

Technical News

Specialists in electrical and automation products, systems and solutions



Power Factor Correction What technology is best for you?

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NHP

INTRODUCTION

Power quality has been a central issue in many installations and systems for years. Poor power quality has many effects on electrical installations, and can drive up energy costs, lower overall energy efficiency, cause nuisance tripping of circuit breakers, and damage and destroy sensitive electrical and electronic equipment. Therefore, it is very important for users to have a good power quality in order to ensure their systems function as required with a good efficiency.

Power quality is often defined in terms of the voltage, frequency and waveform of the electrical supply. Good power quality centres around ensuring the supply is within tolerable limits of the required voltage and frequency limits, with a smooth delivery in the form of a sinewave (in Australia, this is generally focused around 230V at 50Hz). Whilst there are many other definitions which exist for power quality across the electrical and electronic industry, in the context of this Technical News, power quality will be referenced with respect to the power factor.

Power Factor

Power factor is defined as the ratio of real power to apparent power. In AC systems, there are three components which make up AC power:

- Active (or real) power P, measured in Watts (W). This is understood as the useful energy transferred to loads in order for them to operate as required.
- Reactive (or imaginary) power Q, measured in volt-amperes reactive (VAR). This component of AC power is energy which is transferred back and forth between a load and the source, with no net energy transfer to the load and does no 'work'. However, reactive power is still required in electrical systems, as it is the component used in inductive loads to set up the magnetic fields in equipment such as induction motors and transformers.

- Apparent (or complex) power S, measured in volt amperes (VA). This component of AC power is composed of both the active and reactive power, and is the 'true' power of a load. This is the component of power used in electrical design, as a system must be sized to carry the current to transmit the total power of both the active and reactive power.

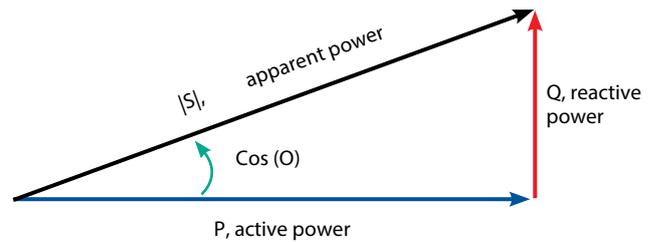


Figure 1- Power Factor Triangle

These three components can be related together by the following mathematical relationships, and represented as components of the power triangle as shown above.

$S = P + jQ$ - this equation defines the apparent power as the sum of vectors of the active and reactive power.

$$|S|^2 = P^2 + Q^2$$

$|S| = \sqrt{P^2 + Q^2}$ - the magnitude of the apparent power is defined here, and this value defines the apparent power in 'real' terms.

For more information around power factor, please refer to Technical News #64 and #65.

WHY CORRECT POWER FACTOR?

There are several reasons why it is important to correct the power factor:

- A lower power factor results in a higher apparent power, which leads to a higher current draw. These higher values place greater stress on transformers and cables, requiring larger cables and transformers to be installed to handle the higher stresses. Improving the power factor allows for smaller cables and transformers to be used, as well as freeing up power on existing transformers.
- Power suppliers commonly charge now on kVA demand tariffs, rather than on kW tariffs. Therefore, the end user is now

paying for all power consumed – both active and reactive power. Improving the power factor will result in a lower reactive power, decreasing energy bills through the lower power draw.

- A higher power factor results in a higher energy efficiency through less 'wasted' power from the reactive power. This leads to, again, lower power bills, greater energy utilisation, and less impact on the environment through lower carbon emissions.

POWER FACTOR CORRECTION

Fixed Capacitors

The simplest method of correcting a lagging displacement power factor is to use a capacitor. This involves connecting a capacitor (or bank of capacitors, generally wired in delta configuration) in parallel with the load which requires the reactive power compensation.

The capacitor solution is designed to supply a fixed amount of VAR compensation to the load as required. This fixed amount which is delivered is ideal to correct the power factor of induction motors, transformers, heaters, and any other loads which have a high time of operation.

Single capacitors which are used to correct the power factor of individual loads are connected in parallel with the load itself. This form of compensation is called individual compensation, and is shown in Figure 3. It is also common practice to group several inductive loads together, and provide compensation for these grouped loads with a bank of capacitors (generally connected in delta configuration) as shown in Figure 4.

