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HOW HARMONICS HAVE CONTRIBUTED TO MANY POWER FACTOR MISCONCEPTIONS

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INTRODUCTION

For those trained in electrical theory, the concept of power factor (PF) used to be fairly simple to understand. However, with the introduction of harmonics generated by today's non-linear loads, power factor analysis has become increasingly complex which has contributed to many power factor misconceptions. Common misconceptions include:

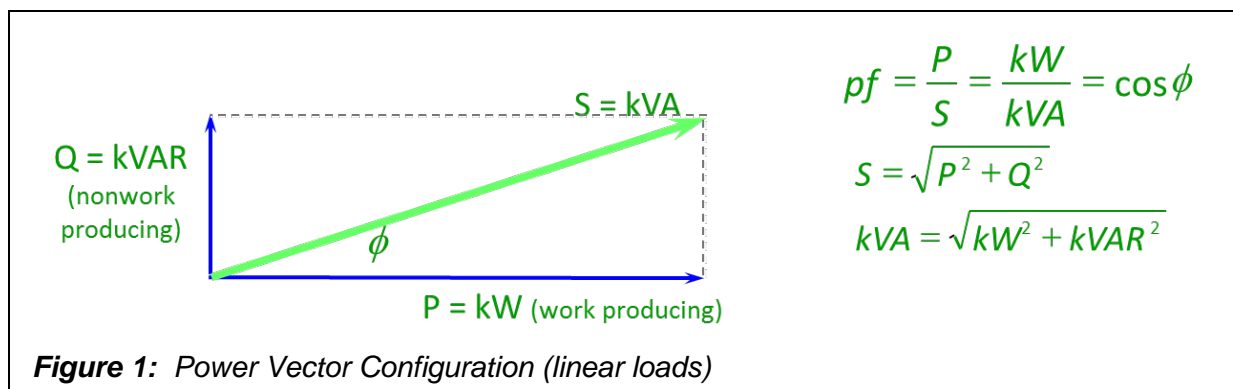
1. Low power factor is normally caused by electrical motors and other inductive loads
2. Any leading power factor is bad
3. Low power factor can always be corrected by adding capacitance
4. Power factor must always remain high to prevent power factor penalties
5. Harmonic filters must always be equipped with contactors to switch out capacitors under light loading conditions
6. Leading power factor is a problem for generators under any condition

Although a low power factor does indicate that a power system is not being effectively utilized, if this occurs only when the system is lightly loaded and the reactive power component (kVAR) is quite low, there is no need for concern. Only when the power factor is quite low under more heavily loaded conditions does it need to be addressed. Placing conditions that are too rigid with respect to power factor can lead to installations that are more complex, costly and unreliable than necessary. And in many instances, a little leading power factor can be effective in compensating for inductive reactive power located elsewhere on the distribution system.

THE POWER TRIANGLE

Power factor is a measure of how effectively a specific load consumes electricity to produce work. The higher the power factor, the more work produced for a given voltage and current. Power factor is always measured as the ratio between real power in kilowatts (kW) and apparent power in kilovoltamperes (kVA).

For linear loads, which are defined as resistive, inductive or capacitive, the apparent power in kVA ($S = V \times I$) is the vector sum of the reactive power in kVAR (Q) and the real power in kW (P). The power factor is $P/S = \cos\phi$, where ϕ is the angle between S and P. This angle is the same as the displacement angle between the voltage and the current for linear loads and is therefore, often referred to as Displacement Power Factor or dPF. For a given amount of current, increasing the displacement angle will increase Q, decrease P, and lower the PF. Purely resistive loads draw their current in-phase with the voltage and have a power factor of 1. When the load is reactive, it stores energy, releasing it during a different part of the cycle.



Inductive loads, such as electric motors, cause their current to lag the voltage, while capacitors cause their current to lead the voltage. Therefore, lagging versus leading describes whether the net reactance is either inductive or capacitive. For circuits with strictly linear loads, simple capacitor banks may be added to the system to improve a lagging power factor due to induction motors or other lagging loads.

