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POWER QUALITY

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4. POWER QUALITY

For long time the main concern of consumers of electricity was the continuity of the supply, i.e. the reliability. Nowadays consumers want not only reliability, but quality too. Power quality is determined by ability of customer equipment to perform properly. If the electrical power is inadequate for those needs, then the "quality" is lacking.

4.1. Interest in Power Quality

The reason to explain the current interest in power quality is growing economic impacts on the network operators (i.e. the utilities) and their customers. The costs associated with "lack of quality" can be large, especially for industrial customers. If for example a production line trips, it may take several hours to restart with severe financial consequences.

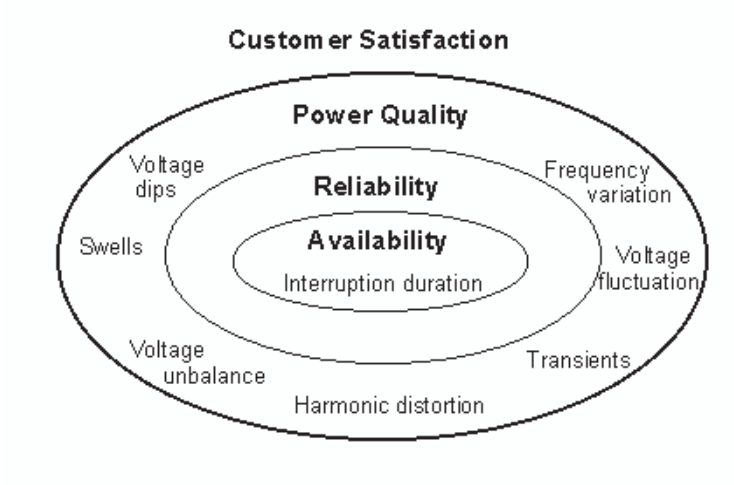


Fig. 4.1 Relationship between availability, reliability and power quality

The devices and equipment being applied in industrial and commercial facilities are more sensitive to power quality disturbances than equipment applied in the past. Equipment containing microprocessor-based controls and power electronic devices, computers, control automation systems, adjustable-speed drives, contactors can be sensitive to many types of disturbances besides actual interruptions (see table 4.1). These devices and equipment can be parts of advanced production or information processes. Processes and equipment have become more interconnected and interrelated which can make them more vulnerable to failure of one component. The whole system is as sensitive as the most sensitive equipment. Malfunction of equipment or misoperation of an important process can affect production continuity resulting in material damages (e.g. in industry), pecuniary losses (e.g. in banking systems) or other losses (e.g. in dispatching centres, hospitals, laboratories).

The power quality problems don't always come from the utility system either. The same equipment, which is sensitive to voltage disturbances, itself often causes voltage disturbances for other customers. Power electronics equipment, such as adjustable speed drives, results in a continuous string of transients (notching) as well as steady state harmonic distortion.

On the other hand, these voltage disturbances affect significantly function of power electronics equipment.

Table 4.1 Equipment sensitivity to voltage disturbances

Equipment	Voltage disturbances								
	Oscillatory transients	Impulsive transients	Dips and undervoltage	Swells and overvoltage	Interruptions	Harmonics	Notching	Noise	Voltage fluctuations
CNC machine	•	•	•	•	•		•	•	
Adjustable speed drives	•	•	•		•	•	•		
Personal computers	•	•	•		•			•	
Programmable logic controllers	•	•	•		•	•	•	•	
Relays, contactors, motor starters		•	•		•				
Fax machine		•	•		•			•	
Metal-halide and high-pressure sodium lighting		•	•		•				•
Telecom switching equipment	•	•	•		•	•	•	•	
Electronic ballast fluorescent lighting		•			•			•	•

4.2. Definition of Power Quality

The quality of delivered electricity, like quality of other goods and services, is difficult to define and quantify. There is not one accepted definition of quality electricity. The quality is mainly determined by the quality of the voltage waveform, as it is impossible to control the currents drawn by customer loads. Voltage quality is not only the responsibility of the network operator but also, in certain respects, depends on producers and customers.

Power quality is the combination of current quality and voltage quality, involving the interaction between the system and the load. *Voltage quality* concerns the deviation of the voltage waveform from the ideal sinusoidal voltage of constant magnitude and constant frequency. *Current quality* is a complementary term and it concerns the deviation of the current waveform from the ideal sinusoidal current of constant magnitude and constant frequency. Voltage quality involves the performance of the power system towards the load, while current quality involves behaviour of the load towards the power system.

There is always close relationship between voltage and current in any practical power system. Although the generators may provide a near-perfect sinusoidal voltage, the current passing trough the impedance of the system can cause a variety of disturbances to the voltage. To understand the basis of many power quality problems is necessary to deal with the interaction between the load and the power system. The power system can only control the quality of the supply voltage; it has no control over the currents that particular loads might draw. Therefore, the standards in the power quality area are devoted to maintaining the supply voltage within certain limits.

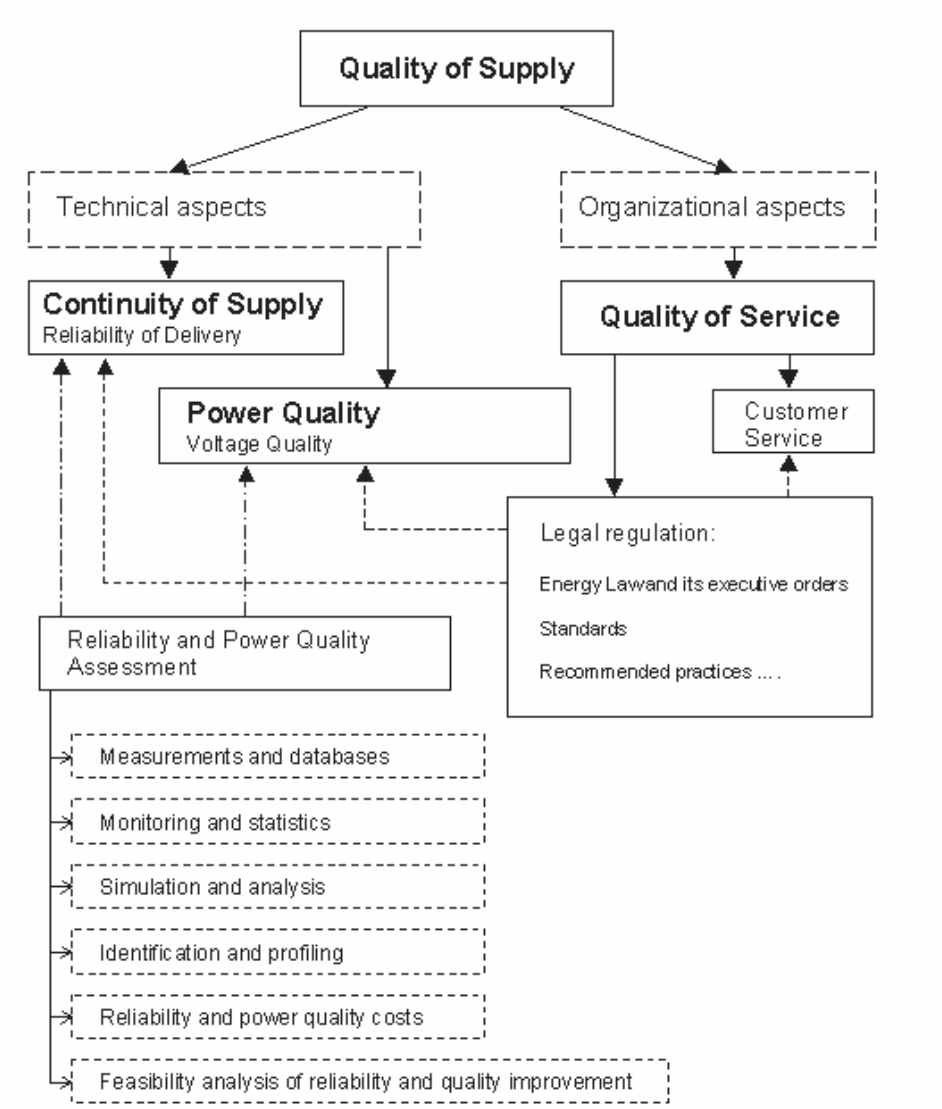


Fig. 4.2 Dimensions of the Quality of Supply

Quality of supply is a combination of voltage quality and the non-technical aspects of the interaction between the utility and its customers. Quality of service in electricity supply has a number of different dimensions, which can be grouped under three general headings:

commercial relationships between a supplier and an end-user, continuity of supply, and voltage quality.

- ***Continuity of supply*** (also referred to as *Reliability of delivery*) is characterized by the number and duration of interruptions. Several indicators are used to evaluate the continuity of supply in transmission and distribution systems (e.g. SAIDI, SAIFI).
- ***Voltage quality*** is concerned with deviations of the voltage from the ideal. The ideal voltage is a single-frequency sine wave of constant frequency and constant magnitude. Voltage quality is described according to the European standard EN 50160 by "the characteristics of the supply voltage concerning: frequency, magnitude, waveform and symmetry of the phases". It can be interpreted as the quality of the product delivered by the utility to the customers.
- ***Quality of service*** *(*also referred to as *Commercial quality)* concerns the quality of relationships between a supplier and a customer. It covers many aspects of the relationship (e.g. transparency of the tariff structure, information supply, responses on customers' complaints, metering, reading and billing), but only some of them can be measured and regulated through standards or other instruments.

4.3. Overview of Power Quality Phenomena

Power quality phenomena (disturbances), i.e. deviations of voltage and/or current from the ideal, can be divided into two types:

- **Variations** are small deviations of voltage or current characteristics from its nominal or ideal value. They are continuous phenomena, e.g. harmonic distortion, variation of voltage rms value, variation of power system frequency. Measuring variations requires continuous recording of their values. The variations are characterised by average and standard deviation.
- **Events** are larger deviations of voltage or current from its nominal or ideal waveform. They only occur occasionally, e.g. interruptions and dips. Measuring events requires a triggering process, e.g. the rms voltage becoming less than a pre-defined threshold. The events are characterised by frequency of occurrence.

4.3.1. Variations

Voltage frequency variations

Voltage variation in which the power system fundamental frequency deviates from its nominal value (e.g. 50 Hz). Slight variations in frequency are due to the dynamic unbalance between load and generation changes. The size of the frequency shift and its duration depends on the load characteristics and the response of the generation control system to load changes. Frequency variations that go outside of accepted limits for normal steady state operation of the power system can be caused by faults on the bulk power transmission system, a large block of load being disconnected, or a large source of generation going off-line. On interconnected power systems, significant frequency variations are rare.

Voltage magnitude variations

Value of the nominal voltage is defined in the standard ČSN IEC 38. Increase and decrease in the voltage magnitude is caused by load variation, actions of transformer tap-changers and switching of capacitor banks or reactors. Very fast variations of the voltage magnitude are referred to as "voltage fluctuations".

Voltage fluctuations

Voltage fluctuations are cyclical variations of the voltage envelope or series of random voltage changes, the magnitude of which does not normally exceed the voltage ranges of 0.9 to 1.1 pu.

Large or rapid variations or variations with frequencies between about 1 Hz to 15 Hz can result in the light flicker. The human eyes are very sensitive to it and above a certain magnitude the light flicker can become rather disturbing. Such voltage variations are often referred to as "flicker", but it is incorrect. The term "flicker" is the visible impact of voltage fluctuations on lamps. The term "voltage flicker" is confusing but sometimes used as shortening for "voltage fluctuations leading to light flicker".

Generally, voltage fluctuations do not damage or upset equipment, excepting the lights. Among the most common causes of voltage flicker in transmission and distribution systems are arc furnaces, spot welders or sawing machines.

Voltage unbalance

Voltage unbalance is a voltage variation in a three-phase system in which the three voltage magnitudes or the phase-angle differences between consecutive phases are not equal. The voltage unbalance is defined by using symmetrical components and is quantified as the ratio between the negative-sequence and positive-sequence voltage component [1], or between zero-sequence and positive-sequence voltage component.

The voltage unbalance is caused by unbalanced phase impedances (e.g. power lines without transposition of phase conductors), or unbalanced loads (e.g. large single-phase loads as arc furnaces, railway traction supplies, an uneven spread of single-phase equipment over the three phase), or combination of both.

Voltage unbalance leads to higher system losses, additional heat production in the winding of motors and transformers, which reduces their efficiency and lifetime. The capacity of transformers, cables and lines is reduced due to negative sequence components. A small voltage unbalance can also cause a large current unbalance in the three-phase diode rectifier. The unbalance can negatively influence most voltage-compounding equipment, protection systems and process control equipment.

Rearranging or redistributing the loads in such a way that the system becomes better balanced, is basic mitigation technique. Reduction of the influence of unbalanced loads may be achieved by connecting them at points with higher short circuit level. Special supply transformers or Static Var Compensators may also be used.

Waveform distortion

Waveform distortion is defined as a steady-state deviation from an ideal sine wave of power (system) frequency principally characterized by the spectral content of the deviation. There are several types of waveform distortion: dc offset, harmonics, interharmonics, notching and noise.

