Hartmut Kiank, Wolfgang Fruth

Planning Guide for Power Distribution Plants

Design, Implementation and Operation of Industrial Networks

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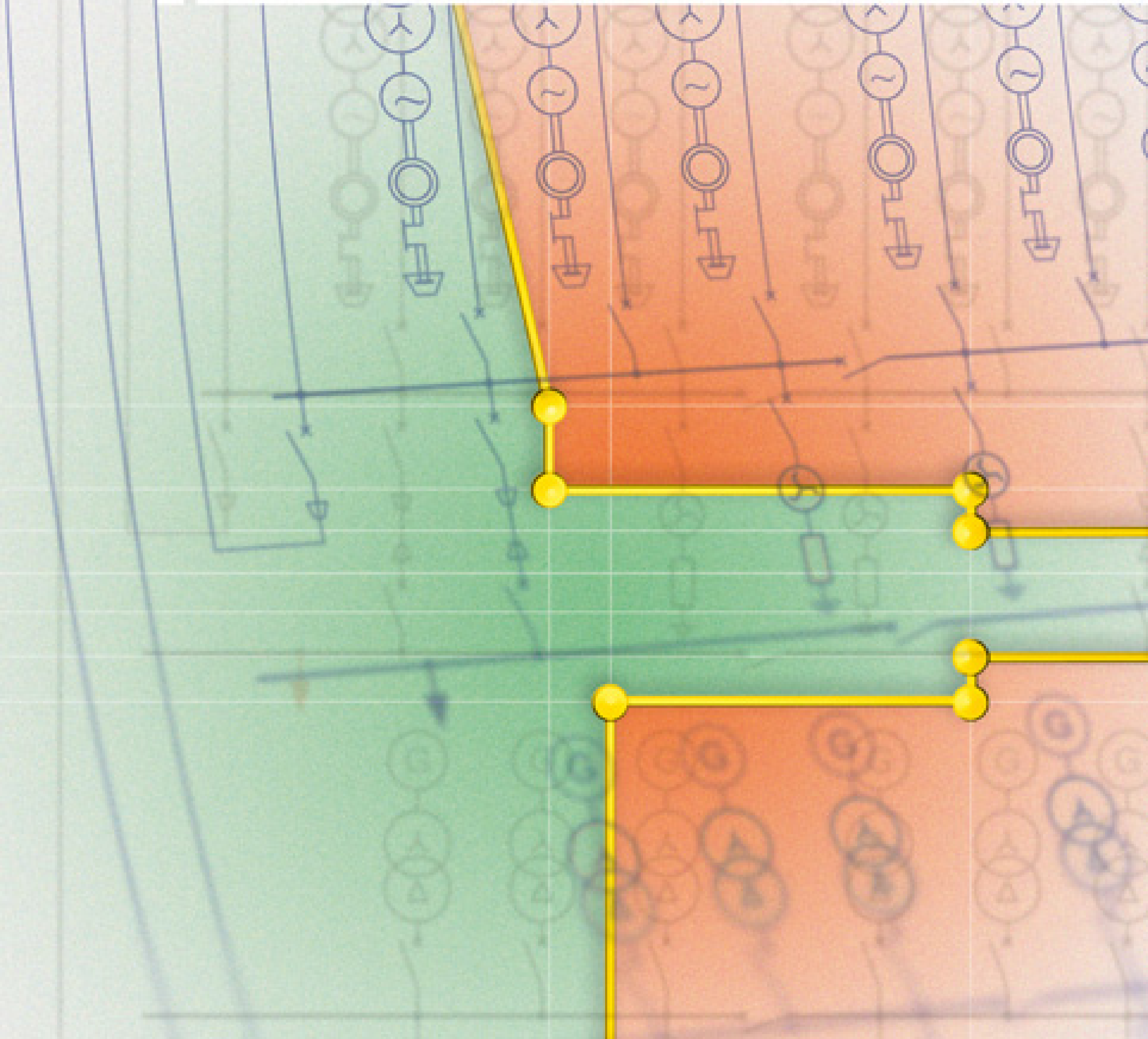

Kiank/Fruth
Planning Guide for Power Distribution Plants

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Foreword

The Power Distribution Market is shifting and undergoing dramatic change. The growing scope of decentralized renewable sources, and interconnection by means of power electronics, just to mention these examples, are adding complexity to network topology. Balancing and safeguarding power, managing the demand, stabilizing voltage and frequency, and – sure enough – optimizing the costs are major drivers that have to be taken into consideration at an early stage in design of an electrical network.

Responding to rapid changes in demand and reconfiguring the network accordingly are bringing the digital world to power distribution. More intelligence in the field and at the component level, in conjunction with digital communication and software, is required in order to meet this challenge. Here again, a well designed network will support the customer in utilizing assets to their full capacity.

