Probing the Impact of Voltage Sags and Swells on Energy-Efficient LED Streetlights

Piyush Verma, Nitish Patel, Faizal Hafiz, Ankur Mishra and Nirmal-Kumar C. Nair
Department of Electrical & Computer Engineering, University of Auckland, New Zealand
pver055@aucklanduni.ac.nz

***Abstract*—Light Emitting Diode (LED) streetlights are playing a critical role in Smart City initiatives of various governments across the world as they facilitate better control over energy usage with a comparatively smaller carbon footprint. The increasing share of LED technology in the global street-lighting market can be considered as one of the major breakthroughs in the street-lighting industry. It is, therefore, necessary to assess this technology from various perspectives. In this study, we evaluate the performance of streetlight from various manufacturers in the presence of grid disturbances. For this purpose, three distinct grid disturbances have been considered, *i.e.*, voltage sag, swell and harmonics. The results indicate that high level of current harmonics could be expected during voltage swell and sag events. Further, the presence of source harmonics has a distinct influence on the streetlights from different manufacturers owing to different converter topologies.**

***Index Terms*—Energy efficiency, power quality, voltage sag, voltage swell, LED lighting**

I. Introduction & Related Work

The advent of LED lightings represents, arguably, a most significant technological breakthrough in the global street-lighting industry. The share of LED streetlights is rapidly increasing in the global street-lighting market. This technology represents the entry point of the smart city and smart community concept. Various countries across the world have taken initiatives for the implementation of LED streetlights owing to its longer lifetime, comparatively reduced maintenance expenses, lower energy consumption, and consequently smaller carbon footprint. Further, LED streetlights can be easily integrated with the other networking devices to enable network-wide communication for the 'smarter' streetlights. The total number of streetlights in the world is growing rapidly due to urbanization and the need to improve the existing infrastructure. The market share of streetlights is expected to increase from 315 million in 2016 to 359 million by 2026 with a global investment of $57 billion in the LED street-lighting market [1]. Considering this emerging market of LED streetlights, this technology needs to be assessed from various perspectives to ensure its smoother integration with the existing grid. The objective of this study is to investigate the behavior of LED streetlights under abnormal grid conditions.

The power quality issues are evolving as a major concern with most of the energy-efficient devices including LED-based lighting technologies [2]. As of now, most of the LED lighting research has been focused on improving the energy efficiency, color quality, light output, light distribution and thermal management [3]-[9]. Little research has been undertaken on power quality issues with the LED lighting technologies, and most of the previous articles on power quality research have been focused on domestic LED lamps and not the LED streetlights. Earlier studies have highlighted the high harmonic emissions and other power quality concerns with LED lighting technologies [10]-[13]. Studies have also indicated that poor quality LED lamps can create significant distortion in the electricity distribution network [14]. The other articles on harmonic issues have also highlighted the high harmonic emission concern and further, the possibility of reducing the aggregated harmonic emission by using a different brand of LED lamps in residential premises [15], [16]. Few other articles have discussed the power quality issues during CFL to LED transition and concluded that adding the LEDs in the combination of lamps are giving significant benefits from demand-side management perspectives[17], [18]. Another work highlights the effect of voltage sag and swells on LEDs performance and explains how it could create a detrimental effect on LEDs [19], [20]. With respect to LED-based street-lighting technology, only a few articles have been published as of now. In general, harmonic emissions from LED streetlamps have been found less than the conventional street-lighting technology. A study has investigated the power quality disturbances with LED streetlights and has summarized that harmonics and transients may cause significant disturbances in the network [21]. The degradation of power quality associated with LED lighting technologies may lead to detrimental effects on the other equipment connected to the network [22]. Most of the existing research is focused on this issue.

The other important aspect with respect to grid-integration is to evaluate the effects of grid abnormalities on the performance of streetlights. Various grid events arising from either utility operation, network faults or due to non-linear consumer load on the Point of Common Coupling (PCC) can significantly affect the performance of the LED streetlights. However, this issue has not received enough attention. Further, the power quality

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performance of the LED streetlight is predominantly dependent on the converter topology used by the manufacturer and, hence, the response of the streetlights from different manufacturers to grid disturbance is likely to differ.

