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Creep Failure Estimation of Distribution Transformers

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Abstract

This paper details about reasons of failure in distribution transformers (DTs). It has been proposed that creep may be a major reason for such failures. The effect of stress, temperature, and material on steady state creep rate on aluminium and copper wires (used in 25 kVA distribution transformers) has been presented. Proposed study confirms that the failure rate of aluminium wound DTs is higher than the failure rate of copper wound DTs in power deficient areas and poor distribution networks. The higher failure rate of aluminium wound DTs has been attributed to the elevated steady state creep rate of the aluminium wire than copper wire.

Keywords: Distribution Losses, Creep, Failure in Distribution Transformers

1. Introduction

In India, the high tension (HT) distribution system is increasing at very fast rate especially in rural areas which requires approximately 6.5 million DTs in 11th plan period during 2007-2012 [1]. DTs are the very important and costly equipments in the distribution network which constitute about 20% of the total cost of a utility. It is important to have reliable and reasonably priced distribution transformers (DTs) for providing power to all sectors of economy for sustainable economic development, human welfare and higher quality of living. For lowering the cost of distribution networks the failure rate and cost of DTs should be low. The cost of the DTs can be reduced by using aluminum wire than copper wire as winding material. However, aluminium wound DTs are subjected to high failure rate in power deficient areas and poor distribution networks. The reasons behind high failure rate of aluminum wound DTs as compared to copper wound DTs are not yet very clearly understood.

In India, the most of the utilities in rural areas have frequent tripping due to demand exceeding generation, forced load curtailment, maintenance and extension work, faults due to poor distribution network and lack of power transmission capacity. Thus, repeated energization of the DTs desired to restore the systems which cause high inrush current [2, 3]. This high current produces high stress and temperature in the DTs windings [4]. The frequent switching of DTs increases the probability that winding conductors may be operated at the stress 66 MPa and temperature well above the ambient temperature 140 ˚C. These conditions of stress and temperature are adequate for creep of the winding conductors. The elongation in metals at elevated temperature and constant stress is understood as creep. This paper experimentally validates the concept that the creep may be one of the reasons for failure of the DTs.

2. Literature Review

Creep of ductile metals at higher temperature is presented by Takeuchi and Argon [5]. The diffusion controls the creep at high temperatures and low stresses [6, 7], dislocation based Harper-Dorn creep [8], and grain boundary sliding accommodated by slip [9]. From all these three theories, only diffusional creep theory is well developed and able to predict the strain rate theoretically. A theory for lattice diffusion of vacancies from grain boundaries under tension and compression is given by Nabarro [6] and Herring [7]. This theory explains the linear variation of strain rate with stress and inverse-squared dependence of strain rate on grain size. Coble [10] extended the theory of diffusion occurring along the grain boundaries and suggested an inverse-cubed relationship between strain rate and grain size at intermediate temperature (0.4-0.6 T_m, where T_m is the melting point of the material in degrees Kelvin). The creep formulation for pure metals and alloys close to their melting point is presented by Harper-Dorn [8]. The operative creep mechanisms at low stresses under specific experimental conditions have been attempted by number of researchers [11-13]. However, creep results of the aluminum and copper wires of diameter 0.8 and 0.62 mm at stress and temperature corresponding to operating conditions at the instant of energization of the DTs have not been presented in the literature.

3. Creep

Creep is progressive deformation of a material at constant stress and temperature [14]. The standard shape of a creep curve has three distinct stages as shown in Figure 1. The slope of the creep curve ($d\varepsilon/dt$ or $\dot{\varepsilon}$) is called creep rate. The first stage of creep is primary creep which is predominantly transient creep. In this stage, the creep resistance of the material increases due to its own deformation. The second stage of the creep is recognized as secondary creep of nearly constant creep rate. This stage is also known as steady state creep. The third stage in creep tests known as tertiary creep occurs mainly at high stresses and at high temperatures.

