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Comparison of Measurement-Based Classification Methods of LED Lamps

ELENA GUTIERREZ-BALLESTEROS [1], SARAH K. RÖNNBERG [1] (Senior Member, IEEE), AND AURORA GIL-DE-CASTRO [2] (Senior Member, IEEE)

[1] Electric Power Engineering Group, Luleå University of Technology, 93187 Skellefteå, Sweden
[2] Departamento de Ingeniería Electrónica y de Computadores, Universidad de Córdoba, 14071 Córdoba, Spain
CORRESPONDING AUTHOR: E. GUTIERREZ-BALLESTEROS (elena.gutierrez.ballesteros@ltu.se)

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ABSTRACT The topology of a device will determine the impact said device has on the grid and how immune that device is for disturbances in the grid. LED lamps are very commonly used devices, with different topologies available in the market, each topology showing different behavior when connected to a grid. For power quality studies, it is important to classify LED lamps, without breaking them to know the topology. Several classification methods are found in the literature with this purpose. In this paper, four methods from different papers for classifying LED lamps have been applied to a group of 21 LED lamps with active power consumption below 25 W. It has been observed that the applicability of the methods may lead to a gap of knowledge needed for classification, leaving space for personal criteria when classifying, that can be afforded using unsupervised Machine Learning. Two unsupervised Machine Learning methods were applied using the electrical parameters and statistics proposed in literature.

INDEX TERMS Classification methods, comparison, LED lamps, machine learning, topology.

NOMENCLATURE

aPFC:	Active Power Correction.
CCR:	Constant Current Regulator.
GMM:	Gaussian Mixture Model.
HOS:	High Order Statistics.
LED:	Light Emitting Diode.
ML:	Machine Learning.
nPFC:	Non Power Factor Correction.
PF_1:	Displacement Power Factor.
PF:	True Power Factor.
PFC:	Power Factor Correction.
PF_d:	Distortion Power Factor.
pPFC:	Passive Power Factor Correction.
THD_I:	Total Harmonic Distortion.
$THDS_I$:	Subgroup Total Harmonic Distortion.
$TH\&IHD_{I,HF}$:	Subgroup Total Harmonic and Interharmonic Distortion in High Frequency.

I. INTRODUCTION

THE main components of an LED lamp are a driving circuit (to convert the signal from AC to DC) and the diodes themselves. The configuration of the components, the topology, might differ significantly between different LED lamps. The most recent version of the standard (IEC 61000-3-2:2018 [1]) includes emission limits from 5 W to 25 W equipment which were not included in previous versions of this standard. Consequently, LED lamps with an active power consumption below 25 W manufactured prior to 2018, could emit significant levels of harmonics without violating any limit imposed specifically for this kind of lamps. The absence of regulation together with a massive replacement towards LED lamps has contributed to have many types of lamps available in the market. The differences appear in the power electronic devices employed in the driver, which use various topologies as well as electronic components [2]. In fact, differences in the circuit elements or circuit schematic implemented by the various manufacturers can result in distinct current waveform measured at the device's terminal [3], changing their actual characteristics as load according to it [4]. Reference [5] concludes that not only the topology is involved in the LED lamps behavior but also the individual components. In [6], it was found that the power factor (PF) could reach up to 0.6 and the current total harmonic distortion (THD_I) varies between 100 and 140%.

A classification is needed in terms of modelling the LED lamps behavior. When forecasting the impact from connecting thousand lamps, or studying the impact on voltage disturbances, a model (or models) of LED lamps is needed. However, the diversity in topologies makes modeling difficult due to the different behaviors against voltage disturbances. The most accurate method would be to open them and check the topology through the observation of the components in the printed circuit, but this would imply to destroy the lamps which will not be useful anymore, and even so, there are small differences among the same manufacture therefore there might not be two identical lamps [7].

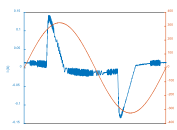
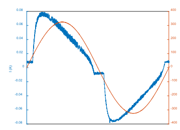
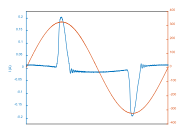
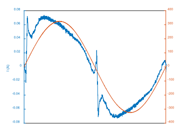
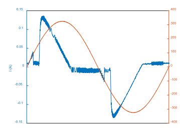
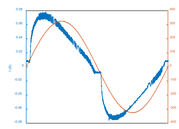
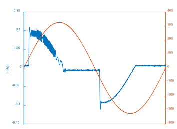
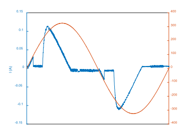
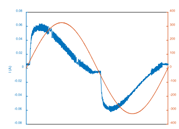
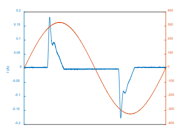
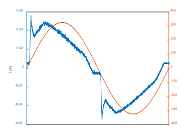
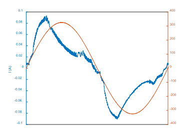
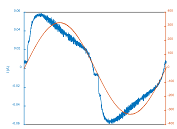
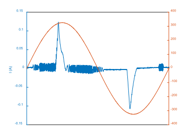
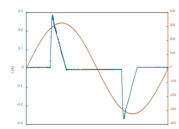
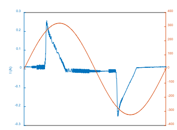
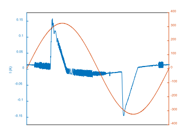
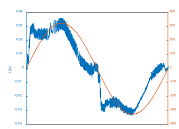
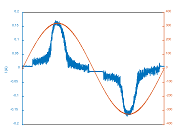
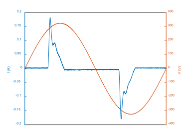
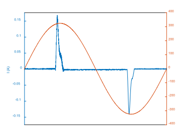
In the existing literature, authors classify LED lamps and other household devices without opening them based on different criteria, for example, measured flicker [2], true power factor (PF) and THD_I [3] or by applying statistics as higher order statistic (HOS) [8]. According to them, a general LED classification is based on the presence of the power factor correction (PFC) block, being active (aPFC), passive (pPFC) or those that simply do not have it (nPFC).