POWER FACTOR AND NON-LINEAR LOADS

Non-linear loads, such as rectifier circuits, don't typically shift the current waveform, instead they distort it. These distorted waveforms can be broken down into harmonic components using Fourier Analysis. The harmonic currents produce no useful work and therefore are reactive in nature. Non-linear loads are extremely prevalent on today's power systems and are typically the result of the rectifiers used to convert AC power to DC in power electronic equipment. Examples include, variable speed drives, computers, broadcasting equipment, compact fluorescent and LED lighting, electrical chargers, induction furnaces and many other devices.

For non-linear loads, the power vector relationship becomes three dimensional with distortion reactive power, H, combining with both Q and P to produce the apparent power which the power system must deliver (Figure 2) [1]. Power factor remains the ratio of kW to kVA but the kVA now has a harmonic component as well. True power factor (TPF) becomes the combination of displacement power factor (dPF) and distortion power factor (hPF). Displacement PF is still equal to $\cos\phi$, with ϕ being the angle between the fundamental current and voltage. Displacement PF can be either leading or lagging. Distortion PF is then True PF (kW/kVA) divided by the dPF. Distortion PF is neither leading nor lagging. For typical non-linear loads, the displacement power factor will be near unity. True power factor however, is normally very low because of the distortion component. For example, the displacement power factor of a variable speed drive will be near unity but its total power factor is often in the 0.7 – 0.8 range unless harmonic mitigation equipment is applied.

Today, with the heavy proliferation of non-linear loads, low power factor on a power system is often the result of a high distortion reactive power component and not inductive reactive power. **Therefore, one can no longer say that low power factor is normally caused by electric motors and other inductive loads.** And since the best way to improve a poor power factor caused by non-linear loads is to remove the harmonic currents, **the traditional means of adding power factor correction capacitors is, quite often, no longer suitable.** In fact, simply adding capacitors may often make the problem worse as they can resonate with the power system inductance.

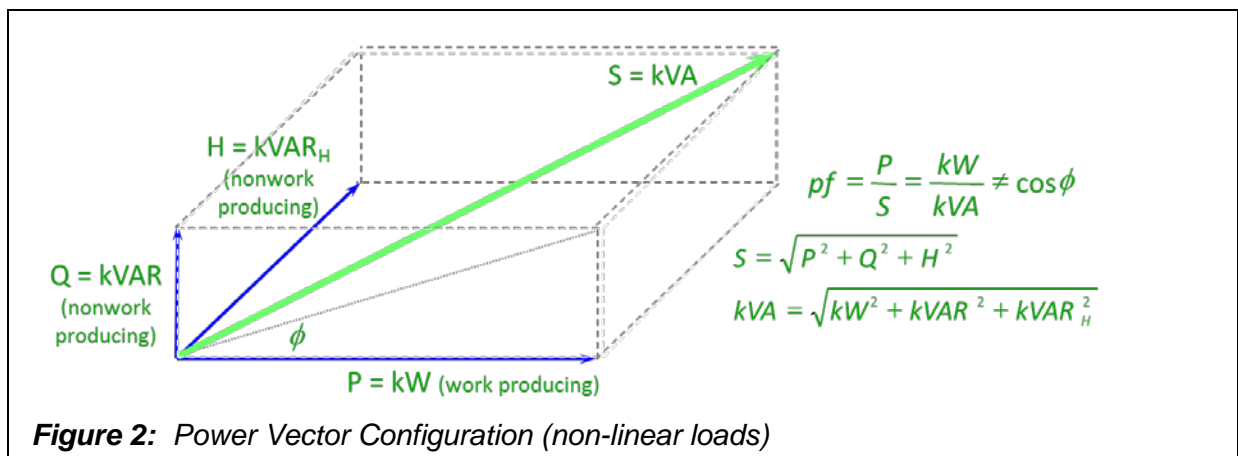


Figure 2: Power Vector Configuration (non-linear loads)

POWER FACTOR PENALTIES

Although there is no universally accepted standard for how Electrical Utilities charge their customers for a low power factor, it appears to be common practice to apply power factor penalties within the demand charge [2]. Most Utilities charge their customers for energy supplied in kilowatt-hours during the billing period plus a demand charge for that period. The demand charge is based upon the peak load during the period. The demand charge is applied by the Utility because it must provide equipment large enough for the peak kVA demand even though the customer's real power demand may be much lower. If the power factor during the peak period (often a 15 minute sliding window) is lower than required by the Utility (usually 0.9 or 0.95), the Utility may also apply a low PF penalty charge as part of the demand charge portion of the bill.