This solution is ideal for correcting the power factor of individual and grouped inductive loads with a known and continuous draw of reactive power.

However, this solution is not often ideal in today's environment as load requirements are continuously changing. As many inductive loads, such as motors, fans, washing machines etc. change their power requirements as the load on the motor changes, this can result in a greater reactive power supply than is necessary.

There are also several issues which are prevalent when capacitors are used. Capacitors are highly sensitive to heat variations, with their average life span heavily dependent on the temperature. For example, Electronic capacitors are rated to operate in Temperature Class D, with the ratings as shown here in Figure 2.

The reactive output of a capacitor is also dependant on the system voltage. The reactive power produced is in proportion directly with the square of its voltage, so as the voltage of the system drops the reactive output of the capacitor drops, and vice versa for a rise in system voltage.

Temperature Class	AMBIENT TEMPERATURE LIMIT		
	Maximum	Max. average over 24 hours	Max. average over 365 days
B	45° C	35° C	25° C
C	50° C	40° C	30° C
D	55° C	45° C	35° C

Figure 2

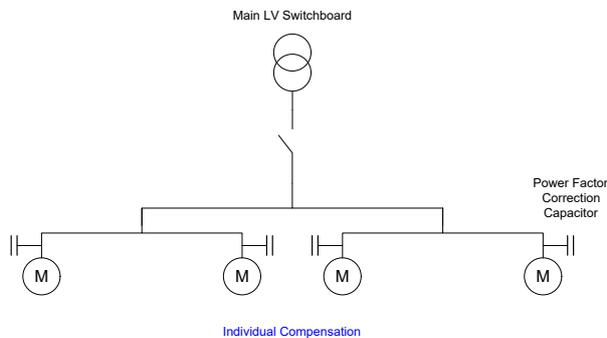


Figure 3

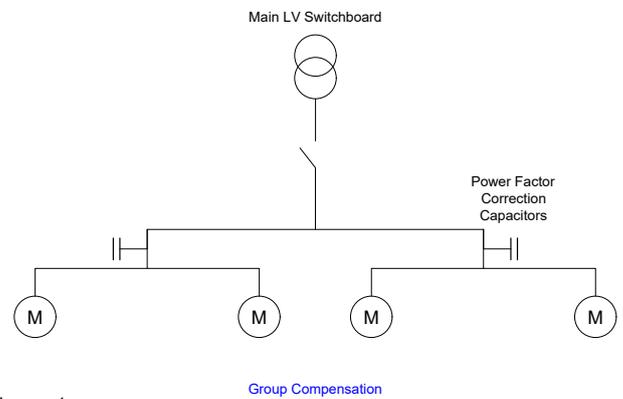


Figure 4

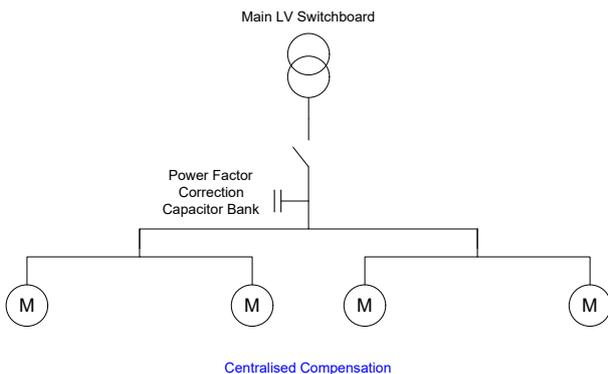


Figure 5

Power Factor Correction capacitors are used across all the different voltage ranges for correction of power factor. Power Factor Correction capacitors can be used in low, medium, and high voltage applications and are very versatile in their use and applications.

Applications: Single motors which are continuously running and where there is a fixed requirement of kVAr, i.e. a conveyor or a fan. Capacitors are useful across most voltage requirements, such as LV, MV, and HV.

Pros	Cons
Fixed capacitors are easy to size for their applications	Highly sensitive to harmonics
Cost effective	Not flexible, cannot respond to Power Factor changes
	Capacitors require regular service and maintenance

Automatic Capacitor Banks

Whilst single capacitors or capacitor banks are useful for correcting the power factor of individual loads (or groups of loads) they are used less and less in practice today. Rather than fixed individual or group compensation, most correction using capacitors is achieved using an automatic capacitor bank. These systems are connected upstream of the inductive devices, and provide reactive compensation to the whole system. This is illustrated here in Figure 5, where the capacitor bank is connected just downstream of the main switch. Automatic capacitor banks have been the standard for Power Factor Correction for 20+ years, and are still active today.