As examples of the large amount of LED lamp topologies, [9] shows two nPFC topologies based in passive components and other topologies with a DC-DC converter: buck, buck-boost or boost converter. The aPFC can also be any of the DC-DC converters cited, this topology includes a second DC-DC converter. The flyback converter as well as other converters from the same family are used if it is necessary to provide galvanic isolation. Companies have therefore many options when manufacturing LED lamps. The consequence is that depending on the circuits used, different current waveforms are obtained.

Reference [10] shows similar behaviors between LED lamps with different topologies, and other cases where no similar behavior is found between LED lamps classified within a similar topology. Reference [10] also states that the behavior of the LED lamps during rapid voltage changes should be studied in relation with their topologies as future work. It shows the need of classifying LED lamps to explain power quality issues.

In this paper, a sample of LED lamps found in the Swedish market, below 25 W, with different topologies and brands has been used to identify the topology in their drivers through four existing non-invasive LED lamp classification methods. The aim of the study is to show how the several topology classification methods perform in other set of LED lamps and to study the level of agreement between them. The methods are based on measurements of other sets of LED lamps. The methods are explained in the cited papers which are all published and are part of the existing literature. The authors rely on the veracity of the methods stated in the references used. Studies are always carried out with limited number of LED lamps and there are new released lamps every day, so not every topology is taken into account when stablishing a methodology. In addition, the usability of two Machine Learning (ML) methods in LED lamps classification is tested.

TABLE 1. LED lamps tested.

LED 01	LED 02	LED 03
5 W	10 W	7.5 W
		
LED 04	LED 05	LED 06
11 W	8 W	11 W
		
LED 07	LED 08	LED 09
6.5 W	7 W	7 W
		
LED 10	LED 11	LED 12
5 W	7 W	10 W
		
LED 13	LED 14	LED 15
9 W	3 W	10 W
		
LED 16	LED 17	LED 18
11 W	5 W	4.5 W
		
LED 19	LED 20	LED 21
12 W	5 W	3 W
		

The remaining sections of the paper are structured as follow:

Section II describes the LED lamps considered in this experiment and their current waveforms are shown in Table 1. Section III explains the applied classification methods that are obtained from the literature. Section IV

TABLE 2. Measured RMS current for each LED lamp.

Measured rms current (mA)									
LED 01	LED 02	LED 03	LED 04	LED 05	LED 06	LED 07	LED 08	LED 09	LED 10
43.8	48.3	57.2	50.2	55.7	48.2	48	45.9	35.8	39.1
LED 11	LED 12	LED 13	LED 14	LED 15	LED 16	LED 17	LED 18	LED 19	LED 20
32	47.8	38.8	23.2	75.7	69.4	41.3	21.4	67.7	39.6
LED 21									
24.8									

gives the classification results strictly applying the considered classification methods. Section V considers the results from a relaxed limit classification, which is nothing other than applying human pattern recognition and considering an understandable range of error for such large variety of LED lamp topology in order to not deduct the usability of the classifications. The use of the information related to the LED lamp topology obtained from the current waveform is discussed. Section VI discusses the usability of unsupervised ML in LED lamps topology classification applying two different methods. Finally, the last section is devoted to the conclusions.

This paper is an extension of [11]. The introduction section has been extended. The current waveform of the LED lamps in Table 1, the rms current of the LED lamps and information about the grid impedance is added. The methodology and results sections have been clarified. The main extension is done in the discussion section where a discussion about Relaxed limit classifications and the classification methods from the literature is added. The use of unsupervised ML is also clarified and discussed. Therefore, new conclusions from the extended information are added.

II. LED LAMPS TESTED

A group of 21 LED lamps currently available in the Swedish market for indoor lighting has been used to classify them using the methods described in Section III. Eleven different brands have been chosen, the active power of the lamps varies from 3 W to 12 W. The list of the LED lamps tested with their current waveform and characteristics given by the manufactures is given in Table 1. The measured rms current (with a Pearson current monitor model 3972) for each LED lamp is given in Table 2. A WW5064 waveform generator connected to two AE Techron 7224 amplifiers connected in series has regulated the supply voltage applied to the LED lamps tested in this paper. Yokogawa DL850 oscilloscope has acquired the data with a 100 kS/s sample frequency. Measurements have been done with sinusoidal supply voltage without harmonic distortion (50 Hz, 230 V rms) after the LED lamp stabilization time [12].

III. METHODOLOGY

Four different classification methods have been applied to our set of LED lamps. The classification methods are focused on the part of the circuit critical to the characteristics of the current drawn from the mains. Those classification methods are based on the following papers cited. The applied procedure in each classification method is explained below. The features used in each classification are summarized in Table 3.

TABLE 3. Features used in each classification.

Classification I	Current waveform shape
Classification II	Power quality indexes
Classification III	Power quality indexes
Classification IV	High order statistics

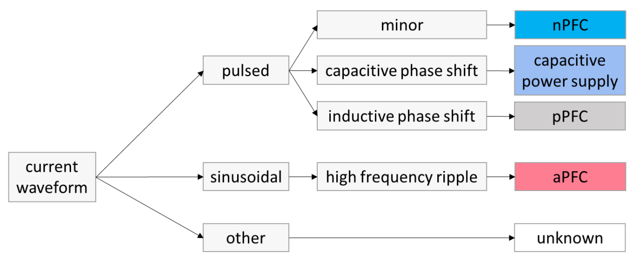


FIGURE 1. Simplified version of classification I method in [13].

A. CLASSIFICATION I

A classification method based on a visual characterization of the measured current waveform shape is presented in [13] to identify circuit topologies of typical household devices, including LED lamps.

The procedure proposed by the authors is a decision tree based on a visual analysis of the measured current waveform, where the first decision is differentiating between pulsed, sinusoidal waveform or none of them. If the waveform does not fit in neither pulsed nor sinusoidal, the topology cannot be determined with this method, which is referred to as unknown topology in [13]. For a pulsed waveform, the tree is divided again based on the phase angle shift between the fundamental current and voltage (displacement power factor (PF_1)) resulting into three groups: bridge rectifier if PF_1 is minor (nPFC), pPFC if inductive phase shift, and capacitive power supply if there is capacitive phase shift. A sinusoidal waveform indicates an ohmic topology or an aPFC topology in case of high frequency ripple.

