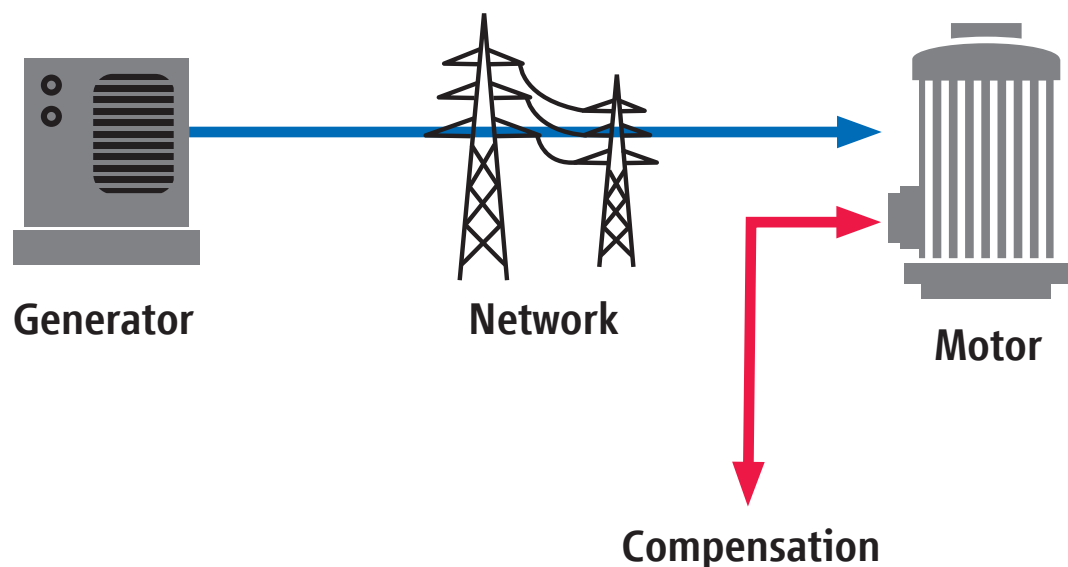


# New Technologies for Reactive Power Compensation in Electrical Networks



A changing Power Grid  
calls for new Reactive Power  
Compensation Solutions to  
improve Power Quality

**New Technologies for  
Reactive Power Compensation in Electrical Networks**

Published by:

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Electronic Manufacturers' Association)

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March 2013

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# Introduction

Germany has one of the world's most reliable networks when it comes to the supply of electrical power. But high supply reliability is not necessarily synonymous with high power quality, which takes into consideration deviations in network voltage from the perspective of the sine wave form or network voltage fluctuations and that of the network frequency. Operational disruptions, equipment failure and the resulting loss of production quality or high downtime costs are more often caused by reduced power quality than by power outages.

A variety of electronic power converters are increasingly being used in both industrial and public grids to ensure efficient utilization of electrical power – from switched mode power supplies and low watt energy saving bulbs to roller drives, multi megawatt electrolysis and even multi gigawatt high voltage direct current transmission (HVDC) systems. These systems' share of the total electrical energy drawn from our grids is growing steadily. The resulting network disturbances such as voltage changes, unbalances, harmonics, commutation notches or interharmonics can lead to a dramatic deterioration in power quality and ultimately to the above consequences if no effective measures are taken. At the same time, there is a reduction in the line short circuit power due to power fed in via electronic components (reduction in grid stability).

Manufacturers of reactive power compensation equipment and systems have been forced to deal with the steady deterioration of power quality. New concepts have focused particularly on how to compensate for increasing

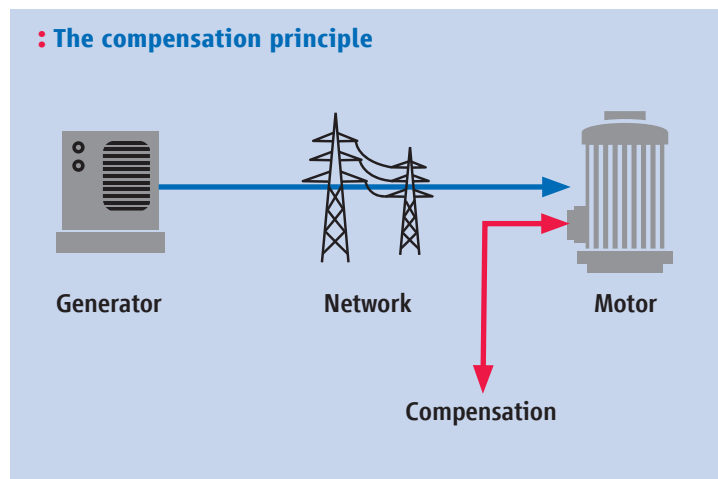
harmonic loads, which reactive power compensation systems with non detuned capacitors are very susceptible to. The most important technologies will be covered in the following:

- Detuned reactive power compensation (capacitive)
- Thyristor switched reactive power compensation (capacitive and inductive)
- Passive filter circuits (capacitive)
- Active electronic filters (capacitive and inductive as 4 or 3 conductor versions)

Some of these technologies only protect the reactive power compensation system against dangerous overcurrents through resonances; others also improve the power quality. Before choosing which system is best with regard to technology, location and costs, measurements of the power quality should be taken and estimates made for the resulting network disturbances on the planned system. Moreover, continuous monitoring of the power quality during the operation of the compensation system protects planners, system operators and network operators from unpleasant surprises.

## 2. Classification of Reactive Power

When we speak of reactive power, we usually think of the displacement power factor, which refers to the fundamental frequency 50/60 Hz and results from the phase shift of currents over the driving voltage. Motors and transformers are the primary causes, but drives in power converter technology that are controlled via phase angle control also play a role.



(Source: ZVEI)

60 per cent of the electrical energy consumed in Germany is implemented as mechanical energy through electric motors – with the corresponding negative impact on the reactive power in the grid. This percentage shows the dominance of the displacement power factor, which is a part of almost every technological process.

In addition to these dominant types of reactive power, other effects are also placing an increasing burden on the power grids:

- Distortion power factor due to harmonics,
- Unbalance power factor with single and two phase consumers,
- Modulation power factor with consumers with highly fluctuating load consumption

It is not uncommon to see all types of reactive power in use in real life applications such as electric arc furnaces and welding plants.

These different types of reactive power are based on the following phenomena, which always result in a reduction in power quality as well:

- Harmonics in the supply current and supply voltage (present view up to the 50th harmonic, expansion up to 9 kHz planned)
- Commutation notches in the voltage due to power electronics
- Flicker in the supply voltage due to periodic current fluctuations in the 9-10 Hz range
- Short term voltage drops due to switching operations of equipment such as transformers and cables and starting up motors
- Unbalance in the supply voltage through the operation of single or two phase consumers

The effects of all of these physical phenomena, which significantly interfere with the supply voltage and thus the secure supply of power, are limited by the relevant standards/directives. A distinction must be made between determining the compatibility levels for the supply voltage and determining the emissions caused by individual devices and systems, which may or may not consist of an array of different devices.

The standard EN 50160 [1] is important for this topic and describes the permissible compatibility levels in the supply voltage of public low, medium and high voltage grids. This standard contains limits for harmonic levels as well as statements regarding the permissible voltage range, flicker, and much more. No statements are made about the permissible commutation notches; in this case, other directives are to be consulted [2].

For industrial grids, the standard IEC 61000-2-4 specifies different compatibility levels, e.g. for the harmonics of corresponding supply classes. A distinction is made here between classes with very sensitive consumers and "clean" power and classes with dominant converter power such as compressor stations and rolling mills.

Principles for calculating the emissions from individual consumers or systems are stipulated in the D-A-CH-CZ Directive [2] for the assessment of network disturbances. Here, the share of the entire power consumption in the grid is proportionately attributed to a customer, e.g. the share of harmonic or flicker generation. If the corresponding emissions exceed the specifications that have been determined, then the customer must take measures to reduce, e.g. harmonics, commutation notches or flicker and coordinate these with the network operator with regard to network compatibility. It is also important to ensure that the influence of audio frequency ripple control systems conforms to applicable standards.

This Directive now applies for low, medium and high voltage and is an important documentation for standardized connection assessment.

In addition to considering individual customer connections in light of the above standards and/or assessment principles, it is very important to limit the emissions coming from devices with ratings  $< 16$  A. Such mass market devices include switched mode power supplies in television sets and computers as well as energy saving bulbs. The very high frequency of use of television sets in the evening hours creates extreme harmonic loads in our public grids every day at these times, the effect of which can be significantly increased through both the middle and high voltage cable networks in particular (resonance ability). This load is the so called preload of the supply voltage that must also be considered when planning customer connections.

# 3. Solutions

The solutions described below are modern technologies in the field of reactive power compensation and represent the best known applications. Over the years, the problems that need to be faced have changed. Devices and systems for reactive power compensation and to improve power quality have also continued to evolve. Whereas only a few years ago the focus was on reducing the costs of reactive power demand and cutting grid losses – today’s challenges are more complex and have to do with complete grid integration.