An automatic capacitor bank consists of a number of ‘steps’ of reactive power installed into a single cabinet, as shown in Figure 6. An example of an automatic capacitor bank system is a 200kVAr unit, consisting of three 50kVAr steps, one 25kVAr step, and two 12.5kVAr steps. The unit uses an automatic power factor regulator which measures the system’s power factor, and switches in and out capacitive banks as required to correct the power factor to the setpoint.

For example, the 200kVAr unit may be currently supplying 112.5kVAr to the system, at a power factor setpoint of 0.96. A situation may develop in which a very large motor comes online, and draws excess VAr in order to operate. As a result, the power factor drops. The controller will recognise this, and switch in a 25kVAr step in order to bring more VAr into the system and restore the power factor to 0.96. The same is true for when systems are turned off – if a bank of lights is switched off, the controller will recognise this and switch out a bank of capacitors so as to not oversupply VAr to the system.

An automatic capacitor bank is a more cost-effective solution for bulk correction compared to fixed capacitors and capacitor banks. Automatic capacitor banks generally also have reactors installed so as to reduce the harmonic impact on the capacitors. The units provide flexibility to the system, as the automatic control switches banks in and out as the system requirements change.

However, automatic capacitor banks also have many issues as a system. As they are still using capacitors to provide the required reactive power, they are still vulnerable to the same problems as described earlier. The systems require regular maintenance in order to operate at an acceptable level, with the need for capacitors to be replaced as they deplete. Contactors also degrade quickly, especially if the load is changing continuously.

Capacitor banks face very slow switching times due to being contactor based, with recommended switching times from 30s to 1min. Most times, the target power factor for an automatic capacitor is set to 0.95. This is because it is difficult for automatic capacitor banks to achieve unity due to quickly changing and inconvenient loads. As well as this, trying to achieve unity power factor stresses the Power Factor Correction more by increasing capacitor uptime and contactor switching cycles, lowering the lifespan of the units.

Applications: Networks which require granular changes in correction, and where switching speed is not a requirement. Examples include commercial buildings such as offices and retail stores, and industrial sites with high uptime. Automatic capacitor banks are ideal across all voltage requirements, including LV, MV, and HV.



Figure 6

Pros	Cons
Lower upfront investment relative to other technologies	Capacitors require regular service and maintenance
Responsive to power factor changes	Not suitable for fast acting/dynamic loads, such as lifts or welding equipment
Easy to install	Slower response times when compared to other technologies available
Simple service and maintenance requirements	Only work with balanced three phase networks
Commonly available	Can only correct for displacement power factor – are unable to load balance or mitigate harmonics
	Highly sensitive to harmonics

THYRISTOR SWITCHED CAPACITOR BANK

A thyristor switched capacitor bank is functionally the same as an automatic capacitor bank. However, rather than contactor based switching, thyristors or solid-state relays are used to switch in the various capacitors and capacitor banks to provide the required kVAR to the system.

A thyristor switched capacitor provides better switching times than a contactor based system. Thyristors are able to provide switching times of around 20 – 40 ms, whilst for contactor based systems the switching times are around 1 minute. Thyristor switches also require less maintenance than contactors, and so provide a longer overall lifespan to the Power Factor Correction unit. Thyristor switching also has lower switching transients than contactors, which helps to again improve the overall lifecycle of

the Power Factor Correction system by placing less strain on the system.

However, whilst the thyristor switched capacitor bank is an improvement over an automatic capacitor bank which uses contactors, they still have many problems. Capacitors are still the main component of the system and bring the same issues which are prevalent in other capacitor based systems such as harmonics and constant maintenance.

Applications: Whenever a faster switching time is required over traditional contactor based systems, such as industrial applications with varying uptime of machinery and equipment. As with most capacitor related technologies, they are ideal for LV, MV, and HV.