DC offset

DC offset is the presence of a dc voltage or current in an ac power system. It can occur due to the effect of half-wave rectification. Direct current in ac networks can have a detrimental effect by biasing transformer cores so they saturate in normal operation. This results in additional heating and reduction of transformer life. Dc components also cause the electrolytic erosion of grounding electrodes and other connectors.

Harmonics

Any periodic non-sine waveform can be described as a sum of sine waves with frequencies being multiples of its (the fundamental) frequency. The non-fundamental components are called “harmonic distortion”. An individual component of an harmonic distortion is called “harmonic”.

The harmonic voltage distortion is largely caused by non-linear characteristics of power system devices and loads. The non-linear load (e.g. adjustable-speed drives, arc furnaces, inverters, UPSs) draws non-sinusoidal current, even for sinusoidal voltage. The harmonic current components cause harmonic voltage components, and thus non-sinusoidal (distorted) voltage in the power system. Some power system devices can behave as non-linear components (e.g. saturated transformers, HVDC links, power electronics devices for control of power flow and voltage). Harmonic distortion can originate also from system resonances (e.g. between transformer inductance and capacitance of a capacitor bank).

Harmonic distortion levels are described by the complete harmonic spectrum with magnitudes of each individual harmonic component (up to 25th harmonic), or the Total Harmonic Distortion (THD) [1]. Due to varying non-sinusoidal current of load, the harmonic voltage distortion is not constant, but it is continuously changing during a monitoring period.

Harmonics can cause the whole range of problems. The main problem is additional losses and following overheating of electrical equipment and wiring, and life reduction. Large harmonic distortion can lead to malfunction of equipment (e.g. ripple control, protection, control and communication systems). There can be a big problem especially in industrial power systems, where is large concentration of distorting loads as well as sensitive loads.

Interharmonics

Interharmonic is a sinusoidal voltage or current having frequency that is not integer multiply of the fundamental power frequency. Interharmonics can appear as discrete frequencies or as a wide-band spectrum.

They are mainly caused by static frequency converters, cycloconverters, induction motors and arcing devices, and can be responsible for serious light flicker problems. The magnitude of interharmonic components is normally small enough not to cause any problem, but sometimes they can excite unexpected resonances between transformer inductance and a capacitor bank. More dangerous are components with lower than the fundamental frequency, referred to as “sub-harmonic distortion”. Sub-harmonic currents can lead to saturation of transformers and damage to synchronous generators. A special case of sub-harmonic currents are those due to oscillations in the earth-magnetic field following a solar flare. These sub-harmonics with the period around 5 minutes can lead to transformer saturation.

Mains signalling voltage

High-frequency signals are superimposed on the supply voltage for the purpose of transmission of information in the power system and to customer’s premises.

Ripple control signals are sinusoidal signals with frequency between 110 and 3000 Hz. These signals are similar to harmonic and interharmonic voltage components. Power line carrier signals are sinusoidal signals with frequency between 3 and 148.5 kHz. These signals can be considered as high-order (inter)harmonics or high-frequency voltage noise.

Mains signalling voltages can interfere with equipment using similar frequencies for some internal purposes. The voltage, and the associated currents, can also cause audible noise

and signals on telephone lines. The magnitude of the mains signals is limited to a few percent of the nominal voltage magnitude.

Notching

Notching is a periodic voltage disturbance mainly caused by the normal operation of power electronics devices when current is commutated from one phase to another during the momentary short circuit between the two participating phases (duration less than 1 ms). The commutation results in a reduction in the supply voltage. The voltage one or more times a cycle becomes (significantly) closer to zero than the ideal sine wave. The notch lasts less than one half-cycle. The voltage notching can cause microprocessor-based control systems and computer equipment to shut down or lock up.

Noise

Noise is defined as unwanted electrical signals with broadband spectral content lower than 200 kHz superimposed upon the power system voltage or current in phase conductors, or found on neutral conductors or signal lines. The voltage noise is the components of supply voltage, which are not periodic at all.

Noise in power systems can be caused by arc furnaces, power electronic devices, switching power supplies, and combination of many different non-linear loads. Noise disturbs electronic devices such as microcomputer and programmable controllers. The problem can be mitigated by using filters and by isolation transformers.

4.3.2. Events

Interruptions

Interruption is an event in which the voltage is close to zero during a certain period of time. Close to zero is defined “lower than 1% of declared voltage“ [1].

Interruptions can be result of power system faults (short circuits) and their clearing by protections. The other causes of interruptions can be equipment failures, protection maltrip (protection operation when there is no fault present), broken conductors, control malfunctions or operator actions. The most of faults result from lightning. The duration of an interruption due to a fault on the power system is determined by the operating time of protection systems. The duration of an interruption due to equipment malfunctions or disconnections can be irregular.

Interruptions can be subdivided based on their duration, thus based on the way of restoring the supply:

- Automatic switching (short interruptions)
- Manual switching (long interruptions)
- Repair or replacement of the faulted component (long interruptions)

Automatic switching or reclosing makes that a long interruption becomes a short one.

According to duration the interruptions are divided into short and long. The interruptions with duration not exceeding 3 minutes [1] are defined short interruptions and they are considered to be voltage quality problems. These short interruptions occur between a few tens and several hundreds times per year. The duration is in about 70% cases less than 1 second.

Interruptions are characterized through their number and duration within given period (e.g. a year). The international standards on power quality haven’t given yet any limitations for interruption frequency and duration.

A further distinction can be made between pre-arranged (so called planned or scheduled) and accidental interruptions. All pre-arranged interruptions are caused by operator actions (e.g. preventive maintenance, repair or changes in the power system).

Undervoltages

Undervoltage is a decrease in the rms voltage to less than normal operating margin (e.g. 0.9 pu.) for a certain period of time.

Undervoltages of various duration are known under different names. Long-duration undervoltage (longer than 1 minute) is normally simply referred to as "undervoltage". It is the result of load switching (e.g. switching on a large load or switching off a capacitor bank) or overloaded circuits. Typical magnitudes are 0.8 to 0.9 pu.

Undervoltages can cause equipment to be much more sensitive to dips and interruptions than it might otherwise be.

Voltage dips (Voltage sags)

Short-duration undervoltages are called "voltage dips" or "voltage sags". A voltage dip is a momentary decrease in the rms voltage magnitude lasting between a half-cycle and 1 minute.

Voltage dips are mostly caused by remote faults (short circuits) in the power system and by energization of heavy loads, or starting of large motors. Voltage dips caused by faults are generally more severe than those caused by the starting of large loads.

Voltage dips are characterised by their magnitude (remaining voltage), duration and number within given period (e.g. a year). Dip magnitudes range from 1% to 90% of the nominal value. The magnitude of dips caused by faults is determined by the electrical distance to the fault and the duration by the fault-clearing time. Most of these dips usually last less than 1 second. In cases of motor starting the voltage decreases to about 80% of the nominal value and then gradually returns to normal in about several seconds or tens of seconds.

The effect of voltage dips on the operation of sensitive equipment can be the same like the effect of short supply interruptions. Equipment such as adjustable-speed drives, programmable logic controllers, relays, motor contractors, computers and other electronic-based machines may be particularly sensitive to voltage dips.

Voltage dips are often associated with a phase-angle jump and some three-phase unbalance.

Overvoltages

Overvoltage is an increase in the rms voltage higher than normal operating range (e.g. 110% of the nominal value) for a certain period of time. Just like with undervoltage, overvoltage events are given different names based on their duration.

Long-duration overvoltages are simply referred to as "overvoltages". During overvoltage a voltage has a value greater than the nominal operating range for a period of time greater than 1 minute. Typical values are 1.1 to 1.2 pu. Long overvoltages originate from load variations (e.g. switching off a large load or energizing a capacitor bank), switching operations or faults (e.g. earth faults). Incorrect tap setting on transformers can also result in system long overvoltages. A resonance between the non-linear magnetizing reactance of a transformer and a capacitance (either in the form of a capacitor bank or the capacitance of an underground cable) can lead to a large overvoltage of long duration. This phenomenon is called ferroresonance, and it can lead to serious damage to power system equipment.

Overvoltages can cause equipment to be much more prone to overheating and insulation failure than it might otherwise be.

Overvoltages of very short duration and high magnitude are called “transients overvoltages”. Overvoltages with duration between a half-cycle and 1 minute are called “voltage swells” or “temporary overvoltages”. Short overvoltages originate mainly from lightning, switching operations and unsymmetrical faults.

Voltage swells

Voltage swell is a temporary increase in the rms voltage higher than normal operating range (e.g. 110% of the nominal value) for duration from a half cycle to 1 minute. Typical rms values are 1.1 to 1.8 pu.

The swells are caused by switching off large loads or by faults in the power systems. They are not as common as voltage dips. They are also characterized by their magnitude and duration. The severity of a voltage swell caused by a fault depends on the fault location, system impedance and grounding. On an ungrounded system, the line-to-ground voltage on the unfaulted phases will be 1.73 pu. during a single-line-to-ground fault, while on a directly grounded system the voltage on the unfaulted phases will little rise or not change.

Swells can cause industrial equipment to shut down, components to overheat, and fuses to blow.

Fast voltage events (Transients)

Fast voltage events are voltage events with a very short duration, typically one cycle of the power system frequency or less. They are referred to as “transients” or “transient (over)voltages”. The term “transients” is not fully correct, as it should be only used for the transition from one steady-state to another. Events due to lightning should not be called transients under that definition.

Fast voltage events can be divided into impulsive transients (mainly due to lightning) and oscillatory transients (mainly due to switching actions). They can damage the components of electronic equipment, cause process control and adjustable-speed drives to trip, upset computers, and corrupt data.

Impulsive transients

A sudden, non-power frequency change in the steady-state condition of voltage, current, or both, that is unidirectional in polarity (i.e. either always positive or negative).

Impulsive transients are characterized by their rise and decay times. They are caused by lightning and by the opening of an inductive circuit. Due to high frequencies involved, the shape of impulsive transients can be changed quickly by circuit components. They are generally not conducted far from the source of where they enter the power system. Impulsive transients can excite the natural frequency of power system circuits and produce oscillatory transients.

Oscillatory transients

A sudden, non-power frequency change in the steady-state condition of voltage, current, or both, that includes both positive and negative polarity values (i.e. the change oscillates around zero).

Oscillatory transients are described by their spectral content (predominate frequency), duration and magnitude.

Oscillatory transients with frequency greater than 500 kHz and a typical duration measured in microseconds are considered high-frequency transients. They are often the results of a local system response to an impulsive transient.

A transient with between 5 and 500 kHz and a typical duration measured in the tens of microseconds is considered as a medium-frequency transient. Medium-frequency transients are results of capacitor or cable switching.

A transient with an oscillation frequency less than 5 kHz and a duration from 0.3 to 50 ms is considered as a low-frequency transient. Low-frequency transients are results of capacitor bank energization, transformer energization, and ferroresonance.

Consequences of transients are limited by consequent insulation co-ordination, by using earth wires on power lines and various overvoltage protection devices.

Rapid voltage changes

They are voltage magnitude steps when the rms value of the voltage shows a fast rise or drop from one constant value to another constant value, both inside the normal operating range (typically from 90% to 110% of the nominal value). The sudden change in the voltage magnitude originates from load switching (e.g. intermittent loading, starting motors), transformer tap-changers and switching actions in power systems (e.g. capacitor banks).

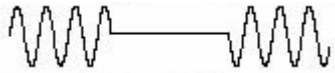
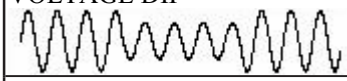
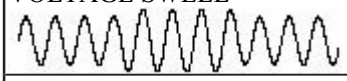
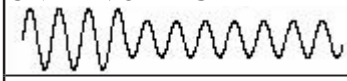
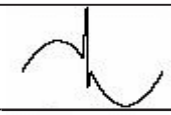
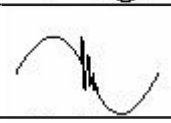
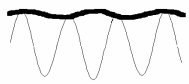
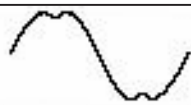
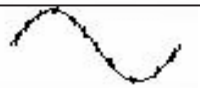
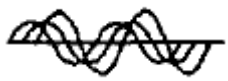
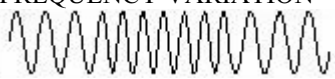
4.4. Power Quality Standards and Regulation

Today the electricity is viewed as a product with certain characteristics, which have to be measured, predicted, guaranteed, improved etc. There exist various forms of legislation, recommendations, and technical standards for voltage quality criteria in different countries to ensure the supply voltage to be within prescribed tolerances.

4.4.1. Electromagnetic Compatibility (EMC)

EMC is the ability of an equipment or system to operate satisfactory in its electromagnetic environment without introducing electromagnetic disturbances intolerable to anything in that environment. At the international level, the International Electrotechnical Commission (IEC) classifies electromagnetic disturbances in conducted and radiated phenomena and gives their definition [2]. Radiated disturbances are emitted by one device and received by another without the need for any conduction. Conducted disturbances need a conductor to transfer from one device to another. These conducted disturbances are within the scope of power quality, radiated disturbances are outside of the field of power system engineering or power quality. In the international standards power quality is treated as a subset of the EMC.