Complying with the highest international standards is of course an essential prerequisite.

A thorough understanding of the customer's needs and processes, whether the customer be a utility or an industrial corporation, is essential and instrumental in designing a robust and reliable electrical network and its protection scheme. Optimized integration and deployment of our state-of-the-art products and solutions will enable you to engineer a highly secure and dependable electrical network, crucial in today's world economy.

This book aims to become a reference for those designing and dimensioning electrical networks. It is likewise intended for engineers and technicians working in the energy industry, as well for students who wish to become familiar with this exciting subject matter and for graduates starting their career in this business.

My warm thanks go to Dr. Hartmut Kiank and his co-author Wolfgang Fruth for their meritorious contributions and dedication in the production of this book. They have created an excellent work, balancing theory and practice and placing this complex topic on an understandable and concrete level. All this is the fruit of their experience in the Power Distribution Solutions Business Segment.

One recommendation though: keep this book open on your desk, use it without moderation, dig into it. You will discover a mine of information, unfolding page by page.

Erlangen, July 2011
Jean-Marc Vogel

Preface

Industrial distribution networks must be reliable enough to ensure that the production and process engineering processes they serve can function efficiently, reliably and with the highest possible quality. This is only possible if the planning decisons made for industrial networks meet all the process requirements for power consumption, supply reliability and voltage quality in a technically optimum and efficient way. Because of their complexity and their far-reaching implications for the supply quality and energy efficiency, planning decisions made in the design, dimensioning and operation of networks must be reached in a particularly responsible and judicious way. This is crucial as the true technical risks are often concealed by the complexity of the planning task at hand. If cost-saving potential is also to be exploited, technical risks can only be avoided with competent planning solutions, that is, using the available process expertise and knowledge of the industry technology, technical knowledge about networks and plants, in-depth product knowledge and sound knowledge of the applicable standards and specifications.

With this aim in mind, this guide attempts to convey the solution competence gained in many years of practical work on process-related design, dimensioning and operation of safe and efficient industrial power systems in a simple and understandable way. While Part A discusses the relevant basis of planning, Part B and Part C offer planning recommendations for medium-voltage and low-voltage industrial power systems. These recommendations also provide details of switchgear and protection equipment for networks as well as the interrelationship between the voltage levels (110 kV, MV, LV).

Recommendations for the design and operation of power systems and the selection and parameteriziation of protection equipment are not always stipulated in standards and specifications. In many cases, they have emerged from many years of positive operating experience and practical expertise. Because regulations can only be applied to strategic network planning to a limited degree and planning conditions can vary greatly, some of the recommendations in this guide do offer a certain margin for discretion. It is in the nature of the matter that discrepancies arise within this discretionary margin between the planning recommendations and procedures in specific branches of industry.

This book addresses engineers and technicians working in industrial power engineering, in industrial companies and planning offices. It also helps students and graduates to familiarize themselves with the subject matter.

This planning guide evolved from an idea by the management of the Power Distribution Solutions Business Segment in the Siemens Energy Sector. I would like to thank all involved members of management expressly for their support in the realization of this book project. Many thanks also go to Wolfgang Fruth for his co-authorship of Section C of this book. I am also much indebted to Ursula Dorn who provided competent and committed support with the electronic preparation of the manuscript. And, last but not least, I would like to thank Dr. Gerhard Seitfudem for the fruitful editorial collaboration.

Any critical comments regarding this planning guide are very welcome.

Erlangen, July 2011

Hartmut Kiank

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A Fundamentals

1 Introduction

1.1 Special aspects of industrial power systems

Power systems are used for the transmission and distribution of electrical energy by means of conduction. Power transmission and distribution is always performed on a number of voltage levels. At the high-voltage, medium-voltage and low-voltage levels, the power systems therefore consist of branches (lines, transformers) and nodes (substations with integrated protection and control equipment). A distinction is made between public and industrial distribution systems because of the differing supply tasks and purposes of the power systems. Industrial distribution systems have features and characteristics that distinguish them from public distribution systems. The distinguishing features of industrial power systems are:

- *High density of loads and switchgear*

  For the distribution of electrical energy in industrial plants, distances between system nodes are relatively short at all voltage levels. For that reason, the ratio of the number of items of switchgear to the total line length is greater in industrial power systems than in public power systems [1.1]. Industrial power systems also exhibit very large loads per unit area. The load per unit area in plants in the metal processing sector, for example, is between 70 and 600 VA/m^2, depending on the structure of the loads in the system. In mechanical workshops, values of between 150 and 300 VA/m^2 can be expected on average. These loads per unit area include the lighting (approx. 20 to 30 VA/m^2) and ventilation (approx. 15 to 20 VA/m^2) [1.2, 1.3].

