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Method of predicting the useful life of ultraviolet lamps in electrotechnical systems under UV radiation

***Abstract**. The results of predicting the useful service life of low-pressure ultraviolet discharge lamps based on the decline of radiant flux during tests up to 2500-3000 hours are presented in the paper. An assessment of their service life was carried out by extrapolating the values of the radiant flux conservation factor until the moment when this factor in 50% of the lamps decreases to 70% of the initial value. The ultraviolet flux was measured using a radiometer for ultraviolet radiant energy after 100 hours, 500 hours, and then every 500 hours up to 6000 hours. Testing of low-pressure discharge lamps was conducted at a supply voltage of 220V, with a mode of 8 switchings per day for 15 minutes each. The empirical curve for the radiant flux conservation factor was chosen by finding the initial constant and the rate of change of radiant flux using the least squares method. The useful service life for the investigated lamps, with a decrease in radiant flux to 70% of the initial value, was estimated at 8.25 thousand hours and correspondingly, for 80%, it was 4.6 thousand hours.*

Streszczenie.** Wyniki prognozowania przydatnego okresu użytkowania lamp wyładowczych o niskim ciśnieniu promieniowania ultrafioletowego na podstawie spadku strumienia promieniowania podczas testów do 2500-3000 godzin przedstawiono w artykule. Ocena ich żywotności została przeprowadzona przez ekstrapolację wartości współczynnika zachowania strumienia promieniowania do momentu, gdy ten współczynnik w 50% lamp zmniejsza się do 70% początkowej wartości. Strumień ultrafioletowy był mierzony za pomocą radiometru promieniowania ultrafioletowego po 100 godzinach, 500 godzinach, a następnie co 500 godzin do 6000 godzin. Testy lamp o niskim ciśnieniu wyładowczym przeprowadzono przy napięciu zasilania 220V, w trybie 8 przełączeń na dzień, każde trwające 15 minut. Empiryczna krzywa współczynnika zachowania strumienia promieniowania została wybrana poprzez znalezienie początkowej stałej i tempa zmiany strumienia promieniowania za pomocą metody najmniejszych kwadratów. Przydatny okres użytkowania badanych lamp, przy spadku strumienia promieniowania do 70% początkowej wartości, został oszacowany na 8,25 tysiąca godzin, a dla 80% odpowiednio wynosił 4,6 tysiąca godzin. **(Metoda prognozowania przydatnego okresu użytkowania lamp ultrawioletowych w systemach elektrotechnicznych pod wpływem promieniowania UV)

Keywords: low-pressure UV lamps, radiant flux, service life, mathematical extrapolation method.
Słowa kluczowe: lampy UV o niskim ciśnieniu, strumień promieniowania, żywotność, matematyczna metoda ekstrapolacji.

Introduction

Low-pressure ultraviolet mercury lamps are reliable light sources [1]. In real operating conditions, the service life of these lamps can reach 10-12 thousand hours [2]. However, scientists and developers of ultraviolet equipment are interested not only in the service life of lamps but also in the pattern of radiant flux decline [3]. The decline in radiant flux over a certain period determines the efficiency of UV lamps [4] in disinfection and irradiation during their operation.

Testing the service life (resource) using traditional methods, as for incandescent and discharge lamps, takes from 2 to 4 years. It is evident that the results of such tests cannot be effectively used to assess the quality of ultraviolet lamps by developers, consumers, and independent conformity assessment bodies. Thus, research and improvement of accelerated methods for assessing the service life of low-pressure ultraviolet lamps are a relevant task.

EU Commission Regulation 2019/2020 [5], which establishes requirements for light sources for general lighting, obliges manufacturers to provide information on the service life of these sources. The service life of UV light sources refers to the duration in hours from the initiation of their use until the point when 50% of the tested lamps [6] exhibit a radiative flux conservation coefficient (RFCC) that gradually decreases to 70% of the initial value. This factor is referred to as the L70 B50 service life [7].

Currently, there is insufficient information regarding the conformity of the declared service life of ultraviolet lamps and UV irradiation systems with the actual test results provided by manufacturers. Therefore, it is also relevant to study the conservation factors of ultraviolet lamp radiative flux and UV systems over their service life and evaluate their service life based on these studies.

Analysis of literary data

Ultraviolet (UV) radiation is a crucial environmental factor in the inactivation of bacteria [8], in the fight against airborne viruses [9], and specifically against SARS-CoV-2 [10], responsible for COVID-19 [11]. UV radiation with an intensity around 254 nm is one of the most widely used methods of disinfection [12, 13] because viruses are sensitive to UV rays due to the high photo-reactivity of nucleic acids. Therefore, most studies on virus inactivation focus on this specific UV_{254} range.