Suppose the peak demand was 800 kW with apparent power consumption of 1000 kVA (a PF of 0.8). If a power factor penalty was applied at 0.9, the Utility would charge the customer as if his demand was $0.9 \times 1000 \text{ kVA} = 900 \text{ kW}$ even though his peak was actually 800 kW, a penalty of 100 kW. Improving the power factor to 0.85 at 1000 kVA demand would lower the penalty to just 50 kW. For power factors of 0.9 to 1.0, there would be no penalty and the demand charge would be based upon the actual peak kW. The demand charge is often a substantial part of the customer's overall power bill, so it is worthwhile to maintain good power factor during peak loading and reducing the harmonic current as drawn by the loads can help achieve this.

It is important to note that, if the low power factor condition only appears when the system is lightly loaded, it will not affect the power factor penalty since that is applied only during peak demand conditions. If the application of power factor correction capacitors or the capacitors used in harmonic mitigating filters results in **a low leading power factor under lightly loaded conditions, that in itself, need not be a concern**. It is only a concern if the power factor remains low and leading under more heavily loaded conditions or if the capacitive reactive power under lightly loaded conditions is quite high. Insisting that power factor never become leading or never go below, say 0.95 leading, is unnecessary. Instead, the maximum capacitive reactive component as a percent of overall rated power should be stipulated. This will be addressed again later in this paper.

An example where power factor correction capacitors were misapplied was on an oilfield in the Midwest USA where almost 150 Electrical Submersible Pumps equipped with variable speed drives were in use. Concerned about the low power factor and reactive power consumed by the site, the local Utility installed PF Correction capacitors at the Oil Company's expense. However, when problems persisted, harmonic distortion levels were measured and found to be excessive which the Oil Company was also required to rectify. Being approached by the Oil Company to provide a solution, Mirus studied the measured values and found that the voltage distortion levels were as high as 14%. This seemed unusual even for the high quantity of ESP's connected. Mirus requested that the Utility take measurements with the capacitor banks disconnected. Results are found in Table 1.

There were two sets of capacitor banks and as each set was removed, both voltage distortion and current distortion lowered. Voltage distortion dropped from over 14% to under 9% which demonstrated that the capacitors were resonating with the power system, providing evidence that **capacitors are not always the best solution for improving a low power factor**. The Utility agreed to keep the capacitor banks disconnected and Lineator AUHF passive harmonic filters were installed on the ESP's to reduce current distortion, lower voltage distortion to less than 5% and improve power factor to greater than 0.95.

CONFIGURATION	KW	PF	%VTHD			%iTHD		
			A	B	C	A	B	C
2 Cap Banks on	12.00	0.94	14.20	14.00	14.40	33.60	31.30	32.10
1 Cap Bank on	11.90	0.95	11.18	12.16	11.70	18.42	20.87	20.68
No Cap Banks on	12.10	0.92	8.00	8.97	8.73	11.41	12.34	12.38

Table 1: Harmonic distortion measurements at an Oilfield equipped with Electrical Submersible Pumps showing resonance with power factor correction capacitors.

POWER FACTOR AND PASSIVE HARMONIC FILTERS

A passive harmonic filter can be an excellent choice for improving power factor when the reactive power component is predominantly harmonics generated by non-linear loads. Having a properly designed harmonic filter however, is critical to ensuring that harmonic mitigation meets the targeted levels without introducing excessive capacitive reactive power under lightly loaded conditions. The large capacitor banks of conventional trap filters and most broadband filters present a high capacitive reactance to the power system which can raise voltages or cause excitation control problems in generator applications. The Lineator AUHF wide spectrum filter on the other-hand, is designed to have a maximum capacitive reactive power of 15% (Figure 3) which is less than ½ of the 35% - 40% of other passive filters.

