POWER FACTOR
TALES

An offensive title but needed. The problem is that Power Factor is not understood well enough to result in sensible guidelines for LED lamp driver designs. The Power Factor can rank from 0 to 1. Certifying Institutions, power companies and authorities increasingly demand a higher power factor for LED lamps. This results often in unnecessary measurements with highly reduced sustainability. This article on PF may kick off discussions on how the LED industry can contribute to more sustainable solutions. Warning! For some of you this story can be shocking. Are we crazy?

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Talking about drivers for LED lamps, the meaning of Power Factor is a source of misunderstanding and wrong interpretations. The increasing call for higher PF on LED lamps makes in most cases no sense. Nowadays a power factor parameter of 0.7 to 1 is considered to be good. The DOE in the USA require for Energy Star certification a power factor of at least 0.7 for LED lamps > = 5W but does that make sense?

What is PF?

PF is the ratio between how much energy is really consumed (Watt) and the energy that's returned to the grid. That part is called Volt x Ampere Reactive (VAR). Many people measure the Volt and Amperes used by the lamp and conclude the lamp using much more energy than specified. VAR is energy NOT used. Power (W) = V x Amp x cosΦ

Like all ratio measurements, Power Factor is a *unitless* quantity.

In a simple equation PF = real power/ apparent power

Formally the PF = sum harmonics (p)/ sum harmonics (a)

It means the PF is a complex combination of displacement of the current and harmonic distortion. Both can affect the power efficiency in the grid. It also means that PF is NOT related with the energy efficiency and quality of the LED lamp and it's NOT an energy saving or quality metric. Power factor is a qualification of the power flow in the electric grid. PF 1 is optimal power flow. PF 0 =poor power flow. With poor power flow there will be more losses in the grid and potential risks of harming equipment by harmonic distortion frequencies. Power utility companies don't like that risk and ask manufactures of LED lamps for high PF. That's mostly unjustified.

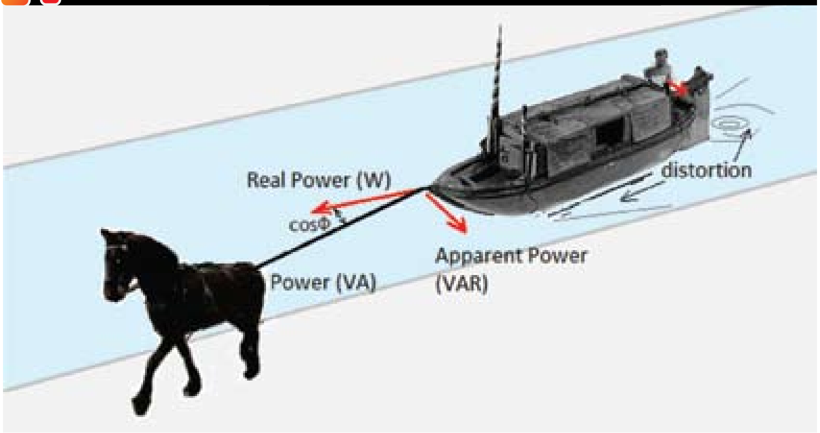
PF simplified

The layman explanation in fig.1 is showing what the various elements in the power factor mean.

Imagine a ship being pulled by a horse. There is an angle between the rope and the direction of the ship. This angle is in power terms the cos . With a long rope the power factor will be high and the boat will move easily forward. With a short rope the power factor will be low and other forces will be needed to keep the boat straight. It has negative effects.

To keep the boat straight the skipper has to push the rudder. This causes a vortex behind the rudder. The worse the power factor the harder the skipper has to correct and the bigger the distortion in the water. With a power factor of 0.5 the cos = 45 deg.

