Effect of Creep on Failure of Distribution Transformers: An Experimental Evaluation

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Abstract: The cold load pick up current during frequent energization of the distribution transformers produces high stress and hot spot temperature in their windings. This condition is responsible for elongation in the winding conductors due to creep. The winding conductors between spacers become loose due to elongation which in turn causes turn to turn fault in the winding. Thus, creep causes failure of the distribution transformers. The steady state creep rate is an important design parameter which specifies strain rate in the wire during steady state creep stage. This paper reports the steady state creep rate of the aluminum and the copper wires used in the windings of the 25 kVA distribution transformers.

Keywords: Cold load pick up (CLPU), creep, distribution transformers, inrush current, steady state creep rate.

1. Introduction

The electrical utilities in power deficient areas and poor power distribution networks have frequent tripping. This is primarily due to forced load curtailment, maintenance, extension work and faults. Thus, repeated energization of the distribution transformers (DTs) is necessary to restore the power distribution networks. A major portion of the entire power demand of a power distribution system is contributed by thermostatically controlled electrical devices. Restoration of these systems produces higher load demand than preoutage load which is known as cold load pick up (CLPU) [1]. In DTs, this condition produces several times higher load current than the normal value which lasts for one to several hours [2]. The CLPU current produces high stress and temperature in the windings of DTs which leads to creep of the winding conductors.

A number of researchers have attempted to identify the operative creep mechanisms at different stresses under specific experimental conditions [3-6]. However, creep of the aluminium and copper wires of diameter 0.8 and 0.62 mm at stress and temperature produced by CLPU current during frequent energization of the DTs have not been presented in the literature. Therefore in this investigation, attempts are made to study the effect of stress and temperature on the creep response of aluminium and copper wires so as to relate the DTs failures with creep and switching of DTs. The steady state creep rate is an important design constraint which is the measurement of strain rate in the wire. In this paper, the experimental results of the steady state creep rate of aluminum and copper wires of diameter 0.8 and 0.62 mm, respectively are presented.
2. Creep Phenomenon

Creep is progressive deformation of a material at constant stress and temperature. The standard shape of a creep curve has three distinct stages as shown in Figure 1. The slope of the creep curve \( (\frac{d\varepsilon}{dt} \text{ or } \dot{\varepsilon}) \) is called creep rate which indicates the elongation of the wire with time [7]. The first stage of the creep is primary creep which is predominantly transient creep represents a region of decreasing creep rate. The second stage of the creep is recognized as secondary or steady state creep that persists for maximum duration among all the three stages of the creep. It is a period of nearly constant creep rate which results from a balance between the competing processes of strain hardening and recovery. The average value of the creep rate during secondary creep is called the steady state creep rate.

![Figure 1: The Creep Curve](image)

The steady state creep rate is the most significant design parameter derived from the creep curve. The higher the steady state creep rate the lower the time for same elongation of the wire which causes turn to turn fault in the windings hence early failure of DTs. The third stage of the creep is known as tertiary creep which occurs mainly at high stress and at high temperature. This stage occurs due to an effective reduction in cross sectional area either due to necking or internal void formation [8].

Takeuchi et al. and Embury et al. [9, 10] presented the creep of ductile metals at higher temperature. The creep at high temperatures and low stresses is controlled by diffusional creep [11, 12], dislocation based Harper-Dorn creep [3], and grain boundary sliding accommodated by slip [13]. From all these three theories, only diffusional creep theory is well developed and able to envisage the strain rate theoretically. Coble [14] 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 \((0.4 - 0.6 T_m, \text{where } T_m \text{ is the melting point of the material in degrees Kelvin})\).

3. Cold Load Pick Up (CLPU)

In normal operating conditions all the connected loads are never switched on or off simultaneously. But, during restoration after an outage, all thermostatically controlled loads come into the “ON” state simultaneously [2]. This condition produces several times higher load demand than preoutage load which is known as CLPU. The CLPU current is divided into four phases [15]: inrush, motor starting, motor running and enduring phases of current. The first inrush current phase is mainly due to magnetization of the distribution transformers which is explained in next section. In the second phase starting current raises approximately 6 times the normal value which last for some seconds. The third phase is due to the current needed in the acceleration of the motor which sustains for about 15
seconds. The fourth phase is due to loss of diversity among thermostatically controlled loads. The load current in this phase varies from 2 to 5 times the normal operating current which persists for one to several hours. The duration of this phase depends upon many factors like the weather, the use pattern and the duration of outage.

