Power Factor Correction (PFC) Basics

Introduction

Power Factor, in simple terms, is a number between zero and one that represents the ratio of the real power to apparent power. Real power (P), measured in watts, is the capacity of the circuit for performing work in a particular time. Apparent power is the product of input current and voltage of a circuit and/or system. Since real power is actually performing work, in an ideal case, real power would be equal to apparent power. Thus, a circuit with a low power factor will use higher currents to transfer a given quantity of real power than a circuit with a high power factor. In practical application, there will be combinations of two or three different power elements in a circuit or system.

Components of AC power flow

AC (Alternating Current) power flow has three components: 1. Real Power (P) - measured in Watts (W); 2. Apparent Power (S) – measured in volts-amperes (VA); 3. Reactive Power (Q) – measured in reactive volts-amperes (VAR). Real power, also called True Power, is a function of a circuit's dissipative elements, usually resistances (R). Reactive power is a function of a circuit's reactive elements, usually inductive and/or capacitive (X). Apparent power is a function of a circuit's total impedance (Z). This can be combinations of resistive, capacitive, and/ or inductive elements.

Real Power

With a pure resistive load, there exists only real power. There will be no reactive powers in a pure resistive load. Also, since there is no reactive power, apparent power will be equal to real power, which makes the Power Factor one for the circuit. A circuit with a power factor of one will have the current and voltage in phase with each other and the shape of the wave forms will be similar to one another. Figure 1 shows a simple resistive circuit and wave forms of voltage and current to better understand real power and how a power factor of one is achieved.

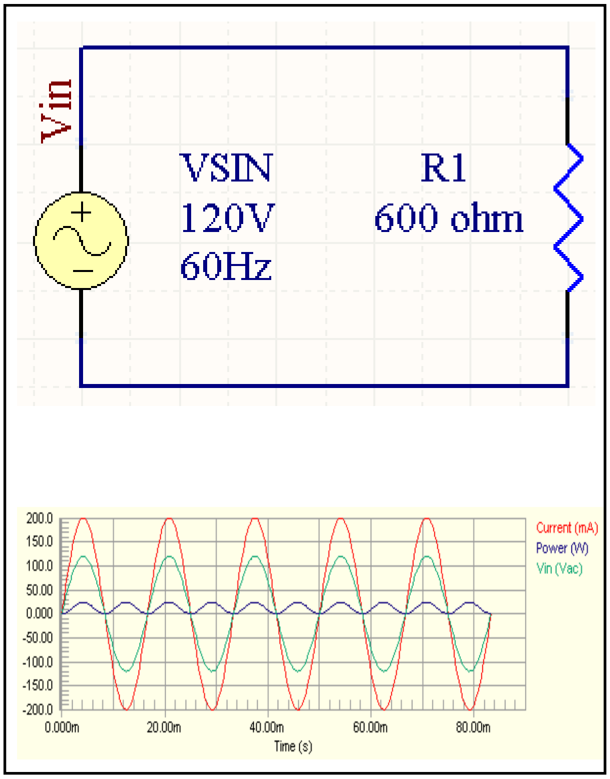

Figure 1. Simple resistive circuit.

P = true power = $I^2R = (0.2A)^2 * 600\Omega = 24W$
Q = reactive power = $I^2X = 0$ VAR
S = apparent power = $I^2Z = (0.2A)^2 * 600\Omega$
$= 24$ VA

Since true power is equal to apparent power, the PF would be one, as expected in pure resistive loads.

Also, the wave forms, current and voltage are in phase to each other and both have the same shape. When these two conditions are met, the power factor of the circuit would be one.

Reactive Power

With pure reactive load, capacitive or inductive, there will be no real power. There will only be reactive power, measured in VAR. Figure 2 shows a simple capacitive circuit and the reactive power of the circuit can be calculated as follows:

Xc = 1 / (2*¶*f*C), where f is the frequency of input voltage and C is the capacitance of the circuit.

