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Impacts of LED lighting on Power Quality

by Remi Bolduc

Executive summary

Lighting represents a significant portion of global energy use, in some cases approaching 10% of all electrical consumption. Thus, replacing incandescent bulbs with LEDs, which use 75% less energy, offers a viable energy efficiency opportunity. However, because LEDs are non-linear loads they can have significant impacts on power quality. This paper reviews these concerns, and assesses the impact of power quality disturbances on LED lighting.

Introduction

Our world faces significant energy challenges. Global energy consumption is expected to grow by at least 56% by 2040. And as companies work to resolve our energy dilemma, they look to improve energy efficiencies in our homes, buildings, industries, and infrastructures.

Within this energy challenge, lighting constitutes a significant portion of the energy challenge. In the United States alone, according to the USA Energy Information Administration (EIA), 279 billion KW/h was used for lighting in 2016, representing approximately 7% of the total electricity consumed in the USA.[1] This represents a significant energy efficiency opportunity, because, when compared with incandescent lighting, Light Emitting Diode (LED) technology consumes 75% less energy. LED replacement is therefore a viable energy efficiency solution to reduce power consumption worldwide.

However, as LEDs continue to replace incandescent lighting, there can be a significant impact on power distribution networks due to the non-linear nature of light emitting diodes. This paper will review the main Power Quality concerns arising from the use of LED lighting on our electrical networks. Further, it will also assess the impact of Power Quality disturbances on LED lighting technology.

[1] US Energy Information Administration, Annual Energy Outlook 2017,

Main components used in LED lighting technology

Compared to an incandescent light bulb, LED lighting technology is significantly more complex. It consists of multiple components, each of which deserve review in order to understand how LED lighting works and why it may have significant impact on Power Quality. Figure 1 outlines the main components that are integral within LED lighting.

- **LED (Light Emitting Diode):** A diode type semiconductor which emits light as current passes through it. LED semiconductor materials convert electrical energy into visible electromagnetic radiation (Light).
- **LED component:** The substrate and primary optical unit of the light assembly. The purpose of the LED component is to protect the semiconductor and to conduct the heat generated from the LED to the dissipation systems.
- **LED module:** The assembly of one or more LED components with optical, mechanical and thermal elements.
- **LED Luminaire:** A complete system consisting of an LED module, a housing, an optical reflector, wiring, connectors, joints, heat dissipation system and in most cases the driver.
- **Driver:** An electronic device which can convert the electric power of a low voltage AC electrical network into electric DC power appropriate for the LED luminaire. The driver can power one or several luminaires. Light dimming function can also be embedded in this component.

