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# TECHNICAL REPORT

## Unified fluorescent lamp dimming standard calculations



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IEC 62750, which is a technical report, has been prepared by subcommittee 34A: Lamps, of IEC technical committee 34: Lamps and related equipment.

The text of this technical report is based on the following documents:

| Enquiry draft | Report on voting |
|---|---|
| 34A/1511/DTR | 34A/1546/RVC |

Full information on the voting for the approval of this technical report can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

The committee has decided that the contents of this publication will remain unchanged until the stability date indicated on the IEC web site under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

A bilingual version of this publication may be issued at a later date.

# UNIFIED FLUORESCENT LAMP DIMMING STANDARD CALCULATIONS

## 1 Scope

This Technical Report applies to fluorescent lamp dimming systems. It deals with the interface of fluorescent lamps and dimming electronic controlgear. A unified framework for standardization of fluorescent lamp dimming systems and the associated parameter calculation method are described in this Technical Report.

Dimming of fluorescent lamps is becoming increasingly important as a strategy for conserving global energy resources. This report is the result of many years of effort by global experts to understand and test fluorescent dimming systems with the objective of standardizing these systems to grow confidence and reliability in the marketplace. Two theoretical frameworks have been merged to create this unified dimming standardization method: the SoS (sum of squares of lead-in-wire currents) and CV (cathode voltage) models. The application of dimming to actual fluorescent lamp and electronic controlgear (ECG) systems is the primary concern for reliability in the application and end-user confidence. Characteristics of the dimming parameter limits described in this report and observed in real system applications such as in situ field diagnostics are offered as informative. The practical need to use substitution resistors for ECG qualification is described in this report and also given as normative parameters in the lamp and ECG standards. No attempt to treat the informative real lamp-ECG system parameters as normative will be made in either the lamp or the controlgear standards.



## 2 Explanation of the dimming requirements

### 2.1 General

This clause gives a general explanation of the dimming requirements found in the fluorescent lamp and controlgear standards. Subclause 2.2 provides an overview of the theoretical framework for the unified dimming standard. Subclause 2.3 provides an explanation of informative limits for the cathode heating based on physical lamp and ECG systems. Subclause 2.4 provides the basis for normative controlgear qualification using substitution resistors. In this Technical Report, the use of primed quantities will signify values obtained when measuring on actual fluorescent lamp and ECG systems. Unprimed quantities refer to standardised quantities when testing ECG on substitution resistors. Although lead wire and lamp discharge currents pertain to actual lamps, they will remain unprimed quantities in this report.

### 2.2 Additional heating

It is a well-known fact that, when lowering the lamp current to decrease the luminous flux (dimming) below a certain current value, the cathode is not heated sufficiently any more by the lamp current. At these dimmed conditions without added ohmic heating, the cathode fall will increase to sustain the lamp current and this results in an increased sputtering of the cathode and thereby a decrease in lamp life. So additional cathode heating is necessary to keep the cathode at a sufficiently high temperature for thermionic emission. The amount of this additional heating current through the cathodes as a function of the lamp current is however dependent on the controlgear circuit layout. There may be a phase shift between these currents like in circuits with a capacitor parallel to the lamp. In other circuits, the additional heating current is delivered by separate heating sources, in which case it is not clear through which lead-in wire which part of the lamp current flows. For a generalized description, these different circuits are included when describing the controlgear requirements.

It has been found that measuring the root mean square (r.m.s.) currents through the two lead-in wires to the cathode and calculating the sum of the mean squares of these two currents as a function of the discharge current can estimate the cathode heating. The sum of squares, *SoS*', needed to keep the cathode at a sufficient temperature, is found to have a linear dependence on the root mean square (r.m.s.) discharge current:

$$SoS' = I^2_{LH} + I^2_{LL} = X'_1 - Y'_1 \times I_D$$

where

$I_D$ is the discharge current;

$I_{LH}$ is $I$ lead high, which is the highest current through either lead-in wire;

$I_{LL}$ is $I$ lead low, which is the lowest current through either lead-in wire.

Alternatively, it has also been found that it is possible to describe cathode heating in terms of root mean square (r.m.s.) voltage applied across the cathode, *CV*', while dimming. To a reasonable approximation in the deep dimming range, the voltage necessary to keep the cathode at a sufficient temperature is also a linear function of the root mean square (r.m.s.) discharge current,

$$CV' = X'_3 - Y'_3 \times I_D,$$

where the coefficients $X'_3$ and $Y'_3$ are constants, different from $X'_1$ and $Y'_1$ in the *SoS*' expression.