  Public distribution systems, on the other hand, generally only exhibit a load per unit area of between 2 and 20 VA/m^2.

  Because of the clear difference in density of loads and switchgear, the network structures preferred for public power supplies are normally unsuitable for industrial supplies [1.4].

- *High short-circuit power*

  High short-circuit powers are required to ensure that large motors and groups of motors can be started and restarted. Industrial power systems must therefore exhibit sufficiently low system impedance. However, a low system impedance is associated with a high level of short-circuit currents and correspondingly high dynamic and thermal stress on the equipment. Calculations must always consider the worst-case short-circuit current stress, like in the case of connected asynchronous motors. When a short circuit occurs, asynchronous motors produce additional short-circuit current that is fed back into the network. Because of the comparatively high short-circuit current stress, fast tripping of protection devices is particularly important in industrial systems [1.5]. For such applications, HV HRC fuses and differential protection devices are therefore preferred.

- *High mechanical and electrical stresses on the switchgear*

  In industrial power systems there are applications that make especially high demands of the switchgear [1.6]. For example, switchgear that is used for reactive-power compensation and for operating arc furnaces is subject to greater mechanical stresses. In reactive-power compensation, capacitors or shunt reactors usually have to be connected and disconnected several times a day. In arc furnace operation, the number of operating cycles can even reach 100 per day. Connection and disconnection of the high-current electrodes of furnace transformers can also result in extremely high electrical stresses.

  Furnace transformers are dynamic loads that, on connection, can cause high-frequency transient activity accompanied by dangerous resonance phenomena. On disconnection, on the other hand, high transient overvoltages are possible because of current chopping and multiple re-ignition. Excessively high transient overvoltages usually result in dielectric overloading of the equipment insulation.

  To ensure that all switching duties in industrial systems are reliably performed, special attention must be paid to the choice of switching devices (for example, the necessary number of operating cycles, reliable switching of large short-circuit currents and of small inductive and capacitive currents) and any necessary protective measures against impermissible overvoltages (for example, surge arresters and/or RC and CR protection circuits coordinated for the power system).

- *Pure cable networks with relatively short distances between substations*

  Industrial power systems are pure cable networks with relatively short distances between substations. Because the cable connections between substations are shorter than in public distribution systems, protection concepts using distance protection devices usually have lower priority. On the other hand, selectivity problems can also occur with protection concepts with time-overcurrent protection devices. The cause of such problems may be the distribution of the fault currents due to the switching state of the system or the setting of a short total clearing time for the selective grading of protective devices. Because of possible restrictions in the use of distance and time-overcurrent devices, differential protection devices are preferred as the main protection in industrial cable networks.

- *Stringent requirements for the supply reliability of the low-voltage system*

  The requirements for the supply reliability of industrial low-voltage power systems are much more stringent than for public low-voltage systems. In public low-voltage systems (secondary distribution systems), the focus is on fulfilling the supply mission during normal operation. The $(n-1)$ principle is not applied or is only applied to a limited extent [1.7]. In industrial LV systems, on the other hand, application of the $(n-1)$ principle is an absolute condition for a reliable supply of power to production processes.

- *Serious perturbations in the system caused by dynamic loads*

  In industrial systems, there are many loads that produce reactive power or alter the sinusoidal shape of the current [1.8]. Operation of large asynchronous motors, resistance welding equipment and converter-fed drives can cause serious system perturbations in the form of voltage fluctuations, voltage dips, voltage unbalance and harmonic voltage distortions. In the case of periodic pulse loads, flicker is also produced. All system perturbations must be limited so that the effects on the load causing it, on the other loads and on individual items of equipment can be kept to permissible values. For that reason, adequate design and dimensioning of industrial systems must also include measures to prevent impermissible system perturbations. Such measures include, for example, starting methods for large high-voltage motors, active and passive tuned filter circuits, reactive-power compensation equipment with closed-loop control and dynamic voltage restorer (DVR) systems.

- *Existence of in-plant generation systems*

  If industrial plants include in-plant generation systems, technical constraints for stable interconnected operation of the industrial in-plant generation network with the public network must be defined [1.4]. If instability due to short-circuit-type faults in the external power system or impermissible reversal of power flow is likely, the in-plant generation network must be put into stable island operation. Islanding is performed using a tripping device for network splitting. The tripping criteria are frequency reduction, voltage dips and direction of power flow and current [1.5].

  To ensure stable island operation, an additional automatic load-shedding system is often required. In the event of falling frequency, loads are shed to adapt the power demand required for the main processes to the sole remaining in-plant generation. After the fault in the public network has been eliminated and automatic synchronization has been performed with the in-plant generation network, the two networks are synchronized and interconnected again.

