Characterization of Commercial LED Lamps for Power Quality Studies

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***Abstract* —Light emitting diode (LED) lamps exhibit nonlinear characteristic causing negative influences on power grid and on public health. High harmonic contents injected by LEDs as well as their sensitivity to voltage fluctuations in the network should be further examined. This paper aims at a better understanding to the characterization of commercial dimmable LED lamps and their impact on power quality parameters. A testbed has been implemented as a platform to investigate current and voltage quality issues by conducting various experimental tests that include power quality concerns such as harmonic analysis, voltage flickering, voltage sag and swell. The experimental setup allows execution of light intensity, harmonic current contents and voltage measurements of commercial LED lamps. Data processing using MATLAB software tool has been used to analyze the results. The percent flicker is used to evaluate varying degrees of flickering happening in LED lighting networks. The effect of changing the light intensity for dimming purposes on the perceptibility of flicker has been studied and discussed as well. The paper provides a solid reference for researchers working on power quality improvement of LED lamps.**

***Index Terms*— Current harmonics, flickering, LED, percent flicker, power quality, voltage sag, voltage swell.**

I. Introduction

FOLLOWING recent developments in the technology of solid state lighting (SSL) and hence light emitting diode (LED) lamps, high luminous, intensity and emission spectrum LEDs are now taking a significant share of the lighting market [2]. Table I shows a comparison between the efficacies of different types of lighting sources given their general efficacy range measured in Lumen/Watt [3]. Manufactures are competing to break through the predicted theoretical luminous efficacy limit 260-300 lm/W of white LEDs [4]. Besides, LED lamp is a high reliability product with long lasting lifetime that ranges from 50000 up to 100000 hours. Moreover, it is considered an ecologically friendly with no toxic substances or ultra-violet emitted energy [3].

However, even though LEDs show the most efficient lighting source, they do not offer the best choice when high power quality (PQ) parameters are essential. Studies have been carried out to evaluate the performance of LEDs compared to compact fluorescent lamps (CFL), High Pressure Sodium (HPS) and incandescent bulbs [5]-[7]. An impedance network model with current sources that represent injected harmonic contents can be used to model LED lamps [6]. LEDs show a better performance in terms of total harmonic distortion (THD) and power factor (PF) in contrast to CFL driven by an electronic ballast. While, a CFL driven by an electromagnetic ballast show higher PQ parameters [7].

TABLE I
COMPARISON BETWEEN THE EFFICACY OF VARIOUS TYPES OF LIGHTING SOURCES [3]

Type of lamp	Lumen/Watt
Incandescent	10 to 35
Mercury Vapor	30 to 80
LED	40 to150
Fluorescent	40 to100
Metal Halide	50 to 115
High Pressure Sodium	85 to 150
Low Pressure Sodium	100 to 200
Induction	50 to 100
Plasma	70 to 150

A driving circuit is necessary to condition the voltage applied to LEDs. Therefore, their actual characteristics as loads will change according to the power electronic devices employed in the driver. Power electronics introduce high harmonic contents in the power network. Some low cost LED bulbs contain high harmonic contents that exceed the requirements specified by the standards IEC 61000-3-2 [9] and IEEE 519 [10]. Different manufactures employ dissimilar filtering techniques that vary between passive, valley-fill and active filters [11]. A frequency-domain LED model to simulate a large-scale of LED lighting network has been presented in [12]. The study shows that despite the low power consumption of LEDs, a large number of LEDs connected to the same bus would pollute the network voltage, increasing the harmonic voltage distortion level. In addition, dimmable LEDs will add additional reduction to the PF with more harmonic contents reaching 360% using TRIAC-based dimmer [13], [14].

To mitigate the injected harmonics, researchers are proposing including a passive filter or a power factor correction (PFC) circuit to the LED internal driver. This will be discussed in details in subsection II.B. A PFC circuit adds complexity, and increases the cost of an individual LED bulb. The authors in [15] recommended connecting a combination of CFL, LED and incandescent bulbs as an optimized solution to avoid their

This is an updated version of conference paper [1]. This new version includes detailed analysis and updated experimental results.

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disadvantages if they were employed individually. This solution is not practical to the user and does not follow the advancements of SSL and power semiconductor devices.

LEDs are also subjected to flickering. Voltage flickering is defined as variations of the voltage magnitude that are periodic and systematic. The magnitude of the voltage does not normally exceed the voltage ranges specified by EN 50160 [16]. The term flicker is derived from the impact of a voltage fluctuation on lighting sources such that the change in the light intensity is perceived by a human eye [17]. Rapid heavy load changes are typically the cause of system flickering. For example, large spot welding machines often operate in or near 5-10 Hz. A human eye/brain is most sensitive to low frequencies. There will be random voltage variations over a wide frequency band when ac electric arc furnaces are in operation that yield to a major source of flickering [18]. Flickering has brought concerns to both utility and end-users, due to human biological effects of light flicker. Potential health risks caused by flickering in LEDs has been addressed in IEEE standards PAR1789 [19]. The risk of epileptic seizure is high when flicker occurs at frequencies within the range of 3–70 Hz. Other less severe neurological symptoms including malaise and migraine might happen due to a visible or invisible flickering. Frequencies of 100 Hz for 50 Hz electric network in Europe or 120 Hz for 60Hz electric network in North America cause distraction and headaches, usually when there is a large variation in the light intensity [19].

Providing constant current to LEDs will reduce the flickering phenomenon due to the correlate relation between the LED forward current and its output light intensity. This approach is not applicable with dimmable LEDs, as they are sensitive to voltage variations in the network. This will be examined in this paper in details. A smart bulb has been introduced as a flicker-free LED in [20]. The dimming signal will be received by an external transceiver to vary the PWM signal duty cycle. However, this technique requires additional wireless communication modules in each individual bulb to support this technology, which adds complexity to the LED driver, and increases the cost of a large lighting network. A unified power quality conditioner has been proposed in [21] as a central comprehensive solution for both flickering and harmonics associated with commercial dimmable LEDs. This is achieved by providing a stable sinusoidal voltage across the LEDs in the occurrence of voltage fluctuations in the power grid.

