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Citation for published version:
Collin, A, Djokic, S, Drapela, J, Langella, R & Testa, A 2019, 'Light Flicker and Power Factor Labels for Comparing LED Lamp Performance', *IEEE Transactions on Industry Applications*.
https://doi.org/10.1109/TIA.2019.2919643

Digital Object Identifier (DOI):
10.1109/TIA.2019.2919643

Link:
Link to publication record in Edinburgh Research Explorer

Document Version:
Peer reviewed version

Published In:
IEEE Transactions on Industry Applications

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Download date: 08. May. 2024

Light Flicker and Power Factor Labels for Comparing LED Lamp Performance

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***Abstract*-- According to current energy efficiency labels, the majority of LED lamps on the market are considered as highly efficient devices. This makes it difficult to distinguish between lamps with different operational characteristics and performance. This paper introduces a comprehensive experimental-based labelling methodology for comparing LED lamp performance with reference to two additional important characteristics: light flicker and power factor. The new labelling methodology reveals that there is high diversity between different LED lamps with different circuit topologies but also for a given topology with different design choices. General consumers and design engineers can benefit from the simple and clear information presented by the set of comparative labels when comparing LED lamp performance.**

***Index Terms*-- Efficiency, labeling, LED lamps, light flicker, power factor, power quality, power system harmonics, testing.**

I. INTRODUCTION

LIGHT-EMITTING DIODE (LED) lamps offer several advantages over competing energy efficient lighting technologies. Higher levels of efficiency (i.e. luminous efficacy), improved light regulation, longer lifetime and better light quality have all contributed to the growing market share of LED lamps. This growth has been supported by the communication of these benefits via on-package labelling, which is an important part of the ongoing global effort in improving energy utilization.

The most prevalent performance labels are the energy efficiency labels. These are found on the majority of electrical devices around the world but there are some noticeable differences between different regions in how this information is communicated to the customer. The EU system is a classification-based approach, which assigns all possible values to a specific class [1]. Several countries, including the majority of South America, have adopted an approach based on the EU label system [2]. The EU is currently updating the comparative labels in response to technological developments [3] – [5].

A similar approach is the star classification, implemented in, for example, India, Japan and Australia/New Zealand (5, 5 and 10 Star intervals) [6] - [8]. However, it is not mandatory for lamps in Australia and New Zealand; only the lumen output, the rated power and lifetime are required. In the US and Canada consumption information is displayed using a continuous scale [9, 10]. This is the least direct means of comparison; however, these countries, along with many others, utilize the Energy Star system to denote that a device satisfies a minimum level of performance with a binary approach [11].

The purpose of these labels can be considered from three perspectives: i) they provide knowledge to general consumers to help them make a more informed choice, ii) they incentivize manufacturers to improve technology and iii) they support lighting system design engineers by providing a standardized set of performance indicators. Although existing labels are effective for comparing efficiency characteristics and some other performance/reliability indicators (expected lifetime, number of switch on/off events etc.), several key characteristics, which reveal the diversity present in modern lamps, are omitted.

This diversity is due to the fact that, unlike incandescent (INC) lamps, energy efficient lamps require a driver circuit to initiate and regulate the light output [12]. In mature technologies, e.g. compact fluorescent lamps (CFLs), there is a high level of similarity in circuit design, resulting in low diversity. However, LED lamps are a newer and still developing technology and can be utilized in a wide range of applications, from replacing INC lamps to the illumination of commercial offices, retail spaces or industrial premises. As the needs and design of the driver circuit can vary between applications, there are currently a large number of different LED driver circuits on the market.

The current LED lamp driver circuits range from simple circuits of only a few components to sophisticated multi-stage power electronic converters. Each driver circuit has specific characteristics in terms of how it interacts with the supply system: both the impact of the device on the supply, e.g. in terms of supply system utilization, and the impact of the supply system on the device, e.g. in terms of the light output. As the impact may be positive, negative or mixed, it is important that this information is readily available to the general consumer or the design engineer, which is currently not the case.

This paper addresses the aforementioned aspects and presents a comprehensive experimental-based labelling methodology to quantify and standardize performance indicators of lighting technology by means of simple comparative labels. The paper extends previous work done by

The authors acknowledge financial support from the Italian Ministry of University and Research (PON03PE-00178-1) and from the National Feasibility Programme I of the Ministry of Education, Youth and Sport of the Czech Republic (LO1210).

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the authors [13]-[14]. The methodology is illustrated by introducing two new labelling indices: one for consumption power factor (PF) and one for light flicker (LF) susceptibility. A LF index (LFI) is proposed using a novel method to measure and quantify LF susceptibility. A PF index (PFI) is introduced to compare high-level power quality characteristics and system utilization. Both LFI and PFI have been developed with respect to industry test procedures, and existing protocols and standards are employed where possible to minimize additional costs.

