Harmonic and Energy Saving Solutions

How Harmonics have led to 6 Power Factor Misconceptions

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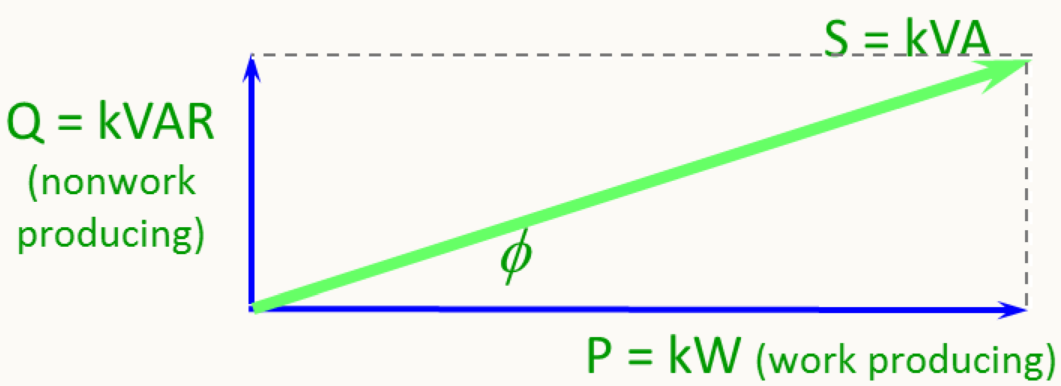
Power Factor Misconceptions

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

Power Factor and the Power Triangle

- Power factor (PF) is a measure of how effectively a specific load consumes electricity to produce work
  - Ratio between Real Power (kW) to Apparent Power (kVA)
- The higher the PF, the more work produced for a given voltage and current
- The Power Triangle (applies only to Linear Loads)
- Often referred to as Displacement PF (dPF)



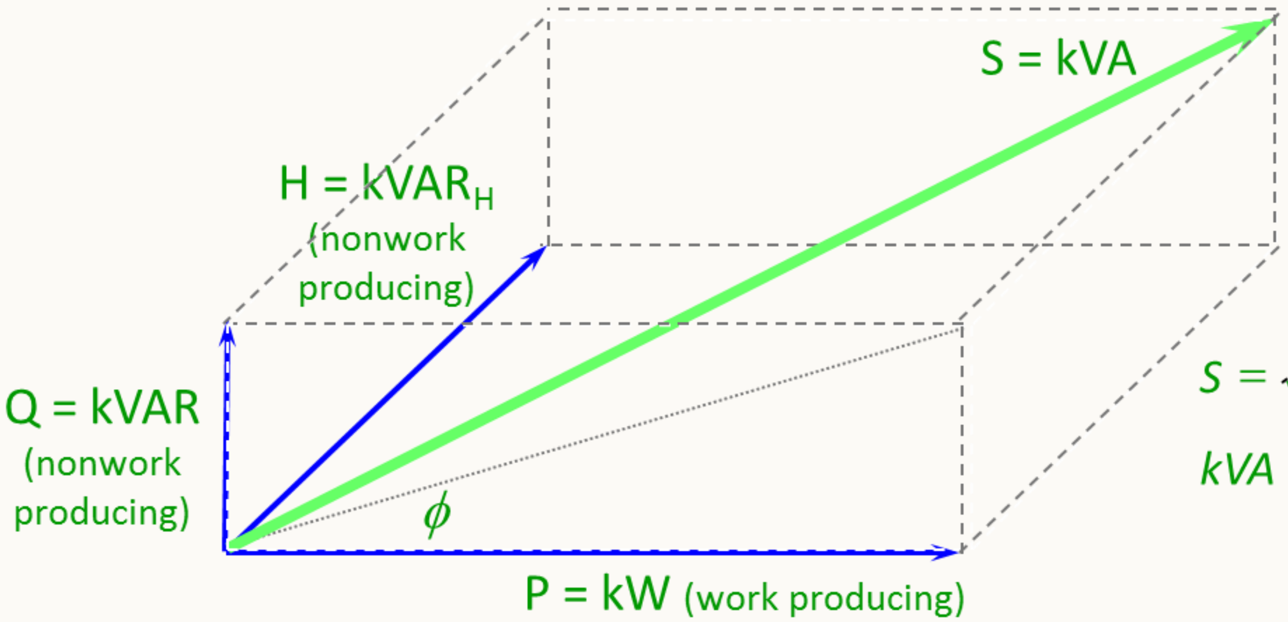
$$pf = \frac{P}{S} = \frac{kW}{kVA} = \cos\phi$$

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

$$kVA = \sqrt{kW^2 + kVAR^2}$$

Power Factor and Non-linear Loads

- Non-linear loads, such as rectifiers, don't typically shift the current, they distort it
  - Harmonic currents that are generated do no useful work and therefore, contribute to reactive power
- The power vector relationship becomes 3 dimensional



$$pf = \frac{P}{S} = \frac{kW}{kVA} \neq \cos\phi$$

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

$$kVA = \sqrt{kW^2 + kVAR^2 + kVAR_H^2}$$

- True PF = Displacement PF (dPF) x Distortion PF (hPF)