The replacement of conventional lighting sources with LEDs dictates the need to perform more studies to examine the characteristics and behavior of commercial LED lamps. In this paper, a broad analysis of the main PQ issues related to the use of LEDs is presented. PQ problems can be classified into two main groups including voltage quality and current quality [8]. The voltage quality can be further categorized into steady state and disturbance as illustrated in Fig. 1. The steady-state category is specified for continuous and periodic characteristics, while disturbance appears randomly and occurs for a short time. For the purpose of this study, the effects of voltage flickering, voltage, current harmonics and the interaction between them are studied as steady state PQ problems. Voltage sag and voltage swell which happen for a short period are studied as disturbance PQ problems. Rest of the paper is organized as follows: Section II provides a review of LED lamp structure, LED driver and international regulations of LED lighting industry. Description of the methodology to evaluate the performance of LEDs, and experimental results are given in section III and section IV respectively.

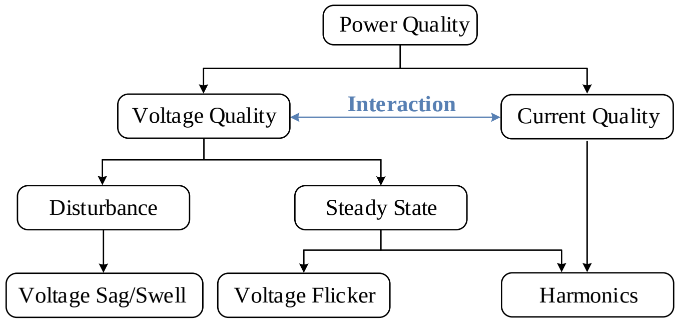

Fig. 1. Power quality problems classification [8].

II. LED Lamp Technology

Fig. 2 gives a sectional view diagram of the structure of a commercial LED lamp. The main components for this study are the LED string and the LED driver.

A. LED Semiconductor material

An LED lamp consists of a solid-state device that emits light when electric current passes through it. LEDs are fabricated by either inorganic semiconductor materials such as; indium gallium nitride (InGaN), aluminum gallium arsenide (AlGa) and gallium phosphide (GaP), or by organic (OLED) carbon based semiconductors [22]. Inorganic LEDs produce concentrated output light. They are mainly applied in residential, commercial and outdoor lighting applications. OLEDs allow for thinner, lightweight and larger surface area displays that can be used in TV, cellphones and tablets [23]. Due to their diffuse output light, they are suitable for indoor and decorative lighting applications. Both technologies continue to advance and develop in different applications.

B. LED Drivers

In order to characterize the behavior of an LED light bulb, it is important to study the operation of its internal driver circuit first. An LED lamp is a dc voltage load. Therefore, LED requires conditioning the input power and a current regulating driving circuit that delivers constant current to the LED. The LED driver is the main source of PQ problems. Various techniques have been developed to improve the reliability as well as the driving circuit of LEDs. LED drivers can be categorized into passive, active and DC driver.

1) Passive Driver

Passive LED drivers comprise only of passive components (e.g. resistors, inductors, capacitors and diodes). They are preferred in outdoor applications due to their high reliability and high efficiency. However, it becomes challenging to achieve low THD and high PF on top of low output voltage ripple. The valley-fill circuit has been proposed and modified shown in Fig. 3 to eliminate the large electrolytic capacitors (E-caps) that limit the life span of LEDs [24], [25]. Passive drivers

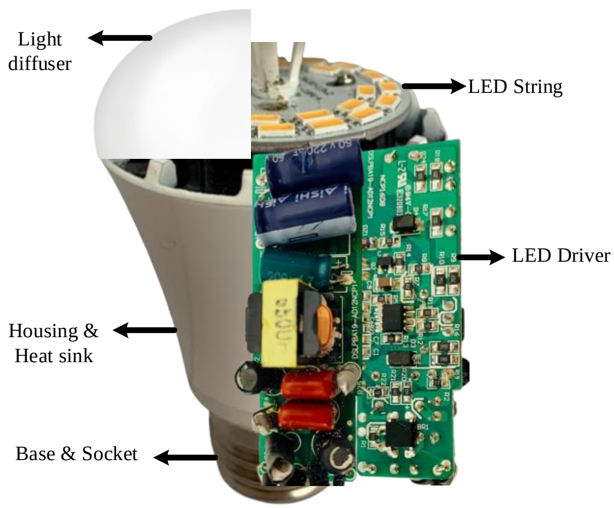

Fig. 2. Sectional view diagram of an LED lamp.

require large inductors that make the driver bulky and heavy.

2) *Active Driver*

Active drivers contain active semiconductor devices operating at high frequency that can achieve precise output control. The Literature classifies active LED drivers according to the number of power stages included [22], [26].

Single-Stage Topology

A single-stage topology has one controller where the ac input voltage is rectified and applied directly to the LED string. A typical single-stage topology is a rectifier bridge then a DC/DC converter that can be either buck, boost or buck-boost. A buck topology is shown in Fig. 4. The rectifying circuit draws current when the instantaneous input voltage exceeds the capacitor voltage as illustrated in the waveforms in Fig. 4. This will result in a high-distorted input current with low PF. The authors in [27] proposed a buck topology with current path control switches for LED segments for improved PF. Another popular single-stage topology is the flyback converter shown in Fig. 5 [28]. Flyback converter topology offers isolation and can function as a PFC. Generally, single-stage topology offers high power density with less number of switching devices. Nevertheless, it suffers from meeting the requirements of both high efficiency and long lifespan for LEDs due to the need of large E-caps at the output to reduce the output ripples.

Multiple-Stage Topology

It is challenging to achieve high PF, low output ripple and current control with one converter. For that reason, researchers introduced adding another converter. A two-stage topology, as given in Fig. 6, is typically used to offer a better performance and a reduction of output ripple. The first stage includes a PFC to shape the input current. The boost topology is mostly used for this stage due to its easy implementation. The second stage includes a DC/DC converter to maintain the voltage and the driving power of the LED string. The two stages will work independently. Having independent control loops and gate drivers will add to the cost of the system. Besides the energy is processed twice which will decrease the overall efficiency. For higher LED lighting applications (>100W), LLC converter has been introduced [29]. Fig. 7 shows a traditional topology for high wattage LED applications. As the PFC DC output voltage is high, an isolation is required. The DC/DC stage consists of a half bridge LLC resonant converter that drives the LED strings. Due to the increased number of switching devices, attention should be given to the switching loss.