Pros	Cons
More responsive to power factor changes	Capacitors require regular service and maintenance
Fast switching times	Only work with balanced three phase networks
Easy to install, service, and maintain	Can only correct for displacement power factor – are unable to load balance or mitigate harmonics
Lower switching transients than contactor based systems	Costlier than contactor based systems
Commonly available	Capacitors are highly sensitive to harmonics

STATIC SYNCHRONOUS CONDENSER

A static synchronous condenser is a DC excited synchronous motor used to correct the power factor of very large industrial sites and systems. Over excited synchronous machines produce a leading power factor, in contrast to induction machines which produce a lagging power factor, especially when they are operating at below their full load.

Synchronous condensers provide step-less reactive compensation to the network, with dynamic Power Factor Correction capabilities. These systems are however used almost exclusively for correction of high voltage systems, providing reactive power compensation in the MVAR range.

Whilst synchronous condensers were previously a popular method in which to correct the power factor, these systems are not so popular in today's networks due to their high costs and maintenance requirements, as well as the noise and vibration they introduce into the system.



Figure 7

Applications: Larger, medium to high voltage networks which require step-less compensation are ideal for correction with a static synchronous condenser.

Pros	Cons
Dynamic, step-less reactive compensation	High amount of noise
Large amount of reactive power available	Large levels of vibrations introduced into the network
High power factor available – up to 0.99	Very high initial investment
	Large maintenance requirements

STATIC VAR COMPENSATOR

Static synchronous condensers have been one of the mainstays in correcting the power factor in medium and high voltage applications for nearly 70 years. However, their high costs, vibration issues, and maintenance make them unpopular today. Static Var Compensators (SVC) are another form of dynamic Power Factor Correction systems available for medium and high voltage applications.

A SVC consists of a mix of the elements shown in Figure 8. This mix consists of at least two of the following elements, of which at least one is thyristor switched:

- Mechanically switched reactor (MSR)
- Mechanically switched capacitor (MSC)
- Thyristor controlled reactor (TCR)
- Thyristor switched capacitor (TSC)
- Harmonic filter

Each SVC system is generally designed for an individual application to suit as required. Combinations of the above elements are used to provide Power Factor Correction as needed for the electrical system, with outputs rating in the MVAR ranges.

As with capacitor technology, the reactive power output of the SVC is dependent on the voltage magnitude. As the voltage drops, so does the reactive power output, and vice versa for a voltage rise.

Applications: SVCs are ideal for MV and HV networks. They are often custom designed and suit most power factor requirements.

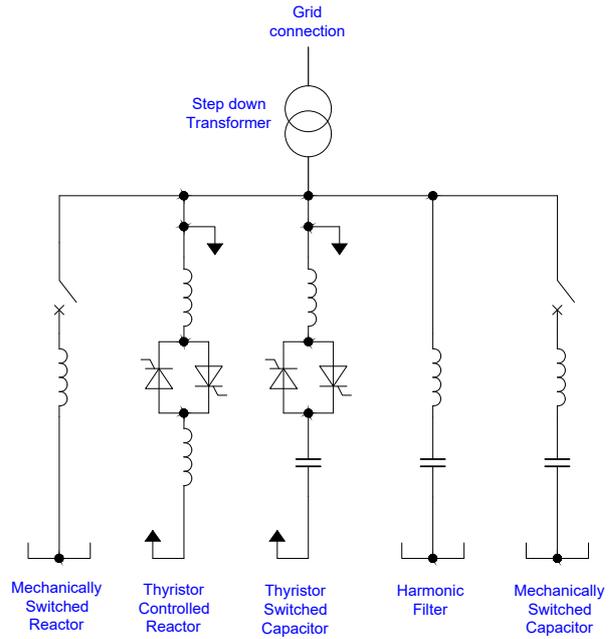


Figure 8

Pros	Cons
Customised solution to fit any requirement	Varying output dependent on voltage
Dynamic compensation	Customised solution is a disadvantage when new additions are included in the network
Highly available components	Continued problems present with capacitors

STATCOM

A static synchronous compensator, known as a STATCOM, is another device used to regulate the power factor in medium to high voltage applications. They operate on roughly the same principles as a synchronous compensator, however, use a voltage source converter as opposed to a rotating machine to provide dynamic Power Factor Correction. STATCOMs use IGBT switching technology to synthesise a sinusoidal waveform using Pulse Width Modulation (PWM) from a DC source, as shown in Figure 9. The output current waveform acts as either a source or a sink for reactive power, and can correct both the leading and lagging power factor.

