Efficiency/Power Factor/Harmonics

by Richard Hutchins

Introduction

Power Factor, Efficiency and Harmonics are all factors that affect the end user. Many times these terms are misunderstood and thus their impact is underestimated. Many papers on these topics are loaded with too much math and not enough real world examples to effectively teach the concept; this paper includes real world waveforms. By the end of reading this paper, you will become fluent in the terms of the industry due to following the examples only showing formulas to validate the point. More expressions are shown than used. This paper will progress from simple to more complex systems, but with the end goal that this paper can be used as a guide in power quality discussions with a customer or site engineer.

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Power consumption fiscal cliff… one watt at a time

According to Apple Computer, over 67 Million iPads have been sold up to July 2012. The Electric Power Research Institute, Inc (EPRI) calculations show that the average energy used by all iPads in the market is approximately 590 gigawatt hours (GWh). In a scenario where the number of iPads is tripled over the next two years, the energy required would be nearly equivalent to two 250-megawatt (MW) power plants operating at a 50 percent utilization rate. A quadrupling of sales in two years would require energy generated by three 250-MW power plants. Perhaps we will need 2 more power plants in the US just to support iPads, and even more plants to support over 70 million iPhones. These units are only 5 –to-10 watts each. With the proliferation of electronics, rising cost of electricity, hard EPA restrictions on cheap energy, and an aging infrastructure, it is ever more important to maximize efficiency in every area possible. Watts to be saved can be found everywhere; it is likely that your microwave burns more watts per week keeping the time than cooking your lunch. [6]

Efficiency in DC Power Systems

Of all the terms in this paper, Efficiency is the simplest to explain. We will start in DC systems and progress to AC systems later. In very basic terms, efficiency is the measure of how much power is not being wasted by a system. More waste is less efficient. In electrical systems, we measure the power entering a system in watts; the unit of measure for work performed. Efficiency is the ratio of (Power-In) -vs. - (Power-Out) as a percentage. Sometimes the work coming out of a system needs to be converted from some other unit of work back into watts so when the efficiency is examined, the equation can be evaluated in like terms. Efficiency is commonly abbreviated (Eff) or (EF%) or simply (η). Efficiency is paramount.

A single Watt of energy is delivered to the load when 1amp (RMS or DC) of current is passing through a 1ohm load for 1second. DC systems don't have Power Factor to complicate the situation. [1]

In Direct Current (DC) systems: $Watts(W) = Adc \cdot Vdc$ (1)

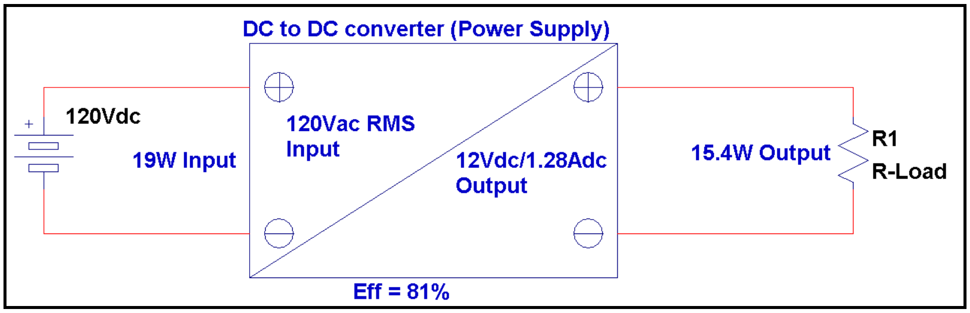

Figure 1 DC/DC converter schematic

V_{IN}=120Vdc A_{IN}=0.158Adc $Watts_{IN}$ = 19W

V_{OUT}=12Vdc A_{OUT}=1.25Adc $Watts_{OUT}$=15W

$$\eta = \left(\frac{15Wout}{19Win}\right) \times 100\%$$ η = 81% Efficiency (2)

$$"Inefficiency" = (19Winput) - (15Woutput)$$ Inefficiency = 4W (heat) (3)

Had a converter been installed with 40%EFF, the input current required to drive the same load would be twice as much, and the heat to dissipate due to inefficiency would also be worse!

Only DC systems like this get to enjoy such simple math to describe the input power in Watts as simply being (amps x volts) in each and every application. In DC systems Power Factor (PF) =1.0. Properly sized inductors and capacitors have little to no real effect on efficiency because they "don't respond" to DC stimulus. There will be more information to follow regarding inductors, capacitors, and PF later.

One important distinction to make on this DC system is that the focus is not on start-up transients, but instead on the steady-state condition where your equipment is operating 99.999% of the time.

You might wonder what happened to the remaining "inefficiency" of 4 Watts. The leftover Watts due to in-efficiency was burned off in the DC/DC converter as heat. While this modest 4 Watt "inefficiency" might not sound like much, it adds up in an equipment room. Perhaps you have hundreds of devices running in a room with an average of 62%EFF; that would be a lot of heat to deal with. Perhaps you have a several kilo-watt system with 75%EFF. All these wasted watts add to the room temperature and your utility bill raising your TCO. If you have critical medical equipment, phone switches, or servers, they require a controlled room temperature. Dealing with the wasted energy (heat) is putting a heavy load on air conditioning systems, and yet a further load & point of failure. So poor efficiency is not desirable because you are paying for the watts you dissipate in heat via the electric bill, and then you pay again in the cost of air conditioning and its associated power consumption.

In electrical systems, not all efficiency calculations are so strait forward. In fact, sometimes you have to convert units. In a motor, you must convert the shaft speed & torque delivered to watts of work. If you wanted to evaluate efficiency in a light bulb, one must convert units like lumens into watts of work. Also consider AC systems with their complex periodic waveforms; it is necessary to work with these units of energy too. Things get more interesting and complicated in AC power systems – vs. - DC power systems.

Intro to AC Power Systems

AC Power Systems have plenty more units, terms, measurements, interesting waveforms and math to describe their behavior. Any formulas presented here are for reference and validation only. The intension of this paper is convey the concept without having to seriously crunch numbers. All the terms and formulas interweave so it is difficult to create a flow of one topic to another without skipping around a bit.

Generally the goal of the electric utility company is to provide a sine-wave voltage to your building at a fixed frequency, fixed voltage, and ideally, pure containing no harmonics.

The frequency is how many cycles are completed in 1second. The unit for frequency is (Hz). In the US, our grid operates at 60Hz, AKA 60cycles per second. The duration in time of one complete cycle is called the period. Typically the frequency is guaranteed +/- 2% (typical +/-0.1Hz). In fact, if the utility spends 15min out of the day sending out 59.5Hz, they will generally try to also spend 15min out of the day at 60.5Hz to make up for it. Many older analog wall clocks were driven off of the line frequency because the grid generally is just that good.

$$Freqency(Hz) = \frac{1}{Period(\text{seconds})}$$ [1] (4)

Thus: $Period(T) = \frac{1}{60Hz} = T = 16.67mS$ → 16.67milli-seconds → 0.01667seconds.

The power generating utility has a goal to deliver voltage with very good regulation. If you put a high current load on the system, the voltage should have very little drop. Typically, voltage regulation up to a building entrance will be +/- 3%. When visiting a customer be observant of what is going on at the site. If you notice the lights dim as a high-powered load is energized, you have poor voltage regulation.

Another goal is to deliver voltage with as low Total Harmonic Distortion (THD%) as possible as to yield a near perfect AC sine wave. A pure sine wave contains no harmonics at all. Any harmonic content changes the shape of the delivered voltage waveform, and that is essentially the definition of distortion. According to IEEE-519-1992, the utility must generally deliver voltage with less than 5% THD up to the Point of Common Coupling. (PCC) The PCC is basically the lowest voltage utility distribution node that both you and a neighboring building share. See IEEE-519-1992.

Formula to plot sine-wave shown in Figure 3 below: $v(t) = V_{PEAK} * \sin(2\pi f t)$ (5)

Where (t) is the time interval vector and (f) is the frequency, π =3.14159, (t) is time along the X-axis, and V_{PEAK} is the highest voltage at the top of the sine wave peak.

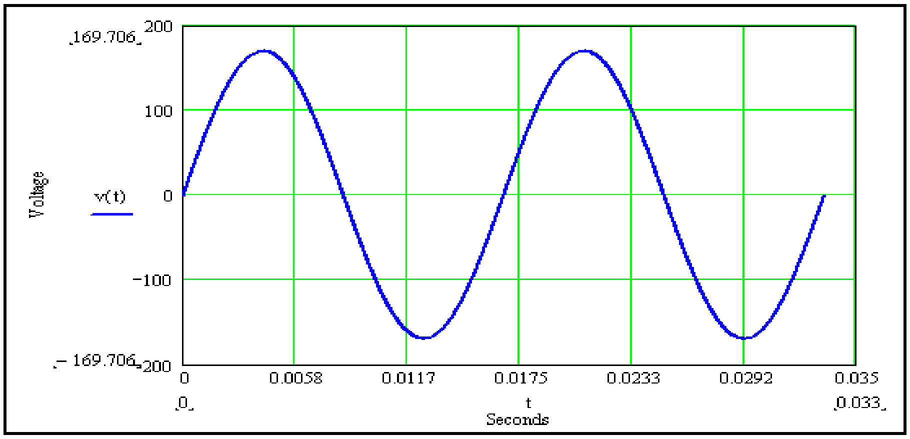

Figure 2 Ideal 120Vac RMS 60Hz sine-wave, 2-cycles.

The sine wave above in Figure 2 was generated perfect, containing no harmonics, shown over 2 complete cycles. In casual conversation, Engineer's hardly ever refer to the sine wave in Figure-2 with Equation (5). It should simply be called a 120V_{RMS} 60Hz sine wave. This is what the voltage coming out of your receptacle at home *should* look like if viewed on an oscilloscope.