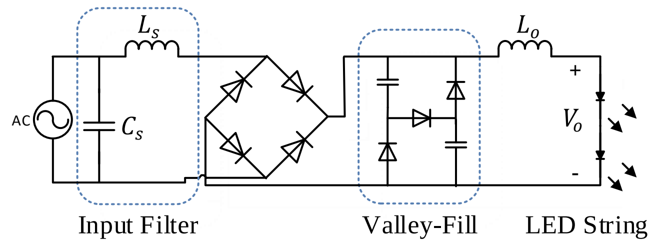

Fig. 3. Passive LED driver based on valley-fill circuit [24].

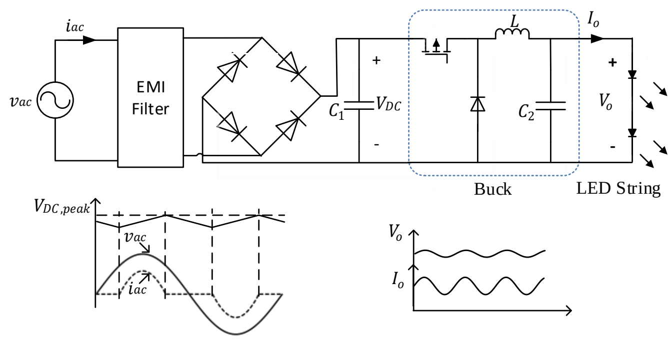

Fig. 4. Single-stage LED driver based on buck converter.

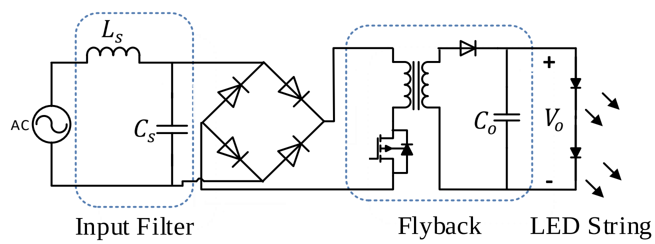

Fig. 5. Single-stage LED driver based on flyback converter.

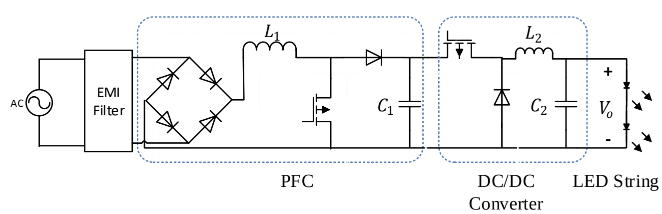

Fig. 6. Two-stage LED driver.

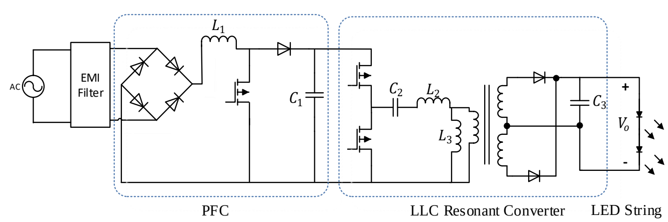

Fig. 7. Conventional two-stage LED driver for high power applications.

Integrated Single-Stage Topology

Integrated single-stage solutions have been introduced in the literature [30], [31] in which the PFC stage and the DC/DC stage are combined in one converter. This is attained by sharing the power transistor to achieve low input current harmonics and low output ripple. Integrated single-stage topology requires less number of switches, control and gate driving circuits. However, high voltage stress will be imposed across the switch. Therefore, it is mostly used in low power application.

3) DC Driver

DC microgrid is now being introduced with the adoption of recent technology of renewable energy sources. In a dc grid, there will be no need for the ac-dc conversion stage increasing the overall efficiency. Recent studies are proposing topologies for LED drivers that are compatible with dc grid. A buck-boost LED dc driver that allows battery operation has been presented in [32], while the authors in [33] have proposed a half bridge inverter with a variable inductor for current regulation. A dc grid does not guarantee a flicker-free environment. The immunity of LED lamps to flickering in low voltage dc networks is still being investigated [34]. This means that fluctuations in the voltage level in a dc grid might also cause visible and invisible light flickering.

It is important to note that flickering levels and amount of harmonics injected by LEDs are not constant and vary with the type of the utilized driving methodology.

C. LED International Regulations

Efficiency, power density, cost and lifetime are the four main criteria to design an LED lamp. However, manufactures must take into consideration international standards and regulations in their selection of an LED driver. The most adopted SSL standards are the IEC standard [9] and the Energy Star program [35]. In IEC 61000 3-2 standard, lighting equipment is under class C for power ratings > 25W or class D for ≤ 25W, in which harmonic contents of the input current, up to order 40, shall not exceed maximum permissible limits. ANSI, IESNA, UL and NEMA are the lighting standards referenced in the Energy Star program that defines performance characteristics and procedures to test SSL products. These criteria are applied for residential and commercial lighting products that are connected to the electric grid. Table II gives general requirements for power supply adopted in LED.

TABLE II
POWER SUPPLY REQUIREMENTS IN ENERGY STAR PROGRAM [35]

Power Factor	Commercial ≥ 0.9, Residential ≥ 0.7
Minimum Operating Temperature	-20°C or below for outdoor applications
Operating Frequency	≥ 120 Hz
Electromagnetic and Radio Frequency Interference	Commercial: Class A in FCC part 18 Residential: Class B in FCC part 18
Transient Protection	IEEE C.62.41-1991, Class A operation.

III. EXPERIMENTAL SETUP

In order to characterize the LED light bulbs working under different PQ conditions, an experimental setup has been implemented, which is used to execute light intensity, harmonic current contents and LED array driving voltage measurements.

A block diagram of the test setup, laboratory setup and the LEDs under test are shown in Fig. 8, Fig. 9 and Fig. 10 respectively. An ac power supply (Keysight AC6801A) is used to provide different ac voltage levels to the LED light bulbs. Besides, the ac power supply output can be controlled by an external reference signal from a function generator, thus it can simulate different voltage quality issues, such as voltage dip, swell and flickering. A 50MHz current probe, a 50MHz differential probe and an oscilloscope (Tek MDS3204) have been used to measure the current and voltage waveforms. A Power Analyzer (Yokogawa WT1800) is used to measure the current harmonics and PF.