Table 4.2 Summary of power quality disturbances

	PQ Disturbance	Frequency / Rise Time	Duration	Magnitude
Amplitude	INTERRUPTION 	collapse	10 ms to 3 min	0
	VOLTAGE DIP 	power frequency	10 ms to 1 min	0.1 to 0.9 pu
	VOLTAGE SWELL 	power frequency	10 ms to 1 min	1.1 to 1.8 pu
	UNDERVOLTAGE 	power frequency	> 1 min	0.8 to 0.9 pu
	OVERVOLTAGE 	power frequency	> 1 min	1.1 to 1.2 pu
	TRANSIENT OVERVOLTAGE (Impulsive Transients) 	rise time: ns to ms	50 ns to 1 ms	0 to 10 pu
	TRANSIENT OVERVOLTAGE (Oscillatory Transients) 	1 kHz to 10 MHz	1 μs to 50 ms	0 to 6 pu
Waveform distortion	VOLTAGE FLUCTUATIONS (FLICKER) 	modulation frequency < 50 Hz	steady-state variation	+/- 0.1 pu
	HARMONICS 	harmonic orders: 0 to 25	steady-state variation	< 0.1 pu
	NOTCHING 	broad-band	steady-state variation	< 0.1 pu
Balance	VOLTAGE UNBALANCE 	power frequency	steady-state variation	---
Frequency	FREQUENCY VARIATION 	49.5 to 50.5 Hz (47 to 52 Hz) for synchronous systems	< 10 s	---

The EMC deals with mutual interaction between equipment and with interaction between equipment and supply. A piece of equipment should be able to operate normally in its environment and not pollute the environment too much. Within EMC there are used three important terms: "emission" is the electromagnetic pollution produced by a device, "immunity" is the device's ability to withstand electromagnetic pollution, „electromagnetic environment" that gives the level of disturbance against which the device should be immune. Emission is related to the term current quality, immunity to the term voltage quality. The immunity of the device should be assessed with reference to its electromagnetic environment (e.g. a power system). A device connected to the power system is exposed to an electrical environment not only due to the combined emission of all devices connected to the system, but also due to all kind of events in the power system (like switching actions, short-circuit faults and lightning).

To achieve EMC, the emission and immunity levels of equipment in its environment must be properly co-ordinated (see Figure 4.3). The emission levels specify the maximum level of electromagnetic disturbance that an equipment or system is allowed to produce, while the immunity levels specify the minimum level of electromagnetic disturbance that an equipment or system must tolerate for maintaining a predefined operational performance.

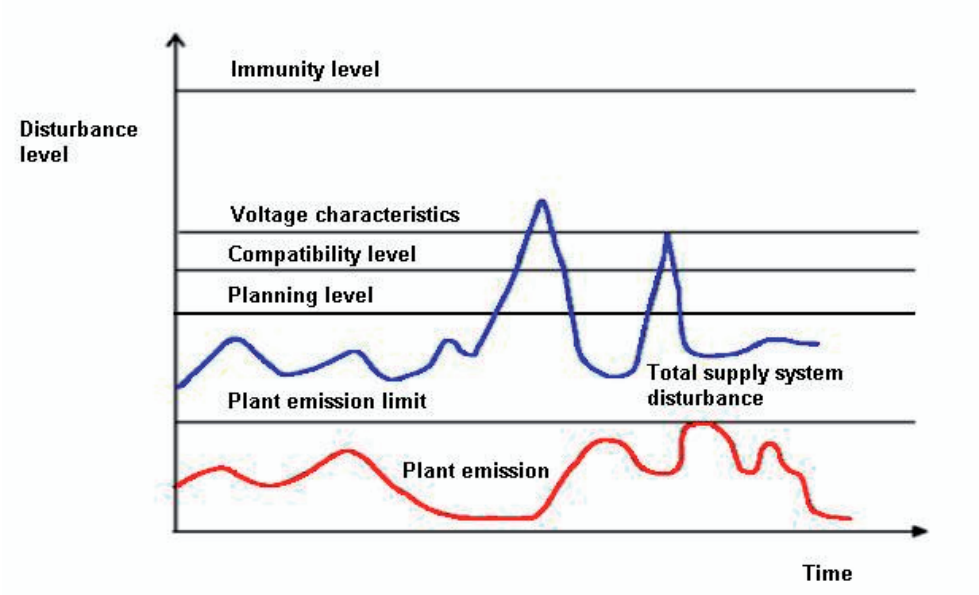


Fig. 4.3 Deterministic representation of the co-ordination of conducted disturbances

The compatibility levels are reference values for co-ordinating emission and immunity requirements of equipment. As both emission and immunity are stochastic quantities, EMC can never be completely guaranteed. The compatibility level is chosen in such way that compatibility is achieved for most equipment most of time: typically 95% of equipment for 95% of the time. The compatibility levels are specified in IEC and CENELEC standards for three reference environments: special supply systems, industrial internal supply systems and public supply systems [3], [4], [5].

The electromagnetic environment for disturbances originating in or conducted through the power system is equivalent to the power quality. When dealing with equipment connected

to a public power system, the characteristics of the voltage at the user supply terminals also become an issue of interest.

Voltage characteristics are quasi-guaranteed limits for some parameters. They are also based on a 95% value, but now only in time. They hold at any location, and are thus an important parameter for customers. Voltage characteristics are a way of describing electricity as a product. Some of voltage characteristics are defined in the EN 50160.

Planning levels are used for certain purposes in evaluating the impact of all disturbing customers or equipment on the system. They are specified by the supply utility and can be considered as internal quality objectives of the utility.

4.4.2. Voltage Characteristics (EN 50160)

The European Committee for Electrotechnical Standardisation (CENELEC) issued the standard EN 50160 "Voltage characteristics of electricity supplied by public distribution systems". The standard EN 50160 is one of the first documents quantifying the voltage quality experienced by customers. It gives the main characteristics of the voltage at the customers supply terminals in public LV (to 1000 V) and MV (between 1 kV and 35 kV) networks under normal operating conditions. "Supply terminals" is defined as the point of connection of the customer's installation to the public system, so called the point of common coupling (PCC).

Voltage quality is determined by the voltage characteristics. Because some incidents affecting the supply voltage are random in time and location, some of the characteristics are described with statistical parameters instead of specific limits, e.g. voltage magnitude. For some characteristics, e.g. voltage dips, interruptions and overvoltages, only indicative values are given.

• **Voltage magnitude** – 95% of the 10-minute averages during one week shall be within ±10% of the nominal voltage. It indicates that the range of variation of the 10 minutes rms values of the supply voltage is U_n±10% for 95% of a week. In short, this means that for more than 8 hours a week there are no limits for the supply voltage value.

• **Frequency variation** - 95% of the 10-second averages shall not be outside the range 49.5 to 50.5 Hz.

• **Voltage fluctuation** - 95% of the 2-hour long-term flicker severity values obtained during one week shall not exceed 1.

Short-term severity P_{st} is measured with a specified equipment over a period of 10 minutes and P_{lt} is calculated from a sequence of twelve P_{st} values over a two-hour interval, according to the expression $P_{lt} = \sqrt[3]{\sum_{i=1}^{12} \frac{P_{sti}^3}{12}}$.

• **Harmonic distortion** – Harmonic voltages are evaluated individually or globally. Individually by their relative amplitude u_h related to the fundamental voltage $U_{(1)}$, where h is the order of the harmonic. For harmonic voltage components up to order 25, values are given which shall not be exceeded during 95% of the 10-minute averages obtained in one week (see Table 4.3). Globally by the total harmonic distortion factor THD that is calculated as follows: $THD = \sqrt{\sum_{h=2}^{40} \left(u_h\right)^2}$. The THD shall not exceed 8% during 95% of the week.

Table 4.3 Values of individual harmonic voltages at the supply terminals for orders up to 25, given in percent of the fundamental voltage $U_{(1)}$

Odd harmonics		Odd harmonics triplen harmonics		Even harmonics	
order h	relative voltage u_h [%]	order h	relative voltage u_h [%]	order h	relative voltage u_h [%]
5	6	3	5	2	2
7	5	9	1,5	4	1
11	3,5	15	0,5	6 … 24	0,5
13	3	21	0,5		
17	2				
19, 23, 25	1,5				

- **Voltage unbalance** – the ratio of negative-sequence $U_{(2)}$ and positive sequence voltage $U_{(1)}$ shall be obtained as 10-minute averages, 95% of those shall not exceed 2% during one week. The unbalance ratio is defined: $\rho_U = U_{(2)} / U_{(1)} * 100$ [%]
- **Signaling voltages** - 95% of the 3-second averages during one day shall not exceed 9% U_n for frequencies up to 500 Hz, 5% U_n for frequencies between 1 and 10 kHz, and threshold decaying to 1% U_n for higher frequencies.
- **Voltage magnitude steps –** these normally do not exceed ±5% of the nominal voltage, but changes up to ±10% can occur a number of times per a day.
- **Voltage dips** - frequency of occurrence is between a few tens and one thousand events per a year. Duration is mostly less than 1 second, and voltage rarely drops below 40% U_n.
- **Short interruptions** – occur between a few tens and several hundred times events per a year. The duration is in about 70% cases less than 1 second.
- **Long interruptions** - frequency of occurrence may be less than 10 or up to 50 per a year.
- **Transient overvoltages** – will generally not exceed 6 kV in a 230 V system.
- **Temporary (power frequency) overvoltages** – will generally not exceed 1.5 kV in 230 V system.

The comparison of the EN 50160 requirements with those of the EMC standards EN 61000, listed in Table 4.4, shows significant differences in various parameters. There is a reason for these differences: the EMC standards concern the utility voltage (the line-to-line or line-to-neutral voltage at the plug or terminal of the electrical device), while EN 50160 deals with the supply voltage (the line-to-line or line-to-neutral voltage at the point of common coupling). The differences between these voltages are due to voltage drops in the installation and disturbances originating from the network and from other equipment supplied from the installation. Because of this, in many standards of the EN 61000 series the equipment current is an important parameter, while the load current is not relevant to the EN 50160.

Table 4.4 Comparison of supply voltage requirements according to EN 50160 and EMC standards EN 61000

Parameter	Supply voltage characteristics according to EN 50160	Low voltage characteristics according to EMC standard EN 61000	
		EN 61000-2-2	Other parts
Power frequency	LV,MV: mean value of fundamental measured over 10 s ±1% (49,5 - 50.5Hz) for 95% of week -6% / +4% (47 - 52Hz) for 100% of week	2%	
Voltage magnitude variations	LV,MV: ±10% for 95% of week mean 10minutes rms values		±10% applied for 15 minutes
Rapid voltage changes	LV: 5% normal 10% infrequently P_{lt}≤1% for 95% of week MV: 4% normal 6% infrequently P_{lt}≤1% for 95% of week	3% normal 8% infrequently $P_{st} < 1,0$ $P_{lt} < 0,8$	3% normal 4% maximum $P_{st} < 1,0$ $P_{lt} < 0,65$ (EN 61000-3-3) 3% (IEC 61000-2-12)
Supply voltage dips	Majority: duration <1s, depth <60%. Locally limited dips caused by load switching on: LV: 10 – 50%, MV: 10 – 15%	urban: 1- 4 months	up to 30% U for 10ms up to 60% U for 100ms (EN 61000-6-1, 6-2) up to 60% U for 1000ms (EN 61000-6-2)
Short interruptions of supply voltage	LV, MV (up to 3 minutes) few tens – few hundreds / year Duration 70% of them < 1s		95% reduction for 5 s (EN 61000-6-1, 6-2)
Long interruption of supply voltage	LV, MV: (longer than 3 minutes) < 10 – 50 / year		
Temporary (power frequency) overvoltages	LV: < 1,5kV rms MV: 1,7 Uc (solid or impedance earth) 2,0 Uc (unearthed or resonant earth)		
Transient overvoltages	LV: generally < 6kV occasionally higher; rise time: ms - µs. MV: not defined		±2kV, line-to-earth ±1kV, line-to-line 1,2/50 (8/20) T_r/T_h µs (EN 61000-6-1, 6-2)
Supply voltage unbalance	LV, MV: up to 2% for 95% of week, mean 10 minutes rms values up to 3% in some locations	2%	2% (IEC 61000-2-12)
Supply voltage unbalance	LV, MV: up to 2% for 95% of week, mean 10 minutes rms values up to 3% in some locations	2%	2% (IEC 61000-2-12)
Harmonic voltage	LV,MV: see Table 4.3	6% - 5th, 5% - 7th 3,5% - 11th, 3% - 13th, THD < 8%	5% 3rd, 6% 5th, 5% 7th, 1,5% 9th 3,5% 11th, 3% 13th, 0,3% 15th, 2% 17th (EN 61000-3-2)
Interharmonic voltage	LV, MV: under consideration	0,2%	

4.4.3. Power Quality Monitoring

In most countries the potential impact of "lack of quality" is growing. It is therefore likely that more measuring equipment will be placed in the network and at customer connection points.

Measurement of voltage characteristics can be divided into three categories according to the purpose of the measurement:

- permanent monitoring, e.g. for verifying contractual obligations – in transmission delivery points, connection points of HV end-users, substations 110 kV/MV
- temporary surveying, e.g. to check the performance of the supply system, or to check user complaints – in connection points of MV and LV end-users
- general investigations.

Measurements and assessment of voltage characteristics have to be made according to standards, e.g. [6], [7]. These standards also define requirements for power quality measurement instruments warranting measurement comparability and repeatability.