Because the waveform is pure containing no harmonics, one may use the following easy formula to calculate the RMS or effective value from the waveform:

$$V_{RMS} = \frac{V_{PEAK}}{\sqrt{2}} \qquad [1]\ (6)$$

$$V_{RMS} = \frac{V_{PEAK}\,(169.7v)}{\sqrt{2}} = 120V_{RMS}$$ (What you *should* see out of your wall outlet at home.)

Remember that formula (6) is effective for pure sine waves only! As soon as the waveforms contain harmonics and is barely visibly distorted, the simple equation no longer gives usable results.

Intro to Power Factor

New terms such as Displacement Factor (DF), Apparent power (VA), Reactive power (VAR) and Real Power (Watt) need to be introduced to properly define Power Factor (PF). In some loads DF & PF terms are interchangeable, however in most real world loads; DF and PF are not equal. Several examples will be explained along the way to better understand what these terms mean.

Compare with the DC efficiency example in Figure-1. If you have 120Vdc entering a 240ohm load, there will be 0.5ADC flowing for 60watts delivered to the load. Similarly, if there is a nice sine-wave 120V_{ACRMS} entering the same resistive load, the RMS current is the same as the DC system, the load will receive 60watts of power to perform work. In Figure-7, the resistive load is a 60watt incandescent light-bulb. Because resistive loads have a Power Factor of 1, the math is easy.

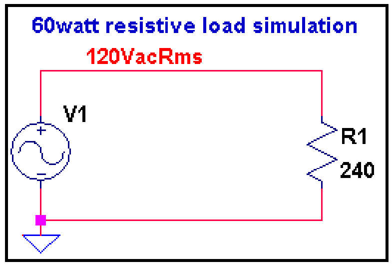

Figure 3 AC Voltage source feeding resistive 60watt incandescent light bulb

The voltage is $120V_{RMS}$, and the Current through the incandescent bulb is $0.5A_{RMS}$.

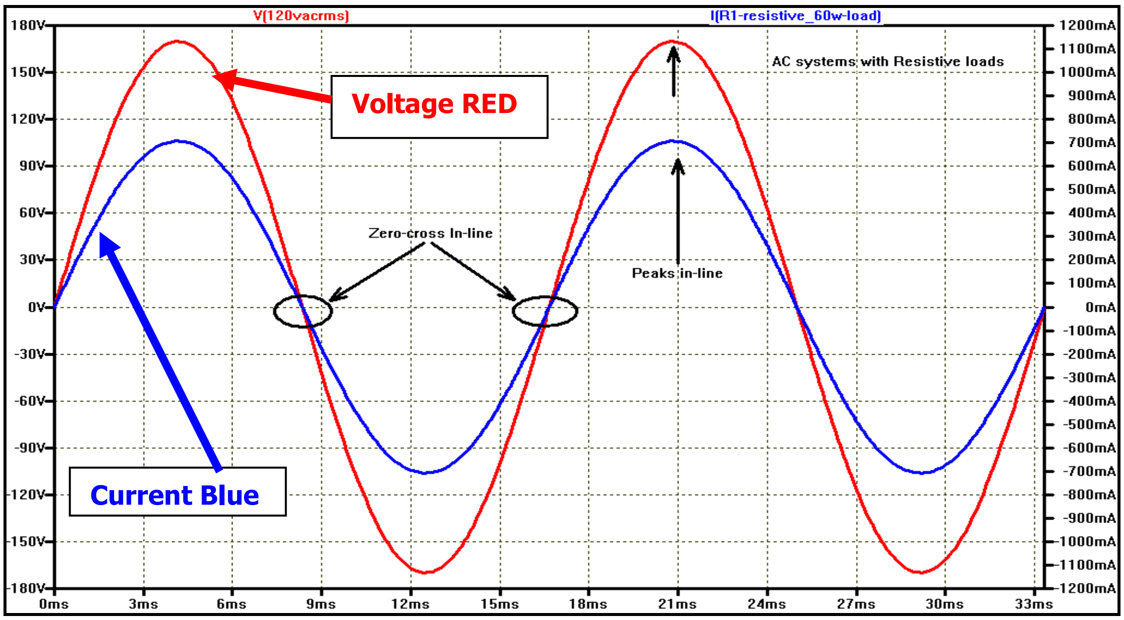

Figure 4 Shows RED=AC-voltage, BLUE=AC current, "in-phase", resistive load, no harmonics, DF=1, PF=1.

Notice that the RED Voltage and BLUE current are in-phase and not distorted. They are both smooth sine waves and they do not have any phase-shift or "displacement". Because there is no horizontal or phase displacement, the DF=1. In this instance, the Power Factor is also a perfect 1.

Displacement Factor = $\cos\theta$ or cos of the phase angle displacement from the voltage to the current. [4] (7)

Both DF & PF are dimensionless numbers ranging from 0 to 1. DF/PF =1 is the result of perfect DF/PF. A DF=0 occurs at 90 degrees displacement between the voltage and current. At this point the load is purely reactive and cannot accomplish any work in watts.

Figure-4 shows pure voltage and current sine waves of the incandescent light bulb and have 0° of displacement; DF= (cos(0)) = DF=1. Or unity DF.

Apparent Power = V_{RMS} x A_{RMS}; Units are "VA" Apparent power is energy delivered. (8)
Apparent Power 60watt incandescent light-bulb = 120Vrms x 0.5Arms = 60VA

REAL Power = 60Watts (Measured with a wattmeter) REAL or TRUE Power is the unit of work being performed.

In this special "IDEAL" non-distorted incandescent light-bulb case where the DF=1 and PF=1. When PF=1, the Apparent power and REAL power are the same quantity. The Apparent Power can be obtained with a True-RMS (T-RMS) hand-held voltmeter and ammeter. So in AC systems with resistive load elements, the Apparent Power happens to be equal to the Real Power because PF=1. This incandescent light bulb is one of few conditions in the real world that approximates this scenario.

The AC motor example in Figure-5 will introduce the difference between Apparent Power (VA) and Real Power (W), and Reactive Power (VAR). The motor is used as an example because it has large phase displacement, yet rather low harmonic content. More on harmonics later.

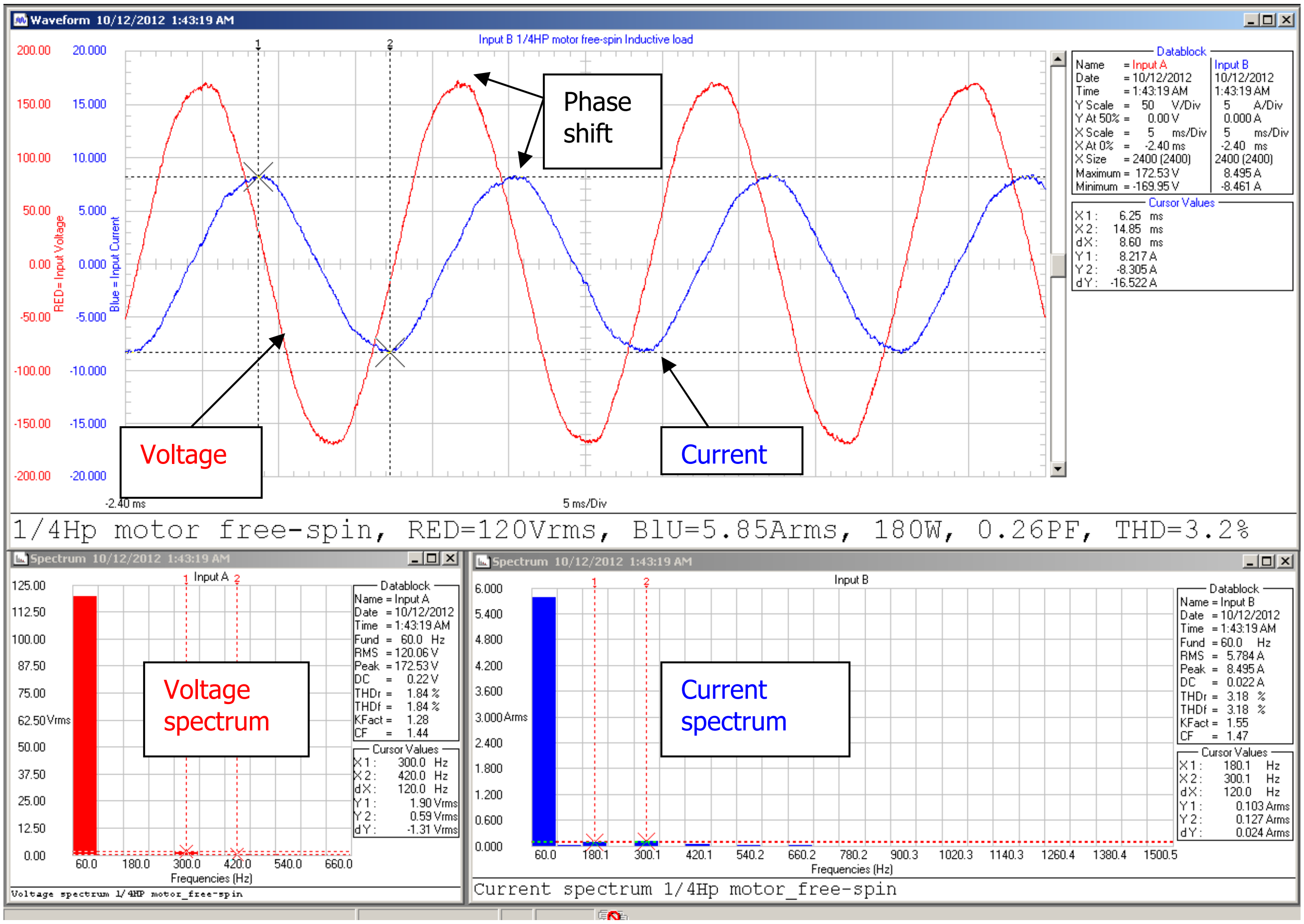

Figure 5 Real 1/4HP motor. 77.76 degrees displacement of current to voltage

Notice that the voltage is leading the current in the motor. This is referred to as a leading PF or a leading DF. It tells us that it is acting inductive like a motor, rather than the load acting resistive like an incandescent light bulb. In Figure-5, the AC motor had 76.76degrees of leading (inductive) displacement between the voltage and the current waveforms.