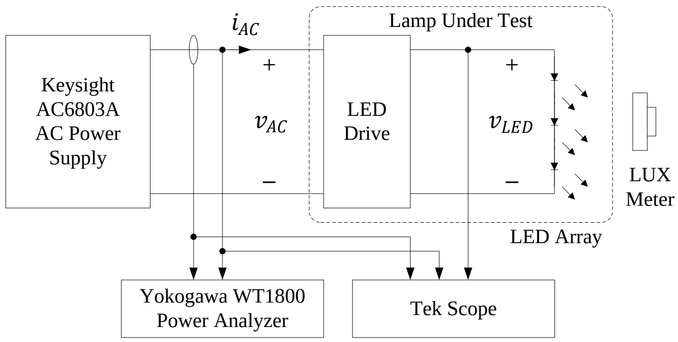

Fig. 8. Experimental setup block diagram.

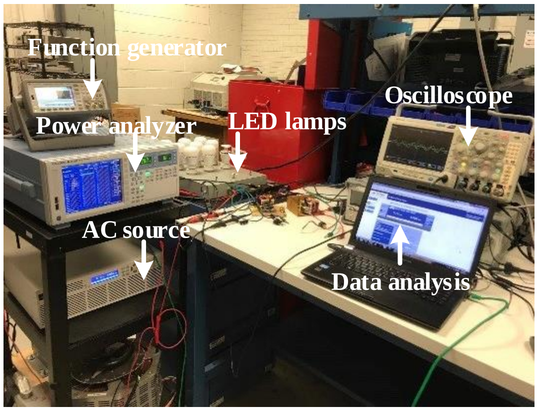

Fig. 9. Laboratory Setup.

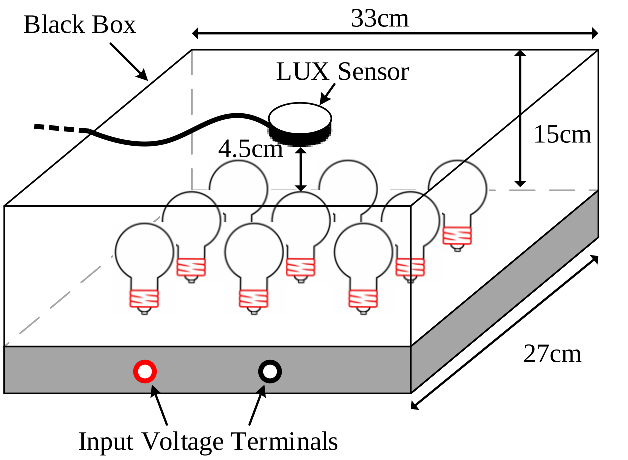

Fig. 10. Black box dimension.

A LUX meter (Anaheim Scientific H100) is used to measure the light intensity of the LED light bulbs when the ac power supply changes across the LEDs. A black box covers the lamp fixture. The detailed of the black box dimension is given in Fig. 10. The LUX meter is placed on the top of the box with 4.5 cm distance from the top of the light bulbs. It is important to mention that the purpose of using the black box is to have a fixed environment for the LEDs setup to analyze the change of the relative light intensity of the LEDs under various PQ conditions. The maximum output light intensity is measured under nominal voltage. Then, relative luminance values are measured under different PQ problems.

The experimental measurements employed in this research have been conducted on 9 LED bulbs (Sunbeam) with 12 W power consumption each that is equivalent to a 60 W incandescent lamp. The LED bulb is Energy Star certified. The internal driver of the LED bulb is a single-stage topology that consists of a bridge rectifier and a buck converter.

IV. Results and Analysis

Since LED lamps mainly employ power electronic devices to convert ac voltage to dc voltage and maintain the LED array driving voltage. These devices bring nonlinear characteristics to the LED lamps. Various tests have been conducted to analyze and characterize the behavior of the LEDs under dynamic and static changes.

A. Harmonic analysis

The first test is to evaluate the current quality of the LED light bulbs. A pure sinusoidal input voltage has been applied directly across LEDs under test. Table III lists the testing conditions under nominal operating point. The internal driver of the LED bulb under this test consists of a PFC topology using buck converter. The maintained output voltage is set to a value lower than the peak ac voltage. Input current will flow when the instantaneous ac voltage is higher than the output voltage. Otherwise, the bridge rectifier is reverse biased. Therefore, there is a zero current zone at the grid voltage zero crossings. Fig. 11 shows the input current drawn by the LEDs with a nominal input voltage of 120V root mean square (rms). Lower bus voltage level is required in a PFC buck topology compared to a PFC boost topology. Nevertheless, achieving high PF and low THD is limited [36]. The input PF, the total harmonic distortion of the voltage (THD_V) and the current (THD_i) have been measured using the power analyzer and given in Table III under nominal operating condition. The results show that the PF of the LEDs under test is acceptable, however THD_i is high since it cannot provide a sinusoidal current at the input.

High harmonics injected to the network will lead to overheating in cables and equipment, high core and copper losses in motors and transformers, and electromagnetic interference with communication systems. Moreover, the interference of two or more nonlinear loads will result in a distorted bus voltage, which in return influences all the loads connected to the same bus. Hence, more harmonic contents will be injected back to the network. The second test is to observe the interaction between voltage and current harmonics. In this test, a distorted input voltage has been applied across the LEDs. The applied voltage contains up to 7th order harmonic components. Fig. 12 shows the waveforms of the applied distorted voltage and the corresponding drawn current by the LEDs. Power analysis measurements have been recorded. The results give an increase of the THD_i from 31.104% to 36.736%, and an increase of input current from 0.876A to 1.130A. Thus, an increase of input power delivered to the load by 3%. These indicate that not only the harmonics level will be higher for a distorted bus voltage, yet a sudden increase in the total power demand will occur especially, if a large number of LEDs are connected.

TABLE III
BASIC PARAMETERS MEASURED FOR LED LAMPS UNDER TEST

Parameter	Value	Parameter	Value
$V_{AC,rms}$	119.93 V	$I_{AC,rms}$	0.876 A
f_{Line}	60 Hz	PF	0.94414
P	98.9 W	S	105.1 VA
THD_V	0.051%	THD_i	31.104%

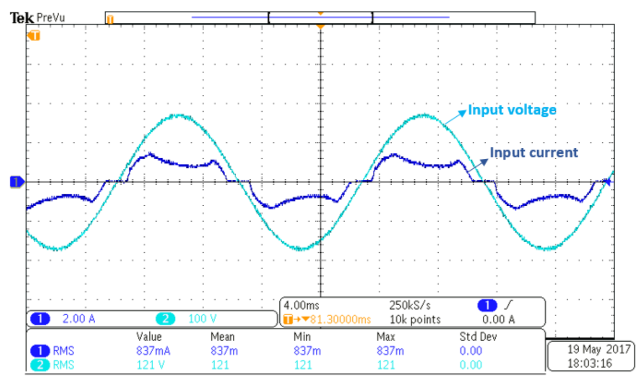

Fig. 11. Input voltage and input current drawn by LEDs.