Xc = 1 / (2*3.14*60*2.2*10^{-6})
= 1205.72Ω

Reactive power (Q) = I^2X
= $(0.1A)^2$*1205.72
= 12.06VAR

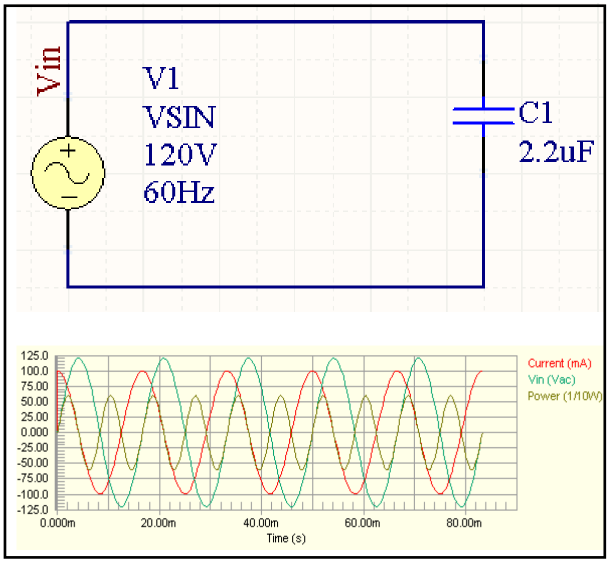

Figure 2. Simple reactive (capacitive) circuit.

One thing to note is the phase angle shift between current and voltage. It can be seen from the waveform that current leads voltage by 90˚ in a capacitive circuits. If this was an inductive circuit, which would have also had only reactive power, current would have lagged voltage by 90˚. In practical application, there are not many capacitive or inductive circuits. What is common is a circuit that is a combination of resistive, inductive, or capacitive in nature.

Apparent Power

Apparent power is the total power of the circuit and it is the addition of real and reactive powers. As mentioned before, this would be the practical situation as most circuits and systems would have resistive and reactive loads. Figure 3 shows a simple LR (inductor-resistor) circuit and the apparent power for the circuit can be calculated as follows:

X_L = 2(2*¶*f*L), where f is the frequency of input voltage and L is the inductance of the circuit.

X_L = 2*3.14*60*3.2
= 1206.37Ω

Z = $(R^2 + XL^2)^{1/2}$
= $1200Ω^2 + 1206.37Ω^2$
= 1.701KΩ

I = 120V/ 1.701KΩ = 70.55mA

Real power (P) = I^2*R
= $(.0755A)^2$*1.2KΩ
= 5.97W

Reactive power (Q) = I^2*X_L
= $(0.0755)^2$*1206.37Ω
= 6 VAR

Apparent power = I^2*Z
= $(0.0755A)^2$*1.701KΩ
= 8.47VA

Power factor in this case would be:

PF = Real power/ Apparent power
= 5.98W/ 8.47VA
= 70.5%

A combined resistive-reactive circuit shown in Figure 3 dissipates more power than it returns to the source. The reactance dissipates no power, but the resistor does.

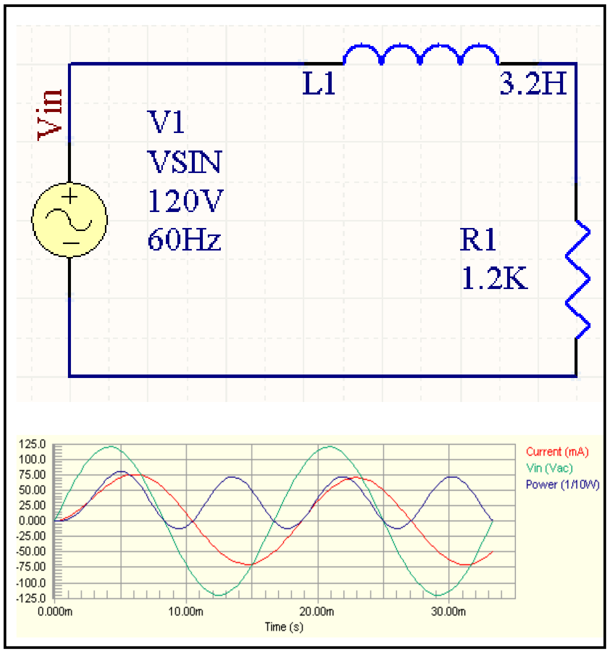

Figure 3. Simple LR circuit.

