# Experimental Evaluation and Classification of LED lamps for Light Flicker Sensitivity


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***Abstract*—The paper reports on the experimental evaluation and classification of LED lamps for light flicker sensitivity. After the description of the experimental setup designed for tests, a classification based on the driving circuits is proposed. For each class, the circuit description and the Gain Factor (GF) curves versus interharmonic frequencies are reported. Finally, a comparison of the different GF curves is presented to show the Light Flicker sensitivity of the tested LED lamps.**



***Index Terms*—LED lamps, light flicker, power quality.**


## I. INTRODUCTION

Market trends confirm that light-emitting diode (LED) lamps can be considered a "winning technology" for residential and commercial lighting applications worldwide [1]. In [2], a comprehensive experimental analysis and classification, according to efficiency and power quality (PQ) indices, was conducted for 28 LED lamps (from 13 different manufacturers) available on the EU residential lighting market. Results showed that LED lamps' characteristics differ significantly from other residential light sources (e.g. compact fluorescent lamps, CFLs) which typically have similar electrical characteristics.

Among PQ phenomena, light flicker (LF) is one of the most important for distribution companies due to customer complaints. It is well known that LED lamps (and CFLs) behave differently from incandescent lamps [3]-[7] and that new flickermeters need to be introduced to correctly measure this phenomenon [8].

In this paper, the work done in [2] is completed to include the LF sensitivity of LED lamps. The paper is organised as follows: after the description of the experimental setup, a classification based on the lamp driving circuits is proposed. For each class, the circuit description and the gain factor (GF) curves versus interharmonic frequencies are reported. Finally, a comparison among the different GF curves is reported, to show the LF sensitivity of the tested LED lamps.


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## II. EXPERIMENTAL SET-UP

Experimental activities have been conducted in the laboratories of the Brno University of Technology.

A block diagram of the test system used for the GF curves measurement is shown in Fig.1. The test system hardware consists of a power amplifier 108-AMX from Pacific Power, an analyzer LMG500 from ZES Zimmer, a PXI instrumentation system and a subsystem for lamps response measurement. The PXI-8106 controls the test system processes and sets, via a programmable waveform generator PXI-5421 and 108-AMX amplifier, parameters of the fundamental and interharmonic voltages. The power source output feeds an LED lamp placed in an Ulbrich-type integrating sphere with a diameter of 2.5 m and supply voltage and lamp input current are measured. The radiant power produced by the lamp is sensed by a photo-head (human's eye spectral correction, bandwidth: DC-327 kHz) [9] and its output, which is proportional to the lamp luminous flux, is measured by DAQ PXI-4472 as part of the PXI instrumentation system. Control of the measurement procedure, including the source and analyzer control, data reading from analyzer and spectra evaluation to obtain the GF curves, is provided by a developed software running on the PXI platform.

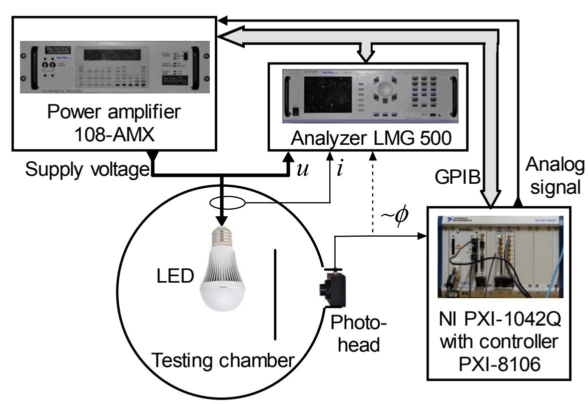



Figure 1. Test system for experimental measurements.

## III. PROPOSED CLASSIFICATION

In [2], four LED lamp categories have been introduced for classification purposes, based on: i) ranges of electrical characteristics; ii) similarity of input ac current waveforms (distinctive waveshape features), and iii) topologies of the electrical circuits.

In this section, these categories are recalled and new sub-categories are introduced to fully characterize the behaviour of the LED lamps in view of the LF performance. For each category and subcategory, the typical circuit and the GF curves are shown, referring to the the lamps whose characteristics are reported in TABLE I.

