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Experimental thermal investigation of an ONAN distribution transformer by fiber optic sensors

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ABSTRACT

Transformers are considered as one of the main and high cost components of the power systems. This is due to the fact that their failure may have negative influence on sustainability and quality of energy. In addition, some failures may lead to high cost for replacement or repair and an unplanned outage of a power transformer is highly uneconomical. As a result, as a major equipment in power systems, its correct functioning is vital to enable efficient and reliable operation of electric power system. A transformer can fail due to any combination of electrical, mechanical or thermal stresses. The normal operation life of a transformer is partially related to the deterioration of its insulation through thermal ageing, which is determined mainly by its daily cyclic loadings. In this paper, heat analysis of a 1.5 MVA Oil-Natural Air-Natural cooling mode distribution transformer is experimentally investigated by equipped fiber optic sensors. The density of the fiber optic sensors is increased at the active parts in critical spots. Temperature measurements are realized according to the transformer losses variation and load variation tests. The thermal behavior of the distribution transformer is obtained. Contrary to the existing studies, the obtained results show that also the structure and the design of the transformer affects the hot-spot position and temperature.

1. Introduction

It is well-known that the electricity supply industry consists of three basic topics; generation, transmission and distribution. Among these parts, transformers are one of the most important components and widely used in all parts of power system [1–3]. Especially, transformers play a critical role in transmission and distribution levels [4]. Any failure in a transformer could lead major power outages and even environmental hazards [5,6]. Because of this reason, these components also take an important role in the sustainability and quality of energy [7,8]. In the first instance, financial losses appear by modification of removing the fault, change of winding or component etc. and for solving this problem, there could be change on routing of power delivery or purchase of power from other power suppliers. However, all these solutions are uneconomical for system operators [5,6,9,10].

The transformers are exposed to the impact of thermal, mechanical, chemical, electrical and electromagnetic stresses during normal and transient loading conditions along their lifetime. These stresses deteriorate the transformer gradually and lower its operational lifetime [5].

Among these stresses, temperature rise in the transformer badly effects the insulation of transformer [3,11–13]. If the insulation is damaged, a fault in the transformer occurs. The transformer losses are among the most important factors in rising of top oil and hot-spot temperature (HST) [14–16]. This causes rapid thermal degradation of insulation [17]. HST, which describes the highest temperature on the oil or winding, is the most important parameter of the transformer's life calculation [18,19]. However, there are several methods to find out the HST, where the best method is using sensors for measurements [20,21].

The variation at the HST has been a very popular research topic. In Ref. [11] online HST was monitored with a small number of fiber optic sensors as bottom, top oil and one at the windings. However, different from the mentioned study in this paper more fiber optic sensors (18 sensors for one of the winding, 24 total sensors) are used to show the temperature variation on several point of the distribution transformer. In addition to that the focus of the mentioned paper is to see the temperature variation at a specific point of the winding. Contrary to this in the proposed study the position of the hot spot and the temperature variation due to the position and loading condition are investigated. In Ref. [14] hot-spot temperature calculation for power transformers were studied and the

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thermal model of a power transformer was investigated. Several sensors were used to determine the temperature variation due to the location on a power transformer was investigated.

Fiber optic technology offers an opportunity for direct HST measurement without any detrimental effects to the dielectric integrity of the transformers [22]. Although fiber optic sensor (FOS) is commonly used in power transformer applications [20,23,24], it has not been commonly used for distribution transformer applications in literature because of their high costs. Conventionally, pt100 temperature sensors are used in distribution transformer applications [25,26].

In this study, thermal effects of different loading variations on a 1.5 MVA Oil-Natural Air-Natural (ONAN) distribution transformer are investigated. For temperature measurement, FOSs are located into critical points where the HST can be observed according to finite element analysis. After routine tests are realized, the variation of the transformer temperature is observed for several loading conditions in the tests based on total losses and nominal current values.

In proposed study, a 1.5 MVA distribution transformer's temperature measurements are made by FOSs, which have more accurate result and less error aberration rate than conventional temperature sensors. Moreover, the distribution transformer's temperature variations are experimentally investigated in significantly more details compared to existing literature examples. In other words, a distribution transformer thermal behavior on different loading conditions are presented. During temperature tests; windings temperature changes are observed vertically and horizontally and effects of core, tank etc. are investigated. Because of its detailed research on distribution transformer temperature pattern, this paper will be a good reference for further studies which are about thermal analysis like transformer design, investigation etc.

In Section 2; development of the test system is elucidated with electromagnetic simulations and description of the tested transformer. The performed temperature tests are explained in Section 3. In final section, the results and future studies are discussed.