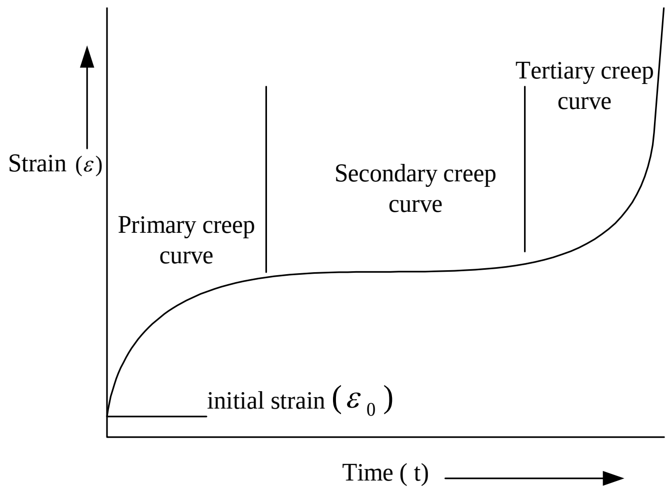

Figure 1: The Creep Curve

4. Magnetizing inrush current

DTs operate with the peak core flux at the "knee" of the transformer core's saturation characteristic. Random energization of DTs can create large flux asymmetries and saturation of one or more winding cores of the transformer which causes magnetizing inrush current in DTs [3]. This is due to the fact that the inductance is very small in this region of the curve as shown in Figure 2(b). The magnetizing inrush current may be 10 to 15 times higher than the full load current. This current is rich in harmonic contents and high direct current components that cause high stress and temperature in the windings of the DTs. The peak value of the magnetizing inrush current under worst energization case is given as follows [3]:

$$i_{0\max} = \frac{h_w}{N_1 A_c}\frac{A_i}{\mu_0}(2B_m + B_{res} - B_{sat}) \tag{1}$$

where,

A_c = Mean area enclosed by a turn of the winding

A_i = Net cross sectional area of the iron core

h_w = Height of the primary winding

N_1 = Number of turns of the energized winding

B_m = Peak value of the flux density in iron at the moment of switching

B_{res} = Remanent or residual flux density which may approximately be taken 0.6 B_m

B_{sat} = Saturation flux density

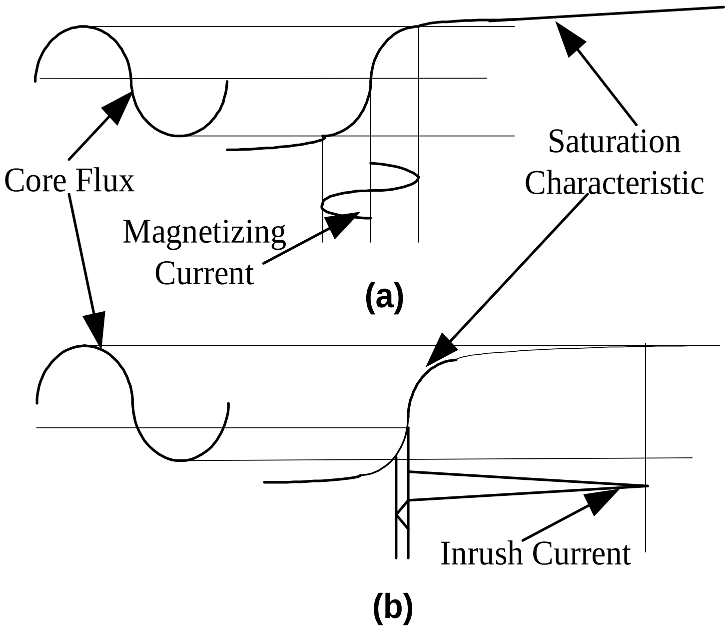

Figure 2: Flux/Current Characteristic (a) Symmetrical (b) Unsymmetrical Core Fluxes

5. Creep Test Equipment and Procedure

5.1 Creep Test Equipment

The test setup consist one muffle furnace that can provide uniform temperature up to 500±1 ˚C. The test wire is placed through the small holes in the muffle furnace on both sides of the furnace. The temperature of the test wire is measured by a K-type thermocouple. This increases the accuracy of the test results. The output of the thermocouple is used as a feedback in temperature controller to maintain the desired temperature. Both the holes in the furnace are closed by fiberglass after placing the test conductor and the thermocouple. The tension is applied on the wire by dead weight through a lever arm at the lower end and fixing the upper end by a clamp. The wire creep test set up is shown in Figure 3.