4. Inrush Current Phenomenon

DTs operate with the peak core flux at the “knee” of the transformer core’s saturation characteristic. A typical core saturation characteristic is illustrated in Figure 2. The sinusoidal core flux is the integral of the applied voltage. The curve shown is a flux/current curve, and the slope at any point is proportional to the winding inductance. Random energization of DTs can create large flux asymmetries and saturation of one or more winding cores of the transformer.

![Figure 2: Flux/Current Characteristic. (a) Symmetrical (b) Unsymmetrical Core Fluxes](image)

With only a modest flux increase beyond saturation or symmetry shift of the flux results in very high magnitude current pulses [16]. 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 steady state magnetizing current of a transformer is about 5% of the full load current. The transient inrush current may be 10 to 15 times higher than the full load current but persists for some cycles. This current produces 100 to 225 times copper losses for short duration than the normal copper losses which in turn increases the temperature of the DTs windings.

5. Mechanical Stresses Produced in the DTs Windings

The conductors of the transformer windings are situated in the region of magnetic leakage flux and are subjected to mechanical forces or stresses. According to Fleming’s left-hand rule, these stresses act perpendicular to the current and leakage flux. Conductors are attracted to each other if current flowing in them has the same direction otherwise these conductors are pushed away from each other [17]. For a two winding core type transformer having concentric winding, the mechanical forces due to CLPU current can be calculated as follows [18-20]:

5.1 Hoop Stress:

Hoop stress is a mechanical stress which acts circumferentially i.e., perpendicular both to the axis and to the radius of the conductor.

\[
\sigma_{mean} = K \frac{I_{ph}^2 R_e}{h_w Z_{pu}^2} \text{ kg/cm}^2
\]

where, \( I_{ph} \) = per phase current
\[ R_{dc} = \text{DC resistance of winding} \]
\[ h_w = \text{Window height} \]
\[ Z_{pu} = \text{Per unit impedance of winding} \]
\[ K = \begin{cases} 0.03 \left( k \sqrt{2}/2.55 \right)^2 & \text{for Cu} \\ 0.02 \left( k \sqrt{2}/2.55 \right)^2 & \text{for Al} \end{cases} \]
\[ k \] is the asymmetric factor whose value is decided on the basis of \( X/R \) ratio with reference to IS: 2006, part -1- 1977, Clause 16.11.2.

5.2 **Internal Axial Force:**
Axial forces bend the winding turns in a vertical direction which in turn increase the pressure on spacers between coils. It is given as follows:

\[ F_i = -\frac{34.5 S_n}{Z_{pu} h_w} \text{ kg} \quad (2) \]

where, \( S_n \) is the kVA rating of the DT. The negative sign indicates that force is acting towards the center of the winding.

5.3 **Maximum Compressive Force:**
The one-third of the internal axial force \( F_i \) exerts on the outer windings of DTs. Therefore, the compressive force on the windings is as follows:

\[ P = \frac{F_i}{A} \text{ kg/cm}^2 \quad (3) \]

where, \( A = \text{Total supported area of the radial spacer (in cm}^2) \)

5.4 **Resultant Stress:**
The maximum value of the hoop stress is two times of the mean value and it is on the inner layer of the high tension (HT) windings. Therefore, the resultant stress on the conductor just below/above the radial spacer of the inner layer of most stressed coil is:

\[ \text{Resultant Stress} = 2\sigma_{\text{mean}} + P + 40 \text{ kg/cm}^2 \quad (4) \]

where, 40 is the tightening force in kg/cm².

The resultant stress due to CLPU current on the inner layer conductors of HT windings of the 25 kVA DTs are calculated between 1.24 to 6.64 kg/mm².

6. **Experimental Set Up and Procedures**

6.1 **Experimental Set Up**
A test chamber has electrical resistance heating system with a blower for maintaining uniform temperature upto 500 °C, within ±1 °C. The test wire is placed through the small holes in the muffle furnace at both the ends. For measuring the temperature of the test wire a K-type thermocouple is placed inside the furnace with a close contact to the test wire. The output of the thermocouple is used as a feedback in temperature controller to maintain the desired temperature. Openings of the heating chamber are closed by fibreglass after placing the test conductor and the thermocouple in the furnace. The upper end of the test wire is fixed by clamp and on the lower end a dead-weight lever arm system is employed to maintain constant tension on the wire specimens under test.
The elongation of test wire is measured by means of digital extension meter (DEM) mounted at the middle of the dead-weight lever arm system. The DEM is capable to measure the change in length upto ±1 µm. The readings of the DEM are transferred to computer system in Microsoft Excel Sheet using data acquisition system through COM port. The readings are set to record in any defined intervals from 1-second to 999-minute. A schematic drawing of the arrangement is shown in Figure 3.