How to improve PF

As noted above, real power is what actually performs work. Therefore, it is important to have a reduced amount of total reactive power, in order to have an efficient system. In other words, the power factor of a system or circuit should be improved when possible. If we consider the circuit in Figure 3, it has a PF of only 70.5% and there is room to improve the PF up to 99%. Since the circuit has an inductive reactance component, there needs to be a capacitive component added to the circuit to reduce overall reactance of the circuit. The waveform in Figure 3 shows the phase shift between the voltage and current for the circuit in consideration. The phase shift causes the PF to be poor. The idea is to make the waveforms, current and voltage, in phase to each other and have the same shape. Since the circuit only has linear loads, the shape of the waveforms is already similar. However, if the loads are non-linear in nature, the PF correction becomes complicated and requires complex circuit to improve PF. This will be detailed later in the section of "Power Factor Correction in non-linear loads". Figure 4 shows the new circuit with added capacitor that would improve PF on Figure 3, close to unity

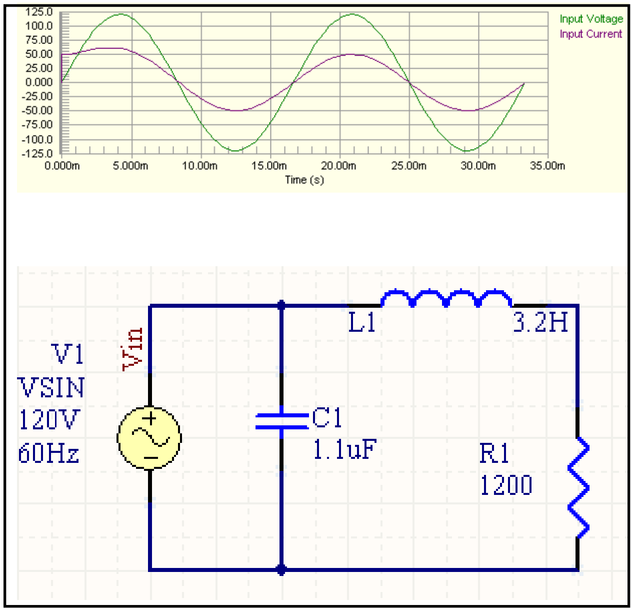

Figure 4. Improved PF circuit.

As can be seen from the waveform, the voltage and current are now in phase with each other and they have similar shape with the same frequency. The waveform also looks very similar to that of a resistive load, even though the circuit has resistive, capacitive, and inductive loads. This clearly indicates that the PF is well improved.

The following shows how the value of the capacitor is calculated and the calculation of improved power factor for the circuit.

First, the value of capacitance is calculated as follows:

$Q = E^2 / X$
$X = E^2 / Q$
$= 120^2/6.0 = 2.4\text{K}\Omega$

$Xc = 1 / 2¶fC$
$C = 1 / Xc2¶$
$= 1 / (2*2.4\text{K}*¶*60)$
$= 1.105\text{uF}$

A standard 1.1 uF capacitor is chosen for this purpose. Calculation of PF:

$Xc = 1 / (2*¶*60*1.1*10^{-6})$
$= 2.411\text{K}\Omega$

$X_L = 2*¶*60*3.2$
$= 1.206\text{K}\Omega$

$R + X_L = 1.206\text{K}\Omega <90^\circ + 1.2\text{K}\Omega$
$= 1.701\ \text{K}\Omega <45.14^\circ$

$I_L = 120\text{V} / 1.701\text{K}\Omega$
$= 70.55\text{mA}$

$Z_{total} = Zc\ //\ (Z_L + Z_R)$
$= 2.411\text{K}\Omega <-90^\circ\ //$
$(1.2\text{K}\Omega <0^\circ + 1.206\text{K}\Omega <90^\circ)$
$= 2.412\text{K}\Omega <0.262^\circ$

$I_{total} = 120 / 2.412$
$= 49.75\text{mA}$

$P = \text{True power} = (70.55\text{mA})^2*1.2\ \text{K}\Omega$
$= 5.97\text{W}$

$S = \text{Apparent power} = (49.75\text{mA})^2*2.412\ \text{K}\Omega$
$= 5.97\text{VA}$

$\text{Improved PF} = 5.97\text{W} / 5.97\text{VA}$
$= 100\%$

As expected, because the above calculations are ideal cases per the concept, the PF is improved to be 100%. In real cases, it is almost impossible to have a PF of 100%, especially with passive components. However, the PF can be well improved to be within an acceptable level, if proper design technique is used.

