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Description:	9/15/2017 - This document was previously docketed in 17-AAER-12
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Comment Received From: Richard Haring
Submitted On: 9/15/2017
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Philips Technical Response for Low Power Mode and PF

Additional submitted attachment is included below.

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Lighting Electronics North America

California Energy Commission
Docket Office, MS-4
1516 Ninth Street
Sacramento California

RE: 17-AAER-12 (Low Power Mode and Power Factor)

Dear Mr. Nelson,

Philips Lighting appreciates the opportunity to provide the attached comments on the Phase 2 Appliance Efficiency Pre-Rulemaking for Low-Power Mode and Power Factor.

Philips Lighting is a global leader in lighting products, systems and services. Our understanding of how lighting positively affects people coupled with our deep technological know-how enable us to deliver digital lighting innovations that unlock new business value, deliver rich user experiences and help to improve lives. Serving professional and consumer markets, we sell more energy efficient LED lighting than any other company. We lead the industry in connected lighting systems and services, leveraging the Internet of Things to take light beyond illumination and transform homes, buildings and urban spaces. In 2015, we had global sales of over 8 billion USD and currently we have approximately 36,000 employees in over 70 countries. Our North American headquarters is located in Somerset, New Jersey.

We are responding to this comments request with two documents; this document provides the technical background necessary to address the posted questionnaire. We are docketing a separate document which addresses each one of the posted questions. After considering the questions posted by the commission, we have four major conclusions.

1) Power factor is a complex metric, not adequately described by current displacement only
2) Power factor in standby mode is a more complex discussion; current instrumentation provides a measurement value; however, it is difficult to correlate this value with the physical reality of an electrical system.
3) It is not prudent to regulate power factor and harmonics in low power modes
4) It will be advisable to wait for ANSI, IEEE, and IEC to determine how to manage the complexity of low power modes and their associated test methods.

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Our Technical analysis and comments begin on the following page. We look forward to working in conjunction with the CEC to resolve this issue.

Sincerely,

Richard Haring
Standards and Regulations
Philips Lighting North America
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847-390-5195

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Lighting Electronics North America

Response to Additional Guidance on Roadmap Proposals

Docket 17-AAER-12: Low-Power Mode and Power Factor

September 18, 2017

Ernesto Mendoza, Mark Pacelle, Richard Haring

Philips Lighting

LED Lighting Devices and Power Quality

Electronic lighting devices operate differently than magnetic lighting devices (ANSI_C822.77-10, 2014; EPRI_1017246, 2003; PNNL_23944, 2014); they are not passive and typically their input current does not change linearly in proportion to a change in input voltage. Indoor (Bunjongjit, Ngaopitakkul, & Leelajindakrairerk, 2017) and outdoor LED lighting (Gil-de-Castro, Moreno-Munoz, Larsson, & Bollen, 2013) harmonic currents and current displacement are frequent concerns for utilities and users (Duarte & Schaeffer, 2010).

Increasingly, LED lighting devices are being adopted, replacing gas discharge lighting devices such as fluorescent lamps or high intensity discharge lamps because of their efficiency (Penning, Stober, Taylor, & Yamada, 2016); furthermore, continued innovation of LED lighting systems results in further reduction of the power consumed to produce the same light output as its gas discharge lighting system equivalents (National Academies of Sciences & Medicine, 2017).

The analysis of power factor for LED lighting devices is relevant to fully understand the energy savings benefits from its massive adoption. Power factor considerations are more complex than before because the adoption of LED technology is coincident with the introduction of connected devices (IoT) (IEEE_SA, 2015; Kofod, 2016). A new power factor analysis may benefit from considering the change in power factor of the device when responding to an IoT command. An LED lighting device may have its power factor affected by dimming, low energy, or other operational modes.

This paper considers LED lighting device power quality in terms of power factor and harmonic currents. It expands in the analysis of the power flow mechanisms across the electrical system (Alexander Eigeles Emanuel, 2010), in terms of harmonic currents and displacement factors, as described in the United States (IEEE_1459, 2010) and the European (IEC_61000_1_7_TR, 2016) standards.

Consequently, a proposal to describe LED lighting device power factor in terms of the displacement power factor and the harmonic power factor, for various modes of operation is discussed. This proposal is consistent with the ANSI lighting device power quality standards (ANSI_C822.77-10, 2014), and their equivalent IEC standards (IEC_61000_3_2_Ed4, 2014).

Measurements Relevant to Power Flow in LED Systems

This paper follows the traditional definitions used in multiple IEEE publications (Aiello, Cataliotti, & Nuccio, 2004; Alexander Eigeles Emanuel, 2010), as well as the IEEE Standard Definition for the Power Measurement of Electrical Power Quantities Under Sinusoidal, Nonsinusoidal, Balanced, and Unbalanced Conditions (IEEE_1459, 2010).

Resistor Energy Flow

According to (Alexander Eigeles Emanuel, 2010), the mains voltage, when it is not distorted, is described as,

$$v = \overline{V}\sin(\omega t)$$

Where

$\overline{V} = \sqrt{2}V$ is the amplitude, and V is the rms value of the voltage v

$\omega = 2\pi f$ is the angular frequency (rad/s), f is the frequency (Hz), and T=1/f is the period

Thus, the measurements relevant to power flow into a resistor (R) connected to the electrical system are,

$$i = \frac{v}{R} = \overline{I}\sin(\omega t)$$

Where

$$\overline{I} = \frac{\overline{V}}{R} = \sqrt{2}I$$

The instantaneous power p_a flowing into the resistor R is obtained by multiplying the instantaneous voltage v, and the instantaneous current i,

$$p_a = vi = \overline{V}\,\overline{I}sin^2(\omega t) = \frac{1-\cos(2\omega t)}{2}\overline{V}\,\overline{I}$$

$$= \frac{\overline{V}\,\overline{I}}{2} - \frac{\overline{V}\,\overline{I}}{2}\cos(2\omega t) = VI - VI\cos(2\omega t)$$

The power flowing into the resistor is cosinusoidal, with an amplitude VI, at double the mains frequency, with a dc offset of VI, and with a peak voltage of 2VI. The instantaneous power mean value P, in one cycle can be calculated as follows;

$$P = \frac{1}{T}\int_0^T \overline{V}\,\overline{I}\,sin^2(\omega t)dt$$

Given

$$T = \frac{1}{f} = \frac{2\pi}{\omega}$$

Then

$$P = \frac{1}{2\pi}\int_{2}^{2\pi} \overline{V}\,\overline{I}\,sin^2(\omega t)d(\omega t) = \frac{\overline{V}\,\overline{I}}{2} = VI$$

Thus, the instantaneous power across the resistor Pa can be re-written as,

$$p_a = P - p_i = P - P\cos(2\omega t)$$

The first term (P) is the average power, known as active power or real power, and is measured in Watts. The second term, p_i = -Pcos(ωt) is an oscillation with amplitude P. This term is present when a sinusoidal voltage supplies power to a resistor.

General Definitions According to (IEEE_1459, 2010);

1) Single Phase, sinusoidal

A sinusoidal voltage source

$$v = \sqrt{2}Vsin(\omega t)$$

Connected to a linear load, will produce a sinusoidal current that could be θ degrees out of phase

$$i = \sqrt{2}Isin(\omega t - \theta)$$

1.1 Single phase, sinusoidal, Instantaneous Power

The instantaneous power p is given by

$$p = vi$$

$$p = p_a + p_q$$

Where

$$p_a = VI\cos(\theta)[1-\cos(2\omega t)] = P[1-\cos(2\omega t)]$$

$$P = VIcos(\theta)$$

$$p_q = -VIsin(\theta)\sin(2\omega t) = -Q\sin(2\omega t)$$

$$Q = VI\sin(\theta)$$

The component p_a is the instantaneous active power; it is produced by the active current component (the current component in phase with the voltage). Thus, the instantaneous active power p_a energy rate of flow is,

$$w_a = \int_{t_0}^{t} p_a dt = P(t-t_0) - \frac{P}{2\omega}[\sin(2\omega t) - \sin(2\omega t_0)]$$

Energy w_a flow is unidirectional from the source to the load. Its steady state rate of flow is always positive, $p_a \geq 0$. As noted in the resistor example above, the instantaneous power has two component terms: the active (real) power P and the intrinsic (oscillating) power $-P\cos(2\omega t)$. This intrinsic power is always present when net energy is transferred to the load; however, this component does not cause power loss in the supplying lines.

The component p_q is the instantaneous reactive power. It is produced by the current reactive component (component out of phase and in quadrature with the voltage). This energy component oscillates between the sources and the electromagnetic energy stored within the inductors’ magnetic fields, capacitors’ electric fields, and moving masses of the connected equipment. Its rate of flow average value is zero; thus, there is no net transfer of energy to the load. However, this power (oscillation) results in power losses (Joule effect, and eddy currents) to the electrical system. The instantaneous reactive power p_q energy rate of flow is shown in the following.

$$w_q = \int_{t_0}^{t} p_q \, dt = \frac{Q}{2\omega}[\cos(2\omega t) - \cos(2\omega t_0)]$$

1.2 Single phase, sinusoidal, Active Power

The active power P (named real power) is the average value of the instantaneous power during the measurement time interval of τ and τ + KT as follows,

$$P = \frac{1}{kT}\int_{\tau}^{\tau+kT} p dt = \frac{1}{kT}\int_{\tau}^{\tau+kT} p_a dt$$

Where

T=1/f	is the cycle period
k	is appositive integer number
τ	is the measurement starting time

P=V I cos (θ)

P is equal to the average of p_a over a period, or an integer number of periods, because p_q averages to zero for any integer number of periods.

1.3 Single phase, sinusoidal, Reactive Power

The reactive power Q (VAR) is the oscillating instantaneous power p_q amplitude.

$$Q = VI \sin\theta$$

$$Q = \frac{1}{2\pi}\oint vdi = \frac{-1}{2\pi}\oint idv$$
$$= \frac{1}{kT\omega}\int_{\tau}^{\tau+kT} v\frac{di}{dt}dt = \frac{-1}{kT\omega}\int_{\tau}^{\tau+kT} i\frac{dv}{dt}dt = \frac{-\omega}{KT}\int_{\tau}^{\tau+kT} v\left[\int idt\right]dt$$

Or

$$Q = \frac{\omega}{kT}\int_{\tau}^{\tau+kT} i\left[\int vdt\right]dt$$

Thus, Q will be positive (Q>0) if the load is inductive, and Q will always be negative (Q<) if the load is capacitive. This means that when the current lags the voltage, the phase angle is positive θ>0, and when the current leads the voltage, the phase angle is negative θ<0.

1.4 Single phase, sinusoidal, Apparent Power

The apparent power S (VA) is the product of the rms voltage and the rms current.

$$S = VI$$

$$S = \sqrt{P^2 + Q^2}$$

The apparent power in a single-phase system under sinusoidal conditions can be understood as the maximum active power that can be transmitted. The instantaneous power p follows a sinusoidal oscillation with a frequency of 2f = 2ω / 2π based on the active power P. The amplitude of the oscillation is the apparent power S.

1.5 Single phase, sinusoidal, Power Factor

The ratio of active power P to the apparent power S ratio is called the power factor.

$$PF = \frac{P}{S}$$

The power factor is the ratio of the actual energy transmitted to the load to the maximum energy that could be transmitted to the load. Accordingly, power factor (PF) is an indicator of energy utilization.