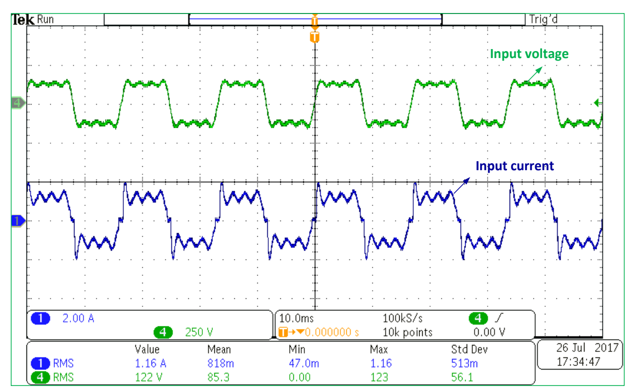

Fig. 12. Distorted input voltage and input current drawn by LEDs.

The chart given in Fig. 13 shows the harmonic current spectrum expressed in mA. The graph highlights two scenarios: harmonic current spectrum with pure sinusoidal input voltage and with distorted input voltage. Higher harmonic components are experienced with the distorted input voltage. The test results are compared with maximum allowable current in IEC 61000-3-2 standard [9]. Harmonic contents exceed for 7th, 9th and 11th harmonic order. Despite the fact that an individual LED bulb adds a minor effect to a large network, the harmonic distortion

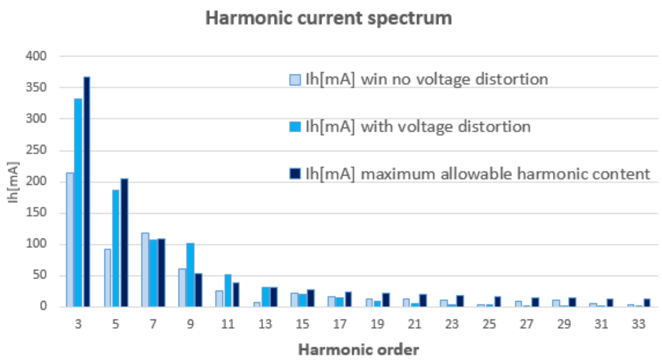

Fig. 13. Harmonic spectrum of the current drawn by the LEDs.

level will be high when several LEDs are connected to the same feeder e.g. street lighting or parking lot lighting.

B. Static relationship between light intensity, LED array voltage and input voltage

It is well known that one of the advantages of using LED bulbs is the compatibility with TRIAC dimmer. The amount of light intensity provided by an LED is proportional to the average current passing through it [38]. The dimming capability is achieved by sensing the input voltage level to adjust the average current fed to the LED string [39]. Subsequently, the output light intensity can be controlled.

A test has been conducted to study the change in the output light intensity by varying the ac-applied voltage across the LED lamps. The ac voltage across the LEDs has been gradually decreased from 120V rms to zero. Below 30V rms, the voltage cannot sustain the LED array and the lamps turn off completely. At 120V the total luminous flux incident on a surface per unit area (illuminance) is found to be 12800 LUX. This value has been taken as the maximum output light intensity of the LEDs under the test condition. As the black box has been used to cover the LEDs in this test, all other measurements are given relative to the maximum output illuminance expressed in percentages. The results in Fig. 14 show that if the applied voltage is reduced, the voltage across the LED will be changed and hence the output light intensity will be decreased accordingly, until it reaches 30V. This means that the LED driver will translate the reduction of the applied voltage into a request of dimming. The reason of light intensity dropping is the LED array driving voltage drops as well. This directly affects the power consumption of the LED devices as well.

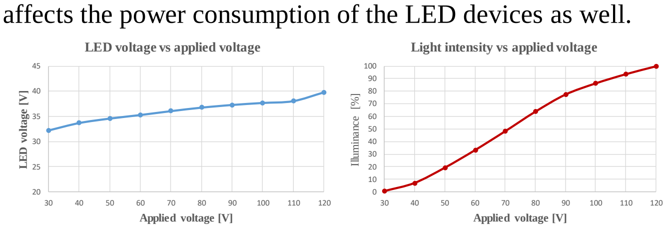

Fig. 14. Input voltage vs LED voltage and light intensity.

C. Dimming with amplitude variation technique

From the discussion in the previous subsection, dimming an LED can be achieved by varying the amplitude of the voltage applied, therefore controlling the LED forward current, hence its light intensity. Table IV shows PQ parameters for a reduced sinusoidal rms voltage across the LEDs under test. The change in the harmonic components is not linear due to the non-linearity of the LEDs. Harmonic contents depend mainly on the PFC circuit implemented in the LED driver. The results depict that the distortion level is still within the permissible limits given that dimming has been achieved by reducing the sinusoidal voltage amplitude. On the other hand, violation of maximum allowable harmonic contents has been observed using TRIAC dimmer [37], as the input voltage will be chopped. Therefore, the voltage applied across the LEDs will be distorted. Moreover, high inrush current will be drawn by LEDs to charge the input filter capacitor.