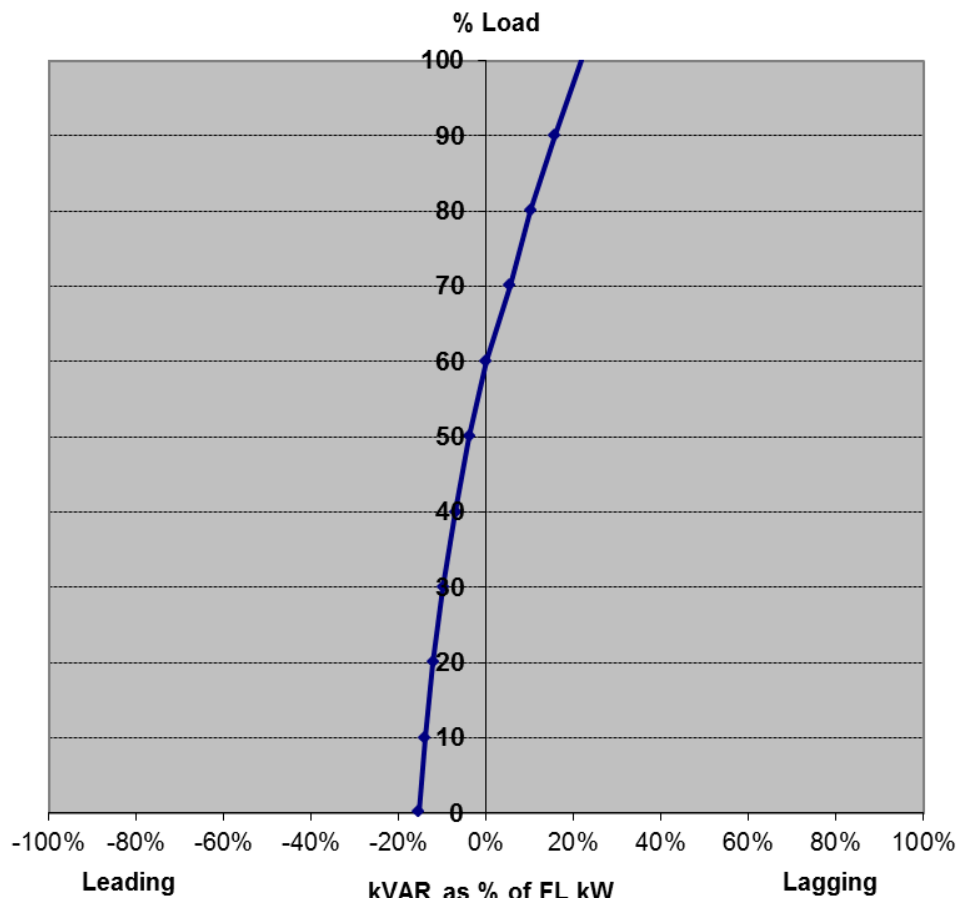


Figure 3: Reactive Power vs % Load for a 300HP, 480V Lineator AUHF

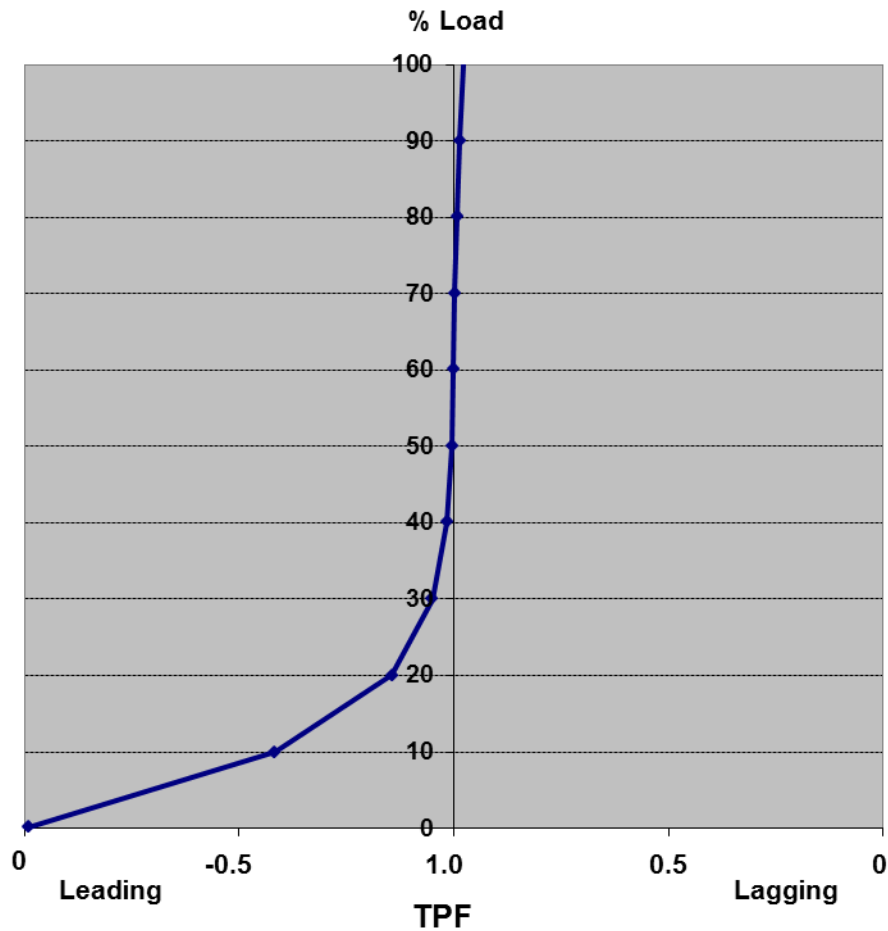


Figure 4: True Power Factor vs % Load for a 300HP, 480V Lineator AUHF

This low level of capacitive reactive power also ensures that the power factor remains high over the normal operating range; PF >0.95 from 30% load to 100% load (Figure 4). Although power factor is low and leading at light loading conditions, the very **low level of capacitive reactive power eliminates the need for contactors to switch out the capacitors** as is required with other filters.

In fact, the Lineator AUHF has been proven to protect the variable speed drive against overvoltage transients and ringing introduced by Utility capacitor switching or SCR voltage notching. Under lightly loaded conditions, when the variable speed drive is most vulnerable, this benefit would not be realized if the filter's capacitors were switched out. Figure 5 and 6 show voltage waveforms at the input and output of a Lineator AUHF where SCR notch ringing on a Drilling Rig caused overvoltages on the electrical bus supplying compressor AC adjustable speed drives [3]. Without the protection offered by the Lineator AUHF, the compressors were failing due to the overvoltages.