Reference: H. Rissik, *The Fundamental Theory of Arc Convertors*, Chapman and Hall, London, 1939

Distortion Power Factor Relationships

Harmonic	%Fund.	%RMS	I^2H^2
1	100%	77%	0.59
3	70%	54%	2.61
5	35%	27%	1.81
7	20%	15%	1.16
9	15%	12%	1.08
11	10%	8%	0.72
13	7%	5%	0.49
15	3%	2%	0.12
17	2%	2%	0.07
19	1%	1%	0.02
21	0%	0%	0.00
I(THD)	83%	64%	
I(RMS)	130%		
PF	0.77		
K Factor			9

Total Harmonic Distortion

$$I(THD) = \frac{\sqrt{I_2^2 + I_3^2 + \ldots + I_h^2}}{I_1} \times 100\%$$

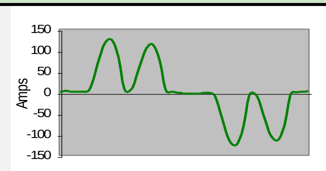
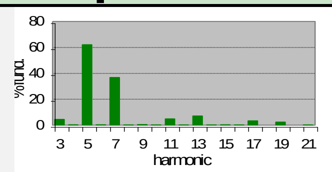
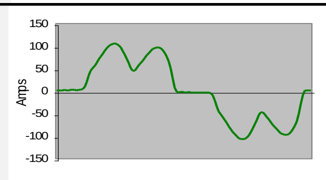
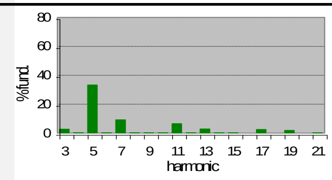
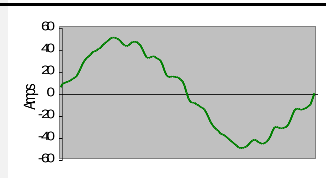
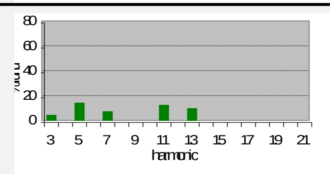
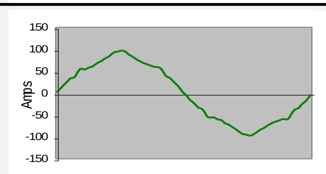
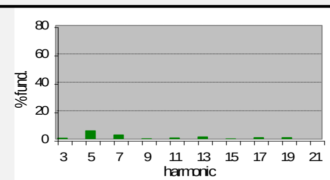
K Factor

$$K\text{-rating} = \sum_{h=1}^{h_{max}} I_h^2 h^2$$

Distortion Power Factor

$$hPF = \frac{1}{\sqrt{1 + (I(THD))^2}}$$

THID & PF Measurements on 60 HP AC VSD

	Input Current			Power
	Waveform	Spectrum	THID	Factor
6-Pulse Rectifier, PWM VSD			72.9%	.79 lag
With 3% AC line reactor			35.6%	.90 lag
12-Pulse VSD			9.3%	.98 lag
With MIRUS LINEATOR™			5.8%	.99 lag

Misconception #1

Low power factor is normally caused by electric motors and other inductive loads.

Reality

Low power factor is most often caused by distortion reactive power introduced by harmonic generating, power electronic, non-linear loads.

Power Factor Penalties

- Most Utilities charge their customers for energy supplied in kilowatt-hours during the billing period plus a demand charge for that period
  - Demand equals peak kW load during a set period (often 15 min)
- If PF is lower than required by the Utility (often 0.9 or 0.95), Utility may also apply a PF penalty. For example,
  - Utility minimum PF = 0.9
  - Peak demand = 800 kW but 1000 kVA (a PF of 0.8)
  - Utility would charge the customer as if the demand were 0.9 x 1000 kVA = 900 kW, a penalty of 100 kW
  - If demand charge is $10/kW/mo, penalty is $1000/mo
- Improving PF to 0.85 at 800 kW demand would lower the penalty to just 47 kW or $470
- For PF's of 0.9 to 1.0, there would be no penalty
- It is important to note that if the low PF appears only under lightly loaded conditions, it will not affect the demand charge

Reference: T.M. Blooming, D.J. Carnovale, *Capacitor Application Issues,* IEEE Transactions on Industrial Applications, Vol 44, No. 4, July/August 2008