The benefits of the proposed indices is demonstrated by evaluating the PFI and LFI from measurements of 24 LED lamps from 13 different manufacturers. The set of lamps has been carefully selected to represent the range of LED lamps currently available on the market (covering rated powers from 3-25 W and including integrated and external driver circuits). A summary of the measured lamps is included in Table A.I of the Appendix. To help interpret the PFI and LFI values of the LED lamps they are grouped by driver circuit topology into eight types and it is shown that each type has a distinct PFI and LFI characteristic. The generality of the labelling methodology is demonstrated by comparing the PFI and LFI of LED lamps with other lighting technologies. This wider analysis examines the correlation between the proposed indices, clearly showing how the new labels can support the design of individual lamps and also promote the use of higher quality lighting technologies in residential, commercial and industrial lighting systems.

The rest of the paper is structured as follows: Section II presents an overview of the LED driver circuit classification; Section III describes the proposed labeling methodology; Section IV and V present the PFI and the LFI; the correlation of the indices is discussed in Section VI for LED lamps and other technologies; conclusions are offered in Section VII.

II. LED Driver Classification

LEDs are semiconductor devices that must be supplied from a dc current source. Fed from a public low-voltage network, this can be achieved in many ways. This section introduces five of the most comment driver circuit technologies (based on LED lamps currently available on the EU market), and proposes eight different types of LED driver circuits. Simplified topologies shown overleaf in Fig. 1. Further details of the circuit topologies are available in [12 - 14].

A. Capacitive Divider Circuit

This circuit, defined as Type I, consists of only a few passive components. A diode bridge rectifier (DBR) is utilized to convert the ac line voltage to dc and an electromagnetic interference (EMI) filter is included to suppress the conduction of high frequency emissions. These two stages are common to all ac offline LED driver circuits. The feature of this circuit is the combination of two capacitors, which form a capacitive divider to reduce the supply voltage magnitude. A resistor limits the current through the series LED chain. The lack of feedback and the basic principle make the light output very sensitive to supply voltage fluctuations. The capacitive nature results in a current waveform approximately +90° out of phase with the supply voltage.

B. Constant Current Regulator Circuit

This circuit, denoted Type II, incorporates an active dc-dc (aDC/DC) converter - a constant current regulator (CCR) - to stabilize the output current through the series LED chain. The CCR is normally realized as an integrated circuit, and is able to provide a constant current to the LED string over a wide voltage range. As there is some output regulation, even if no energy accumulator is present, the light output of can be less sensitive to supply voltage fluctuations than Type I. As the CCR is fed directly from the DBR, the line current corresponds to the current drawn by the CCR, i.e. the LED chain, suffering by non-conduction angle in each half-period.

C. Offline Switch-mode driver circuit

The full-wave rectifier with smoothing capacitor feeds a dc-dc converter to regulate the voltage across and the current through the LED chain. The dc-dc converter can be implemented with fixed control (Type III) or with feedback (Type IV). In this paper, fixed control is referred to as passive dc-dc (pDC/DC) and feedback as active dc-dc (aDC/DC). In these modes the converters are operating as active or passive switch-mode power supplies (a/pSMPS). As Type III operates with fixed control, it is expected to provide a steady response in terms of LF and PQ. The improved output regulation of Type IV will result in the light output being less sensitive to variations in the supply voltage, but the variable switching frequency will provide a wider spread of power quality responses. The dc link capacitor has to be sufficiently large for suitable control of the output dc voltage ripple. This is similar to the circuit typically found in CFLs and the resulting narrow pulse waveforms of the line currents are comparable.

D. Double-stage Switch-mode Driver Circuit

Double-stage (D-S) topologies are composed of two separate switch-mode dc-dc converters, where each performs a dedicated role. The first converter, starting from the ac side, serves as an active power factor correction (aPFC) unit and a pre-regulator, while the second (the output SMPS) provides load feeding according to the specific requirements. As in the previous case, the output dc-dc converter can be fixed control (Type VII) or with feedback (Type VIII). Due to the use of two dc-dc converters, both types exhibit only a small sensitivity to light flicker. However, the high cost and volume required mean that the D-S topology is presently not considered for household applications, although they are very commonly used in external LED drivers in commercial and industrial applications.

E. Single-stage Switch-mode Driver Circuit

Single-stage (S-S) circuits originate from merging both stages of the D-S together. As such, they usually cannot provide all of the D-S circuit functionalities properly and can offer either better regulation of the ac line current waveform or better regulation of the output to the LED chain, at the expense of the other. Based on this, the design approach can be divided into ‘PF control’ (Type V) and ‘output control’ (Type VI). The output control utilises a passive PFC (pPFC) unit.