As the aim of this paper is to classify LED lamps, ohmic devices appearing in [13] have been removed from the tree as Fig. 1 shows. The bridge rectifier topology is here called nPFC to keep consistency with other methods.

A survey was carried out between different people in order to see the percentage of agreement about LED lamps classification. Twelve people were asked to classify the LED lamps following the diagram in [13] (simplified in Fig. 1). Since [13] does not restrict who should use the method, half of the surveyed people had a previous knowledge about LED lamps topology classification.

TABLE 4. **Classification II based on PF and THD_I in [3] and [8].**

Topology	PF	THD_I
nPFC	PF < 0.6	80 % < THD_I
nPFC (capacitive divider)	PF < 0.6	THD_I < 30 %
pPFC	0.6 ≤ PF ≤ 0.9	40 % ≤ THD_I ≤ 80 %
aPFC	0.9 < PF	THD_I < 40 %

TABLE 5. **Types of LED lamps in classification III [14].**

Type	Description	Topology
A	Full-wave Rectifier with Smoothing Capacitor and DC-DC Converter Circuit	nPFC
B	Capacitive Dropper Circuit	-
C	CCR Straight Circuit	-
D	Switch-Mode Driver Circuit	aPFC

TABLE 6. **Criteria classification III [14].**

Type	PF	PF_1	PF_d	$THDS_I$ (%)	$TH\&IHD_{I,HF}$ (%)
A	0.41-0.60	0.86-0.97	0.44-0.67	106.49-197.61	9.67-43.15
B	0.39-0.59	0.44-0.71	0.80-0.92	43.18-64.19	5.91-12.35
C	0.88-0.96	1.00	0.88-0.96	27.71-53.61	2.05-4.25
D	0.70-0.95	0.82-0.98	0.67-0.99	10.10-58.71	2.42-53.94

B. CLASSIFICATION II

In [3], a classification method is introduced for household devices based on the THD_I and PF calculated over measured voltage and current. The resulting groups are nPFC, nPFC with capacitive divider, pPFC and aPFC topologies following Table 4.

According to the methodology stated in [3], to classify an LED lamp in a specific type, both PF and THD_I must be within the limits of that type as proposed by the authors.

C. CLASSIFICATION III

Reference [14] classifies LED lamps based on their $THDS_I$ (subgroup total harmonic distortion), $TH\&IHD_{I,HF}$(subgroup total harmonic and interharmonic distortion in high frequency) [15], PF, PF_1 and PF_d (distortion power factor).

The LED lamps in [14] are Type A, B, C and D corresponding with the topology described in Table 5. Type A has an nPFC topology, Type B a capacitive circuit, Type C a constant current regulator (CCR) straight circuit and Type D an aPFC topology.

The limits in Table 6 are given experimentally by the LED lamps tested in [14] under a 230 V rms sinusoidal supply voltage without distortion. The source impedance, as stated in [14], only has an impact for high frequency distortion. According to [14], after testing the LED lamp characteristics against different waveform shapes of the supply voltage, the most reliable parameters are PF, PF_1 and PF_d. Parameters should be within the limits in Table 6 to define an LED lamp within a topology group. For one lamp, if a parameter fits in more than one type, the type that has more parameters in common is chosen.

TABLE 7. **Examples of HOS values for each topology in [8].**

Topology	Statistical reference values		
	Variance	Skewness	Kurtosis
nPFC 1	0.1	1.9	6.73
nPFC 2	0.04	3.09	13.52
pPFC	0.2	0.92	3.54
aPFC	0.36	-0.09	1.93

D. CLASSIFICATION IV

Reference [8] proposes an automatic classification method of household devices based on the current waveform characterization in the higher-order statistics (HOS) space. Different waveform shapes exhibit different distributions and in consequence different statistical values. The authors propose to use HOS such as variance, skewness and kurtosis to characterize the waveform shape as well as the deviation from the mean value.

The difference between nPFC 1 and nPFC 2 in [8] is due to the current waveform but both are considered to be in the same category since the classification is based on the type of power factor correction.

As result of the procedure described in [8], different regions are found in the HOS space. The values in Table 7 are an example of the HOS values for each topology as given in [8].

IV. RESULTS

In this section, every LED lamp from the tested sample has been strictly classified according to the four respective methods described in Section III. The following results are obtained. The used colors for the topologies in each method in the tables and figures from Section III are also used in this section.

A. CLASSIFICATION I

Twelve people were asked to classify the LED lamp by looking at the current waveform and following the diagram in [13] (simplified in Fig. 1). Table 8 shows the results of the survey in percentage (percentage of surveyed people considering the LED lamp within each topology), where the topology with higher agreement is highlighted with the colors indicated in Fig. 1 for each topology. In addition, the percentage of people with previous knowledge is expressed between parentheses, i.e., when classifying an LED lamp, if a topology is agreed by the 16.67 % of the people, two persons, and one has previous knowledge, the percentage appearing between parentheses is 50%: 16.67 % (50 %).

The percentages of agreement for classifying an LED lamp have been in the range from 58.33 % to 100 %.

There are four LED lamps fully classified (100 % of agreement) as aPFC but five LED lamps are mostly classified within this topology with less percentage of agreement (75 % to 91.67 % of agreement) which means that there are doubts in distinguishing between sinusoidal and pulse waveforms, even

TABLE 8. Survey results from classification I.