2. Development of test system

The purpose of this study is to monitor the temperature changes of a distribution transformer. For this reason, firstly critical points where the HST can be observed are determined using finite element analysis. Then, a 1.5 MVA distribution transformer equipped with FOSs is built. In this section; electromagnetic simulations, a short description of the tested transformer and position of the installed FOSs are introduced.

2.1. Electromagnetic simulations

In this part of the study, ANSYS Maxwell is used for electromagnetic simulations to determine the critical thermal points of the transformer active part. Mesh densities are selected separately to make the analysis more detailed and to reduce simulation computational time. Fig. 1 shows the main and meshed view of the transformer.

In Fig. 2, the distribution of magnetic field density and its vector display is shown. The system is set for taking all analysis results between 0.08 and 0.1 s by sample time 500 μs.

In both magnetic field density and vector display, it is observed that magnetic field density is high around of the windings and at the corners of the core window. The reason of this is that the path of the magnetic field tries to pass through the corner. The same reason could be stated for the minimum magnetic field density places which one can see from upper and bottom side of the core. The magnetic field path forces the windings, similar to how it forces the corners. These stresses cause the heat losses on the core and windings. When the magnetic field vectors are considered, the most forced parts occur close to the windings top. These critical points come about the windings 1/5 ratio height close to top [27,28]. Computational Fluid Dynamics analysis should be done for more accurate positioning for HST point. However, there are detailed studies in literature. The number of FOSs are increased in the experimental study considering the critical points mentioned in Ref. [29].

2.2. Test system and installation of the fiber optic sensors

In the experimental study, a 3 phase hermetically sealed oil type transformer is used for the tests. The power of transformer is 1500 kVA and the nominal voltages are 11000/415 V which has ONAN cooling. Both low-voltage (LV) and high voltage (HV) windings have two axial cooling ducts (CD). The LV and HV windings consists of 14 layers and 11 layers, respectively. The LV windings' first CD is between fifth and sixth layers and the second CD is between tenth and eleventh layers. The HV windings' first CD is between fourth and fifth layers and the second CD is between eighth and ninth layers.

The transformer was equipped with a total of 24 FOSs. Eighteen FOSs are mounted to the active part (core and windings) of transformer. Other six of them are used for recording the bottom oil and top oil align 1st and 2nd coils, radiator oil input and output.

All active part FOSs are fitted to the medium coils (2nd). According to the studies in literature and the simulations shown in Section 2.1, the hottest points of winding occurs 1/5 height near to top. For this reason and to find out the temperature changes core to winding periphery FOS is mounted to all gaps at 424 mm which means 80% winding height (WH) [27,28] (Fig. 3).

The FOSs have been placed in CD whereas the hot spot may be within the winding. For this reason to minimize the measurement errors, an ONAN type distribution transformer is chosen because OFAF, ODAF etc. has higher oil flow in the CD which will increase the mentioned effect. Also, sudden changes in the loading condition will increase the mentioned effect. Because of this, at least 45 min time interval is chosen. Another application to minimize the mentioned effect is increasing the surface contact area of FOS. Thus, all FOSs are compressed CD surface.

The FOS installation starts from core to winding periphery. First gap is between core and LV winding and one FOS (FOS 1) is mounted at this gap to 424 mm (80% WH) (Fig. 4). Second gap is the LV windings' first CD and three FOSs (FOS 2, 3, 4) are mounted at this gap to 85%, 80% and 75% WH (450.5, 424, 397.5 mm). Third gap is the LV windings' second CD and five FOSs (FOS 5, 6, 7, 8, 9) are mounted at this gap to 85%, 80%, 75%, 50% and 20% WH (450.5, 424, 397.5, 265, 106 mm). Fourth gap is between LV and HV windings and one FOS (FOS 10) is mounted at this gap to 80% WH (424 mm). Fifth gap is the HV windings' first CD and five FOSs (FOS 11, 12, 13, 14, 15) are mounted at this gap to 85%, 80%, 75%, 50% and 20% WH (450.5, 424, 397.5, 265, 106 mm). And the last gap is the sixth gap and it is the HV windings' second CD and one FOS (FOS 16) is mounted at this gap to 80% WH (424 mm). Last two FOSs (FOS 17, 18) of active part is inserted to 80% WH and 20% WH of the HV windings' first CD but faced to tank side. Four FOSs (FOS 19, 20, 21, and 22) are mounted for measuring bottom and top oil temperatures align to two windings, one of them is in the middle. Finally, for the radiator's input and output oil temperatures, two FOSs (FOS 23, 24) are mounted (Tables 1 and 2).

It is aimed that the FOS does not obstruct the normal operation of the transformer when it is settled. For this reason, special apparatuses are designed and installation is completed. Installation of the 18 FOSs placed in the coil is completed before placement of the yoke (Fig. 5-a). After the installation of the FOSs listed in Table 4 is