TABLE I. TESTED LAMPS

| *Type* | *Name* | *$P_{rated}$ (W)* | *Lum. flux (lm)* | *Color Temp. (K)* | *Dimmable (Y/N)* |
|---|---|---|---|---|---|
| A1 | LED J | 10 | 806 | 2700 | N |
| A2 | LED B | 6 | 410 | 3400 | N |
| B | LED 13 [2] | 9 | 806 | 3000 | N |
| C1 | LED 18 [2] | 8 | 1010 | 2700 | Y |
| D1a | LED 27 [2] | 14 | 1055 | 3000 | Y |
| D1b | LED 24 [2] | 15 | 1500 | 6000 | N |

In general, the GF is expressed as a relative change in the output flux level divided by a relative fluctuation in the voltage for a given fluctuation frequency [5] - [7].

In [3], a new concept, called the luminous flux gain factor ($GF_\Phi$) based on the concept of "interharmonic families", was introduced. The $GF_\Phi$ of the luminous flux for a given background interharmonic voltage component superimposed on the fundamental is given by the following equation:

$$GF_\Phi = \frac{\Phi_{h-1}/\Phi_{DC}}{V_{IH}/V_1}, \tag{1}$$

where $\Phi_{h-1}$ is the amplitude of the interharmonic component of the lamp's luminous flux belonging to the VIsible Family [3] $VIF_{h-1}$, $\Phi_{DC}$ is the luminous flux dc component, and $V_{IH}$ and $V_1$ are the background interharmonic and fundamental components of the supply voltage, respectively. The mentioned voltage interharmonic family produces luminous flux components at the following frequencies, intervening visible range (0, 50) Hz:

$$f_\Phi = \left| h \cdot f_1 - 1 \cdot f_{IH} \right|. \tag{2}$$

In tests, a supply voltage with a fundamental component of lamp rated voltage (230 or 240 Vrms, 50 Hz) and an interharmonic component of $V_{IH}/V_1*100$=2% at frequencies from 1 up to 800 Hz (in steps of 1 Hz) was applied to each lamp. All basic principles were respected during the measurements; such as 20 minutes warm-up period of lamp, stabilization in every measurement step, etc. The evaluation procedure to obtain the GF curve can be found in [7]. Finally, it is important to recall that interharmonic voltages are able to produce the same voltage fluctuations caused by pure amplitude modulation [10].

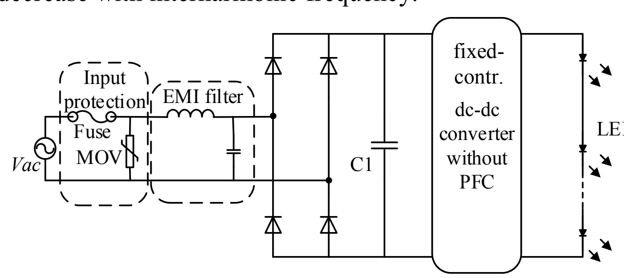
### *A. Type A: Full-wave Rectifier with Smoothing Capacitor and Switch-Mode DC-DC Converter Circuit*

In [2], a first category (Type A), based on a full-wave rectifier with smoothing capacitor ac-dc stage and dc-dc converter circuit (without power factor correction, PFC, circuits) was proposed. This circuit uses a simple full-bridge diode rectifier, dc-link bulk storage capacitor (C1), variable input protection (fuse, resistor, metal-oxide varistor, MOV), input electromagnetic interference (EMI) filter and output switch mode dc-dc converter to set LED string voltage/current. The specific dc-dc converter topology will change based on the application and/or manufacturer.

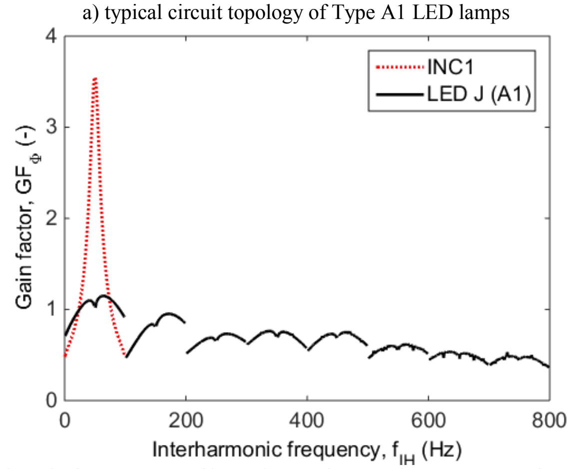
Light Flicker studies require a further subdivision between fixed-control (Type A1) and feedback-controlled (Type A2) dc-dc converters regarding output regulation.