LED	Topology			
	nPFC	aPFC	Capacitive power supply	Unknown
01	8.33 % (100 %)	-	91.67 % (45.45 %)	-
02	8.33 % (0 %)	75 % (55.56 %)	16.67 % (50 %)	-
03	75 % (33.33 %)	-	25 % (100 %)	-
04	-	100 % (50 %)	-	-
05	16.67 % (100 %)	8.33 % (100 %)	66.67 % (37.50 %)	8.33 % (100 %)
06	-	100 % (50 %)	-	-
07	-	16.67 % (50 %)	83.33 % (50 %)	-
08	16.67 % (100 %)	-	75 % (33.33 %)	8.33 % (100 %)
09	-	83.33 % (50 %)	16.67 % (50 %)	-
10	16.67 % (100 %)	-	83.33 % (50 %)	-
11	-	75 % (55.56 %)	16.67 % (50 %)	8.33 % (0 %)
12	-	91.67 % (45.45 %)	8.33 % (100 %)	-
13	-	100 % (50 %)	-	-
14	41.67 % (40 %)	-	58.33 % (57.14 %)	-
15	16.67 % (100 %)	-	83.33 % (40 %)	-
16	8.33 % (100 %)	-	91.67 % (45.45 %)	-
17	8.33 % (100 %)	-	91.67 % (45.45 %)	-
18	-	100 % (50 %)	-	-
19	25 % (33.33 %)	75 % (55.56 %)	-	-
20	16.67 % (100 %)	-	83.33 % (40 %)	-
21	83.33 % (40 %)	-	16.67 % (100 %)	-

though this distinction seems to be straightforward. However, aPFC is the only group which has been clearly identified by all the surveyed people. LED 05 and LED 07 are mostly classified as capacitive power supply but around 8 % or 17 % of the surveyed people classified them within aPFC topology.

Twelve LED lamps have more percentage of agreement either in nPFC or capacitive power supply, both belong to pulsed waveform, but there is not an agreement to clearly separate them according to the phase angle shift. The 75 % from these twelve LED lamps divide their percentages of agreement only between nPFC and capacitive power supply topology i.e., nobody classified them as aPFC (sinusoidal waveform) or unknown topology, revealing difficulties in classifying according to phase angle shift within pulsed current waveform. Usually, there is a clear favorite topology, but for LED 14 the percentage of agreement is 41.67 % for nPFC topology and 58.33 % for capacitive power supply topology (almost half say a minor phase angle and the other

TABLE 9. Classification II results according to PF and THD_I.

Topology	LED lamps
nPFC	01, 03, 10, 14, 15, 16, 17, 20, 21
pPFC	19
aPFC	04, 13
Unknown	02, 05, 06, 07, 08, 09, 11, 12, 18

TABLE 10. LED lamps parameters and colors according to classification III results (blue: Type A; Purple: Type B; Red: Type D).

LED	Parameters used for classifications (II / III)					
	II/III	III				II
	PF	PF_1	PF_d	$THDS_I$ (%)	$TH\&IHD_{I,HF}$ (%)	THD_I (%)
01	0.35	0.53	0.67	110.61	17.26	110.65
02	0.89	0.92	0.97	24.99	3.78	24.99
03	0.27	0.51	0.54	157.76	8.74	157.77
04	0.93	0.95	0.98	18.24	5.73	18.25
05	0.52	0.63	0.82	69.91	8.95	69.92
06	0.89	0.91	0.98	21.81	4.89	21.82
07	0.46	0.54	0.85	60.95	13.37	61.02
08	0.52	0.66	0.78	79.68	6.68	79.68
09	0.78	0.81	0.96	29.72	7.18	29.74
10	0.29	0.51	0.56	148.60	14.02	148.60
11	0.88	0.90	0.98	20.89	5.43	20.89
12	0.82	0.87	0.94	36.02	3.75	36.03
13	0.90	0.93	0.97	25.92	4.36	25.92
14	0.21	0.44	0.49	178.53	42.78	178.85
15	0.31	0.54	0.57	142.84	10.26	142.84
16	0.38	0.58	0.67	111.35	16.71	111.36
17	0.32	0.50	0.64	121.56	20.70	121.59
18	0.88	0.90	0.98	20.38	10.47	20.44
19	0.68	0.82	0.83	67.89	14.01	67.92
20	0.29	0.52	0.56	147.17	13.37	147.18
21	0.13	0.36	0.37	250.33	42.42	250.34

a capacitive phase angle). Surveyed people with previous knowledge had more doubts in choosing between these topologies.

There are three lamps (LED 05, LED 08 and LED 11) that were classified as unknown topology by around 8 % of surveyed people.

None of the tested LED lamps is classified with a pPFC according to this classification method.

B. CLASSIFICATION II

The results of this classification based on the PF and THD_I values (Table 4) are shown in Table 9. Table 10 contains the PF and THD_I values for all the tested LED lamps. According to classification II method where both PF and THD_I must be within the limits proposed by the authors to belong to each group, the sample of lamps was categorized into nPFC (42.9%), pPFC (4.76%), aPFC (9.5%) and none of them into an nPFC with capacitive divider (not shown in the table). For the other 42.9% (the same number as nPFC group), either PF or THD_I do not strictly fit within the limits from any mentioned category, classifying those lamps as a new group named unknown topology. Within this unknown group, PF in LED 05, LED 07 and LED 08 indicates an nPFC topology while the THD_I indicates a pPFC topology. For the rest of the LED lamps categorized within this unknown topology, the PF indicates pPFC topology while the THD_I points to an aPFC topology. LED 02, LED 06, LED 11 and LED 18 have a PF varying between 0.88 and 0.9, closer to the limit to be considered as aPFC topology as their THD_I values clearly indicate, but strictly following Table 4, those lamps cannot be grouped in any of them. LED 09 and LED 12 have a similar case with the PF 0.78 and 0.82 respectively, and THD_I pointing to an aPFC topology.

C. CLASSIFICATION III

The results of classification III from the set of lamps are shown in Table 10. To facilitate the recognition of topologies according to values in Table 6, same colors have been used as in that table, where blue, purple and red cells are parameters strictly within limits for Type A, Type B and Type D respectively. White cells correspond to values outside the limits in Table 6. There is not Type C within the set of LED lamps used for this paper, as it can also be seen comparing the current waveforms from the LED lamp samples with the Type C rectangular waveform in [14] which has a displacement power factor of one.

All but one lamp (LED 03) deemed corresponding to Type A (blue, nPFC) fit when considering PF_d, $THDS_I$ and $TH\&IHD_{I,HF}$. Looking at the parameter PF_1 these lamps would instead correspond to Type B and looking at PF they would not fit at any group. LED 03 has a $TH\&IHD_{I,HF}$ value of 8.74 % which is within Type B and Type D limits but the value is also close to the lower limit of Type A (9.67 %). LED 21 may agree with Type A according to very low PF (0.13) and very high $THDS_I$ (250.33 %) but those values are not exactly within the limits used for the classification as shown in Table 6.