The objective of this study is to bridge this gap by assessing the effects of two most common grid disturbances, '*voltage sag*' and '*voltage swell*' on the LED streetlights of two different manufacturers. Further, to emulate a non-linear consumer on the PCC, the experiments were repeated with 3rd, 5th and 7th harmonics added on the fundamental supply voltage. The 3rd, 5th and 7th harmonics were 12%, 8%, and 5% respectively. Each streetlight was evaluated in terms of power quality and energy consumption.

The remainder of this paper is organized as follows: Section II presents the experimental setup. This is followed by the results and discussion in section III. Section IV concludes the work.

II. Experimental Setup

To evaluate the effects of grid disturbances, the experimental facility was set up at the Power System Research Laboratory at the University of Auckland, New Zealand as shown in Figure 1. All grid disturbances were generated through '*Grid Emulator*' (California Instruments AMETEK MX15-1/1Pi). For the comprehensive investigation, two distinct LED streetlights from the different manufacturer have been used in this study: from Manufacturer 'B' (35W) and Manufacturer 'C' (40W); respectively denoted as 'SB35' and 'SC40' throughout this article. In total, four disturbances were generated to evaluate the performance of each lamp, as shown in Table 1. The response of streetlight was recorded through Power Quality meter (`PQ Box 200') and analyzed using MATLAB.

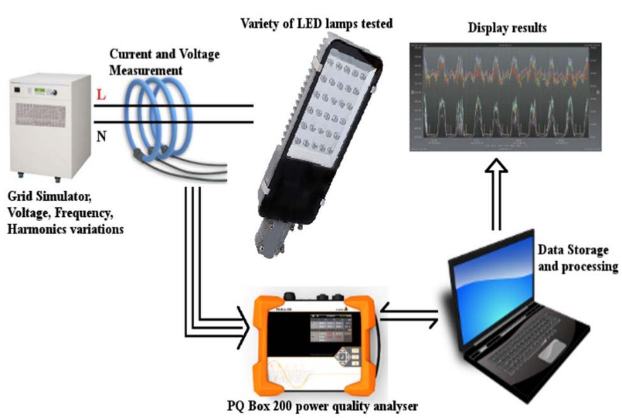

Fig. 1. Experimental setup for testing of LED lamps

TABLE I
PQ Events Investigated

Cases	Event	Explanation
Swell	Event 1	20% Voltage Swell for 15 cycle duration
	Event 2	20% Voltage Swell for 15 cycle duration with 3rd, 5th and 7th harmonics in supply voltage
Sag	Event 3	50% Voltage Sag for 15 cycle duration
	Event 4	50% Voltage Sag for 15 cycle duration with 3rd, 5th and 7th harmonics in supply voltage

All the experiments were repeated twice to check the consistency of the results. The streetlights were kept on for around an hour before any measurements to get an accurate result during its normal operation. Testing was conducted in two parts. During the first experiment named as "*without Supply voltage harmonics*", no additional harmonics in the supply voltage was introduced, and it was found that the original supply voltage harmonics was less than 0.15% during the experiment. In case of the second experiment named as "*with supply voltage harmonics*", 3rd, 5th, and 7th harmonics with 12%, 8%, and 5% respectively were introduced.

Finally, in both cases, five important parameters which include percentage current THD, k-factor, power factor, active power, and reactive power were assessed, and the results were compared.

III. Results & Analyses

The performance of the streetlights was benchmarked through nominal supply voltage (230 V, 50 Hz). All the key results are listed in Table II. Current total harmonic distortion from these streetlights was varying between 5-20% and also the power factor was varying in a wide range. Street-light SB35 has a low power factor of 0.935. In terms of distortion power that measures the losses due to high harmonics and low power factor, SC40 has shown 5.76 VAR (Volt-Ampere Reactive) with the higher consumption among these two streetlights.

TABLE II
Measured Parameters for Streetlights

Cases	SB35	SC40
Current (A)	0.166	0.186
Current THD (A)	0.019	0.025
Current THD (%)	14.34	19.26
Power Factor	0.935	0.962
Displacement Power Factor	0.941	0.971
Active Power (W)	35.53	41.02
Reactive Power (VAR)	13.47	11.63
Distortion Power (VAR)	4.42	5.76
Apparent Power (VA)	38.00	42.64

Note that the results in Table II represent a base case scenario for both the streetlights. In the next stage, the performance is evaluated in the presence of the grid events shown in Table I. The objective is to evaluate the impact of grid disturbances such as *voltage sag* and *swell* on important PQ and energy consumption parameters. The key PQ parameters investigated in this study include Current THD, K-factor and power factor. The response of both the streetlights to these events have been discussed in the following subsections.