Misconception #2

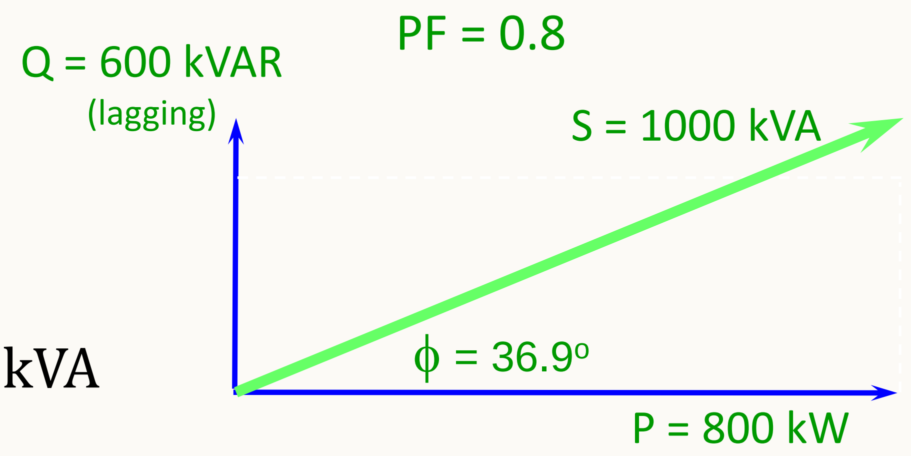
PF must always remain high to prevent power factor penalties.

Reality

PF penalties are only applied at times of peak demand. Therefore, low PF during light loading conditions has no consequence.

Power Factor Correction (PFC) Capacitors

- For a low displacement power factor, PFC capacitors are often used to improve PF



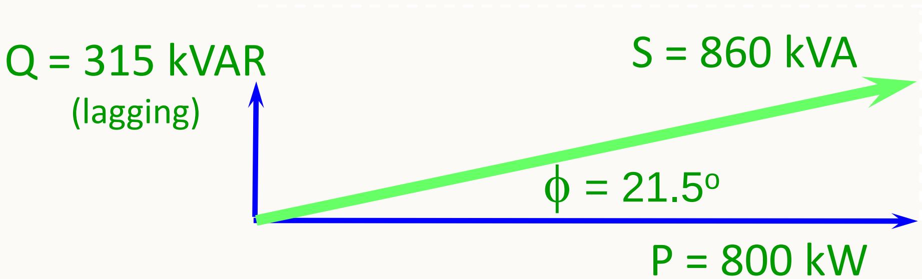
- kVAR of capacitance required to improve PF from 0.8 to 0.93,

$$\mathrm{S = P\ /\ PF = 800\ /\ .93 = 860\ kVA}$$

$$\text{Since, } \mathrm{Q} = \sqrt{S^2 - P^2}$$

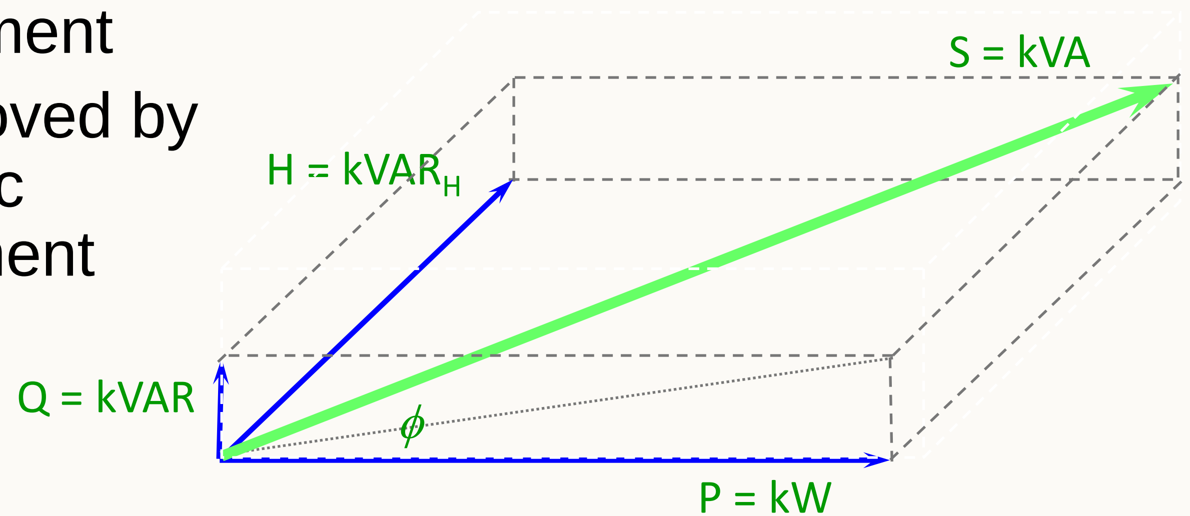
$$\mathrm{Q} = \sqrt{860^2 - 800^2} = 315\ \mathrm{kVAR}$$