STATCOMs have many advantages over SVC systems. STATCOMs are able to switch much faster than SVCs, and provide correction

of displacement power factor from -1 to +1. As well as this, the STATCOM is able to maintain constant current characteristics across different voltage ranges, whilst the SVC reactive power output is dependent on the voltage.

STATCOMs are generally used in high voltage and medium voltage networks for dynamic Power Factor Correction.

Applications: Networks which have a wide range of power factor requirements, from leading to lagging, which require fast switching and dynamic compensation, are well suited to correction via a STATCOM.

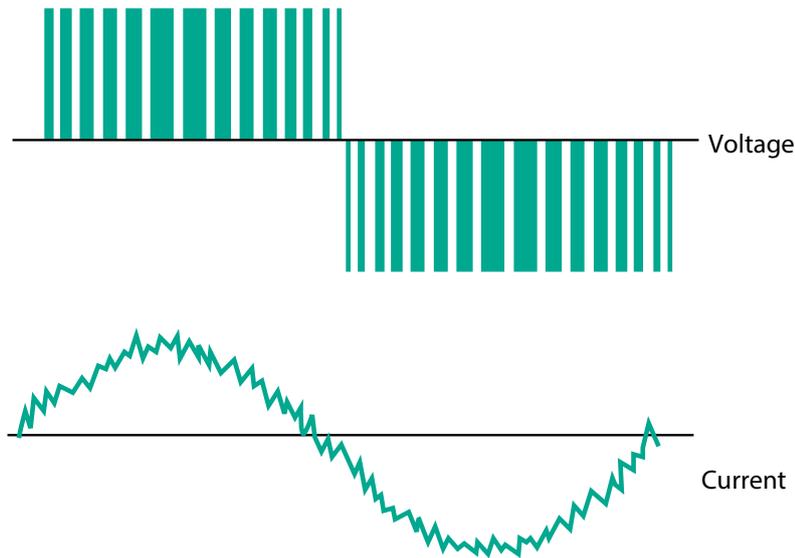


Figure 9

Pros	Cons
Dynamic, step-less compensation	High initial investment
Fast switching to react to changing loads	Large maintenance requirements
Provide correction over the entire power factor range, from -1 to +1 power factor	
Maintains constant correction capabilities no matter the grid voltage	

STATIC VAR GENERATOR

As discussed earlier, the Power Factor Correction environment today is requiring solutions which are more dynamic in nature, and can respond to quickly changing loads and requirements. One device which can respond to these requirements is a Static Var Generator (SVG).

A SVG is a piece of equipment designed to respond quickly and dynamically to changes in reactive power requirements. The SVG has a similar operating principle to an active harmonic filter. The SVG will detect a lagging current within the load by detecting the phase angle difference, and inject into the network a current of the same magnitude, but of opposite polarity (ie. 180° out of phase) to the current waveform in the network. This is shown below in Figure 10 – if the load current is lagging the load voltage, the SVG will inject a capacitive (ie. leading) current into the network to create system balance.

A SVG has many advantages over a capacitor based system. The SVG can respond to a wide range of power factor issues, from leading to lagging, and does so dynamically, mapping the kVAr requirements and providing power factor over 0.99. A capacitor based system can only correct for fixed amounts of power, and automatic bank systems only correct granular amounts resulting in constant over or under compensation. This is shown in Figure 11.

SVGs have a much faster response time than capacitor banks. As they often require pulling in capacitors via contactors, the response time is much slower – Traditional Power Factor Correction can and should be set in at least tens of seconds or minutes to avoid excess switching of capacitors. Capacitor banks are also unable to correct for reactive imbalance across each phase. This capability is inbuilt with the SVG, as it corrects each phase individually (when used in a 4-wire configuration).

The performance of the SVG is virtually unaffected by low voltage grid levels, unlike a capacitor, which as described earlier, varies its reactive power output depending on the voltage. As well as this, the SVG eliminates the possibility of introducing a resonant condition into the network, as opposed to capacitors.

SVG technology also has a greater service life than capacitor based systems. Capacitor banks require replacement of capacitors as they deplete over time. Alongside this, constant switching and high inrush currents expose the contactors of capacitor based systems to a high level of wear, and these must also be regularly replaced. The maintenance schedule for a capacitor based system is also recommended to be undertaken every 3 months. This leads to costly shutdown times and long-term maintenance issues and requirements, leading to higher overall costs. The SVG offers a system with minimal maintenance required, roughly once every 12 months.

