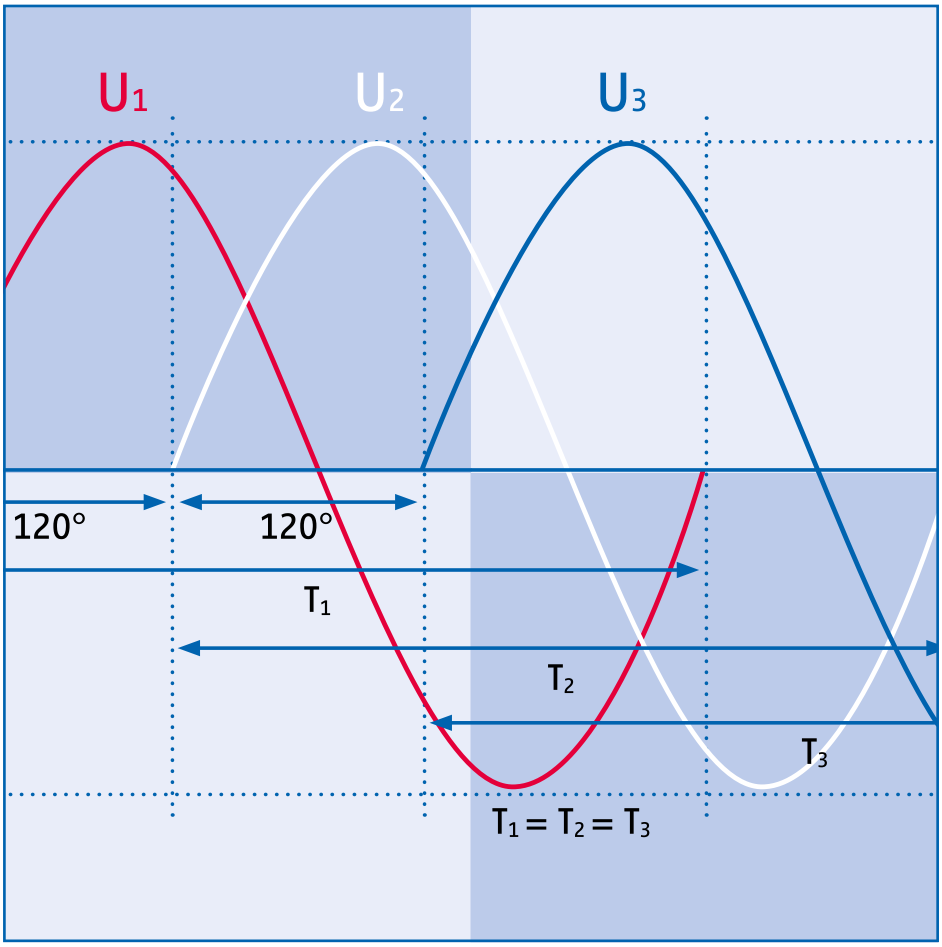
Guideline

Improving Power Quality in Electrical Networks



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Improving Power Quality in Electrical Networks

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Content

1 Introduction

The power supply sector has seen many changes over the past two decades, including a shift from energy production by large power stations with high-performance synchronous generators to a predominantly decentralised supply network. This has led to a significant increase in decentralised generation plants with lower output capacities and, for the most part, power electronics-controlled feeds. The result of this development on the generating side are changes to the „internal technical values" of transmission and distribution grids. Grid impedances are increasing, which means that loads are having a greater negative impact on grid voltages.

While this has been going on at the "generating end", the „load end" has also been – and still is – undergoing a dynamic transformation.

In both industrial and public grids, a variety of power electronic energy converters are increasingly being employed to use electrical energy more efficiently. Apart from the very large number of switched-mode power supply units installed in electronic devices, this also includes LED lighting with a low connected load rated in watts. In this context, it is also worth mentioning the constantly rising proportion of electric motors in industrial applications and in infrastructures, whose speed is controlled via frequency converters with a high connected load rated in kilowatts.

The development of the charging infrastructure for electromobility is currently one of the main focal points of public debate. The accompanying sharp increase in demand for electrical energy is predominantly in the kilowatt range when rated per unit.

