LIGHT INTENSITY IMMUNITY PERFORMANCE OF LED STREET LAMPS UNDER POWER QUALITY DISTURBANCES

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ABSTRACT

An increasing application of LED street lamps brings out an important question regarding their immunity against power quality disturbances. The behaviour of commonly used lighting equipment such as incandescent lamps, compact fluorescent lamps (CFL), and gas-discharge lamps is known. However, knowledge on immunity of LED based lighting equipment is still limited, particularly in street lighting aspect. In this paper, immunity of LED street lamps is determined for voltage dips, short interruptions, voltage fluctuations and supraharmonics. A series of experiments has been performed with respect to test levels defined in IEC 61000-4-11, IEC 61000-4-15 and IEC 61000-4-19. Voltage dips and short interruptions cause higher short-term light flicker severity values that might lead to unintended consequences for car drivers and pedestrians. Interharmonics can result in light flicker, but the impact is very limited, only one lamp exceeds the limits. Supraharmonics impact the current but have minor impact on the visible light. The supraharmonic current can be 25 times nominal. This could decrease the lifetime of equipment.

INTRODUCTION

LED street lamps, an integrated light, have become attractive in recent years due to their energy efficiency and cost saving properties [1]. By replacing high pressure sodium lamps, currently in use, with LED street lamps 46% energy saving is estimated by 2030 [2].
LEDs, in street lamps, have fast response characteristic with respect to injected current that is controlled via power electronic converters. When the lamps are subjected to any voltage disturbance in the grid, it is possible that light intensity is impacted, and so an adverse effect can occur for car drivers and pedestrians [3]–[5].
Occurrence of power quality (PQ) disturbances in the grid depends on many factors such as nonlinear load/generation, location, impedance etc. Well know PQ disturbances are inter/harmonics, voltage dips and short interruptions. Also, supraharmonics injected by power line communication and switching of power electronics equipment have received attention in recent years [5]–[7].
One way to analyse impact of PQ disturbances on the lamps' illuminance is to expose them to those disturbances in a controlled way. For example, it was shown that non-synchronized supraharmonics can result in intermodulation of light intensity in low-wattage LED lamps [5]. In [8], it was concluded that the sensitivity of LED lamps to voltage dips depends on DC-link capacitor and ballast configuration. The need for research on low-wattage LED lamps under voltage dips was emphasized in [9]. Several papers show sensitivity of low-wattage LED lamps with respect to inter/harmonics. Since the converter and control strategy differ, it results in variety in light intensity variation when lamps are exposed to interharmonics [10], [11].
Although the behaviour of low-wattage LED lamps under PQ disturbances was established in different studies, less attention has been paid to LED street lamps, which require higher safety and operation in harsh environment. This paper analyses the impact of PQ disturbances on the light intensity variation in LED street lamps. The lamps have been exposed to PQ disturbances and the results have been assessed in terms of lighting metrics such as short-term light flicker severity and modulation depth. Exceeding of limits has been interpreted in terms of consequences in driving.

METHOD

Testing procedure, description of test profiles and assessment technique of obtained results are discussed in this section.

Experiment setup

In order to uncover the behaviour of the LED street lamps under power quality disturbances, an experimental setup is configured as shown Fig. 1. Voltage waveforms are generated by a signal generator and amplified by using an amplifier. Lighting and electrical quantities are recorded as 100 kS/s sampling frequency.

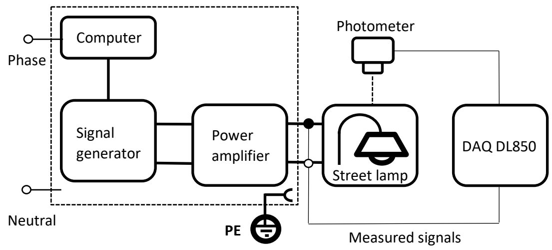


Fig.1 LED street lamp testing mock-up

Test profiles description

For immunity test of LED street lamps, voltage dip/short interruption and interharmonics profiles have been applied. Before the test profile application, the lamps have been exposed to a background test profile, which is 230 V and 50 Hz, within one-hour thermal stabilization time [12].

Voltage dips

For observation of sensitivity of LED street lamps to voltage dips and short interruptions, five different voltage dips were chosen from IEC 61000-4-11[13]. Table I shows residual voltage and durations for these dips.