1.6 Single phase, sinusoidal, Complex Power

A construct of a complex quantity where the active power is the real part and the reactive power is the complex part defines the concept of Complex Power (measured in VA).

$$S = P + jQ = VI^*$$

$$V = V < 0^\circ$$

$$I = I < -\theta$$

$$I^* = I < \theta$$

This construct is useful in the study of power flow. The apparent power (S) is the vector sum of the real power P and the reactive power Q. The phase angle θ is the phase angle of the complex impedance Z (**Z=V/I**). A full description of the "power triangle" (S,P,Q) conventional notation can be found in common literature (Alexander Eigeles Emanuel, 2010). The conventional description uses a Cartesian plane with the active power as the horizontal axis and the reactive power as the vertical axis. The reference direction for the active power delivered to the load is towards the left, and the reference direction of the reactive power delivered to the same load is towards the top.

2) Single Phase, Steady-State, Periodical, Non-Sinusoidal according to (IEEE_1459, 2010)

Instantaneous voltage and current, steady-state, non-sinusoidal, periodical quantities contain two main components: the power system frequency components v_1 and i_1 and components with other frequencies v_H, i_H (distortion).

$$v = v_1 + v_H$$

$$v_1 = \sqrt{2}V\sin(\omega t - \alpha_1)$$

$$v_H = V_0 + \sqrt{2}\sum_{h\neq 1} V_h \sin(h\omega t - \alpha_h)$$

$$i_1 = \sqrt{2}I\sin(\omega t - \beta_1)$$

$$i_H = I_0 + \sqrt{2}\sum_{h\neq 1} I_h \sin(h\omega t - \beta_h)$$

The corresponding squares of the rms values are:

$$V^2 = \frac{1}{kT}\int_{\tau}^{\tau+kT} v^2 dt = V_1^2 + V_H^2$$

$$I^2 = \frac{1}{kT}\int_{\tau}^{\tau+kT} i^2 dt = I_1^2 + I_H^2$$

Thus, the square of the distortion values are:

$$V_H^2 = V_0^2 + \sum_{h \neq 1} V_h^2 = V^2 - V_1^2$$

$$I_H^2 = I_0^2 + \sum_{h \neq 1} I_h^2 = I^2 - I_1^2$$

Direct voltage and current components V_0 and I_0 must be included for accuracy; however, significant direct voltage and current components are rarely present in alternating current (ac) power systems. Small amounts of direct voltage and current components (traces) are common nonetheless.

Distorted waveforms may include harmonics in which its frequency is not an integer number of the fundamental frequency. These harmonics are named inter-harmonics. A special group of inter-harmonics has a frequency lower than the electrical system frequency (h<1); and have periods larger than the system (fundamental) frequency. They are named sub-synchronous frequency components or sub-synchronous inter-harmonics (previously known as sub-harmonics).

Regardless if the waveform consists of harmonics with a frequency (nf) higher than the fundamental, the correct rms and power values are calculated by defining the measurement interval as kT (IEEE_1459, 2010). The measurement time interval needed to accurately measure power and rms values of a waveform that contains an inter-harmonic is the last common multiple of the periods of the fundamental component and the inter-harmonic component.

$$T = Period\ of\ the\ fundamental$$

$$f_i = Inter - harmonic\ frequency$$

$$T_i = \frac{1}{f_i}$$

$$kT = mT_i$$

Where k, and m are integer numbers.

When the measurement interval time has been chosen in such a way that it does not include an integer number of the subharmonics period ($kT \neq mT_i$), the inter-harmonics current, voltage and power are measured incorrectly. This error is reflected in measurement accuracy of the full waveform. The measurement error is further increased by the fact that cross products between current and voltage inter-harmonics do not yield instantaneous powers with zero mean value.

If at least one inter-harmonic has an irrational number order (h), then the observed waveform is defined as nearly periodic (a type of non-periodic waveform). Nearly periodic waveforms require an infinite time interval (kT) of measurement to yield power and rms values accurately. This error has been observed as minor in practical situations where the bulk power is carried by the fundamental (IEEE_1459, 2010; Pajic & Emanuel, 2009; Peretto, Willems, & Emanuel, 2007).

The larger the measurement interval time kT, the lesser the error caused by inter-harmonics (Peretto et al., 2007). The active power measurement error from the presence of inter-harmonics is strongly affected by the voltage and current phase angle. The closer the phase angle is to 90° the larger the error (Peretto et al., 2007). Previous research has suggested that error can be reduced to ± 0.2% in the presence of inter-harmonics if m=20 (IEEE_1459, 2010; Pajic & Emanuel, 2009).

2.1 Single Phase, Steady-State, Periodical, Non-Sinusoidal, Total Harmonic Distortion (THD)

The overall waveform distortion, as compared to its fundamental, is expressed as the total harmonic distortion. The voltage and current total harmonic distortion expressions are:

$$THD_V = \frac{V_H}{V_1} = \sqrt{\left(\frac{V}{V_1}\right)^2 - 1}$$

$$THD_I = \frac{I_H}{I_1} = \sqrt{\left(\frac{I}{I_1}\right)^2 - 1}$$

2.2 Single Phase, Steady-State, Periodical, Non-Sinusoidal, Instantaneous Power (W)

$$p = vi$$

$$p = p_a + p_q$$

The power terms include multiple frequencies as follows:

$$p_a = V_0 I_0 + \sum_h V_h I_h \cos\theta_h \left[1 - \cos(2h\omega t - 2\alpha_h)\right]$$

Thus, the instantaneous power is equal to the sum of harmonic active powers. The harmonic active power of order h is caused by the harmonic voltage of order h and the component of the harmonic current of order h in-phase with the harmonic voltage of order h. Each instantaneous active power of order h has two terms: 1) an active (real) harmonic power $P_h = V_h I_h \cos\theta_h$, and 2) the intrinsic harmonic power $-P_h \cos(2h\omega t - 2\alpha_h)$ which does not contribute to net transfer of energy or additional power loss in conductors.

Similarly, the term p_q can also be expressed in multiple frequencies.

$$p_q = -\sum_h V_h I_h \sin(2h\omega t - 2\alpha_h) + 2\sum_n \sum_{\substack{m \\ m\neq n}} V_m I_n \sin(m\omega t - \alpha_m) sin(n\omega t - \beta_n) + \sqrt{2}V_0 \sum_h I_h \sin(h\omega t - \beta_h) + \sqrt{2}I_0 \sum_h \sin(h\omega t - \alpha_h)$$

This term p_q does not produce a net transfer of energy; its average value is zero. Nonetheless, the currents related to non-active power cause additional losses.

The angle

$$\theta_h = \beta_h - \alpha_h$$

is the phase angle between the phasors V_h and I_h.

2.3 Single Phase, Steady-State, Periodical, Non-Sinusoidal, Active Power (W)

$$P = \frac{1}{kT}\int_{\tau}^{\tau+kt} p\,dt = \frac{1}{kt}\int_{\tau}^{\tau+kt} p_a\,dt$$

$$P = P_1 + P_H$$

Where

P_1 is the fundamental active power

P_H is the harmonic active power

2.4 Single Phase, Steady-State, Periodical, Non-Sinusoidal, Fundamental Active Power (W)

The fundamental active power is the power related to the fundamental (first) harmonic. Thus, it is called 60 Hz active power for a 60 Hz electrical system.

$$P_1 = \frac{1}{kT}\int_{\tau}^{\tau+kT} v_1 i_1 = V_1 I_1 \cos(\theta_1)$$

2.5 Single Phase, Steady-State, Periodical, Non-Sinusoidal, Harmonic Active Power (non-fundamental active power) (W)

The harmonic active power P_H encompasses all other components unlike the fundamental active power.

$$P_H = V_0 I_0 + \sum_{h \neq 1} V_h I_h Cos\theta_h = P - P_1$$

Non-sinusoidal active power may include inter-harmonics and sub-synchronous inter-harmonics; thus, h may be a non-integer number. Calculating inter-harmonics power separately requires caution; a measurement error will be introduced if the measurement interval kT is not an integer number of periods T/h.

2.6 Single Phase, Steady-State, Periodical, Non-Sinusoidal, Fundamental Reactive Power (var)

$$Q_1 = \frac{\omega}{kT}\int_{\tau}^{\tau+kT} i_1\left[\int v_1\right]dt$$

$$Q_1 = V_1 I_1 \sin\theta_1$$

2.7 Single Phase, Steady-State, Periodical, Non-Sinusoidal, Apparent Power (VA)

$$S = VI$$

Apparent power is the maximum active power that can be supplied to a load under ideal conditions. One important property of apparent power (S) is that the power loss (ΔP) at the feeder that supplies the apparent power S, is nearly a linear function of S^2 (A. E. Emanuel, 1999).

$$\Delta P = \frac{r_e}{V^2}S^2 + \frac{V^2}{R}$$

Where

R is an equivalent resistance representing the transformer core losses and cable losses

R_e is the effective Thevenin resistor

Theoretically, R_e can be calculated from the loss equivalence as follows,

$$r_e I^2 = r_{dc}\sum_h K_{sh} I_h^2$$

Where

I= S/ V

$K_{sh} > 1$

R_{dc} is the Thevenin dc resistance (Ω)

K_{sh} is a coefficient that accounts for the skin and proximity effects, as well as the losses caused in the cable sheath. This coefficient is a function of three elements: 1) the harmonic frequency, 2) the conductor's geometry, and 3) the conductor's material. Thus, the R_e value is affected by the harmonic's spectrum.

2.8 Single Phase, Steady-State, Periodical, Non-Sinusoidal, Fundamental Apparent Power (VA)

The fundamental apparent power S_1 and its components P_1 and Q_1 define the electromagnetic field energy rate of flow associated with the fundamental voltage and current.

$$S_1 = V_1 I_1$$

$$S_1^2 = P_1^2 + Q_1^2$$

2.9 Single Phase, Steady-State, Periodical, Non-Sinusoidal, Non-Fundamental Apparent Power (VA)

The apparent power resolved in terms of the fundamental and harmonic voltages and currents follows (A. E. Emanuel, 1995),

$$S^2 = (VI)^2 = (V_1^2 + V_H^2)(I_1^2 + I_H^2) = (V_1 I_1)^2 + (V_1 I_H)^2 + (V_H I_1)^2 + (V_H I_H)^2 = S_1^2 + S_N^2$$

$$S_N = \sqrt{S^2 - S_1^2}$$

The non-fundamental apparent power results in three components:

$$S_N^2 = D_I^2 + D_V^2 + S_H^2$$

2.10 Single Phase, Steady-State, Periodical, Non-Sinusoidal, Current Distortion Power (var)

$$D_I = V_1 I_H = S_1(THD_I)$$

2.11 Single Phase, Steady-State, Periodical, Non-Sinusoidal, Voltage Distortion Power (var)

$$D_v = V_H I_1 = S_1(THD_v)$$

2.12 Single Phase, Steady-State, Periodical, Non-Sinusoidal, Harmonic Apparent Power (VA)

$$S_H = V_H I_H = S_1(THD_I)(THD_V)$$

$$S_H = \sqrt{P_H^2 + D_H^2}$$

2.13 Single Phase, Steady-State, Periodical, Non-Sinusoidal, Harmonic Distortion Power (var)

$$D_H = \sqrt{S_H^2 - P_H^2}$$

The non-fundamental apparent power has been approached in previous research (A. E. Emanuel, 1995; Muñoz-Galeano, Alfonso-Gil, Orts-Grau, Seguí-Chilet, & Gimeno-Sales, 2015), assuming a $THD_v < 5\%$, by

$$S_N \approx S_1\sqrt{(THD_I)^2 + (THD_v)^2}$$

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This expression yields an error less than 0.15% for any THD_I. Furthermore, for $THD_V <$ 5% and $THD_I > 40\%$, the following approximation yields an error of less than 1%.

$$S_N \approx S_1(THD_I)$$

2.14 Single Phase, Steady-State, Periodical, Non-Sinusoidal, Non-Active Power (var)

$$N = \sqrt{S^2 - P^2}$$

This power quantity used to be called fictitious power. The non-active power should not be confused with the reactive power; it is only in the case of sinusoidal waveforms that $N=Q_1=Q$.