There are three LED lamps that are Type B based on most of their parameters. $THDS_I$ in LED 05 is not within limits for any type, however the closest limit to its value (69.91 %) is the upper limit of Type B (64.19 %). In LED 07, the $TH\&IHD_{I,HF}$ value is within the limits of Type A and Type D but also close to the upper limit of Type B. LED 08 has a PF_d corresponding to Type D but it is also close to the lower limit of Type B (0.80). $THDS_I$ for LED 08 is not within the range for any type, although close to Type B upper limit (64.19 %).

Eight LED lamps have all their parameters within Type D limits (red cells) corresponding to aPFC topology. Although the PF_1 for LED 09 is outside the limits for Type D by 0.01, it is considered within this type. LED 19 has most of the parameters within Type D, its PF is close to the lower limit of Type D (0.70) and its $THDS_I$ is not so far from the upper limit of Type D (53.61 %).

D. CLASSIFICATION IV

Fig. 2 shows the results from classification IV method. Three regions can be distinguished and linked to an nPFC (blue circles), pPFC (purple circles) or aPFC (red circles) according

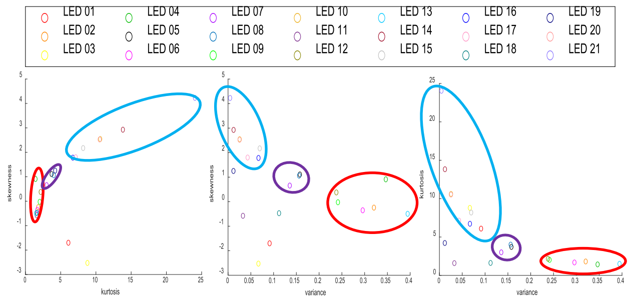


FIGURE 2. Classification IV results. The circles represent the different topology regions found: nPFC (blue), pPFC (purple) and aPFC (red).

to the descriptions of the statistic values linked to each topology given in [8]:

- nPFC: high kurtosis and skewness and low variance.
- pPFC: intermediate values of kurtosis, skewness and variance.
- aPFC: low kurtosis and skewness and high variance.

Five LED lamps (LED 01, LED 03, LED 11, LED 18 and LED 19) have some statistics that fall outside the specified regions in [8] (shown outside the encircled areas in Fig. 2).

V. COMPARISON OF THE EXISTING METHODS

Only [14] gives a specific method for LED lamps classification, the rest of the methods considered in this paper are for classifying electronic devices in general. The discussion presented here is based on the results obtained for LED lamps that may differ with the results for generic devices.

Each paper gives different levels of details on how to perform the measurements that the classification methods are based on, [14] gives the most detailed information with the type of source, source impedance, waveform shape, rms voltage, distortion, data acquisition device and sampling frequency while the other papers give information about the source waveform shape and the distortion, but the rest of information is sometimes not written. The effect of background distortion from each laboratory, source impedance and e.g., operational state should be considered when measuring devices since it may change the results obtained and therefore the classification [16].

A. RELAXED LIMITS CLASSIFICATIONS

From the results included in Section IV, and in order to compare the different classification methods, a more generic and simplified classification result from each method is given in Table 11. The results shown in Table 11 are obtained applying a classification based on relaxed limits, applying the criteria explained in Sub-section V-A.1 for each classification method. Sub-section V-A.2 compares the results from the relaxed limits classifications applied (Table 11). The relaxed limits classification is nothing other than applying human pattern recognition and considering an understandable range of error for such large variety of LED

TABLE 11. Classification based on relaxed limits.

Topology	LED lamps classification			
	I	II	III	IV
nPFC	**03**, 21	**01**, **03**, 10, 14, 15, 16, 17, 20, 21	**01**, **03**, 10, 14, 15, 16, 17, 20, 21	10, 14, 15, 16, 17, 20, 21
Capacitive power supply	**01**, **05**, **07**, **08**, 10, 14, 15, 16, 17, 20	X	X	X
Type B	X	X	**05**, **07**, **08**	X
pPFC	-	**05**, **07**, **08**, **19**	X	**05**, **07**, **08**
aPFC	02, 04, 06, 09, **11**, 12, 13, **18**, **19**	02, 04, 06, 09, **11**, 12, 13, **18**	02, 04, 06, 09, **11**, 12, 13, **18**, **19**	02, 04, 06, 09, 12, 13
Unknown	-	-	-	**01**, **03**, **11**, **18**, **19**

TABLE 12. Topologies comparison between classifications.

Classification I	Classification II	Classification III	Classification IV
nPFC	nPFC	Type A (nPFC)	nPFC 1
Capacitive power supply	nPFC (capacitive divider)	Type B (capacitive)	nPFC 2
pPFC (inductive)	pPFC	Type C (rectangular)	pPFC
aPFC	aPFC	Type D (aPFC)	aPFC

TABLE 13. Statistics in LED lamps according to classification IV.

LED	Variance	Skewness	Kurtosis	LED	Variance	Skewness	Kurtosis
01	0.09	-1.70	6.09	11	0.03	-0.58	1.60
02	0.32	-0.24	1.81	12	0.24	0.38	2.16
03	0.07	-2.53	8.79	13	0.39	-0.50	1.51
04	0.35	0.91	1.43	14	0.01	2.93	13.83
05	0.16	1.11	3.71	15	0.07	2.17	8.19
06	0.30	-0.35	1.69	16	0.07	1.78	6.73
07	0.14	0.66	3.01	17	0.04	1.80	7.14
08	0.16	1.06	4.01	18	0.11	-0.47	1.62
09	0.24	-0.02	2.02	19	0.01	1.25	4.22
10	0.03	2.54	10.61	20	0.03	2.53	10.53
				21	0.004	4.23	24.05

lamp topology in order to not deduct the usability of the classifications. In the table, the numbers in color and bold represent LED lamps that have different topology depending on the classification method. Examples from that are LED 11 and 18 or LED 19. Equal color indicates same change in the topology according to the different classification methods, as happens with LED 01 and 03 or LED 05, 07 and 08. An X in a cell indicates that the classification does not include the topology. A dash indicates that no LED lamp is classified within the topology. The topologies cells are filled by the colors represented in Table 12. Sub-section V-A.2 explains the topologies comparison between classifications. Cells of same color indicate similar group characteristics.