DF = 0.212 = cos (77.76°); Please note that 0.212DF is very close to the measured 0.26PF

Apparent Power = 120Vrms * 5.85Arms = 702VA (measured with independent T-RMS Voltmeter & Ammeter)

REAL Power = 180Watts (measured with Wattmeter).

* Notice that in the motor; 702VA is a lot more than 180Watts! In the incandescent light bulb in Figure-4, 60VA = 60Watts. Why does the light bulb behave differently than the motor? In the motor, there was considerable phase displacement and in the light bulb there was not.

$$PF = \frac{REAL\_Power(Watts)}{Apparent\_Power(V \cdot A)}$$ This is the top ruling equation for determining PF. [2] (9)

1/4HP motor… $PF = \frac{REAL\_Power(180Watts)}{Apparent\_Power(120V \cdot 5.85A)} = \frac{180W}{702VA} = 0.256PF$ (9)

What is the difference between Apparent Power-(VA) and REAL-Power Watts (W)? Both seem to be obtained by evaluating the product of volts and amps, but slightly different. Wattmeter's take the product of the sample-by-sample instantaneous voltage and current waveforms, then averaged that result over 1 period.

In Figure-5 AC motor, the Generating utility had to provide 702VA while the load only consumed 180W for real work. Remember the Watt is the unit of real work being done, and that the voltage is about constant. This means that the utility had to generate several more amps to the motor than what was being used for actual work. If the PF on the motor were "1", ideally the current *should* have been 180W/120V for 1.5Amps; why was the measured current 5.85Amps?

The difference is called Reactive Power "Q" measured (VAR) imaginary current with not-so-imaginary consequences which flows 90degree from real current , and it is sloshing back and forth between the source and the inductive load. This can happen any time the load presents an inductive (leading) or capacitive (lagging) PF. Reactive Power is measured in a unit VAR which is (V x A "Reactive").

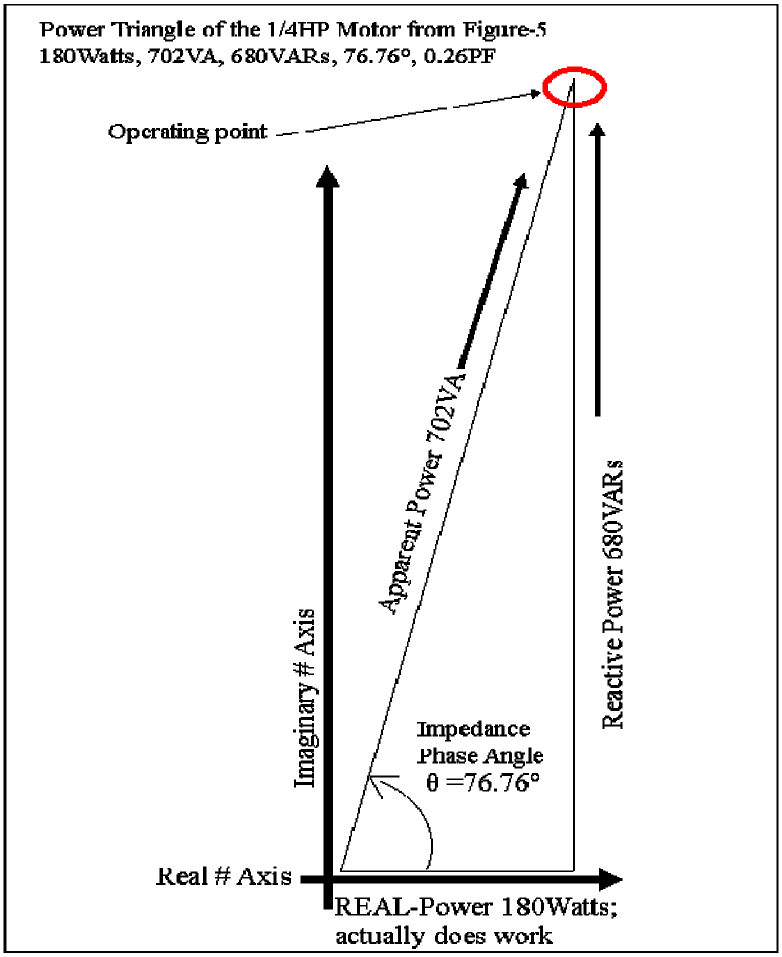

Figure 6 Power-triangle for 1/4 horse motor in Figure-5 [8]

$VA = \sqrt{(W^2) + (VAR^2)}$ (Apply Pythagorean Theorem)

Reactive Power "Q" $(VAR) = \sqrt{(702VA^2) - (180W^2)} = 680VAR$

So the motor was using a modest 180Watts for real work, but the utility has to supply 702VA to account for the 680VAR's sloshing back and forth between the source and load that does not contribute to the motor's work. Remember the generating voltage is about constant. If you need more VA for the same volts, more amps will be required to satisfy the hunger for VA. That is 4.35Amps EXTRA that the utility had to generate for this motor because of a poor PF.

- Efficiency tells you the ratio how well the unit uses the REAL-Power required by the unit to do work.
- Power Factor tells you how effectively you are using the VA delivered.

Utilities have to handle the burden of generating extra amps for loads with poor PF. Your building distribution transformers, circuit breakers, wiring all must be sized to handle the extra amps from a load with lousy PF. If your loads had ideal PF, you could have smaller transformers, wiring, and circuit breakers to support the same load.

- In theory: Let's say you replaced your 0.25PF devices with new devices with a PF of 1. For the same distribution transformer, circuit breaker in the panel, and wire gauge in the conduit, you could run 4 new devices where only 1 ran in the past.
- In practice: PF of 1 is very hard to obtain and 0.9PF might be more realistic. At least 3 devices could be run where only 1 device ran before.

Word to the wise: many people consider the phase displacement between volts and amps (cosθ) to be the Power Factor (PF). The concept of PF is generally introduced with pure sine waves containing zero harmonic distortion, and this just doesn't match real world waveforms. Formulas provided by higher level specialized textbooks [2] take the discussion of PF to a deeper level than introductory texts, and include waveform distortion in the calculation for PF. PF and DF are not always the same. When you are dealing with very pure sine wave currents that have phase displacement, then DF = PF. However, anytime you encounter the current distorted with harmonic content; PF ≠ DF. Harmonics can only make PF worse, not better. [3]

The term Real Power and the unit Watts are only to be associated with work being done. VA's are units of energy, but do not directly equate to work being done. Unless you see the term REAL-Power (aka True-Power) and the unit WATT, you should be skeptical as that person may be inadvertently referring to Apparent Power-(VA).

Let me make two important conjectures about PF.

1. Starting from an ideal sine-wave voltage, if the load current drawn from the source is out of phase (DF far less than 1), but with sinusoidal wave-shape, poor PF will result like the 1/4HP motor example.
2. Starting from an ideal sine-wave voltage, if the load current has little-to-no displacement (DF=1), but high Harmonic distortion (THD), poor PF will result.

Here is another derivation of PF in Equation (10) that verifies the above conjectures.

$$PF = \left(\frac{1}{\sqrt{1+THD_i^2}} * DF(\cos\theta) \right) = \left(\frac{real\_Power(Watts)}{Apparent\_Power(VA)} \right) \qquad [2] \quad (10)$$

Looking at left Equation (10) above, there is a distortion term in the beginning and a DF term on the right. Without crunching numbers, you can deduce that even if the DF=1 (no displacement between voltage & current), but there was really bad distortion, the PF would suffer. On the other hand, if DF→0, and there is no THD, the PF will suffer. The derivation of PF in Equation (10) showing both DF & THD terms often overlooked by several reference materials.

So DF can only equal PF if the THD is 0%; this just doesn't happen much in the real world.

In Equation (10); if DF=1, and there is 100%THD, the best PF you could attain is 0.707.

Now let's review Efficiency, PF, VA, and VAR's with a far more common AC-to-DC power supply and compare/contrast with the DC/DC converter in Figure-1. Note that the input has been changed from DC battery power to $120V_{ACRMS}$, but the overall output section & efficiency are the same. This AC to DC converter shown below in figure-6, is to contrast the DC efficiency example in Figure-1.