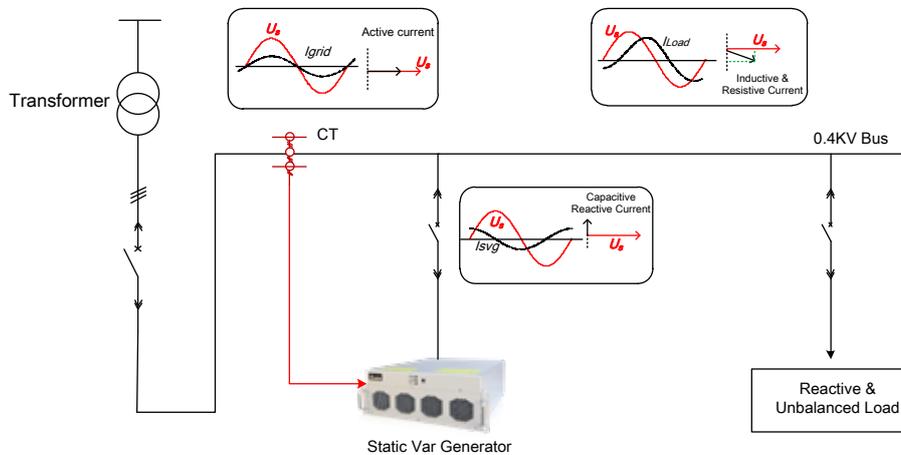


Figure 10

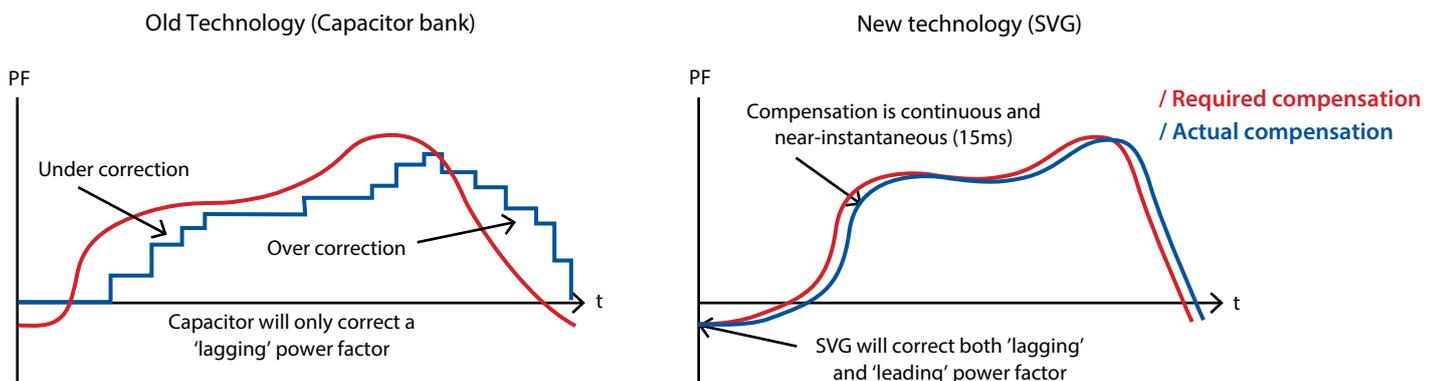


Figure 11: Old technology Vs. New technology

SVGs are often used in low voltage networks. They can be used in some medium voltage networks with the use of a transformer to provide excellent Power Factor Correction Capabilities.

Applications: Low voltage electrical networks with loads which change their power factor requirements very quickly are ideal for SVGs. This includes sawmills, welding equipment, and injection moulding machines.

Pros	Cons
Corrects power factor to >0.99	Higher initial investment relative to static technology
Dynamic, step-less compensation from -1 to +1 power factor	No harmonic mitigation
Fast response times (<20ms)	
Load balancing capabilities	
Power Factor Correction across multiple phases	
Low maintenance requirements	

ACTIVE HARMONIC FILTERS

Another method of correcting the power factor is to use an active harmonic filter. An active harmonic filter operates by constantly monitoring the load current, and generating and injecting adaptive currents which have the same magnitude but opposite phase angle as the harmonic currents which are detected, as illustrated in Figure 12. This adaptive current essentially removes the harmonic currents which are detected, restoring the waveform of the grid current to a smooth sinewave and correcting the power factor.