1) CRITERIA

From Classification I method, a classification is given based on the most voted topology since the level of agreement among surveyed people is high in general. The outcome of Classification I might vary based on, among others, number of people taking part in the survey and their previous knowledge.

From the results commented in Classification II, there are LED lamps that were classified as unknown as they do not strictly fall into the limits of any considered topology but are close to them, so that, a classification considering relaxed limits is given. Six out of nine LED lamps previously classified as unknown topology have a THD_I typical of an aPFC topology. They do however have a PF below the defined limit (between 0.78 and 0.9) that can be considered within an aPFC topology only if a more relaxed lower limit is used. An aPFC topology leads to a low THD_I and a high PF but the PF limit seems to be lower than 0.9 for LED lamps classification based on the results from the other classification methods as well as the proximity of the values obtained to the limit defined in [3]. These LED lamps are classified as aPFC topology applying relaxed limits (Table 4), i.e., allowing 14.3 % of error (variation) respect to the limit (PF=0.91, since the criteria is $0.9 < PF$). Similarly, LED 05, LED 07 and LED 08 have the THD_I within the limits for the pPFC topology and the PF close to its low limit (0.52, 0.46 and 0.52 respectively). Applying relaxed limits, i.e., allowing a 23.34 % of error respect to the limit (PF=0.6, since the criteria is $0.6 \leq PF \leq 0.9$), these LED lamps are classified as pPFC in Table 11.

From Classification III, a pattern is found in LED lamps with PF_d, $THDS_I$ and $TH\&IHD_{I,HF}$ corresponding to Type A, PF_1 corresponding to Type B and low PF. Those LED lamps may have a similar topology. The topology points to be nPFC even though it may differ from the Type A (nPFC) topology from Classification III. LED 03 only differs from the pattern on the $TH\&IHD_{I,HF}$ where the value is close to the Type A low limit, with 9.62 % of error. LED 21 has low PF, high $THDS_I$ and $TH\&IHD_{I,HF}$ in agreement with Type A characteristics. Its PF_1 (0.35) is close to the low limit for Type B (0.44) which would agree with the pattern described above, and its PF_d (0.37) is close to the low limit for Type A (0.44). The percentages of error allowed are 20.45 % and 15.9 % for the respective parameters. Those characteristics lead LED 21 to be classified as nPFC (similar topology to Type A as mentioned above) which would agree with the results from the other classifications.

Those are examples suggesting that classification methods should use relaxed limits due to the large variety of LED lamps topologies in the market. The LED lamps which follow the described pattern with a majority of Type A parameters plus LED 03 and LED 21 are classified within an nPFC topology in Table 11. LED lamps with most of their parameters within Type B or Type D are classified within Type B and an aPFC topology respectively.

From Classification IV, to clarify the results obtained in Fig. 2, Table 13 gives the values of the HOS found for each LED lamp. The colors indicate the topology within which the parameter is classified as defined in Table 7, Section III. The criteria applied is based on the closest reference value, i.e., the examples of HOS values given in Table 7. As can be seen, several LED lamps do not have all the statistics closer to the topology references given as example, even if they are classified within a topology in Section IV. This explains the dispersion of results within regions, which are not easy to define.

LED lamps with HOS outside the regions described in [8] are found. From those LED lamps, LED 01 and LED 03 have the skewness characteristic of an aPFC topology but variance and kurtosis are closer to the reference for nPFC, it puts them in a region not observed in [8] in the graphics where the skewness is represented. LED 11 and LED 18 have skewness and kurtosis according to the aPFC characteristic, but the variance is closer to the nPFC reference, this position them in a region not observed in [8] in the graphs where variance is represented. LED 19 has the skewness and kurtosis closer to the pPFC reference but a low variance corresponding to the nPFC topology, placing this LED lamp in a region not observed in [8] in the graphs where variance is represented. Each one of those LED lamps could be considered within the topology which example references are closer to the HOS values obtained, since two over three statistics point to the same topology. However, those LED lamps remain considered unknown topology in Table 11 since the criteria proposed for understanding the results from Section IV is not proven valid. It is not a matter of limits as in the other classifications since in this one the limits are regions in the graphs, and different regions from [8] are found.

2) COMPARISON

Classification I defines a capacitive power supply topology, containing LED lamps with a current waveform similar to an nPFC topology but with a capacitive phase shift which does not belong to the other classification methods. For this reason, nPFC and capacitance power supply topologies are grouped together to compare in a generic way with the other classifications. In Table 11, it is observed that Classification II and III classify the same LED lamps as nPFC topology. Classification IV also agree, except for LED 01 and LED 03 which are considered unknown topology, even though, the topology example references lead to point these lamps as nPFC topologies. Classification I also agrees in almost the same LED lamps, except in LED 05, LED 07 and LED 08 (the reason is explained in the following paragraphs), considering nPFC and capacitive power supply LED lamps as a single group.

The methods disagree in the definition of pPFC: Classification I considers that pPFC refers to inductive components, Classification II and IV consider that it refers to either inductive or capacitive components and Classification III considers Type B (Capacitive Dropper Circuit) which is a capacitive topology. For this reason, LED 05, LED 07 and LED 08 are classified together in different groups depending on the method but all of them agree that they should have a predominant capacitive component in their topology.

Table 12 summarizes the topologies relationship. The cells in blue correspond with nPFC topologies, the purple cells are topologies with a strong capacitive characteristic and the red cells are aPFC topologies. The topologies in grey cells are not found in this set of LED lamps.

Classification I and III classify the same LED lamps within an aPFC topology, and Classification II only differs in LED 19, considered pPFC. Classification IV agrees with the other classifications in most of the LED lamps for the aPFC topology. However, as it happens with the nPFC topology, two LED lamps (LED 11 and LED 18) are classified as unknown, even though the topology example references lead to point these lamps as aPFC topologies. Classification IV considers LED 19 unknown topology, even though, the topology examples references lead to point the lamp as pPFC similarly to Classification II does.