- *Many hours of use of the electrical equipment and installations*

  The optimum utilization of capital-intensive production plants and the necessity for economically viable production are resulting in high numbers of hours of use of the electrical equipment and installations. In some branches of industry, utilization periods of up to 8,000 h/a are reached [1.9]. Due to the many annual utilization hours, especially energy-efficient and low-loss power supplies should be aimed for.

- *Close linking of power transmission, distribution and process control*

  In industry, the two primary functions of an electrical power system, transmission and distribution of electrical energy, are closely associated with the specific production process. For the association of functions close to the process, an integrated flow of information between protection, control and automation systems is required. This requirement is often only met by multifunctional industrial control systems for power distribution and process control.

The special aspects explained above underline the main differences between public and industrial distribution networks. These result in different planning recommendations for the design and dimensioning of industrial power systems.

1.2 Need for complete power system and installation engineering solutions

Most power systems used in industry have been developed over a long period of time. The result of such developments are system configurations that have arisen historically and do not meet all the requirements for

- high cost-efficiency and energy efficiency,
- clear mode of operation,
- sufficient redundancy in case of a fault,
- selective protection tripping and quick fault clearance,
- personal safety according to the rules of the employer‘s liability insurance association (e.g. accident prevention regulation BGV A3) or the technical regulations for safety at the workplace (e.g. TRBS 2131),
- short-circuit withstand capability of the equipment,

- high electromagnetic compatibility (EMC),
- low environmental impact

equally well and/or in compliance with the standards. It is the task of the system planners to reassess the historically arisen structures and to develop overall solutions for a cost-efficient and reliable power supply.

Every expansion or upgrade of a system offers an opportunity to develop a complete power system and installation solution [1.10]. This can include the following measures:

- reinstallation of cables for system expansions for production reasons,
- connection of additional system distribution substations or transformer load-centre substations for the power supply to new factory halls or production areas,
- replacement of cables that have become unreliable or prone to short circuit,
- replacement of MV switchgear having insufficient or obsolete safety standards,
- restructuring measures at the incoming supply and distribution level (e.g. implementation of a new nominal system voltage).

In industry, too, the pressure to boost efficiency in the reliable operation of distribution systems will force a departure from restrictively handled investments in isolated measures. The necessary efficiency boost and investment security is offered only by sustainable investments based on a complete power system and installation solution. Only with such a solution can a cost-efficient and reliable power supply with lasting customer benefit be ensured. Moreover, increasing electricity costs, lower pay-back times and new legal regulations encourage investment in energy-efficient complete solutions [1.11].

1.3 Task of system planning

In planning the power supply for industrial plants, decisions have to be made about system design, dimensioning and mode of operation. These decisions must be characterized by sufficient quality of supply (= supply reliability + voltage quality) and high efficiency. While the quality of supply is solely determined by the specific requirements of the production process in question, the efficiency largely depends on the available potential for cost reductions. It is up to system planning to resolve the conflict between making use of cost reduction potential and achieving a high quality of the supply [1.12]. The following planning aspects serve to resolve this conflict:

- definition of new and improvement of old system structures,
- selection of switchgear configurations and basic switchgear circuits,
- determining the location for substations and choosing the routes for cables and lines,
- dimensioning the equipment according to current-carrying capacity for load current and fault current,
- method of neutral earthing for operation of galvanically separated MV networks,
- process-dependent use of the $(n-1)$ failure criterion,
- definition of starting methods for large high-voltage motors,
- specification of solutions for putting industrial power systems with in-plant generation and imported power into stable island operation,
- definition of measures for compensating for flicker and dynamic voltage dips,

- definition of measures to limit system perturbations caused by harmonics,
- drawing up reactive-power assessments and derivation of appropriate compensation measures,
- elaboration of selective and reliable system protection and generator protection concepts,
- choice of electrical equipment according to ambient conditions (e.g. climate, pollution degree, fire load, explosion protection).

These planning aspects show how multifaceted and demanding the planning of industrial power systems is. Because of its multifaceted nature and complex effects on the quality of supply and efficiency, planning decisions must be made especially responsibly. Moreover, decisions on system design, dimensioning and method of operation made in the planning phase can only be corrected to a limited extent in the subsequent project planning and processing phases.