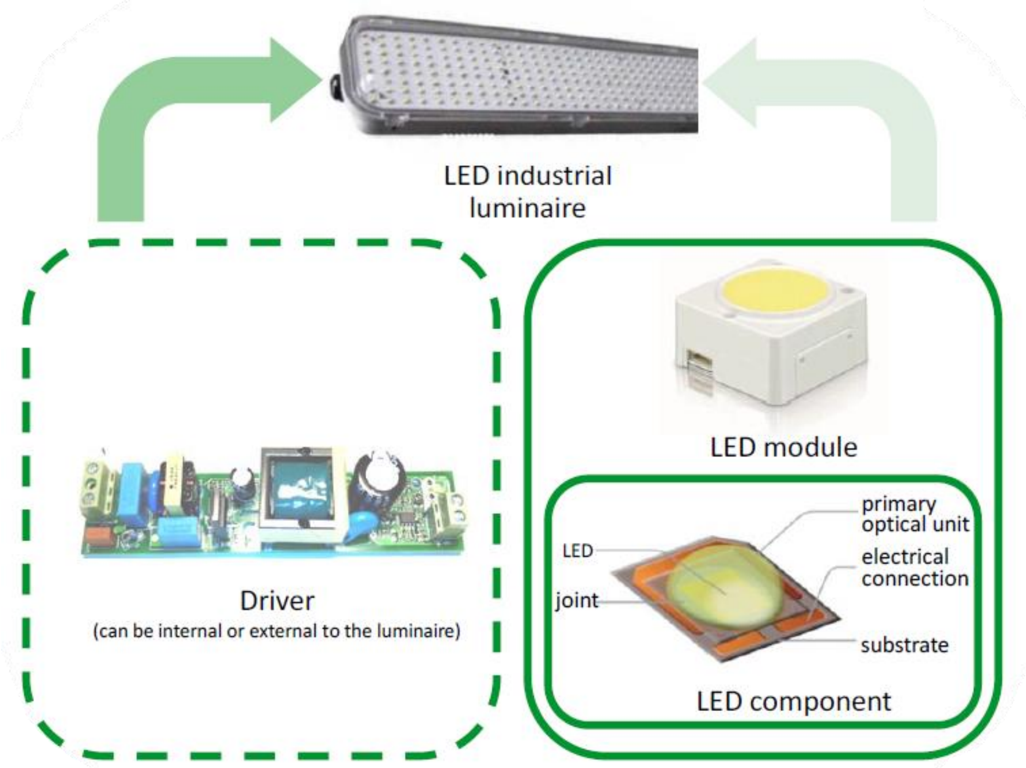


Figure 1

Main components used in LED lights.

LED lighting and harmonic emissions

Harmonic emission (or harmonic generation) is a primary power quality concern. When AC power is converted to DC power via a semi-conductor, high frequency current – known as harmonics – is generated during the conversion. The harmonic spectrum and magnitude will vary based on the semi-conductor technology used and the type of network connection (single phase or three phases). LED lights are typically single phase loads and are connected phase to neutral. Single phase DC rectifiers are notorious for generating a wide harmonic spectrum – 2^{nd} to 50^{th} order – with dominant zero sequence 3^{rd} harmonic order. Generally speaking, elevated harmonic distortion level will stress the electrical distribution network when the Total Demand Distortion (TDD) exceeds the IEEE 519-2014 harmonic standard limits.

Zero sequence harmonics

When dealing with single phase rectifier, specific attention must be given to the zero-sequence harmonics, particularly the 3^{rd} harmonic order as it will have the highest magnitude in the harmonic spectrum. The singularity of the zero sequence harmonics (3^{rd}, 6^{th} , 9th, 12^{th} , 15^{th}, …) is that they add up perfectly in the neutral conductor, and the neutral current magnitude can reach 1.732 times the level of current flowing in the phase conductor. This presents a risk for neutral conductor overload.

To resolve this issue, the most common solutions involves using a neutral conductor with a cross section of the phase conductor. Figure 2a, b and c show the phase current and the neutral current generated by single phase rectifier loads and their generic harmonic profile. In Figure 3 you can see the current waveform of a 15 W LED light; the waveform greatly deviates from a regular sinewave because it's rich in harmonic current. The current harmonic magnitude extracted from the waveform are represented in Figure 4.

Figure 2

A: Phase (Ir, Is, It) and neutral (In) current supplying non-linear single phase loads.

B: Phase current harmonic spectrum of non-linear single phase loads.

C: Neutral current harmonic spectrum of non-linear single phase loads.