6.2 Experimental Procedures

To determine the engineering creep curve of aluminum and copper wires, a constant tensile load is applied to a specimen maintained at a constant temperature. The elongation of the specimen is measured as a function of time. The general procedure adopted for creep tests are as per ASTM specification E139-06. A new test specimen of aluminum and copper wire of 180 mm long having diameter 0.8 and 0.62 mm, respectively are taken in each instance from the same coil of wires. The stress is taken between 1.24 to 6.64 kg/mm$^2$ and temperature 100 and 140 °C for creep test. After the specimens are placed in the test chamber a bias tension approximately 0.3 kg is applied at ambient temperature. This bias is sufficient to elastically straighten the wires but is not enough to impart any consequential creep. The actual measurement of creep is on a 150 mm gauge length so any effects which might be associated with the dead-end clamps are eliminated. The tensile loads are applied to the test wires through the lever arm system by means of dead weights. After the final test tensions are applied, the temperature is raised at a rate such that about 4-5 minutes are sufficient for the muffle furnace to reach the final test temperature. The temperature is then held constant for the test duration. At the end of the test the furnace is turned off and allowed for cooling to room temperature.

7. Results and Discussion

The CLPU current produces high stress and temperature in the windings of DTs [21, 22]. The frequent switching of DTs increases the probability that winding conductors may be operated at the stress between 1.24 to 6.64 kg/mm$^2$ and temperature well above the ambient temperature i.e., hot spot temperature which is 100 °C or in some cases 140 °C. The stress and hot spot temperature are calculated as per loading profile given in IS 6600:1972. The time constant of DTs windings is very low around 10 minutes. Thus, the temperature rise in the windings is very fast. These conditions of stress and temperature during frequent energization of DTs are sufficient for elongation of the winding conductors due to creep. The elongation causes loosening of the winding conductors between spacers. If elongation or strain in the wire is more than the allowable gap
between two layers of the winding then turn to turn fault occurs [23]. Thus, DTs are failed due to creep of the winding conductor.

Creep phenomenon is a typical plastic deformation of crystalline solids at higher temperatures. At temperature above $0.4 T_m$, the diffusion is predominant and so can stimulate the plastic deformation. Deformation due to diffusion takes place through the dislocation sliding and climbing. Also, diffusion can heal the deformed microstructures. Therefore, deformation process is homogeneous as the viscous medium [12]. Generally, the homogeneous deformation is known as steady state creep behaviour for a wide strain range. Hence, the steady state region is a large part of the creep life of the material at high temperature. At lower temperatures, the effect of diffusion on creep behaviour of crystalline solids is negligible but the work hardening is more matter at the initial stage of plastic deformation.

The creep curve for aluminum wire at $100 \, ^\circ C$ and stress $1.24 \, \text{kg/mm}^2$ is shown in Figure 4. At this condition, the steady state creep rate is obtained approximately as $1.96 \times 10^{-4} \, \text{mm/mm/hour}$. The creep curve for aluminum wire at $100 \, ^\circ C$ and $6.64 \, \text{kg/mm}^2$ is shown in Figure 5. At this condition, the steady state creep rate is computed approximately as $26.04 \times 10^{-4} \, \text{mm/mm/hour}$. The creep curve for aluminum wire at $140 \, ^\circ C$ and $4 \, \text{kg/mm}^2$ is shown in Figure 6. At this condition, the steady state creep rate is found approximately as $25.54 \times 10^{-4} \, \text{mm/mm/hour}$. The creep curve for aluminum wire at $140 \, ^\circ C$ and $6.64 \, \text{kg/mm}^2$ is shown in Figure 7. At this condition, the steady state creep rate is obtained approximately as $44.68 \times 10^{-4} \, \text{mm/mm/hour}$.

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Type of Wire</th>
<th>Temp. (°C)</th>
<th>Stress (kg/mm²)</th>
<th>Steady State Creep Rate (mm/mm/hour)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Aluminum</td>
<td>100</td>
<td>1.24</td>
<td>$1.96 \times 10^{-4}$</td>
</tr>
<tr>
<td>2.</td>
<td>Aluminum</td>
<td>100</td>
<td>6.64</td>
<td>$26.04 \times 10^{-4}$</td>
</tr>
<tr>
<td>3.</td>
<td>Aluminum</td>
<td>140</td>
<td>4</td>
<td>$25.54 \times 10^{-4}$</td>
</tr>
<tr>
<td>4.</td>
<td>Aluminum</td>
<td>140</td>
<td>6.64</td>
<td>$44.68 \times 10^{-4}$</td>
</tr>
<tr>
<td>5.</td>
<td>Copper</td>
<td>140</td>
<td>4</td>
<td>$1.18 \times 10^{-4}$</td>
</tr>
<tr>
<td>6.</td>
<td>Copper</td>
<td>140</td>
<td>6.64</td>
<td>$1.79 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