TABLE IV
POWER QUALITY PARAMETERS WITH VARYING VOLTAGE AMPLITUDE

Applied rms voltage	Fundamental current [mA]	3rd harmonic [mA]	5th harmonic [mA]	7th harmonic [mA]	THD_i [%]
110	843.1	145	125.5	98.5	25.64
100	846.7	65	138.9	72.2	20.31
90	829.2	54.9	118.5	52.4	17.35
80	749.8	101.9	93.6	41.6	19.37
70	630.8	117.8	82.4	24	22.98
60	504.7	128.6	63	5	27.86
50	369.7	129.4	33.7	15.2	34.71
40	226.4	108.4	2.4	18.3	44.19
30	106.8	74.1	29.4	3.1	60.59
< 30	LEDs turn off				

D. Flickering and sensitivity to voltage fluctuations

Flickering is a rapid change in the intensity of light bulbs, which causes a visual change in the light intensity. The effects caused by voltage flickering depend mainly on the amplitude and the frequency range of voltage variations. In this paper, the percent flicker will be calculated as a measure of flickering as follows [40],

$$Percent\ flicker = \frac{\max LUX - \min LUX}{\max LUX + \min LUX}$$

Amplitude modulation (AM) technique is used to emulate flickering. A programmable ac-source with a modulated amplitude signal is applied to the LEDs. The amplitude-modulated signal is expressed by:

$$s(t) = [A_c + A_m \sin(2\pi f_m t)] \sin(2\pi f_c t) \quad (1)$$

where:

$$\text{Carrier signal: } c(t) = A_c \sin(2\pi f_c t) \quad (2)$$

$$\text{Modulation signal: } m(t) = A_m \sin(2\pi f_m t) \quad (3)$$

and, $$\text{Modulation index: } m = \frac{A_m}{A_c} \quad (4)$$

The modulation index is a measure of how much a modulated signal is varied with respect to its unmodulated level. The effect of changing the modulation frequency and the modulation index (m) on the output light intensity has been investigated. Fig. 15 shows an amplitude-modulated signal with 60 Hz carrier frequency, 4 Hz modulation frequency waveforms and

8% modulation index. It can be seen that the LED voltage is fluctuating with the same frequency as the input voltage.

A string of LED has I-V characteristics similar to a diode. An LED is a p-n junction with a dynamic resistance that shifts as the forward current changes. A slight change of an LED voltage will result in a large change in LED current. The LED string can be modeled as a threshold voltage in series with a dynamic resistance [30]. Therefore, an assumption has been made in the measurements; the dynamic response of the LED array is very quick for changing the array voltage to the light intensity and cannot be recorded using the LUX meter. Hence, curve fitting has been done using Fig. 14 measured results to map the light intensity to the scope measured LED array voltage. Fig. 16 shows a steady state input voltage of 120 V rms without voltage flickering, which results in high frequency changes (including the double line frequency and the switching frequency) in the light intensity that are not observable by human eyes. Yet, there is no low frequency variation in the light intensity. In contrast, a further experiment by inputting a modulated ac signal to represent voltage flickering that has frequencies of 60±15 Hz, shown in Fig. 17. In order to have a better observation of low frequency components, high frequency signals, which are not observed by human eyes, are removed by using data processing in the light intensity data with MATLAB software tool. A waveform with a low frequency variation of light intensity can be seen at the bottom row of Fig. 17. The low frequency variation in the LED voltage caused a visible rapid change in the illuminance of the LEDs. It is the reason to have observable flickers from LED light bulbs. Fig. 18 shows that for slower flickering frequencies less than 5 Hz, the variation of light intensity is very slow to be observed by a human eye. However, these invisible variations might cause a health risk as addressed by the PAR1789 standards, as the sensitivity of a human eye to flickering differs from one person to another.

The effect of varying the modulation index (*m*) on the percent flicker is shown in Table V. The percent flicker is calculated for input voltage flickering with a 2% step change in *m*. The results verify that, lower *m* meaning lower voltage peaks variations will result in lower flickering.

The observed light intensity by a human eye is dissimilar from the light intensity measured by a lux meter. The relation between the measured and the perceived light intensity is nonlinear and governed by the following [40],

$$P_i\,(\%) = 100 * \sqrt{M_i\,(\%)/100} \qquad (5)$$

where: P_i is the perceived light intensity, and M_i is the measured light intensity.

For instant, a bulb that is dimmed to 5% of its full intensity will be perceived by 22.4%, while 80% dimming level will be perceived as 89.4%. Fig. 19 shows the measured and the perceived light for LEDs under test under different applied voltage levels. It can be noted that at low dimming levels the perceived light intensity will be higher than the desired one. The reason is at low light levels, the human eye enlarges the pupil to permit a greater amount of light to enter the eye [40]. In order to examine if this difference would improve the percent flicker for the end-user, various light intensities have been considered. Dimming has been achieved by varying the amplitude of the sinusoidal voltage across the LEDs. Fig. 20 and Fig. 21 show measured and perceived light intensity with input voltage flickering at 100% and 16% light intensity respectively. Perceived illuminance for 16% dimming level is found to be 40%. The percent flicker has been calculated when the lamps are dimmed.

Measured and perceived percent flicker under various dimming levels applying same modulation index and same frequency flickering input voltage are given in Table VI. The results indicate that dimming LEDs would increase the amount of flicker produced even though the perceived percent flicker is improved compared to the measured one. In other words, LEDs are more sensitive to flickering in the presence of dimming.

TABLE V
PERCENT FLICKER FOR 2% STEP CHANGE IN MODULATION INDEX

m	2%	4%	6%	8%	10%
Percent flicker	38.01%	41.26%	41.26%	43.17%	43.17%

TABLE VI
PERCENT FLICKER UNDER DIFFERENT DIMMING LEVELS

Applied voltage	40V	60V	80V	100V	120V
Light intensity	7%	34%	66.5%	89.5%	100%
PF (measured)	66.28%	43.17%	25.02%	8.44%	4.4%
PF (perceived)	37.9%	22.7%	12.71%	4.23%	2.2%

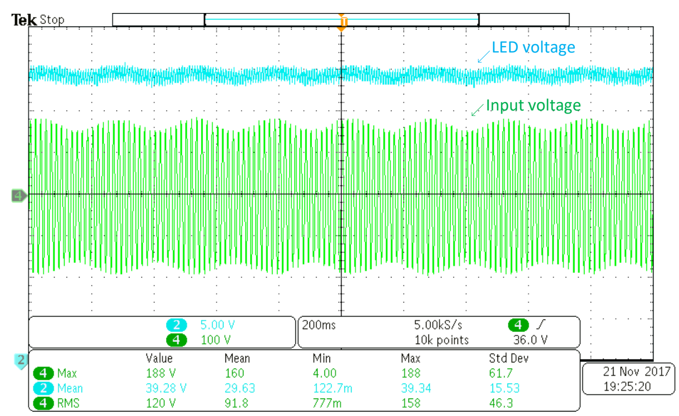

Fig. 15. Applied voltage flickering to LED.