PF in non-linear loads

So far, all the example circuits considered have linear loads, meaning the current wave form matches that of the voltage. Non-linear loads create harmonic current on top of the original AC current and the current wave form is no longer a sine wave. The total harmonic distortion, known as THD, should be taken into consideration when dealing with non-linear loads. Also, harmonics cannot be improved or cancelled by adding linear components, such as capacitors or inductors. In the case of non-linear loads, different, yet more complex, methods need to be considered to improve PF correction and minimize THD. In many cases, the method used is active power factor correction utilizing a dedicated Integrated Circuit, known as IC, which is much more complex than a passive power factor correction method.

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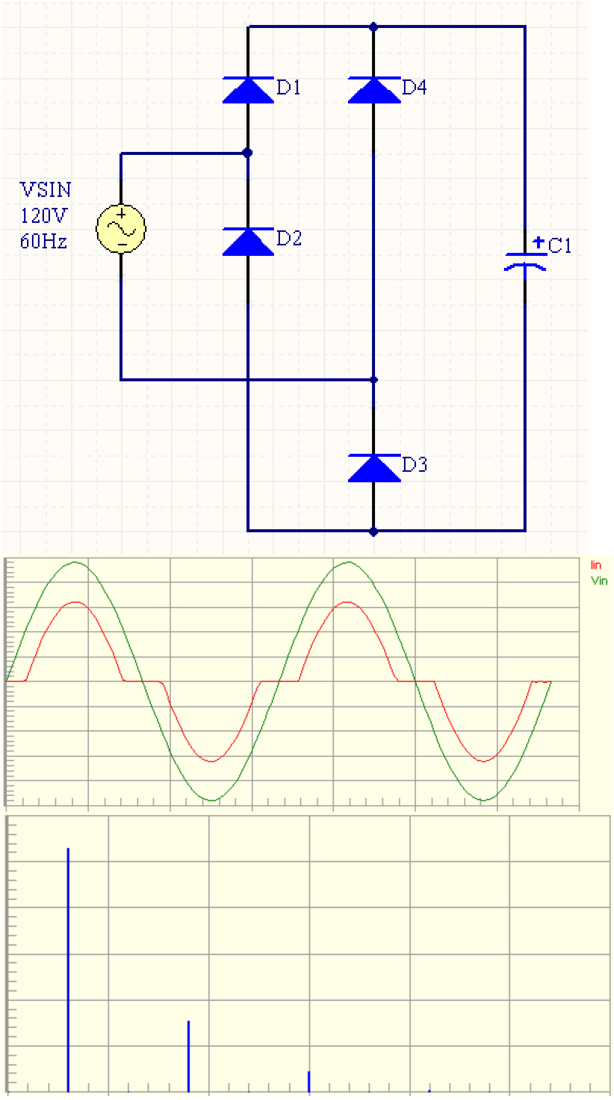

Figure 5. Simple rectifier circuit.

A typical non-linear load of a power system can be rectifiers. Figure 5 shows a simple circuit that can be found in AC-DC power supplies. It can be seen from the picture that the current waveform is not a sine wave as it would be with linear loads. Also shown are the harmonic contents at different frequencies, fundamental frequency, 3rd, 5th and 7th harmonics. Note that the magnitude of the harmonic contents decreases as level (1st, 3rd, 5th, etc) increases.

How to improve PF and THD

As mentioned already, in this case, an active PFC circuit would be utilized to improve PF and reduce THD. The purpose of the active circuit is to shape the input current to match that of the input voltage. Figure 6 shows the operation of the circuit and the resulting current waveforms.