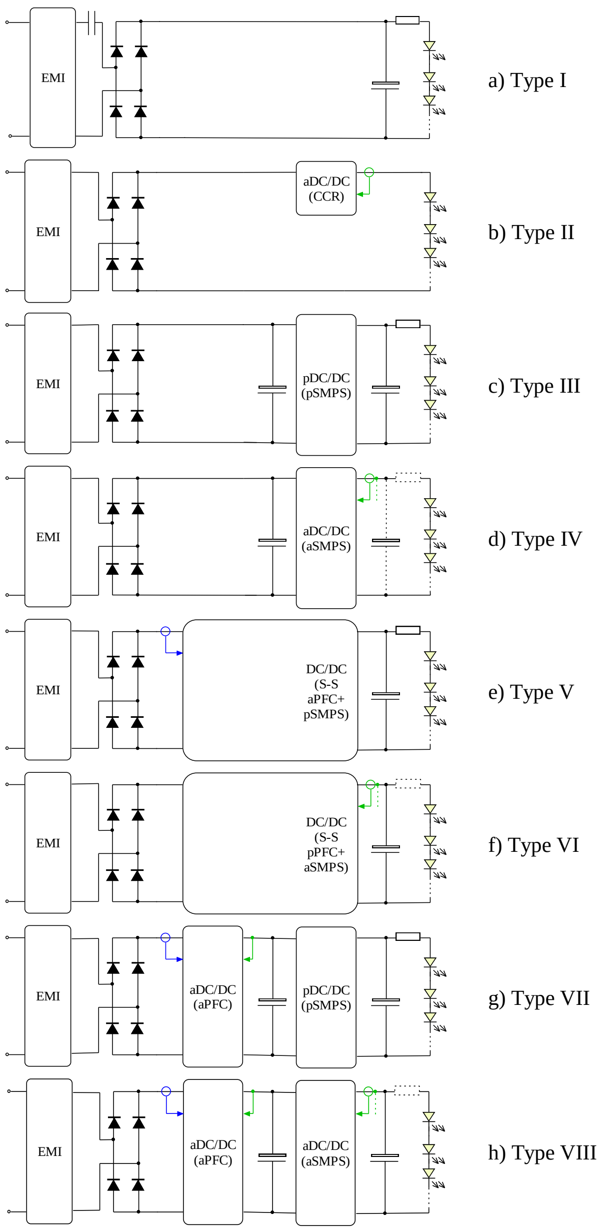


Fig. 1. Typical LED driver topologies and classification.

III. Lamp Performance Labels

The rationale of the methodology applied in this paper is introduced; the methodology is inspired to the energy efficiency indicator for lamps and luminaires applied in the EU [1]. The development of performance labels consists of three stages which define: the index to be classified, a reference condition and the performance class separation. The EU energy efficiency indicator for lamps and luminaires is outlined in Appendix B

1) *Step 1 - Definition of the index to be labeled:* The first step is to identify and define the measureable quantity to be characterized.

2) Step 2 - Definition of reference condition: From a technical perspective, setting the reference value to a minimum acceptable level will produce a natural threshold for the index. Note this need not necessarily be the worst expected performance, but can set a minimum target level of performance. This can be considered analogous to the approach followed by binary label systems, e.g. the Energy Star label.

3) *Step 3 - Definition of entire range and class subdivision:* Once the minimum reference value has been established, a maximum possible operational limit should be defined, thus providing upper and lower boundaries the entire performance range. Following this, the number and division of intervals within the range must be set. If the index is linear then the range intervals can be set accordingly; alternatively, the intervals may be set based on knowledge of the technological trends of the appliance type under consideration. This is the approach of the current EU guidelines, discussed in Appendix B.

IV. Power Factor Labelling

This section first introduces the power factor and its physical significance. The labelling methodology is then applied to define a comparative label, which is applied to the sample of LED lamps measured for this paper.

A. Power factor

The true input power factor referred to in further text simply as the power factor *PF* is determined by calculating the ratio of the active input power *P* and the apparent input power *S* (1):

$$PF = \frac{P}{S} \tag{1}$$

where: the active input power and apparent input power are defined as:

$$P = \frac{1}{kT}\int_{\tau}^{\tau+kT} vi\,dt \tag{2}$$

$$S = V_{rms}I_{rms} \tag{3}$$

where: v, i, V_{rms} and I_{rms} are the instantaneous and rms values of voltage and current.

For a given *S* and *V*, maximum utilization of the line is obtained when *P* is equal to *S*; hence, the ratio is a utilization factor indicator which can be considered as a good physical reference quantity for labelling purposes.

When the total harmonic distortion of the voltage (THD_V) is less than 5 % and it is possible to assume that the total harmonic distortion of the current (THD_I) is greater than 40 %, as is often the case in real world applications, it is convenient to use the approximation in (4) [15]:

$$PF = \frac{P}{S} \cong \frac{PF_1}{\sqrt{1+THD_I^2}} = PF_1 \cdot PF_D \tag{4}$$

where: PF_1 is the fundamental power factor and the term PF_D is used in this paper to refer to the distortion power factor.