There is disagreement between an aPFC (Classifications I and III), a pPFC (Classifications II) and unknown topology (Classification IV) for LED 19. This indicates that even if the classifications agree, the classified topology may not be the real one.

B. KNOWLEDGE FROM CURRENT WAVEFORM

A visual classification based on the current waveform (Classification I) is sensitive to personal criteria as shown by the disagreement in the classification of some LED lamps. Surveyed people had significant doubts to decide between considering a sinusoidal or pulsed waveform. In case of deciding a pulsed waveform, there were doubts about considering capacitive or minor phase shift according to Classification I method.

Surveyed people with previous knowledge in LED lamps classification stated that the limits are not defined and sometimes characteristics from different topologies can be appreciated in a single lamp. Some of them asked for more information about the lamps to decide the topology. This suggests the joint use with other methods. Others proposed an additional classification between capacitive power supply and nPFC topologies, which supports the results obtained pointing to a relaxed limits classification in the classifications based on parameters.

Information based on experience that can help to clarify the topology and to know more about the LED lamp characteristic is given:

- A sinusoidal current waveform shifting 90 degrees respect to the voltage leads to think that there is a capacitor presents in the AC side.
- A small peak, at the voltage zero crossing, before the main current peak indicates that the LED lamp is dimmable.

This information complements the one from [13] based on the distinction between sinusoidal or pulsed, the high frequency ripple and the phase shift.

C. IMPROVING USABILITY OF THE TOPOLOGY CLASSIFICATION METHODS

No classification method strictly applied does clearly classify the whole group of tested LED lamps, only some of the LED lamps. Relaxed limits classification methods lead to generic classifications e.g., the relaxed limits classifications used in this paper. As it can be seen in Table 11, doing relaxed limits classifications with different methods gives similar results. This means that all those methods give a consistent general idea about the topology of the LED lamps.

To apply relaxed limits classifications, it is recommended to use a parameters-based classification as a base (as Classification methods II and III). The first step should be recognizing the current waveform shapes from where the parameters are obtained (Classification I method is useful here). The second step would be to apply the parameters-based classification. The last step is to recognize patterns and allow an understandable error from the limits stablished by the parameters-based method. The current waveform shape could give better understanding of the deviations from the original limits and give extra information about the LED lamp.

Applying relaxed limits classifications does not mean that all the LED lamps would be classified, some LED lamps could remain as unknown topologies, but it increases the usability of the classification method. Considering in the original classification the LED lamp as unknown when any of the parameters is unknown or any parameter differs from other in the topology, the percentage of unknown LED lamps are 42.85 % and 66.67 % for Classifications II and III respectively; while all the LED lamps were classified after applying relaxed limits classifications, meanly applying relaxation of the limits in Classification II and pattern recognition in Classification III.

Classification IV is an automatic classification method based on HOS, so it finds a great usability in ML, therefore the outlier values will be considered by the ML method implemented. As earlier shown, two over three statistics point to the same topology when the LED lamps are considered within the topology which example references (given in Table 7) are closer to the HOS values obtained. This kind of information could be useful for this purpose.

VI. NEW APPROACH FOR LED LAMPS CLASSIFICATION

The applicability of relaxed limit classification is a possible solution for classifying the unknown LED lamps left after strictly applying a classification method, but it makes the classification sensitive to personal criteria. Unsupervised ML is a tool that finds patterns and similarities in a dataset. The concept of relaxed limit classification leads to think about the usability that unsupervised ML can have on LED lamps topology classification for obtaining a unified criteria to cover this issue.

A. UNSUPERVISED MACHINE LEARNING

Unsupervised ML finds patterns and similarities in a dataset. A dataset contains the values of certain features of the object of study for a number of observations. Unsupervised ML classifies the observations in clusters according to the values of their features. In this case, the object of study is a set of LED lamps, the features are the different electrical parameters and HOS considered, and the observations are each of the LED lamps from the set. Unsupervised ML classifies the observations in a number of clusters defined by the user. At least, the topology of one lamp from a cluster must be known to associate a cluster with a topology. It should be noticed that unsupervised ML cannot be applied to a single lamp.

The number of clusters is chosen equal to the number of classification topologies (nPFC, aPFC and pPFC), i.e., the LED lamps are divided in three clusters. Four datasets are used. Dataset 1 and 2 uses the electrical parameters from Classification II and III respectively as features, Dataset 3 uses the HOS from Classification IV and Dataset 4 uses electrical parameters and HOS all together. The data are normalized before training the model. Each observation corresponds to an LED lamp from the set studied. Two methods are applied: k-mean clustering method and Gaussian Mixture Model (GMM) method. Both are performed using MATLAB.

1) K-MEANS CLUSTERING MODEL

The algorithm of the method is stated in [17]. The algorithm determines as many centers as cluster were indicated, three in this case (k=3). Each cluster is formed by the LED lamps which features have the shortest distance to the group center. The algorithm is repeated twenty times. The grouping with the lowest sum of distances between features and centers of those ten repetitions is the result shown. The Squared Euclidean distant is used for calculations.

2) GAUSSIAN MIXTURE MODEL

A GMM is a distribution fit made up of k multi-dimensional Gaussian distributions, three in this case (k=3). The observations are clustered according to their probability to belong to each k Gaussian distribution [18]. The MATLAB function fitgmdist fits GMM to data using the iterative Expectation-Maximization (EM) algorithm. The EM algorithm was repeated twenty times and the result is the fit with the largest loglikelihood [19]. It was applied specifying the use of diagonal covariance matrices.

TABLE 14. LED lamps three Clusters results using ML methods.