To verify power quality level, the utilities have to archive results of measurements and assessment of voltage characteristics together with information on power system conditions and parameters in time of measurement. Power quality data are also used on purpose of the power quality benchmarking in European countries [12].

4.4.4. Power Quality Regulation

The EN 50160 gives only general limits, which are technically and economically possible for the supplier to maintain in public distribution systems and which provide a minimum, a barely adequate quality supply. Most suppliers routinely exceed these limits by a large margin. If the customer has higher requirements for supply quality, a separate agreement between the supply utility and the customer must be made. The part or whole standard EN 50160 can be replaced by this contract. The utility can namely guarantee higher power quality to the important industrial and commercial customers. On basis of contacts the utility could also supply low quality power to some customers at advantageous, i.e. lower, price.

There are typical areas that will be addressed in power quality contracts:

- Reliability/power quality concerns to be evaluated
- Power system performance indices to be used
- Expected level of power system performance (baseline)
- Penalty for performance outside the expected level and/or incentives for performance better than the expected level (financial penalties, performance-based rates, shared savings, etc.)
- Measurement/calculation methods to verify and accurately assess system performance, means of evaluating compliance
- Responsibilities for each party in achieving the desired performance
- Responsibilities of the parties for resolving problems

The generation, transmission and distribution of electricity are carried out by different organisations. These organisations are in relationship supplier-customer. For this reason the

power quality contract can be made not only between a supplier (distribution company) and end-users, but also between transmission network operators (TRANSCO) and distribution companies (DISTCO), distribution companies and independent power producers (IPPs), retail energy marketer (REAILCO) or the energy service company (ESCO) and end-users. Figure 4.4 illustrates some of the important relationships, where power quality considerations will be included in the contracts.

To meet customer demands on higher power quality the utilities often have to install mitigation devices or to make changes in structure of the power system. Costs associated with changes in structure of the system are generally very high and can influence electricity price. There is a need to make decision what mitigation technique is most cost-effective. Most customers prefer solution of power quality problems on the supply system side. Question is whether the customers are willing to accept the higher price of electricity.

With the introduction of competition between utilities power quality becomes an issue for the regulator, because power quality problems can affect the economic position of the utilities on market. The regulator may use economic incentives to guarantee minimum power quality levels. Power quality regulation is a governmental responsibility in some countries as Spain and Portugal; in other countries it is among the responsibilities of independent regulators.

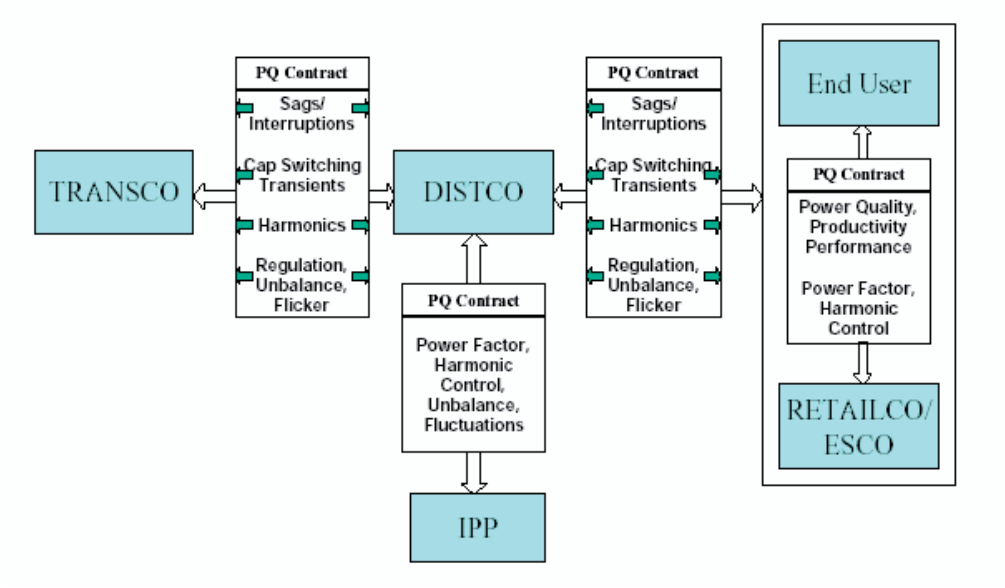


Fig. 4.4 Power quality contracts in the new electric utility industry structure

In the Czech Republic, the Energy Regulatory Office (ERO) was set up in 2001 as an independent administrative authority for regulation in the energy industry. Required quality of supply and services connected with regulated activities in electric power systems is expressed by standards of power quality [8]. There are used concepts of guaranteed and overall standards of performance. Guaranteed standards relate to quality factors for individual customers and carry a penalty payment. Overall standards relate to the overall provision of supply and services measured and regulated at the system level, and are used for benchmarking of power system performance of the utilities. Voltage quality is not as heavily regulated as commercial quality and continuity of supply. Voltage quality standards are in

accordance with the Rules of the Electricity Distribution System Operation [9], the Rules of the Electricity Transmission System Operation or voltage parameters in power quality contract accepted by customer and utility. Voltage parameters described in the Rules of the Electricity Distribution System Operation are based on the EN 50160 and are authorized by the ERO.

4.5. Voltage Dips

Besides interruptions the voltage dips (sags) belong to most monitored events in power systems from point of view of power quality. Voltage dips are short-duration reduction in rms voltage caused by short-duration increases of current. The most common causes of overcurrents leading to voltage dips are faults, motor starting and transformer energizing. Voltage dips caused by faults are generally more severe than those caused by the starting of large loads.

The big interest in voltage dips is due to their effect of voltage dips on an operation of sensitive equipment that is the same like the effect of short supply interruptions, but voltage dips are more frequent than interruptions. Moreover, the voltage dips originate not only in the local distribution network, but they can be caused by fault hundreds of kilometres away in transmission systems. Voltage dips are thus much more global problem than interruptions.

4.5.1. Definition, Characterisation and Indices

A voltage dip is a momentary decrease in the rms voltage magnitude lasting between a half-cycle and 1 minute. Voltage dips are characterised by their magnitude (retained voltage) and duration. Dip magnitudes range from 1% to 90% of the nominal value. Most dips usually last less than 1 second.

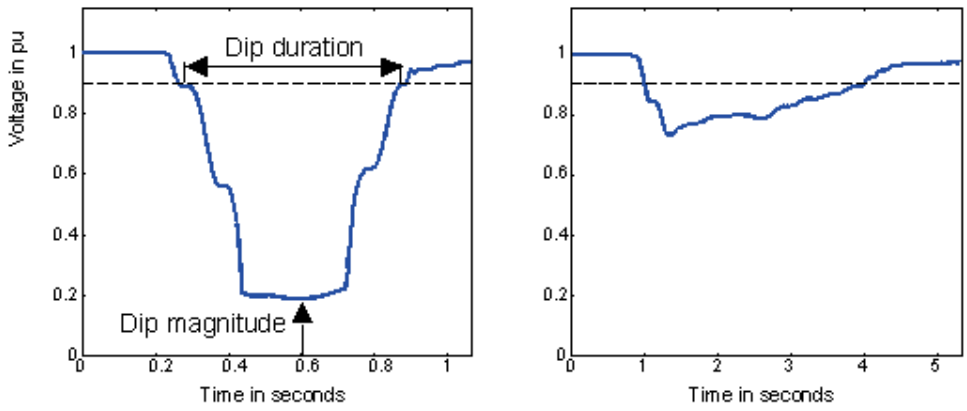


Fig. 4.5 Voltage dip caused by fault and by motor starting

The magnitude of dips caused by faults (i.e. the voltage during the fault) is determined by the electrical distance to the fault, and the duration by the fault-clearing time. In cases of motor starting the voltage decreases to about 80% of the nominal value and then gradually returns to normal in about several seconds or tens of seconds.

Voltage dips are often associated with a phase-angle jump and some three-phase voltage unbalance. The voltages experienced at the equipment terminal during a voltage dips condition depend on the equipment connection (delta or star connection), type of a fault

(symmetrical or non-symmetrical) caused the dips and winding connection of transformer/s between equipment and fault position. There are 7 types of unbalanced voltage dips (A, B, C, D, E, F and G) that can occur at equipment terminals [10].

Voltage dip indices describe the performance of a site and even of the whole network; they typically give the frequency for events with given values of magnitude and duration. A commonly used method of presenting the performance is by means of the voltage dip table. Example of the voltage dip table is shown below.

Table 4.4 Unipede (International Union of Producers and Distributor of Electric Energy) Table

Voltage dip % Un	20≤t< 100 ms	100≤t<500 ms	0,5 ≤ t < 1 s	1 ≤ t < 3 s	3 ≤ t < 20 s	20≤ t < 60 s	60≤t< 180 s
90 > u ≥ 85							
85 > u ≥ 70							
70 > u ≥ 40							
40 > u ≥ 1							
1 > u ≥ 0							

The voltage dip table can be presented as a bar chart. The length of each bar is proportional to the number of dips in the corresponding range of the table. The customers are not usually interested in the number of voltage dips in a given magnitude and duration range, but in the number of times when a piece of equipment will trip due to dips.

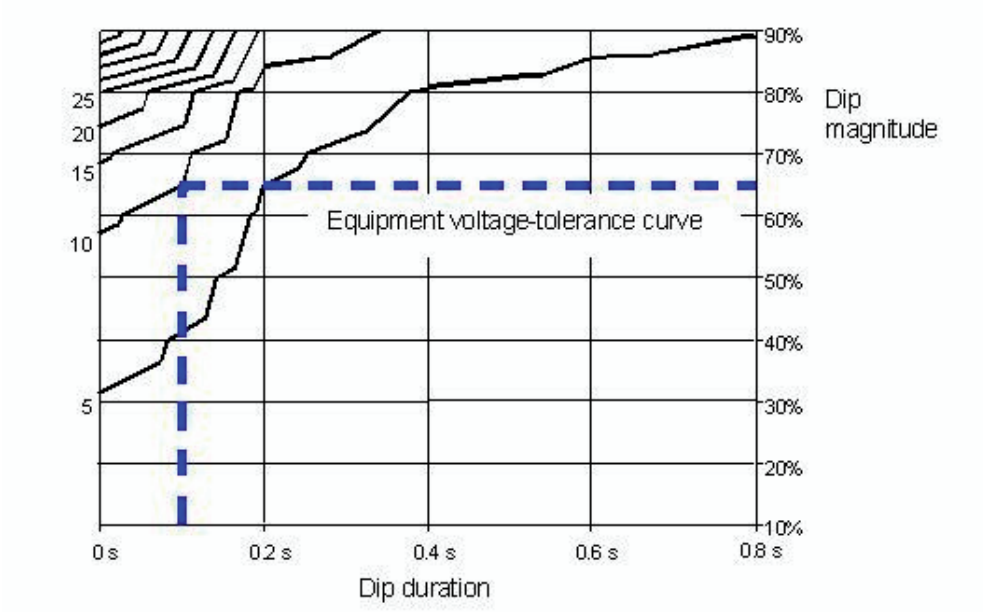


Fig. 4.6 Voltage Dip Co-ordination Chart with equipment voltage-tolerance curve

For direct comparison of equipment behaviour with system performance, the Voltage-Dip Co-ordination Chart is more suitable. The contour lines of the chart give the number

of dips as a function of severity of the event. To predict the number of equipment trips the co-ordination chart of supply performance is combined with the equipment voltage-tolerance curve (see Figure 4.6). For example shown, there are 5 events per a year where the voltage drops below 40% of nominal for 0.1 s or longer. There are equally 5 events more severe than 70% magnitude and 250 ms duration. It can be seen from Figure 4.6 that the equipment with voltage tolerance curve plotted in the chart will trip 10 times per a year.

Tables and charts are suitable for presenting results of power quality monitoring in specific supply point and for assessment equipment compatibility with supply system. For comparison of different sites a smaller number of indices is preferred. The commonly used SAFRI indices quantify system performance by just one number.

SARFI (System Average RMS Variation Frequency Index) is a power quality index that provides a count or rate of voltage dips, swells, and/or interruptions for a single monitoring location, a single customer site, a feeder, a substation, or an entire power system. The index basically relates how often the magnitudes of voltage dips are below a specified threshold. There are two types of SARFI indices:

- *SARFI-X* corresponds to number of voltage dips below a voltage threshold. For example, SARFI-90 considers voltage dips and interruptions that are below 90% of the nominal rms voltage.
- *SARFI-Curve* corresponds to number of voltage dips below an equipment compatibility curve. For example SARFI-ITIC relates to voltage dips and interruptions that are below the lower ITIC (Information Technology Industry Council Computer Business Equipment Manufacturers Association) curve.

Example: How to calculate the SARFI-X and SARFI-ITIC index for a single site?

Monitoring period - 50 days	
Voltage magnitude	Duration
83 %	220 ms
73 %	23 ms
9 %	55 s
23 %	130 ms
0%	5 s
0%	5 s
15 %	30 ms
0 %	41 s
58 %	750 ms
65 %	36 ms
33 %	450 ms

SAFRI-X		
Index	Count per 50 day	Rate per 30 days
SARFI-90	10	6.0
SARFI-70	8	4.8
SARFI-50	6	3.6
SARFI-30	5	3.0
SARFI-30	5	3.0
SARFI-10	3	1.8

SARFI-30 = 5 per 50 day

SARFI-30 = 0.1 per a day

SARFI-30 = 0.1·30 = 3 per 30 day

It can be seen from Figure 4.7 that the SARFI-ITIC index is 8 over period of 50 days, respectively 4.8 over period of 30 days.

