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Prevention of hot spot temperature in a distribution transformer using magnetic fluid as a coolant

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ABSTRACT

A Mn–Zn ferrite magnetic fluid (TCF-56) having 5.6 mT fluid magnetization and high pyromagnetic coefficient, ($\partial M/\partial T = 177$ A/m K) has been investigated as a coolant in a 3 kW prototype transformer for overloading condition (167%). The winding temperature of a transformer submerged in magnetic fluid reaches at 396.8 K after 3 h of overloading, which is 20 K lower, when the same experiment was carried out with pure transformer oil. Similarly, core and top oil temperature also decrease by 14 and 21 K, respectively, when TCF-56 is used. This cooling performance of TCF-56 attributes to the thermo-magnetic convection, which sets up due to the significant change in magnetization of the fluid with increasing temperature. This can be explained using the Rayleigh number. The normal life of a transformer under 167% overloading condition is calculated for pure oil and TCF-56. The result shows nine times increase in normal life expectancy in TCF-56 fluid compared to use of pure oil. The study leads to the conclusion that Mn–Zn ferrite magnetic fluid (TCF-56) used in a transformer can deliver more power than its nameplate rating with an improved normal life.

1. Introduction

A transformer is a static electrical device that operates using the principle of mutual induction. During the power transfer some amount of the input power is dissipated as losses, such as core loss, hysteresis loss, eddy current loss and stray loss. These losses are of the order of 1% of its full rated load and can be minimized by (i) using superior magnetic material for the core, (ii) tuning the thickness of the steel lamination, (iii) by closing the leakage flux lines, etc. With the increasing power rating of the transformer, these losses also increase, results in the temperature rise inside the transformer. The upper limit of temperature rise in the individual parts of a transformer must meet the criteria as defined in the relevant standards [1,2]. To conform to these specifications, one needs cooling mechanisms to disperse the high temperature induced by the losses. The typical cooling mechanism used for this is a natural air flow or insulating oil flow.

In an oil cooled distribution transformer, the heat transfer mechanism is grounded on the Archimedes law. But this is relatively poor and less efficient, due to which a large temperature gradient across the oil reservoir is observed, which results into creation of a localized region of intense temperature between the core and windings and between the windings, known as the “hot spot”. The hot spot causes degradation of the insulation of the winding as well as the conductive components of a transformer, which finally results in a continuous sparking. Because of this, the insulating oil decomposes, forms an oil-carbon and decreases flash point of the oil. All these eventually lead to the failure of a transformer.

The hot spot temperature (HST) determines the normal lifespan of a transformer on loading. The permitted value of HST at rated load is specified by ANSI (American Standards Institute). This is a function of resistive temperature rise in the winding [2]. To forestall and/or trim down the hot spot winding temperature, an auxiliary cooling mechanism with fins or pumping devices to spread the oil inside the transformer tank is often employed. However, addition of fins requires more space and increases the overall weight of the transformer. On the other hand, oil pumps are cumbersome, consume power and need regular maintenance. The alternate way to enhance the heat dissipation is to modify the transformer oil cooling properties.

Potential to replace the insulating oil by magnetic fluid to eliminate “hot spot” in the transformer core and its winding is

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observed by many researchers [3–21]. The idea is to use a magnetic fluid (ferrofluids) whose Curie temperature is close to the device's temperature (393 K) so that convection due to magnetic buoyancy is achieved [3]. The resultant convective flow transfers the heat, becomes colder and regains its magnetization to complete the regenerative cycle [22]. This offers opportunities in the passive cooling of electrical circuits, machinery, and processes [23]. It is to be added here that, Bahiraei et al. [24–26] have studied hydrothermal characteristics of water based Mn–Zn ferrite nanofluid within annulus, square cavity and double-pipe heat exchanger in the presence of a magnetic field. According to this report, heat transport increases between fluid and wall.

Numerous theoretical calculations for 2D [20] and 3D [21] model transformer working under nominal condition indicates hot spot temperature lowers by 10–30 K when magnetic fluid is used. Nevertheless, the experimental results [16–20] reported by V. Segal [17] have shown 3.6 K reductions in winding temperature. Similarly, Stoian [18] has observed 3.4 K reduction inside the coil core temperature powered by a 50 Hz AC power. The magnetic fluid used in the experiments was magnetite dispersed fluid having a high Curie temperature 858 K [27]. Hence, to attain to the theoretical value of temperature decrement, one requires a magnetic fluid whose Curie temperature is near to the device temperature and should also have high pyromagnetic coefficients in the operating range of temperature. This is a motivation behind this study.

In the present work, we have designed a Mn–Zn magnetic fluid having Curie temperature (380 K) near to the device temperature. The fluid has a high pyro-magnetic co-efficient, ($\partial M/\partial T = 177$ A/m K) this is nearly five times higher than magnetite ($\partial M/\partial T = 29.8$ A/m K), in the working range of temperature (373–393 K). To check the efficiency of the synthesized magnetic fluid as a coolant, the experiment was conducted on a custom designed single phase 3 kW prototype transformer for the overloading conditions. The normal life expectancy under overloading condition is estimated using the results.