2.15 Single Phase, Steady-State, Periodical, Non-Sinusoidal, Fundamental Power Factor

$$PF_1 = cos\theta_1 = \frac{P_1}{S_1}$$

The fundamental power factor is used to evaluate the fundamental power flow. It is also known as the displacement factor.

2.16 Single Phase, Steady-State, Periodical, Non-Sinusoidal, Power Factor

$$PF = \frac{P}{S}$$

$$PF = \frac{P}{S} = \frac{P_1 + P_H}{\sqrt{S_1^2 + S_N^2}} = \frac{\left({}^{P_1}/_{S_1}\right)\left[1 + \left({}^{P_H}/_{P_1}\right)\right]}{\sqrt{1 + \left({}^{S_N}/_{S_1}\right)^2}} = \frac{\left[1 + \left({}^{P_H}/_{P_1}\right)\right]PF_1}{\sqrt{1 + THD_I^2 + THD_V^2 + (THD_I THD_V)^2}}$$

The overall degree of harmonic injection produced by a large nonlinear load, or by a group of loads, or a group of consumers, can be estimated from the ratio S_N / S_1. The characteristics of the fundamental power flow are described by S_1, P_1, PF_1, and Q_1.

In the specific case of $THD_V <$ and $THD_I > 40\%$, the power factor is re-expressed as

$$PF \approx \frac{PF_1}{\sqrt{1 + THD_I^2}}$$

It is useful to consider that in typical non-sinusoidal situations, $D_I > D_V > S_H > P_H$.

Note 3 to (IEEE_1459, 2010) to Single Phase, Steady-State, Periodical, Non-Sinusoidal, Power Factor is relevant for empirical measurements. "*In most common practical situations, it is difficult to measure correctly the higher order components of P_H using simple instrumentation. The main reason for this difficulty stems from the fact that the phase angle between the voltage phasor V_h and the current phasor I_h may be near / 2±π, so even small errors in phase angle measurement can cause large errors in P_H, even to the extent of changing the sign of P_H. Thus, one should use instrumentation optimized specifically for measurements of P_H components when making technical decisions regarding harmonics compensation, energy tariffs, or the quantification of the detrimental effects made by a nonlinear or parametric load to a particular power system*" (IEEE_1459, 2010, p. 13).

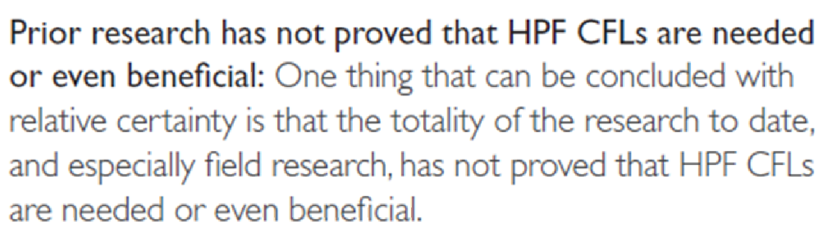
The lighting product standards (ANSI_C822.77-10, 2014) and (IEC_61000_3_2_Ed4, 2014) are consistent with the definitions described above.

Lighting Devices Power Factor Considerations

Power Factor and Energy Efficiency Lighting

Defining minimum power factor for energy efficiency lighting has been debated for a long time. Power factor may be affected by current displacement or by current harmonic content as shown in the previous section; more often, power factor is affected by both. It is notable that Electronic Compact Fluorescent Lamps (CFLi) with a power factor of about 0.5, were successfully used to increase lighting equipment efficiency in the past (Penning et al., 2016).

The CFLi energy saving program implementation was successful in the United States and other countries. The United States Agency for International Development recommended a minimum CFLi 0.5 power factor to other countries when developing their national policies (USAID, 2010). (See Figure 1.)



Prior research has not proved that HPF CFLs are needed or even beneficial: One thing that can be concluded with relative certainty is that the totality of the research to date, and especially field research, has not proved that HPF CFLs are needed or even beneficial.

Figure 1. *Picture showing a portion of the USAID document.*

Note adapted from: USAID. (2010). Power Factor Policy Implications for the Scale Up Programs.

The United States Agency for International Development study encompassed various elements such as: laboratory empirical data, results from field studies, net capacity, technical trade-offs, electricity price elasticity, and local conditions. At its core are findings that the total rms current consumed by a low power CFLi (25W) was a fraction of the current from its equivalent light output incandescent lamp (100W). (See Figure 2.)

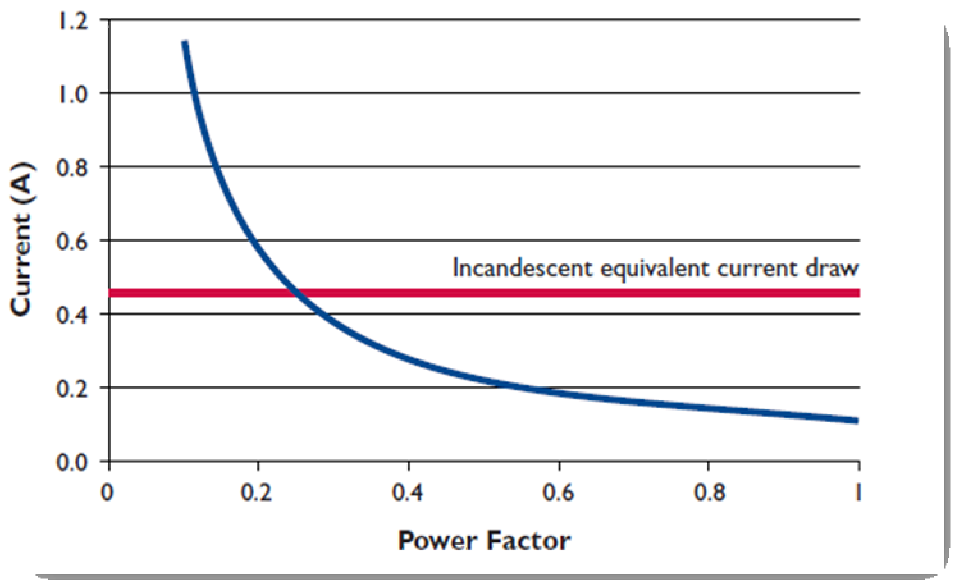


Figure 2. *Picture describing the CFLi low power factor current needed to produce the same amount of light as its equivalent incandescent lamp.*

Note adapted from: USAID. (2010). Power Factor Policy Implications for the Scale Up Programs.

A similar argument remains valid when migrating from CFLi's to LED self-ballasted lamps. The most popular LED self-ballasted lamps are approximately 8W to 12W, which are replacing 26W CFLi lamps (National Academies of Sciences & Medicine, 2017). It is possible to argue that this change will impact the net capacity to an even lesser amount because it is a transformation from low power factor to the same lower power factor, only with less rms current (total rms and each harmonic rms too).

The United States Agency for International Development findings are consistent with the National Electrical Manufacturer Association publication (NEMA_LSD8, 2014). (See Figure 3.)

Self Ballasted Lamp Power Factor Implications – An Example

$$PF = \frac{\text{Power Consumed in Watts}}{\text{Voltage} \times \text{Current}} \qquad P = VI \qquad I = \frac{W}{PF \times V}$$

Compare: PF Implications of a 25W Self Ballasted Lamp, and 100W Incandescent Lamp

Voltage RMS	Power Watts	PF	Self Ballasted Lamp Input Current	100W Incandescent Input Current
120	25	1.0	0.208	0.833
120	25	0.9	0.231	
120	25	0.8	0.260	
120	25	0.7	0.298	
120	**25**	**0.6**	**0.347**	
120	25	0.5	0.417	
120	25	0.4	0.521	
120	25	0.3	0.694	
120	25	0.2	1.042	
120	25	0.1	2.083	

25W Self Ballasted Lamp @ 0.6 PF draws ~0.5A less than 1.0 PF 100W Incandescent Lamp

Figure 1
CFL Power Factor Implications

Figure 3. *Picture from NEMA LSD 8 comparing the rms current of a low power CFLi and its light output equivalent incandescent lamp.*

Note adapted from: NEMA_LSD8. (2014). Power Quality Implications of Self-ballasted Lamps in Residences.

Power Quality in Terms of Displacement and Distortion as Alternative to Power Factor

ANSI, IEEE, and IEC standards have all introduced the use of harmonic factor and displacement factor as an alternative to power factor a few years ago. Assuming that the input current and input voltage are periodical or nearly periodical, the power factor can be measured as described in the previous section by,

$$PF = \frac{P}{S} = \frac{P_1 + P_H}{\sqrt{S_1^2 + S_N^2}} = \frac{\left({}^{P_1}/{}_{S_1}\right)\left[1 + \left({}^{P_H}/{}_{P_1}\right)\right]}{\sqrt{1 + \left({}^{S_N}/{}_{S_1}\right)^2}} = \frac{\left[1 + \left({}^{P_H}/{}_{P_1}\right)\right] PF_1}{\sqrt{1 + THD_I^2 + THD_V^2 + (THD_I THD_V)^2}}$$

which could be further simplified assuming that the input voltage is pure sinusoidal because, 1) the voltage distortion THD_V is zero, 2) the $THD_I THD_V$ multiplication factor is zero, and 3) the P_H is also zero because all voltage harmonics except for the first harmonic are assumed to be zero. Thus,

$$PF = \frac{P}{S} = \frac{PF_1}{\sqrt{1 + THD_I^2}}$$

With,

$$PF_1 = \frac{P}{S_1} = \cos\theta_1$$

Or,

$$PF = \frac{\cos\theta_1}{\sqrt{1 + THD_I^2}}$$

Where

$\cos\theta_1$ is the cosine of the first harmonic phase angle respect to the voltage (df)

$\sqrt{1 + THD_1^2}$ is the harmonic factor (hf)

Thus, lighting device power factor can be described by two basic metrics, displacement factor and harmonic factor under the conditions described above.

$$PF = df * hf$$

This simplification is based on (IEEE_1459, 2010). It is consistent with the American National Standard for *Lighting Equipment, Harmonic Emissions, Related Power Quality Requirements* (ANSI_C822.77-10, 2014), the European Lamp Companies Federation paper, *The Influence of Lighting Equipment on the Power Quality of the Grid* (ELCF, 2011b), LightingEurope's paper, *The Influence of Light Sources on the Public Power Supply System* (LightingEUROPE, 2014), and IEC technical report *Power Factor in Single Phase Systems under non-sinusoidal Conditions* (IEC_61000_1_7_TR, 2016).