Active harmonic filters have the same capabilities as a SVG, and correct the power factor in much the same way. The SVG however will only inject current at the fundamental frequency (ie. 50Hz), whilst an active harmonic filter will correct at many different frequencies. Active harmonic filters correct for both the displacement and distortion power factor, and help to correct the total power factor.

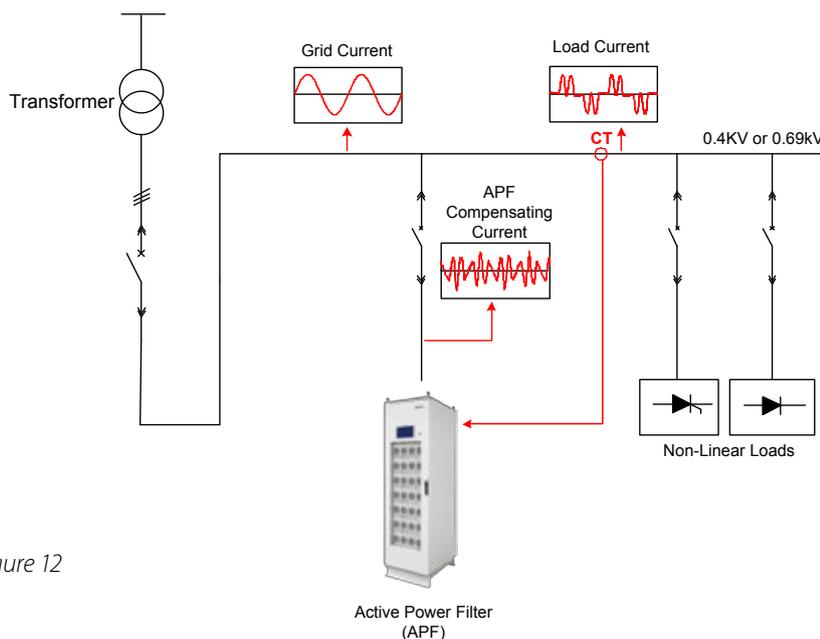


Figure 12

An active harmonic filter can operate under any load condition, up to their rated capacity. They are able to correct for a wide range of different harmonic currents – generally, most active harmonic filters are able to correct from the 2nd order up to the 49th, ensuring a mitigation of most harmonics within the network. The fast and dynamic operation of the active filter also means they are able to react to fast changing conditions in the network, guaranteeing a constant correction of the power factor. As well as this, active power filters are often installed at the point of common coupling in a plant, covering the whole installation. This ensures that the harmonics across an entire installation are corrected for, rather than a single load or machine.

Active harmonic filters are ideal for installation in retrofit environments, in situations where a wide range of different harmonics are present, or where there is a large number of non-linear devices continuously changing their load profiles.

When sizing an active harmonic filter, it is necessary to determine the compensation current which is required by the system and choose the right size of filter. As well as this, 3-wire and 4-wire options must be considered. 3-wire active harmonic filters are used in situations where the loads are 3-phase and balanced, whilst 4-wire filters are used where the loads are unbalanced, or single-phase.

Applications: Active harmonic filters are ideal in for use in networks where there is a high level of harmonic distortion, or where there are many non-linear loads connected. They provide fast reaction and high levels of compensation to ensure a high power factor.

Pros	Cons
Fast switching times (<20ms)	Higher cost due to increased capabilities
Harmonic mitigation, from 2nd to 49th	
Can balance loads	
Can correct for power factor across different phases (4-wire configuration)	
Can correct for both displacement and distortion power factor	

HYBRID CORRECTION

In today's environment, it is becoming common to provide a hybrid method of Power Factor Correction. This involves mixing the different methods of Power Factor Correction to provide a more cost effective or more efficient solution in the required environment.

Mixed Dynamic and Fixed Power Factor Correction

One method of correcting the displacement power factor involves using fixed Power Factor Correction alongside a dynamic method. In using this method, the bulk of the power factor is supplied via a fixed capacitor bank, whilst the final part of the reactive power requirement is supplied by the dynamic correction method, such as a SVG.

This is ideal where a large part of the reactive power requirement is unchanged, with the final part of the correction being supplied dynamically by a product such as a SVG. This helps to drive down product costs while still providing fast, profiled reactive compensation. This is shown in Figure 13.