Fig. 1 forces and consequences



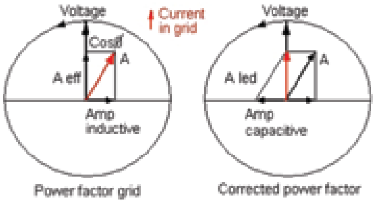
and only half of the horsepower will be moving the boat forward. Let's assume the canal is the power grid. The impact of the distortion is highly related to the amount of power. If we would pull the boat by a cat instead of a horse there won't be much disturbance of the water. With a couple of horses we could create distortion in the water which would flood the shore and cause serious damage. In analogy with a grid operator, distortion will disturb the energy flow in the grid and may damage other equipment. What we see is that the amount of power is of more influence than the actual power factor. In some cases a low PF could even be helpful. For instance when we have the horse pulling the boat and a cat helps pulling at the other side of the canal with a much shorter rope. The power factor would be corrected.

In electric terms

When AC voltage is rising in an inductive circuit, the current will start to rise later due to opposition from that inductor. Rising of the current is opposed by the magnetic permeability of the core in a coil. The magnetic polarization direction will be set. When the voltage is no longer rising, the current will be maximal and the energy is stored in the inductor. Such charge we may know from an inductor in cars to ignite the spark plugs. When the voltage is over the top of the sinusoid, the voltage is changing direction. The charged energy is however also to be released. It will be released to the power grid during the falling of the voltage. Then the whole process starts over by changing the direction of the magnetic polarization in the opposite direction. In fact the coil is charged by the grid and then discharged to the grid, a process like pouring water from one cup in another and then back again. There is no energy consumed.

A LED lamp of 5W with a power factor of 0.5 will cause a current in the grid of 44 mA. This is twice as much as a LED lamp with a power factor of 1.

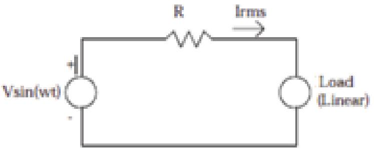
The real consumed power is V x Amp x PF = 230 x 0,044 x 0.5 = 5W. However, if this LED would have a capacitive power factor with a current of 44 mA, part of this current will be eliminated in the grid or better stated, compensated by an inductive fan or refrigerator pump in the house or somewhere else. The power from the power plant to run the lamp did not increase. The correction energy is obtained from reactive energy present in the grid. Power grids have generally an inductive power factor. Physical power is generated by motors which in copper and magnets (inductive). When we apply a capacitive LED lamp with a very poor power factor of 0.1, it would correct the power factor of the grid in a positive way.



The real thing

This section is for those who want to understand the PF displacement part (cosΦ) and the distortion part in detail.

First we consider the ideal sinusoidal situation as shown in the schematic:



The voltage and current at the load are

(2) $V(t) = V_1 \sin(\omega_0 t + \delta_1)$

$I(t) = I_1 \sin(\omega_0 t + \Phi_1)$

where V_1 and I_1 are peak values of the 50/60 Hz voltage and current, and δ_1 and Φ_1 are the relative phase angles. The true power factor at the load is defined as the ratio of average power to apparent power, or:

(3) $$pf_{true} = \frac{P_{avg}}{S} = \frac{P_{avg}}{V_{rms} I_{rms}}$$

For the purely sinusoidal case, (3) becomes:

(4) $$pf_{true} = pf_{disp} = \frac{P_{avg}}{\sqrt{P^2 + Q^2}} = \frac{\frac{V_1}{\sqrt{2}} \frac{I_1}{\sqrt{2}} \cos(\delta_1 - \theta_1)}{\frac{V_1}{\sqrt{2}} \frac{I_1}{\sqrt{2}}} = \cos(\delta_1 - \theta_1)$$

where *pf displ* is commonly known as the displacement power factor, and where $(\delta_1 - \Phi_1)$ is known as the power factor angle (cos□). Therefore, in sinusoidal situations, there is only one power factor because true power factor and displacement power factor are equal.

For sinusoidal situations, unity power factor corresponds to zero reactive power Q, and low power factors correspond to high Q. Since most loads consume reactive power, low power factors in sinusoidal systems can be corrected by simply adding shunt capacitors. The correction capacitor should preferably be as close to the inductive source as possible in order to avoid correction currents to flow long distances through the grid. Capacitive LED lamps would be distributed throughout the grid at the end of the nodes and contribute to compensation of inductive loads.