A. Effects of Voltage swell:

The voltage swell was generated by increasing the voltage magnitude by 20% over nominal 230 V and for the duration of 15 cycles. In the first case (Event 1, Table I), the voltage swell is directly fed into the ac signal supplying the streetlights. In the second case (Event 2, Table I), 3rd 5th and 7th harmonics were appended in the input supply voltage to simulate the non-linear loads on the PCC.

The results indicate that SC40 is more susceptible to the voltage swell events (Event 1 and 2, Table I). For both events, a higher performance degradation was observed in all the PQ parameters of SC40: *current THD, k-factor, reactive power and power factor*. The response of streetlights to swell events is discussed at length in the following subsections.

(i) Event 1: Swell without supply voltage harmonics:

The grid emulator was used to generate a 20% voltage swell for 15 cycles as seen Fig. 2(a) and Fig. 3(a). For this event, the supply voltage harmonics is less than 0.15%. The response of SB35 and SC40 to this event is shown respectively in Fig.2 and Fig.3. These results demonstrate a strong influence of voltage swell on the performance of both streetlights. A significant increase in the current THD was observed in response to the voltage swell. The consequent changes in the K-factor indicate the heating stress on the distribution transformer.

The comparative analysis of the current THD (Fig. 2 and 3) indicates the significantly different response of SB35 and SC40. For the entire duration of voltage swell, a significant increase in the current THD of SC40 is observed (20% to 70%), as seen in Fig. 3. On the other hand, with SB35 the significant increase in current THD is observed during the event transitions, as indicated in Fig. 2. A similar response is observed in K-factor (Fig. 2(c) and 3(c)) and power factor (Fig. 2(d) and 3(d)) as well. These results also indicate that SC40 comparatively susceptible to swell; during swell, the power factor of SC40 reduced from around 0.95 to 0.8 (Fig. 3(d)) whereas the drop was limited to 0.88 with SB35 (Fig. 2(d)).

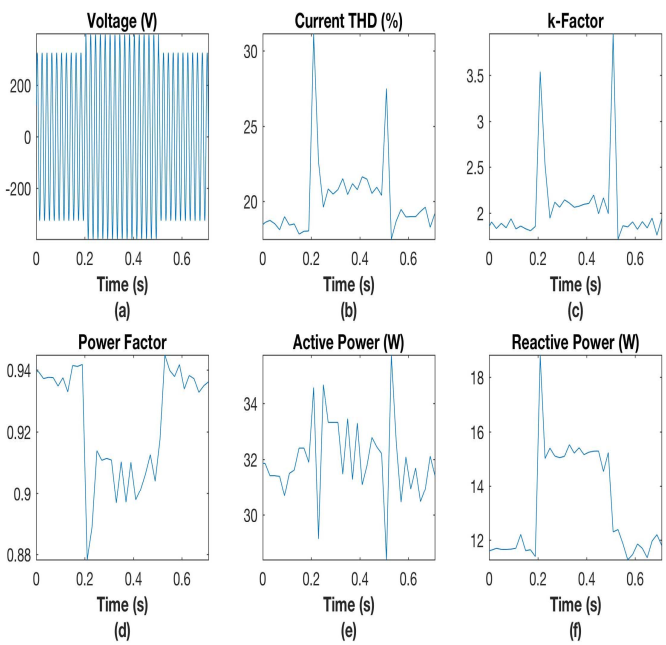

Fig. 2. Key results for SB35 during voltage swell

Further, the active power and reactive power of the streetlights were also monitored during the voltage swell period. The effect of swell is more profound on the reactive power for both SB35 and SC40. The increment in reactive power during the voltage swell period has been found to be more when compared to the increment in the active power. The increment in order of 150% was observed in the reactive power of SC40, as seen in Fig. 3(f). A similar, but comparatively smaller, the increment was observed in the reactive power of SB35 as well, as shown in Fig. 2(f).