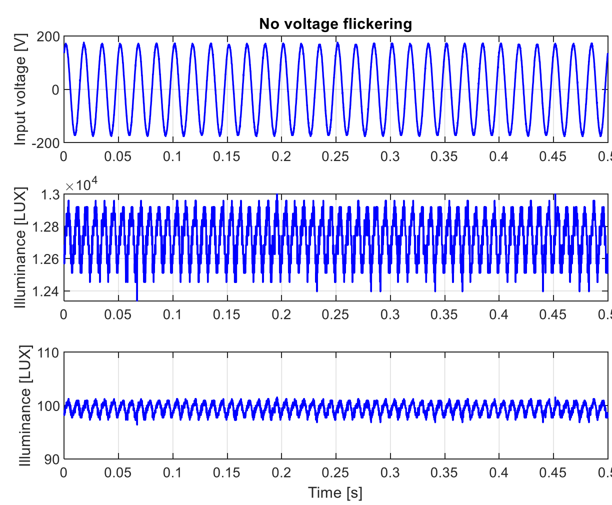

Fig. 16. LED voltage and light intensity with no flickering input voltage.

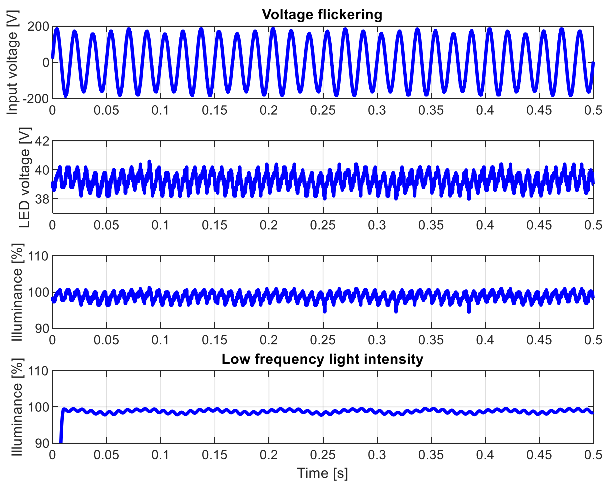

Fig. 17. LED voltage and light intensity with 15 Hz voltage flickering.

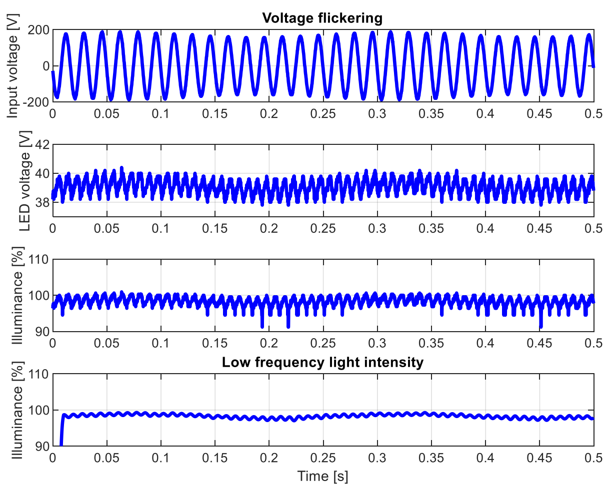

Fig. 18. LED voltage and light intensity with 4 Hz voltage flickering.

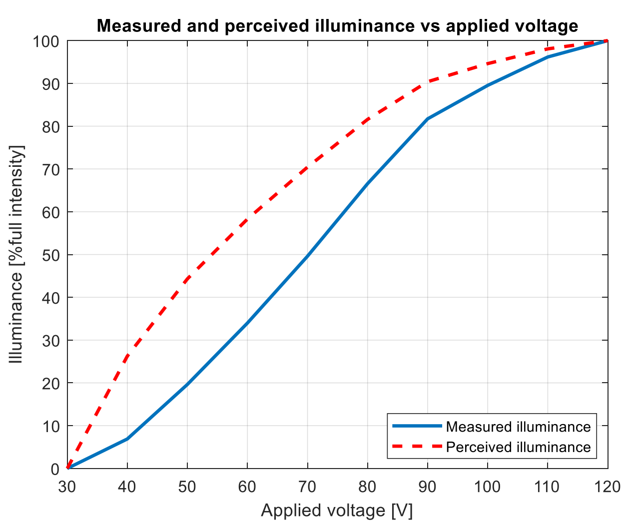

Fig. 19. Measured and perceived light intensity under different voltage levels.

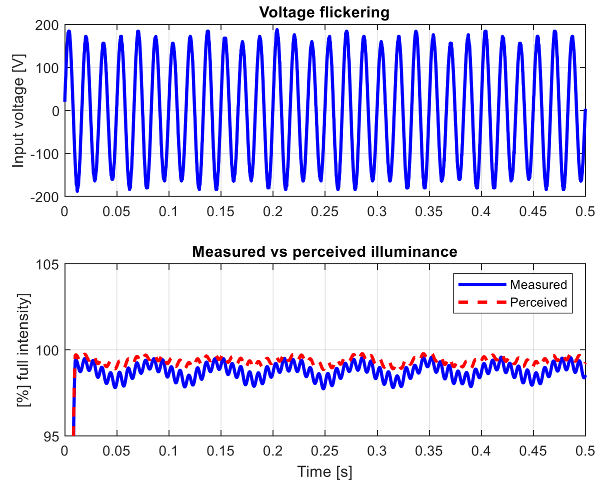

Fig. 20. Measured and perceived illuminance for 100% light intensity with voltage flickering.

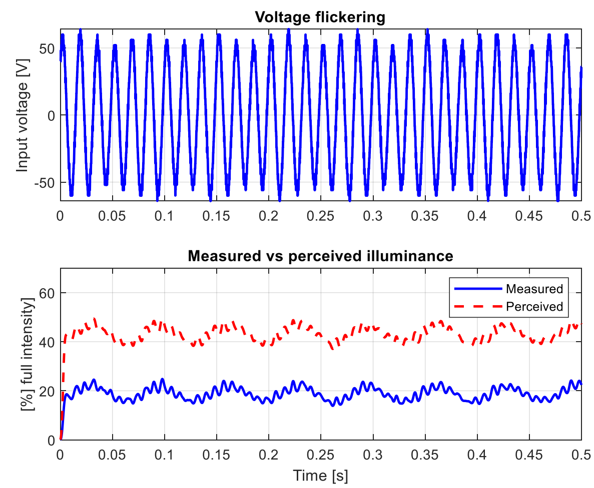

Fig. 21. Measured and perceived illuminance for 16% light intensity with voltage flickering.