Consider the following example: an LED luminaire has been proposed to replace a specialized lamp in the fashion industry; its light output is used to inspect fabric colors. The purpose of this example is to describe the use of the displacement factor and the distortion factor as an alternative to power factor. It is not meant to describe all LED devices, neither to characterize them as low displacement nor low harmonic factor devices.

The original source is an incandescent lamp set of about 220W. The alternative LED source is rated 40W. The total rms current consumed by the original light source was approximately 1.83 A;

$$Irms = \frac{P}{V * PF} = \frac{220W}{120Vrms * 1} = 1.833\ Arms$$

The alternative 40W LED source, operating with a power factor of 0.5, will operate with an input current of about 0.67 A;

$$Irms = \frac{P}{V * PF} = \frac{40W}{120Vrms * 0.5} = 0.666\ A\ rms$$

The replacement LED luminaire electrical data is displayed in Tables 1 and 2.

Table 1

Testing Data of a 40W LED Luminaire

60HZ 120V	
DATE	5/03/17
TIME	16:32:08
VRMS	120.19
IRMS	0.64
WATTS	39.78
VA	76.89
VTHD	0.31
ITHD	156.72
PF	0.52

Table 2

First Harmonic Data for a 40W LED Luminaire

Harmonic	Current Amps	%Dist to Fund	Phase	Freq
1	0.34	100	15.86	60.00

Rad Phase
0.277

The replacement 40W LED luminaire displacement factor is 0.962.

$$df = cos\theta_1 = \cos(0.277) = 0.962$$

Thus, the replacement 40W LED luminaire input current is almost in phase with the mains voltage; the power factor degradation is a consequence of the harmonic distortion. This is consistent with the THD_I measurement of 156.72%. The replacement 40W LED luminaire distortion factor is 0.537.

$$dh = \frac{1}{\sqrt{1 + THD_I^2}} = \frac{1}{\sqrt{1 + (1.57)^2}} = 0.537$$

Therefore, the power factor is 0.52.

$$PF = df * dh = 0.962 * 0.537 = 0.52$$

The use of the alternative metric yields the same result as the traditional metric; however, it directly identifies the root cause. The power quality degradation from this device may be addressed by filtering out harmonic currents, as opposed to adding capacitors to change the current phase, which would make power quality worse.

The use of these two parameters has been introduced by some California utilities as well (PG&E, 2007). Reportedly, power quality is better represented by displacement factor and harmonic factor (ELCF, 2011a, 2011b; Alexander Eigeles Emanuel, 2010). The use of these two parameters provides utilities, end users, and consultants information about the root causes of power quality degradation (ANSI_C822.77-10, 2014; IEC_61000_1_7_TR, 2016); this information is useful in developing a successful mitigation strategy.

These dyadic alternative metrics lead to two complementary standards; one for harmonic content and one for displacement factor. The harmonic current limits for lighting devices are standardized in the North American region and contained in the ANSI harmonic currents emission standard (ANSI_C822.77-10, 2014). Whereas the displacement factors are still under research.

The European community has been incorporating the displacement factors proposed by the European Lamp Companies Federation (ELCF, 2011b), and LightingEurope (LightingEUROPE, 2014) and already in IEC lamp standards (see Figure 4).

Table 2: Mains-voltage self-ballasted lamps and LED modules

Metric	Limit			
	$P \leq 2W$	$2W < P \leq 5W$	$5W < P \leq 25W$	$P > 25W$
$\kappa_{displacement}$ $(\cos\ \varphi_1)$ *)	No Limit	≥ 0.4	≥ 0.7	≥ 0.9
$\kappa_{distortion}$ To be regulated by IEC 61000-3-2 **)	No Limit	No Limit	Clause 7.3b	Clause 7.3a

Figure 4. *Picture showing LightingEurope's paper table 2, displacement factor as a function of the lamp power.*

Note adapted from: LightingEUROPE. (2014). LightingEurope Position Paper on The Influence of Light Sources on the Public Power Supply System**.**

The United States and the European standards require additional research to incorporate limits for low power mode of operation below two watts.

The harmonic limits defined in (ANSI_C822.77-10, 2014) seem to be adequate to protect the electrical network. Research considering concerns about harmonic losses in the electrical system by utilities and end users seem to indicate that contributors other than lighting have a stronger effect (EPRI_1017098, 2007). Regardless, the latest edition of (ANSI_C822.77-10, 2014) incorporates new limits for LED devices to better protect electrical infrastructure to additional harmonic losses. Consistent with Electrical Power Research Institute (EPRI) research ((EPRI_1017098, 2007), since LED self-ballasted lamps produce less harmonic currents of the same order than their CFLi light output equivalents, the mass adoption of LED self-ballasted lamps will reduce the power system losses derived from eddy currents and proximity effects.

Low Power Mode Power Quality Considerations

Low Power Mode Power Quality has not been deeply researched; the concept of an interconnected world with electronic devices in standby mode which wait for an action command is relatively new (IEEE_SA, 2015; Minerva, Biru, & Rotondi, 2015; Park et al., 2016).

Measuring standby mode power is complex; an LED device in a standby mode may be consuming energy for the lighting function standby and supporting other functions such as video cameras, sensors, and communications. Let us first consider an example consistent with an LED driver that supports additional communications and features when receiving a command to power off the current output for the LED module; thus, powering off the light output (see Figure 5).

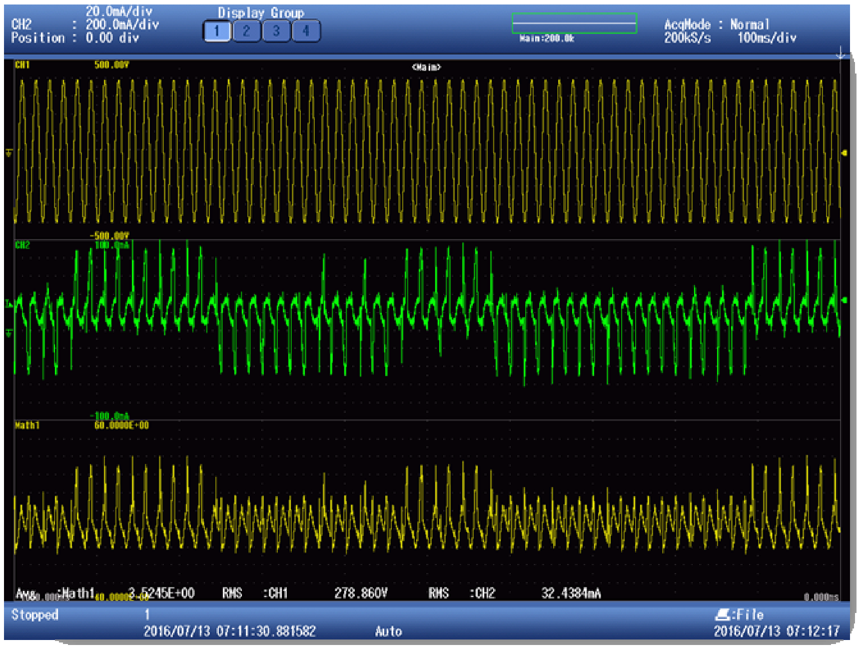


Figure 5. *Picture describing the input voltage, current, and power of an LED device in low power mode operation.*

The top trace shows input voltage, the second trace is the input current, and the third trace is the average of the instantaneous voltage times the instantaneous current which represents the input power. We have selected an LED device with a relatively high input power in low energy mode to enable clear scope measurements. Otherwise, the input current may be too small, making it difficult to measure, thus the scope reading may become illegible.

The input current is not periodic; it has current bursts due to sensor scanning and random current peaks. The input current non-periodicity challenges the measurement paradigms noted in the definitions section. This section describes how to measure rms and power quantities in periodical, or semi-periodical conditions. While the American National Standards Institute/American National Standard Lighting Group (ANSI/ANSLG) is considering an energy averaging method to estimate the input power consumption in non-periodical conditions; not enough research has been made to investigate how to measure the rms current, or the apparent power under the conditions described in Figure 5.

A power analyzer connected to the mains will provide a power factor number as a response to the electrical inputs; however, it is unclear what this number will mean in terms of the electrical system's physical reality. An in-depth understanding of the power analyzer's algorithms to deal with this complex non-periodical form is needed to be able to translate the readings from the power analyzer to the electrical system's physical reality.

Nonetheless, not all LED devices in low power mode operation may have random current peaks, or current bursts large enough to produce an error larger than 1%. See measurement in the measurement errors note in the general definitions, section item 2.5.

Consider a simple digital LED device which has no function other lighting. The input current may be small enough to challenge the resolution of the power analyzer. Initial observations of these types of LED devices seem to indicate a high displacement factor when operating in low energy mode.

Reportedly, displacement factor seems to be correlated to LED device power; the higher the device power, the higher the displacement factor. This seems to be a consequence of different filtering circuits and capacitors needed as the LED device power increases. A high displacement factor may lead to large measurement errors. See the general definitions section, item 2.16 note on measurement errors.

Initial observations indicated that voltage dedicated self-ballasted LED lamps with a standby function tend to have a power factor slightly higher than 0.5 in normal operation. They have a low power factor in standby mode with a high distortion factor, but with almost no displacement factor. As noted, a high distortion factor may lead to large measurement errors. Again, refer to the general definitions section, item 2.16 note on measurement errors.

Figure 6 describes minimum displacement factors for LED devices as a function of the standby power for various nominal power levels, derived from initial observations. These values are consistent with the IEC displacement factors for LED self-ballasted lamps, with a power equal to or higher than 2W. However, one needs to consider that limited data to model LED device power factor in standby mode exists.