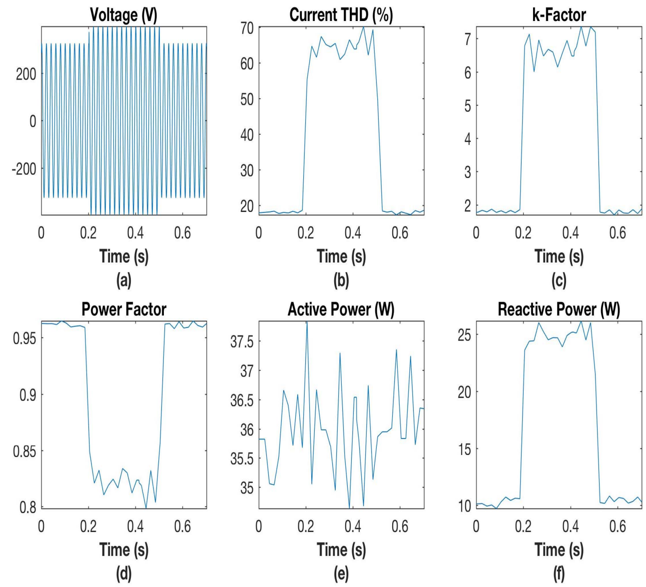

Fig. 3. Key results for SC40 during voltage swell

(ii) Event 2: Swell with supply voltage harmonics:

In this case, along with the 20% voltage swell for 15 cycles, 3^{rd}, 5^{th} and 7^{th} harmonics in supply voltage were also introduced to see the impact of distorted voltage swell on the performance of LED streetlights.

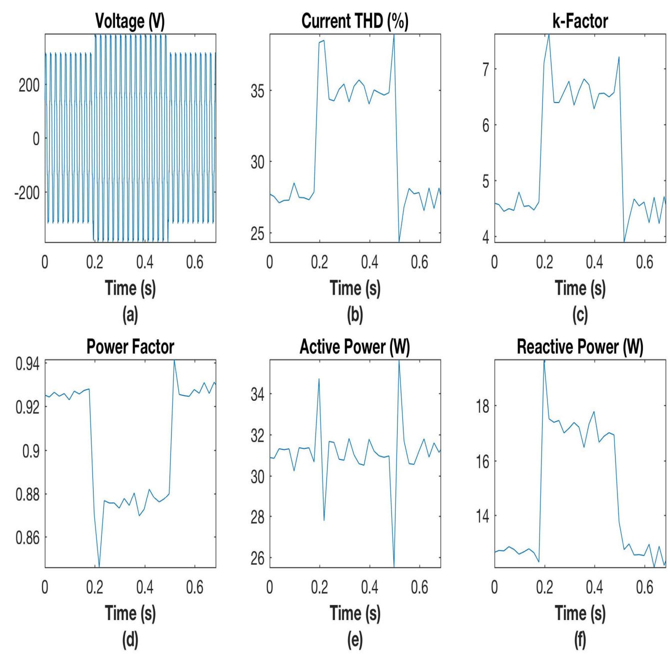

Fig. 4. Key results for SB35 during voltage swell with supply harmonics

The variation in current THD in response to the Event-2 are shown in Fig. 4(b) and 5(b). In response to the Event 2, the current THD of SB35 increases to 34-35%. Note that, this higher increment in THD compared to Event 1 (Fig. 2(b)) can be explained by the presence of harmonics in the supply voltage. A similar pattern was observed with the K-factor as well.

Fig. 5(b) shows the response in current THD of SC40 during Event 2. Interestingly, the increment in THD is lower compared to the Event 1 (Fig. 3(b)). This indicates a possible cancellation of the harmonic component generated by SC40 against the harmonics present in the supply. Due to this harmonic cancellation, an improved response to Event 2 is observed in current THD, reactive power and power factor of SC40; compared to Event 1 responses (Fig. 3), a smaller increment is observed in these parameters (Fig. 5).