For lamps used in various irradiation systems for bactericidal disinfection of water in pools [14, 15], disinfection of powdery materials [16], pre-sowing irradiation of agricultural crops [17], it is crucial to know the parameters of UV radiation. Among these parameters, the decline in UV flux [18] over the service life and the predicted burning duration, during which the lamps can operate while maintaining the necessary level of UV irradiation [19], should be noted. This consideration takes into account sensitivity [20] and the hazards associated with ultraviolet lamps [21, 22].

Useful service life [6] is the period during which the radiant flux of the lamp, under specific power and operational conditions, does not decrease below a set level, such as 60%, 70%, or 80% of the initial value.

During the service life of lamps, a decrease in ultraviolet radiation flux occurs due to the oxidation of mercury in the lamp and the deposition of reaction products on the inner surface of the bulb, reducing the transparency of the glass under the influence of UV radiation and other factors [23].

Recommended Method for Predicting Service Life Based on Flux Decay The recommended method for predicting service life based on the decline of radiant flux involves fitting an empirical exponential function to describe the obtained data on flux decay separately for each testing condition. Further extrapolation of this fitted function to the point in time where the radiant flux decreases to a minimally acceptable level (e.g., 70% of the initial value) allows for the estimation of the useful service life of ultraviolet lamps.

Based on the flux values $F_1, F_2 \dots F_m$ obtained through measurements at the time $t_1, t_2 \dots t_m$ it is necessary to select a function $F = F(t)$, which describes the process not only within the time interval (t_1, t_m) but also beyond it (at points $t_{m+1}, t_{m+2} \dots t_{m+m}$). The accuracy of flux estimation depends significantly on the selection of the empirical function. The form of the function can be approximated by placing measurement data in a Cartesian coordinate system and connecting them with a smooth curve, then comparing the obtained curve with the graph of an already known function.

Using computer programs, coefficients for several types of empirical formulas can be found simultaneously, and the calculated values can be compared with measurement data. This necessitates the development of algorithms for calculating these coefficients. The method of least squares has found the most application (with relatively straightforward calculations) in this context.

In processing measurement results and identifying the functional dependence between parameters, it is essential to calculate the root mean square deviation σ, the deviation at each point ε_i, and the relative error between measurements and calculated data. The magnitude of the root mean square deviation indicates the proximity of the experimental and calculated points, while the signs of deviations provide information about the placement of experimental and calculated points relative to the graph of empirical functions.

Processing experimental data to identify the law of radiant flux decay is expediently carried out based on the results of completed studies. The selection of a function is made both by the magnitude of the root mean square deviation and the value of the relative error at the measured points.

After choosing the function, the question arises about establishing a history, i.e., determining the number of measurement points of radiant flux during the lamp burning process on which the trend will be built. Generally, the longer the history, the more accurate the forecast.

As an example of predicting the useful service life based on the decay of radiant flux, methodologies for LED modules can be considered [6, 24]. In this case, the service life is defined as the period during which the light source emits a specified radiant flux. The recommended method for predicting useful service life based on radiant flux decay involves fitting an empirical exponential curve to describe the obtained data on radiant flux decay for each testing condition.

Experimental data used for the described extrapolation are initially normalized to unity (100%) at 0 hours of burning for each sample within the given sample set, and then averaged at each point of radiant flux decay measurements.

Further extrapolation of this fitted function to the point in time where the radiant flux decreases to a certain acceptable level (e.g., 80%, 70%, or 60% of the initial flux) allows for the estimation of the useful service life. The fitting of the empirical exponential curve of radiant flux decay over time has a general form:

(1) $$F(t) = B\,exp(-\alpha t),$$

the determination of the initial constant B and the rate constant of radiant flux decay α is performed using the least squares method. After calculating the constants B and α, the sought value of the burning duration (service lifeservice life τ_p) during which the reduction to the specified level of radiant flux occurs is computed from the expression:

(2) $$\tau_p = \frac{ln\left(100 \cdot \frac{B}{p}\right)}{\alpha}$$

where p is a specified level from the initial radiant flux.