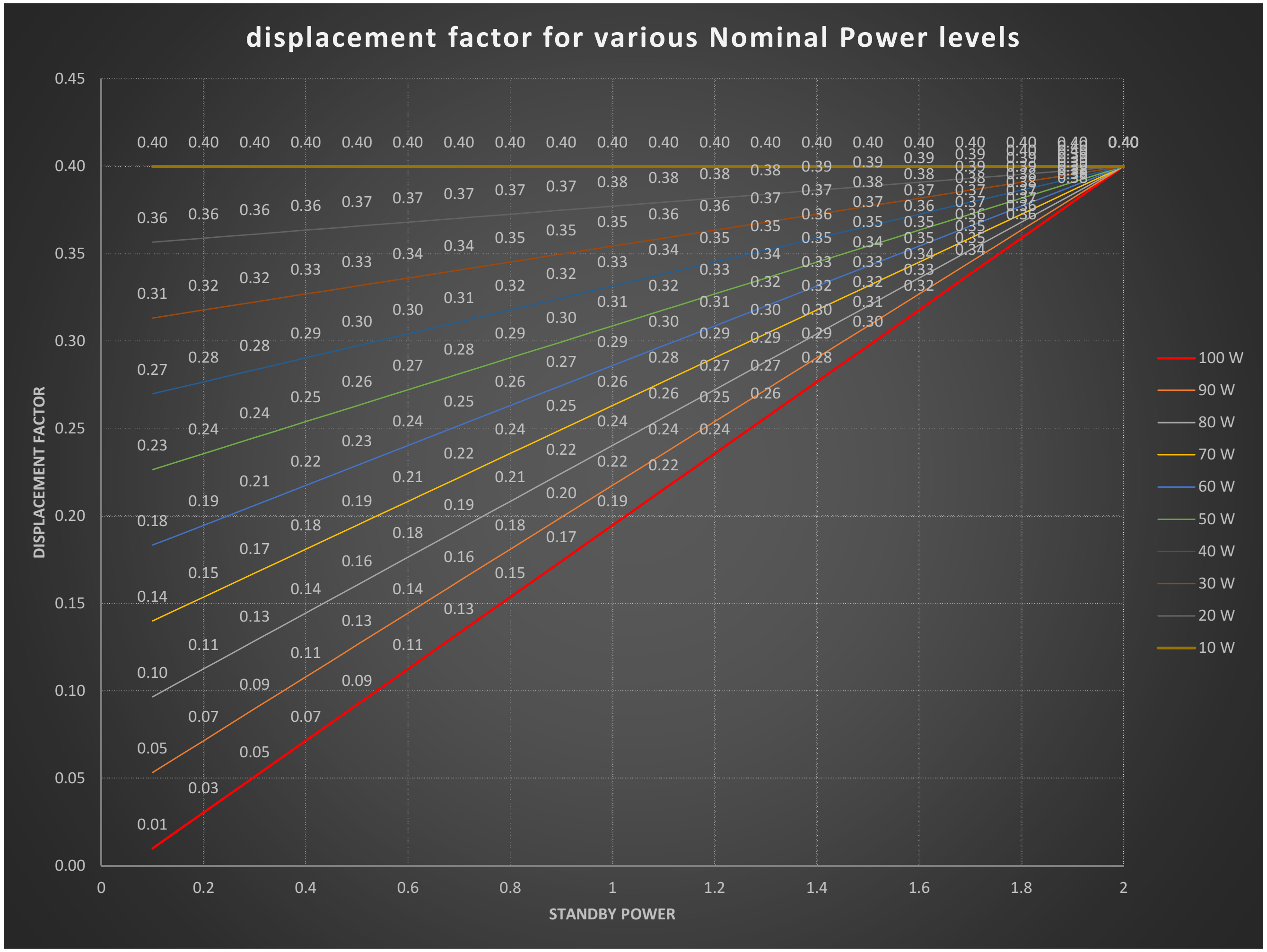

displacement factor for various Nominal Power levels
DISPLACEMENT FACTOR
STANDBY POWER
100 W
90 W
80 W
70 W
60 W
50 W
40 W
30 W
20 W
10 W

Figure 6. *Illustrating depicting LED device displacement factor as a function of the standby power for various nominal power levels.*

Additional Considerations

The massive growth of connected (IoT) devices has raised concerns about the potential power quality degradation if multiple devices were to go into standby at the same time (IEA, 2016). Power quality for aggregated devices is a complex research topic; modeling harmonic cancellation when connecting various devices is a complex task. Research by (W.Mack Grady, Mansoor, Fuchs, Verde, & Doyle, 2002) concluded, "*Harmonic current cancellation due to phase angle diversity, and attenuation due to system impedance and the corresponding voltage distortion, are two key factors that tend to reduce the net harmonic currents injected by large numbers distributed by single-phase loads*" (W.Mack Grady et al., 2002, p. 1094). This diversity cancellation phenomenon is of practical interest for harmonics of the 7th order and higher.

Furthermore, this research's last conclusion (W.Mack Grady et al., 2002) states, "*The current harmonics produced by the most common high-distorting load, the capacitor-filtered diode-bridge rectifier, tend to distort the applied voltage in such as manner as to reduce the current distortion. In other words, these loads exhibit a partial self-compensating effect*" (W.Mack Grady et al., 2002, p. 1094) deserves further research because it describes typical LED device topology. Thus, a massive introduction of standby devices may self-correct the harmonic distortion if this research (W.Mack Grady et al., 2002) holds true. Considering research from

(Ponce-Silva & Moreno-Basaldúa, 2015), alternative definitions of energy for power meters may complement this view.

(Meyer, Peter, & Heidenreich, 2011) seems to be in support of the harmonic cancellation effects among small electronic household equipment specifically.

The challenges of low power mode non-periodicity measurements may be addressed by adopting a new definition of the apparent power based on an rms power measurement, as suggested by (Fiorucci, 2015). This technique will allow power evaluation while avoiding losses of information related to the absence of the harmonic phases in the traditional definition of Apparent Power (S). This proposed method seems to be consistent with ANSI/ANSLG's considerations of averaging energy in a defined window of observation to represent standby power.

Research by (Gil-de-Castro et al., 2013) seems to support that notion that the adoption of LEDs to replace other electronic lighting technologies will result in power quality improvement. This is based on the fact that LED lighting devices produce the same amount of light even when consuming less power (less input current) than their traditional technology equivalents.

Empirical Observations

The testing data reported in this section provides an initial set of observations; further testing and additional research is needed before advancing to hypothesis testing. The testing data has been collected by an ISO 17025 approved laboratory which includes (ANSI_C822.77-10, 2014) in its accreditation scope.

Self-Ballasted Lamp Full Light Output and Standby Mode

The electrical input parameters of a smart LED self-ballasted lamp which includes a day-light sensor were collected in two modes of operation; Full Light output and Standby mode. See Table 3. The lamp was operated from a 120V, 60 Hz power supply with a voltage distortion less than 0.25%. Thus, it is acceptable (IEEE_1459, 2010) to consider the mains voltage as a sinusoidal power supply. Thus, the power factor can be expressed in terms of the multiplication of the displacement factor (df) times the distortion factor (dh) as described above.

$$pf = df * dh = cos\theta_1 * \frac{1}{\sqrt{1 + THD_I^2}}$$

Table 3, Smart LED Self Ballasted Lamp Electrical Data

	Standby	Full Out	
Vin	119.75	119.8	Vrms
Iin	6.15	113.28	Arms
Pin	0.277	8.106	W
PF	0.38	0.59	
THD	243.7	114.7	%
I1 (mA)	2.314	74.35	mArms
Phase1	0.0375	0.4456	
cosPhase1	0.999297	0.9023522	
PFCal	0.38	0.59	

The line labeled PF is the power factor reported by the power analyzer, and the line labeled PFCal is the power factor calculated from the multiplication of the displacement factor times the distortion factor,

$$PFfull = \frac{\cos(0.4456)}{\sqrt{1 + 1.14^2}} = 0.59$$

$$PFstandby = \frac{\cos(0.0375)}{\sqrt{1 + 2.437^2}} = 0.38$$

The alternative metric (df*dh), and the power analyzer reported number both yield the same power factor value. However, the alternative metric provides better insight to which extent the power factor change is caused by current displacement respect to the voltage supply, and which extent is caused by current distortion. The power factor change was not rooted in current displacement in this case; but rather in an increase in the current distortion.

A power analyzer capable to measure and report harmonic current phase angles with the necessary accuracy to enable power factor comparison was used in this first experiment. It will be discussed how to replace the first harmonic phase angle by the phase harmonic current in the next experiments. Regardless, the power analyzer measurement algorithms assume that the voltage, current, and power may be described by a Fourier series. Thus, the electrical quantities are periodical or semi-periodical (IEC_61000_1_7_TR, 2016; IEEE_1459, 2010). One may not always verify this assumption with devices operating in standby mode.

Digital Smart LED Drivers Full Output Power and Standby Mode

A set of four different models of LED drivers were tested operating from a 120V, 60 Hz power supply, which operates with a low voltage distortion (below 1%) in the extreme condition of a 300W load. Table 4 is a test results summary.

Table 4, LED driver electrical parameters operating at full output power and standby mode

	300W		40W A		150W		40W B	
	Full	Standby	Full	Standby	Full	Stanby	Full	Standby
VRMS	119.79	120.08	120.03	120.08	119.92	120.08	120.02	120.08
IRMS	2.74	0.08	0.40	0.01	1.41	0.04	0.40	0.02
WATTS	327.62	0.33	48.00	0.39	168.22	0.39	47.55	0.44
VA	328.18	9.25	48.07	1.25	168.65	4.26	47.91	2.27
VTHD	0.13	0.11	0.10	0.10	0.12	0.10	0.10	0.10
ITHD	5.04	10.17	4.47	167.41	6.27	26.20	8.15	76.33
PF	1.00	0.04	1.00	0.32	1.00	0.09	0.99	0.19
I A RMS H1	2.736	0.071	0.400	0.005	1.403	0.033	0.397	0.013
Phase H1	0.027	1.535	0.019	0.912	0.030	1.473	0.072	1.294

The experiment includes two different models of 40W LED drivers. They include different “smart” features; the driver with more standby mode features had a slightly higher power consumption in standby mode.

300W LED Driver

Let’s review the 300W driver power quality analysis first. It is possible to use the approach considering the voltage is sinusoidal, with a non-sinusoidal (distorted) periodical current, given that the power supply has a limited voltage distortion in the power of usage. Thus, the power factor can be found by multiplying the displacement factor times the distortion factor.

Alternatively, the displacement factor can be measured by calculating the real power to the first apparent power ratio (derived from the first harmonic current) (IEEE_1459, 2010) as described in the section Measurements Relevant to Power Flow in LED Systems.

$$df = Cos\theta_1 \quad hf = \frac{1}{\sqrt{1+THD_I^2}}$$

$$PF = df * hf = \frac{cos\theta_1}{\sqrt{1+THD_I^2}}$$

Or

$$df = \frac{P}{S_1} = \frac{P}{V * I_1} = PF_1$$

$$PF = \frac{P}{V * I_1 * \sqrt{1+THD_I^2}}$$

The power factor calculation, in terms of the power to the first apparent power, does not require to have an accurate measurement of the first harmonic phase; rather, one may need an accurate measurement of the first harmonic. Frequently, most of the LED device's power is carried by the first harmonic, or is at least a main contributor, as we will show here below. Table 5 shows a comparison of the displacement factor calculated as the $\cos\theta_1$ and the real power to the first apparent power ratio W / S; as well as a comparison of the power factor calculated by the alternative metric and the value reported by the power analyzer.

Table 5, Comparison of displacement factor and power factor measurements for a 300W LED Driver at full output power mode

Cos ϕ1	0.9996
THD	0.05

Validation	
error df %	0.0144
error pf %	0.0068

Calculated PF

PF	0.99837

Calculated displacement

P / S_1	0.9998

$$df = cos\theta_1 = 0.9996$$

$$df = \frac{P}{S_1} = \frac{P}{V * I_1} = 0.9998$$

The difference among these two displacement factor calculations is less than 0.02%, and the difference among the power analyzer power factor measurement and the alternative test method is less than 0.007%. Both of these differences are smaller than the power analyzer resolution; thus, the power analyzer reported power factor and the alternative test method reported power factor are the same for practical purposes.

The 300W LED driver analysis includes an active power factor correction circuit that yields high power factor and a low harmonic content. See Figure 7.