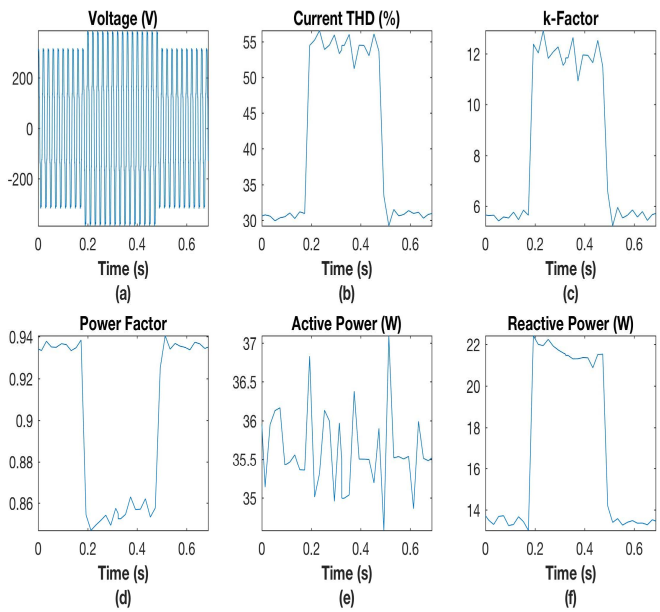

Fig. 5. Key results for SC40 during voltage swell with supply harmonics

B. Effects of Voltage sag:

Both the voltage sag events (Event 3 and 4, Table I) were emulated for the duration of 15 cycles and with 50% reduction in the nominal voltage, *i.e.*, (115 V, 50Hz). Further, the effects of non-linear loads on the PCC have been emulated in the Event 4 by appending 3rd 5th and 7th harmonics over the voltage sag.

(i) Event 3: Sag without supply voltage harmonics:

The responses of SB35 and SC40 to the Event 3 are respectively shown in Fig. 6 and Fig. 7. Both streetlights have shown an increase in current THD in response to the voltage sag. However, the increase in THD is momentarily and coincides with the beginning and end of the event as seen in Fig. 6(b) and Fig. 7(b). The similar response is observed in k-factor as well. Note that, the decrease in voltage magnitude during sag events leads to reduced reactive power consumption which results in an improved power factor during sag event as seen in Fig. 6(d) and Fig.7(d).

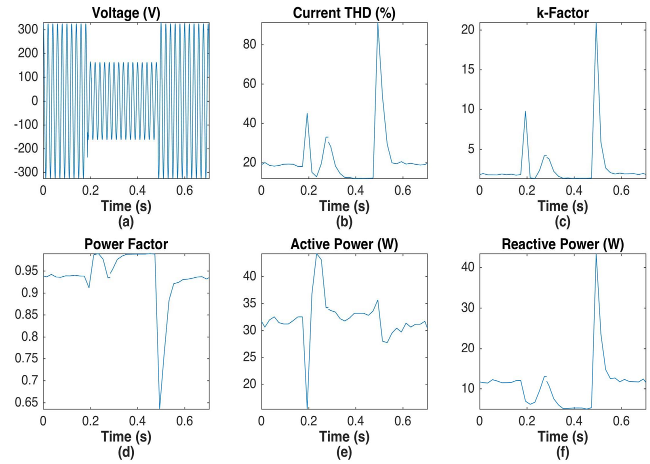

Fig. 6. Key results for SB35 during voltage sag without supply harmonics

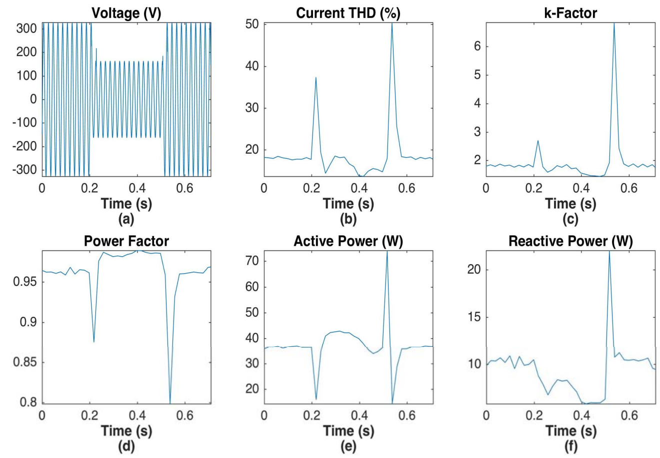

Fig. 7. Key results for SC40 during voltage sag without supply harmonics

(ii) Event 4: Sag with supply voltage harmonics:

In this event, 3rd, 5th, and 7th harmonics were appended upon voltage sag. Fig.8 and Fig. 9 respectively show the power quality and energy consumption performance of SB35 and SC40 to this event. When the supply voltage harmonics were introduced, SB35 has shown slightly improved performance in terms of lowered peak THD and a lesser increase in reactive power at the end of voltage sag instant. There was no major effect in SC40 streetlights were noticed.