The dimming range of discharge currents for which additional heating is necessary is given by a maximum value, $I_{Dtrans}$, which defines the transition between normal and dimming operation, and a minimum value, $I_{Dmin}$, specified in the lamp standard. These values are expressed relative to the cathode test current, $I_{test}$, designated in the relevant IEC datasheets. This cathode test current is defined in the relevant IEC standard as the current to be applied when measuring the cathode hot resistance. An indirect measure related to the overall cathode temperature is the ratio, $R_h/R_c$, where $R_h$ is the "hot" resistance during operation and $R_c$ is the "cold" resistance at 25 °C. For a nominally performing filament, the measured hot resistance will usually correspond to a hot-to-cold resistance ratio, $R_h/R_c$, of 4,75. The range of discharge currents, $I_{Dmin} \leq I_D \leq I_{Dtrans}$, specified for dimming is typically ~10 % of $I_{test} \leq I_D \leq$ ~80 % of $I_{test}$ for many lamp designs[1]. For discharge currents above the dimming range, $I_D \geq I_{Dtrans}$, additional cathode heating is not required, but not forbidden as long as the value for the maximum current in any lead, $I_{LHmax}$, is observed. Explicit values for the dimming range of discharge current and cathode test current are specified in the lamp datasheets.



## 2.3 Cathode heating limits

The SoS model is developed from assumptions about the cathode hot spot. This is the location where the discharge arc attaches to the electron-emitting region of the cathode. As the discharge current is lowered into the dimming region, a hot spot remains localized until the lamp current is lowered below $I_{D30}$, approximately 30 % of $I_{test}$. In this region of dimming where the lamp current is greater than or equal to $I_{D30}$, values for the critical "minimum SoS" ($SoS'_{min}$) are set to prevent cathode sputtering and the resulting short lamp life.

At low dimming currents, the discharge attachment becomes diffusely attached to the cathode and the hot spot no longer is localized or stationary. Also, the hot spot tends to lose a well-defined location when high or excessive heating currents are applied to the cathode.

[1] It is important to note that $I_{test}$ is defined as a cathode related current parameter and does not necessarily relate to the lamp discharge current or the dimming range for lamp designs in some regions.

Therefore, at low currents, or to describe the upper boundary of acceptable cathode heating, the $CV'$ becomes a preferred approach to standardizing the cathode-heating requirement. In the region of dimming where the lamp current is lowered below $I_{D30}$, values for the minimum cathode voltage, $CV'_{min}$, are set to prevent premature cathode destruction by sputtering.

Excessive additional heating will result in overheating of the cathode and thereby accelerated end blackening of the lamp. To protect the cathode from overheating, resulting in excessive barium evaporation (end-blackening) and possible mercury starvation in the lamp, a maximum heating level should be set for the cathode voltage. This maximum cathode voltage, $CV'_{max}$, is set to limit the cathode temperature below a temperature typically corresponding to a cathode resistance ratio of $R_h/R_c < 5{,}2$.

The uncoated part of the cathode can be overheated by the combination of high additional heating and the discharge current itself (mainly in the higher dimming region). Setting a maximum, $I_{LHmax}$, to the higher lead-in wire current, $I_{LH}$, will protect these parts of the cathodes.

For controlgear design guidance, a target line $SoS'_{tgt}$ is also defined. It is a best setting for the cathode heating to be sufficiently far away from the critical minimum and maximum.

To summarize, the cathode heating informative limits are given by the following set of criteria uniquely defined over the dimming region of lamp currents. The voltage measured across the leads of each cathode in the system should generally lie above the minimum heating line $CV'_{min}$ and below the maximum heating limit $CV'_{max}$. The measured $SoS$ current values should lie above the minimum line $SoS'_{min}$ and the measured lead-in wire currents shall not exceed the $I_{LHmax}$ limit.



| | | |
|---|---|---|
| Lower limit: | $SoS'_{min}\ [I_{LH}^2 + I_{LL}^2] = X'_1 - Y'_1 \times I_D$ | for $I_{D30} \leq I_D < I_{Dtrans}$ |
| Lower limit: | $CV'_{min} = X'_3 - Y'_3 \times I_D$ | for $I_{Dmin} \leq I_D < I_{D30}$ |
| Upper limit: | $CV'_{max}$, $I_{LHmax}$ | for $I_{Dmin} \leq I_D < I_{Dtrans}$ |
| Target: | $SoS'_{tgt}\ [I_{LH}^2 + I_{LL}^2] = X'_1 - 0{,}3Y'_1 \times I_D$ | |