The following solutions are not exhaustive; numerous phenomena generally occur simultaneously, so it is highly recommended to consult with a specialist

Possible solutions	Non detuned compensation		Detuned compensation		Thyristor switched compensation		Passive filter		Active filter	
	LV	HV	LV	HV	LV	HV	LV	HS	LV	LV
<b>Phenomena and application fields</b>										
Voltage fluctuations					x	x				x
Commutation notches										x
Flicker										x
Unbalance										x
Transients										x
Harmonics			x	x	x	x	x	x	x	x
Power reduction of power lines	x <sup>1</sup>	x <sup>1</sup>	x	x	x	x	x	x	x	x
Reactive power cost reduction	x	x	x	x	x	x	x	x	x	x

(Source: ZVEI)

*Note:*

LV: Low voltage < 1000 V

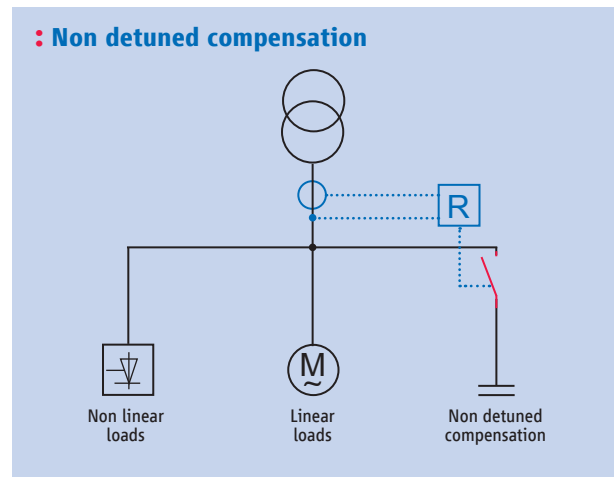
HV: High voltage > 1000 V

<sup>1</sup> Can lead to amplification of harmonic currents

### : Non detuned compensation

With non detuned compensation, capacitors are used as a purely capacitive branch. In the past, this was the standard solution used to save on reactive power costs calculated by the power supplier (utility company). This involves reducing the apparent power in the supply line and thus reducing the line and transformer losses.

With the changing network conditions and the rising burden of harmonics, the risk of power overload due to resonances increases. This leads to the advancement of compensation technologies.



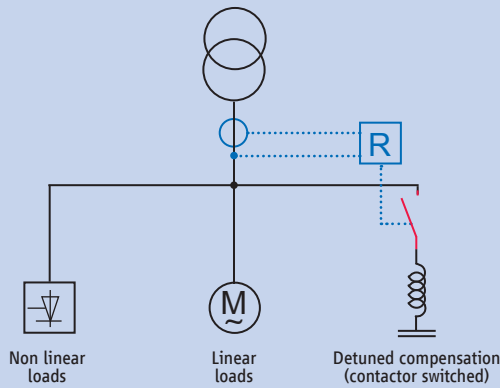
(Source: ZVEI)

### : Detuned compensation (detuned filter circuits)

Apart from the actual basic task of reactive power compensation, the risk of overcurrent due to resonance can largely be ruled out by properly selecting the type of detuning for the compensation system and the design of the capacitors and inductors used. Today, detuned compensation is state of the art technology.

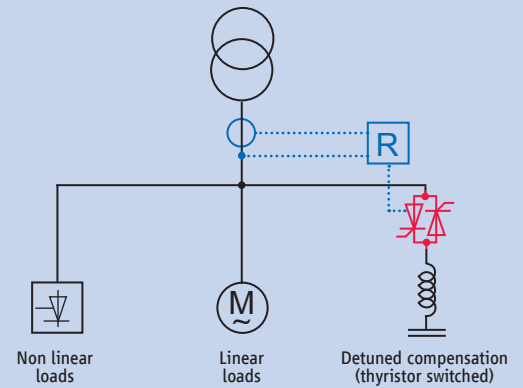
The degree of detuning can also be chosen so as to reduce specifically selected low frequency harmonics in the customer network or to keep the audio frequency ripple control undisturbed in the distribution network. Ageing components and increasing harmonic levels due to changing device technologies mean that equipment and systems must be monitored to detect the risk of overload in a timely fashion.