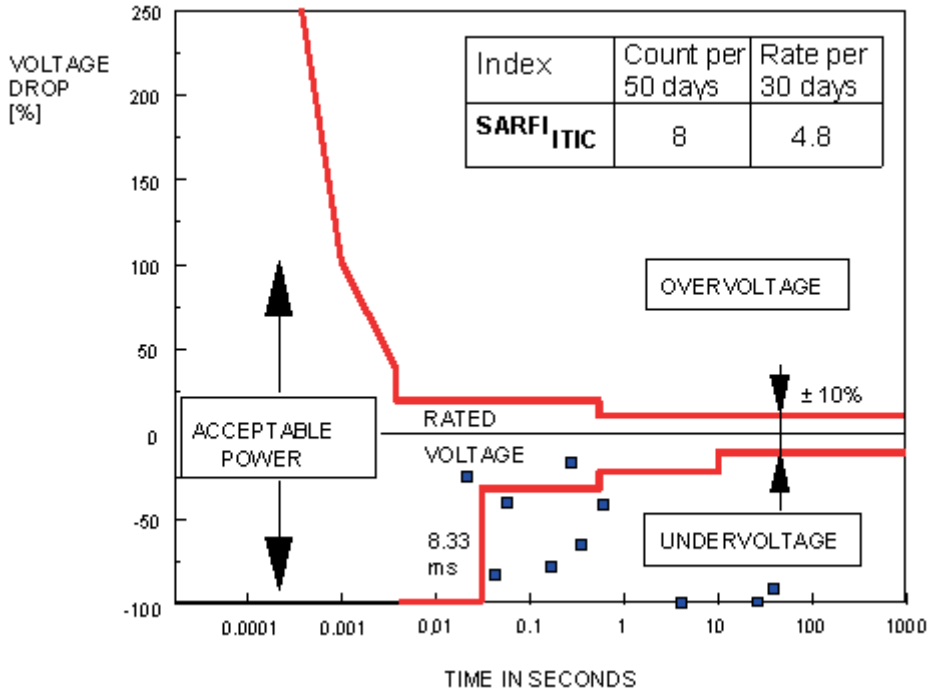


Fig. 4.7 The ITIC power acceptability curve

4.5.2. Effects on Sensitive Equipment

A reduction in voltage due to a fault leads to a reduction of the power transfer from the generators to the motors. The motors slow down and the generators speed up. This phenomenon limits the fault-clearing time in the system and also rules the connection of wind farm to the grid. If the speed of induction motor has reduced to less than 95 %, it will draw nearly the full start-up current. Since all the motors are "starting" together, this may be the cause of further problems. Motor starting dips become a concern when they lead to excess loss of speed for neighbouring motors (or speed gain for generators). Typical limits for stability concern in distribution systems are 70% voltage during 1 second.

The effect of voltage dips on the operation of sensitive equipment can be the same as the effect of short supply interruptions. Equipment such as adjustable-speed drives, programmable logic controllers, relays, motor contractors, computers and other electronic-based machines may be particularly sensitive to voltage dips. Industry equipment are interconnected, consequently a trip of any component can affect the production process (e.g. plastics, petrochemicals, textiles, paper, semiconductor, and rubber industries).

Many modern (power-)electronic devices like computers, process-controllers and adjustable speed drives already experience operational problems when the voltage drops below 85% for 40 ms. These events occur ten times per a year or more.

Mercury discharge lamps are extinguished at around 80% of nominal voltage and require time to restrike. Sodium discharge lamps have a much higher striking voltage when hot than cold, so that the hot lamp may not restart after a dip.

Some adjustable speed drives are designed to ride through voltage dips. The ride through time can be anywhere from 0.05 to 0.5 seconds, obviously depending on the manufacturer and model. Adjustable speed drives can be damaged by voltage dips and are usually fitted with under voltage detectors that trip at 15 % to 30 % below nominal voltage.

Programmable logic controllers (PLCs) are an important category of equipment for industrial processes because the entire process is often under the control of these devices. The sensitivity to voltage dips varies greatly, but portions of an overall PLC system have been found to be very sensitive.

The acceptability of supply power as a function of duration versus magnitude of voltage disturbances is generally described by power acceptability curves. Well cited power acceptability curve is the ITIC curve (Figure 4.7), originally designed to identify mainframe computer vulnerability to power supply disturbances. The ITIC curve is applied to a wide range of unintended applications, e.g. adjustable speed drives, fluorescent lighting, general (unspecified) loads, and modern solid state (and microprocessor based) computer loads.

4.5.3. Mitigation

There are the various ways to mitigate voltage dips [10]:

- Reducing the number of short-circuit faults: there are several number methods as tree-trimming, animal guards, using covered wires for overhead lines, replacing overhead lines by underground cables, improving maintenance etc. As most of severe voltage dips are due to faults, this fact directly affects the frequency of dips.
- Reducing the fault-cleaning time by using current-limiting fuses, faster static circuit breakers, inverse-time over-current protections etc. This requires improved protection techniques or a new generation of circuit breakers.
- Improved network design and operation such that short-circuit faults result in less severe events: changes in network configuration, installing the local generation near sensitive load, feeding the sensitive load from two or more substations, installation of fast switches, e.g. static transfer switches, for fast transfer of sensitive loads from a primary source to an alternative supply that is unaffected: distribution feeder or a standby power supply. This has been common practice in the design of industrial power systems. The main mitigation method against interruptions is the installation of redundant components (parallel feeders, loop system, multiple sources). But the redundant components can worsen conditions during voltage dip events mainly caused remote faults.
- Improving the immunity of the equipment: making the equipment immune against all voltage dips also solves the problem, but it is unfeasible for most equipment.
- Mitigation equipment at the interface: the most commonly used method is connecting mitigation equipment between the sensitive load and the supply network. Different devices are currently available for the mitigation of voltage dips.

Motor-generator sets consist of motor supplied by plant power system, synchronous generator supplying the load and flywheel, all connected to common axis. This system enables long-duration ride through (several seconds), but can only be used in industrial environments due to its size, noise and maintenance requirements.

A constant voltage, or ferro-resonant, transformer (CVT) works in a similar manner to a transformer with 1:1 turns ratio which is excited at high point on its saturation curve, thus providing output voltage which is not affected by input voltage variations. This solution is suitable for low-power constant loads.

Electronic tap changers use fast static switches to change the transformation ratio of a transformer. They can be connected in series on the distribution feeder and placed between the supply and the load. In future they may be part of distribution transformers.

All modern mitigation techniques are based on power electronic devices with the voltage-source converter (VSC) being the main building block. There are used various terms for this kind of device, like „compensator", „conditioner", active filter" or „controller". The voltage controllers (series, shunt and combined) are able to compensate the drop in supply voltage even to ridethrough interruption of supply. For not too deep voltage dips they are possible to compensate the drop in voltage magnitude by injecting reactive power only, but for full compensation both reactive and active power are needed. A number of energy storage options are possible: both classical ones (batteries, capacitors) as well as modern ones (superconducting coils, high-speed flywheels, supercapacitors). Capacitors are used for ridethrough times around 1 second, batteries for ridethrough times of 10 minutes and longer.

A series voltage controller consists of a voltage-source converter connected in series with the distribution feeder by means of an injection transformer. It can inject voltages of controllable amplitude, phase angle and frequency into the distribution feeder, thus restoring the voltage to critical loads during dips. This controller is possible to perform perfect voltage compensation in less than half a cycle. This solution, although still costly, is very attractive for large industrial customers (a few MVA) which have very high power quality demands. It allows for the protection of the entire plant from voltage sags (usually down to 50% magnitude and a few hundred milliseconds' duration) through the installation ofonly one device. This device for large loads is also called DVR (dynamic Voltage Restorer).

The shunt-connected voltage controller (sometimes called static Compensator – StatCom, static condensor – statCon, or static var compensator – SVC) is a voltage source converter that is shunt connected to the distribution feeder. The shunt controller is normally used not for mitigating voltage dips, but for the implementation of other functions such as power factor correction, the mitigation of load fluctuation (including voltage flicker) and active filtering purposes. The whole set of power electronic solutions to power quality problems, including static transfer switches, active harmonic filters and voltage controllers, is often referred to as "*Custom Power*".

The most popular VSC-based device is the so-called UPS (Uninterruptible Power Supply). The UPS consists of a diode rectifier followed by an inverter, the energy storage is connected between them. During normal operation, power coming from the ac supply is rectified and then inverted. During a voltage dip or an interruption, the energy released by the battery block maintains the voltage at the dc bus. Depending on the storage capacity of the battery block, it can supply the load for minutes or even hours. Low cost, simple operation and control have made the UPS the standard solution for low-power equipment like computers.

For higher-power loads the UPSs are not economically feasible due to the two power conversions and high requirements for maintenance of the batteries. The backup power source can be used instead of UPS. As soon as a disturbance is detected, the sensitive load is isolated from the power system by a static switch and supplied from the stored energy. For storing energy, either batteries (Battery Energy Storage System - BESS) or small-sized

Superconducting Magnetic Energy Storage (SMES) systems can be used. The main advantages of the SMES as compared to the batteries are the reduced size and lower maintenance requirements.

4.6. Voltage Fluctuations (Voltage Flicker)

4.6.1. Definition and Causes of Voltage Fluctuations

Voltage fluctuations are periodic variations of the voltage envelope or a series of random voltage changes, the magnitude of which does not normally exceed the voltage range ±10% of the nominal voltage (see Figure 4.8).

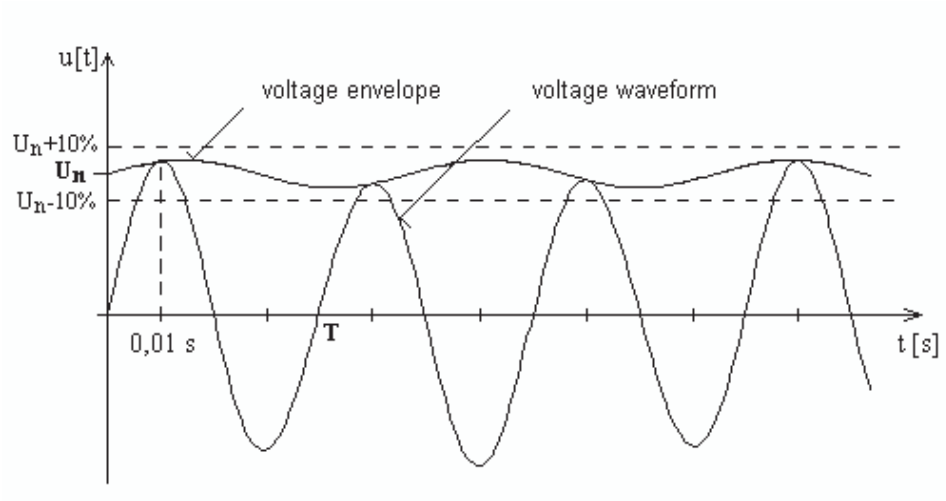


Fig. 4.8 Voltage envelope during periodic voltage variations

For any supply line, the voltage at the load end is different from that at the source (see Figure 4.9). Voltage change at the load-end of the line is expressed:

$$\frac{E-U_0}{U_n} \approx d = \frac{\Delta U}{U_n} = \frac{1}{U_n^2} \cdot (R \cdot P + X \cdot Q) = R \cdot \frac{P}{U_n^2} + \frac{Q}{S_k} = \frac{\sqrt{3}}{U_n} \cdot (R \cdot I \cos\varphi + X \cdot I \sin\varphi) \tag{4.1}$$

where *E* is the source voltage
U0 is the voltage at the load terminals
I is current
X, R is equivalent impedance, reactance and resistance of the line respectively
P, Q, S is active, reactive and apparent power of the load
Sk is short-circuit level at the point of load connection.

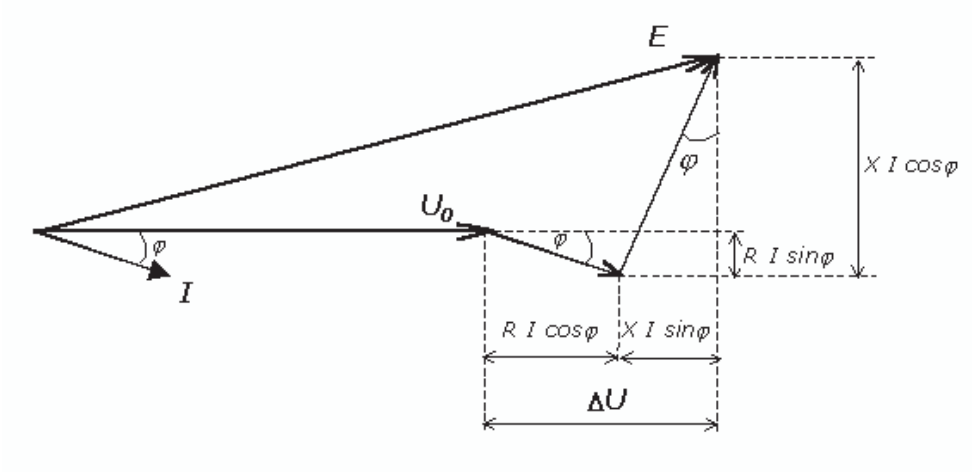


Fig. 4.9 Phasor diagram of supply line for resistive/inductive load

As the load increases, the current in the line increases, thus increasing the voltage drop across the line.