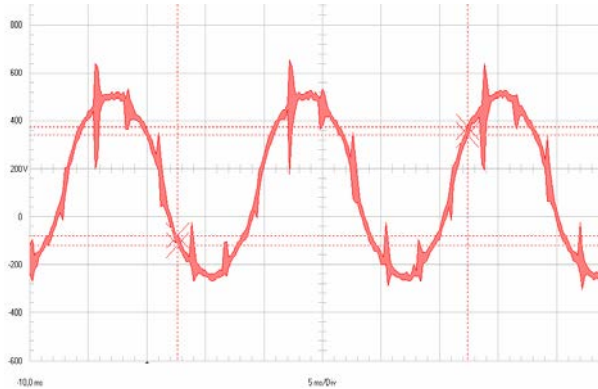


Figure 5: Voltage waveform at input to Lineator AUHF harmonic filter

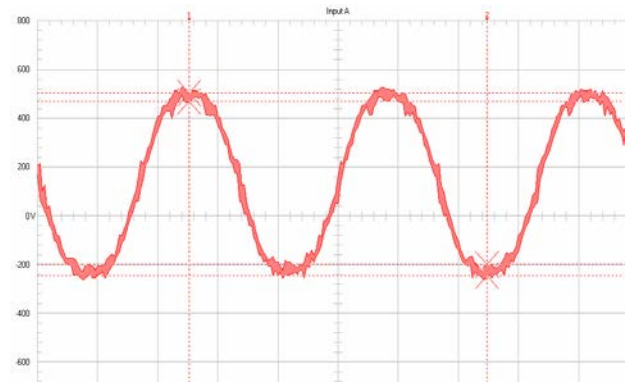


Figure 6: Output voltage waveform cleaned up by Lineator AUHF harmonic filter

GENERATORS, LEADING PF AND CAPACITIVE REACTANCE

The ability of a generator to handle leading power factor loads is often raised as a concern [4][5]. Although it is true that excessive capacitive reactive power can cause voltage regulation, excitation control and other issues with a generator's operation, they can definitely tolerate a leading power factor at certain levels. All generator manufacturers publish reactive power capability curves for their generators from which a user can determine the acceptable levels of reactive power for the generator, both capacitive and inductive [6]. Figure 7 shows the Reactive Power Capability Curve for a typical synchronous generator with the Lineator AUHF reactive power consumption shown in green.