Thus, with the recommended level $p = 0{,}7$ from the initial flux, we have:

(3) $$\tau_{70} = \frac{ln\left(100 \cdot \frac{B}{0{,}7}\right)}{\alpha}$$

The least squares method is applied as follows: taking the logarithm of both sides of the relation (1), we obtain:

(4) $$ln\,F(t) = ln\,B\,exp(-\alpha t)$$

Denoting $ln\,F(t) = y$, $-\alpha = m$ and $b = ln\,B$ and we get the equation of a straight line:

(5) $$y = mx + b$$

For a set of n experimental points on the graph (x_1, y_1), (x_2, y_2),…,(x_n, y_n) the least squares method for the constants m and b yields:

(6) $$m = \frac{n\sum xy - \sum x \sum y}{n\sum x^2 - (\sum x)^2}$$

(7) $$b = \frac{\sum y - m\sum x}{n}$$

where n is the total number of averaged experimental points denotes summation over the range of $x_k = t_k$, $y_k = ln\,F_k$, $k = 1,2 \dots n$.

Performing the necessary calculations we find the values of $B = exp\,b$ and $\alpha = -m$.

Materials and methods of research

The aim of the work is to experimentally determine the decay of radiant flux in low-pressure mercury discharge lamps during operation and select a mathematical model for predicting the useful service life of these lamps.

The investigation involved low-pressure discharge lamps with a power of 20 watts, type ZW20D15W(Y). Lamp testing was conducted at a supply voltage of 220V, in a mode of 8 switches per day for 15 minutes each.

Measurements of ultraviolet flux in the UV-C wavelength range were carried out using a radiometer for ultraviolet radiant energy after 100 hours, 500 hours, and subsequently every 500 hours up to 6000 hours.

For each of the samples, the final radiant flux was divided by the initial flux. The average value of all tested samples was determined, and the average value of the radiative flux conservation coefficient (RFCC) was calculated. The mathematical model was constructed using the method of mathematical extrapolation.

Results of the research

We conducted studies on the radiant flux conservation coefficient during the operation of a batch of 20W lamps, consisting of 10 units. The radiant flux was measured after 100 hours, 500 hours, and subsequently every 500 hours up to 6000 hours.

The lamp parameters during the measurement of the radiant flux were stabilized - the supply voltage during the flux measurement was maintained with an accuracy of ±2%. The measurement results of RFCC and the calculation results are presented in Table 1.

The forecasted useful service life of the investigated UV lamps based on the stability of the radiant flux to the level of 0.6 of the initial value is 12500 hours, to the level of 0.7 is 8250 hours, and correspondingly to the level of 0.8 is 4600 hours.

Calculations were performed based on measurements up to 3000 hours. To assess the accuracy of the forecast, testing was extended to 6000 hours, and the relative error of the forecast from the experimental data at measurement points was evaluated. The error did not exceed ±3%.

Table 1. Results of radiant flux measurements and calculations when fitting the empirical curve using the least squares method

Time, hours	Radiant flux, relative unit	$ln\,F\,(t)$	*x*	*y*	*xy*	x^2
100	1					
500	0,97	-0,0305	500	-0,03	-15,3	250000
1000	0,93	-0,0726	1000	-0,07	-72,6	1000000
1500	0,92	-0,0834	1500	-0,08	-125,1	2250000
2000	0,90	-0,1054	2000	-0,11	-210,8	4000000
2500	0,88	-0,1278	2500	-0,13	-319,5	6250000
3000	0,86	-0,1508	3000	-0,15	-452,4	9000000
3500	0,85	-0,1625	3500	-0,16	-568,8	12250000
4000	0,82	-0,1985	4000	-0,20	-794,0	16000000
5000	0,79	-0,2357	5000	-0,24	-1178,5	25000000
6000	0,75	-0,2877	6000	-0,29	-1726,2	36000000
α	A constant rate of radiant flux reduction					0,0000366
B	Predicted initial constant					0,9469585
τ_{60}	The calculated value of the service life L_{60} (hours)					12467,9
τ_{70}	The calculated value of the service life L_{70} (hours)					8256,15
τ_{80}	The calculated value of the service life L_{80} (hours)					4607,75

Conclusion

The described mathematical model predicts the useful service life of ultraviolet lamps based on the stability of radiant flux. This method allows for estimating the useful service life of low-pressure ultraviolet lamps based on the results of tests for the decline in radiant flux caused by material degradation during lamp operation.

The useful service life of UV lamps in the UV-C spectrum range can be assessed through incomplete tests after 2500-3000 hours, with a precision of up to ±3% in measuring the decline in radiant flux. The useful service life (with a decrease in radiant flux to 70% of the initial value) for the investigated lamps is estimated at 8.25 thousand hours. The useful service life (with a decrease in radiant flux to 80% of the initial value) for the investigated lamps is estimated at 4.6 thousand hours.

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