The sum of installed power components and the steady increase of these electronic loads – with highly non-linear current characteristics – will increasingly compromise power quality, especially in the low- and medium-voltage distribution grids.

In short sections, this guide explains how power quality is influenced and what the causes and effects are.
To reduce the respective causes of a negative influence on power quality, this brochure presents technical approaches which should be discussed in detail with the solution providers.

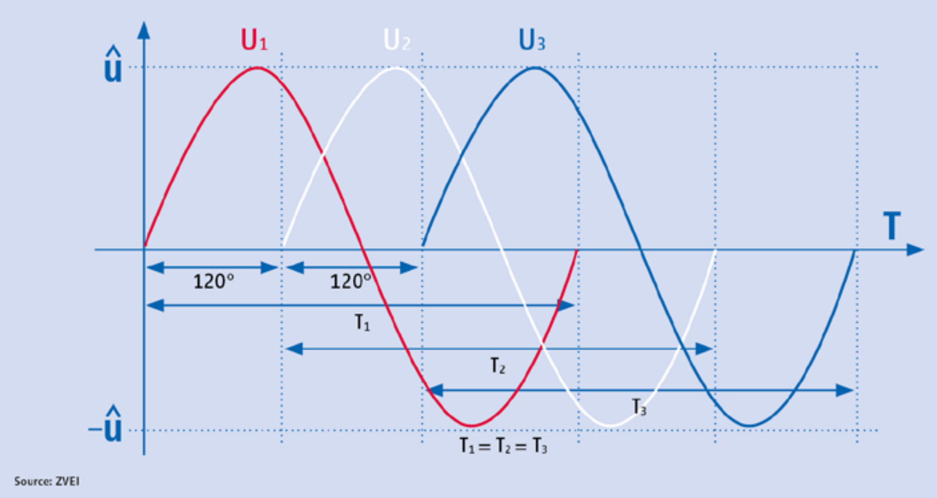
2 Power Quality

Ensuring high quality voltage is essential for the most efficient use of electrical energy.

In the three-phase AC networks that are predominantly used, the power quality at the respective load connection points is ideal if voltages

- maintain a symmetrically constant level of the nominal value at all times, without interruptions
- have a constant frequency at all times
- exhibit a sinusoidal waveform at all times.

Ideal voltage curves



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These ideal quality characteristics of electrical voltage are theoretical in nature and are not achieved in real-world networks.

2.1 Influences on Power Quality

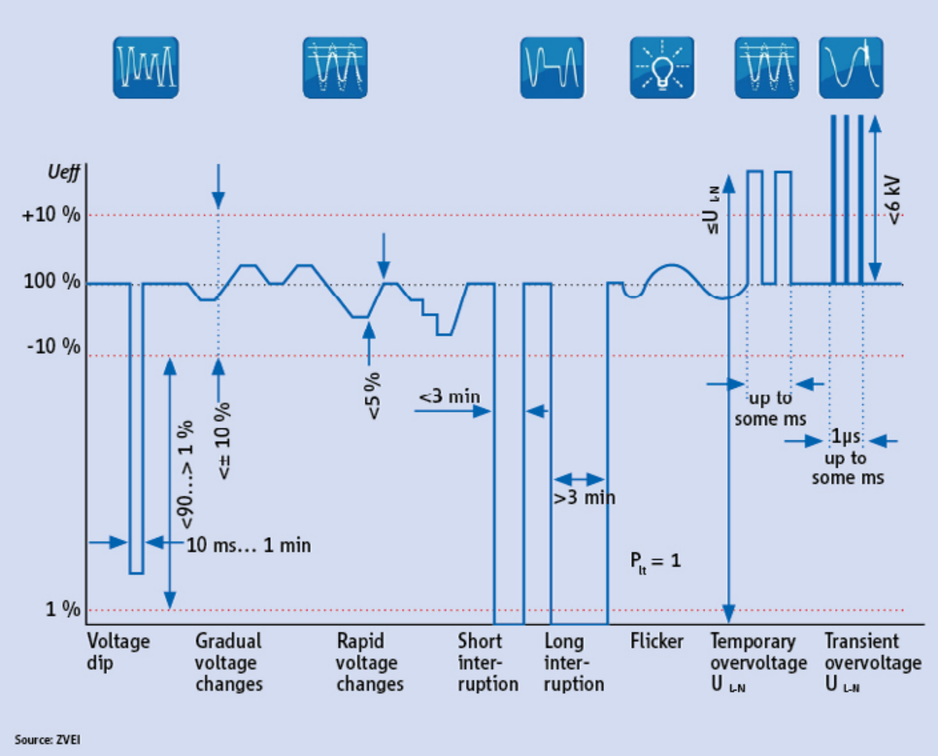
The voltage we usually receive from public low-, medium- and high-voltage power grids under normal operating conditions as grid users, is fundamentally subject to a variety of influences.