Assuming that the equivalent resistance of the line (or the power system) is negligibly small compared with its reactance (X > 10R), which holds true for practical MV and HV supply systems, the relative value of voltage changes at the load-end of the line mainly depends on changes of reactive power of the load.

The relative value of voltage change at the load-end of the line can be estimated by using the apparent power of the load S and the short-circuit level S_k of the supply circuit:

$$d = \frac{\Delta U}{U_n} \cong \frac{S}{S_k} \tag{4.2}$$

Depending on its cause, voltage change ΔU can take the form of a voltage drop having a constant value over a long time interval, a slow or rapid voltage change, or a voltage fluctuation. The primary cause of voltage changes is the time variability of the reactive power demand of rapidly fluctuating loads, e.g. arc furnaces, rolling mill drives, main winders, starting of induction motors, welders, boilers, power regulators, electric saws and hammers, pumps and compressors, cranes, elevators etc. Variations in generation output of wind turbines can also have the same effects.

4.6.2. Effects of Voltage Fluctuations

Large or rapid voltage variations or variations with frequencies between from about 1 Hz to 15 Hz can result in the flickering of light sources which can cause significant physiological discomfort, physical and psychological tiredness, reduction of concentration - in some situations causing accidents in the workplace. The effect is popularly referred to as “flicker”.

On basis of research of the human reaction to the fluctuation of luminous flux, the perceptibility and flicker severity curves were determined (Figure 4.10). These curves shows the threshold of perception of flicker plotted against percentage voltage change (y axis) and frequency of change (x axis). The curves are determined for sinusoidal or rectangular voltage fluctuations. The area below the curve defines acceptable flicker levels. The response of the

human eye has the characteristic of a band-pass filter between 0.5 Hz and 35 Hz, with maximum sensitivity at a frequency around 1080 changes per a minute. For incandescent light sources, voltage fluctuations of circa 0.3 % of the average value are detected at this frequency.

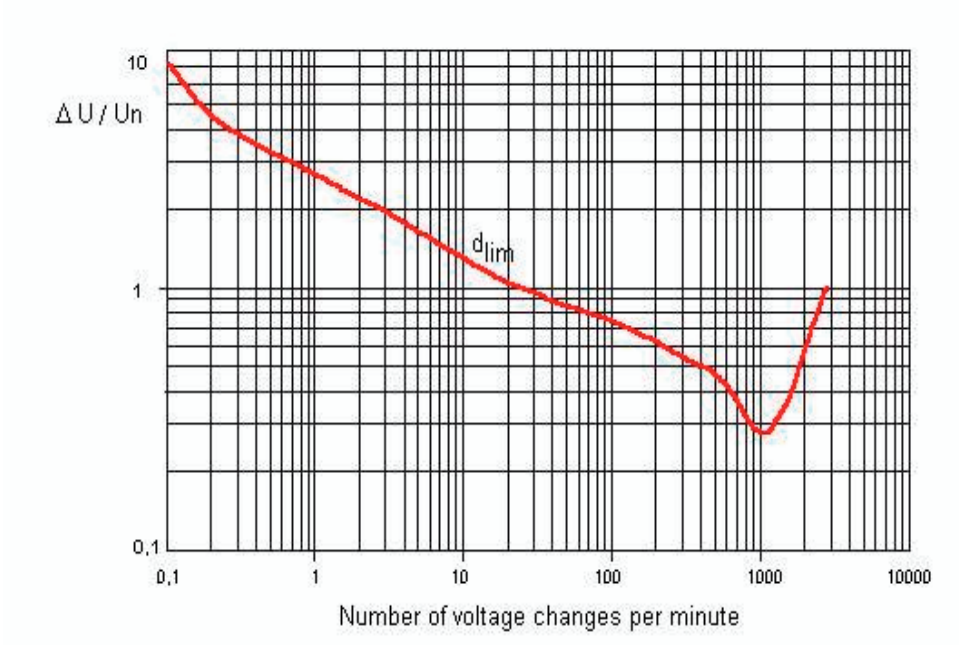


Fig. 4.10 Flicker perception characteristic for square-shaped voltage changes applied to 60 W bulbs

Voltage fluctuations can cause problems with the stability of electrical devices and electronic circuits. Irregular operation of contactors and relays can cause severe disruption to production processes. Voltage fluctuations at the terminals of an induction motor cause changes in torque and slip, and consequently affect the production process. In the worst case they may lead to excessive vibration, reducing mechanical strength and shortening the motor service life. The usual effect of voltage fluctuation in phase-controlled rectifiers with dc-side parameter control is a reduction of power factor and the generation of non-characteristic harmonics and interharmonics. In case of drive braking in an inverter mode it can result in commutation failure and consequent damage of system components.

4.6.3. Characteristics of Voltage Fluctuations

The defining characteristics of voltage fluctuations are:

- the amplitude of voltage change (difference of maximum and minimum rms or peak voltage value, occurring during the disturbance),
- the number of voltage changes over a specified unit of time.

Physiological effects of voltage fluctuations depend on the amplitude of luminous flux changes, the frequency spectrum and the disturbance duration. The basic parameters that determine voltage fluctuations are the short-term flicker severity P_{st} and long-term flicker

severity P_{lt} index. These parameters refer to voltage fluctuation effects on lighting, and their influence on humans (Figure 4.10). The flicker severity indices are defined having value 1 for percentage voltage changes and frequency of these changes lying just on the flicker severity curve.

Short-term flicker P_{st} is measured over a ten minute period. For periodical voltage changes with relative magnitude d and frequency of changes r, the index P_{st} can be determined by using the flicker severity curve:

$$P_{sti} = d / d_{\lim} \tag{4.3}$$

where d_{lim} is the point on the curve for frequency of changes r.

For other types of voltage changes, the procedure of P_{st} calculation is described in the standard PNE 33 3430.

Long-term flicker P_{lt} is calculated from P_{st} values over two hours time frame:

$$P_{lt} = \sqrt[3]{\sum_{i=1}^{12} \frac{P_{sti}^3}{12}} \tag{4.4}$$

The superposition of individual flicker sources i can be calculated:

$$P = \sqrt[\alpha]{P_1^\alpha + P_2^\alpha + ... + P_m^\alpha} \tag{4.5}$$

$\alpha=1$ linear superposition for voltage fluctuations with identical waveshape,

$\alpha=2$ superposition of stochastic voltage fluctuations with similar profile, e.g. wind power stations,

$\alpha=3$ superposition of independent stochastic voltage fluctuations, used for most voltage fluctuations,

$\alpha=4$ superposition of independent stochastic voltage fluctuations originated from arc furnaces, without simultaneous reflow cycles.

4.6.4. Propagation of Voltage Fluctuations

The flicker source (fluctuating load) is located in the node C. Voltage fluctuations are characterized by modulation voltage U_{FC} caused by this fluctuating load. Voltage fluctuations, caused in the node C, propagate into the network and change their magnitudes.

From the node C toward the supply network (i.e. upstream) the voltage fluctuation level decreases in the way the network impedance decreases. Assuming that all network impedances have almost the same phase angle:

$$\frac{U_{FC}}{U_{FD}} = \frac{Z_{CE}}{Z_{DE}} = \frac{S_K^{(D)}}{S_K^{(C)}} \tag{4.6}$$

where U_{FD} is voltage fluctuation in the node D caused by the fluctuating load connected to the node C
Z_{CE} is the short circuit impedance in node C (impedance between the nodes C and E)
Z_{DE} is the short circuit impedance in node D
$S_K^{(i)}$ is short circuit level in node *i*.

The flicker is equal to voltage fluctuations thus short-term flicker severity in the node D is determined:

$$P_{st}^{(D)} = P_{st}^{(C)} \cdot \frac{S_K^{(C)}}{S_K^{(D)}} \tag{4.7}$$

Because of $S_K^{(D)} > S_K^{(C)}$, in direction C to the supply (i.e. upstream) the voltage fluctuation decreases $P_{st}^{(D)} < P_{st}^{(C)}$.

Toward the load (i.e. downstream) the voltage fluctuation remains constant $P_{st}^{(A)} \approx P_{st}^{(B)} \approx P_{st}^{(C)}$, if there is no major generator or asynchronous motor providing a considerable amount of short circuit power. The transfer factors are equal to 1 under ideal conditions, but practical measurement results in values in the range of 0.9 to 1.

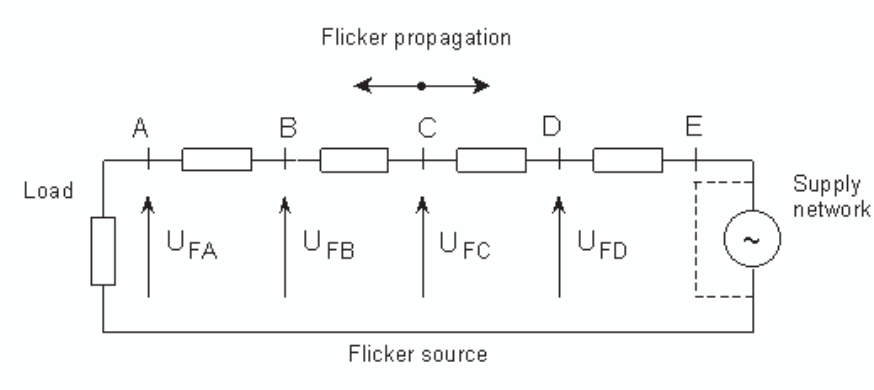


Fig. 4.11 Flicker propagation in a network

4.6.5. Mitigation of Voltage Fluctuations in Power Systems

The effects of voltage fluctuations depend first of all on their amplitude, influenced by the characteristics of the power system, and rate of their occurrence, determined by the technological process, i.e. type of load and character of its operation. Mitigation measures are usually focused on limiting the amplitude of the voltage fluctuations; the technological process is seldom influenced.

As follows from expression (4.1), the amplitude of voltage fluctuations can be limited in two ways:

- **increasing the short circuit power** (with respect to the load power) at the point of coupling to which a fluctuating load is connected. In practical terms, this means:

- connecting the load at a higher voltage level
- supplying this category of loads from specified lines
- separating supplies to fluctuating loads from steady loads by using separate windings of a three-winding transformer
- increasing the rated power of the transformer supplying the fluctuating load
- installing series capacitors.

- **reducing the changes of reactive power in the supply system** by installing dynamic compensators/stabilisers. Their effectiveness depends mainly on their rated power and speed of reaction. By drawing reactive power at the fundamental frequency they produce voltage drops on the supply network impedances. Depending whether the reactive power is inductive or capacitive, the rms voltage value at the point of common connection (PCC) can be increased or reduced.

Static VAR compensators (SVCs) (other than STATCOM) employ capacitive and/or inductive passive components that are (thyristor-)switched, phase controlled or combined with controlled core saturation. Static compensators are considered to be the most advantageous solution for improving the power supply quality, in both technical and economic terms.

Self-commutated converter voltage sources and reactive current/power sources (e.g. STATCOM - Static Synchronous Compensator) use pulse width modulation for controlling the voltage and reactive power. The switching states of semiconductor devices determine the value and character of reactive power (inductive or capacitive).

4.7. Harmonics

Harmonic distortion is largely caused by nonlinear devices in power systems. Although the supply voltage is sinusoidal, the nonlinear load draws a non-sinusoidal (distorted) current. Any non-sinusoidal but periodic waveform can be decomposed into a sum of sinusoidal components with frequencies being multiples of its (the fundamental) frequency ω:

$$i(t) = \sum_{h=0}^{\infty} i_h(t), \text{ where } i_h(t) = \sqrt{2} \cdot I_h \cdot \sin\left(h\omega t + \partial_h\right) \tag{4.8}$$

The fundamental frequency wave is referred to as the fundamental component. The non-fundamental components are called “harmonic distortion”. An individual component (with frequency that is an integer multiply of the fundamental frequency) of a harmonic distortion is called “harmonic”. The multiple of fundamental frequency is referred to as “order of the harmonic”. For example, a component with the frequency being triple of the fundamental frequency is called a third harmonic. The component with zero frequency $i_0(t)=I_0$ is referred to as “dc offset”. When both positive and negative half cycles of non-sinusoidal waveform have identical shapes, the harmonic distortion contains only odd harmonics.