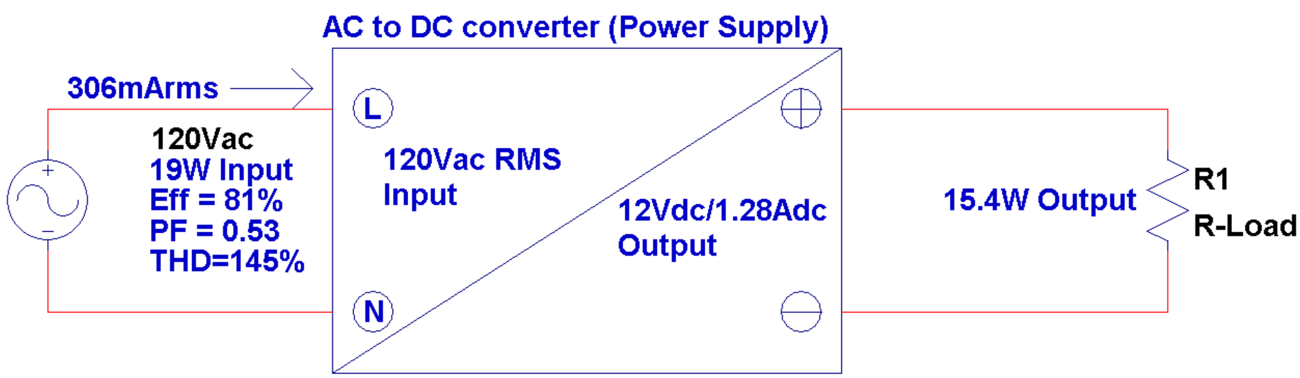

Figure 7 AC to DC converter example contrast to Figure-1 DC/DC converter

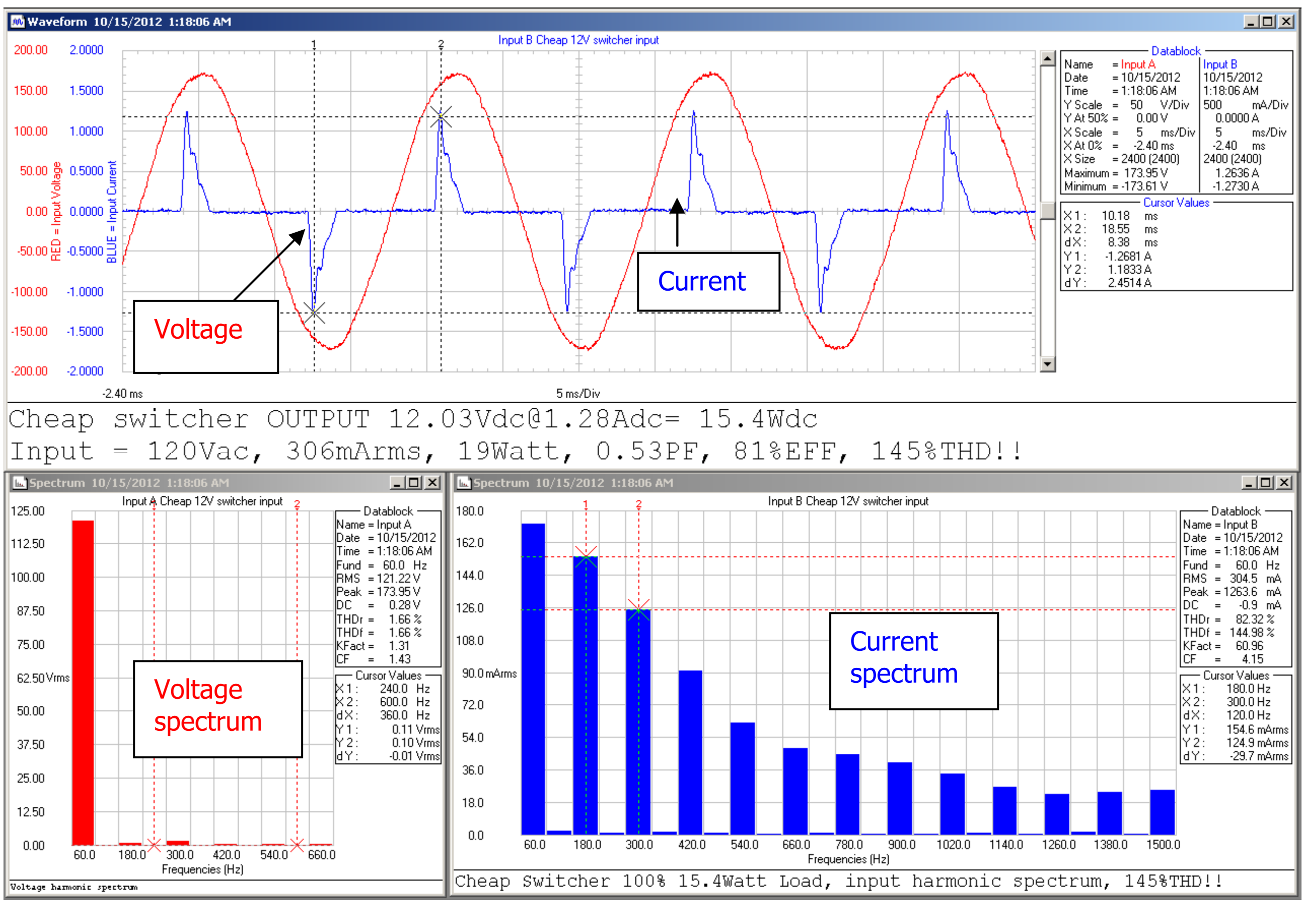

Figure 8 Measured results for AC-to-DC converter in Figure-6 Not La Marche product

Notice that for the same input power and efficiency, the AC-to-DC converter required more RMS input current than the DC-to-DC converter in Figure-1. This is due to PF and Harmonics which go hand and hand.

Harmonics

In this paper, up to now, harmonics has been referred to several times. Let's define what harmonics are. Harmonics as they pertain to power systems are undesirable multiples of the line frequency that end up being added to the original or "fundamental" 60Hz sine wave. Harmonics added to the pure sine wave distorts the original pure sine content. The distortion can be measured and defined as Total Harmonic Distortion (THD%) The THD is essentially a ratio of all the harmonic energy added as a ratio to the fundamental energy.

145%THD observed in the input current to the AC-to-DC converter in Figure-6/7 means that there is more current flow in the wiring due to harmonic content than fundamental current. Harmonics are detrimental to PF.

$$THD\% = \left(100 \cdot \frac{\sum Harmonic\_content(I_{Distortion})}{Fundemental\_content(I_{S1})}\right) = \left(100 \cdot \sqrt{\sum_{H \neq 1} \left(\frac{I_{SH}}{I_{S1}}\right)^2}\right) \quad [2] \quad (11)$$

Don't worry about Equation (11), all decent watt-meters and many digital oscilloscopes evaluate the THD% for you at the press of a button. With Equation (11), it is important to keep in mind that THD is really a ratio of harmonic content to the fundamental sine wave. I have witnessed instances up to 200% THD, but not on a La Marche product.

To help drive the concept of what harmonics are, let me give some non-power system examples.

In musical instruments, the violin, guitar, and piano can all play a concert "A" note with a fundamental 440Hz frequency. However, each instrument sounds different. This is because of harmonics or what musicians call overtones. The way the string vibrates the wood body in a piano is different than the wooden sound chamber of a violin and they sound because the harmonic content is different these harmonics are desirable.

Here is another example, and everybody seems to love music. Have you ever turned up the volume so loud that the sound was terribly distorted? Electrically speaking, distortion really is the perfect term for it. When distorted, there are harmonics (generally odd harmonics in solid-state amps, and even harmonics in tube amps) superimposed onto the original signal changing the shape of the music's electrical signal, and in result the music sounds distorted too. Assuming that you haven't blown your speakers, odd harmonics change the sound in a terrible way.

When discussing harmonics and frequency content, one is working with imaginary numbers with a real life impact. Getting back to the point, harmonics and thus distortion of the intended delivery is about a 200 year old science. A French mathematician Jean Fourier (1768 - 1830) discovered that ANY periodic (repeating) wave shape could be represented by the sum of several sine waves. This gave birth to the Fourier series equation. Conversely, you can take any distorted wave and back calculate each of the harmonic terms that created that monster. You can create or dissect square-waves, triangle waves, and some really ugly real world waves out of summing sine waves. So any time you look at some horribly distorted current/voltage, remember that it is made of an elegant combination of simple pure sine waves that are added to the fundamental.

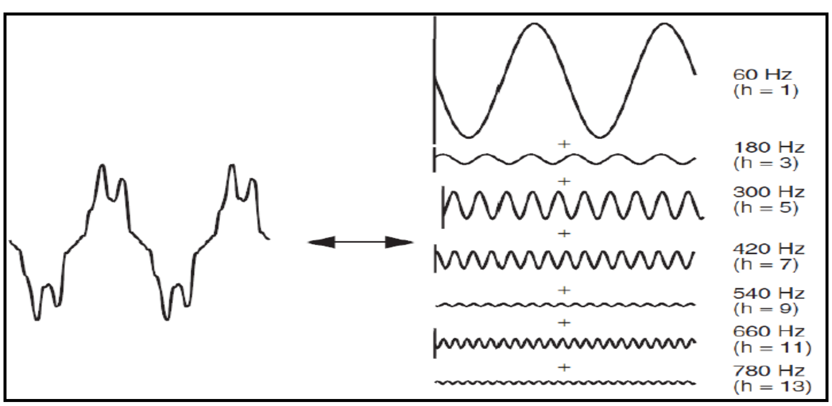

Figure 9 Distorted waves are composed of Harmonics added to the Fundamental [5]

Equation (12) to shows the premise behind how a square wave can be constructed out of individual harmonics:

$$v(t) = \frac{4V}{\pi}\left(Sin(\omega t) + \frac{1}{3}Sin(3\omega t) + \frac{1}{5}Sin(5\omega t) + ... \right) \quad [5] \quad (12)$$

For each sine wave harmonic term above, note that the amplitude has gone down by the inverse of the harmonic order. The 3rd order harmonic has (1/3) the amplitude of the fundamental and so on. Equation (12) is the recipe to create square waves and each real world wave shape has its own unique recipe. When evaluating Power Quality, one generally does not need to model the waveform into an equation as shown in Equation (12). Using the Fourier series, you can break out each of the harmonic terms, adjust their amplitudes and create any periodic waveform. Much of this work is done behind the scenes in modern PQ equipment.