Both the public power grid and the internal building/company networks connected to it are subject to load fluctuations. In addition, electrical devices and systems can cause interference effects which disturb the grid and various external events, such as transmission line damage, earth faults caused by foreign bodies or lightning strikes can also disrupt the power supply.

2.2 Causes and Effects

Power quality is most often influenced by the **current flow characteristics** of the connected consumer loads in the grid. Depending on the **grid impedance** before the connection point of the load, the voltage changes according to the current flow characteristics.

Influencing the voltage in accordance with the current flow characteristics



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Slow and fast voltage changes are caused by “normal” load changes. This should not be a problem in terms of voltage drop if the grid equipment (transformers, cable and power cross-sections, etc.) is dimensioned appropriately. The situation is different when large loads are connected or in the case of short circuits on upstream grid levels which cause more or less severe **voltage dips**, depending on the grid impedance.

Short periodic loads or pulsating loads from, for example, presses, arc furnaces, welding equipment or similar cause short voltage fluctuations which are known as flickers. **Flickers** create a subjective impression of unsteadiness in visual perception caused by temporal fluctuations in luminance or spectral distribution. The perceptibility of a change in luminance is only considered disturbing above a certain frequency. At a standardised short-term flicker severity of $P_{st} > 1$, the variations in luminance caused by voltage fluctuations are perceived as annoying by 50% of the test observers.

Under normal operating conditions, the voltage must not deviate from the nominal value of the supply voltage by more than 10%. **Temporary overvoltages** are caused mainly by load disconnections or transmission line switching in high-voltage networks. The latter are returned to the tolerance bandwidth by tap changers in the power transformers. These regulating processes can take a few seconds.

Transient overvoltages in power grids are caused by the disconnection of inductive grid equipment (e.g. transformers) and the occurrence of lightning strikes in the vicinity of or on those electricity supply networks. These surges typically peak within a microsecond to a few milliseconds. Overvoltages of this kind can either occur as a strongly damped oscillation or have a steep rise and subsequently decay back to zero without oscillation. In real-world power grids, the ideal sinusoidal supply voltage is subsequently distorted by harmonic voltages. **Harmonic voltages** are typically caused by harmonic currents from non-linear loads that cause harmonic voltage drops across the grid impedances. These drops are superimposed over the sinusoidal supply voltage. Non-linear loads are usually all loads with power electronics (switched-mode power supply units, rectifiers, frequency converters, etc.) whose characteristic current curve is not sinusoidal. In this case, the current has harmonic components that are defined by their order, which is equal to an integer multiple of the 50 Hz fundamental frequency.

The spectrum of harmonic components depends on the type of circuitry of the power electronics. If the voltage levels of individual or several orders of harmonic voltages in a grid area exceed the standardised compatibility levels, this usually results in malfunctions of mostly electronic loads.

The compatibility levels for harmonic voltages of the respective order are described in the pertinent standards [1, 2, 3, 4] up to the 50th order. Nowadays, excessive harmonic voltage distortions are the most common reason for poor power quality and malfunctions.