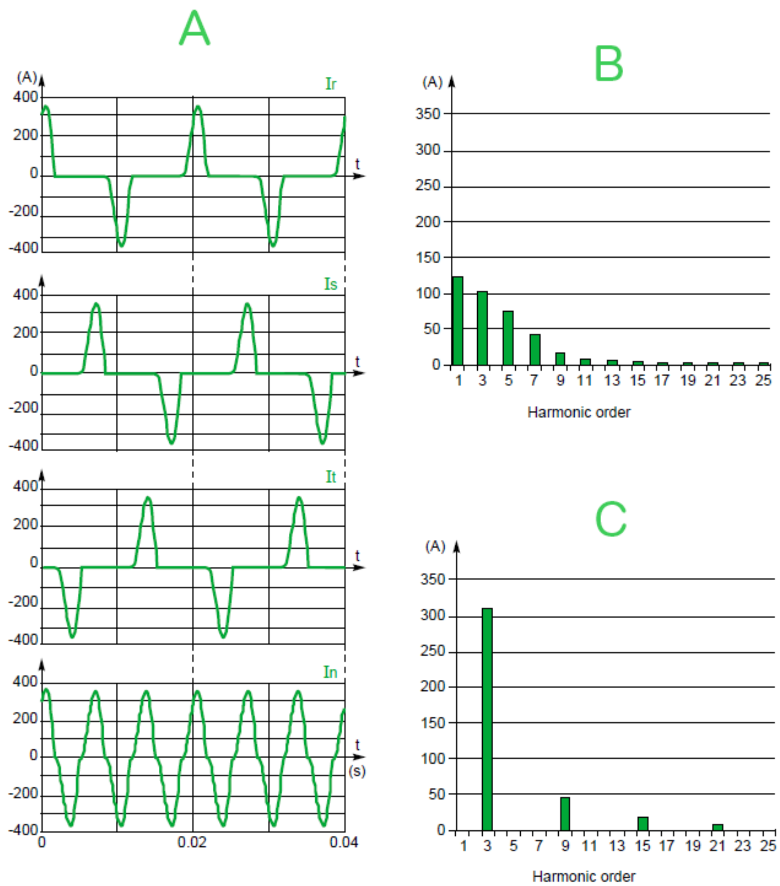


Figure 3

Current waveform of a 15 W LED light.

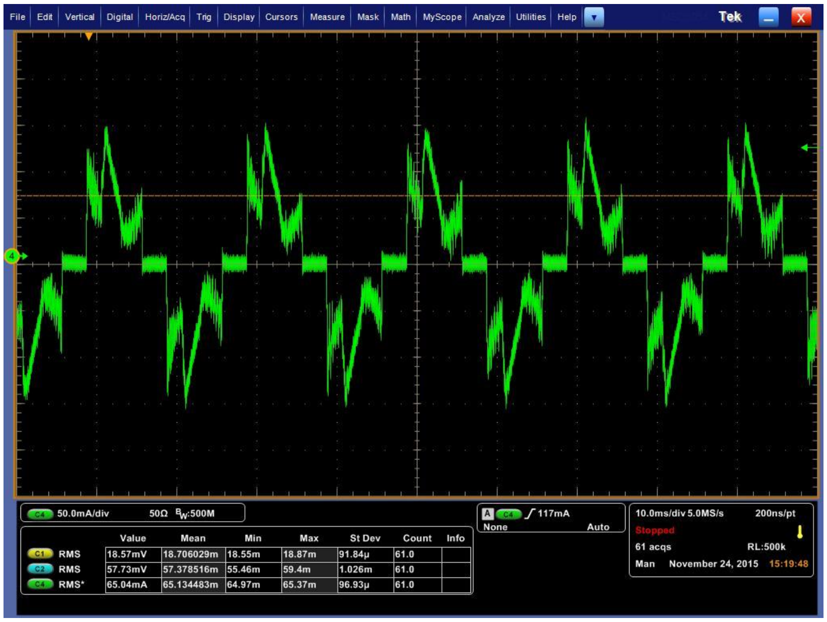
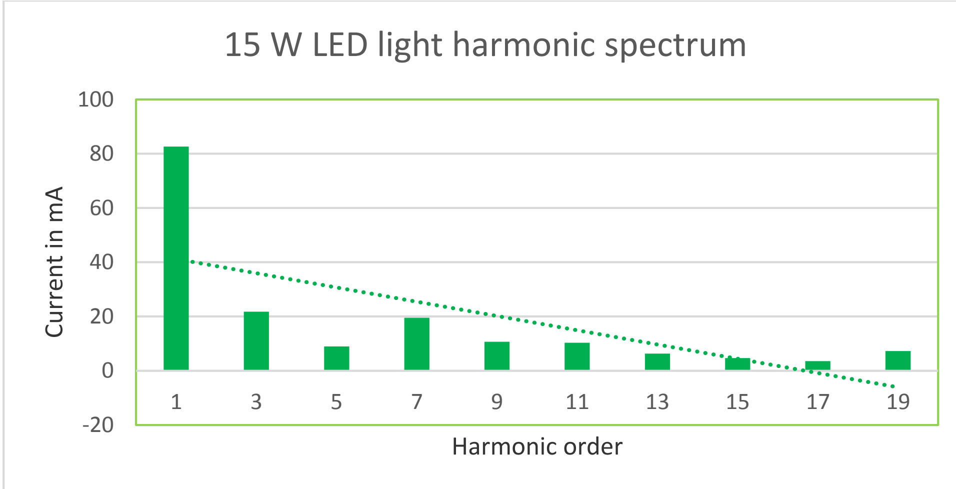


Figure 4

Harmonic spectrum of a 15 W LED light.



