approach using artificial intelligence methods is proposed in [1]. The approach depends on the training set, and it may be hard to generalize it for all transformers. Magnetic flux entropy [5] and leakage flux-based methods [6] are also other investigated solutions. The main drawback of these methods is that it may be challenging to measure the local variations in flux for incipient winding faults.

None of these methods are recognized as the final solution for interturn fault detection since all suffer from significant drawbacks. All the above-mentioned methods or other fault diagnosis methods are for the postfault condition when the fault has already occurred, and the asset needs to be disconnected as soon as possible to prevent catastrophic damage and expansion of the fault. The introduced predictive methods are so limited. In [7], a predictive diagnosis method has been proposed using vibration sensors. This method can be effective when there are negligible environmental vibration sources. Since transformers usually operate in places with a considerable amount of vibration, such as substations, cities, and industrial locations, employing this approach might not be reliable. Infrared thermography has been proposed in [8] as a predictive approach; however, it is limited to external defects, such as loose connections. There are some

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 prognosis methods using dissolved gas analysis [9], [10] that use the intelligent techniques, as well as a dissolved gas analysis method for diagnosis. The main drawback of these methods is that the fault should have already taken place at a level for which there is enough energy for chemical reactions. Moreover, these methods are not applicable for dry transformers.

In this article, an electromagnetic–thermofluid finite-element method (FEM) is employed to analyze the temperature condition of the transformer in the early stages of insulation deterioration. The transformer is simulated using two FEM software tools, one for electromagnetic simulation and another for thermofluid simulation, and they interact and exchange data to provide the desired multiphysics simulation framework.

By using the introduced simulation framework, the thermal behavior of the transformer for various insulation conditions is studied, and based on the observations, a prognostic method is proposed to detect and locate the area where the insulation is prone to failure. The winding types considered are multilayer, crossover, and disk-type windings. Both the oil-filled transformers and dry transformers are simulated here. Moreover, it is shown that the load of the transformer has no impact on the results.

II. ELECTROMAGNETIC–THERMOFLUID MODELING OF TRANSFORMER

Analytical solutions to some engineering problems, such as electromagnetic potential, heat transfer, and fluid flow, require the solution of differential equations with boundary conditions. Utilizing FEM for problem-solving includes three main steps. First, the space of the problem should be meshed into contiguous elements with a suitable geometry based on the problem. In this step, the characteristics of each region are also defined. Then, the initial condition of the model should be defined. Finally, the boundary conditions should be imposed.

Currently, several tools are available for solving this numerical problem [11]. In this article, ANSYS products are employed for this purpose. ANSYS Electromagnetics is utilized for electromagnetics calculation, and ANSYS Fluent is deployed to solve the thermofluid model. Electromagnetic and thermofluid problems cannot be solved independently, because the result of either can change the conditions of the other. The copper energy loss and magnetic energy loss of the winding and core generate heat and increase the temperature.

In addition, based on the location in which this temperature rises, the fluid inside the transformer starts to flow. The intrinsic characteristics of the regions determine how this generated heat is dissipated and cause the flow of fluids. Therefore, it is necessary that these two models have interactions and transfer of data after each step of calculations. ANSYS has made this available by introducing ANSYS Workbench, which is a software tool helpful when the interaction between different tools is necessary.

A. Insulator Model

When the insulation becomes weak, its electric characteristics change. Breakdown voltage, dielectric loss tangent, and resistivity are introduced as three electric characteristics that vary with the insulation age [12]. The equivalent circuit of the insulation and dielectric loss tangent are shown in Fig. 1(a) and (b), respectively. The insulator equivalent circuit includes a resistor and a capacitor. According to Kohtoh et al. [12], as the insulator ages or become more vulnerable to faults, the value of the equivalent resistance decreases, but the value of the dielectric loss tangent increases and the capacitor remain almost unchanged. Thus, to implement the insulation in the simulations, its equivalent circuit is deployed for which the value of the equivalent resistance decreases when dielectric degrades.