*1) Type A1: Full-wave Rectifier with Smoothing Capacitor and Fixed-control Switch-Mode DC-DC Converter Circuit (without PFC)*

Figs. 2a and 2b show the typical circuit of Type A1 LED lamps and GF curves of the typical 60W incandescent (INC) lamp (red dotted curve) and tested LED lamp versus interharmonic frequency. The response of the Type A1 LED lamps is comparable to that observed in case of a typical screw-base CFL with a built-in electronic ballast [3]. It is possible to observe from Fig. 2b that in the frequency range from 0 to 100 Hz, where the INC lamp produces light flicker, the LED lamp is less sensitive in a limited range around the fundamental frequency, while in the remaining part of the range it is more sensitive. Concerning frequencies over 100 Hz, the GF curves, shaped into characteristic bells, decrease with interharmonic frequency.




a) typical circuit topology of Type A1 LED lamps




b) gain factor curves of incandescent lamp and Type A1 LED lamps

Figure 2. Type A1 LED lamp: Typical circuit topology and GF curves.

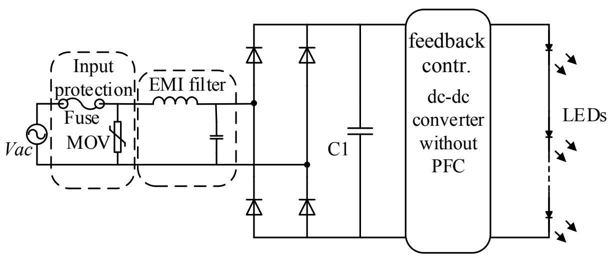
As shown in [3], the shape is determined by the capacity of C1 and the load of the lamp's converter circuit.

*2) Type A2: Full-wave Rectifier with Smoothing Capacitor and Feedback-Controlled Switch-Mode DC-DC Converter Circuit (without PFC)*

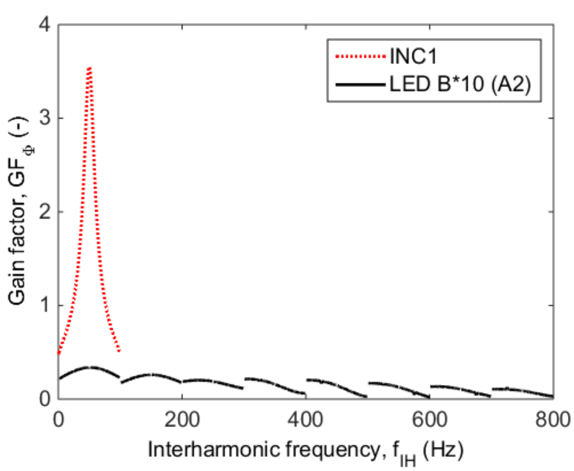
Figs. 3a and 3b show the typical circuit of Type A2 LED lamps and the GF curves of the typical 60W incandescent lamp (red dotted curve) and the tested LED lamp versus interharmonic frequency. The LED B GF curve is multiplied by 10 to make the shape visible.

From Fig. 3b, it is possible to observe that the tested lamp is of very limited sensitivity to produce LF, compared with incandescent lamps. This is due to the active control of the dc-dc converter by means of output feedback loop, which is able to compensate the dc voltage variations due to supply side voltage fluctuations caused by interharmonics.

Even if the bell like shape of GF curve in each doubled harmonic range, due to energy transfer via the dc bulk capacitor, is still present and observable in figure, the strong LF attenuation effect compared to Type A1 is evident, as the LF related sensitivity is about 20 times lower.




a) typical circuit topology of Type A2 LED lamps




b) gain factor curves of incandescent lamp and Type A2 LED lamps

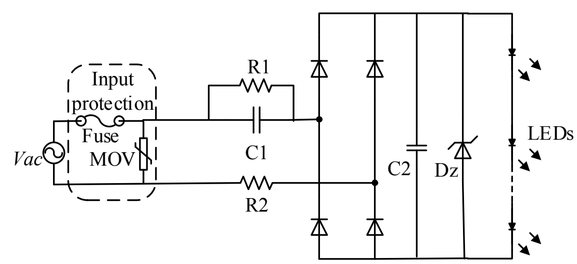
Figure 3. Type A2 LED lamp: Typical circuit topology and gain factor curves.