Harmonic emission limit for LED lighting equipment as per IEC 61000-3-2

Like any other appliance, LED lamps must comply with several directives. The IEC 61000-3-2 standard sets harmonic limits for equipment that draws 16 Ampere or less. Per this standard, equipment is classified within four classes – in which Class C is lighting equipment. This also includes light dimmers.

For lighting equipment having an active input power greater than 25W, the harmonic current shall not exceed the relative limits given in Table 2 of the IEC 61000-3-2, represented here in Table 1.

Table 1

Excerpt taken from IEC 61000-3-2. Table 2

Harmonic order (n)	Maximum harmonic current as percentage of the fundamental frequency (%)
2	2
3	30*λ (see note 1)
5	10
7	7
9	5
11 to 39, odd harmonics only	3

* Note: λ is the circuit power factor

Lighting equipment having an active input power smaller than or equal to 25W shall comply with one of the following two sets of requirements:

- the harmonic currents shall not exceed the power-related limits of Table 3, column 2 of the IEC 61000-3-2 which is represented here in **Table 2**, or:
- the third harmonic current, expressed as a percentage of the fundamental current, shall not exceed 86 % and the fifth harmonic current shall not exceed 61 %.

Table 2

Excerpt taken from Table 3 of IEC 61000-3-2

Harmonic order	Maximum harmonic current per watt (mA/W)	Maximum harmonic current (A)
3	3.4	2.30
5	1.9	1.14
7	1.0	0.77
9	0.5	0.40
11	0.35	0.33
13 to 39 (odd	3.85/n	See table 1

Harmonic emission in electrical network by LED lighting

Based on the information reviewed in this paper, LED lighting equipment will generate a relatively high level of harmonic distortion in current. For example, a 25W LED lamp that respects the IEC 61000-3-2 – where it injects 85% of third harmonic and 61% of 5th harmonic – obtains THD(I) of 105%, which is extremely high. Fortunately, LED lights have very low power consumption, only drawing milli-Ampere. As well, the newer design of luminaire drivers introduces power factor correction capacitors. This not only improves power factor (PF), but also offers some harmonic filtering. **Figure 4** indicates the harmonic spectrum of LED lighting with a power factor correction capacitor.

Note (in **Figure 4**) that the harmonic spectrum is much improved with a THD(I) of 43%. Further, if diversity of load is introduced in the circuit, some natural harmonic attenuation will occur via current vector cancellation, as well as when resistive loads are added to the same circuit, when further harmonic attenuation occurs. Normally, since the harmonic current flowing through the network impedance is low due to the low power consumption of LED lights, it has very little impact on the total harmonic distortion in voltage. It is normally kept below a THD(V) of 5%.

A harmonic issue could arise in an electrical circuit if a very high density of LED lighting is present with a low diversity factor. In this case harmonic overload may occur on the bus, on the auxiliary transformer, and in the neutral conductor. For this type of situation, external harmonic mitigation such as an active harmonic filter device should be considered.

Figure 5

An active harmonic filter can eliminate harmonics

Power factor of LED lights

There are several types of LED drivers on the market and the Power Factor impact will vary based on the type of rectifier used, if they are uncompensated, compensated with capacitors and if they have built in passive filter or active filtering device. Socket type bulbs with power below 10 W tend to be uncompensated and they have a PF ranging from 45% to 80% lagging. See Table 3 for details.

LED panels which consist of several strips of LEDs placed in parallel in the panel and fed from an external ballast normally have a PF greater than 90% lagging when operating above 50% loading and a PF ranging from 30% to 85% when operating below 50% loading. The dimmer which is an integral part of the ballast has a big impact on the Power Factor. See Table 4 for details.