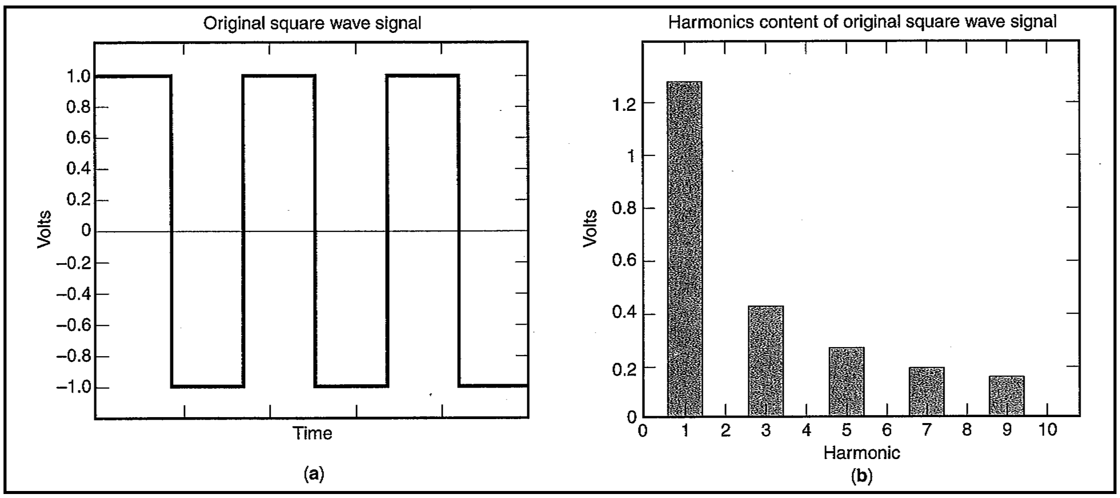

Figure 10 (a) square wave. (b) Chart depicting the relative amplitudes of each of the Harmonics. [5]

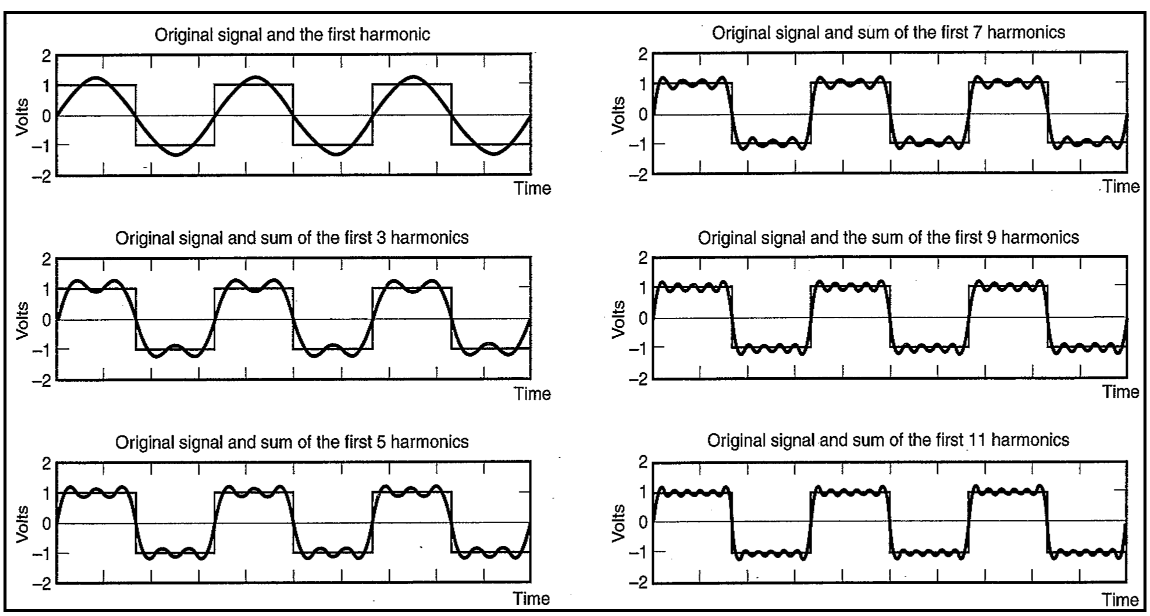

Figure 11 "Original" refers to the square wave and shows that for each harmonic term added, you get closer to visualizing the square-wave recipe. [5]

In the vast majority of cases, the voltage is delivered to the load as a near perfect sine wave, and the end-user's device generates current harmonics. You can tell that with all these harmonics running around that there is extra energy required to be handled by the generating source and the distribution network.

Short List of problems caused by Harmonic content

A. High harmonic distortion can destroy Power Factor. Even when the voltage and current are in phase, bad distortion can cause bad power factor as proven by Equation (10).

B. Triplen harmonic currents are additive in the neutral leg of a 3-phase "Y" transformer. Normally linear load currents cancel in the neutral and thus many older buildings have under-sized neutral returns. As you can see from the real world waveforms, the third and ninth harmonic are so pervasive in non-PFC switching and linear power supplies, that Triplen harmonics are a real problem. Un-planned neutral currents will overheat the neutral leg in the transformer and breaker boxes and they don't have any over-current protection. This can cause building fires.

C. Triplen harmonics being returned to a 3-phase building step-down transformer can also circulate through the primary Delta winding adding to the wire and core losses. You would typically need to use a "K-Factor" rated transformer that had been specially designed and upsized to handle the harmonics in order to avoid overheating. Delta windings do the rest of the building a favor in trapping Triplen harmonics.

D. 5^{th} Order Harmonics cause zero-sequence flux paths within 3-phase motors that can cause additional core and wire losses and even Magnetostriction damaging the motor and the motor controller. Zero sequence flux actually rotates around the core in a different direction than the primary flux causing core heating.

E. Harmonic currents can induce Electro-Magnetic Interference (EMI) problems. Any time current is passed through a wire it creates a radiating magnetic field around the conductor. As the harmonics get higher in frequency and a strong enough amplitude, it can interfere with radio communications and other equipment. When you drive under power lines and the radio gets fuzzy, EMI/RFI is being caused by harmonics flowing within the cable.

F. Harmonic current can induce voltage feed distortion. Every voltage feed has some inherent source impedance. In power distribution networks, this is not only the wire resistance, but the inductance too. As harmonic currents are pulled through the source impedance, they can induce voltage drops at those harmonics that eventually distort the voltage. If you detect distorted voltage, any combination of the following 3-things have happened:

    1) You have equipment that is introducing too much current harmonic content and perhaps not compliant with IEEE-519-1992.

    2) Your neighboring building sharing the same PCC has equipment introducing too much current harmonic content; perhaps not compliant with IEEE-519-1992.

    3) The Utility or distribution company has a feed to the PCC that is too high of an impedance; perhaps not compliant with IEEE-519-1992

In the case of line powered battery chargers & power supplies in general, different technologies induce different harmonic current content signatures just like the tone of a violin –vs.-the piano, only not so pretty. There are several different signatures of current harmonics generated by different technologies that can be viewed on an oscilloscope.

Root Mean Square (RMS)

Because text-book Equation (6) won't work in real-world high harmonic content waveforms, one must learn how to measure the RMS or "Efective" value of a voltage or current that contains high harmonic content.

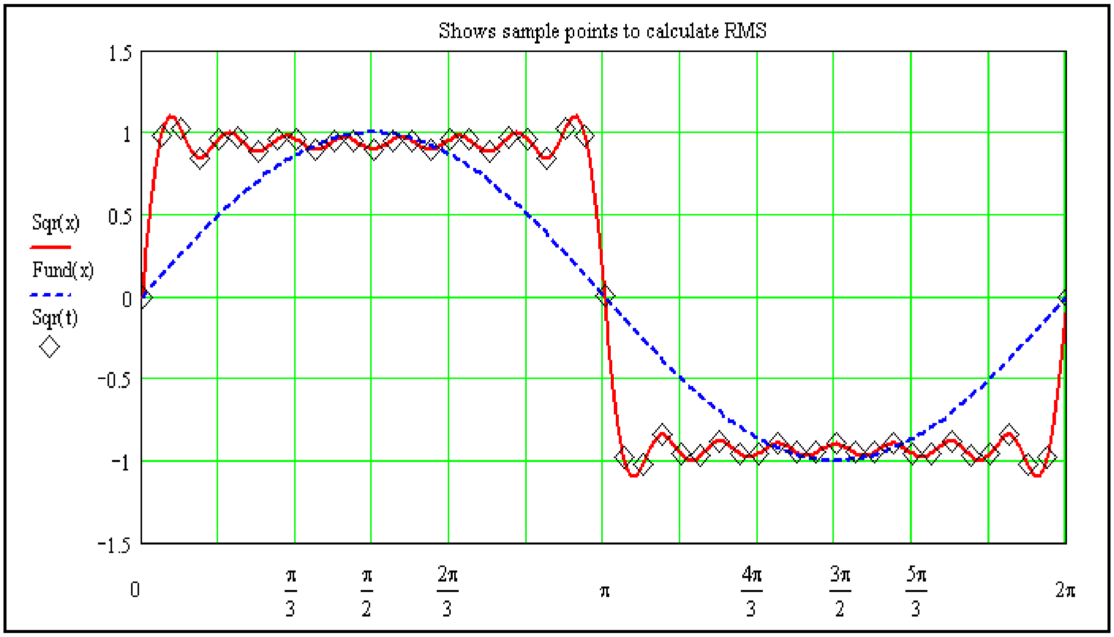

Figure 12 The RED plot show a near square 60Hz distorted waveform; 1-cycle shown with sample-dots.

For any wave shape: $$Amplitude_{RMS} = \sqrt{\frac{x_1^2 + x_2^2 + x_3^2 + ...x_n^2}{n}} \quad (9)$$

"x" is the instantaneous amplitude at that point; "n" is the number of sample points.

Here is the hard way. → Please take a glance at Equation (9); where "n" represents the number of sample points taken along the waveform period, and each "x" represents the instantaneous amplitude measured at each point along the waveform. For example you could measure the voltage on a scope at the few points along the waveform depicted in Figure-11, then use Equation (9) to calculate the RMS of ANY periodic waveform. You must have enough evenly spaced points over the whole period to get useful results.

Here is the easy way. → Luckily, any modern "True-RMS" digital multimeter can make this measurement automatically. Also just about any modern digital oscilloscopes can make the RMS measurement of any periodic waveform at the press of a button saving hours of time. Word to the wise; DON"T BOTHER USING A MULTIMETER/AMMETER UNLESS IT STATES "TRUE-RMS" OR "T-RMS" right on the front label. Unless your DMM says "TRUE-RMS" it won't calculate properly for distorted waveforms and all your measurements on non-pure waveforms will be flat out wrong. Non T-RMS meters give such poor results to distorted signals that we got rid of any non T-RMS meters in the lab at great cost to avoid accidentally recording a voltage improperly.