In addition to the aforementioned harmonics whose frequency is an integer multiple of the fundamental currency, currents with interharmonic frequencies also occur with non-linear loads, which generate voltages with interharmonic frequencies across the grid impedances, and which are also superimposed over the sinusoidal supply voltage. The voltages known as interharmonics cause amplitude modulation of the supply voltage in low-voltage networks at frequencies close to the fundamental frequency (50 Hz or 60 Hz) to which lighting equipment in particular reacts sensitively and a flicker effect can occur. DIN EN 61000-2-2 [2] specifies compatibility levels as reference values for **interharmonics** in low-voltage networks near the fundamental frequency which correspond to the compatibility level for flicker effects. It is also important to mention that no normative agreements have yet been reached on compatibility levels for voltages of interharmonic frequencies in public electricity supply networks, as there is not yet sufficient information available on possible effects. However, it is recommended not to allow higher voltage levels than the compatibility level specified for the next higher even harmonic.

For voltage distortions above the 50th harmonic order (> 2,5 kHz), also called supraharmonics, it is generally irrelevant whether the frequencies occur as harmonics or as interharmonics. Voltage distortions can be present as discrete frequencies as well as in frequency bands. Compatibility levels for symmetrical voltage distortions above the 50th harmonic order up to 9 kHz are specified for EMC coordination when setting emission limits for unwanted symmetrical emissions [2]. Voltage distortion levels are determined in bandwidths of 200 Hz around a centre frequency. The centre frequencies for 50-Hz grids are in the range of 2600 Hz to 8900 Hz.

Commutation notches occur in the normal operation of rectifier circuits or also in diode bridges with natural commutation. In power converters, the thyristor valves are switched over periodically, i.e. during the commutation process, the respective following thyristor in the next phase ignites while the thyristor to be cleared is still conducting. Due to this overlap, also called commutation time, two phases are short-circuited for a few microseconds and very high commutation currents occur. This can lead to steep voltage dips across the grid impedances. These so-called commutation notches have a disruptive effect on equipment that is connected to the same node or even to the upstream grid level.

If there is a heavily unbalanced current load on the three-phase power grid in a grid area, this leads to unbalanced effective values of the voltages between the conductors. Unbalanced current loads are mostly caused by powerful single-phase or two-phase consumer loads connected between two outer conductors or between an outer conductor and the neutral conductor. The degree of **voltage unbalance** is expressed with sufficient accuracy as the ratio of the negative sequence component of the voltage to the positive sequence component. Typical effects of voltage unbalance are, for example, the magnetic fields built up by the negative voltage sequence in electrical machines. The magnetic fields act against the direction of rotor rotation, reduce machine torque, and increase the thermal losses due to the induced currents in the rotor. In addition to the higher losses, which lead to a significant reduction in service life and reduced machine torques, pulse vibration torques may also occur. These lead to additional mechanical stress and reduced service life.

3 Determining and Assessing Power Quality

3.1 Measuring Power Quality

To measure power quality, type A instruments as defined in IEC 61000-4-30 [5] must be used. This ensures that the measurement results comply with relevant standards and can be used without any restrictions.

When determining power quality, the focus should also be on the current flow of the connected loads. It is imperative to measure the currents as well as the voltage.

Whatever measuring technology is used, it must be ensured that it is capable of measuring voltages and currents with correspondingly high frequencies so that it is possible to examine the measurement results in conformity with the standards.

A 10-minute interval should be selected in order to evaluate the recorded harmonics. Modern measuring instruments often also provide the option to map additional intervals. In many cases, it is necessary to examine the 10-minute mean values to check for the presence of highly dynamic events in the electrical network. For this reason, measuring instruments provide maximum readings for 10 and/or 200 ms periods, depending on the quality of device, which should be evaluated with regard to their impact on power quality.

3.2 Assessing Power Quality

Power quality or power ratio measurements are analysed according to the following standards or guidelines:

- DIN EN 50160 [1] describes the expected voltage limits and characteristics at any given transfer point in public low-, medium- and high-voltage power grids. The voltage limits and characteristics listed in the standard cannot be uses as values for EMC compatibility or as limits for the input of network disturbances from the systems or devices of a grid user connected to the public grid.

- DIN EN 61000-2-2 [2] is concerned with conducted disturbances of the voltage and signalling network communication systems **in public low-voltage networks** up to 690 V in the frequency range from 0 Hz to 150 kHz.
  The specified compatibility levels apply to the node – usually the connection point – with the public grid.

- DIN EN 61000-2-4 [3] is concerned with conducted disturbances of the voltage **in industrial and non-public AC networks up to 35 kV.**
  The compatibility levels for voltage disturbances are divided into environment classes 1 to 3.