This approximation clearly shows that the power factor consists of two components: one related to the phase shift between the voltage and current fundamental, i.e. the fundamental power factor PF_1, and the other caused by the harmonic content. The term PF_D is used in this paper to refer to the distortion power factor when discussing this second component.

The results in Fig. 2 for the LED lamps measured for this paper demonstrate the relationship between power factor PF, displacement power factor PF_1 and current distortion (represented by PF_D). The measurement set-up used is described in [13, 14]. Fig. 2 shows that the majority of the measured LEDs lie close to the case of load with no current harmonics. The lamps with the highest distortion content, i.e. the lower values of PF_D, are all of Type III and IV.

As for measurement of power and testing conditions, the setup from IEC 61000-3-2 can be adopted [16]. Lamps should be tested at rated voltage and the worst case should be considered when the lamp is destined for a range of supply voltages.

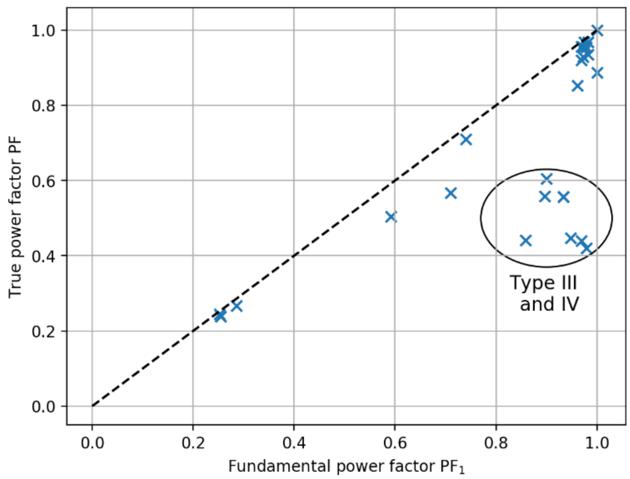


Fig. 2. Power factors of the measured LED lamps. Symbols mark the measured values and the dashed line represents the load characteristic with no distortion.

B. Methodology

1) *Step 1 - Definition of the index to be labeled:* Due to the relationship between harmonic content THD and power factor, the emphasis has been on establishing limits that are simple to assess and that are in keeping with the practices of this industry, e.g. [16]. Accordingly, the PFI can be defined as (5). As discussed in Section III, this converts a measurable quantity with respect to a reference condition PF_{ref}.

$$PFI = \left(2 - \frac{PF}{PF_{ref}}\right).10 \qquad (5)$$

where: the scale factor 10 was introduced for the sake of clarity.

2) *Step 2 - Definition of reference condition*: Several international standards define a minimum performance level for the power factor PF of lamps, directly or even indirectly. A selection of these values is presented in Table I. The minimum power factor PF value will change between regions and also as a function of the lamp rated power. However, in the power range of most interest to LED and future lamp technology, the minimum values range from 0.45 to 0.55. Therefore, a minimum power factor value of 0.5 is taken as the reference condition for PF_{ref}. The power factor PF values are minimum design requirements set by energy efficiency organisations, and that technical legislation may require a lower minimum value, e.g. the minimum power factor PF in the US is 0.5 [17].

Table I also includes, where available, the maximum allowable harmonic limits, expressed in terms of THD. These values are not defined by energy efficiency organisations but by EMC standards.

TABLE I
MINIMUM PERFORMANCE REQUIREMENTS OF TRUE POWER FACTOR AND MAXIMUM HARMONIC LIMITS FOR LED LAMPS

Rated power (W)	Region							
	EU		Australia,NZ		US		India	
	PF (-)	THD (%)	PF (-)	THD (%)	PF (-)	THD (%)	PF (-)	THD (%)
	[18]	[21]	[19]	/	[11]	[17]	[20]	[20]
$P \leq 2$	NL	NL	0.55	/	NL	200	0.9	32
$2 < P \leq 5$	0.45							
$5 < P \leq 25$	0.5	~95 *			0.7			
$P > 25$	0.9	~34 *						

Where: 'NL' = No limit
* calculated from individual limits for harmonics

3) *Step 3 - Definition of entire range and class subdivision:* In order to define the range of the index and the class division therein, a maximum and minimum value must first be quantified. For PF, the maximum theoretical value is 1.0; the corresponding PFI value is 0.0. The minimum allowable PF value, as previously discussed, is 0.5; resulting in a PFI = 10.

The proposed class subdivision is reported in Table II. The boundaries of Class A and Class B, which are indicative of high performance, are 0.95 and 0.9. This aligns with the terminology in [19], with the value of 0.9 taken as the threshold of high performance. The target 0.7 power factor PF value of the US Energy Star creates the boundary between PFI Class D and E, which can be considered the threshold between acceptable and good performance.