**: Detuned compensation**



(Source: ZVEI)

**: Thyristor switched compensation**



(Source: ZVEI)

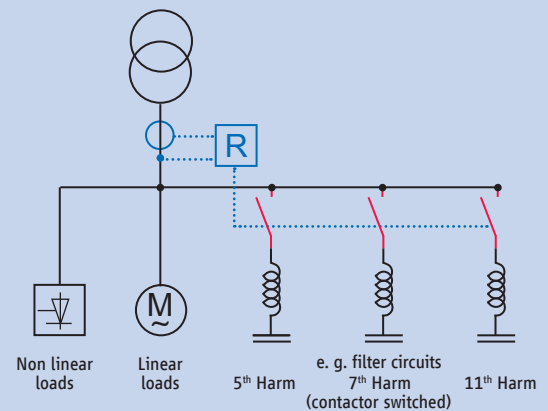
**: Thyristor switched compensation**

When the load dynamics do not permit staged compensation switched via a contactor, then this is replaced by a combination of thyristors and diodes. Together with fast data acquisition and control, real switching operations in the range of a few mains cycles are then possible without switching transients. This makes it possible to correct rapid reactive power changes nearly without delay and, in some cases, this eliminates the flicker effect from load surges. A major advantage of this type of solid state switching is that it prevents switch on current loads such as those that occur in conventional detuned compensation. This gentle switching has significant advantages, especially for sensitive consumers that are connected on the same power level (e.g. supply of bank buildings, etc.).

**: Passive filters (tuned filter circuits)**

Passive filters have the natural resonance frequency set very closely to that of the harmonic current to be filtered from a consumer or a group of consumers such as drive power converters. To prevent transients of the same filter circuits, the tuning frequency is inductively detuned by 5–10 Hz. This effectively filters the harmonic current coming from the source and prevents it from being transferred into the distribution network; this greatly reduces the load from harmonic current on the supply line/transformer.

**: Passive filters (tuned filter circuits)**



(Source: ZVEI)

### : Passive filters (tuned filter circuits)



(Source: ZVEI)

This method works in the 3<sup>rd</sup> to 5<sup>th</sup> harmonic range and requires at least one filter stage per network harmonic to be filtered. The risk of overload is particularly high, especially with passive filters. Constant monitoring and regular maintenance is absolutely essential. Furthermore, passive filters can only partially adapt to load changes. By combining resistors in parallel to filter circuit reactors, high pass filters can be established for harmonics.

Passive filter circuits are only capable of reducing commutation notches in the supply voltage if, e.g. filter circuits are simultaneously switched on for the 5<sup>th</sup>, 7<sup>th</sup> and 11<sup>th</sup> harmonic.

Precise calculations of the effect of passive filter circuits generally require trained specialists and the use of powerful simulation software.

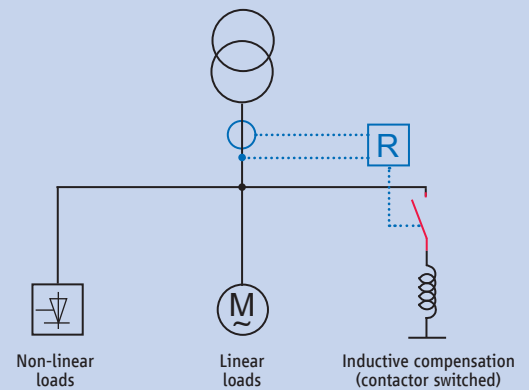
### : Inductive compensation

The sharp increase in the amount of cabling in our grids and especially the increasing number of photovoltaic and wind farms being connected makes it necessary to compensate for the capacitive loading capacity at certain times of the day using inductors. Similar to controlled compensation systems, these can be contactor or thyristor switched on the low voltage level or switched on and off on the medium voltage level using circuit breakers with RC circuits.

The capacitive reactive power removed from the network is also charged when a specific target power factor is exceeded, so these systems pay for themselves in a short period of time.

This only marginally affects the impedance of the network.

### : Inductive compensation



(Source: ZVEI)

### : Active filters

An active filter is an electronic system that uses active power to actively improve the power quality. Active filtering is a modern technology that is very versatile. It can cancel out harmonics of different orders, perform dynamic reactive power compensation both capacitively and inductively, or compensate for voltage unbalances.

For harmonic compensation, a specific degree of compensation can be set for each individual harmonic. Thus, only the set limit values agreed with the network operator are filtered.



Thanks to the high dynamics, some active filters are even able to effectively correct changes in the current waveform, which are represented by commutation notches. In addition to compensating the three conductors, active filters also offer the possibility of reducing harmonics on the neutral conductor. The 3<sup>rd</sup> harmonic adds up arithmetically in the neutral conductor, which can lead to heavy loads or to capacity overload of the neutral conductor. An active filter reacts immediately with its degree of compensation set to a specific measuring point for each harmonic. In principle, this means it is not affected by other effects in the network and thus does not change the network structure in terms of the resonance points. It continues to deliver its rated performance when it is "overloaded", and evenly limits the compensation level. This has the advantage that the maximum filter compensation performance is available even with excessive harmonic loads.