PHILIPS

Lighting Electronics North America

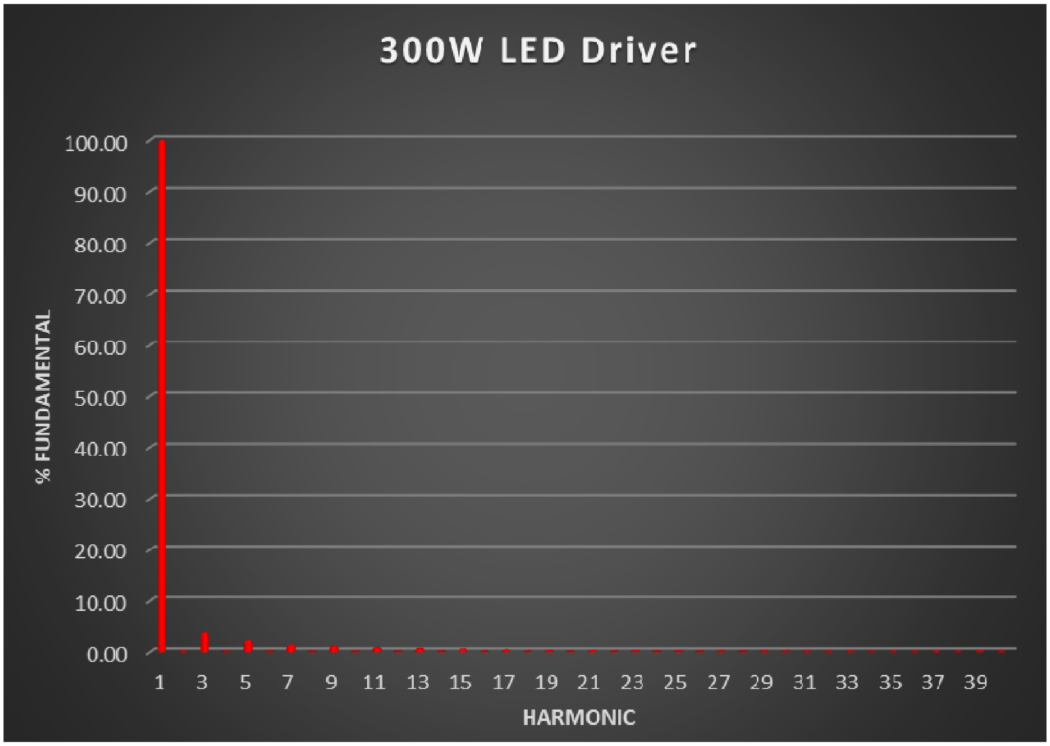


Figure 7, *300W Led Driver Harmonic Currents*

The power analyzer reported harmonic currents content matches the theoretical expectations. All power is carried by odd harmonics; no even harmonics were present. The fundamental harmonic is carrying most of the power and it is in phase with the power supply voltage. The active power factor correction circuit drives a repetitive sinusoidal current. The testing conditions are ideal for an accurate voltage, current, and power measurement. The power factor measurement difference when using different test methods is smaller than the power analyzer resolution.

Following the same rational, Table 6 shows the comparison of the results of the two displacement factor calculations for the 300W LED driver in standby mode, and the difference between the power analyzer reported power factor and the calculated power factor

Table 6, Comparison of standby mode power factor and displacement factor for a 300W LED Driver

Cos ϕ1	0.0361
THD	0.10

Validation	
error df %	5.7479
error pf %	0.3189

Calculated PF

PF	0.04

Calculated displacement

P / S_1	0.0381

The difference between the two displacement factor calculations is almost 6%, and the difference for power factor calculations is about 0.32%, both differences increased in one order of magnitude. Figure 8 shows the 300W LED driver operating in standby mode harmonic content, as reported by the power analyzer.

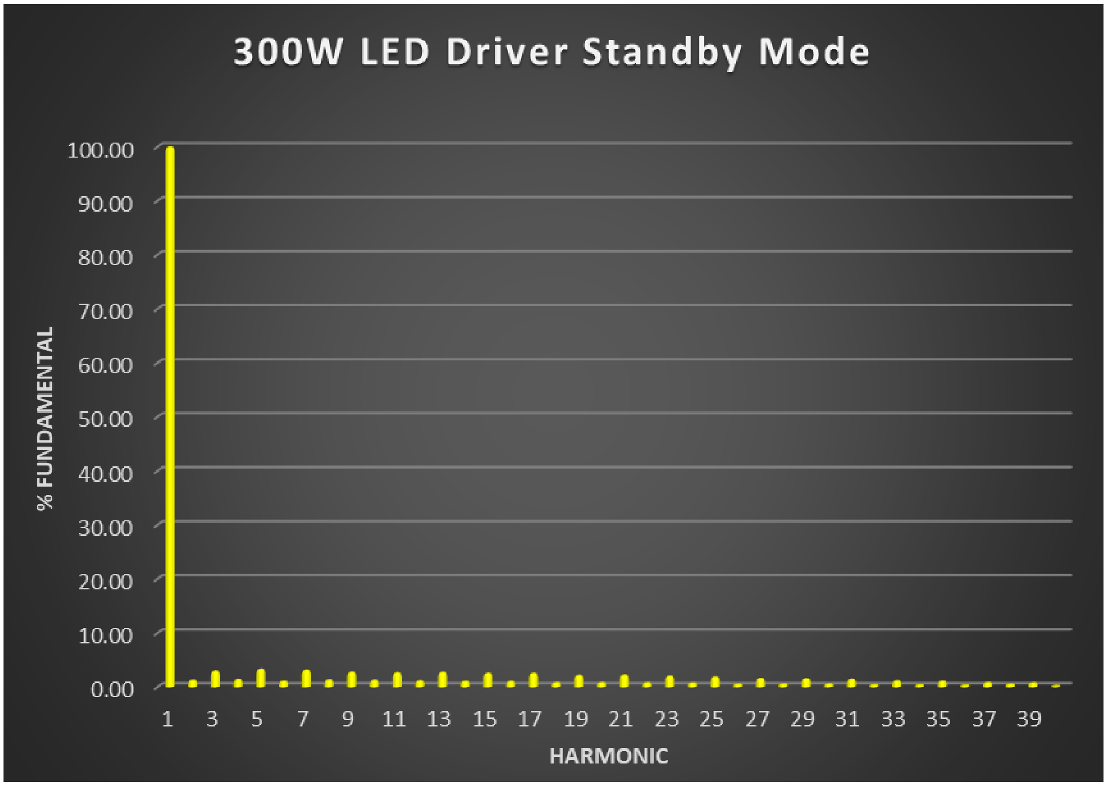


Figure 8, *300W LED driver Standby Operation Mode*

The harmonic content is still small; most of the power is still carried by the fundamental harmonic. However, the even harmonics, while small, are still visible. The 300W LED driver in standby mode operation yields a low power factor. The current displacement seems to be the root cause of the power factor erosion. A displacement factor error may affect the mitigation of the measurements chosen to improve power factor. Additional research is needed to understand these two displacement factor errors. Two initial potential considerations are; 1) the input current non-periodicity in this mode of operation, or 2) the power analyzer current resolution in relationship to the small input current.

40W LED Driver (A)

The 40W LED driver (A) operated at full light output resulted in high power factor, low harmonic distortion, and a minimum error between the power factor and displacement factor measurements. See Table 7.

Table 7, Comparison of power mode, displacement factor and power factor measurements for a 40W LED Driver (A) at full output

Cos ϕ1	0.999810655
THD	0.04

Validation	
error df %	0.0533
error pf %	0.0375

Calculated PF

PF	1.00

Calculated displacement

P / S_1	1.0003

Similar to the 300W case, the errors are smaller than the power analyzer resolution, and the harmonic content is small as well. We are not reproducing the harmonics chart to keep the length of this document manageable; however, the harmonic content has a similar profile as the previous one, a full copy of the harmonics chart can be requested from the authors.

Table 8 shows the comparison of displacement factor measurements and power factor measurements for a 40W Led driver (A) in standby mode of operation.

Table 8, Comparison of power factor and displacement factor for a 40W LED Driver (A) in standby mode

Cos ϕ1	0.61225592
THD	1.67

Validation	
error df %	4.1573
error pf %	-0.3290

Calculated PF

PF	0.31

Calculated displacement

P / S_1	0.6377

Here too, the difference between the displacement factor measurement and the power factor measurement increased. Furthermore, the power analyzer harmonic currents reported challenge the basic theoretical assumptions described at the beginning of this section. See Figure 9.

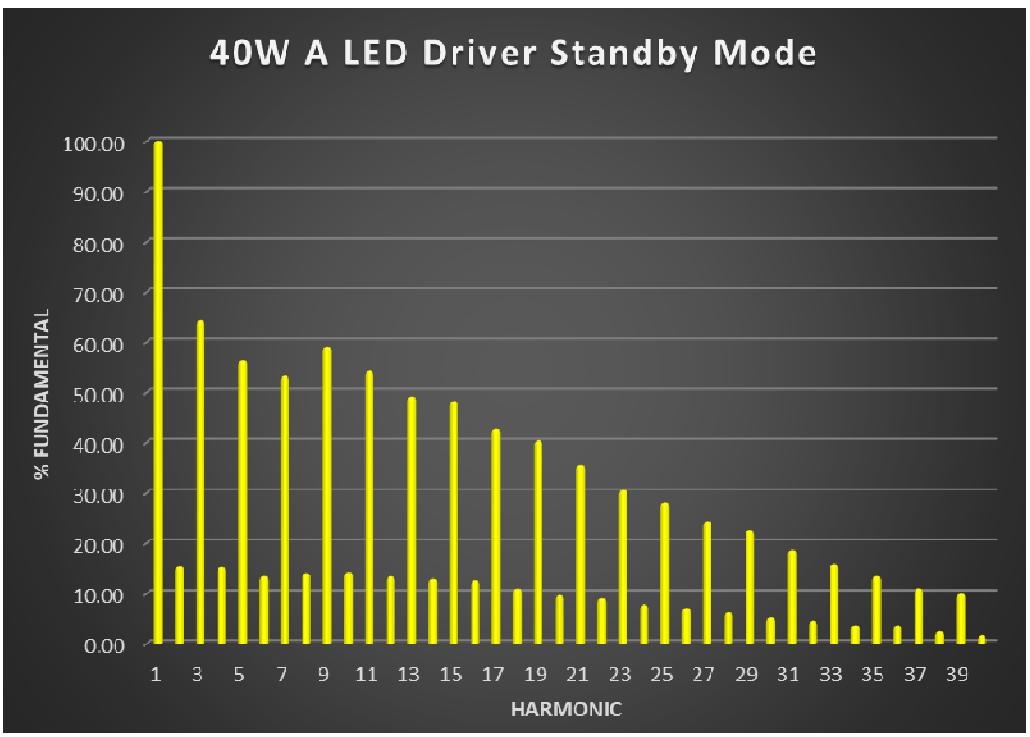


Figure 9, *40W LED driver (A) Standby Operation Mode*

Apparently, the rms current carried by the odd harmonics from the 3rd to the 39th is higher than the power carried by the fundamental harmonic. In addition, the odd harmonics seem to carry a significate rms current compared to the standby total rms current. Additional research is needed to clarify the root cause of the displacement factor, harmonic factor, and harmonic emissions measurement errors.

150W LED Driver

The operation of a 150W LED driver at full light output resulted in high power factor, low harmonic distortion, and a minimum error between the power factor and displacement factor measurements. See Table 9.