Other experiments conducted on street lighting show that for LEDs, street lights ranging from 30 W to 200 W that the PF of these devices are normally in the range of 92% to 98%. See Table 5 for details.

The Energy Star program requirements for integral LED Lamps gives us one more reference. Where lamp power of 5 W or less, there is no Power Factor requirement and for lamp with a power greater than 5 W, the PF must be greater than 70% lagging.

Needless to say, a wide range of results and references are possible here. The trend is that low power LED lamps of 10W or less (and older LED technology) will have low PF, and that LED luminaires greater than 10W (and newer technology) will have PF greater than 90%.

In the event of an installation with poor Power Factor due to LED lighting, the external capacitor-based compensation equipment can be used to correct the PF. In such a case, it's recommended to use de-tuned capacitor systems as they are designed to correct PF in harmonic rich networks.

Table 3

Power Factor of tested LED bulbs

Brand	Nominal Power (Watts)	Power Factor (PF)
Brand 1	4.0	0.69
Brand 1	7.0	0.72
Brand 2	4.5	0.47
Brand 2	8.0	0.79
Brand 3	5.0	0.46
Brand 4	3.0	0.47
Brand 5	5.0	0.56

Table 4

Power Factor measurements results for a 49.5 Watt LED panel equipped with a 60 Watt ballast

LED Dimming	Active Power (Watts)	Power Factor (PF)
100%	44.8	0.958
90%	37.8	0.952
80%	34.2	0.948
70%	29.6	0.942
60%	26.0	0.934
50%	21.3	0.911
40%	17.6	0.885
30%	13.7	0.841
20%	9.9	0.756
10%	1.9	0.221

Table 5

Power Factor of tested LED street lights

LED Luminaire	Nominal Power (Watts)	Power Factor (PF)
LED 1	32	0.922
LED 2	65	0.953
LED 3	67	0.983
LED 4	147	0.962
LED 5	182	0.972

Inrush current caused by LED drivers and the choice of circuit breaker

In the initial moments after the luminaire is energized, a significant transient current appears (up to 253 times the rated current according to Schneider Electric measurements). The duration of the transient current can be less than 1 ms for one luminaire. The transient is due to the capacitors used to perform the power factor correction (the power factor of PF compensated luminaires is generally greater than 90%, since the luminaire drivers include a power factor correction stage). Note that when a capacitor is first energized it must charge and it has a very low impedance, therefore it draws a high inrush current.

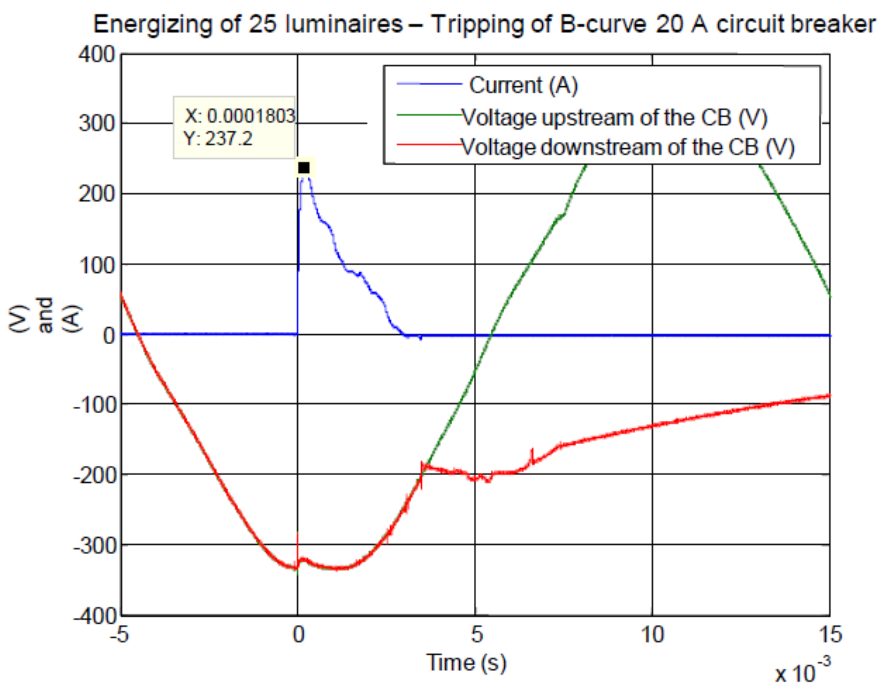
In any electrical network the choice of circuit-breaker depends on the nature of the load powered. The rating depends on the cross section of the cables to be protected and the over current protection curves are chosen according to the load's inrush current.