The compensation of the reactive power is so highly dynamic that it even enables flicker compensation. It is also possible to compensate the capacitive operation that frequently occurs in computer centres or to implement an operating point, e.g. for UPS systems.

An active power filter performs several functions at the same time. Through targeted use it is possible to resolve special power quality problems virtually independently of an existing reactive power compensation system. System overload does not result in device disconnection and failure of the entire filter effect. Harmonics can be compensated across the entire spectrum up to the 50<sup>th</sup> harmonic.

## **: Conclusion**

To be able to also use reactive power and harmonic compensation in cases where simple standard solutions have little or no effect, it is important to put more energy into thinking about new solutions. The technologies presented above are not always just individual solutions, but can also be combined as hybrid solutions. A user with a mixture of loads with different characteristics is a good example: Conventional inductive consumers installed along with many drives controlled by frequency converters. Thus, there are two problems to solve: Reducing harmonics to limit values that can be produced by the converters with a simultaneously high power factor, and compensating the inductive reactive power of the other consumers. Modern active power filters are able to solve both problems at the same time. To keep investment costs low, a hybrid solution is often employed in which the classic passive filter circuits for the 5<sup>th</sup> and 7<sup>th</sup> harmonic simultaneously compensate the fundamental frequency reactive power of the remaining consumers. Only the higher frequency harmonics, which are much smaller with regard to the size of the currents, are dampened to a compatible level with an active filter. However, such solutions require a detailed analysis of the planned use, measurements at the connection point and technical network calculations.

Advice and analysis by experts is essential and helps to find a solution that quickly pays for itself.

## **: General safety instructions for high voltage capacitors**

ZVEI has put together safety instructions for the use of high voltage capacitors [3]. Among other topics, the instructions cover risk factors for the capacitors, risks in the event of an error and how to minimize risk through proper maintenance. It is also necessary to carry out capacity measurements and thermal validation of cabinets and terminal connections.

## 4. Outlook

In view of the current discussion on increasing energy efficiency and reducing CO<sub>2</sub> emissions, it can be expected that reactive power and harmonics will come into greater focus also with regard to politics. Reactive power drawn from the grid and network disturbances in the form of harmonics cause additional losses in the transmission and distribution network, which must be covered through the use of primary energy in power plants. Fair, source related distribution of the costs will certainly be more of a topic in the future.

This makes capacitive and inductive compensation in a specified coverage area – possibly with infeed from local power stations – an important factor. Transport of reactive power over long distances is not possible without significantly influencing the voltage range.

Thus, one of the future challenges will be to exploit the unused savings potential through the increased use of reactive power compensation systems and systems to improve power quality.

Comprehensive grid monitoring can be a tool for this purpose, with permanent recording of the power flow, the total harmonic distortion of currents and voltages, and other parameters related to power quality. This type of monitoring effectively supports a load management system that intelligently coordinates the startup times of major consumers in times of peak demand. Furthermore, approaches are becoming evident in which, with relatively little effort, a large effect (prevention of reactive power, reduction of harmonics) can be achieved in the network. This may also help to identify and fix problematic trends early on, e.g. loads on lines and transformers.

Another task for the future is in the area of standardization and implementation in the form of directives for all participants in network operation. The existing gaps in the standards must be closed, for example by defining limit values for conducted disturbances up to 9 kHz. Moreover, the discussion on the distribution of costs for power quality will need to consider whether costs should be increasingly allocated to the respective network participants and thus to the potential sources causing the reduced power quality.

Optimally designed compensation systems that take into account the requirements of the equipment and systems to be compensated:

- Reduce energy costs by complying with the contractually agreed power factor,
- Enable the planned connection of consumers with a high level of load fluctuation,
- Reduce losses in equipment in customer systems such as transformers and cables as well in the transmission and distribution network of the network operator,
- Stabilize public and industrial networks by reducing total harmonic distortion, and
- Sustainably reduce CO<sub>2</sub> emissions.

In-depth knowledge and modern, safe and sophisticated system configurations for reactive power compensation can be used to improve power quality even more and help meet all the challenges of comprehensive reactive power compensation for low to high voltage applications.

## 5. Sources

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[2] D-A-CH-CZ „Technical Rules for the Assessment of Network Disturbances basic guideline 2007 and supplement on high-voltage power 2012

[3] General Safety Recommendations for Power Capacitors

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