TABLE I

Test levels for voltage dip application

Dips	Residual voltage	Duration	Classes as IEC 61000-2-4
Dip #I	0%	½ cycle	Class 2
Dip #II	0%	1 cycle	Class 2
Dip #III	40%	10 cycles	Class 3
Dip #IV	70%	25 cycles	Class 3
Dip #V	0%	250 cycles	Class 3

Interharmonics

In order to obtain the performance of the lamps under voltage fluctuation [14], a set of voltage signals including interharmonics has been applied as given in equation (1):

$$u(t) = V_m \left(1 + \frac{\Delta V}{V}\cos(\omega_{ih} t)\right)\cos(\omega_m t) \qquad (1)$$

Where V_m and ω_m represent the mains voltage and frequency, respectively. ΔV/V is the voltage fluctuation rate and ω_{ih} is the applied fluctuation frequency. Instead of application of each interharmonics, only mandatory frequencies as shown in Table II were used. These fluctuations are able to generate $P_{st}^{LM} = 1$ values that are known as annoyance threshold for an incandescent lamp.

TABLE II

Voltage fluctuation levels for interharmonics application

Hz	Voltage fluctuation ΔV/V	Hz	Voltage fluctuation ΔV/V
0.5	2.32%	15	0.43%
1.5	1.06%	20	0.70%
5.0	0.44%	23	0.89%
8.8	0.25%	25	1.37%
10	0.26%	33	2.12%

Supraharmonics

The lamps have been subjected to a supraharmonic voltage of 3 V sweeping from 2 kHz up to 150 kHz. According to IEC 61000-4-19, the supraharmonic voltage is superimposed on the fundamental voltage in pulses. Pulse time is 3 s, which is representative of continuous exposing due to AC/DC converters or power line communication (PLC) signalling. The pause time is employed as 200 ms that represents time-limited characteristic of disturbance.

Assessment technique

In order to be able to analyse immunity of LED street lamps, performance metrics and thresholds in terms of function of equipment are needed. In this study, two performance metrics were considered, as follows:

Short-term light flicker severity: P_{st}^{LM}

It is a measure of flicker that is constituted considering human perception of light intensity variation. $P_{st}^{LM} = 1$, is the threshold where an average human can perceive flickering lights, frequencies up to 80 Hz is included in the P_{st}^{LM} calculation [15]. P_{st}^{LM} is employed as an assessment criteria and one-unity as threshold.

Modulation depth: MD

Change in light signal over time is known as modulation depth [16]. MD is an indicator of how light intensity variation is sensed. Both magnitude and frequency play roles in the assessment. For instance, light intensity changes above 80 Hz are invisible to humans regardless of magnitude. The most sensitive frequency is 8 Hz for humans. IEEE 1789-2015 recommends thresholds for MD with respect to frequency up to 10 kHz [17].

$$MD = \frac{L_{max} - L_{min}}{L_{max} + L_{min}} \qquad (2)$$

RESULTS

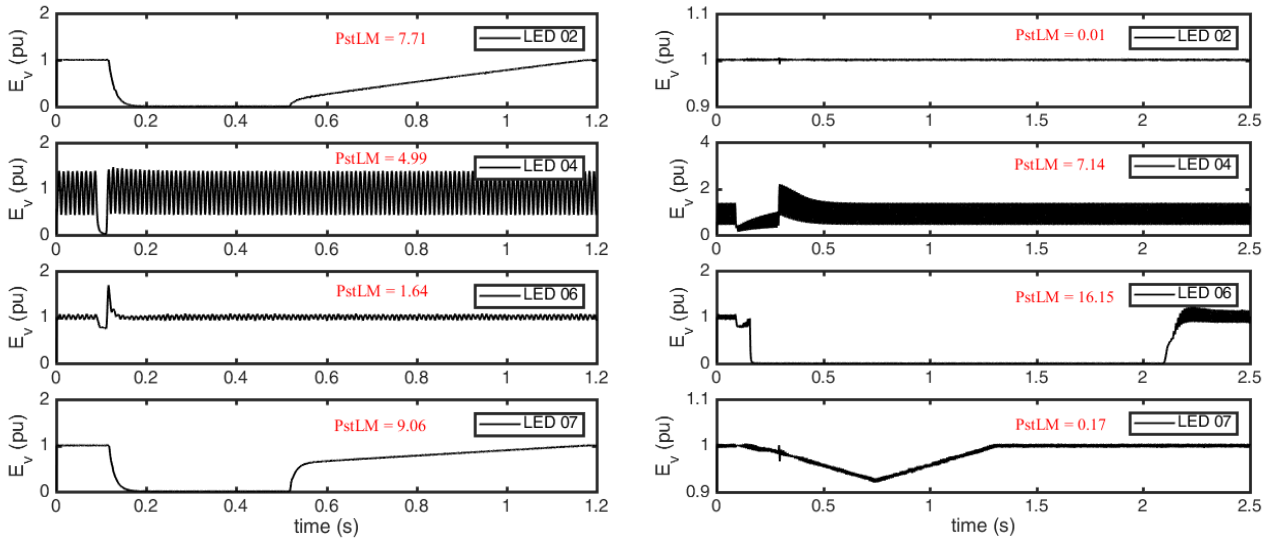
In this section, test results and observations are presented as below.