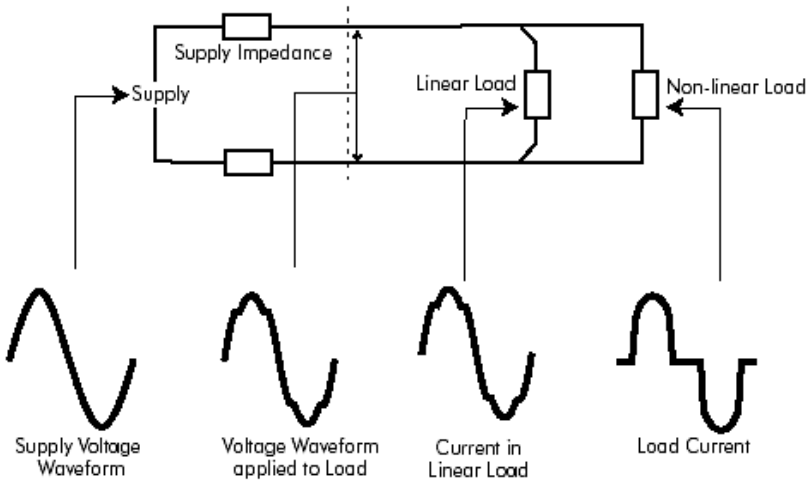


Fig. 4.12 Voltage distortion caused by a non-linear load

4.7.1. Origin of Voltage Harmonic Distortion

The harmonic currents drawn by disturbing load pass through the source impedance and cause a voltage drop for each harmonic. A harmonic voltage drop is proportional to the source impedance at the point of common coupling (PCC) and the harmonic current:

$$U_h = Z_{Sh} \cdot I_h \tag{4.9}$$

This results in voltage harmonics appearing at the PCC and distortion of the supply voltage (Figure 4.12). Due to varying non-sinusoidal current of load, harmonic voltage distortion is not constant, but it is continuously changing during a monitoring period.

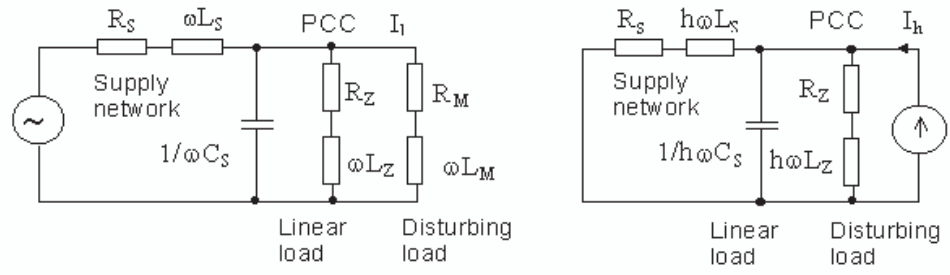


Fig. 4.13 Equivalent circuits for fundamental frequency ω (a) and for harmonic frequency hω (b)

For nearly all analyses, the harmonic-producing loads are treated as current sources. The equivalent circuits of a network with connected linear and harmonic-producing loads are shown in Figure 4.13. At the fundamental frequency, the equivalent system impedance is inductive, often dominated by the supply transformer reactance. The supply voltage is

assumed to be sinusoidal, i.e. to have only fundamental frequency, so that the voltage source is shunted for harmonic frequencies in this figure (b).

In real power systems, the voltage at the PCC is already distorted by the harmonic currents drawn by other consumers.

4.7.2. Resonances in Power Systems

The response of the power system is as important as the source of harmonics, because the response at each harmonic frequency in the PCC determines the true impact of the non-linear load on harmonic voltage distortion.

In all circuits containing both capacitances and inductances, a resonance may develop in which the voltage and current at the resonance frequency reach very high values. This is the origin of most problems with harmonic distortion on power systems. Shunt capacitors, e.g. for power factor correction, do not create harmonics, but severe harmonic distortion can be sometimes attributed to their presence.

A) Parallel resonance

From the perspective of harmonic source the shunt capacitor appears in parallel with the equivalent system inductance at harmonic frequencies (Figure 4.14). The supply voltage is assumed to be sinusoidal, thus the voltage source is shunted for harmonic frequencies.

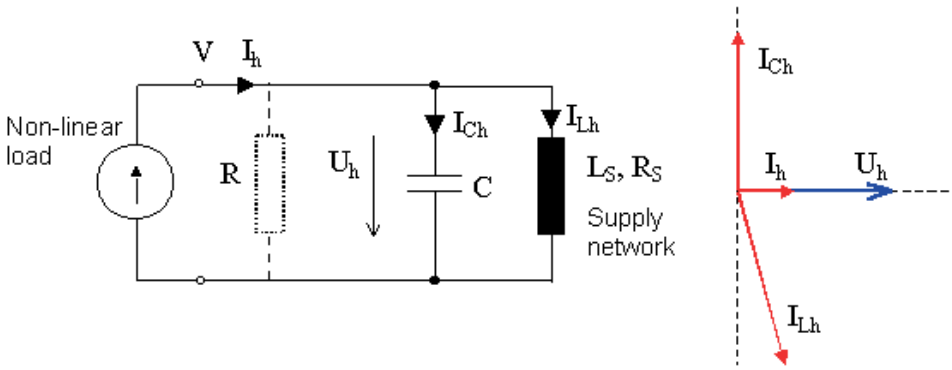


Fig. 4.14 Parallel resonance equivalent circuit

The parallel resonance occurs when $\omega C = 1/\omega L_S$. The resonance frequency is expressed:

$$f_r = \frac{1}{2\pi}\sqrt{\frac{1}{C \cdot L_S}} \tag{4.10}$$

The equivalent system inductance can be computed from short-circuit capacity of the system S_k:

$$\omega \cdot L_S = \frac{U^2}{S_k} \cdot \frac{f}{f_{50}} \tag{4.11}$$

and the capacitive reactance from rating of capacitor bank Q_C:

$$\omega \cdot C = \frac{Q_C}{U^2} \cdot \frac{f}{f_{50}} \tag{4.12}$$

Then the resonance frequency can be expressed:

$$f_r = f_{50} \cdot \sqrt{\frac{S_k}{Q_C}} \tag{4.13}$$

At the resonance frequency, the impedance of the parallel combination of the equivalent inductance and capacitance as seen from the harmonic current source becomes very large. In case the resonance frequency is equal to frequency of harmonic current generated by non-linear load, harmonic voltage at the PCC is very large because of $U_h = Z_h \cdot I_h$. The voltage distortion at the PCC is very severe. Due to parallel resonance the harmonic current flowing through the capacitor I_{Ch} is higher in comparison with the harmonic current injected by disturbing load I_h (Figure 4.14).

The capacitor is affected by overloading and it is recommended that power factor correction capacitors are de-tuned. "De-tuning" means connecting a reactor in series with the PFC (power factor correction) capacitor so that the capacitor/inductor combination behaves as a capacitor at the fundamental frequency, but it has defined behaviour for harmonic frequencies.

B) Series resonance

From the perspective of supply network, a shunt capacitor and the inductance of a transformer may appear as series LC circuit (Figure 4.15). The supply voltage is assumed to have the fundamental component and harmonic component U_h.

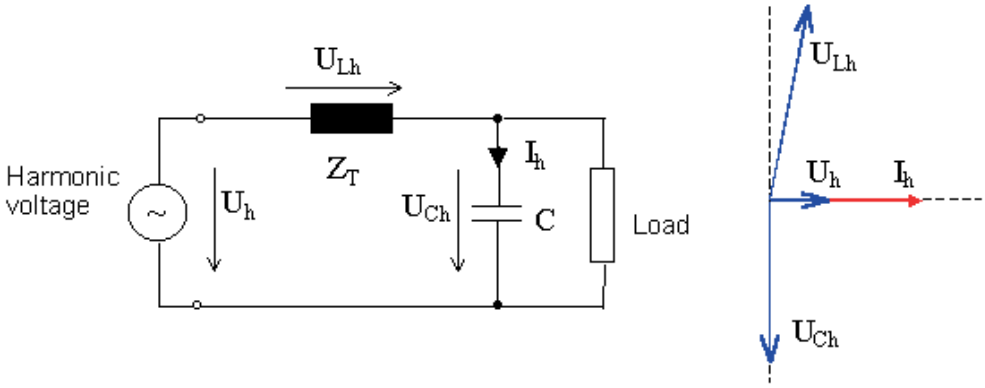


Fig. 4.15 Series resonance equivalent circuit

The series resonance occurs when $\omega L_T = 1/\omega C$.

The resonance frequency is expressed:

$$f_r = \frac{1}{2\pi}\sqrt{\frac{1}{C \cdot L_T}} \tag{4.14}$$

The transformer inductance can be computed from short-circuit voltage u_k and rating of the transformer S_T:

$$\omega \cdot L_T = \frac{U^2}{S_T} \cdot u_k \cdot \frac{f}{f_{50}} \tag{4.15}$$

and the capacitive reactance from rating of capacitor bank Q_C:

$$\omega \cdot C = \frac{Q_C}{U^2} \cdot \frac{f}{f_{50}} \tag{4.16}$$

Then the resonance frequency can be expressed:

$$f_r = f_{50} \cdot \sqrt{\frac{S_T}{Q_C \cdot u_k}} \tag{4.17}$$

If the resonance frequency corresponds to the frequency of the harmonic supply voltage, the impedance of the LC circuit as seen from the supply network becomes very low and the harmonic current flowing through the capacitor I_h is high. The capacitor is overloaded which leads to overheating and potential failure of capacitor.

Some network operators use sound frequencies to control street lighting, night storage heating, and other systems for demand-side management of the load in their system. The closer the signal frequency at supply voltage is to the resonance frequency, the more the capacitor is overloaded. To mitigate this event a parallel LC rejection filter, tuned to the signalling frequencies, is connected in series with the power-factor-correction capacitor.

4.7.3. Power System Quantities under Nonsinusoidal Conditions

In nonsinusoidal conditions a harmonically distorted waveform is made up of sinusoids of harmonic frequencies with different amplitudes. The rms value of the waveforms are computed as the square root of the sum of rms squares of all individual components:

$$U = \sqrt{U_0^2 + U_1^2 + ... + U_h^2} = \sqrt{\sum_{k=0}^{\infty} U_h^2} \quad \text{or}$$

$$I = \sqrt{I_0^2 + I_1^2 + ... + I_h^2} = \sqrt{\sum_{k=0}^{\infty} I_h^2} \tag{4.18}$$

where U_h and I_h are rms value of the harmonic components h

$$u_h(t) = \sqrt{2} \cdot U_h \cdot \sin\left(h\omega t + \beta_h\right), \text{ respectively}$$

$$i_h(t) = \sqrt{2} \cdot I_h \cdot \sin\left(h\omega t + \alpha_h\right) \tag{4.19}$$

The active power *P* is the rate at which energy is expended, dissipated, or consumed by the load. Active power can be computed by averaging the product of the instantaneous voltage and current, i.e.

$$P = \frac{1}{T} \cdot \int_0^T u(t) \cdot i(t) \cdot dt \tag{4.20}$$

This equation is valid for both sinusoidal and non-sinusoidal conditions. For the non-sinusoidal condition, the total active power is the sum of active power of all individual components:

$$P = P_0 + \sum_{h=1}^{\infty} P_h = U_0 \cdot I_0 + \sum_{h=1}^{\infty} \left(\frac{1}{T} \cdot \int_0^T u_h(t) \cdot i_h(t) \cdot dt \right) = U_0 \cdot I_0 + \sum_{h=1}^{\infty} \left(U_h \cdot I_h \cdot \cos \varphi_h \right) \tag{4.21}$$

where $\varphi_h = \beta_h - \alpha_h$ is the phase angle between voltage and current of harmonic component *h*.

For the sinusoidal condition, *P* resolves to the familiar form:

$$P = U_1 I_1 \cos \varphi_1 = S \cos \varphi_1 \tag{4.22}$$

The apparent power *S* is defined as product of rms value of voltage and current waveform:

$$S = U \cdot I = \sqrt{\sum_{h=0}^{\infty} U_h^2} \cdot \sqrt{\sum_{h=0}^{\infty} I_h^2} \tag{4.23}$$

Analogous to the active power, the reactive power is the sum of reactive power at each frequency:

$$Q = \sum_{h=1}^{\infty} Q_h = \sum_{h=1}^{\infty} \left(U_h \cdot I_h \cdot \sin \varphi_h \right) \tag{4.24}$$

In the non-sinusoidal condition, $S^2 \geq P^2 + Q^2$, for this reason new quantity so-called distortion power *D* is introduced:

$$D = \sqrt{S^2 - (P^2 + Q^2)} \tag{4.25}$$

$$D = \sqrt{\sum_{j \neq k}^{\infty} \left[U_k^2 \cdot I_j^2 + U_j^2 \cdot I_k^2 - 2 \cdot U_k \cdot I_k \cdot U_j \cdot I_j \cdot \cos\left(\varphi_k - \varphi_j \right) \right]} \tag{4.26}$$

Distortion power is useless additional contribution to apparent power that increases power losses in the system and reduce capacity of devices.