Now that you know HOW to establish an RMS measurement of any periodic waveform (voltage or current), let me explain what it means. In the early days of electricity being distributed by Edison, the voltage was DC. It had problems of distribution where nearly every city block needed its own power plant. The competing AC technology came from Nikola Tesla, a former scorned Edison employee, who sold AC patents to Westinghouse. Tesla realized the distribution problems with DC early on and solved them with AC, the application of step up/down transformers and the invention of 3-phase power. This topic has been covered by many books, papers, and documentaries. During the debate as to which power distribution scheme was better, the term RMS, effective, or heating voltage was used for apples-to-apples comparison of AC systems to DC systems.

$1A_{RMS}$ has the same heating effect as 1Adc through the same resistive load. [1]

AC systems have dominated power distribution for more than 100 years for numerous reasons.

Now that you know EFF, RMS, Harmonics, and THD, you are starting to sound like a Power Quality Engineer.

Real World Measurement examples

Here are several real world examples of measured input EFF, PF, Harmonics, THD shown below to stitch it all together.

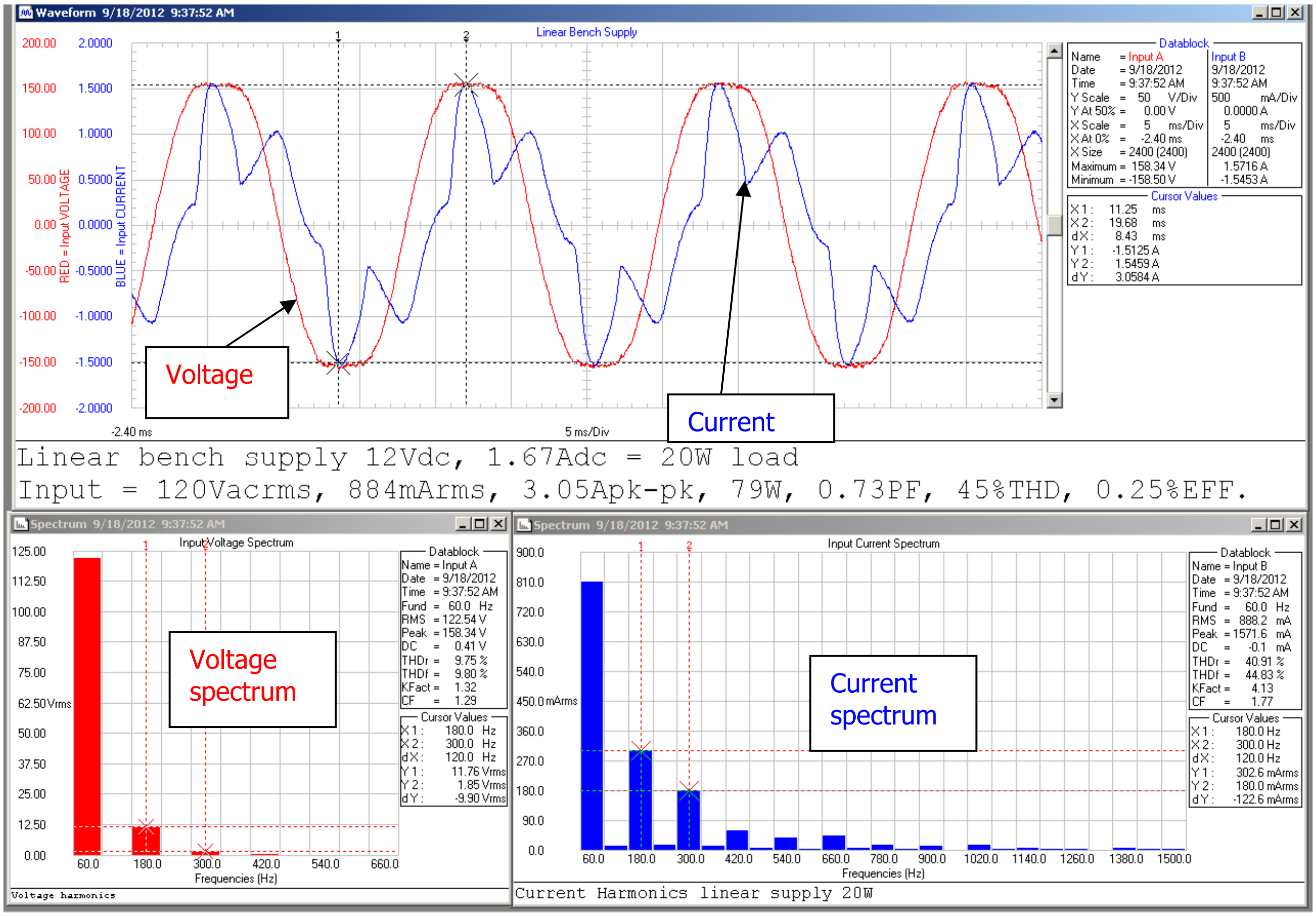

Figure 13 The old trusty bench Linear power supply has ugly harmonics too. Not La Marche product

You will notice that power supplies and other connected devices each have a “signature” response in the current waveform caused by the harmonic content. An A75DE SCR charger will have a different current wave-shape signature and harmonic spectrum content than a TPSD controlled Ferro; See Figure-16 & 17.

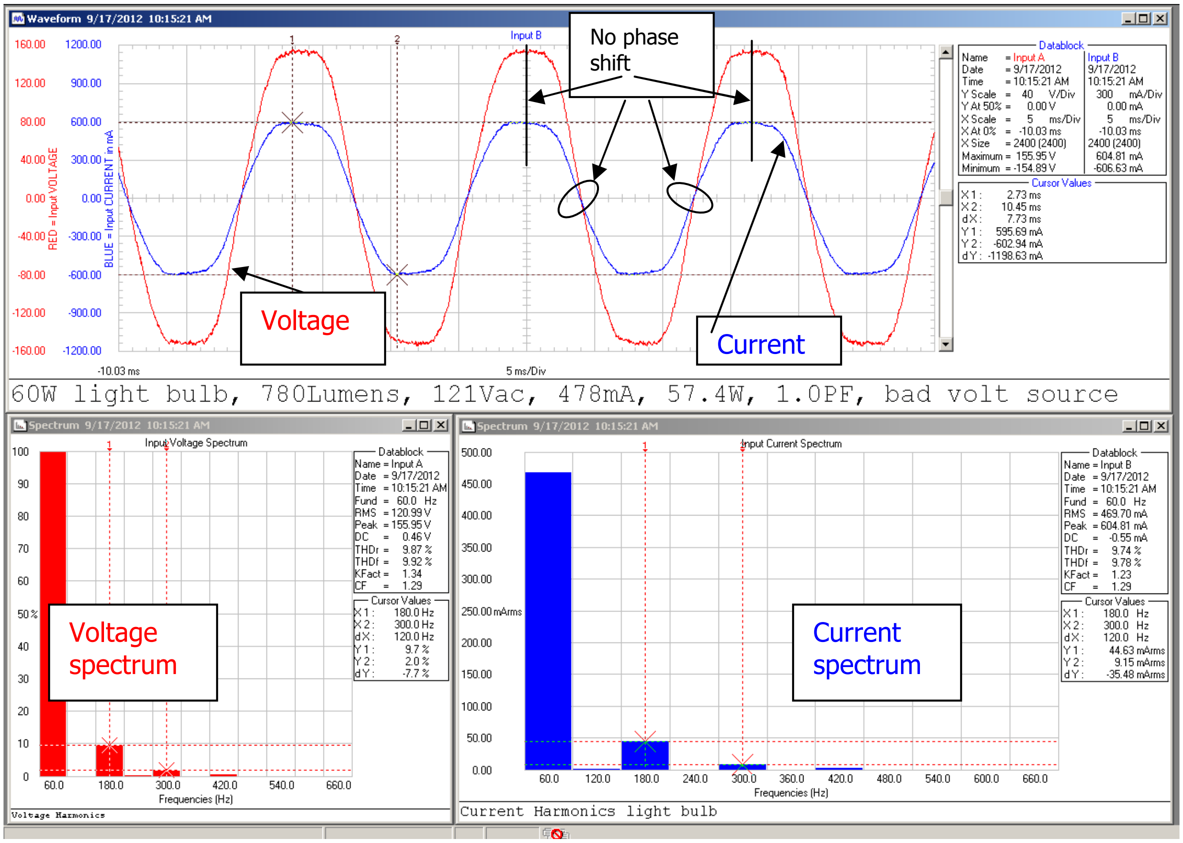

Figure 14 60W incandescent that matches Figure-3. Resistive load tracks voltage harmonics