Power Factor in Non-sinusoidal Situations

In non-sinusoidal situations, where network voltages and currents contain harmonics the PF will have harmonics in the currents.

Harmonics are caused by system nonlinearities such as transformer saturation, electronic dimmers and diode bridge rectifiers. The significant harmonics (above the fundamental, i.e., the first harmonic) are the 3rd, 5th, and 7th multiples of 50/60 Hz. Total Harmonic Distortion (THD) is the ratio of the rms value of the harmonics (above fundamental) to the rms value of the fundamental, times 100%. Based on the THD one can derive the displacement PF and the distortion PF.

In general, one cannot compensate for poor distortion power factor by adding shunt capacitors. Only the displacement power factor can be improved with capacitors. This is especially important in load areas that are dominated by single-phase power electronic loads, which tend to have high displacement power factors but low distortion power factors. In these instances, the addition of shunt capacitors may worsen the power factor by inducing resonances and higher harmonic levels. A better solution is to add passive or active filters to remove the harmonics, or to utilize low distortion power electronic loads. Power factor measurements for some common single-phase residential loads are given in **Table1**, where it is seen that their current distortion levels fall into the following three categories: low (THDI ≤ 20%), medium (20% < THDI ≤ 50%), high (THDI > 50%).

$$pf_{true} = \frac{P_{avg1}}{V_{1rms} I_{1rms}} \bullet \frac{1}{\sqrt{1 + (THD_I / 100)^2}} = pf_{disp} \bullet pf_{dist}$$

It can be seen that the home devices with a decreasing PF show increasing THD percentages. However, the table can be quite misleading since the amounts of power are not equal.

Table 1:

Power Factor and Current Distortion Measurements for Common Single-Phase Residential Loads

Load Type	pf_{disp}	THD_I	pf_{dist}	pf_{true}
Ceiling Fan	0.999	1.8	1.000	0.999
Refrigerator	0.875	13.4	0.991	0.867
Microwave Oven	0.998	18.2	0.984	0.982
Vacuum Cleaner	0.951	26.0	0.968	0.921
Fluorescent Ceiling Lamp	0.956 *	39.5	0.930	0.889
Television	0.988 *	121.0	0.637	0.629
Desktop Computer and Printer	0.999 *	140.0	0.581	0.580

What is the effect of the power consumption?

To make our point we will calculate with a PF of 0.5 which is generally considered quite poor. Let's take a 5W LED lamp with PF 0.5. The measured current = 42 mA. One can measure the resistance of the grid by using a linear load like a 1 KW electric heater. Measure the voltage at the power plug with and without the heater. The current is 4.3A and the voltage drop was 2.1 V. This means that the resistance of the grid from the power plant to the heater is Δ V /4.3 = 0.49 Ohm. At 42 mA that results for the energy supplier in a loss in the grid of I^2R = 0.00086 W or 0.8 mW! Taking a 40W incandescent lamp the power loss in the grid is 14.7 mW. This is eighteen times more loss in the grid for a lamp with a PF of 1!

In comparison, my 2 kWh microwave oven at home is drawing 8.7 Amp and causes a loss of 37 W in the same grid. That's 46.250 times more loss in the grid than one 5W LED lamp with a (bad?) PF of 0.5. In other words we can install 46,250 so called bad PF LED lamps of 5W before we cause the energy supplier the same power loss in the grid as when running one microwave. To be more precise, the loss in the grid with 46,250 LED lamps will even be much less than that of ONE microwave since the PF displacement of LED lamps is generally with a leading current. With the LED lamps distributed throughout the grid, they will compensate with their leading currents the lacking currents anywhere in the grid (displacement compensation). It is similar to what is stated before with the pouring cups, the grid is dynamic, you could say breathing, so it's absorbing and compensating reactive currents from devices. Since there are many other devices with much higher energy consumption throughout the grid, the effect of low power LED lamps is completely neglectable. Realize that the power loss in the grid = P (W) =R grid (i1+i2+i3+i4+....)^2. This means a large current is always dominant and the effect of the small currents are neglectable. P (W)= 0,49 (4,3 + 0,042)^2. To comply with energy star (getting rebates on lamp actions), the DOE in the US requires that LED lamps meet PF 0,7 and in professional applications PF ≥0,8. In the UK the Energy Saving Trust requirement for LED lamps is a PF > 0.9 from 2011.