Because no normative tripping threshold curves exist for transient less than 10 ms, Schneider Electric performed measurements during a lighting installation in a commercial building. This was deemed to be a typical installation that will help with circuit-breaker selection. A B-curve 20 A rating circuit breaker (see **Figure 6**) was tripped upon energizing a circuit powering 25 luminaires (with a capacity of 56 watts each). The following was observed:

- a rated power of 1400W,
- a maximum transient inrush current is 237 A,
- the duration of the transient current was 2.5 ms

Figure 6

Tripping of a B-curve 20 A circuit-breaker

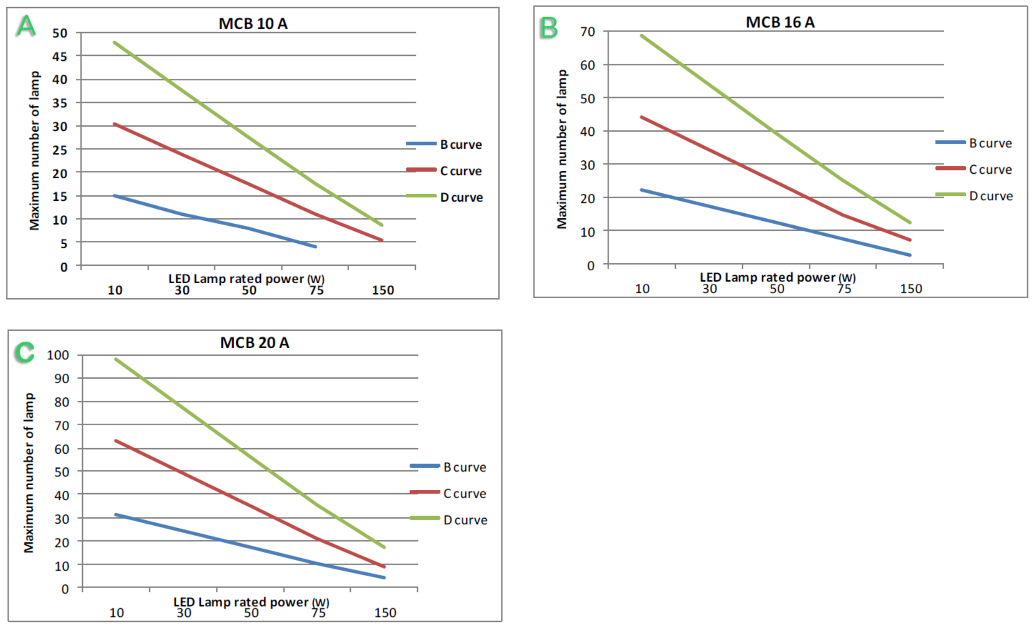


In order to address this situation, an appropriate choice of the circuit breaker device must be made during the design phase (see Figures 11a, 11b and 11c). The peak value of the current at switching on depends on the energizing time, the number of luminaires forming the lighting circuit, and the short-circuit power and architecture of the network.

The curves presented in Figures 11 (a, b and c) provide information relating to the number of luminaires that can be connected downstream of a circuit breaker depending on its characteristics (rating and tripping curve of the magnetic protective device). These curves were produced based on the unfavorable conditions which generate a maximum current peak at circuit energizing.

Figure 7

Number of luminaires downstream of a circuit breaker



Also impacted by the LED lights high inrush current are the commuting contactors. Contactor deratings given by manufacturers must be taken into account in the design phase in order to obtain the best adapted coordination with LED luminaires and performances compliance (electrical endurance).