$$\mathrm{Q_C = Q_L - Q = 600 - 315 = 285\ kVAR}$$



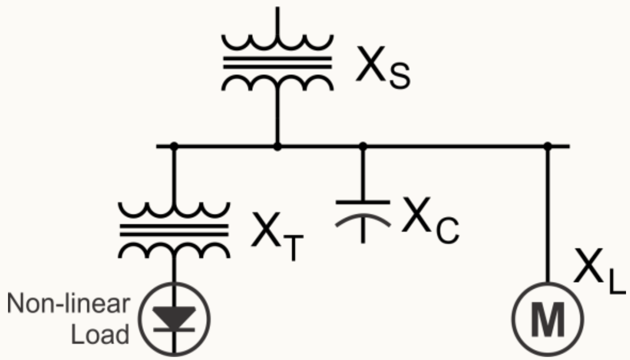
Misapplication of PFC Capacitors

- PFC capacitors can be beneficial when PF is low due to inductive loads, such as fixed speed motors
- But they can make matters worse when the low PF is due to distortion reactive power introduced by non-linear loads
- When Q is low but H is high, PFC capacitors will provide minimal improvement
- PF must be improved by applying harmonic mitigation equipment

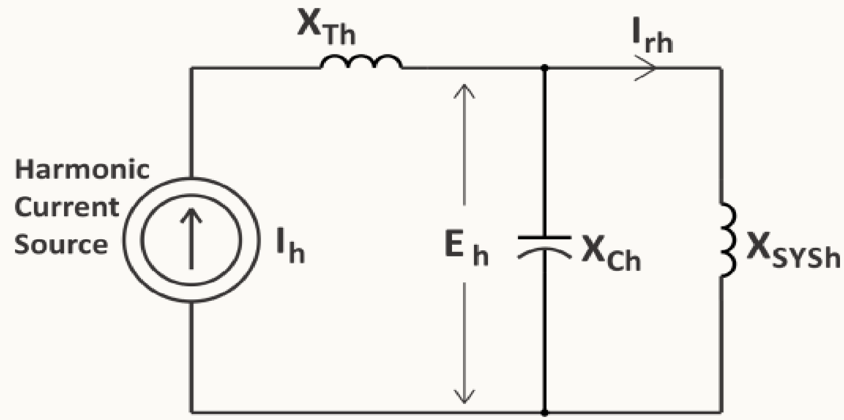


- Misapplication of PFC capacitors can lead to overcompensation and resonance with the power system

Power System Harmonic Resonance



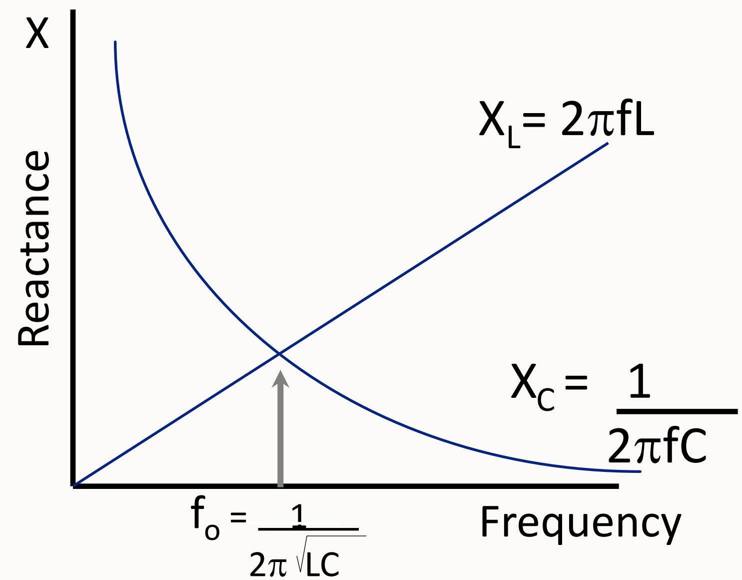
Single Line Diagram



Equivalent Diagram

Resonance will occur when:

$$X_{Ch} = X_{SYSh} \qquad (X_{SYSh} = X_S \,||\, X_L)$$



At resonance, the circulating current is limited only by the resistance in the circuit.

Problems that can result include:

- High current and voltage distortion
- Destroyed capacitors and their fuses
- Damaged surge suppressors
- Failure of connected equipment
- System shutdowns

Power System Resonance

An Oil Field in Mid-West USA was equipped with many Electrical Submersible Pumps (ESP’s) creating high levels of ITHD & VTHD

Problem:

- PF correction capacitors installed by Utility were failing frequently
- Oil company was forced to install harmonic mitigation

Solution:

- Resonance was eliminated by turning off PFC capacitors
- Passive harmonic filters were installed on all ESP’s to reduce VTHD to < 5%

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

Misconception #3

Low PF can always be corrected by adding capacitance.

Reality

If low PF is due to distortion reactive power, adding power factor correction capacitors will not only be of minimal benefit, they may very likely make the harmonic problem worse by resonating with the power system impedance.