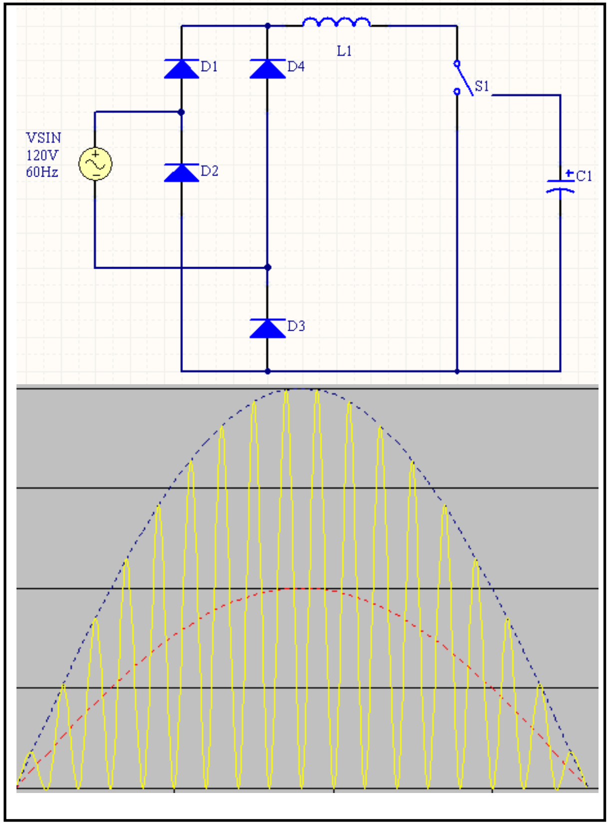

Figure 6. Active PFC circuit and current waveform.

The idea is to turn the switch (S1) on and off at a different rates during the cycle, such that the average inductor current follows the shape of the input voltage. In a real circuit, the switch will be replaced by the PF correction IC. The function of the IC would be to generate the appropriate duty cycle of the PWM (Pulse Width Modulation) that will eventually perform the function of turning on/ off the switch.

In Figure 6, which is the resulting current waveform of an active PF correction circuit, the yellow curve is the peak inductor current and red curve is the average inductor current. The picture shows an expanded view of the waveform and, in general, the frequency of such switch is in the micro or kilo hertz range.

Once the current and voltage waveforms are in phase, with a non-linear load, the PF can be approximated using the following equation.

$$PF = 1 / SQRT[1 + (THD\ \% / 100)^2]$$

(where THD is the Total Harmonic Distortion)

As mentioned earlier, once the voltage and current are in-phase with each other, the PF of the circuit would be closer to 100%. Since this application guide only explains the basics of PF, no further examples on PF or THD is given.

Power Factor and Energy Star

Energy Star requirements for electronic devices becomes more and more populous to address the energy savings, green energy, CO_2 reduction, and a total green environment. For this reason, the emerging Solid State Lighting luminaires are also required be Energy Start rated. The Energy Star requirement on Power Factor for residential and commercial applications are >70% and >90%, respectively. This means that any LED luminaire or system power supply should have the required PF in order to have the Energy Start status. LEDs are DC current driven devices with the exception of few AC powered LEDs. When LEDs are DC powered, the AC main power should be converted into DC and attention should be paid when designing the power supply to meet the energy star PF requirements. When AC LEDs are powered using AC, because LEDs are not resistive and non-linear in nature, the PF becomes very poor. In these cases, special attention needs to be paid to PF and THD needs to be paid.

Conclusion

Power Factor is becoming more and more of a challenge due to energy star requirements for electronic devices. LED luminaires are also bound to this requirement if the luminaire were to qualify for energy star certification. Understanding the basics of PF and how to correct PF to improve it to an acceptable level will help address the issue in the very early stages of the design. The additional circuitry required to have PF correction will add cost, require more space, add more failure modes, and slightly impacts the overall reliability of the system. Addressing all these issues at the very early stage of the design, especially if the system is to be certified by UL, energy star, etc..., will significantly contribute to the success of a system.

Author: Muhinthan Murugesu, Applications Engineer

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