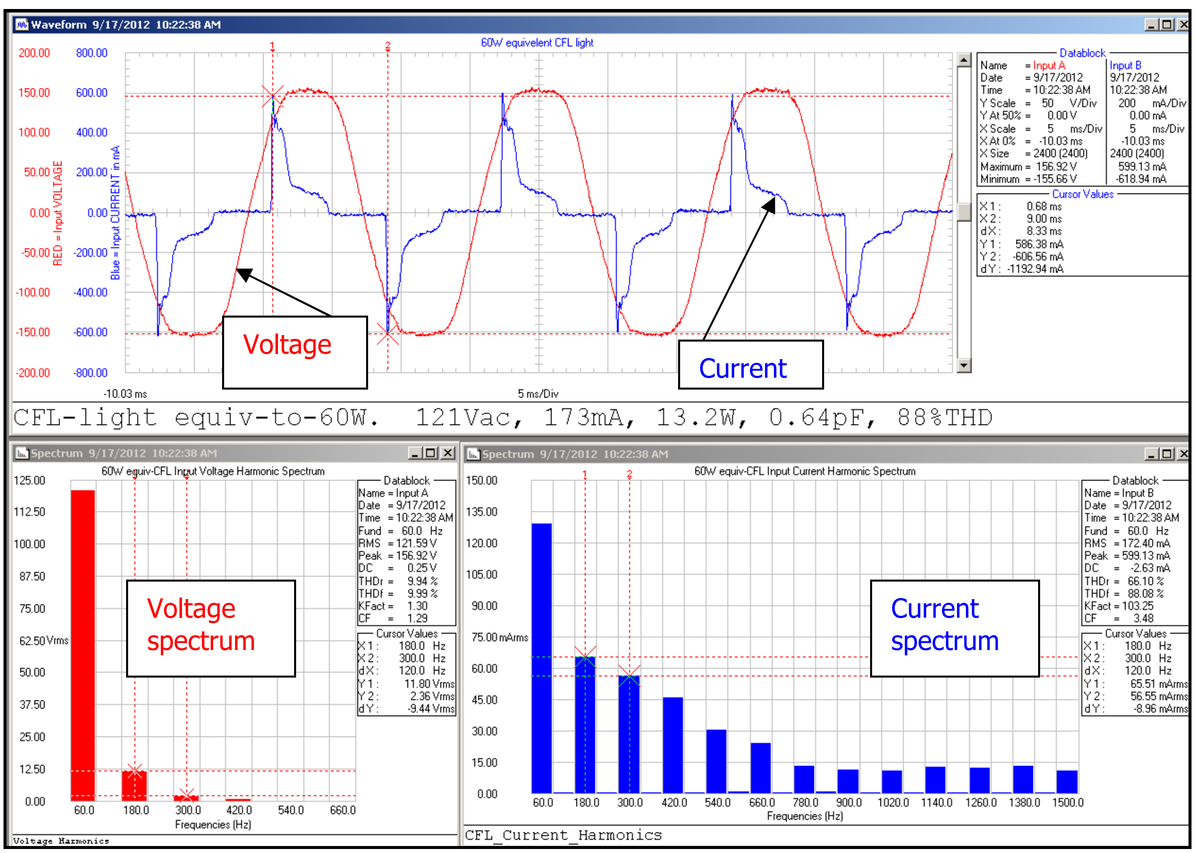

Figure 15 Shows CFL 60W replacement 13.2W, 88%THD, 0.64PF

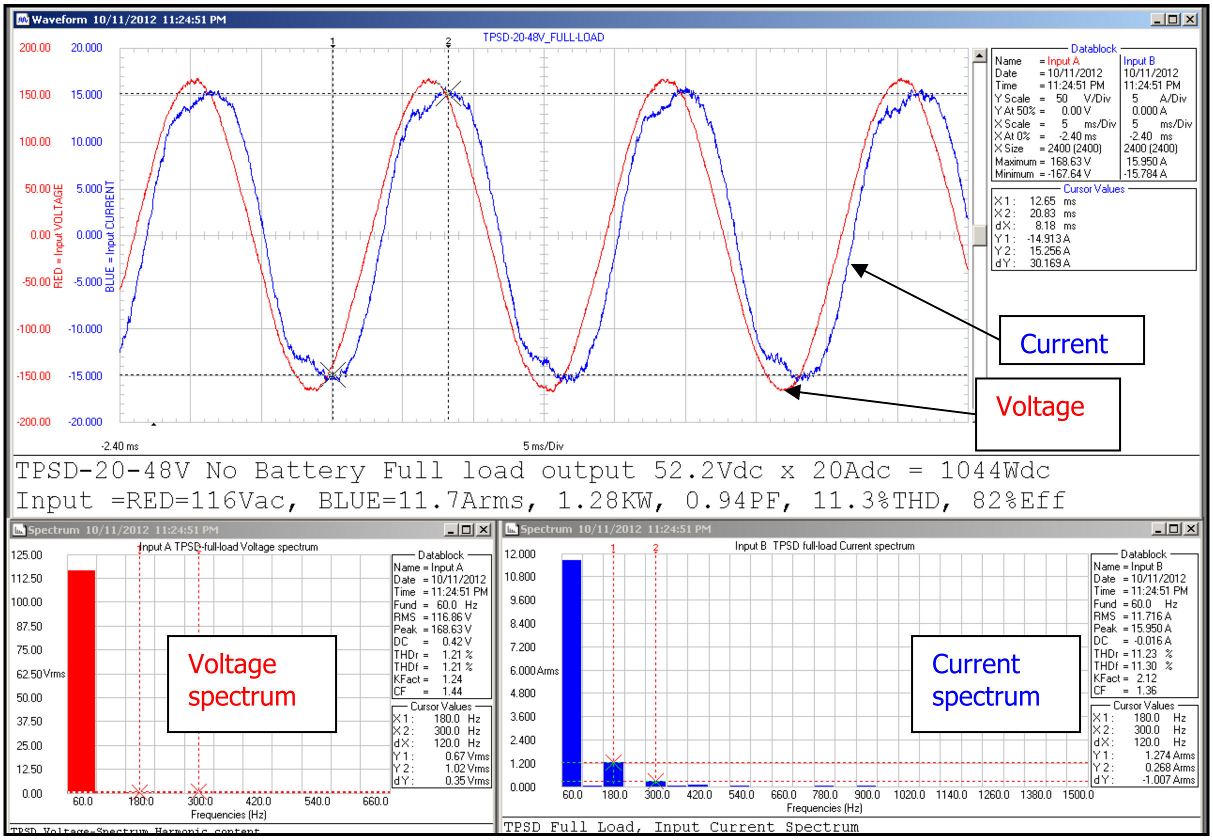

Figure 16 TPSD @ full load, shows high PF / Low Harmonics & THD. Highest quality in Line Freq technology

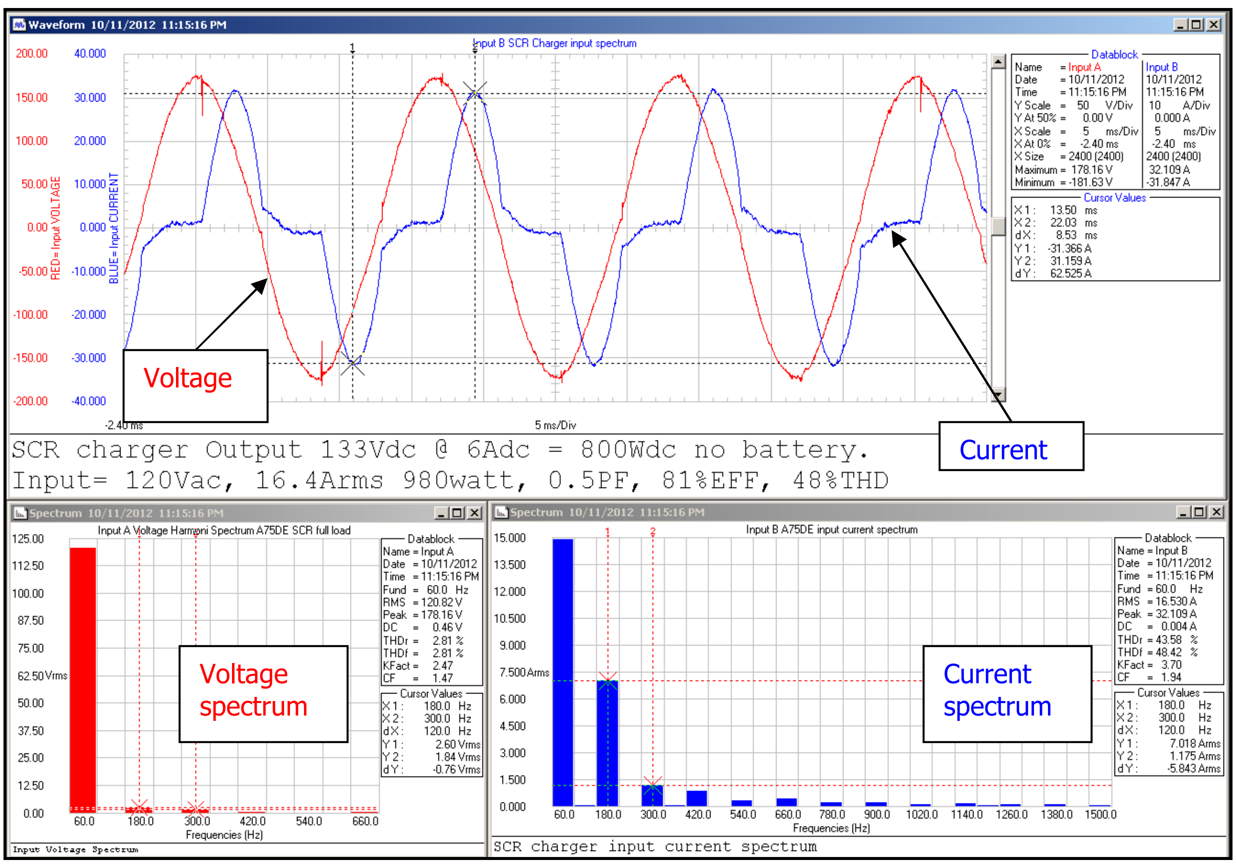

Figure 17 A75DE Charger no-battery, full-load.