Sensitivity to Voltage dips & Short Interruptions

Light intensity variations under voltage dips and short interruptions are given in Fig. 2 for selected lamps.

Short interruption with one cycle duration are shown in Fig. 2(a). LED 02, LED 04 and LED 07 extinguish and result in higher P_{st}^{LM} values while LED 06 keeps operation without going zero light intensity. An overshoot is observed in LED 06 at 1.7 per unit (pu). This lamp exhibits lower P_{st}^{LM} value that means less annoyance or perception rate. All four lamps present P_{st}^{LM} values above the threshold.

Fig. 2(b) shows results for 40% residual voltage during 10 cycles. LED 02 is the least impacted one, giving $P_{st}^{LM} = 0.01$. LED 06 extinguishes for about 2 seconds. It raises the P_{st}^{LM} value as high as 16.15. During extinguishing period, the visibility of an object on the road might be lost, which might have unacceptable consequences. LED 07 is well below the threshold of $P_{st}^{LM} = 1$. LED 04 keeps providing light, but in decreased magnitude during the dip. An overshoot can be observed reaching 2 pu. The lamps can extinguish for longer than the dip duration.



a) Short interruption at one cycle duration

b) Voltage dip at 40% residual voltage and 10 cycle duration

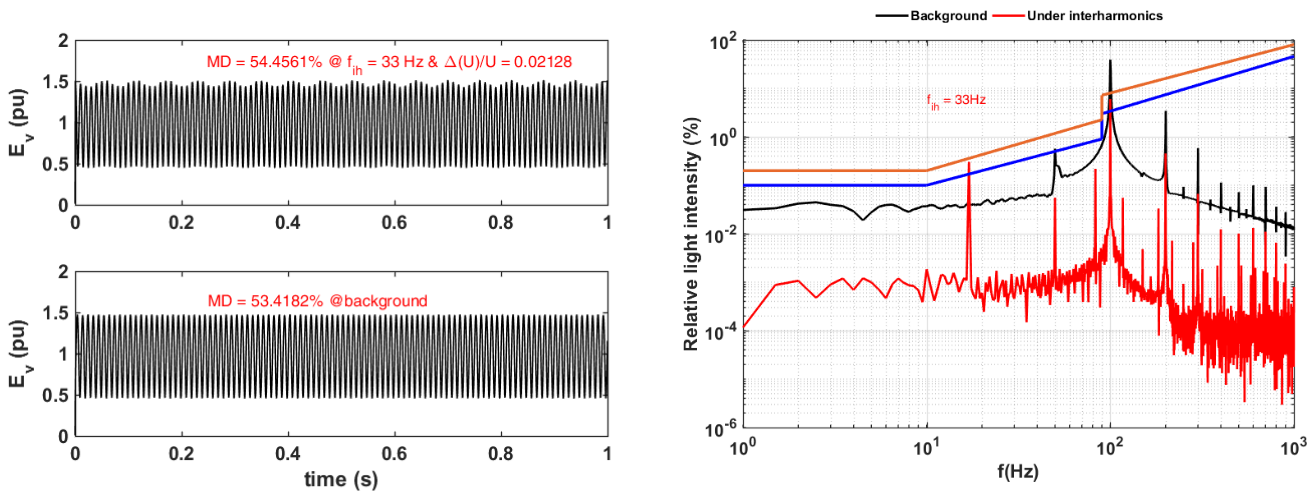
Fig.2 Voltage dip and short interruption application results