Table 9, Comparison of power factor and displacement factor measurements for a 150W LED Driver at full output power mode

Cos ϕ1	0.999562662
THD	0.06

Validation	
error df %	0.0110
error pf %	0.0205

Calculated PF

PF	1.00

Calculated displacement

P / S_1	0.9997

Similar to the 300W case, the errors are smaller than the power analyzer resolution, and the harmonic content is small as well.

Table 10 shows the comparison of displacement factor measurements and power factor measurements for a 150W Led driver in standby mode of operation.

Table 10, Comparison of power factor and displacement factor measurements for a 150W LED Driver in standby

Cos ϕ1	0.097242442
THD	0.26

Validation	
error df %	0.5435
error pf %	2.2156

Calculated PF

PF	0.094

Calculated displacement

P / S_1	0.0978

Here too, the difference among the displacement factor measurement and the power factor measurements increased. The reported power analyzer harmonic currents also challenge the basic theoretical assumptions described at the beginning of this section, but to a lesser degree. See Figure 10.

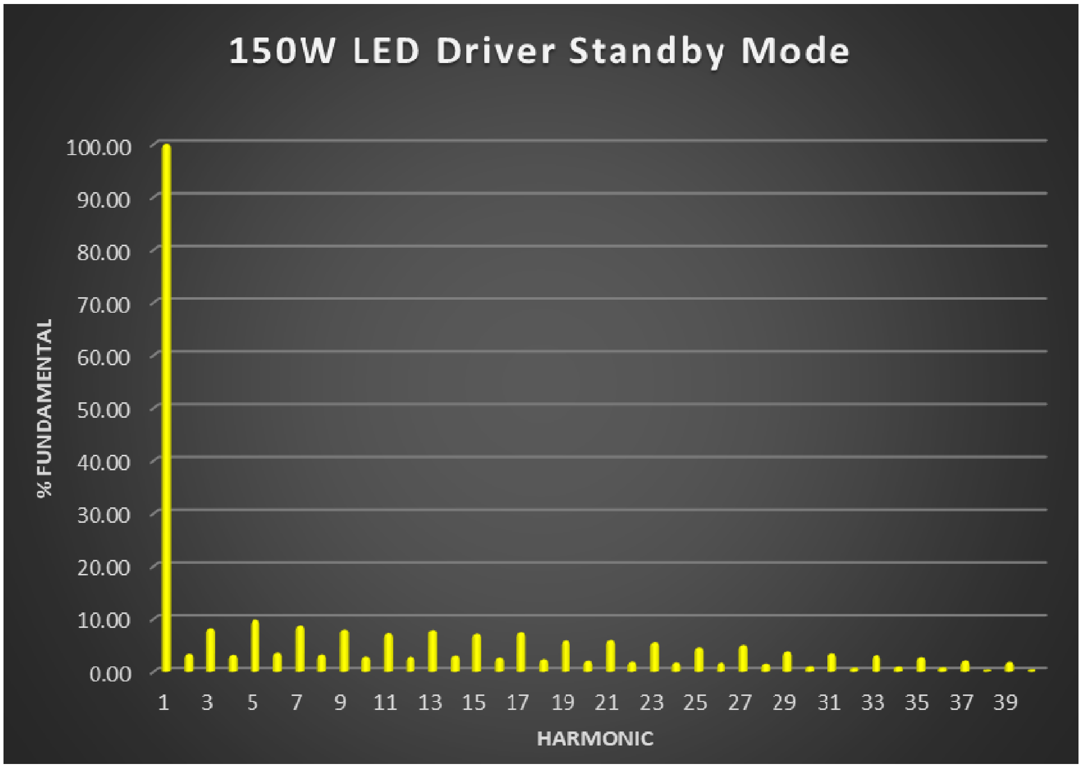


Figure 10, *150W LED driver Standby Operation Mode*

Additional research is needed to clarify the root cause of the displacement factor, harmonic factor, and harmonic emissions measurement errors.

40W LED Driver (B)

The 40W LED driver (B) full light output operation resulted in high power factor, low harmonic distortion, and a minimum error among the power factor and displacement factor measurements. See Table 11.

Table 11, 40W LED Driver (B) full output power mode, displacement factor and power factor measurements comparison

Cos ϕ1	0.997420114
THD	0.08

Validation	
error df %	0.0687
error pf %	0.1642

Calculated PF

PF	0.99

Calculated displacement

P / S_1	0.9981

Similar to the 300W case, the errors are smaller than the power analyzer resolution, and the harmonic content is small as well. Again, we are not reproducing the harmonics chart to keep the length of this document manageable; however, the harmonic content has a similar profile as the previous one, a full copy of the harmonics chart can be requested from the authors.

Table 12 shows the 40W B Led driver in standby mode of operation displacement factor measurements and power factor measurements comparison.

Table 12, 40W B LED Driver in standby mode power factor and displacement factor comparison

Cos ϕ1	0.273524445
THD	0.76

Validation	
error df %	0.505
error pf %	11.847

Calculated PF

PF	0.22

Calculated displacement

P / S_1	0.2749

Here too, the difference among the displacement factor measurement and the power factor measurements increased. Furthermore, the power analyzer harmonic currents reported challenge the basic theoretical assumptions described at the beginning of this section. See Figure

11. The power factor difference among the power analyzer report and the alternative test method is the highest for this driver.

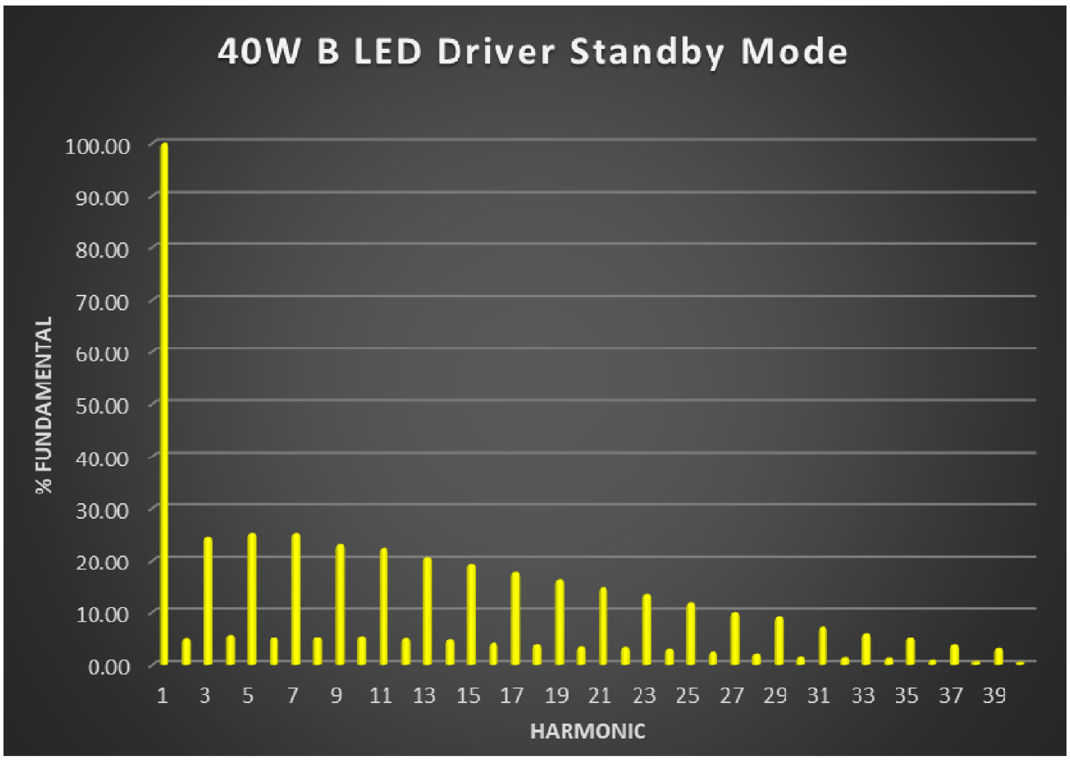


Figure 11, *40W LED driver (B) Standby Operation Mode*

As in previous examples, additional research is needed to clarify the root cause of the displacement factor, harmonic factor, and harmonic emissions measurement errors.

Harmonic Currents Diversity Considerations

Figure 12 shows the 3rd harmonic of all the drivers considered in this document, plotted in a Cartesian Plot. Each colored dot represents the end of the arrow of a vector associated with the 3rd harmonic of each driver. For example, the red dot at the left of the chart represents the end of the vector describing the 300 W, full light output 3rd harmonic current rms (107.9 mA rms), and its phase (-171 º). The 3rd harmonics for standby mode are small compared with those for the full output power operation; they are all grouped in the light blue dot closer to the center of the chart. While it is difficult to evaluate if the current algorithms embedded in the power analyzer could correctly resolve the Fourier transformation; these results seem to indicate that the electrical system running the drivers under study at full power will operate in standby mode with substantially less 3rd harmonic with a similar phase as the 3rd harmonic in full power operation.