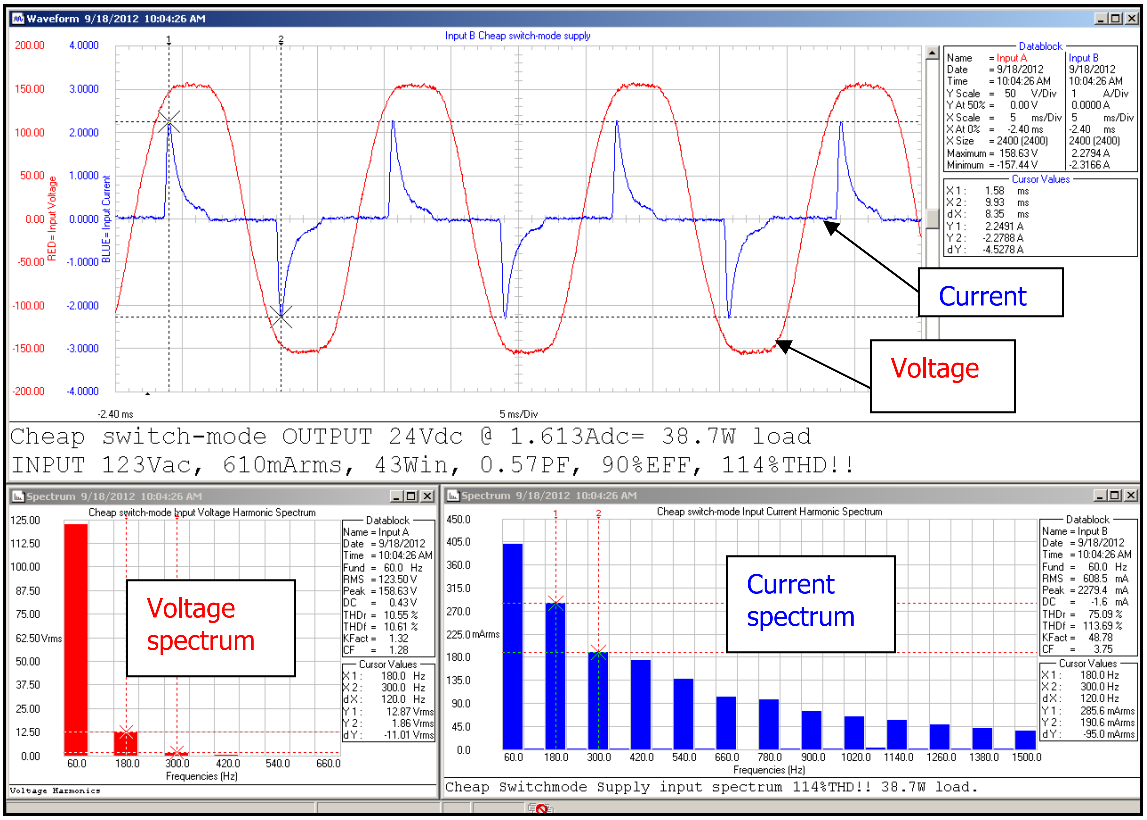

Figure 18 Cheap Switch-mode Power supply 50Watt rating, BAD PF, 114% THD, Not LMC product

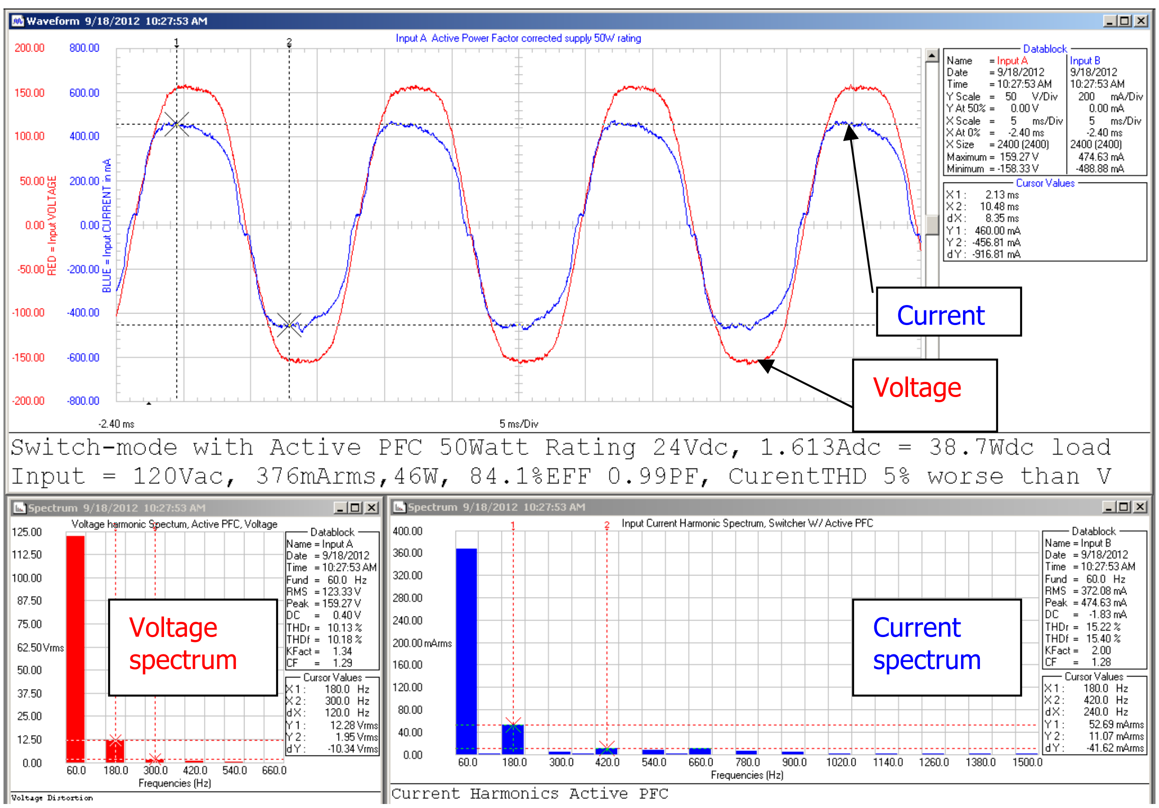

Figure 19 Active PFC 50W converter to compare with Figure-17, Not LMC product

Compare Figure-18 to Figure-19. Both power supplies have the same wattage rating, applied load, and input voltage. Notice how the PFC corrected switch-mode supply has virtually no harmonic content compared to the non-PFC supply. Also the PFC supply has no phase-shift and follows the shape of the voltage distorted or not. Even though the efficiency of the PFC power supply in Figure-19 is slightly worse than the cheap-switcher in Figure-18, the input current was nearly half. Figure-19 is the preferred option.

Power Factor Penalty

Many electric utilities across the nation have been implementing Power Factor Penalties within your monthly bill. Those utilities that don't do so right now, certainly will soon. Generating all those extra amps to satisfy poor PF and harmonic content isn't cheap. In fact, the ability to measure & thus bill especially commercial users of electricity specifically for PF is embedded within most upcoming Smart Metering systems.

The following example was taken directly from AustinEnergy.com [10]

Power factor adjusted demand is calculated using this formula:
Billing Demand = Peak Demand (kW) × .85 ÷ by metered power factor

The following example applies to a large grocery store, school, or retail with a metered power factor of 75%.

Before the power factor adjustment the bill was:
500 kW x $14.03 = $7,015.00

With PF adjustment:
500 kW (.85 ÷.75) = 566.67 kW →
566.67 kW × $14.03 (summer demand rate) = $7,950.38

The difference due to the power factor adjustment is: $935.33
That calculates to a $935.33 a 13.3% penalty for this example due to 75% PF!
Recalculated the same example but with a 50% PF
= $12,155.00 a 73.3% PENALTY

Clearly after only two data points, it is obvious that poor PF is about to get very expensive, very fast. As more electric utilities adopt similar billing strategies and Smart Metering, it will hurt more pockets and drive up demand for all types of equipment that does not incur line current harmonics leading to poor PF and a RED bottom line.

Conclusion

Considering the proliferation of electronics today in all applications, and the rising cost of generating electricity with various fuel sources, every watt counts. Bad PF and EFF can kill the end user's TCO. The future is bright for up and coming designs that have near unity-PF, near zero harmonic content, low THD, and maximum efficiency that can still maintain high reliability. The TPSD maintains that goal with rock solid reliability and serviceability. In fact, changing out other chargers for a TPSD could improve your bottom line without going to active PFC switch-mode supplies that generally require active cooling that is not conducive to a non serviceable environment.

Nobody can take all this in overnight. Several examples of Efficiency, DF, PF, VAR, VA, Harmonics, and RMS were covered in order to explain Power Quality issues with minimal math. Several examples were outside of La Marche product to provide you a broader general background. Please use this paper as a reference and a guide when issues or the discussion comes up. As always, La Marche is not only your solutions provider, but also your partner available to help at any time.

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Glossary

1Joule = 1amp x 1volt at any instantaneous moment in time.

1Watt = Volt x Amp POWER averaged over 1-second. Example: 10Joule pulse that lasts 1/10th of a second = 1watt of power. Unit of power measuring work performed over a period of time.

CFL = Compact Florescent Light

EPRI: The Electric Power Research Institute, Inc. www.epri.com conducts research and development relating to the generation, delivery and use of electricity for the benefit of the public as an independent nonprofit.

Fundamental: The root frequency and generally the intended sine wave to carry power. In the U.S., the fundamental is 60Hz.

Harmonics: Sine waves that are integer multiples of the fundamental frequency.

Harmonic order: 3rd order harmonic would be a frequency 3-times the fundamental, in our case 180Hz. A 6th order harmonic would be 360Hz.

HP=Horse Power. 1HP = 746Watts. 1/4HP=186Watts

Inter-harmonic: generally even-ordered harmonics and very rare in power systems.

K-Factor Transformer: A transformer that has been specially designed to handle high-harmonic current content.

Magnetostriction: a deformation of a magnetic material causing mechanical strain. This can cease a motor.

ODD-ordered harmonics, 3rd, 5th, 7th, 9th, etc are most common.

PCC: Point of Common Coupling; The lowest voltage utility distribution node that both you and a neighboring building share. This is where IEEE-519 would measure voltage enter your building and its harmonic content.

PF: Power Factor; Ratio of Watts to VA

PFC: Power Factor Correction, can be found on higher quality switch-mode power-supplies. A circuit that actively manipulates the input current wave shape and displacement to eliminate harmonics, and make the PF very close to a perfect "1". This circuit will make a load appear as a purely resistive load.

TCO = Total Cost of Ownership.

THD: Total Harmonic Distortion is the measure of how distorted a signal is from the intended sine wave usually expressed as a percentage.

Triplen-Harmonics: multiples of 3rd order harmonics, 3rd, 9th, 15th 27th. Triplen harmonics have special properties when evaluating 3-phase power systems.

VA: Volt Amp product; unit of Apparent Power

VAR: Volt Amp product of Reactive circulating energy; unit of Reactive Power due to non perfect PF.