E. Voltage sag and swell

This test aims to examine how LEDs would react in the presence of a voltage sage Fig. 22 or a voltage swell Fig. 23. Different levels of voltage sag have been applied across the LEDs as shown in Fig. 22. The voltage sag levels are 90%, 70% and 50% of nominal voltage respectively. The figure shows that at the event of a voltage sag, the LED voltage, which is the dc voltage applied to the LED string, will be affected and reduced as well. This happened because the LED driver interpreted this voltage reduction as a request to dim the LEDs. Hence, the controller will react to achieve a new operating point driving the LED string at a lower voltage and a lower forward current. Since the light intensity of the LED changes linearly with its forward current, this reduction in the LED voltage, even if it is for a short time, will result in a corresponding decrease in the bulb output illuminance. This disturbance will cause a visible light flickering that might disrupt the end-user.

Furthermore, it has been observed that the lamps will malfunction and turn off for a voltage sag less than 25% of rated voltage as shown in Fig. 24. The figure shows that the LED voltage reaches the new operating point quickly however the controller fails to maintain the new voltage level. As a result, the capacitor starts to discharge through the internal sensing resistors. The controller starts to react again to charge up the capacitor but the energy provided by the input source was not large enough, therefore the controller fails again. During this period, the LEDs completely turn off until the voltage sag is over. The input current starts to increase charging up the capacitor until the operation reaches steady state.

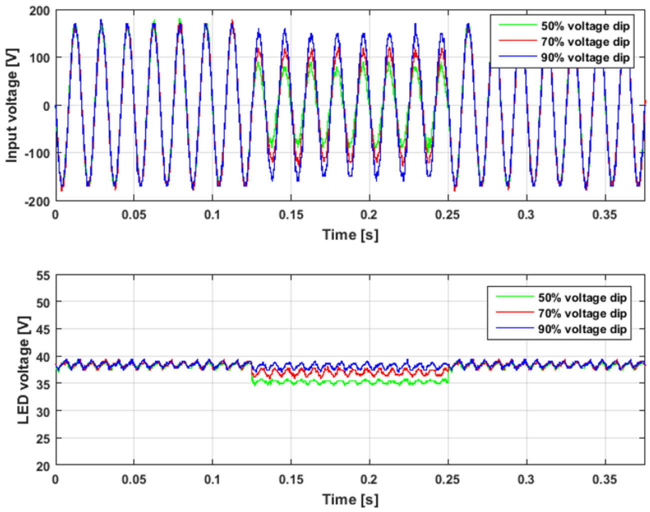

Fig. 22. Voltage across the LED for different applied voltage sag levels.

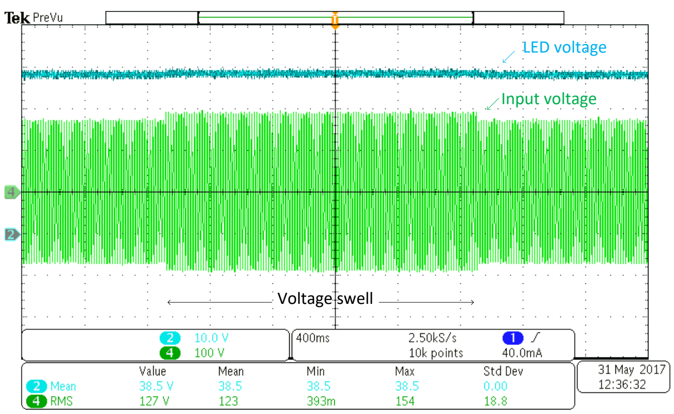

Fig. 23. Voltage swell at 132V.

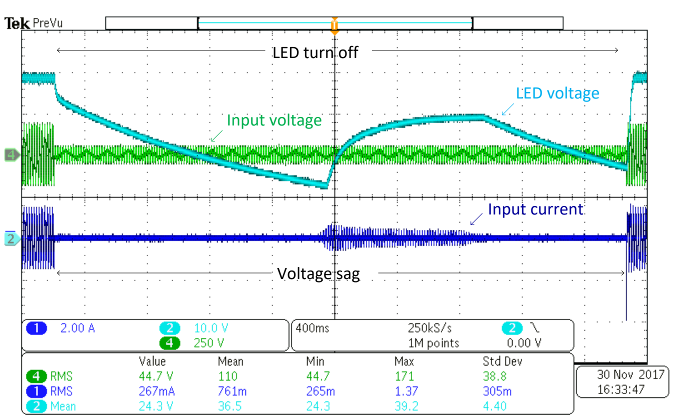

Fig. 24. LED voltage at 23% voltage sag.

This can be dangerous especially in street light applications, where it might distract the drivers and cause unexpected response that possibly lead to road accidents. The sensitivity of LEDs to a voltage swell is similar to their sensitivity to a voltage sag. A voltage swell of 110% of nominal rated voltage has been applied to the LEDs as shown in Fig. 23. As a result, the voltage across the LEDs has increased respectively. The input power consumed by the 9 LEDs under test has also been increased to 112 W, which means for a large-scale of LEDs, a voltage swell might cause a sudden increase in the total network power demand.

V. Conclusion

Characterization and evaluation of commercial dimmable LEDs have been done through an experimental platform. Light intensity measurements, current and voltage waveforms were collected under numerous power quality conditions. The collected data had been processed using MATLAB software tool. The key findings of the conducted tests can be concluded into two main power quality issues associated with the utilization of LED lighting technology; harmonics injection affecting the utility side and flickering phenomena affecting the end-users. The results showed that the LEDs under test inject harmonic contents to the network that should not be ignored especially for applications that require a large number of connected LEDs. To achieve dimming, amplitude voltage variation had been applied across the LEDs. It is recommended varying the amplitude of the applied sinusoidal voltage across the LEDs, rather than using conventional dimming technique such as TRIAC-dimmer system to achieve dimming. This will limit the injected harmonics to the level designed by the manufacture. The results also indicate that the performance of LEDs is significantly affected by the quality of the grid. Flickering in LEDs light intensity had been observed in response to various grid events. The amount of flicker produced by an LED lamp was found to be dependent on the amplitude and the frequency of which the voltage variations occur. This stresses the need to develop a comprehensive power quality improvement technique for such an application.

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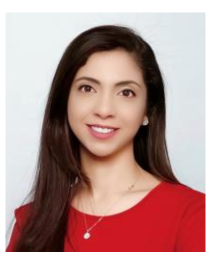

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