For three-phase circuits (power supply of luminaires between a phase conductor and the neutral conductor), switch gear and control gear of the three-pole type is preferable to a control device of the four-pole type. Not switched, the neutral conductor will help to prevent a harmful voltage surge at power frequency from being applied across the terminals of the luminaire if the neutral conductor fails to close.

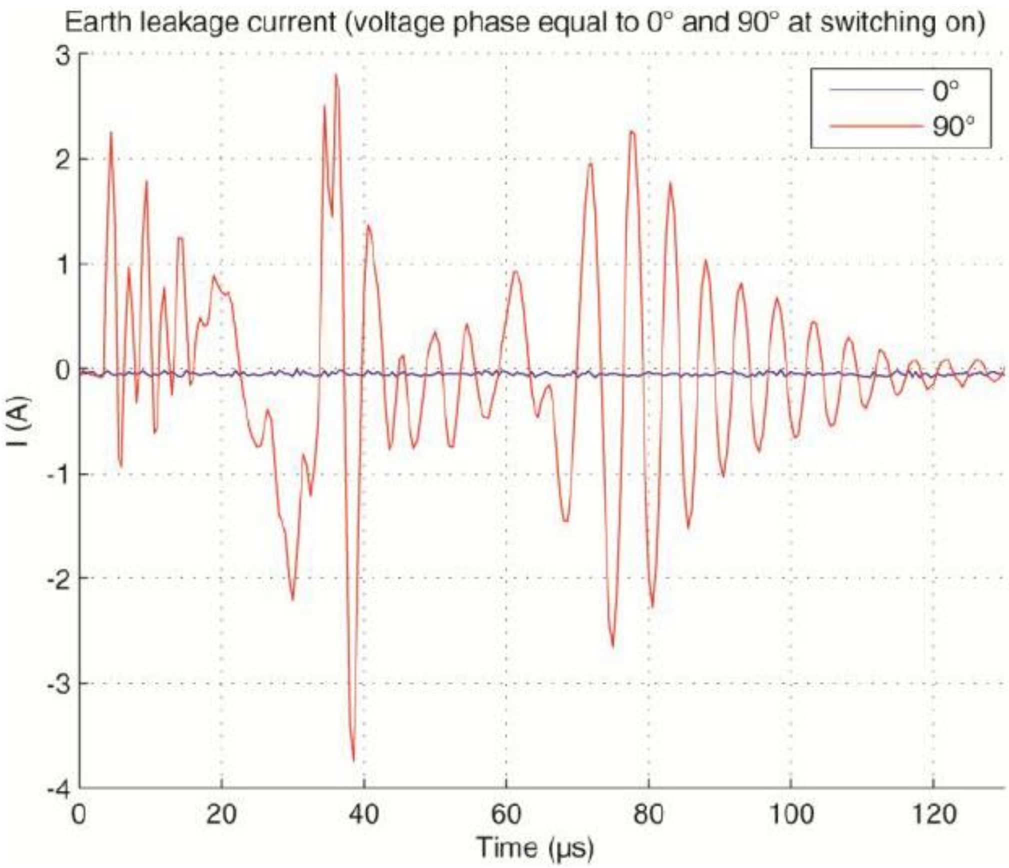
Alternatively, a smart solid state contactor activated at the voltage zero crossing can be used for LED energization. The operating principle of the static relay consists of the following: when the control voltage is applied to the relay input, an internal static component performs the switching function at zero crossing of the voltage wave. The precision at switching (connection to the network) is excellent. The inrush current is then reduced. Thus, it is possible to use circuit breakers without derating. The number of luminaires that can be powered by a single circuit is limited only by the thermal withstand of the smart relay.

LED earth leakage current

The Schneider Electric measurements showed that the leakage current is at maximum for switching on at the voltage peak. The frequency of this transient current is high (about 100 kHz). For switching on at zero voltage, the leakage current is practically zero (see Figure 8).