Fig. A1.1 shows how system planning and the phases of the renewal process in industrial plants are interlinked. It is evident that system planning and system operation are

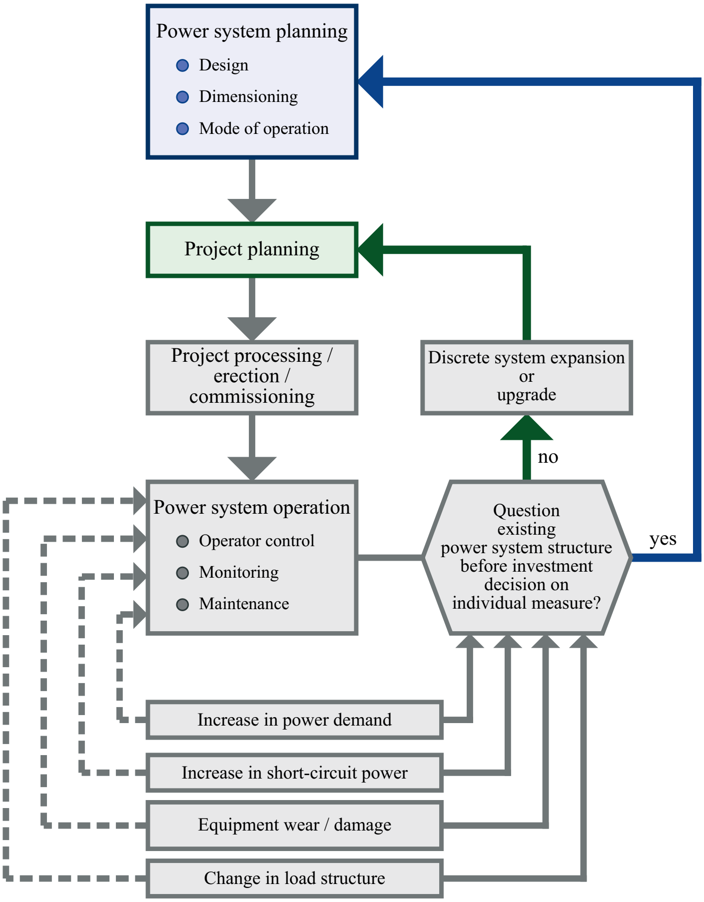


Fig. A1.1 Phases of the renewal process in industrial plants interactively linked by decisions to be made about the necessary consequential investments. Power system operation after commissioning is characterized by

- operating and monitoring measures and
- maintenance and service measures.

The measures for system operation are subject to external influences. The distinctive influencing factors over the many years of operation of industrial systems are:

- in some cases sudden increase in load due to expansion of production,
- increase in active short-circuit power due to replacement of the transformers with larger rated power or smaller percent impedance voltage in the upstream power system,
- ageing and natural wear of the equipment,
- damage to equipment in case of a fault and
- change in load structure due to the growing proportion of EMC-sensitive loads (e.g. IT equipment and computer systems) and harmonic sources (e.g. replacement of conventional incandescent and fluorescent lamps with energy-saving types, modernization of the drives from variable-speed to static converter technology, preferred use of variable-speed drives with power electronics).

The requirements for reliability of system operation can also be affected by changes in regulations and standards. Standards are acknowledged rules of technology that are constantly adapted to the current state of knowledge. This adaptation of standards to the current state of the art can make new system planning advisable.

New system planning is always recommended when the existing structure of the distribution system has to be reconsidered before the decision on whether to invest in a new system expansion is made (see Fig. A1.1). The task of system planning then includes efficient definitions for design, dimensioning and mode of operation adapted to the modified requirements. The planning definitions for the design and dimensioning in this case must especially consider basing the power system on clear structures and the creation of technically and economically expedient margins for the load and fault current-carrying capacity of the equipment. The industrial power system planning as a whole ensures that today‘s production and process engineering can be managed with efficient use of energy, reliably and with the highest possible quality.

2 Basic workflow for planning

2.1 Top-down principle

The development of network and installation concepts for industrial power supplies requires a systematic and strategic approach. This approach involves taking an overall view across all voltage levels (110 kV, MV, LV) that are important for supplying power to the production process.

The top-down principle is especially suitable for systematic planning because decisions with long-term binding consequences must be made with a very broad view and much experience [2.1, 2.2]. Fig. A2.1 shows the basic planning process for industrial power systems based on the top-down principle.