## B. *Type B: Capacitive Dropper Circuit*

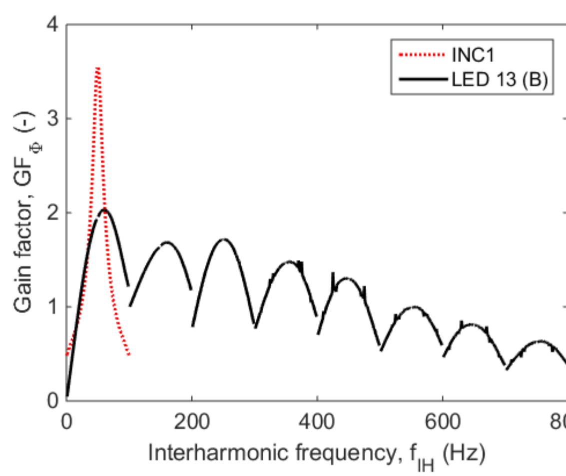
Figs. 4a and 4b show the typical circuit of Type B LED lamps and the GF curves of the typical 60W incandescent lamp (red dotted curve) and of the tested LED lamp versus interharmonic frequency.

Type B lamps are very cheap and produced for the low-end market due their circuit simplicity. The lack of feedback control and the basic principle of a capacitor divider on which the lamp design is based, make this category the most sensitive to voltage fluctuations.

This is evident in Fig. 4b, where it is possible to observe that Type B lamps exhibit characteristics similar to Type A1 lamps. However, the gain is about twice as high. Moreover, in the range from 0 to 100 Hz, it is closer to the gain of the standard incandescent lamp. For frequencies higher than 100 Hz, the sensitivity (GF curve) decreases with frequency.




a) typical circuit topology of Type B LED lamps




b) gain factor of incandescent lamp and Type B LED lamps

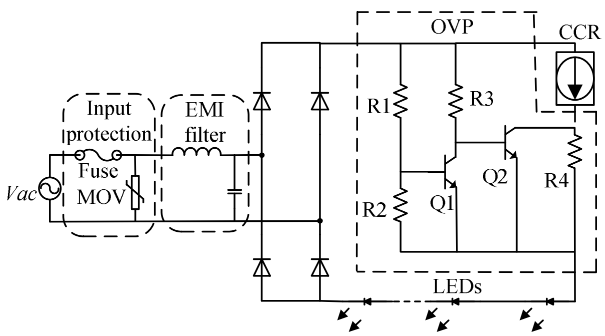
Figure 4. Type B LED lamps: Typical circuit topology and gain factor curves.

*C. Type C: CCR Straight Circuit*

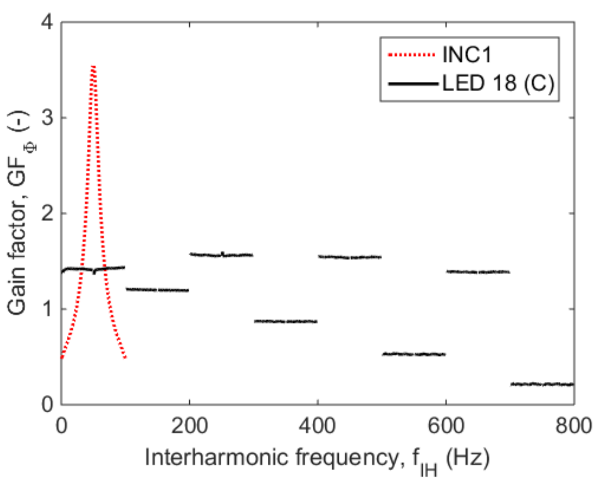
In [2], another category based on a constant current regulator (CCR) circuit was introduced. Light Flicker studies require a further subdivision between linear and discrete CCR (a cascade switching), denoted as Type C1 and Type C2, respectively, but in this paper only results for Type C1 are reported.