B. Electromagnetic Model

Electromagnetic fields in transformers can be modeled using the following differential equation [12]:

\[ \nabla \times \left( \frac{1}{\mu} \nabla \times \mathbf{A} \right) = \mathbf{J} - j \omega \varepsilon \mathbf{A} + \omega^2 \mu \mathbf{A} \]  

(1)

where \( \mu \) [H/m] is the permeability, \( \mathbf{A} \) [Wb/m] is the magnetic vector potential, \( \omega \) [rad] is the angular frequency, \( \sigma \) [S/m] is the power conductivity, and \( \mathbf{J} \) [A/m²] is the current density. By numerically solving this differential equation considering its boundary conditions, the ANSYS Electromagnetics software provides the results using FEM.

Fig. 2(a) shows the schema of the modeled oil-filled transformer with multilayer winding. Fig. 2(b) presents the flux distribution of the transformer when the flux is maximum in one leg. The peak flux in the core is around 1.8 T located on the knee of the magnetization characteristic as expected. Moreover, the maximum temperature of the winding is around 96 °C, which is acceptable and normal.

C. Thermofluid Model

Thermofluid analysis encompasses four main fields, which are heat transfer, thermodynamics, fluid mechanics, and combustion. Since no exothermic reaction happens in normal and close to normal operating conditions in the power transformers, there is no need for combustion analysis. Similar to electromagnetics analysis, heat analysis, thermodynamics, and fluid mechanics are based on the extracted differential equations and can be performed using numerical calculations, which is out of the scope for this article. For this purpose, ANSYS Fluent is used.

In this article, ANSYS Electromagnetics suite and ANSYS Fluent are used in a multiphysics simulation framework,
which has become possible using ANSYS Workbench. In each time-step, first, the electromagnetics calculation is performed in ANSYS electromagnetics environment. The result is sent to ANSYS Fluent using the Workbench framework, and by considering the electric loss, thermos-fluid analysis is performed in ANSYS Fluent, and the final temperature is sent back to ANSYS electromagnetics for the next step. This loop of analysis and exchange of data provides an electromagnetics–thermofluid analysis framework to study the thermal behavior and condition of the windings and insulators when insulation is prone to fault.

Finally, Fig. 3(a) presents the temperature near the winding for the transformer at its normal operation condition, and Fig. 3(b) shows the temperature condition near the winding in the presence of weak insulation.

**D. Transformer and Insulation Model**

Three transformers with different winding structures are modeled and shown in Fig. 4. For the multilayer winding, the insulator is prone to a fault between two adjacent layers. For instance, in Fig. 4(a), the insulation between the two layers in a multilayer winding and the middle of the layers is aged, and it is likely that a physical or mechanical stress can cause a fault in that spot. The resistivity of this area is lower and this fact is used in simulations. Fig. 3(b) shows the temperature around the edges of the layers for the weak insulation between the second and third layers from left where the resistance of the insulation is still high.

It is noted that the temperature is not balanced anymore and is reduced in that part, but it rises in the healthy part. The reason is that the current for the weak insulation is less compared with the normal operating condition. Fig. 4 shows the fault between the adjacent sections.

Fig. 4(a) shows the fault between the two adjacent layers in a multilayer winding. Fig. 4(b) shows the cross section of a crossover winding and an example of the fault. In this case, the whole section is involved in the fault. When the fault is between two internal layers, the temperature near the fault location is similar to what is observed for the multilayer winding. Faults and temperature conditions in this type of winding are similar to a disk-type winding. Fig. 3(c) presents the disk-type winding.

A healthy transformer is simulated using FEM, and the results are shown in Fig. 5(a). Also, electromagnetic–thermofluid FE simulation is carried out, and the temperature near the winding of the transformer is illustrated in Fig. 5(b). In the normal operating transformer, the maximum temperature around the transformer is 103 °C, which is acceptable for this type of transformer.

**III. Fault Prediction in a Multilayer Winding-Type Transformer**

Experimental results show that the resistance of the insulator decreases due to aging [12]. Therefore, if the insulator of
a spot has faced accelerated aging or is damaged in the manufacturing process, the resistance of that part may be lower.

