Degradation processes in tungsten filaments at high temperatures

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Abstract. Degradation processes in tungsten filaments of lighting lamps under normal operating conditions are experimentally studied. The duration of each measurement in continuous mode is about 18 hours. To increase the measurement accuracy, subtraction (compensation) of the constant component of the voltage is used. To compensate for the constant component of the voltage, a low noise reference DC voltage source is used. Using this scheme allowed decreasing the influence of the inherent noise of power supplies without suppressing degradation processes. It is shown that the relative change in resistance during the measurement does not exceed 2.8⋅10⁻³. It is also shown that the joint influence of voltage fluctuations of power supplies and low noise reference voltage source on the measurement results corresponds to a relative change in a resistance equal to 2.8⋅10⁻⁴. The study of degradation processes can be used to assess the reliability (and durability) of products in electrical engineering and radio electronics.

1. Introduction
One of the methods for evaluating the reliability and durability of products in electrical engineering and radio electronics is to test the device under extreme operating conditions (accelerated tests [1]), in particular, at high temperatures and in strong electromagnetic fields. To develop accelerated test methods under normal operating conditions, which allows estimating the service life of devices, it is necessary to study the degradation processes (i.e., changes in parameters) in devices with sufficiently high accuracy. In this paper, the filaments of incandescent lamps are the research objects. The research subject is degradation processes in the filaments of incandescent lamps.

The purpose of this work is to study degradation processes in tungsten filaments of incandescent lamps under normal operating conditions. The following tasks were set:

- to analyze the scientific and technical literature on degradation processes and low-frequency fluctuations;
- to develop methods that allow studying degradation processes and low-frequency fluctuations;
- to perform tests of incandescent lamps under normal operating conditions, using the developed method.

2. Description of research methods

2.1. Description of method
In this paper, to assess the intensity of degradation processes in the filament, the dependence on the time of the relative deviation of its resistance $R_F(t)$ on the initial resistance $R_F(0)$ is investigated. This relative deviation is found by the formula

$$\delta_{R_F}(t) = \frac{R_F(t) - R_F(0)}{R_F(0)}.$$  \hspace{1cm} (1)

Due to a low value of the relative deviation of resistance, it is difficult to detect it directly using digital methods. This difficulty can be eliminated by using compensatory measurement methods, for example, the current compensation method [2], the voltage compensation method [3], the bridge method of compensation of the constant component of the current [4]. When using the bridge method, not only voltage fluctuations of power sources are effectively suppressed, but also degradation processes in the filaments. In this regard, the bridge method is not suitable for studying degradation processes. When using the voltage compensation method using an additional power source, the additional source operates in idle mode, due to which the level of fluctuations in its output voltage is lower than that when using the current compensation method. In this regard, the method of voltage compensation on a wire resistor connected in series with a thread was used in this work. A low-noise DC reference voltage source was used for compensation. The $R_F$ resistance of the filament was calculated by the formula

$$R_F = \frac{U_{ps} R}{U_{comp} + U_{mV}} - R,$$  \hspace{1cm} (2)

where $U_{ps}$ is the voltage of the power source used for heating the filament, $R$ is the resistance of the wire resistor, $U_{mV}$ is the voltage measured by a multimeter, $U_{comp}$ is the output voltage of a low-noise DC reference voltage source.

2.2. Scheme of the experimental setup

Figure 1 shows the scheme of the experimental setup.

![Figure 1. Scheme of the experimental setup.](image-url)
digital multimeter: amplifier, low-pass filter, 16-bit analog-to-digital converter (^#). The serial interface made with galvanic isolation according to the RS-232 standard is denoted as Int. The personal computer is denoted as PC.