The steady state creep stage has not been examined for copper at $100 \, ^\circ C$ and $6.64 \, \text{kg/mm}^2$. The creep curve for copper wire at $140 \, ^\circ C$ and $4 \, \text{kg/mm}^2$ is shown in Figure 8. At this condition, the steady state creep rate is obtained as $1.18 \times 10^{-4} \, \text{mm/mm/hour}$. The creep curve for copper wire at $140 \, ^\circ C$ and $6.64 \, \text{kg/mm}^2$ is shown in Figure 9. At this condition, the steady state creep rate is obtained as $1.79 \times 10^{-4} \, \text{mm/mm/hour}$. The steady state creep rates for all the conditions described above are summarized in Table 1.
The effect of temperature, applied stress and material on steady state creep rate and time required for turn to turn fault due to creep are discussed as follows:

7.1 The Effect of Temperature
The effect of temperature is drastic and critical on the creep behaviour of aluminum and copper wire. The diffusion is active and important in these experimental conditions whereas recrystallization is not recognized. The diffusion would accelerate the plastic deformation and result in shortened rupture. For aluminum wire at 6.64 kg/mm$^2$, the steady state creep rate at 140 °C is approximately 1.7 times than at 100 °C. Hence, DTs are failed earlier at higher operating temperature conditions.

7.2 The Effect of Applied Stress
The creep curve depends upon the applied stress. As the applied stress increases, the creep curve changes from a logarithmic creep to a steady state creep. For aluminum wire at 100 °C, the steady state creep rate at 6.64 kg/mm$^2$ is approximately 13.3 times than at 1.24 kg/mm$^2$. For aluminum wire at 140 °C, the steady state creep rate at 6.64 kg/mm$^2$ is 1.75 times than at 4 kg/mm$^2$. At 140 °C, the steady state creep rate for copper wire at 6.64 kg/mm$^2$ is around 1.51 times than at 4 kg/mm$^2$. Hence, DTs are failed earlier at higher stress. A survey has also been performed on about 100 damaged HT windings of aluminum and copper wound DTs and it is observed that 70% of the windings are damaged from their inner side. This fact suggests that stress developed in the HT windings due to CLPU current is highest on their inner side.

7.3 The Effect of Material
The creep curve depends on the material also. The steady state creep rates of aluminum wire at 140 °C corresponding to 4 and 6.64 kg/mm$^2$ are 21.64 and 24.96 times, respectively than copper wire. This fact suggests higher failure of aluminum wound DTs than copper wound DTs in the same operating conditions. Data have been collected for
failure rate of DTs and it is found that failure rate of aluminum wound DTs is 30% more than copper wound DTs.

8. Conclusions

This paper presents the experimental results of steady state creep rate of aluminum and copper wires of diameter 0.8 and 0.62 mm, respectively at different temperature and stress conditions. The effect of temperature, stress and material on steady state creep rate is also studied. The temperatures for tests are taken 100 and 140 °C corresponding to the hot spot temperature in the HT winding of DTs. The stresses for tests are taken corresponding to the stress produced due to CLPU current on inner side of HT winding of DTs. For aluminum wire, the steady state creep rate at 140 °C is found approximately 1.7 times than at 100 °C, at same stress 6.64 kg/mm². For aluminum wire at 100 °C, the steady state creep rate at 6.64 kg/mm² is determined approximately 13.3 times than at 1.24 kg/mm². For aluminum wire at 140 °C, the steady state creep rate at 6.64 kg/mm² is obtained approximately 1.75 times than at 4 kg/mm². For copper wire at the temperature 140 °C, the steady state creep rate at 6.64 kg/mm² is approximately 1.51 times than at 4 kg/mm². At 140 °C, the steady state creep rate corresponding to 4 and 6.64 kg/mm² are respectively about 21.64 and 24.96 times more for aluminum wire than copper wire.

The proposed study substantiates that the creep is the reason of DTs failure especially in power deficient areas and poor power distribution networks where frequent energization of DTs is required. DTs are failed earlier at higher temperature and stress conditions. Also, the failure rate of aluminum wound DTs is more than copper wound DTs due to high steady state creep rate of aluminum wire than copper wire. It is recommended to design the aluminum wound DTs with lower current density and low temperature rise of the winding to reduce their failure rate and cost. The present study can also be used in deciding use of aluminum wire in the applications where aluminum is preferred than copper due to low cost and lower density.

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