These variations in the resistance of the insulator lead to a change in the current flowing through the affected winding [e.g., red part in Fig. 4(a)], and the copper loss varies. Therefore, the balance in the temperature condition near the affected winding is impacted. Fig. 6 shows the current of the affected winding for different insulator resistances. In Fig. 4(a), this part is shown in orange.

Using the FE electromagnetics simulations, the changes in the current going through the insulation for different insulator resistances are shown in Fig. 7. This part is shown using a red flash icon in Fig. 4(a). This exhibits that by decreasing the resistance, first, the current decreases, and then, when it exceeds 1 pu, there is a fault, and it dramatically increases.

When the resistance of the insulation in the fault location starts to decrease, the current has a shorter path to flow. Therefore, a portion of the winding current flows through the insulation. Moreover, the flux in the core induces a current with an opposite phase angle of the main current inside the affected part of the winding. Hence, the current vector of the affected part is in the opposite phase angle of the winding current. Thus, it reduces due to the decrease in the resistance of the insulation. The main idea in this article is to predict the fault when the resistance of the insulator is still relatively high, and the current in the affected part of the winding is not so high to damage the winding and accelerate insulator deterioration. Since in Fig. 7 the current is in per unit of the nominal transformer current, the high current can mean more than 1 pu. In Fig. 7, it can be seen that the insulator resistance can become as low as 200-Ω nominal current. Thus, relatively high can mean as low as 200 Ω.

Fig. 8 shows the location of the temperature sensors. There are two rows of temperature samples, one from the top of the winding and other from the bottom. Fig. 9 shows the simulation results for the weak insulation between different
winding layers. The weak or aged insulation is assumed to be in the middle of the layers. When a smaller portion of the winding is affected by the fault, the difference between the temperature curves is more, because only one side of the winding is affected by the fault. In the worst-case scenario, the whole two layers are involved, and there is no difference between the temperatures curves; however, the fault can be detected by comparing the curves of faulty and healthy phases.

Fig. 10 shows the flowchart of the proposed prognostic method. The transformer signals for processing are the temperature of the \( n + 1 \) points where \( n \) is the number of layers; therefore, \( n + 1 \) is the number of employed sensors. In the simulated transformer, \( n = 14 \). By connecting these points, the temperature curve of the transformer can be obtained

\[
\frac{\Delta T_i}{\Delta n} = T_{i+1} - T_i \quad (2)
\]

\[
\frac{\Delta^2 T_i}{\Delta n^2} = \frac{\Delta T_{i+1}}{\Delta n} - \frac{\Delta T_i}{\Delta n} = (T_{i+1} - T_i) - (T_i - T_{i-1}) \quad (3)
\]

where \( T_i \) is the temperature between layers \( i \) and \( i+1 \). If there are two or more points with the positive second derivatives, there is a peak in the curve, and the fault has occurred. If the first point with positive second derivation is defined as \( i \), the fault takes place between layers \( i \) and \( i+1 \).

Finally, the quantity of the layer involved can be determined by comparing the temperature curve with the temperature curve of the another row in the same winding or the curves in the other phases. The further the fault point in the faulty curve is from the same point in the curve of another row, the less quantity of layers involved. Considering all points of the curve, the further the curves of the faulty phase is from the temperature curves of other phases of the same transformer, the more the quantity of the layer involved. By determination of the involved winding, the vulnerable insulation can be located more precisely.

IV. FAULT PREDICTION IN DISK- OR CROSSOVER WINDING-TYPE TRANSFORMER

In Section III, fault prediction between layers was simulated, and a fault prognostic approach was introduced. If each disk of a disk-type winding is considered as a layer, the same approach can be applied to predict the fault between two adjacent disks as well. This kind of fault is shown in Fig. 3(a) and (b). In Fig. 11, the simulation results for vulnerable insulation in different locations can be seen. Fig. 12 shows the first and second derivatives when the vulnerable insulation is between the second and third layers. It can be seen that layer 3 is the only one for which both first and second derivatives are positive. Based on the algorithm, the vulnerable insulation is between the second and third layers. Fig. 13 shows the sensor locations. One example of the simulation for one winding has been shown in Fig. 14. One of the concerns regarding the
Fig. 9. Simulation results of temperature curves for insulators prone to a fault in different layers for the multilayer winding-type transformer.