### 2.4 Substitution resistors for electronic controlgear qualification

For normative ECG testing, the lamp discharge impedance is approximated using substitution resistors, $R_L$, having values ($R_{L10min}$, $R_{L10max}$, $R_{L30}$ and $R_{L60}$) given at 10 %, 30 % and 60 % of the test current, $I_{test}$. Ambient temperature and lamp geometry are known to have a major influence on the lamp impedance. At $I_D = I_{Dmin}$ a minimum, $R_{L10min}$, and maximum value, $R_{L10max}$, of the lamp substitution resistance is specified to allow for a rough approximation of the thermal dependency of the lamp impedance. These resistor values are set at –30 % and + 30 % of the nominal lamp impedance at $I_D = I_{Dmin}$. At $I_D$ = 30 % ($I_{D30}$) and 60 % ($I_{D60}$) of $I_{test}$, the nominal value of the lamp impedance is specified for the substitution resistance value. These discharge current values have been chosen in the dimmed region where proper setting of electrode heating is important for reliable lamp operation throughout the rated lamp life. To summarize the lamp discharge substitution resistor set, the following abbreviations are used:

- low impedance discharge at $I_{Dmin}$: $R_{L10min}$;
- high impedance discharge at $I_{Dmin}$: $R_{L10max}$;
- discharge impedance at $I_{D30}$: $R_{L30}$;
- discharge impedance at $I_{D60}$: $R_{L60}$.

For any ECG that does not operate with a continuous range of dimming current (e.g. step dimming controlgear), the lamp substitution resistor is selected to approximate the lamp discharge impedance. This impedance approximation uses linear interpolations for $R_{Lmin}$ from $R_{L10min}$ to $R_{L30}$, $R_{Lmax}$ from $R_{L10max}$ to $R_{L30}$, and $R_L$ from $R_{L30}$ to $R_{L60}$ for the range of lamp discharge current from $I_{Dmin} \le I_D < I_{Dtrans}$ in this report,

$$R_L = \frac{(R_{L60} - R_{L30})}{(I_{D60} - I_{D30})} \cdot (I_D - I_{D30}) + R_{L30} \qquad \text{for } I_{D30} < I_D < I_{Dtrans}$$

$$R_{Lmin} = \frac{(R_{L10min} - R_{L30})}{(I_{Dmin} - I_{D30})} \cdot (I_D - I_{D30}) + R_{L30} \qquad \text{for } I_{Dmin} \le I_D < I_{D30}$$

$$R_{Lmax} = \frac{(R_{L10max} - R_{L30})}{(I_{Dmin} - I_{D30})} \cdot (I_D - I_{D30}) + R_{L30} \qquad \text{for } I_{Dmin} \le I_D < I_{D30}$$

The selected resistor shall have a resistance value within 20 % of the calculated $R_{Lmin}$, $R_{Lmax}$, or $R_L$ value for the lamp operating current of the ECG under test. For normative ECG, qualification test conditions are specified in IEC 60929.

In addition, the cathode impedance is approximated with substitution resistors. Since the heating characteristics of resistors $P \sim V^2$ or $P \sim I^2$, differ significantly from actual cathodes, $P \sim V^{1,4}$ or $P \sim I^{3,2}$, three substitution resistance values, $R_{test1}$, $R_{test2}$, and $R_{test3}$, are given for each cathode for controlgear qualification tests. The $R_{test1}$ value, chosen to account for typical cathode impedance variation and provide most cathodes with moderate auxiliary heating $R_h/R_c \ge 4,3$ is used when testing the lower cathode-heating limit, $SoS_{min}$. The $R_{test1}$ value is approximately equal to 4,6 $R_c$ for typical T5 cathodes. Nevertheless, as a rule of thumb, $R_{test1}$ should be chosen on the order of 4,75 $R_c$. Note that, due to the selection of $R_{test1}$ values exceeding the typical cathode impedance, values for cathode heating limits will differ from the informative physical lamp-ECG system values when qualifying ECG on substitution resistors. The $R_{test2}$ value, chosen to approximate the cathode impedance with a high level of auxiliary heating $R_h/R_c$~5,2, is used when testing the upper cathode-heating limit, $CV_{max}$ and $I_{LHmax}$. The $R_{test3}$ value is chosen to approximate the typical cathode impedance when heated only with auxiliary current to a temperature corresponding to $R_h/R_c$~4,3. The $R_{test3}$ substitution resistor is used when testing ECG for the lower cathode heating limit, $CV_{min}$, at the deepest dimming lamp currents that provide only negligible heating from the discharge current. This selection of $R_{test3}$ is the most accurate representation of the typical cathode at the deep dimming current and therefore provides a robust test of ECG that may use different cathode heating circuit topologies.



The normative qualification of ECG is specified only at the values of cathode substitution resistances defined above, not continuously along the lamp current dimming curve. Related to these values, a test procedure and a test circuit are given in the performance standard for electronic controlgear, IEC 60929.