TABLE II
POWER FACTOR INDEX CLASSES AND RANGE INTERVALS

Class	PFI range
A	PFI < 1
B	1 ≤ PFI < 2
C	2 ≤ PFI < 4
D	4 ≤ PFI < 6
E	6 ≤ PFI < 10
F	10 ≤ PFI

C. Application to LED lamps

The methodology is applied to the 24 LEDs measured for this work. The results in Fig. 3 demonstrate the spread of the PFI values present in currently available LED lamps and the effectiveness of the proposed index as means of comparison. Overall, with the exception of Type II, the circuits without power factor correction, i.e. Type I, III and IV, perform the worst for this index.

Conversely, the most sophisticated circuits, Type VII and VIII, are both Class A, and therefore, provide the best utilization of the supply network. Although these results may be expected, the PFI also quantifies the extent of variations which can exist in a given circuit type: Type VI can extend from PFI Class A to Class D, inclusive. values of Type I and IV extend beyond the PFI value of 10, which represents the reference condition, indicating that the power factor of these LED lamps is less than 0.5. This performance is considered unacceptable in a number of regions.

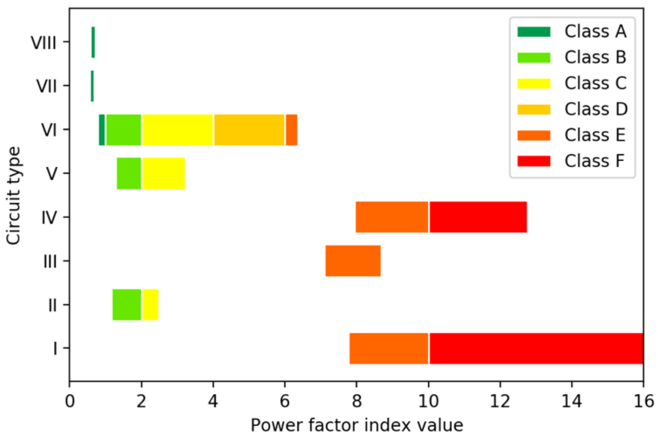


Fig. 3. Calculated power factor index values and classes for the eight circuit types considered.

V. Light Flicker Labelling

A. Light flicker

LF is a well-known directly visible fluctuation of the light intensity produced by light sources in the presence of supply voltage fluctuations. The only standardized measurable quantity on which a proper labelling index can be based on is the LF severity index *Pst* introduced by the IEC only with reference to standard incandescent 60 W lamps in [21] which describes the technical specifications of the Flickermeter. Recently, the so called Light Flickermeter (L-FM), whose specification are contained in the IEC technical report [22], has been recognized as an objective method for testing the sensitivity of any lighting equipment against mains voltage fluctuations generalizing the use of the index *Pst*; the aim of this Techical Report is to allow the lighting industry to gain experience with flicker sensitivity/immunity tests.

In the scientific literature there are three main approaches to quantify and compare the sensitivity of lamps to voltage fluctuations, those based on: i) Gain Factor curves [14, 22, 23, 24, 25]; ii) *Pst* curves for a given voltage fluctuation (e.g. sinusoidal amplitude modulation, SM, or rectangular amplitude modulation, RM) [26] and iii) *Pst* =1 curves (also known as Interharmonic/Flicker curves) [27, 28]. Both approaches ii) and iii) require L-FMs [23, 28] or alternative approaches [29] to be used. GF curves are a very practical and easy to measure tool for lamps classification, but not intended to quantify the LF severity on humans (which is crucial for labelling). On the other hand, *Pst* based approaches are intrinsically able to quantify the human sensitivity and are also able to catch instability phenomena, typically of random nature, related to the control of the lamp and manifested as *Pst* background [30]. Moreover, testing sensitivity by measuring *Pst* under fixed-given disturbance level is significantly faster than finding immunity level, i.e. for which the *Pst* =1 [29]. The next challenge is the selection of the proper test signal(s) to minimize testing burden. Due to natural nonlinearity in lamps' response, a single-shot test signal/ point able to represent real world performance [31, 32] does not exist, therefore more complex testing including a range of test points (test sequence) is required.

For the abovementioned reasons, combined with the authors experience, in this paper, the normalized $\hat{P}_{st}$ measured by means of L-FM and caused by a rectangular modulated supply voltage of fixed magnitude m_{RM} versus the modulation frequency f_m as defined in (6), is used as physical measurable quantity to start the labeling definition:

$$\hat{P}_{st}(f_m) = \frac{P_{st}(f_m)}{m_{RM}}. \qquad (6)$$

Rectangular modulation was selected due to ability of the several interharmonic components, contained in its spectrum, to trigger the lamps' response in a more comprehensive way compared to sinusoidal modulations or even single interharmonic components. The proposed range of modulation frequencies from 0 to the fundamental frequency, f_1. seems to be adequate to reveal lamps' response by voltage components up to 4 f_1, as it is particularly important in networks where Ripple Control Signalling is used [31]. Normalization is introduced in order to unify measure in case of different test disturbance levels. Nevertheless, the modulation depth m_{RM} is recommended to be chosen in the range from 1 % to 3 %V_1.