Sensitivity to Inter/harmonics

Most of the tested lamps are immune to interharmonics with a few exceptions. For instance, when 33 Hz is applied on LED 04, it results in an amplitude modulation at 17 Hz (i.e. 50-33 Hz) as seen in Fig. 3(a). IEEE 1789 defines the limits for MD so that there is no undesired light intensity variation. The limits set by IEEE 1789 are exceeded at 17 Hz as seen in Fig. 3(b) where the orange and blue lines represent low-risk and no observable risk regions, respectively. There are additional components, next to the interharmonics, seen as sidebands at ±17 Hz, but they are below the limits. When this lamp is subjected interharmonics, 33 Hz in this case, it can result in visible flicker.

The interharmonics voltage magnitudes are defined based on the response of a 60 W incandescent lamp; LED street lamps perform better than incandescent lamps. Arc furnaces, photovoltaic (PV) inverters and wind turbines are possible sources of interharmonics but levels of interharmonics in the low voltage grid are usually low and the risk of flicker in LED street lamps due to interharmonics is therefore low.

For harmonics, two types of distorted waveforms, flat-top and pointed-out, have also been applied. These can be obtained by applying individual harmonics 3, 5 and 7 with different magnitudes and phase angles. There is only one lamp impacted by harmonics. Applying pointed out waveform causes a 2% increase in MD.



a) Time domain light intensity variation

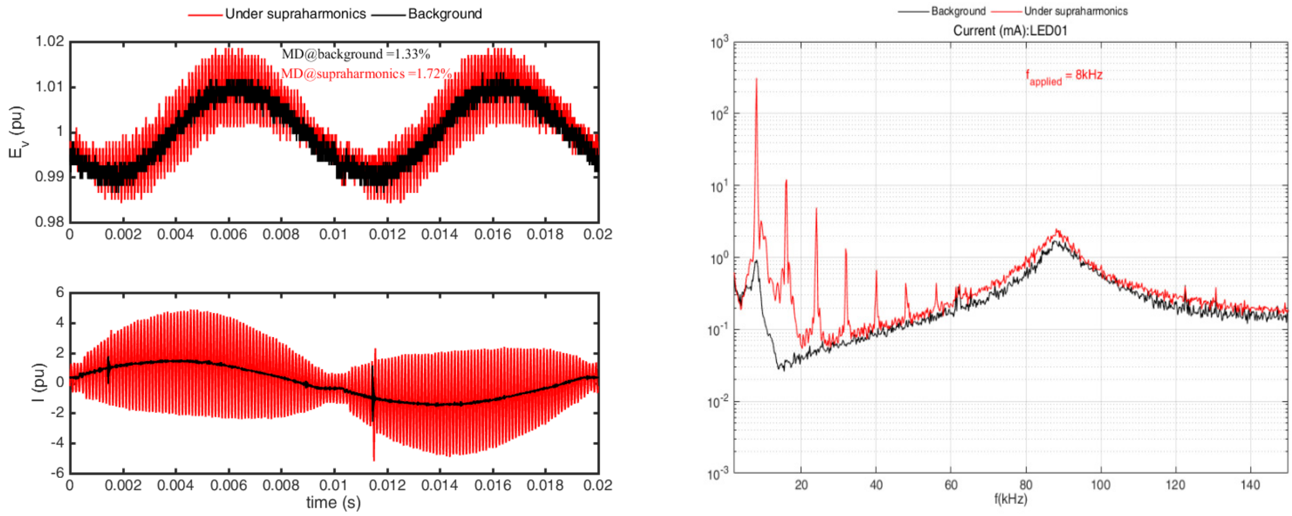
b) Light intensity dft components

Fig.3 Light intensity variation and components with and without interharmonics for LED 04

Sensitivity to Supraharmonics

All lamps have been tested under supraharmonic voltage at 3 V ranging from 2 kHz to 150 kHz. Most of the LED street lamps tested have no impact on the light output, except LED 01. When a supraharmonic voltage at 8 kHz is applied, it passes through the circuit and can be observable in the light intensity signal as shown in Fig. 4(a). This results in increased MD, too. The impact of 8 kHz fluctuation in the light intensity on an observer is unknown.