Power factor (*PF*) is a ratio of useful power to perform real work (active power) to the power supplied by a utility (apparent power). In non-sinusoidal conditions, the power factor that takes into account the contribution from all active power, including both fundamental and

harmonic frequencies, is known as the true power factor:

$$PF = \frac{P}{S} \tag{4.27}$$

In sinusoidal conditions, the power factor can be computed as the cosine of the phase angle and is commonly referred to as the displacement power factor:

$$\cos\varphi = \frac{P_1}{S_1} = \frac{P_1}{\sqrt{P_1^2 + Q_1^2}} \tag{4.28}$$

4.7.4. Harmonic Phase Sequences

In a perfect balanced three-phase system, the harmonic phase sequence can be determined by multiplying the harmonic number *h* with the normal positive-sequence phase rotation. Phase harmonic currents can be generally described:

For a harmonic *h*:

$$I_h^A$$
$$I_h^B = I_h^A \cdot e^{-jh120^\circ}$$
$$I_h^C = I_h^A \cdot e^{+jh120^\circ}$$

For the third harmonic *h = 3*: (Figure 4.16 b)

$$I_3^A$$
$$I_3^B = I_3^A \cdot e^{-j3\cdot120^\circ} = I_3^A \cdot e^{-j360^\circ} = I_3^A$$
$$I_3^C = I_3^A \cdot e^{+j3\cdot120^\circ} = I_3^A \cdot e^{+j360^\circ} = I_3^A$$

For the fifth harmonic *h = 5*: (Figure 4.16 c)

$$I_5^A$$
$$I_5^B = I_5^A \cdot e^{-j5\cdot120^\circ} = I_5^A \cdot e^{-j600^\circ} = I_5^A \cdot e^{+j120^\circ}$$
$$I_5^C = I_5^A \cdot e^{+j5\cdot120^\circ} = I_5^A \cdot e^{+j600^\circ} = I_5^A \cdot e^{-j120^\circ}$$

For the seventh harmonic *h = 7*:

$$I_7^A$$
$$I_7^B = I_7^A \cdot e^{-j7\cdot120^\circ} = I_7^A \cdot e^{-j840^\circ} = I_5^A \cdot e^{-j120^\circ}$$
$$I_7^C = I_7^A \cdot e^{+j7\cdot120^\circ} = I_7^A \cdot e^{+j840^\circ} = I_5^A \cdot e^{+j120^\circ}$$

Phase sequences for other harmonic orders can be determined in the same way.

Harmonics of order *h = 1, 7, 13, ...* are generally positive sequence.
Harmonics of order *h = 5, 11, 17, ...* are generally negative sequence.
Triple-N harmonics (*h = 3, 9, 15, ...*) are generally zero sequence.

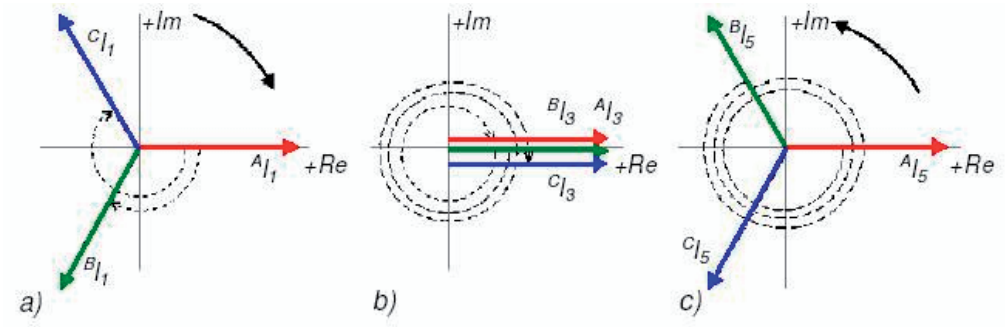


Fig. 4.16 Harmonic phase sequences

4.7.5. Sources of Harmonics

Commercial and modern industrial facilities are characterized by the widespread application of non-liner loads. Commercial facilities are dominated with power-electronic loads like computers, TV sets, UPSs, high-efficiency fluorescent lighting with electronic ballasts, single-phase switched mode power supplies (SMPSs), or adjustable-speed drives for the heating, ventilation and air conditioning loads, and elevator drives.

Adjustable-speed drives, arc furnaces and saturable devices generating harmonics are mainly found at large industrial customers where mitigation methods are applied to limit the resulting voltage distortion. Therefore the resulting voltage distortion is mainly determined by small non-linear loads, although large non-linear loads sometimes cause local problems.

Power-electronic devices (e.g. rectifiers, power convertors) generate harmonic currents of odd orders (5., 7., 11., 13...). The value of harmonic current component is approximately in inverse proportion to its order:

$$I_h \approx \frac{1}{h} \cdot I_1 \qquad (4.29)$$

Capacitor banks are often incorrectly mentioned as a source of harmonic distortion. They are not a cause of harmonic distortion, but the resonance with (mainly transformer) inductances leads to an amplification of the harmonic currents and voltages generated by non-linear loads.

4.7.6. Effects of Harmonics

The main effect of current harmonic distortion is additional losses ($\sum_{h=2}^{\infty} I_h^2 \cdot R_h$), resulting in overheating of electrical equipment and wiring, and life reduction. Transformers are affected in two ways by harmonics. Firstly, the eddy current losses, normally about 10 % of the loss at full load, increase with the square of the harmonic order. This results in a much higher operating temperature and a shorter life. Heavily distorted current waveforms require a re-rating of transformers. The effect is also present for cables and lines, but to a lesser extent. The second effect concerns the triple-N harmonics. The triple-N harmonic currents circulate in the delta winding of transformers and do not propagate onto the supply system, so delta wound transformers are useful as isolating transformers. The circulating current has to be taken into account when rating the transformer.

The triple-N harmonic currents lead to a large sum current through the neutral conductor. This current may cause overheating of the neutral conductor therefore the cables carrying triple-N currents must be de-rated. The problem is especially present in LV installations with large amounts of computers or energy-saving lighting.

Harmonic voltage distortion leads to harmonic currents through linear loads. These harmonic currents may cause extra losses in the loads which requires de-rating of the load. The effect is especially severe for lower-order voltage harmonics at the terminals of rotating machines. Negative sequence voltages have the same effect. The presence of voltage distortion limits the immunity of the machines for voltage unbalance.

The capacitor banks are mainly affected by high-order harmonics. The impedance of the capacitor reduces as frequency rises, therefore the capacitor is likely to carry quite high harmonic currents and be overheated. A more serious problem is that the capacitor and the inductance of the supply system can resonate at or near one of the harmonic frequencies. When this happens, very large harmonic voltages and currents can be generated often leading to the catastrophic failure of the capacitor banks. Resonance can be avoided by adding an inductance in series with the capacitor so that the combination is just inductive at the lowest significant harmonic. This solution limits also the harmonic current that can flow in the capacitor.

Some sensitive electronics loads are affected by distorted voltage waveform, e.g. multiple zero-crossing. Further, the presence of harmonic overvoltage may cause faster ageing of the insulation. Large harmonic distortion can lead to malfunction of equipment (ripple control, protection, control and communication systems) or can impact energy and demand metering.

4.7.7. Mitigation of Harmonics

Harmonic problems can be mitigated by reduction of harmonic voltage or current distortion, or by improving the immunity of equipment. The more common way of reduction the harmonic problem is by installing filters.

Passive filters, typically LC-series connections, shunt the unwanted harmonic current components. The harmonic currents generated by the non-linear loads remain high, but they do not spread through the system and do not cause much harmonic voltage distortion.

The single-tuned filter has impedance:

$$Z_F = R + j(\omega L - {}^{1}\!/_{\omega C}) \tag{4.30}$$

At resonance frequency $f_r = \dfrac{1}{2\pi\sqrt{L \cdot C}}$, when $(\omega L - {}^{1}\!/_{\omega C}) = 0$, the filter is practically a short circuit. Only the resistance, mostly of the reactor winding, remains to be considered, but it is sufficiently low (Figure 4.17b). The current at the resonance frequency produced by disturbing loads flows back towards the supply source and the filter where it divides in inverse proportion to their impedances. Since the filter impedance is almost zero, the harmonic current flowing onto the supply network is very small and, consequently, the harmonic voltage distortion on the supply voltage is reduced.

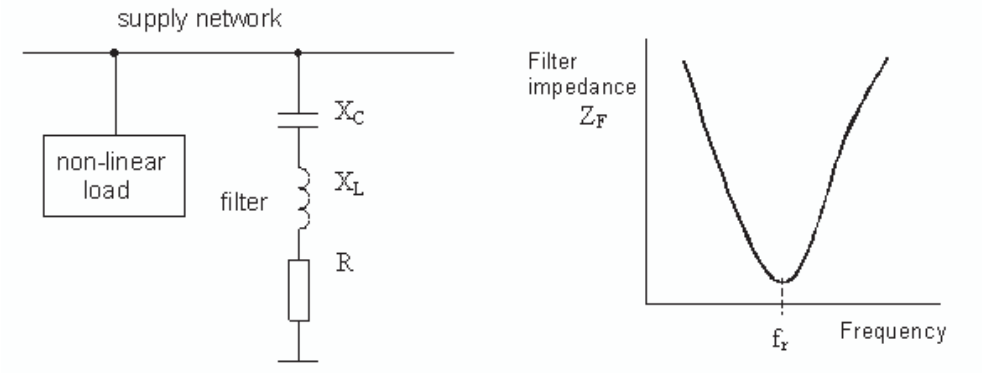


Fig. 4.17 Passive single-tuned filter (a) and its impedance/frequency characteristic (b)

In practice, the functions of harmonic current filtering and power factor correction are often combined. The value of the capacitor determines the reactive compensation available. The value of inductor is specified to determine the harmonic behaviour.

The disadvantages of passive filters (high risk of overload, introduction of new resonances) has led to development of so-called active filters (AF) working by electronically supplying the current or voltage harmonic components into a non-liner load. The concept of the parallel active filter is simple (Figure 4.18a).

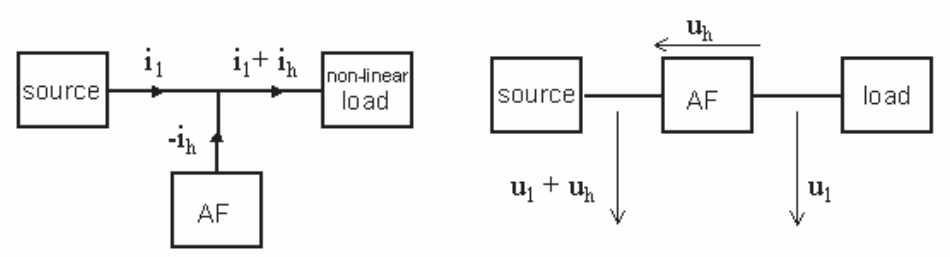


Fig. 4.18 Principle of parallel active filter (a) and series active filter (b)

The active filter (conditioner) is connected in parallel with the supply system. This electronic device analyses the current harmonics drawn by the non-linear load, and generates exactly these harmonics. As a result, harmonic currents are supplied from the AF and fundamental current from the supply system so that the current supplied by the power source remains sinusoidal. In practice, the harmonic current required from the supply is reduced by about 90 %. The AFs can work independently on the system impedance characteristics that means they do not resonate with the system. They can also solve other power quality problems such as flicker or improving power factor.

Series conditioner, connected in series in the distribution network (Figure 4.18b), compensates both the harmonic currents generated by the load and the voltage distortion already present on the supply system. It can be used for protection of the sensitive loads against distorted supply voltage. Hybrid conditioners, combining an active conditioner and a passive filter, may be cost-effective solution. The passive filter carries out basic filtering

(e.g. 5th harmonic) and the active conditioner, due to its precise and dynamic technique, covers the other harmonic orders.

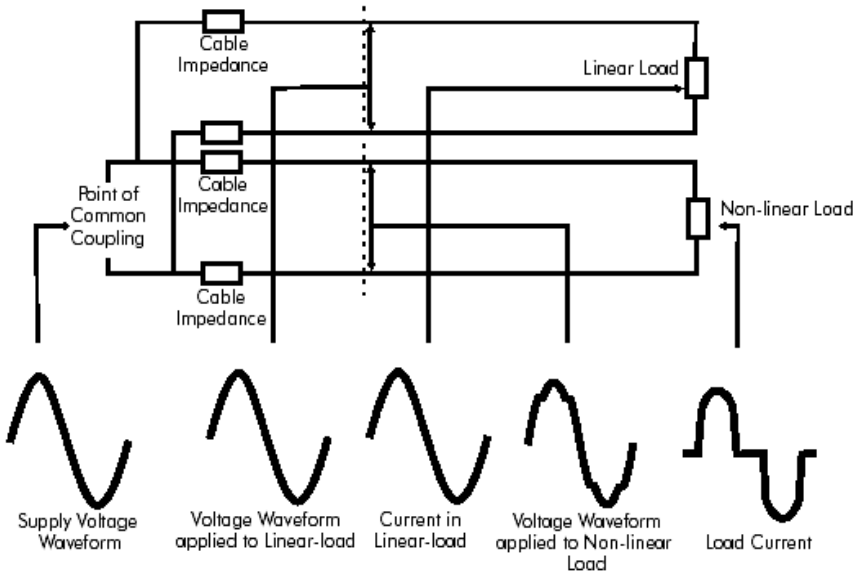


Fig. 4.19 Separation of linear and non-linear loads

Other mitigation methods include improvements in the network (de-rating of transformers, separation of sensitive and disturbing loads – Figure 4.19) and improvements in the load. The latter includes a more sinusoidal current waveform (reduced emission), but also an increased immunity to voltage distortion. Reduced emission is seen as the preferred long-term solution of the harmonic distortion problem.

Delta-connected isolated transformers and zig-zag transformers (i.e. star configuration auto transformers with particular phase relationship between the windings that are connected in shunt with the supply system) are effective against triple-N harmonics but have no effect on other harmonics.

4.8. References

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