*1) Type C1: Linear CCR Straight Circuit*

The linear CCR is a type of a self-biased transistor, maintaining the flowing-through current constant (i.e. CCR) over a wider voltage range, as required to supply the LED string. To avoid damage of the CCR transistor, an overvoltage protection (OVP) circuit is integrated and activated when the CCR voltage is larger than a threshold voltage. In order to achieve the sinusoidally-shaped waveform of ac line current and circuit efficiency, the CCR is typically fed by an ac-dc stage consisting of a full-bridge uncontrolled rectifier with no output (dc side) capacitor. Therefore, the line current corresponds to the current drawn by the CCR, but its conduction range in each half-period of the system frequency is reduced by the CCR - LED string chain bias voltage [2].




a) typical circuit topology of Type C1 LED lamps




b) gain factor of incandescent lamp and Type C1 LED lamps

Figure 5. Type C1 LED lamps: Typical circuit topology and gain factor curves.

Figs. 5a and 5b show the typical circuit of Type C1 LED lamps and the GF curves of the typical 60W incandescent lamp (red dotted curve) and the tested LED lamp versus interharmonic frequency.

It is very interesting to observe that due to the absence of any energy storage (no dc capacitor) the GF (Fig. 5b) remains constant in each frequency sub-range of 100 Hz width (double of supply voltage fundamental frequency) with different values in all frequency sub-ranges. While the GF level of Type C lamps is inversely proportional to the current conduction time, the GF curve scattering is related to the CCR regulation loop response to input voltage fluctuation. As with Type A1 lamps, Type C1 lamps are less sensitive in a limited range around the fundamental frequency when compared to incandescent lamps, but are more sensitive in the remaining part of the range.

*D. Type D: Active Power-Factor-Corrected Single or Multi-Stage Driver Circuit*

In [2], a single category covering all LED lamps utilizing any switch-mode driver circuit with active power factor correction (aPFC) was introduced.

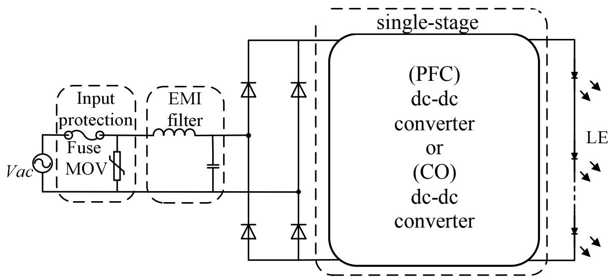
However, study of Type D LED lamp LF performance requires a further subdivision, distinguishing between single-stage (S-S) and double-stage (D-S) topologies, both providing aPFC.

*1) Type D1: Single-Stage Switch-Mode Driver Circuit*

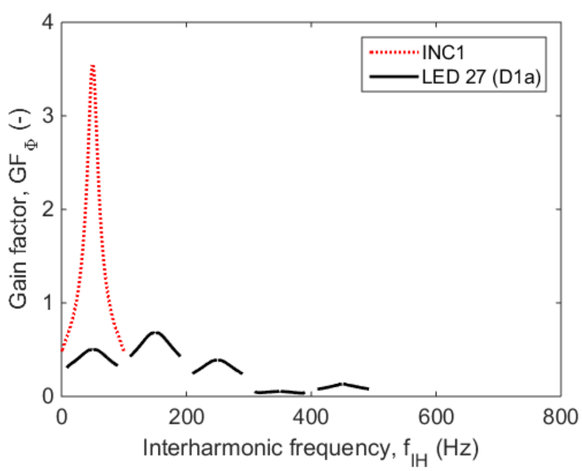
Single-stage aPFC topologies are very common for low power self-ballasted lamps. The typical circuit of Type D1 LED lamps is shown in Fig. 6a. The S-S aPFC circuits originate from D-S topologies composed of two separate switch-mode dc-dc converters, where each performs a dedicated role. The first converter, starting from the ac side, serves as PFC and a pre-regulator, while the second (the output) provides load feeding according to the specific requirements. Merging both together, an S-S circuit is obtained, which usually cannot provide all of the D-S circuit functionalities properly. Therefore, S-S drivers, taking into account applicable topologies, can offer either better ac line current waveform, or better regulation on constant output, but not both. This will have an effect on LF performance. In this view, two separate D1 categories (D1a and D1b), based on the converter control strategy, have to be introduced. Type D1a LED lamps are of "(PFC) aimed" control, while type D1b LED lamps are of "regulation on constant output (CO) aimed" control.