The lamp current is however affected as given in Fig. 4 (below). The current shows frequency dependent characteristic, the peak current could be 25 times the nominal current for LED 06. This could have an adverse effect, e.g. failure and reduction of lifecycle of the lamps. In Fig. 4(b), it is seen that 8 kHz and its multiples are present in the spectrum of the current. A component of 8 kHz, without multiples, is present even without this voltage being applied and this is most likely the switching component of this LED driver.



a) Time domain light intensity and current variation b) LED street lamp current dft components

Fig.4 Light intensity variation and components with and without supraharmonics for LED 04

DISCUSSION AND CONCLUSION

There is a diversity in the results of tested lamps when they are subjected to a power quality disturbance.

Table III shows a summary of the power quality phenomena tested and their impact on the LED street lamps. Phenomena containing a risk of visible light impact are shown in red shading. The lamps exhibit most similarities for 0% residual voltage during 250 cycles where all the lamps extinguish. LED 05 and LED 08 are not impacted for other voltage dips and interruptions. LED 02 shows major impact under 0% residual voltage and ½ and 1 cycle as zero light intensity for about 1 second.

The green color in Table III represent that there is no or minor risk that LED street lamps do not operate properly, i.e. no impact on a driver or pedestrian. In this group, the impact is either too small or there is no perceived variation. Yellow colour indicates that there might be a risk of light intensity variation that a person can perceive.

The range of residual light intensity during the dip is indicated in Table III. In addition, the time of dip duration in light with respect to applied dip duration is given for comparison.

When exposed to interharmonics, only one lamp, LED 04, exceeded the limit of MD as defined in IEEE 1789. Impact of interharmonics on LED street lamps is however limited. LED 01 and LED 09 increases in MD but the MD remained below the limits.

Tested LED street lamps are immune to supraharmonics in terms of impact on P_{st}^{LM} or MD, however supraharmonics can interfere into circuit and result in fluctuation in the light intensity at corresponding frequency e.g. 8 kHz for LED 01 below the limits.

The most severe impact on light intensity variations has been observed for voltage dips and short interruptions. The extinguishing time is unpredictable and more research is needed for understanding the mechanisms behind this. Extinguishing of lamps for more than 1 second can be an issue in street lighting. Consequences of losing light temporary is unclear. How the driver's visibility is impacted in terms of visibility should be further investigated.

Table III

PQ phenomena	Impact on light output								
	LED1	LED2	LED3	LED4	LED5	LED6	LED7	LED8	LED9
0% residual voltage, ½ cycle duration	±10%, duration equal to dip duration	100%, >1 second	100%, >1 second	95%, dip duration.	No impact	-20% to +70% duration equal to dip duration	100%, 0.4 seconds	No impact	±10%, duration equal to dip duration
0% residual voltage, 1 cycle duration	10% to 20%, duration equal to dip duration	100%, >1 second	100%, >1 second	95%, dip duration.	No impact	-20% to +70% duration equal to dip duration	100%, 0.4 seconds	No impact	±10%, duration equal to dip duration
40% residual voltage, 10 cycles duration	<10%, limited to start and end of dip	No impact	<10% during dip	±50% 3 times dip duration	No impact	100% >1 second	10%, 6 times dip duration	No impact	<10%, limited to start and end of dip
70% residual voltage, 25 cycles duration	<10%, limited to start and end of dip	No impact	No impact	±50% 2 times dip duration	No impact	<10%, limited to start and end of dip	10%, 3 times dip duration	No impact	<10%, limited to start and end of dip
0% residual voltage, 250 cycles duration	100%, 1.3 times the dip duration	100%, 1.2 times the dip duration	100%, 1.2 times the dip duration	100% 1.1 times the dip duration	100%, 1.2 times the dip duration	100%, 1.3 times the dip duration	100%, 1.2 times the dip duration	100%, 1.3 times the dip duration	100%, 1.05 times the dip duration
Interharmonics	Light modulation measured, not seen	No impact	No impact	Light modulation seen	No impact	No impact	No impact	No impact	Light modulation measured, not seen
Supraharmonics	Light intensity at kHz range	No impact	No impact	No impact	No impact	No impact	No impact	No impact	N.A

MISCELLANEOUS

Acknowledgments

This work was sponsored by Bertil and Brit Svenssons foundation for lighting technology.

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