As the profile changes quickly, the SVG reacts fast and provides the final part of the compensation. As can be seen in Figure 13, the SVG also absorbs leading power factor, and continues to correct the power factor to 0.99.

Mixed Displacement and Distortion Power Factor Correction

Along with mixing different methods to correct either the displacement or distortion power factor, it is also becoming commonplace to combine the correction of both displacement and distortion power factor. This is the ideal solution with which to correct the power factor, as both displacement and distortion have large effects on electrical networks. This correction may be as simple as combining capacitor bank correction with passive filters on drives and other devices, or more complex solutions combining rack based linear and non-linear load correction devices in a single cabinet to provide a complete correction solution.

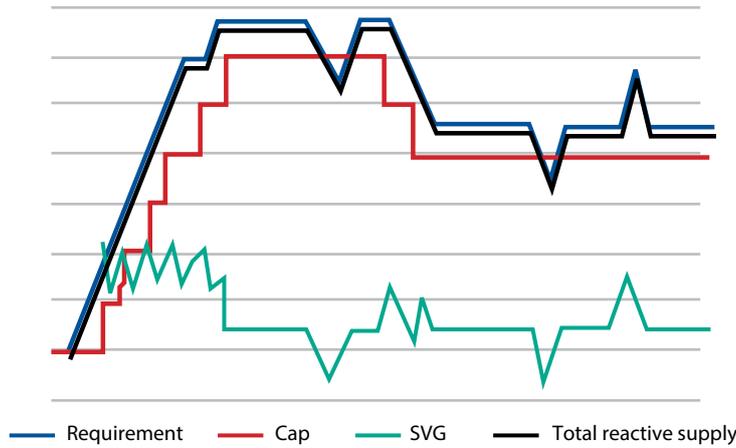


Figure 13

Correction Technology	Response Time	Correction Capability (cos ϕ)	Compensation Capability	Harmonics	Applications
Fixed Capacitors	N/A	Fixed kVAr compensation	Lagging power factor	Can lead to resonant issues	Small, single induction motors
Automatic Capacitor Banks	1s – 5s	Around 0.95 - .97	Lagging power factor	Can lead to resonant issues	Larger sites and buildings with slow changing demand in reactive power
Thyristor Switched Capacitor Bank	20ms – 40ms	Around 0.95 - .97	Lagging power factor	Can lead to resonant issues harmonic currents	Larger sites and buildings with slow changing demand in reactive power
Synchronous Condenser	Instantaneous. Around 10ms	Can correct to 0.99	Both lagging and leading power factor	Unaffected by network harmonics	Large, industrial MV sites requiring large levels of compensation and where there are also harmonic issues
Static Var Compensator (SVC)	20 – 30ms	If correctly built, can correct to > 0.99	Both lagging and leading power factor	If capacitors are used in the SVC circuit they can be vulnerable to network harmonics	Large, industrial MV sites requiring higher levels of reactive power
STATCOM (Static Synchronous Compensator)	<10ms	Corrects to > 0.99	Both lagging and leading power factor	Unaffected by network harmonics	Large, industrial MV sites where high levels of reactive power is required and response time and high power factor is essential
Static Var Generator (SVG)	Complete: 15ms – 20ms	Corrects to > 0.99	Both lagging and leading power factor	Unaffected by network harmonics	MV sites and installations requiring a continuously corrective reactive power, where a fast response speed and a unity power factor is critical
Active Harmonic filter (AHF)	Instant: ~300 μ s	Corrects to > 0.99	Both lagging and leading power factor	Can correct harmonics from 2nd to the 50th order	Sites where harmonics are causing significant issues



CONCLUSION

Power factor and the issues around power factor have been dominant parts of the discussion around power quality for many years, and will remain so within the foreseeable future. As has been shown, there are many different methods with which to correct the power factor within installations.

In deciding which method to use, a proper power quality audit is required in order to determine what are the main issues which affecting your installation, and from here, decide on which solution will be a best fit for your system. This can be decided by determining whether it is the displacement or distortion power factor which is affecting your system more; and then determining which solution provides a lower total cost of ownership.

It is important to correct the power factor within your installation as it can provide many benefits within your system, by freeing up space on your transformer, mitigating nuisance tripping, and lowering your energy bills. The first step is to conduct a power quality audit, determine your issues, and provide a method to correct this. After doing so, it is important to continue to monitor and maintain your power factor in order to continuously manage your power quality.

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