Power Factor and Passive Harmonic Filters

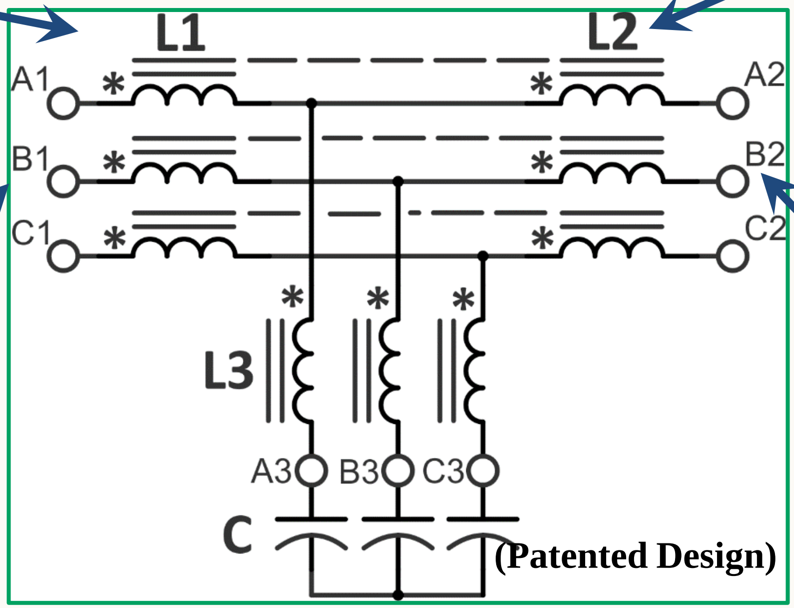
- A passive harmonic filter can be an excellent choice for improving power factor when the reactive power component is predominantly harmonics generated by non-linear loads
- Having a properly designed harmonic filter however, is critical to ensuring that harmonic mitigation meets the targeted levels without introducing excessive capacitive reactance 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

Wide Spectrum Harmonic Filter Connection Diagram

Multiple windings on a common core

High impedance L1 winding

Compensating winding L2 lowers through impedance reducing voltage drop



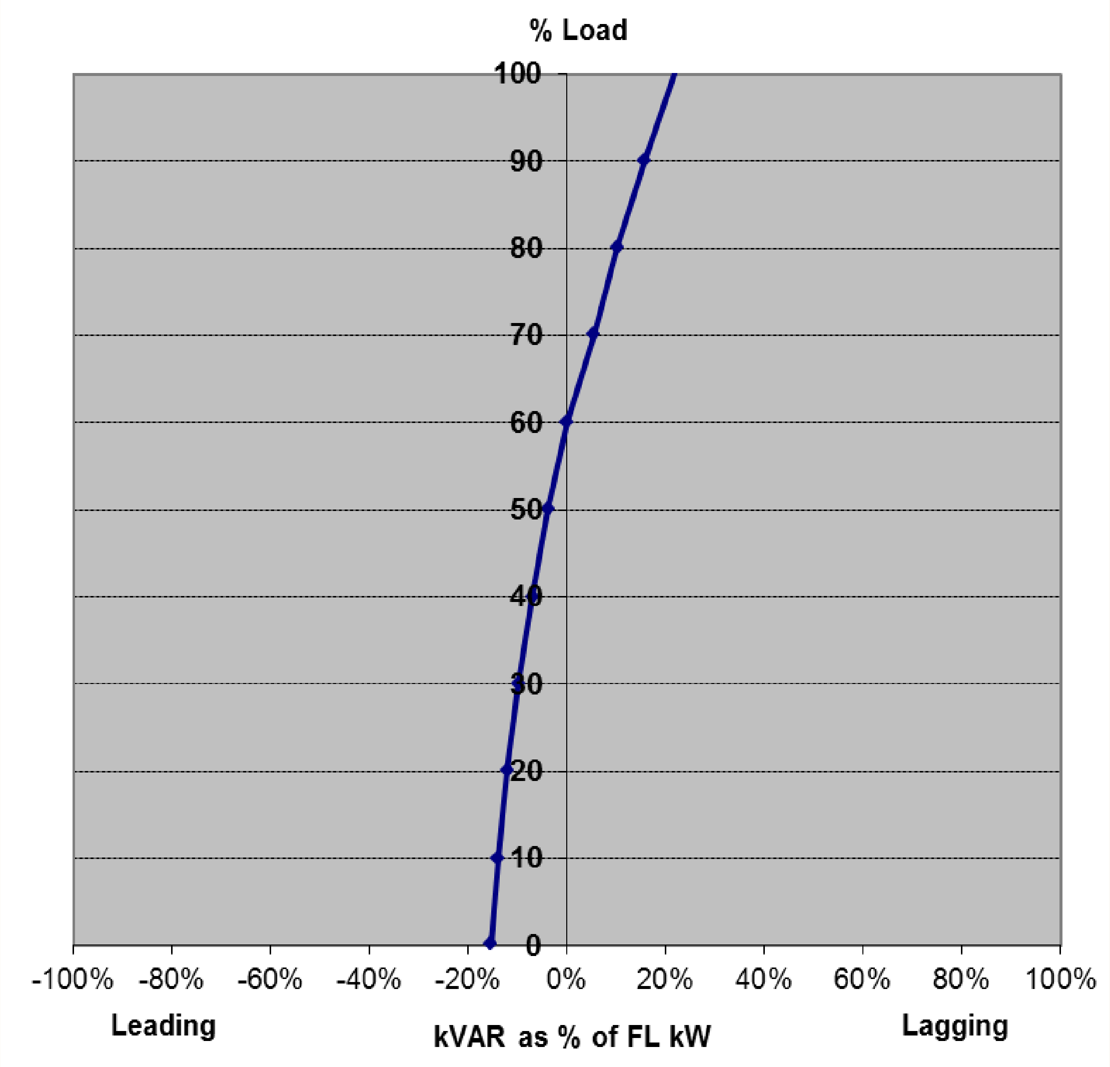
Input tuned below 5th to prevent importation of upstream harmonics