Figure 3: Wire Creep Test System

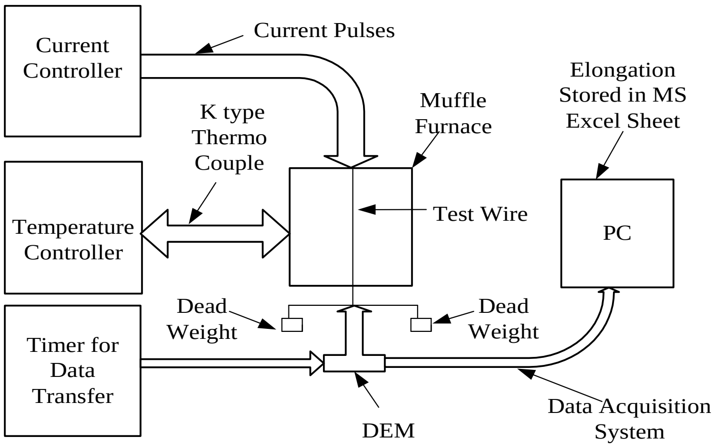

Figure 4: Schematic of Wire Creep Test System

The absolute elongation in the test wire is measured by means of digital extension meter (DEM) with accuracy ±1 micrometer which is mounted at the middle of the dead-weight lever arm. The DEM is capable to measure the change in length up to ±1 micrometer. The elongation data is stored automatically in MS Excel sheet by data acquisition through COM port. A schematic drawing of the arrangement is shown in Figure 4.

5.2 Creep Test Procedure

The general procedure adopted for creep tests are as per ASTM specification E139-06. The test specimens of aluminum and copper wires of 180 mm long are taken in each instance from the same coil of wires. The actual measurement of creep elongation is on 150 mm gauge length which eliminates any effect associated with the dead-end clamps. The test tension and temperature are applied and held constant for the test duration.

6. Results and Discussions

The creep tests have been initiated in the laboratory on the new wire of aluminum and copper of diameter 0.8 and 0.62 mm, respectively used in 25 kVA DTs at the stress 66 MPa and temperature 140 ˚C. The creep curve for aluminum and copper wires are shown in Figure 5. At stress 66 MPa and temperature of 100 ˚C, the elongation in the aluminum wire is 0.44 mm. At the stress 66 MPa and temperature 140 ˚C, the elongation in the 50 hours in aluminum and copper wires are 1.1 mm and 0.2 mm, respectively.

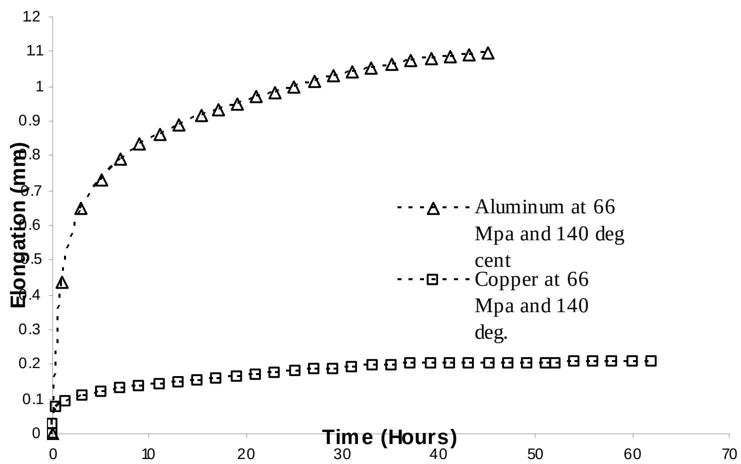

Figure 5. Creep curves for aluminum and copper wire

The elongation in aluminum wire is 5.5 times than for copper wire at the same temperature of 140 ˚C and stress of 66 MPa. This fact suggests the higher failure rate of aluminum wound DTs than copper wound DTs in frequently energized operating conditions in power deficient area and poor power distribution networks.

7. Conclusions

This paper presents the experimental creep results of aluminum and copper wires having diameter 0.8 and 0.62 mm, respectively used in 25 kVA distribution transformers. The temperature for test is taken 140 ˚C corresponding to the maximum hot spot temperature in the HT winding of DTs. The stress for tests is taken corresponding to the maximum stress produced due to inrush current on inner side of high voltage winding of DTs. The effect of material on elongation of the aluminum and copper wires has been presented. Proposed study confirms that the creep elongation in the aluminum wire is more than that in the copper wire. This leads to the fact that the higher failure rate of aluminum wound DTs than copper wound DTs in the power deficient areas and poor power distribution networks. In these areas high stress and high temperature produce in the windings during repeated energization of the distribution transformers. The effect of different stress and temperatures on the elongation of aluminum and copper wires will be considered in the future work.

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