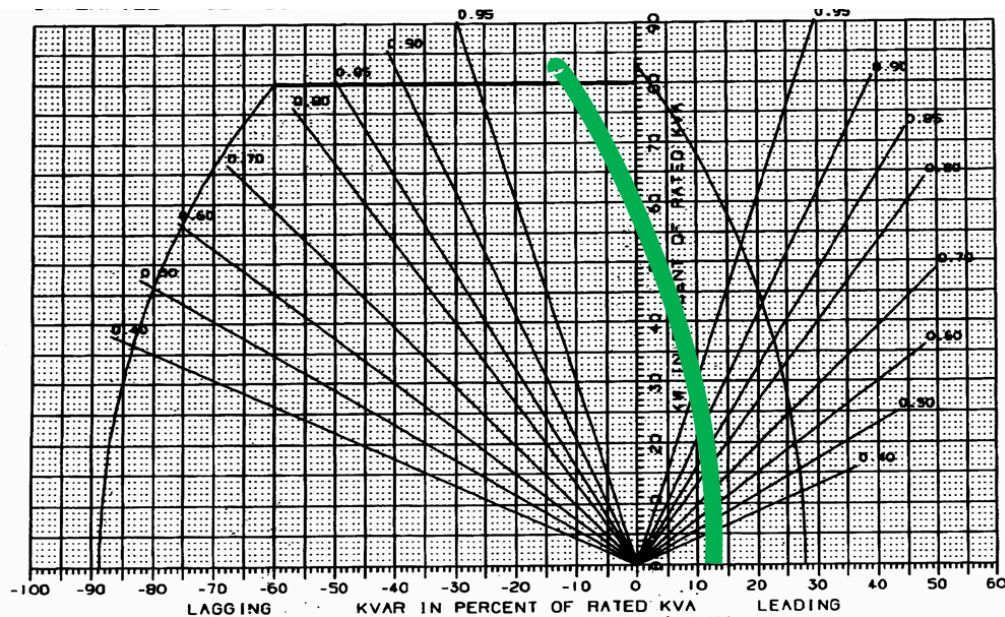


Figure 7: Typical Generator Reactive Power Capability Curve with Lineator AUHF reactive power consumption shown to be well within the acceptable operating envelope.

In this graph, kW loading of the generator is on the Y-axis and kVAR on the X-axis with capacitive or leading to the right and inductive or lagging on the left. Radial lines indicate various load PF's. For this generator, the envelope shows that at no load reactive power must be less than 28% leading but can be as much as 89% lagging. The Lineator AUHF reactive power consumption line is shown in green and is comfortably within the generator's capability envelope. The **leading power factor of the filter is not a problem for the generator** and it is therefore, unnecessary to switch out the capacitors under light loading.

CONCLUSION AND SUMMARY

There are many benefits for a power system to have a high power factor but that doesn't necessarily mean that a low leading power factor at light loads is a problem. Harmonics generated by non-linear loads introduce distortion reactive power which will lower power factor. The conventional method of installing power factor correction capacitors however, is not an effective way of increasing power factor under these conditions. In fact, power factor correction capacitors can often make the situation worse if they happen to resonate with the power system inductance.

What is required is removal of the harmonic currents to lower distortion reactive power. Passive harmonic filters can be effective in this regard but they must not introduce too much capacitive reactive power. To ensure this, **specifications should (i) require power factor above 0.95 leading or lagging while operating in the load range from 30% to 100% and (ii) a maximum capacitive reactive power at no load of 15% of kW rating.** Meeting these conditions will help ensure that the power system power factor remains above power factor penalty levels when supplied by the Utility and will not introduce operational issues when supplied by a generator.

Placing conditions that are too rigid with respect to power factor can lead to installations that are more complex, costly and unreliable than necessary. And in many instances, a little leading power factor can be effective in compensating for inductive reactive power located elsewhere on the distribution system.

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