  Class 1 applies to protected supply areas, such as technical laboratories or data processing facilities. The compatibility levels for voltage interference levels are lower than those for public power grids.

  Class 2 specifies compatibility levels for voltage interference levels that are generally identical to the compatibility levels for public low- and medium-voltage grids. Devices and systems developed for operation on these public networks can be used in industrial and non-public power grids.

Class 3 applies exclusively in industrial grids for system-internal connection points with predominant converter loads, welding machines, large motors that are started frequently or rapidly fluctuating large consumer loads.

- DIN EN 61000-2-12 [4] is concerned with conducted disturbances of the voltage in the frequency range up to 9 kHz, with an extension to 148.5 kHz, especially for network signal transmission systems, in public medium-voltage networks with voltages between 1 kV and 35 kV. The specified compatibility levels apply to private connection points to the public medium-voltage network or to the connection points of network stations that feed into public low-voltage networks.

4 Circuitry Measures to Maintain & Improve Power Quality

Circuitry measures, as described in electrical engineering literature, can be leveraged to reduce the negative effects of consumer loads on the power quality in special applications, or to reduce the effects of a given poor power quality on consumer loads. Normally, these circuitry measures are already implemented during the prior planning and construction of systems and grids. Subsequent changes to systems and grids, on the other hand, are usually associated with high expenses and operational interruptions.

Below are some examples of circuitry measures, which are described in more detail in the technical literature.

- **Increasing the pulse number of rectifiers**
  By selecting a higher pulse number when designing powerful rectifier systems, a shift and reduction of harmonic currents into a higher order range can be achieved. For this reason, the increase in pulse number is mentioned in the literature as a measure to reduce the lower order harmonic currents.

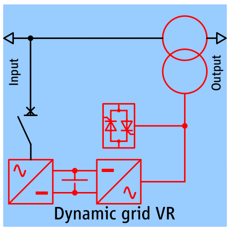
- **Using transformers with different vector groups**
  By using transformers with specifically selected different vector groups, the harmonic currents on the low voltage side of two grids, for example, are not transferred in phase to the grid on the high voltage side. This results in partial cancellation effects of harmonic currents and thus a reduction of harmonic current levels in the common harmonic network. However, the two networks on the low voltage side cannot be coupled because the voltages are not in phase.

- **Segregation into grid areas for sensitive and non-sensitive loads**
  The operation of larger consumer loads or large numbers of rapidly fluctuating large consumer loads (power converters, welding machines, etc.) causes voltage fluctuations, voltage dips and high harmonic loads. Simultaneous operation of these insensitive loads together with sensitive loads in the same grid is very likely to lead to malfunctions. When planning new industrial grids in a foresighted manner, it should therefore be considered whether it would make sense to build two separate networks instead of one common network. The higher capital expenditure for constructing two separate networks is not insignificant. A comparison of measures to ensure power quality with devices and/or systems for joint operation in one network should be examined.

5 Measures to Maintain & Improve Power Quality with Devices and Systems

In existing internal networks, it is customary for the most part for all loads to be operated on common subnetworks. Depending on which loads are in the subnetworks and how the subnetworks have been dimensioned, there are more or fewer influences on the level and waveform of the voltage. At the same time, all internal networks are always subject to influences from upstream networks. The following section presents different technical approaches as to which measures are available to maintain and improve power quality with devices and systems.