Figure 8

Earth leakage current test results



The permanent earth leakage current at 50 Hz is generally less than 1 mA for a luminaire. Given that lighting circuits are protected by earth leakage protection devices of 300 mA rating, many luminaires can be installed downstream of a protective device. For a frequency of 100 kHz, the current is not detected by the earth leakage protection devices.

Power Quality phenomena that affect LED lighting performance

This paper has examined Power Quality disturbances caused by LEDs; however, poor Power Quality also has a negative impact on complex lighting apparatus. Specifically, there are four Power Quality phenomena that can affect LED lighting performance:

1. Variation of the voltage supply greater than +/- 10% of nominal, for up to 1 minute:
    - As mentioned earlier, LED lighting uses electronic components in its driver circuits and these components are sensitive to the magnitude of the supply voltage. Too high of a supply voltage may lead to a decrease in the lifespan of the electronic associated with the LED lighting system. Furthermore, depending on the driver design, a change in the steady state voltage supply may lead to a change in the LED light Lumen output, an increased in voltage supply may result in an increased light output, and vice-versa. Like any other electronic equipment, if the voltage falls too low, the LED light will simply extinguish.
2. Flicker which is a periodic change of the supply voltage waveform envelope:
    - Change of the electrical supply voltage envelope, as known as flicker, may create variation in the LED system output light intensity. The flicker is highly dependent on the electronic driver conception, therefore the flicker severity for any given long term (PLT) or short term (PST) flicker level will vary for each type of LED system.
3. Harmonics and voltage waveform distortion:
    - The combinations of dimmer and LED driver for LED lighting is complex. Dimmable LED driver circuits contain electronics designed to detect the operation of the dimmer and adjust the output to the LED lamp accordingly. In some cases, where the dimmer and driver are operating on an electrical network with high level of voltage distortion and distorted voltage waveform they can produce flickering light output. Furthermore, a high THD(V) can stress the electronic components dielectric which in turn can shorten their lifespan.
4. Voltage transient:
    - Often LED lighting retro-fit or new installation projects are justified by the energy savings they produce; however, the pay back may take a few years, therefore we must expend their lifespan as much as possible. Like any other electronic equipment, LED luminaire are susceptible to voltage/current transients that can damage the driver Line to Line or Line to Neutral terminals and/or create insulation breakdown Line-ground or Neutral to Ground. It’s recommended to protect LED luminaire via the use of Surge Protection Devices (SPD) installed upstream in the distribution board.

Conclusion

It is important to understand the Power Quality impact these devices will have on low voltage networks. The biggest impact seen is the inrush current generated during energization of LED. When connecting a lighting circuit to a feeder circuit breaker and commuting contactor, manufacturer derating recommendation should be respected to avoid nuisance tripping of the circuit breaker and premature failure of the controlling contactor.

LED lights are non-linear loads and will generate harmonics in LV networks. However, the situation is minimized because they consume very little power; each luminaire only injects milli-Ampere on the distribution system. However, harmonic issues could be encountered when a high density of LED lights are installed. In this situation, external harmonic mitigation can be considered, for example 3-phase, 4-wire Active Harmonic Filters.

Depending on the LED technology employed low Power Factor can be seen on a LED circuit; there again, the low power consumption of these devices help reduce the overall impact they will have on an installation Power Factor. Nevertheless, external de-tuned reactive compensation systems can be used to correct their Power Factor if reactive power absorption from the Utility becomes an issue.

Earth leakage current was reviewed as well and it was determined that it will not have much impact on the Power Quality of the network.

The secondary goal of this paper was to determine if poor Power Quality could affect the LED light performance. It was determined that electrical network with poor Power Quality could reduce the LED lighting life span and affect its Lumen output and/or make the light flicker which can be discomforting for building occupants.

About the author

Remi Bolduc is the Competency Center Manager for Power Solutions in Schneider Electric. He started his career with the Hydro-Quebec Utility in service and maintenance of HV switchgear, followed by 6 years with S&C Electric in application of MV switchgear. For the past 18 years he has held various technical and commercial roles for Schneider Electric where he has specialized in Power Quality Correction. Mr. Bolduc graduated with a degree in Electrodynamics and has lectured in over 200 Power Quality seminars around the world.

References

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