Fig. 4 shows normalized $\hat{P}_{st}$ curves experimentally measured by an L-FM versus the modulation frequency f_m with modulation depth of m_{RM}=2 %V_1 for a standard incandescent 60 W lamp and for four exemplary lamps from Table A.I of Type I, IV, V and VI. The different sensitivities of the different classes are evident (e.g. ranging from 1 % to 50 % of that corresponding to the incandescent lamp around 10 Hz).

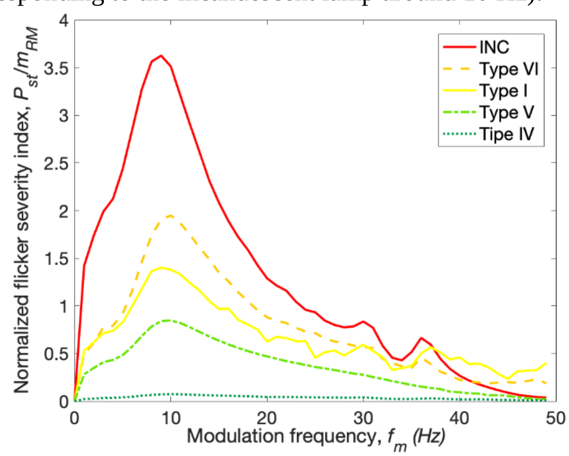


Fig. 4. Normalized light flicker severity index curves experimentally measured by a light flickermeter versus modulation frequency for standard incandescent lamp and for four exemplary lamps from Table A.I belonging to Types I, IV, V and VI. INC is the reference 60 W incandescent lamp.

B. Methodology

1) *Step 1 - Definition of the index to be labeled:* Based on the previous discussion, and in order to have a simple and compact index capable of quantifying the LF sensitivity *LFS* it is possible to refer to (7) which makes use of input data such as those reported in Fig. 4:

$$LFS = \sqrt{\frac{1}{(f_{m,MAX} - f_{m,MIN})} \int_{f_{m,MIN}}^{f_{m,MAX}} \hat{P}_{st}^2(f_m) df_m} \qquad (7)$$

where: $f_{m,MIN}$ and $f_{m,MAX}$ are the minimum and maximum considered modulation frequencies.

Integrating the squares of the test point results $\hat{P}_{st}$ respects the quadratic *Pst* summation rule, and allows a possible variable f_m step to be taken into account. Nevertheless, the f_m step should not exceed 2 Hz, where 1 Hz step was adopted in this paper.

2) *Step 2 - Definition of reference condition:* The reference condition can be obtained applying equation (7) to the standard incandescent lamp. The calculated value LFS_{INC} is then used as a reference value LFS_{ref} to calculate the LFI of the other lamps:

$$LFI = \frac{LFS}{LFS_{ref}} \cdot 10 \tag{8}$$

where: the scale factor 10 was introduced for the sake of clarity.

3) *Step 3 - Definition of entire range and class subdivision:* The range of variation of the LFI goes from the value 0, which represents an ideal flicker free lamp, to a value which is not limited by 10, i.e. incandescent reference lamp LFS_{INC}. Values higher than 10 represent lamps which are more sensitive than reference incandescent, representing excessive sensitivity. The proposed class intervals are shown in Table III.

TABLE III
LIGHT FLICKER INDEX CLASS DEFINITIONS

Class	LFI RANGE
A	LFI < 2
B	2 ≤ LFI < 4
C	4 ≤ LFI < 6
D	6 ≤ LFI < 8
E	8 ≤ LFI < 10
F	10 ≥ LFI

C. Application to LED lamps

Fig. 5 shows the ranges of calculated LFI values, with the corresponding classes, for the set of lamps in Table A.I, for each LED driver type. It is possible to observe that the entire range from 0 to more than 10 is quite well covered. Circuit topologies from Type V to VIII are labeled as A or B showing almost no sensitivity to voltage fluctuations. Types I and II can be labelled from B to F depending on the specific lamp design choices made by the manufacturers for a given topology.

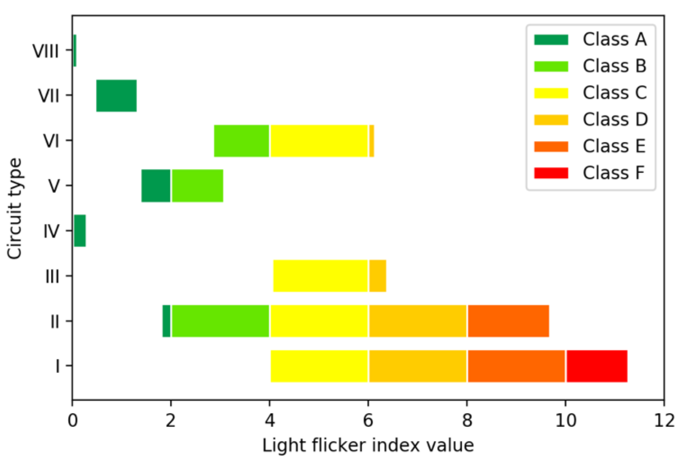


Fig. 5. Calculated light flicker index values and classes for the eight circuit types considered.