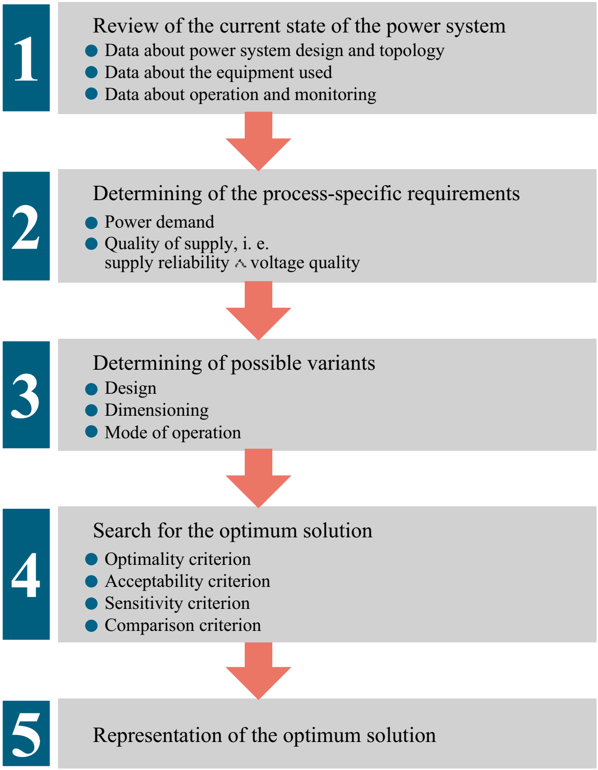


Fig. A2.1
Basic planning process for decisions with long-term binding consequences

2.2 Determining the state of the existing system

The state of the existing system is required to transform historically arisen industrial system structures into clear and simple structures that meet all process-dependent requirements for power demand and quality of supply in a cost-efficient way.

The following data must be recorded to determine the state of the existing system:

a) *Data about power system design and topology*

These include data that are contained in schematic and topological system plans, development plans and machine installation plans. In particular, these are data about

- the physical location of the incoming supply from the upstream system,
- the locations of substations for power distribution,
- the routing of the MV and LV cables,
- the buildings on the factory site,
- the in-plant production areas with local load centres and
- the general structure of the industrial power system.

b) *Data about the equipment used*

These data include system and plant data about the incoming supply and the equipment in the system. Table A2.2 shows a general view of the equipment data to be included to determine the basic state for industrial power system planning.

c) *Data about operation and monitoring*

The system planner requires the following information about operation and monitoring:

- method of neutral earthing of the MV system (isolated neutral (OSPE), resonant neutral earthing (RESPE), low-impedance neutral earthing (NOSPE) or solid earthing),
- type of LV system earthing (electromagnetically compatible TN system with a centrally earthed PEN conductor, TN-S system, TN-C system, TN-C-S system, TT system or IT system),
- relevant circuit states (normal operation (NOP), operation under fault conditions (OPFC)),
- organization of the power system management (e.g. from occurrence to elimination of a fault),
- measured load values of 110-kV/MV transformers, MV/LV transformers and MV cable connections,
- measured voltage values at selected MV and LV nodes (RMS values of the load voltage, values for the magnitude, duration and frequency of voltage dips),
- data about the load structure (presence of large asynchronous motors, converter-fed drives, resistance welding equipment, arc furnaces, large test bays, etc.),
- data from the logbooks of individual items of equipment (commissioning and maintenance times, diagnostic results and faults),
- data about the protection and automation equipment (automatic switchover, UPS, protection relays and their settings, control equipment, alarming equipment, etc.)

Provision of the necessary information for determining the state of the existing system is increasingly supported by information and data processing systems (IT systems) [2.3, 2.4].

Table A2.2 Required equipment data of the basic state (power system data)

Upstream system						
Utility company	Nominal operating voltage U_{nN} [kV]	System short-circuit power		R / X ratio [1]	Asymmetrical current peak factor κ [1]	System time constant τ [1]
		Maximum value $S''_{\mathrm{k-max}}$ [MVA]	Minimum value $S''_{\mathrm{k-min}}$ [MVA]			

110-kV/MV transformer(s)														
Transformer name	Rated voltage		Rated power S_{rT} [MVA]	Percent impedance voltage		Load losses P_{k} [kW]	No-load losses P_0 [kW]	No-load current i_0 [%]	Vector group	Additional voltage per tap step u_{k} [%]	Tap setting		Percent impedance voltage at	
	primary U_{rT1} [kV]	secondary U_{rT2} [kV]		complex u_{rZ} [%]	ohmic u_{rR} [%]						lowest tap s_{min} [1]	highest tap s_{max} [1]	lowest tap u_{uZ} [%]	highest tap u_{oZ} [%]

MV substations (short-circuit strength and MV/LV transformer data)															
Substation or node name	Short-circuit strength parameters					Parameters of the connected transformers									
	Rated voltage U_{m} [kV]	Rated short-circuit breaking current I_{sc} [kA]	Rated short-circuit making current I_{ma} [kA]	Rated short-time withstand current I_{thr} [kA]	Rated short time t_{thr} [sec]	Number of identical transformers n [1]	Rated voltage		Rated power S_{rT} [MVA]	Impedance voltage at rated current		Load losses P_{k} [kW]	No-load losses P_0 [kW]	Vector group
							primary U_{rT1} [kV]	secondary U_{rT2} [kV]		complex u_{rZ} [%]	ohmic u_{rR} [%]			