## 3 Determination of limit values

### 3.1 General

This clause provides the details by which the limit values for *SoS* and *CV* are determined. It is important to keep in mind that the lamp discharge and cathode substitution resistor values as well as the limit criteria for normative testing of ECG are negotiated quantities. The values are set taking typical sources of cathode and lamp variation into account to provide reliable dimming for compliant ECG operating in real systems. When developing normative limits for the unified dimming standard, special care is taken to match the auxiliary heat delivered to a typical cathode at $I_{D30}$ by the $SoS'_{min}$ and $CV'_{min}$ informative limit lines for the lamp and controlgear system. A discontinuity in delivered auxiliary heat between these cathode heating limit lines should be avoided for practical system design. Due to the selection criteria of substitution resistors for controlgear qualification (see 2.4) comparisons of the normative quantities ($SoS_{min}$, $CV_{min}$ and $CV_{max}$) with informative quantities ($SoS'_{min}$, $CV'_{min}$ and $CV'_{max}$) will result in apparent discontinuities. This clause is divided into three subclauses. Subclause 3.2 explains the derivation of the minimum *SoS* limits. Subclauses 3.3 and 3.4 describe the procedure for setting minimum and maximum *CV* limits respectively. Each description builds from practical limits for the cathode heating based on physical lamp and ECG systems to explain how the normative limits are determined for ECG qualification using substitution resistors.

## 3.2 Minimum sum-of-squares – $SoS_{min}$ ($I_{D30} \le I_D < I_{Dtrans}$)

Establishment of minimum auxiliary heating limits in the hot spot region begins with the parametric values for the sum-of-squares (SoS) model. In this model, the values for the lamp current range, $I_{D30} \le I_D < I_{Dtrans}$, and for the SoS constants are coupled to the cathode test current, $I_{test}$, at which a cathode reaches a specified resistance and temperature, given by $R_h/R_c$~4,75. These parametric values were determined through examination of reliability testing data and are considered applicable to many lamp designs. Table 1 gives approximate mathematical expressions for these parameters.

**Table 1 – SoS parametric values**

| | | |
|---|---|---|
| Minimum dimming discharge current, $I_{Dmin}$ | | ≈ 0,1 $I_{test}$ |
| Maximum dimming discharge current, $I_{Dtrans}$ | | ≈ 0,8 $I_{test}$ |
| Lower limit of auxiliary heating | $SoS_{min}$: $I_{LH}^2 + I_{LL}^2 = X_1 - Y_1 \times I_D$ | $X_1 \approx 1{,}8\ I^2_{test}$, $Y_1 \approx 1{,}85\ I_{test}$ |
| Target | $SoS_{tgt}$: $I_{LH}^2 + I_{LL}^2 = X_1 - 0{,}3\ Y_1 \times I_D$ | $X_1 \approx 1{,}8\ I^2_{test}$, $Y_1 \approx 1{,}85\ I_{test}$ |



### 3.2.1 Lamp and electronic controlgear systems – $SoS'_{min}$

Since dimming operation is intended for actual physical lamps on ECG, system cathode heating limits for $SoS'_{min}$: $I_{LH}^2 + I_{LL}^2 = X'_1 - Y'_1 \times I_D$ over the dimming range above $I_{D30}$ are desired for informative purposes. The selection of the cathode substitution resistor, $R_{test1}$, sets the cathode heating normative ECG requirement in the SoS model. As noted in 2.4, the selection of $R_{test1}$ to account for cathode resistance variation results in differences between the normative *SoS* heating limit and the heating of actual cathodes in lamps operating on the same ECG. Values for the coefficients $X'_1$ and $Y'_1$ are determined through a transformation from the substitution resistor network to the lamp-ECG system. Since the auxiliary heat delivered to the cathode is the fundamental parameter that maintains thermionic emission under dimming conditions (see 2.2), it will be maintained invariant in the transformation. To carry out this transformation, it is important to know the characteristics of typical cathodes. A maximum lead wire resistance, $R_{LW}$, is specified in the lamp standard datasheets to minimize the biasing effect on the delivered auxiliary heat. Therefore, lead wire resistance is considered negligible for this calculation. The following is a detailed description of the transformation.

In the SoS model, the lead wire currents, $I_{11}$, $I_{12}$, $I_{21}$ and $I_{22}$, consist of two components: the auxiliary heating current and the lamp discharge current that also contributes to the heating of the cathode. Similarly for the fundamental test circuit (see Figure 1) that simulates lamp conditions using substitution resistors and is specified for ECG qualification, the total heat delivered to the cathode substitution resistor, $R_{test1}$, is considered to have two components: the auxiliary heat and the lamp discharge current heat.