Voltage characteristic	Manifestation	Cause	Device- and system-based measures
Voltage level	**Gradual voltage changes** in upstream networks	Fluctuations depending on the time of day and/or feed-in	**Transformer tap changer** (distribution grid operator)
	Rapid voltage changes in upstream networks	**Switching of large loads** in upstream networks	**Dynamic mains voltage regulator**
	Voltage dips in upstream networks	**Short circuit or earth fault** in upstream network	
	Temporary overvoltages in upstream networks	**Load disconnections or** transmission line switching in high-voltage networks	
	Transient overvoltages in upstream networks	**Lightning strikes** in upstream networks	**Surge arrester**
	Rapid voltage changes in internal network	**Switching of large loads** in internal network	**(Motor) start-up compensation**
			Dynamic compensation (thyro / statcom)
	Flicker in internal network	**Short periodic loads or** pulsating loads in internal network	**Dynamic compensation** (thyro / statcom)
	Voltage unbalance in internal network	**Heavily unbalanced current load** in internal network	**Active filter (current controlled)** **dynamic compensation** (statcom)
Voltage waveform	**Harmonics (voltage)** in upstream networks	**Non-linear loads** in upstream networks (parallel grids)	**Passive filters**
			Controlled passive filters
			Active filters (voltage controlled)
	Harmonics (current/voltage) in internal network	**Non-linear loads** in internal network	**Passive filters**
			Active filters (voltage or current controlled)
	Commutation notches in internal network	**Power converters and/or frequency converters** in internal network	**Series reactors** (at the grid connection PC/FC) **High pass filters**
			High pass filters
	High frequency noise in internal network	**Clock frequencies** of electronic loads, **resonance points** from capacitance and inductance in the grid	**High pass filters**



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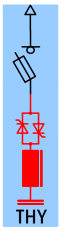
- **Dynamic voltage regulators**
  Dynamic voltage regulators – also called dynamic voltage restorers – are used wherever rapid voltage changes, voltage dips or temporary overvoltages lead to unplanned and costly production downtimes. Such occurrences can also cause impairments in product quality and/or costly wear and tear on machinery. Dynamic voltage regulators are used in the low voltage between the transformer and the low-voltage main distribution system or before the feed-in of a subdistribution system with load feeders to be protected.

  With the basic configuration shown – series transformer and AC/AC converter with DC link – it is possible to restore voltage dips of up to 30% or 40% on the output side to the target value. It is likewise possible to reduce temporary overvoltages of up to 20% to the target value. Online control detects a deviation from the target value more or less directly (approx. 150 µs) and adjusts the deviation to the target value within half a mains voltage cycle. Depending on the extent of the voltage dip and the load required at that moment, a dynamic voltage regulator is able to maintain the voltage target value for at least 30 seconds. In the event of overload or short circuits, the system protects itself without interruption by means of an electronic bypass switch. The control function can be permanently deactivated without any adverse effects using a mechanical bypass switch (not shown) to allow maintenance or to eliminate malfunctions.



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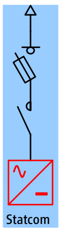
- **Dynamic compensation systems – thyristor switched**
  Dynamic compensation systems are regulated, thyristor switched capacitor stages with a protective reactor against excessive harmonic currents. This type of compensation system is used whenever inductive reactive power surges from load systems with fast operating cycles, such as welding machines, cranes, conveyor systems, lifts, etc., need to be compensated. The fast correction of reactive power surges leads to a reduction in voltage dips and flickering, which have a disruptive effect on other consumer installations or cause irritating visual effects.



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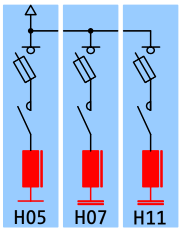
- **Dynamic compensation systems – statcom**
  Statcom is the term for a statically operating compensation system that dynamically adapts capacitive or inductive fundamental reactive power in a wide power range and can make it available for the respective tasks. In contrast to rotating phase shifters, which suffer from corresponding mechanical wear and tear, the reactive power is provided by power electronics and can thus react far more quickly and dynamically to load fluctuations.

  A statcom is usually used for the dynamic reactive power control and flicker compensation of rolling mills, conveyor machines and path compensation, as well as for dynamic voltage stabilisation in weak grids or for long cable connections through the controlled provision of capacitive or inductive reactive power.



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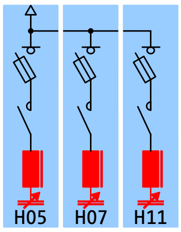
- **Passive filters**
  In classic passive filters, the natural resonance frequency of the filter stage is set very close to the harmonic current of the load or group of loads to be filtered, providing a low-impedance bypass parallel to the grid impedance for the respective harmonic current of the originators. This filters out the harmonic current effectively and does not transfer it to the distribution grid. This method works in the range of the 3rd to 25th harmonics and requires at least one filter stage for each harmonic to be filtered. The risk of an overload is particularly high with passive filters, making constant monitoring and regular maintenance essential. Passive filters are also limited in their ability to adapt to load changes. By combining them with resistors parallel to the filter reactor, high pass filters can be constructed for higher harmonics. In most cases, the exact calculation of the effect of passive filter circuits requires advanced simulation software and experienced specialists.