VI. CORRELATION BETWEEN LFI AND PFI

This section examines the correlation between the proposed LFI and PFI for LED lamps. A wider analysis also presents LFI and PFI results for alternative light technologies, specifically: incandescent lamps (INC) directly connected to the ac supply voltage, linear fluorescent tubes with electronic ballasts (LFT), extra low voltage halogen incandescent lamps (HIL) fed by an electronic step-down converter and CFLs.

A. Correlation of LFI and PFI for LED lamps

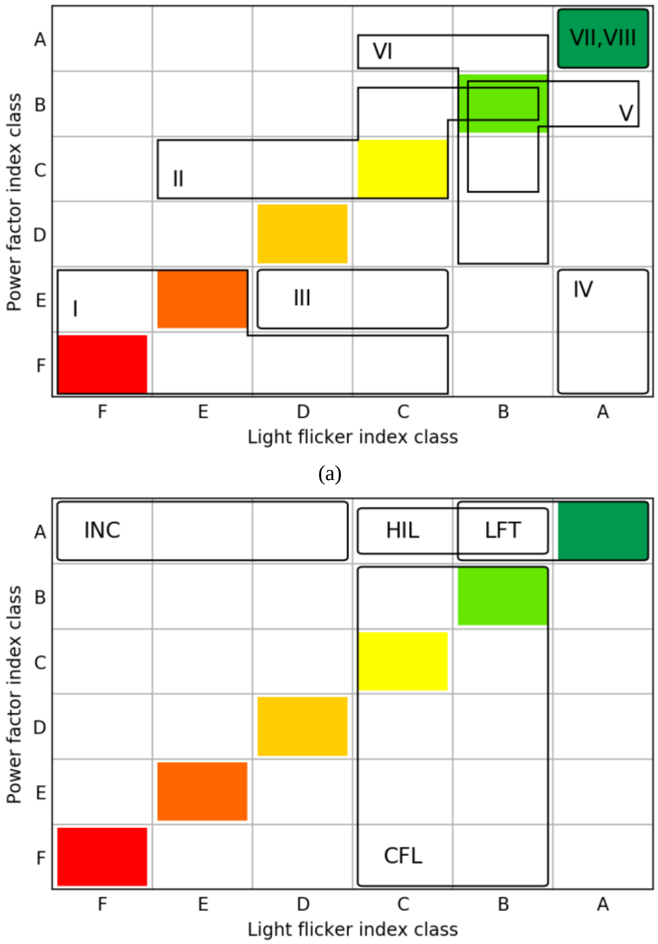
Fig. 6(a) presents the correlation of the LFI and PFI values for the measured lamps. The boundaries have been designed to provide a general representation of the coverage of each individual driver type. From Fig. 6(a) it is possible to observe that:

- Overall, the more sophisticated circuit topologies provide the best solution, as expected.
- Several diagonal elements are populated, suggesting that LF and PF performance are not mutually exclusive;
- Despite the simple circuit design, Type II performs well, and, except for cases where the best LF performance is required, provides advantages over the more sophisticated Type IV, which has a very poor PFI score;
- Type III, IV, VII and VIII show a distinctively clustered response;
- Conversely, the Type I, II, V and VI are distributed over a number of different cells, evidencing the impact of design choices for a given circuit topology on the lamp performance. The ability to capture this variation is one of the benefits of the proposed labelling system, as it encourages the selection of components of suitable value and quality.

B. Correlation of LFI and PFI for other lighting technologies

Fig. 6(b) provides the correlation of LFI and PFI for alternative lighting technologies. As these technologies are more mature it was possible to select two lamps to approximate the total variation of PFI and LFI within a technology. These results are also included in Table A.I of the Appendix using the proposed PFI and LFI classes and ranges. In Fig. 6(b) it is possible to observe that:

- INC are most susceptible to LF, as expected, but have unity PF, and ideal PFI value;
- CFLs offer a moderate improvement over INC in terms of LF but can operate with much lower PF (this is predominantly PFd with THD values exceeding 100%);
- HIL and LFTs are comparable to the best LED technologies, which is a consequence of the external ballast circuits which perform similarly to the S-S and D-S (Type VII and VIII) circuits in LED lamps;
- Generally, the CFL topology is most similar to LED Type III but differences are observed. PFI values overlap, with some increase in the spread in the values of CFL technology if single stage electronic ballast is employed. In that case, the CFL characteristics are close to LED Type VI.