Output tuned near 7th to remove load side harmonics

Should be designed with smaller cap bank to reduce voltage boost and reactive power at no load

WSHF Reactive Power

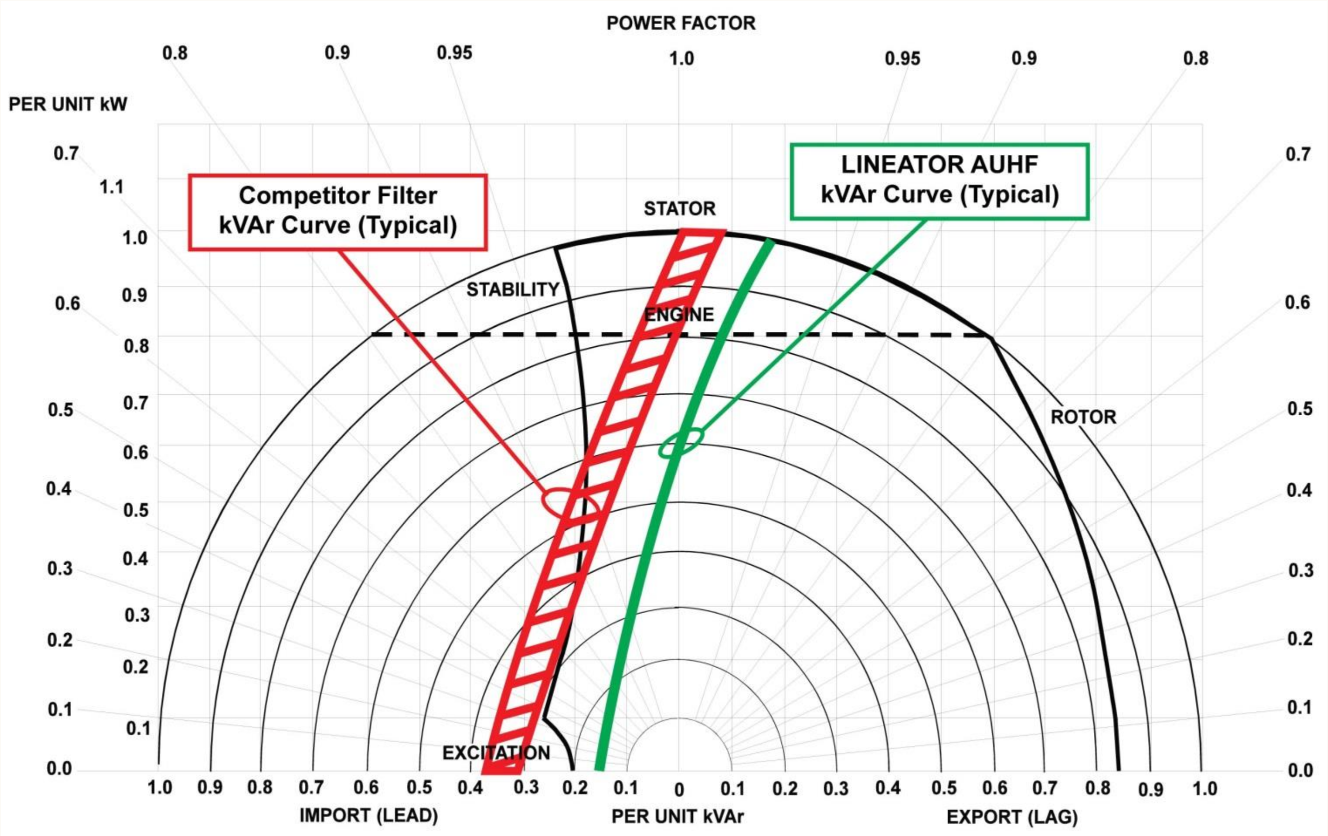
- Best when designed for <15% capacitive reactive power at no load
- Ensures compatibility with generators
- Many passive filters are designed with kVAR/kVA ratios in the 35% - 40% range



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

Generator Reactive Capability Curve

Maximum capacitive reactance <15% falls comfortably within the Generators acceptable limits