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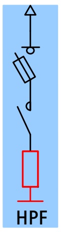
- **Voltage controlled passive filters**
  As described above, the problem with classic passive filters is that they have to be designed with a generous margin or they run the risk of switching off due to overload just when the harmonic load is greatest, i.e. when the filter is most needed. One solution to this problem is to monitor the filter current and change the tuning frequency depending on the filter current.

  When the harmonic voltage increases, the tuning frequency is reduced when the permissible filter current is exceeded. This results in an increase in the impedance and thus a reduction in the filter current. When the harmonic voltage decreases, resulting in a drop in filter current, the tuning frequency is then increased again. To control the tuning frequency, it is possible to change either the capacitance or the inductance of the filter stage. This can be done, for example, by means of a stage structure consisting of a fixed inductance, a main capacitor and several smaller capacitors which can be switched into the circuit to create a variable capacitance.



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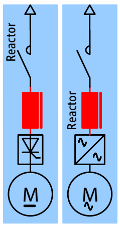
- **High pass filters**
  A high pass filter principally consists of a resistor and a capacitor connected in series. As the name suggests, a high pass filter allows interference voltages with high frequencies to pass and thus ensures that the 50 Hz fundamental voltages in AC voltage networks are effectively filtered from superimposed high-frequency interference voltages. Interference voltages with high frequencies are caused by commutation processes and swiching frequencies in power electronic circuits. They can cause flickers especially in LED lighting and cause audible noises in electronic power supply units or lighting ballasts.



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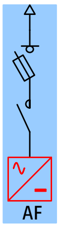
- **Reactors**
  In order to limit the rate of current change during commutation processes effectively, reactors should be connected before powerful power converters and frequency converters. As current peaks contribute to the distortion of the sinusoidal fundamental frequency, their reduction causes a weakening of the distortion and thus a reduction of the harmonics and the supraharmonics.



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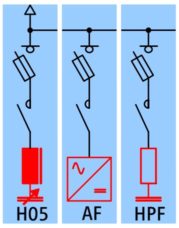
- **Active filters**
  Active filters compensate harmonics up to the 50th order with a high degree of accuracy. Active filters do this by measuring the current and voltage of a grid segment and actively feeding currents with corresponding frequencies and opposite phases into the grid segment in order to cancel out harmonic currents from loads. Active filters can be adjusted or adapted very precisely to the respective requirements at any time and cannot be overloaded. In addition, current active filters also perform the functions of flicker compensation and voltage balancing by using the effect that inductive reactive power lowers the mains voltage and capacitive reactive power increases it.



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- **Active filters combined with passive filters**
  If required, economical and broadband filter solutions up to 9 kHz can be created in combination with voltage-controlled passive filters for the 5th harmonic and/or high pass filters, for example.

6 Summary

The changing supply situation due to the integration of decentralised, mostly renewable generators into the public power grid as well as the steadily growing share of electronic loads have a negative effect on the power quality. As this trend will continue in the coming years, it is absolutely vital to address the issue of power quality.

Apart from the causes and manifestation of low power quality, this guide also shows various approaches to solving the problem. Since both the characteristic and impact of low power quality can vary greatly and differ in every individual case, a detailed analysis of the situation at the specific site is strongly recommended.

If any of the problems described above occur, the ZVEI recommends arranging for a professional network analysis. The resulting findings are the prerequisite for the power quality expert to devise a reliable but above all also economically viable solution, which can consist of individual components and filters or a combination of various technologies.

However, low power quality can also be avoided. For this reason, we recommend identifying the expected network disturbances early on during the planning phase of electrical systems and taking appropriate precautions in advance. This applies not only to the installation of new systems but also to the expansion of machinery or production lines, and when upgrading existing lighting systems to LED technology. ZVEI's power quality experts will be happy to answer any technical questions that may arise.

7 Reference List

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