3. Experimental research and results

3.1. Experimental research of relative deviation of resistance

Because the power released on the wire resistor is significantly less than the maximum power that it can dissipate, degradation processes in the resistor and fluctuations in its resistance were not taken into account. The contribution of fluctuations of voltage $U_{PS}$ to the measurement error is reduced because at high temperatures of the filament $R_p \gg R$, and therefore

$$\frac{U_{PS}}{U_{comp}} = \frac{R_p(0)}{R} + 1 \gg 1.$$ \hspace{1cm} \text{(3)}

In this regard, only the dependence of $U_{mV}$ on time was measured in this work, and the values of $U_{PS}$, $U_{comp}$, and $R$ were considered constant. Considering also that $\left|U_{mV}(t)\right| \approx U_{comp}$ the following formula can be obtained

$$\delta_{R_p} \approx \frac{U_{PS}}{U_{comp}} \cdot \frac{U_{mV}(0) - U_{mV}(t)}{U_{PS} - U_{comp}}.$$ \hspace{1cm} \text{(4)}

Figure 2 shows the obtained dependence of the relative change in the resistance of the filament on time for three different 25 W lamps of the same manufacturer.

![Figure 2. Relative change in the resistances of the filaments of three lamps.](image)

Curve 1 has a minimal trend. Therefore, lamp 1 has the minimum degradation rate. Quasi-continuous and relaxation processes [5] are most noticeable on curve 2, pulse processes [6] are most noticeable on curve 3.

Using the additional measurement results, the root-mean-square deviations of $U_{PS}$, $U_{comp}$ and their contribution to root-mean-square deviations $\delta_{R_p}$ were estimated (see Table 1).
Table 1. The root-mean-square deviations of $U_{PS}$ and $U_{comp}$ and their contribution to root-mean-square deviations $\delta_R$.

| Voltage | The root-mean-square deviation, V | Contribution to root-mean-square deviations of $\delta_R$ |
|---------|----------------------------------|------------------------------------------------------|
| $U_{PS}$ | $4.86 \cdot 10^{-2}$ | $2.5 \cdot 10^{-4}$ |
| $U_{comp}$ | $1.11 \cdot 10^{-3}$ | $1.2 \cdot 10^{-4}$ |

The root-mean-square deviations $\delta_R$ due to $U_{PS}$ and $U_{comp}$ fluctuations are equal to

$$\Delta \delta_R = \sqrt{(\Delta \delta_R U_{PS})^2 + (\Delta \delta_R U_{comp})^2} = 2.8 \cdot 10^{-4},$$

(5)

where $\Delta \delta_R U_{PS}$ and $\Delta \delta_R U_{comp}$ are contributions to root-mean-square deviations $\delta_R$, respectively. This value is 2-7 times less than the measured root-mean-square deviations $\delta_R$ and about 10 times less than the $\delta_R$ variation range during the measurement.

3.2. Experimental research of spectral power densities of relative deviation of resistance

In this paper, centered implementations of $U_{mV}$ are used to find the spectral power densities (SPD) of $\delta_R$:

$$S_{\delta_R}(f) \approx \frac{U_{PS}^2 S_{U_{mV}}(f)}{U_{comp}^2 (U_{PS} - U_{comp})^2},$$

(6)

where $S_{U_{mV}}(f)$ is the spectral power density calculated for the centered implementation of $U_{mV}$.

Figure 3 shows the smoothed spectral power densities, respectively, for the curves shown in figure 2. The first SPD points containing information about constant components are not shown. To smooth out the spectral power densities, a program [7] with the same filtering parameters as in the works [2, 4] was used.

Figure 3. Smoothed spectral power densities of relative change in the resistance of the filaments of three lamps.
The values of the SPD of curve No. 1 are on average 2.7 times less than the corresponding values of the SPD of curve No. 2 and 13 times less than the corresponding values of the SPD of curve No. 3. The large roughness of the curves in the high-frequency region is due to the noise of the power sources.

4. Conclusion
Degradation processes in three incandescent lamps have been studied. It is shown that the relative change in resistance during the measurement does not exceed $2.8 \times 10^{-3}$. Uncertainty of relative change in the resistance of the filaments has been estimated. This uncertainty is 10% of the variation range of the studied value during the measurement. The developed experimental method provides reliable isolation, registration, and quantitative analysis of degradation processes in incandescent lamps against the background of low-frequency noise of measuring equipment and the research object.

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