(a)

(b)

Figure 6. Correlation between LFI and PFI, where roman numerals indicate the circuit type: (a) LED lamps (b) alternative lighting technologies, where INC = incandescent; HIL = halogen incandescent lamp, LFT = linear fluorescent tube; and CFL = compact fluorescent lamp.

VII. Conclusions

This paper has presented a methodology to quantify and standardize performance indicators of lighting technology. This fits within existing frameworks and supports global efforts on standardization:

- The light flicker index (LFI) and the power factor index (PFI) present additional information for customers and design engineers in the form of “comparative labels”;
- LFI represents a technology specific index, but the same approach can be applied for other characteristics and for other types of load. The PFI is more widely applicable as all electrical loads can be characterized in this way;
- The indices help to see qualitative differences between LED drivers’ solutions available on market. They are even able to capture variations between different implementations of the same driver Type (e.g. due to component selection). The gives valuable information to customers and designers to control EMC issues in large and small/domestic scales;
- Currently, there a large number of different LED driver circuits and the proposed labels can help promote better technologies as LED driver technology converges.

VIII. Appendix

A. Lamp data

TABLE A.I
Measured Lamp Data: Power Factor Index and Light Flicker Index Values

Lamp		Circuit	PFI		LFI	
Type	id	Type	Value	Class	Value	Class
LED	1	I	8.6	E	10.2	F
LED	2	I	9.9	E	8.0	E
LED	3	I	15.2	F	4.4	C
LED	4	I	14.7	F	5.4	C
LED	5	I	15.1	F	5.6	C
LED	6	II	2.3	C	8.8	D
LED	7	II	1.3	B	2.0	B
LED	8	III	7.9	E	5.8	C
LED	9	IV	11.2	F	0.2	A
LED	10	IV	11.6	F	0.2	A
LED	11	IV	8.8	E	0.1	A
LED	12	IV	11.2	F	~0.0	A
LED	13	IV	8.9	E	0.1	A
LED	14	IV	8.9	E	0.3	A
LED	15	IV	11.1	F	0.3	A
LED	16	V	1.6	B	2.6	B
LED	17	V	2.9	C	2.8	B
LED	18	V	1.4	B	1.5	A
LED	19	VI	0.9	A	4.1	C
LED	20	VI	5.8	D	3.3	B
LED	21	VI	0.9	A	5.6	C
LED	22	VI	0.9	A	3.2	B
LED	23	VII	0.6	A	0.7	A
LED	24	VIII	0.7	A	~0.0	A
INC	1	/	0.0	A	7.2	D
INC	2	/	0.0	A	10	F
HIL	1	/	0.2	A	2.5	B
HIL	2	/	0.2	A	4.1	C
LFT	1	/	0.2	A	0.5	A
LFT	2	/	0.2	A	3.2	B
CFL	1	/	9.8	F	4.4	C
CFL	2	/	1	B	2.8	B

B. EU energy efficiency label approach

The energy efficiency indicator for lamps and luminaires applied in the EU is here outlined using the three steps methodology introduce in Section III.

1) *Step 1 - Definition of the index to be labeled:* In [1], an energy efficiency index (EEI) is defined as (A.1). This is effectively the power of the lamp P scaled by a factor α and normalised by a reference condition P_{ref}:

$$EEI = \frac{\alpha P}{P_{ref}} \tag{A.1}$$

2) *Step 2 - Definition of reference condition:* In (A.1), the general form of the index is normalised by a reference value P_{ref}. In the case of EEI in [1], P_{ref} is the reference power obtained from the useful luminous flux of the lamp Φ_{use} by the following formula:

$$P_{ref} = \begin{cases} 0.88\sqrt{\phi_{use}} + 0.049\sqrt{\phi_{use}} & ,\phi_{use} < 1{,}300\ lm \\ 0.07341\phi_{use} & ,\phi_{use} \geq 1{,}300\ lm \end{cases} \tag{A.2}$$

3) Step 3 - Definition of entire range and class subdivision: The ranges for the EEI in [1] are shown in Table A.II. Table A.II clearly shows that the class separation was formed along technological lines, where the levels for the energy efficiency classes are set in a way that the same technology occupies at least one adjacent bin. This allows some grading and variation even between the same lighting technology. The values in Table A.II also demonstrate the impact of new technology on the definition of classes: as more efficient technologies come online (i.e. LEDs) there is a need to introduce new classes at the top end of performance, i.e. A+ and A++, which can create confusion amongst the target audience.

TABLE A.II
EEI CLASSES FOR LAMPS

Class	EEI	Lamp Type			
		LED	CFL	HIL	GIL
A++	EEI ≤ 0.11	✓			
A+	0.11 < EEI ≤ 0.17	✓			
A	0.17 < EEI ≤ 0.24	✓	✓		
B	0.24 < EEI ≤ 0.60	✓	✓	✓	
C	0.60 < EEI ≤ 0.80			✓	
D	0.80 < EEI ≤ 0.95			✓	✓
E	EEI > 0.95				✓

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