Figs. 6b and 6c show the GF curves of the typical 60W incandescent lamp (red dotted curve) and the tested Type D LED lamp versus interharmonic frequency.

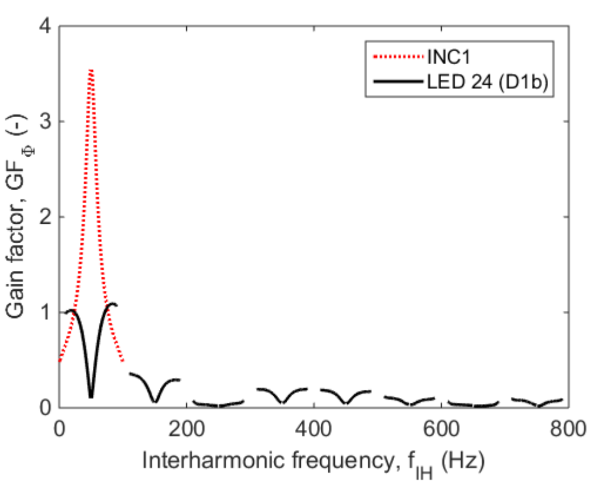
Concerning the GF (Fig. 6b), it is possible to observe that in the frequency range 0-100 Hz the tested lamp belonging to Type D1a is less sensitive to voltage interharmonics, than the incandescent bulb. It can also be seen that the PFC-focused control strategy is characterized by: i) bell shape GF curve segments, connected to the non-driven charging of a dc bulk capacitor (as in the case of Types A and B lamps), which has to be present and is placed in the output stage, and ii) smoothed scattering of the GF curve segments related to the dominant input current control mode, similar to Type C lamps. Compared to Types A1, B and C lamps, the sensitivity of Type D1 lamps to light flicker related to voltage disturbances is reasonably reduced.




a) typical circuit topology of Type D1 LED lamps




b) gain factor of incandescent lamp and Type D1a LED lamps




c) gain factor of incandescent lamp and Type D1b LED lamps

Figure 6. Type D1: Switch-Mode Driver Circuit (with a-PFC) and gain factor curves

As shown in Fig. 6c, Type D1b lamps behave differently. It is possible to observe that in the frequency range from 0 to 100 Hz, where the INC lamp produces light flicker, the LED lamp is, in the relevant range closer to the fundamental frequency, less sensitive. Concerning frequencies over 100 Hz, the GF curve decreases quickly with interharmonic frequency. The change in the GF shape in each segment, compared to the Type D1a lamp, is due to a dominant constant output regulation mode that actively compensates any variation in the output level introduced by input voltage fluctuations.

### 2) *Type D2: Switch-Mode Driver Circuit (double stage)*

The Type D2 double-stage driver circuit topology is very common in the case of external LED drivers and is also employed in electronic ballasts for linear fluorescent lamps, or in high intensity discharge lamps with input power over 25 W. However, the double stage topology is not presently considered in self-ballasted LED lamps for household applications. Therefore, it is out of the paper scope. However, it is important to note that a D-S topology typically performs output stabilization at the first (PFC) stage, or even at both stages, resulting in very small sensitivity of the D-S LED drivers to flicker related voltage disturbances (even lower than of Type A2 lamps), as they provide low distortion of ac line current with very high power factor.

## IV. COMPARISON OF GF CURVES

In order to compare light flicker sensitivity of different lamps, two frequency ranges have been selected. The first frequency range is from dc (0 Hz) to 100 Hz, corresponding to the only range in which incandescent lamps are sensitive to voltage fluctuations and produce LF.

In this frequency range, the GF curves of the tested LED lamps are normalized with reference to the GF curve of the standard incandescent lamp, as shown in Fig. 7.