Such requirements are counterproductive for energy saving, harming environment and the LED industry. Already for decades in Europe there are no directives on PF for loads under 25W. It should also be realized that the efficacy (lm/W) of LED chips is still increasing, meaning that the average power demand for LED lamps will reduce over time. If we see today 50 lm/W will increase in the next two years to 100 lm/W.

In industrial applications it's often heard that you pay for the PF losses. Therefore the PF of each lamp should be high because we talk about thousands of lamps in one building. Again we take a worse case sample. A 23W tube with poor PF of 0.5 is causing 0.2A of current, resulting in less than 20 mW energy loss in the grid. Compared with the loss of the mentioned microwave an equivalent of 1.888 tubes of 23W with a poor PF of 0.5 will cause the same loss in the grid. In practice it will prove to be substantially less since the inductive ballasts in the old tube fixture will normally be maintained. When combined with the often capacitive tube the combination is optimized. In addition, capacitive compensation is in industrial installations already in place. When applying LED tubes the installation will be over compensated. Lesson learned here is that one should not look at the PF of the tube itself but the PF in the application. PF is a property of the power grid, NOT the lamp.

Effect of high PF demand on the environment

Better PF lamps require additional electronic components for PF correction in the lamp. This results in unnecessary complex drivers and reduced efficacy. The cost increase for high PF on LED lamps is 30%, the electronic waste increases by 50% and dimensions with 25 to 30%. All this to compensate 37W of total power loss in the grid caused by 46,250 low PF LED lamps! We talk here about 46,250 more compensation capacitors, coils and other electronics. From an environmental point of view lamps with a high PF should be banned! With that respect a power factor of 0.5 to 0.6 would be much better if it requires less components and creates less efficacy loss.

High PF lamps will have a lower efficacy (lm/W) and require more cooling thus more heat sink (more CO2). Generally the efficacy of the 5W lamps will decrease by 5% when corrected to high PF. To keep the same light intensity this would mean that the power consumption increases by 5%. The 5W lamp will than require 5.25W to do the same job. For 46,250 lamps this cost then consumers 46,250 x 0.25W = 11,562 W of additional energy to save the energy supplier 37W! This makes no sense!

The increase of components used will also decrease reliability (MTBF) and lifetime of the lamp, altogether bad for the LCA, carbon footprint and lifetime of the lamp, and bad for the environment. An interesting test done by the Luleå University in Sweden is found on the internet: Power Quality (PQ) test Luleå University with 560 LED lamps in a hotel, before and after replacing incandescent lamps http://www.slideshare.net/sustenergy/led-powerqualityenergysavinglamps. More interesting is the conclusion in that presentation that field tests have failed to find evidence of the types of harmonic issues that many of the simulation studies had predicted.

Conclusion: common sense!

Discussions on PF accelerated out of proportion. Manufacturers try to comply with directives and conditions which make no sense.

Lemnis started in 2005 their mission to reduce carbon emissions by introducing LED lamps with low PF specifically for the reason of low CO2 footprint and optimal LCA. Lemnis is certainly not promoting low PF as an objective by itself but wants to explain that there are other ways of solving technical challenges. Harmonics can be filtered at building level (if required) and are more of a concern to the utility company. To maintain their principles Lemnis fights un-credible and harming directives at all levels, even in court. We realize that much of our apparently unconventional way of thinking 'green' is not yet generally accepted.

However, if this article woke up the minds of designers and regulatory institutions to think over the consequences of their decisions and it results in better and really sustainable solutions, then it has served its purpose; "a better planet for all of us".

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