2. Experimental

2.1. Synthesis and characterization of magnetic fluid

A chemical co-precipitation method is used to prepare magnetic nanoparticles of Mn–Zn ferrites. The particles were coated with oleic acid and dispersed in transformer oil (TASHOIL-50, Tashkent transformer oil, Baroda, India) conforming to IS: 335/1993 [15]. The magnetic property of the transformer coolant fluid (TCF-56) is measured using vibrating sample magnetometer (model LakeShore VSM 7404). Fig. 1a shows the room temperature magnetic response of the fluid. The experimental data were fitted using standard Langevin's theory with log-normal particle size distribution. The value of saturation magnetization (Ms) derived from the fit is 5.6 mT [15]. The temperature dependent magnetic properties are measured using modified Quincke's experiment [28,29]. Fig. 1b shows the plot of the change in entropy of the fluid as a function of temperature under a constant magnetic field of 0.1 T. The Curie temperature, thus obtained by fitting the data with the equation mentioned in our earlier paper [29] is 380 ± 1 K. The pyromagnetic co-efficient ($\partial M/\partial T$) obtained using the ratio of the difference of magnetization at 303 K and at the Curie temperature to the temperature difference. The value of $\partial M/\partial T$ is 177 A/m K. This is nearly five times higher than magnetite based magnetic fluid (29.8 A/m K). The same tube is used to measure the thermal expansion coefficient (β_0) of the oil as well as magnetic fluid.

The thermal conductivity (λ) as a function of temperature is measured using the principle of transient hot wire technique (Flucon LAMBDA system). Fig. 1c shows the variation of thermal conductivity with temperature for TCF-56 and pure oil TASHOIL-50. The value of λ for TCF-56 is 2.5% higher compared to that of the base oil at all the temperatures under investigation (303–338 K). In addition, under the influence of parallel magnetic field, thermal conductivity of TCF-56 shows a further enhancement of 38% at 0.226 T field (Fig. 1d). The specific heat capacity of fluid, (c_p), (Fig. 1e) at 303 K (derived using the value of thermal conductivity and density) is lower than that of TASHOIL-50. This agrees with earlier observation by Anne et al. for 13 different nanoparticles-base fluids compared to the base fluid [30]. The temperature dependent viscosity (η) of the fluid is measured using Anton Paar rheometer (model Rheolab QC) in the range of 293–338 K (Fig. 1f). Both fluids exhibit Arrhenius behavior and value of activation energy is 6.18 ± 0.02 and 6.08 ± 0.02 kcal/mol, respectively for pure oil and magnetic fluid which remains nearly same. This indicates that at this concentration, flow rate will not be hindered by viscosity change.

The electrical resistivity is measured as per the IS 6262/6103 standard using I.R Tester and Oil dissipation factor meter purchased from Power Electronical, Nashik, India. The resistivity of TASHOIL-50 is of the order of 8×10^{11} Ω m and that of TCF-56 is 7.4×10^{8} Ω m. The value of resistivity decreases by three orders of magnitudes. The decrease in resistivity of the fluid is because of the lower value of electrical resistivity of the particles ($\sim 10^{-1}$ Ω m) [31] compared to that of the insulating oil ($\sim 10^{11}$ Ω m). Similarly, breakdown voltage (BDV) (model PE-OBDV-6, Power Electronical, Nashik, India) is measured for both samples as per IS 6792 using the gold plated spherical electrodes fixed at 2.5 mm gap. The average of five measurements was taken. The average value of the BDV for TCF-56 (69.5 kV) shows 115% enhancement compared to TASHOIL-50 (32.3 kV). This superior electrical breakdown performance compared to that of pure oil is due to the electron charging of the nanoparticles to convert fast electrons from field ionization to slow negatively charged nanoparticles charge carriers with effective mobility reduction by a factor of about 1×10^{5} [32]. The parameters obtained at 303 K for TASHOIL-50 and TCF-56 are presented in Table 1.

2.2. Design and fabrication of prototype transformer

A 3 kW (230 V, 13 A) prototype transformer was designed and fabricated to conduct the experiment. The core of the transformer was made up of cold rolled Non Grain Oriented steel laminations (CRNO) material with core dimension of 2.58×10^{-3} square meter and 7 number core sizes. 18 SWG wire was used for winding the primary and secondary coil. A mild steel (MS) cabinet of 6 mm thickness was made with volume capacity of 3.5 L of the transformer oil. The output of the transformer was connected to 3 heating coils, each of 2.5 kW power rating. Fig. 2a shows the schematic representation of a model transformer whereas Fig. 2b shows the photograph of prototype transformer used for the experiment. The temperature distribution in a prototype transformer under overloading condition (167%) is measured by submerging the transformer in the TASHOIL-50 and magnetic fluid (TCF-56), separately. The temperature at core (T_{Core}), winding ($T_{Winding}$), top of the oil ($T_{Top\ oil}$) and bottom of the oil ($T_{Bottom\ oil}$) were monitored using four thermocouples (LM35, precision temperature sensor, 218–423 K, accuracy 0.5 K, calibrated at 294 K) positioned at these parts as shown in Fig. 2a.

3. Results & discussion

3.1. Temperature profile of prototype transformer

The temperature profile for TASHOIL-50 and TCF-56 obtained in prototype transformer is shown in Fig. 3. From Fig. 3a–c it is clear