MV(LV) substations (load and motor data)												
Substation or node name	Load data			Data of the connected motors								
	Maximum power demand P_{max} [MW]	Power factor $\cos\varphi$ [1]	Maximum simultaneous motor power $g\cdot a\cdot\Sigma P_{\mathrm{rM}}$ [MW]	Number of identical motors n [1]	Rated voltage U_{rM} [kV]	Rated power P_{rM} [kW]	Rated current I_{rM} [A]	Efficiency η_{rM} [%]	Power factor $\cos\varphi_{\mathrm{rM}}$ [1]	Ratio of starting current to rated current $I_{\mathrm{start}}/I_{\mathrm{rM}}$ [1]	Synchronous speed n_{syn} [min^{-1}]	Number of pole pairs p_{M} [1]

MV(LV) cables												
Name of the cable connection	Type	Rated voltage U_{m} [kV]	Current-carrying capacity I_{r} [A]	Resistance per unit length in the positive-sequence system at		Reactance per unit length in the positive-sequence system X'_1 [Ω/km]	Resistance per unit length in the zero-sequence system R'_0 [Ω/km]	Reactance per unit length in the zero-sequence system X'_0 [Ω/km]	Specific earth-fault current I'_{CE} [A/km]	Rated short-time current		Rated short time t_{thr} [sec]
				20 °C R'_{1-20} [Ω/km]	90 °C R'_{1-90} [Ω/km]					Conductor I_{thr1} [kA]	Screen I_{thr2} [kA]	

Short-circuit current limiting reactors						
Name of the short-circuit current limiting reactor	Rated voltage U_{rD} [kV]	Rated current I_{rD} [A]	Rated voltage drop u_{rD} [%]	Reactance X_{D} [Ω]	Rated short-time current I_{thr} [kA]	Rated short time t_{thr} [sec]

Generators					
Name of the generator	Rated voltage U_{rG} [kV]	Rated power P_{rG} [MW]	Nominal power factor $\cos\varphi_{\mathrm{rG}}$ [1]	Subtransient reactance x''_{d} [%]	R/X ratio at the connection point [1]

2.3 Determining the requirements

Industrial distribution systems must be planned in such a way that they meet all process-related requirements for

- power demand and
- quality of supply

cost-efficiently and the production process to be supplied with power can run energy-efficiently, reliably and with the highest possible quality. How these process-related requirements for the planning of industrial distribution systems are determined is explained below.

2.3.1 Power demand

The magnitude of the power demand must be determined for each location. The power demand refers to the process-related maximum power of individual loads and groups of loads and the total power demand of the industrial plant. The annual maximum demand for an industrial plant is calculated as follows:

$$P_{\text{max}} = b \cdot \sum_{i} P_{\text{pr-i}} = g \cdot \sum_{i} P_{\text{max-i}} \tag{2.1}$$

b	demand factor
g	coincidence factor
$P_{\text{pr-i}}$	power rating of a load or a group of loads i
$P_{\text{max-i}}$	maximum active power consumption of a load or group of loads i

Guidance values for the demand factor b and the coincidence factor g are listed in Table A2.3. The power demand for the production processes that are performed in a relatively limited space (e.g. factory halls) can also be determined using per-unit-area factors [2.6]. Assuming that the loads are approximately evenly distributed over the production area, the power demand is calculated as follows:

$$P_{\text{max}} = A \cdot P' \tag{2.2}$$

A	production area in m^2
P'	load per unit area in W/m^2

Table A2.4 lists guidance values for loads per unit area. Depending on the type of production and level of automation, higher or lower loads per unit area must be applied.

Equation (2.2) can be used to calculate the power demand of a modern data centre. The power demand calculation is based on a load per unit area of $P' = 1{,}500\ \text{W/m}^2$ [2.10].

To calculate the long-term power demand, the system planner must also consider how the production process may develop in the future. One indicator of this is the present potential for future expansion of production (e.g. spare space that could be used to increase production or productivity in the factory halls or on unbuilt areas of the factory site). To take a possible load increase in the industrial plant into account, [2.11] proposes a power rating for the incoming supply that is 30 % to 50 % larger than that calculated according to Eq. (2.1).