Cluster	k-means	GMM
Dataset 1 (Parameters from Classification II as features)		
Cluster	k-means	GMM
1	1, 5, 7, 8, 16, 19	1, 3, 10, 14, 15, 16, 17, 20, 21
2	2, 4, 6, 9, 11, 12, 13, 18	2, 4, 6, 9, 11, 12, 13, 18
3	3, 10, 14, 15, 17, 20, 21	5, 7, 8, 19
Dataset 2 (Parameters from Classification III as features)		
Cluster	k-means	GMM
1	1, 3, 5, 7, 8, 10, 15, 16, 17, 20	1, 3, 10, 14, 15, 16, 17, 20, 21
2	2, 4, 6, 9, 11, 12, 13, 18, 19	2, 4, 6, 9, 11, 12, 13, 18
3	14, 21	5, 7, 8, 19
Dataset 3 (Parameters from Classification IV as features)		
Cluster	k-means	GMM
1	1, 3, 5, 7, 8, 11, 18, 19	1, 3, 10, 14, 15, 16, 17, 19, 20, 21
2	2, 4, 6, 9, 12, 13	2, 4, 6, 9, 11, 12, 13, 18
3	10, 14, 15, 16, 17, 20, 21	5, 7, 8
Dataset 4 (Parameters from Classification II, III and IV as features)		
Cluster	k-means	GMM
1	1, 3, 5, 7, 8, 10, 15, 16, 17, 19, 20	1, 3, 10, 14, 15, 16, 17, 20, 21
2	2, 4, 6, 9, 11, 12, 13, 18	2, 4, 6, 9, 11, 12, 13, 18
3	14, 21	5, 7, 8, 19

The results applying the ML methods explained before are shown in Table 14. The k-means method can give different results depending on the dataset i.e., depending on the features used. The GMM method gives almost the same results using different datasets. LED 19 is the only one that change cluster, it is assigned to Cluster 1 instead of Cluster 3 when using Dataset 3. Furthermore, each cluster obtained using the GMM method contains LED lamps that the classification methods in the literature pointed to have similar topology.

Comparing the results from the Classifications methods and the ML methods, the k-means method groups attending to a deterministic criteria (the shortest distance), what can be compared to a strictly application of the limits used in the Classification methods. The GMM method defines the clusters based on probabilities (likelihood applied in relaxed limits). It is shown that the k-means clustering method gives different results depending on the parameters used as features, as it happens considering strict limits in the Classification methods. The GMM gives quite consistent results independently of the parameters used. In addition, the GMM clusters are similar to the resulting groups that most of the classification methods give when applying relaxed limits.

VII. CONCLUSION

Different classification methods have been tested and compared in a systematic way using a new set of lamps. Using the classification methods strictly may lead to a gap of knowledge on the topology of some LED lamps. A suggestion for the enhancement of the usability of the parameters-based classification methods is given in this paper by applying the so-called relaxed limit classification, which leads to have a consistent general idea about the topology of the LED lamps. The results show that opening the LED lamp is necessary to know its topology due to the large variety of LED lamp topologies and the uncertainty in using a classification method based on measured current. The LED lamps used to define the classification methods studied appeared in the market when there were no harmonic limits for lamps with power below 25 W according to IEC 61000-3-2 (2014). Lamps today could have a significantly different topology, as manufacturers need to reduce the harmonic emission to comply with the current version of the standard, IEC 61000-3-2 (2018). Some parameters (used in the classifications) could change in new lamps since the standard limits the current emission (THD_I) and therefore, some topologies may disappear. It does not hold for LED lamps under 5 W. The classifications in this paper give a consistent general idea of the LED lamps topology when considering a relaxed limits classification methodology. However, this does not ensure that the real topology has been identified, since a relaxed limits application of a method makes it sensitive to personal criteria, i.e., the criteria to decide up to what point the limits should be relaxed. Regarding sensitivity to personal criteria, GMM method is a ML tool that can be used to avoid it, since it shows quite consistent result using different LED lamps features and comparing with the relaxed limit classification results. A deeper classification, i.e., within more specific topologies e.g., a classification within 10 different topologies, will provide better knowledge about the LED lamp topology. Even that, it does not guarantee to find the real topology. If the number of topologies groups is too broad, a classification loses its meaning. Applying the limits strictly leads to a lack of knowledge that may invalidate the method. The limits are experimentally obtained from a sample of LED lamps so that cannot include the large number of topologies in the market. A drawback from classifications based on limits is that the measurement set up should be carefully defined and followed.

The current waveform gives important information to classify LED lamps that cannot be obtained from the parameters used for the classifications. The downside is that different people looking at the waveform might draw different conclusion and the uncertainty in this classification is therefore significant. To use a measured index like PF or THD_I is in that sense better as a measured value can be used and compared without any bias. The uncertainty here lies in how to perform the measurements, how to decide the limits and what to do with devices which values are close to the limit. The use of the current waveform information is suggested to be used together with a classification method based on electrical parameters.

The power quality issues in LED lamps can be explained by their topologies. In studies which conclude such relationship, the topology classification method or criteria for classification used either must be explained in detail, specifying every consideration taken or the knowledge of the real topology (opening the LED lamps) is needed. When the first option is taken, the study is sensitive to the topology classification method used to verify the results and therefore making difficult the comparison of the results with other studies. The use of a different criteria can change the classification of the LED lamps, i.e., the topology considered for the LED lamps, as shown in this paper with the results from each classification method and with the relaxed limits comparison between the classification methods.

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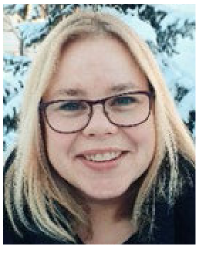
ELENA GUTIERREZ-BALLESTEROS received the B.S. degree in industrial electronic engineering and the M.S. degree in distributed renewable energies from Universidad de Córdoba, Córdoba, Spain, in 2018 and 2019, respectively. She is currently pursuing the Ph.D. degree in electric power engineering with the Luleå University of Technology, Skellefteå, Sweden.



SARAH K. RÖNNBERG (Senior Member, IEEE) received the Ph.D. degree in electrical power engineering from the Luleå University of Technology, Sweden, in 2013. She is currently a Professor with the Department of Engineering Sciences and Mathematics, Luleå University of Technology. Her research interests include supraharmonics, power system harmonics, and power quality in general.

AURORA GIL-DE-CASTRO (Senior Member, IEEE) is currently an Associate Professor with the Department of Electronics and Computer Engineering, Universidad de Córdoba, Spain. She has authored or coauthored several papers in journals and international conferences. She has been involved in research projects at a local and state level. Her research interests include smart grids, the Internet of Things, and power quality, more concretely, low- and high- frequency harmonics on domestic equipment and lighting.