Maximum Capacitive Reactance introduced by Filter

Maximum Capacitive Reactance typical of other filters

Misconception #4

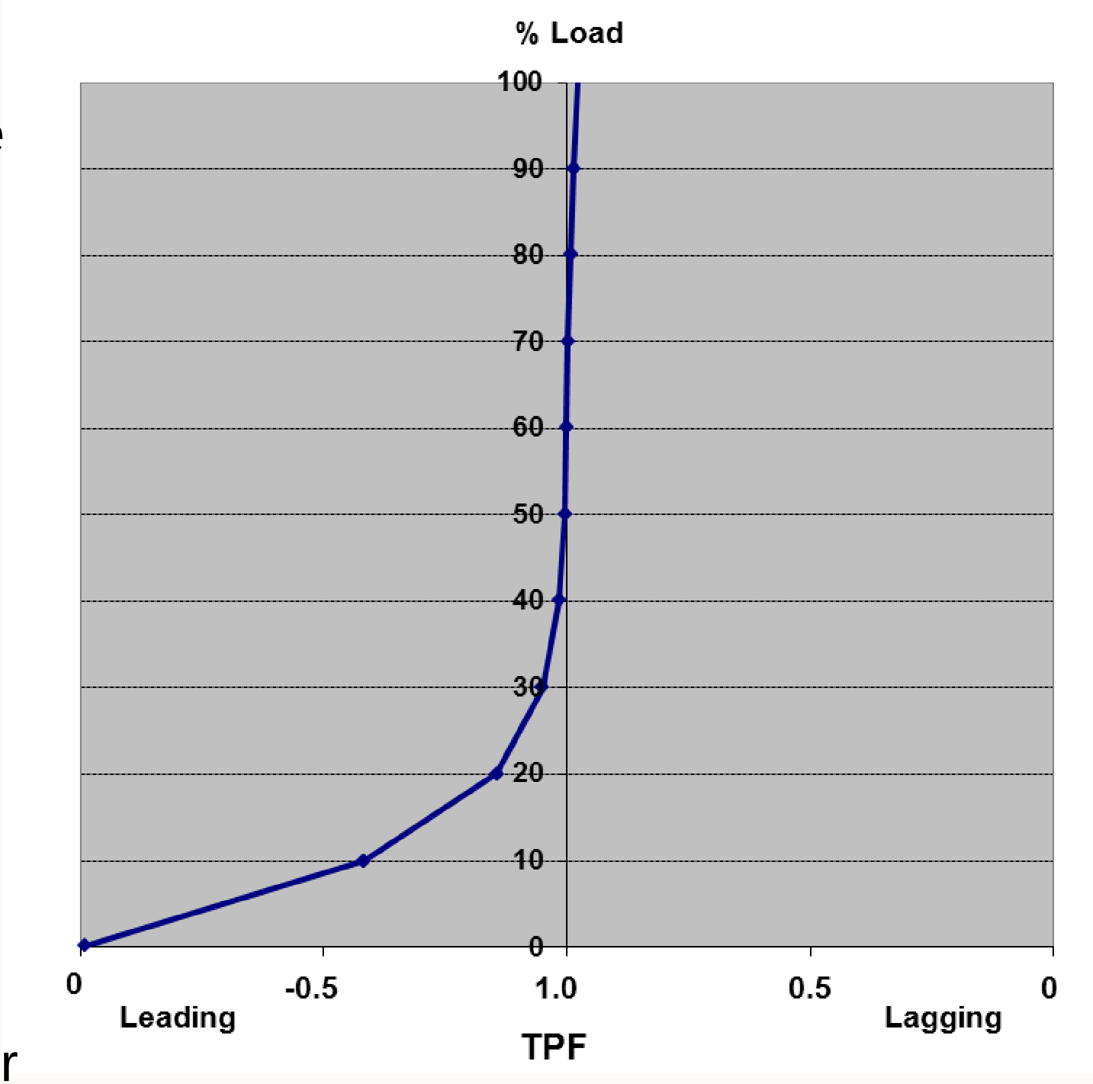
Leading PF is a problem for generators under any condition.

Reality

Although it is true that generators typically handle inductive loads better than capacitive loads, they are capable of handling a leading PF load provided the capacitive reactance remains within the generator's reactive power capability curve. A harmonic filter with < 15% maximum capacitive reactance will meet this requirement.