It is possible to observe that:

- as previously commented, Type A1, Type C and Type D1b LED lamps are more sensitive than standard incandescent lamps symmetrically outside the frequency ranges from 24 Hz to 74 Hz, from 32 Hz to 68 Hz, and from 24 Hz to 74 Hz, respectively;
- Type B LED lamps exhibit a non-symmetrical sensitivity with respect to incandescent lamps, which is mostly lower from dc to 50 Hz and mostly higher from 50 (62) Hz to 100 Hz;
- Types A2 and D1a are less sensitive than incandescent lamps, mainly due to the dc-dc converter control of the driving current of the LED chain.

Concerning the second frequency range, from 100 Hz to 800 Hz, where the GF curve of the incandescent lamps are equal to zero, normalization of GF curves of the tested lamps is not applied, as shown in Fig. 8.

It is possible to observe from Fig. 8 that the sensitivity of different LED lamps depends on the driver type and varies in wide ranges. Particularly, all tested LED lamps, except Type B, are less sensitive than Type C. Type B lamps exhibit higher or lower sensitivity depending on the frequency ranges.

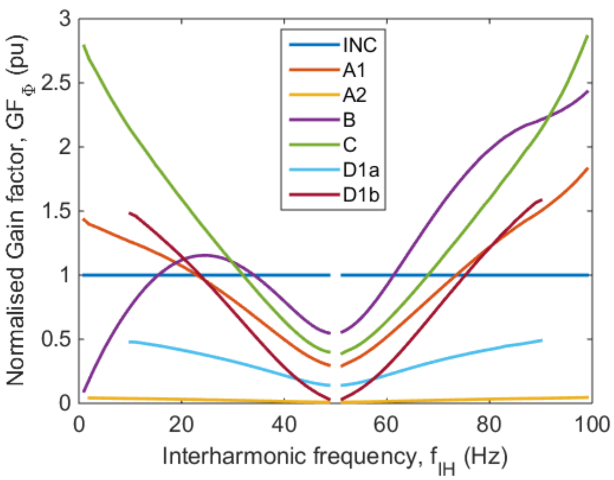



Figure 7. Comparison of GF curves of alltested LED lamps normalized with respect to the incandescent lamp GF in the frequency range [0-100 Hz].

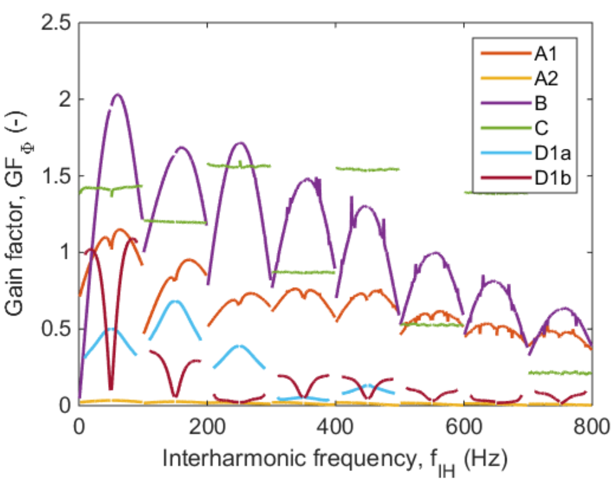



Figure 8. Comparison of GF curves of all tested LED lamps in the frequency range from 1 Hz to 800 Hz.

## V. Conclusions

In this paper, the previous work done by the same authors on the efficiency and PQ characteristics of commercially available LED lamps for residential applications in [2] has been completed to include the LF related sensitivity of LED lamps. After the description of the experimental setup, a classification based on the driving circuits from [2] has been revised and new subcategories of LED lamps are proposed. For each (sub)category, the circuit description and the GF curves versus interharmonic frequencies have been reported. Finally, a comparison between the different GF curves has been reported, to show the ranges of LF sensitivity for all tested LED lamps.

It is clear from the presented results that the rapid development of LED lamp technologies, together with the larger number of producers has resulted in dramatic differences in lamps' LF performances. The main conclusion of the paper is in line with the previous findings from [2], i.e. that LF sensitivity of LED lamps is strongly influenced by the lamp design and the implemented circuit topology. Accordingly, the LED lamp LF performance classification presented in this paper can be combined with the previous classification of LED lamp harmonic emission and operational performance, in order to define a preliminary selection tool for lighting system designers. Furthermore, both the methodology and results presented in this paper can be used for practical evaluation of the actual PQ and flicker performance of different LED lamps. This is the subject of further work by the authors.

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