Fig. 10. Flowchart of the proposed prognostic approach to detect and locate the vulnerable insulation.

A proposed approach might be variations in load and its impact on the temperature. The impact of the load level is studied. It is observed that the variations in the loading of the transformer does not affect the derivatives of the curves and only changes the temperature of all points. Fig. 15 shows the results for two different loads in the transformer with multilayer winding.

V. EXPERIMENTAL RESULTS AND DISCUSSION

A 20-kV·A transformer with accessibility to the terminals of different parts of the windings is considered to perform experimental tests and demonstrate that the decrease in the resistance of the insulation will have similar results with the simulations. Since the current in the winding is the main source of heat and temperature variations, if current variations in the experiments and simulations follow the same pattern, the same will apply for the temperature. The implemented testbed can be seen in Fig. 16. For data acquisition, the Unipower network analyzer, Unilyzer 902, is used. Two rheostats are utilized to

| TABLE I |
| SPECIFICATIONS OF TRANSFORMER |
| Nominal power (VA) | 1500 |
| Primary voltage (V) | 380 |
| Secondary voltage (V) | 220 |
| Connection type | YNyn0 |
| Number of primary winding turns | 640 |
| Number of secondary turns | 318 |
implement different resistances. As shown in Fig. 16, several taps are available. These taps represent available points of connections to different parts of the winding. It gives the ability to make a parallel connection between rheostats and part of the winding. Fig. 17 clearly shows that the experimental and simulations results are close. Table I summarizes the

specifications of the tested transformer. The experimental results have been given in Table II.

As explained in the literature review, the main drawback of the existing transformer fault prognostic and diagnosis methods is that they are not effective in incipient stages. By using the presented simulations and experimental results, it is illustrated that the proposed method in this article is an effective prognostic method and is capable of detecting the
TABLE II
FAULT CURRENT EXPERIMENTAL RESULTS

<table>
<thead>
<tr>
<th>Fault Resistance (Ω)</th>
<th>170</th>
<th>160</th>
<th>150</th>
<th>140</th>
<th>130</th>
<th>120</th>
<th>110</th>
<th>100</th>
<th>50</th>
<th>20</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fault Current (A)</td>
<td>-0.0849</td>
<td>-0.0849</td>
<td>-0.0951</td>
<td>-0.1011</td>
<td>-0.1087</td>
<td>-0.1180</td>
<td>-0.1291</td>
<td>-0.152</td>
<td>-0.2854</td>
<td>-0.717</td>
<td>-1.3899</td>
</tr>
</tbody>
</table>

Fig. 16. Experimental testbed.

Fig. 17. Comparison of simulation and experimental results.

The main advantage of the introduced method in this article in comparison with the diagnosis methods is that it will give the alarm before the occurrence of the fault when the insulation is vulnerable and prone to fault. The method proposed in [8] is based on sensor vibrations. The noises and environmental sources of vibrations cause errors in the output of this method. While in the proposed method in this article, the environmental factors cannot have significant impacts since it uses the temperature inside the transformer.

VI. CONCLUSION

In this article, a prognostic approach for transformer failure was explained. By using the proposed method, vulnerable insulation detected and located in the early stages when preventive actions can save the winding of the transformer. Since this is a predictive method, there are no unexpected outages. A finite-element-based simulation framework was demonstrated in which a thermos-fluid–electromagnetic model was applied to simulate the transformer. It was shown that changes in the resistance of the transformer insulation could affect the temperature near the winding. It was shown that in the very early stages of insulation deterioration, the current in the faulty part of the winding decreases. However, if the resistance of the insulator becomes too low and allows the flow of high current, it will lead to the flow of this high current in the transformer winding. More current causes more loss and higher temperatures and may damage the winding and adjacent insulators and propagate the fault. The calculated results were validated by the experimental results.

REFERENCES


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