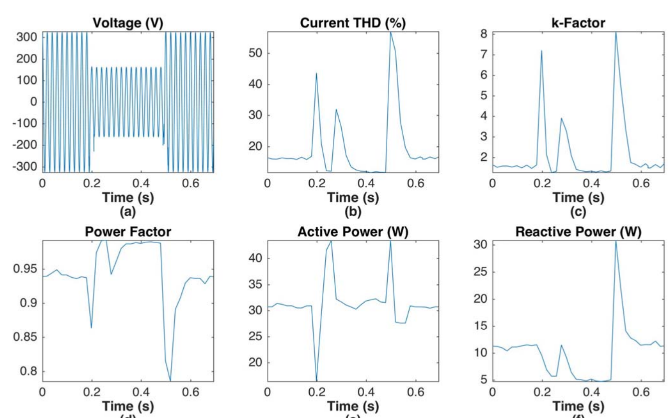

Fig. 8. Key results for SB35 during voltage sag with supply harmonics

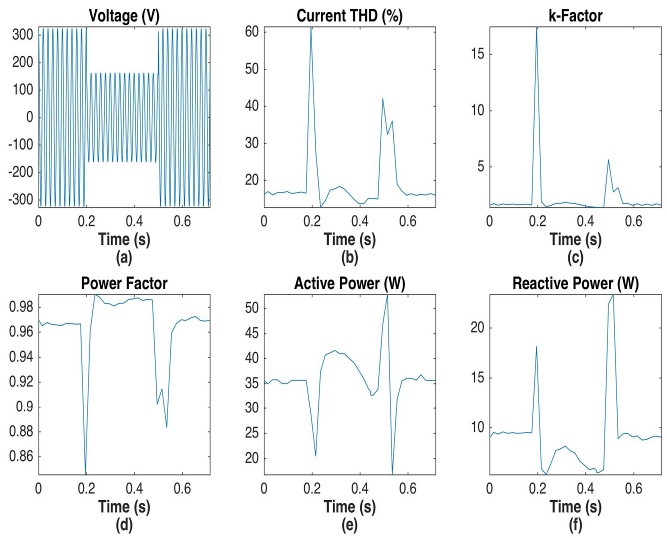

Fig. 9. Key results for SC40 during voltage sag with supply harmonics

In summary, all the results were compared and analyzed to find the streetlight which was less affected with grid disturbances and has been summarized in Table III. It was found that SB35 streetlight has performed best in most of the parameters in voltage swell. However, in case of voltage sag, SC40 seems to be performing better in key power quality and energy consumption parameters.

TABLE III
IDENTIFICATION OF STREETLIGHTS THAT PERFORMED BEST IN RESPECTIVE PARAMETERS

Event	THD	K-factor	Power Factor	Active Power	Reactive Power
Voltage Swell	SB35	SB35	SB35	SC40	SB35
Voltage Swell with Harmonics	SB35	SB35	SC40	SB35	SB35
Voltage Sag	SC40	SC40	SC40	SB35	SC40
Voltage Sag with Harmonics	SB35/ SC40	SB35	SC40	SB35/ SC40	SC40

IV. Conclusion

The effects of two distinct grid events have been investigated on two different brands of LED streetlights. The performance of the streetlight was evaluated for a different combination of events and considering the presence of the other non-linear load at the PCC. The results of the investigation convincingly demonstrate that the performance of the streetlight is significantly affected by the grid events. Especially, the performance degradation was found to be more severe during voltage swell events with sustained deterioration in THD, k-factor, power factor and reactive power for the entire duration of the event.

The results also indicate the difference in the response of the streetlights due to underlying controller topology. Though the nature of most responses to the grid events is similar for both SB35 and SC40, the degree of performance degradation differs significantly which can be ascribed to different converter topology adopted by the manufacturers. The results indicate that SB35 performed better during voltage swell whereas SC40 performed better during voltage sag events. However, given that the effects of voltage swell are more severe, in general, SB35 is preferred over SC40. Further, in the presence of supply voltage harmonics, streetlights have shown addition and cancellation of harmonics up-to certain extent. This underlines a need for the detailed investigation of streetlights in response to the grid events before system-wide selection.

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