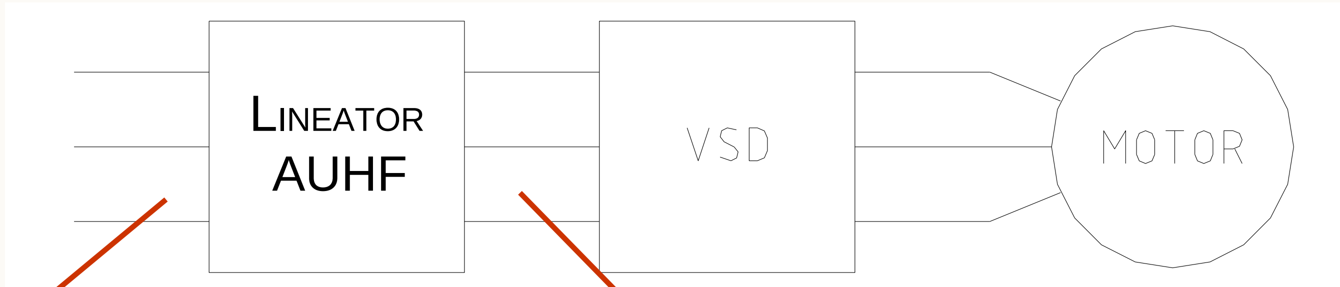
WSHF Power Factor

- TPF remains high in normal operating range
  - >.95 from 30% to FL
- Leading PF at light loads is of little consequence since capacitive kVAR's are kept low:
  - Little voltage boost
  - Compatible with Generators
  - No PF Penalties
  - No contactor needed to switch out caps
- Other filters will remain leading until much heavier loads are reached



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

WSHF Can Protect Against Line Side Transients



INPUT

OUTPUT

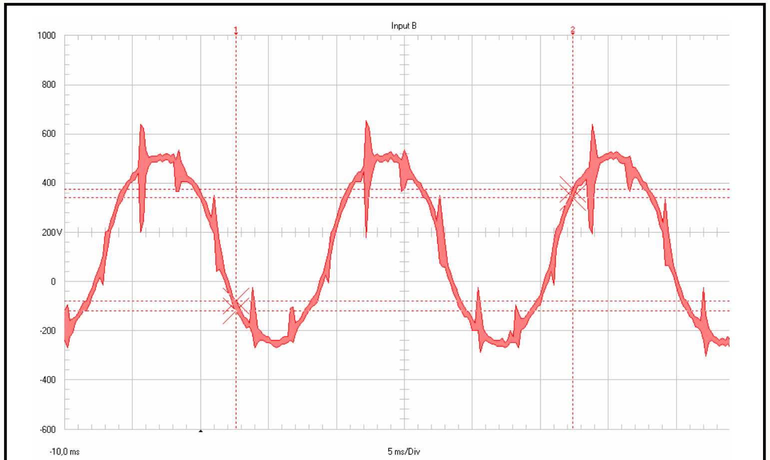


Figure 2: Voltage waveform at input to harmonic filter

Voltage Notching Caused by DC Drives on Off-shore Oil Platform

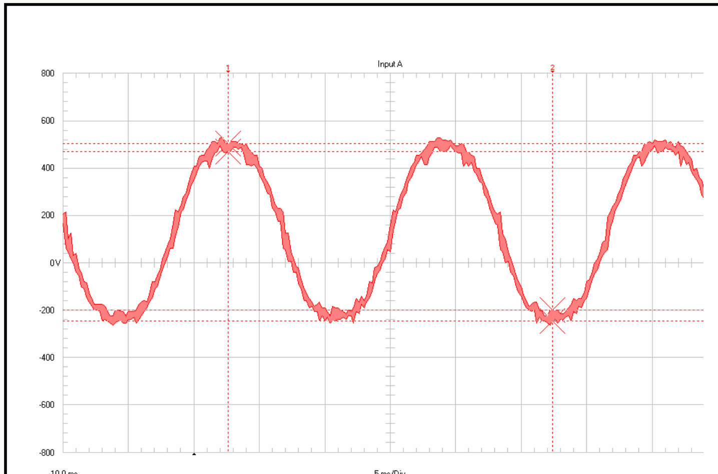


Figure 3: Voltage waveform at output of harmonic filter supplying AC Drive

Notches Dramatically reduced on Output of Lineator AUHF

- With capacitors left in, WSHF protects VSD from overvoltage transients caused by SCR's or Utility PFC cap switching

Misconception #5

Harmonic filters must always be equipped with contactors to switch out capacitors under light loading conditions.

Reality

A properly designed passive harmonic filter with < 15% maximum capacitive reactance as a % of kVA rating does not require a contactor to switch out capacitors at light loads. In fact, keeping the capacitors in the circuit can help protect the VSD from overvoltage transients.

Misconception #6

Any leading PF is bad.

Reality

There are many conditions under which a leading PF will not cause problems. In fact, if the other loads on a power system are inductive, introduction of some capacitive reactive power can be a good thing as it could provide some compensation to improve overall PF.

Summary

- Harmonics generated by non-linear loads have led to many power factor misconceptions
- In reality:
  - Low PF is often caused by harmonic generating, non-linear loads rather than inductive loads
  - PFC capacitors are not always the right solution for low PF and they can introduce system resonance issues
  - PF must be high during peak demand loading to prevent PF penalties but can be low at light loading conditions
  - Properly designed harmonic filters do not need capacitor switching contactors
  - Providing that reactive power remains within a generator's reactive power capability curve, it can handle a leading PF load
  - Low leading PF is not necessarily a bad thing as long as the capacitive reactive power is low

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