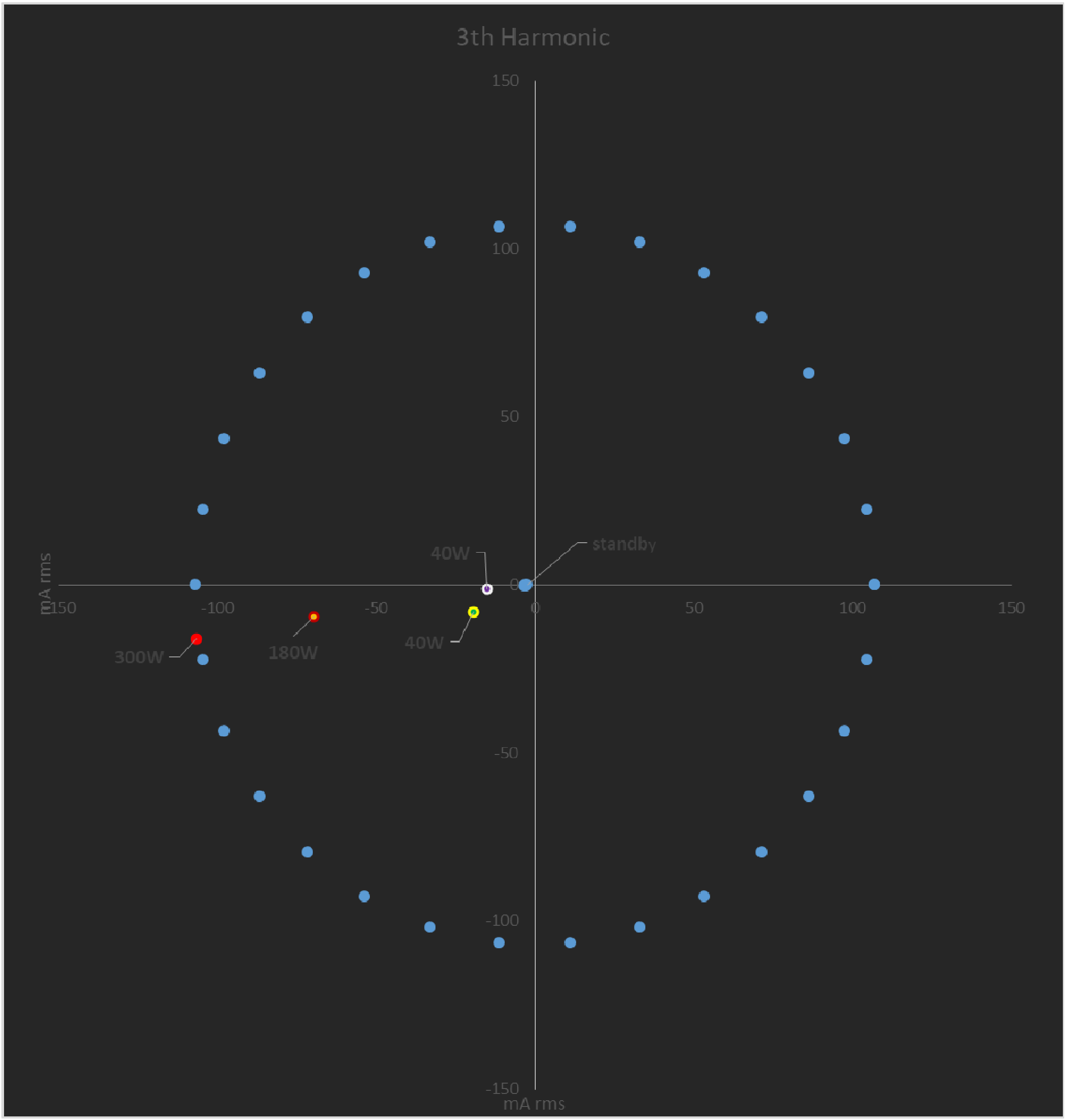


Figure 12, *3rd harmonics of all LED drivers considered in this document*

Note that the circle of light blue dots described is simply a reference for measuring the harmonic phase angles.

Figure 13 describes the 5th harmonic content in a similar way.

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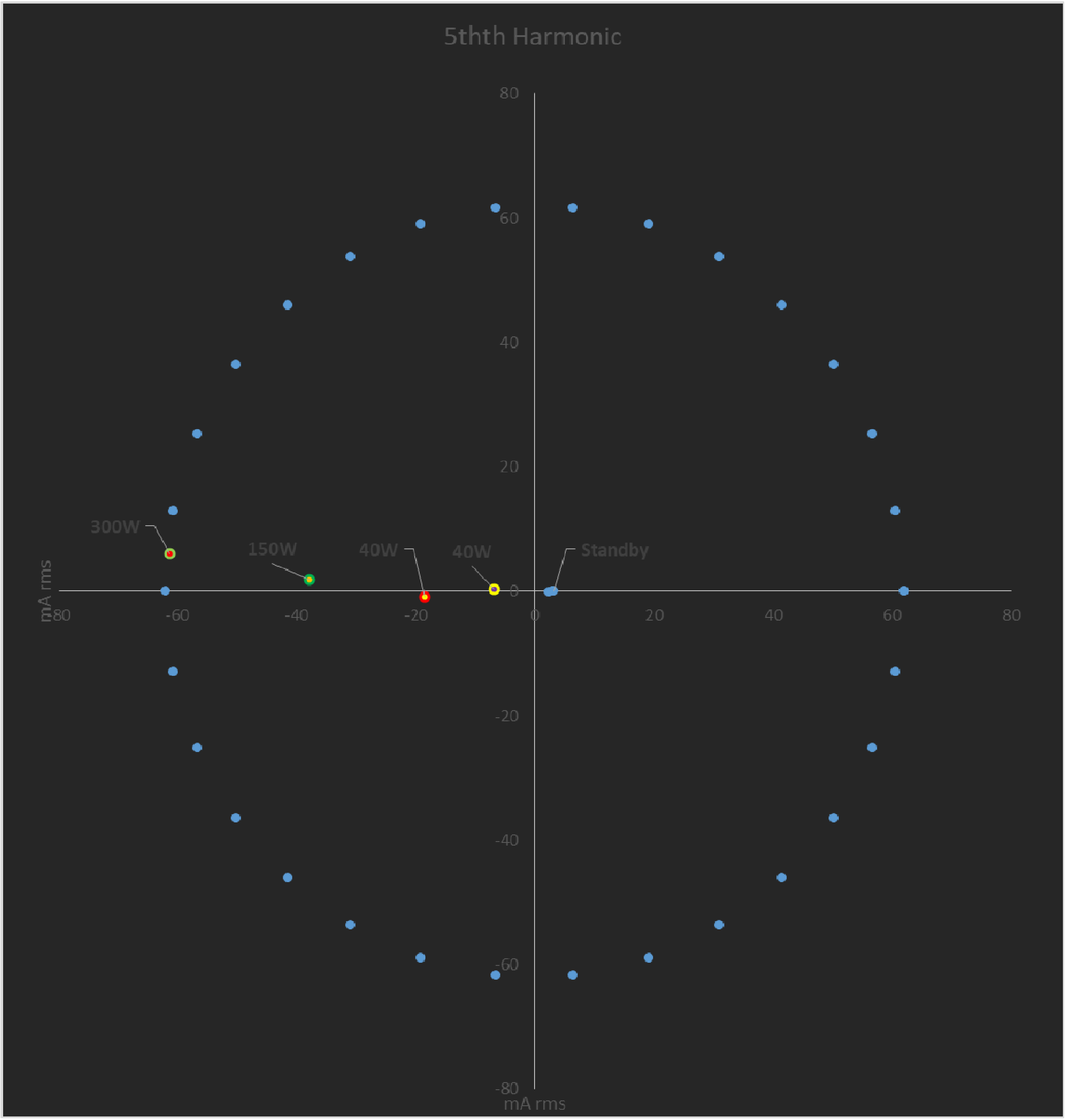

Figure 12, *5th harmonics of all LED drivers considered in this document*

Note that the circle of light blue dots shown is simply a reference for measuring the harmonic phase angles

Further research is needed to evaluate the accuracy of the Fourier transformation embedded in the power analyzer to represent the standby mode of operation and the real energy saving consequence of these harmonics considering diversity among LED systems.

Conclusions

The literature review, field observations, and the empirical test results suggest two major outcomes for measurement techniques, and two limitations:

1) *Power Factor measurements for LED systems and devices operating at full power may be accurate when following the existing methods described in (ANSI_C822.77-10, 2014), and (IEEE_1459, 2010).*
2) *Accurate Power Factor measurements of LED systems and devices operating in a standby mode requires further research.*
3) *LED self-ballasted lamps, LED devices, and systems operating at full power should be measured in terms of harmonic factor and displacement factor. The displacement factor limits seems to be adequately described by the IEC as shown in Figure 4 (LightingEUROPE, 2014) , and the distortion limits are described in (ANSI_C822.77-10, 2014). It would seem that ANSI C82.77 WG needs to enhance the power quality standard to incorporate harmonic diversity, and other*

harmonic cancellation phenomena. This is necessary to prevent an over regulation of this mode of operation.

4) *When operating in standby mode the Power Factor of LED lamps or other LED devices, is often very poor (measured PF = 0.04 to 0.32). The question is: Does it matter? Fortunately it doesn't! Due to the strict regulation on standby power the standby current and its harmonic components are only a small fraction of the current during normal operation. These very small currents do not impact the network nor the connected equipment. Setting requirements to PF in standby mode would lead to additional costs without any benefit.*

Power Factor is a complex metric intended to describe the power flow transfer efficiency through a system. Electrical power providers are committed to maintain low voltage distortion. This commitment supports the financial interest of both the electrical power consumer and the electrical company (Duarte & Schaeffer, 2010).

Power Factor may be affected by the electrical power provider's generation and distribution quality, and by the characteristics of consumer loads (Alexander Eigeles Emanuel, 2010; Gonzalo, 2014). Power Factor has been traditionally described in terms of the ratio of real power to the apparent power (Ponce-Silva & Moreno-Basaldúa, 2015); however, formulating Power Factor in terms of the displacement factor and the harmonic factor (ANSI_C822.77-10, 2014; IEEE_1459, 2010) yields more useful information to consumers and Electrical power companies.

$$PF = \frac{P}{VA} = df * hf = cos\theta_1 * \frac{1}{\sqrt{1 + THD_I^2}}$$

The above described formulation assumes that the voltage and current waveforms are periodical or semi-periodical (IEEE_1459, 2010), and that the voltage distortion can be neglected due to the strict voltage distortion control imposed by the Electrical companies. No linear loads, operating without repetitive currents are difficult to measure accurately (Fiorucci, 2015; Peretto et al., 2007).

LED systems such as a lamp with an on / off lighting control tend to operate with repetitive voltage and current waveforms, whereas smart LED systems and devices tend to operate with a no repetitive current waveforms and with a magnitude smaller than the capabilities of most commercial power analyzers. See Figures 8, 9, 10, and 11. Thus, power factor measurements for LED systems in full output power mode tend to be accurate; whereas, power factor measurements for the same device or system, operating in standby mode is challenging (IEEE_1459, 2010).

It is, in fact, difficult to correlate a Power Factor reading from of a power analyzer (utilizing the current power measurement algorithms)of an LED device or system in standby mode to the Physical effects at the distribution transformer or the installation wiring (ELCF, 2011b).

This is true for other types of power supplies as well (Muñoz-Galeano et al., 2015; Ponce-Silva & Moreno-Basaldúa, 2015) .Thus, additional research is needed to determine the best way to measure LED devices or systems in standby mode.

The IEC has followed a similar approach, and they are also embracing the use of harmonic factors and displacement factors in their power quality standards (IEC_61000_1_7_TR, 2016; IEC_61000_3_2_Ed4, 2014).

Displacement factor has been used frequently to model power generation effectivity, cost, financial impact (Duarte & Schaeffer, 2010) , and distribution loses due to low power factor (EPRI_1017246, 2003; PG&E, 2007).

Power factor for LED systems, and LED self-ballasted lamps operating at full power, can be accurately described in terms of displacement factor and distortion factor. The maximum harmonic factor has already been established in (ANSI_C822.77-10, 2014; EPRI_1017098, 2007; W.Mack Grady et al., 2002). It is expected that the displacement factor may align with the current IEC requirement. See Figure 4. Thus, a modern approach for LED systems operating at full power may be described as; the LED device or systems shall comply with the displacement factor described in Figure 4, and the harmonic content described in (ANSI_C822.77-10, 2014).

The general inception of no linear lighting loads in the electrical grid (Bunjongjit et al., 2017; W.Mack Grady et al., 2002; Meyer et al., 2011) , and the particular inception of smart connected devices (IoT) (Blamco et al., 2015) capable of operating in standby mode are challenging the electrical power long established metrics and measurement tools (Fiorucci, 2015; W Mack Grady & Gilleskie, 1993; Pajic & Emanuel, 2009).

It is unclear if a high power factor for LED self-ballasted lamps, devices, or systems is financially justified. Reports for harmonic diversity and harmonic cancelation suggest that such phenomena may correct, at least in part, a low efficiency power transfer flow across the electrical system. See Figures 11 and 12. Additionally; the United States Development Mission for ASIA, and NEMA's LSD 8 papers concluded that introduction of a low power factor LED device or system will not result in a grid degradation because the total rms current remains substantially lower than its equivalent discharge lighting device or system. See Figures 2 and 3 (NEMA_LSD8, 2014; USAID, 2010).

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