Table A2.3 Demand factor *b* and coincidence factor *g* for calculation of the power demand of plants in various industries (guidance values)

Factors for determining the power demand			
Industry	Demand factor *b*		Coincidence factor *g*
	acc. to [2.5]	acc. to [2.6, 2.7]	acc. to [2.8]
Machine manufacturing	0.20 ⋯ 0.25	0.23	0.95 … 0.99
Automotive industry	0.25	--	0.95 … 0.99
Paper and cellulose industry	0.50 ⋯ 0.70	0.34 ⋯ 0.45	0.95
Textile industry (spinning, weaving)	0.60 ⋯ 0.75	0.32 ⋯ 0.62	1.00
Rubber industry	0.60 ⋯ 0.70	0.45 ⋯ 0.51	0.92
Chemical industry incl. oil industry	0.50 ⋯ 0.70	0.60 ⋯ 0.70	0.95
Cement factories	0.80 ⋯ 0.90	0.50 ⋯ 0.84	0.97
Food and beverage industry	0.70 ⋯ 0.90	--	1.00
Underground hard coal mining	1.0	0.36 ⋯ 0.64	--
Open-cast brown coal mining	0.7	0.70 ⋯ 0.80	--
Metallurgy	0.50 ⋯ 0.90	0.33	1.00
Woodworking industry	--	0.15 ⋯ 0.30	0.98
Mechanical workshops	--	0.15 ⋯ 0.30	0.99
Rolling mills	0.50 ⋯ 0.80	--	--
Foundries	--	0.40 ⋯ 0.50	0.94
Breweries	--	0.40 ⋯ 0.50	--
Footwear factories	--	0.40 ⋯ 0.52	0.99

Table A2.4 Guidance values for loads per unit area *P'*

Production workshops / loads	Load per unit area P' in W/m^2	
	acc. to [2.6]	acc. to [2.9]
Mechanical workshops	200 ⋯ 400	50 ⋯ 250
Toolmaking	50 ⋯ 100	70 ⋯ 100
Punch shops	150 ⋯ 300	80 ⋯ 120
Press shops	150 ⋯ 300	300 ⋯ 450
Welding equipment	300 ⋯ 600	150 ⋯ 250
Painting and curing equipment	300 ⋯ 1,000	200 ⋯ 400
Electroplating	600 ⋯ 800	--
Synthetic resin extrusion shop	100 ⋯ 200	--

The process-related calculation of the power demand also has an impact on the selection and dimensioning of the equipment and the reactive-power compensation. The details of these planning aspects (choice of transformer power rating according to the load carrying capacity or voltage stability criterion, determining of the necessary capacitive power by the multiple coefficient method) will be explained in Chapters 11 and 12.

2.3.2 Quality of supply

The necessary quality of supply is derived from the requirements that the production process has in terms of supply reliability and voltage quality. For that reason, the quality of supply necessarily includes both supply reliability and voltage quality.

The quality of supply is evaluated by the following coordinating conjunction:

$$QS = SR \wedge VQ \tag{2.3}$$

QS quality of supply
SR supply reliability
VQ voltage quality

Only if this AND conjunction is fulfilled (QS complies with the process if SR and VQ comply with the process), can production processes be performed reliably and with the highest possible quality.

2.3.2.1 Supply reliability

The supply reliability (SR) is an essential component of the quality of supply (QS). Its determinants are the frequency and duration of supply interruptions. A low frequency of supply interruptions is largely achieved by high quality assurance standards in production and assembly of the electrical equipment. Moreover, correct selection and dimensioning of all equipment indirectly contributes to reduction of future supply interruptions.

The technically plannable duration of supply interruptions and the maximum interruption duration throughout which a production process can be continued without damage or costs due to losses are especially important for practical system planning. This interruption duration depends on failure events that can occur with a plausible minimum probability at the various levels of the power system (110 kV, MV, LV). The influence of a failure event on continuation of the production process without damage or outage costs can be analysed in two steps:

- *Step 1*

  Enumeration of failure events, i.e. definition of failure events above a plausible minimum probability [2.12]. In clearly structured systems, failure events with a plausible minimum probability are mainly primary single failures. Double faults and difficult combinations of failures can usually be excluded from consideration. Failures of MV busbar and LV high-current busbar systems are considered highly unlikely.
- *Step 2*

  Examination of the effects of the failure event on the power supply of the production process.

To make a sound *SR* planning decision, clarity must be obtained about the permissible interruption duration of the production process and the duration of supply interruptions that can be planned in technical and economic terms. Table A2.5 shows interruption durations that can be used to plan supply reliability, divided into classes.

Table A2.5 Classification of the interruption duration

SR class	Measure for ending or controlling a disturbance / fault-induced interruption	Interruption duration T_u
1	Repair or replacement of the damaged equipment followed by manual reclosure	$\text{h} < T_u \le \text{d}$
2	Local manual load transfer	$\text{min} < T_u \le \text{h}$
3	Load transfer by means of remote control	$\text{sec} < T_u \le \text{min}$
4	Simple automatic load transfer (e. g. controlled by residual voltage)	$300\,\text{msec} < T_u \le \text{sec}$
5	Automatic rapid load transfer	$30\,\text{msec} \le T_u < 300\,\text{msec}$
6	Thyristor-based, static high-speed transfer	$T_u \ge \mu\text{sec}$
7	Isolation of the fault location by protection equipment	$T_u = 0$ $\text{msec} \le t_{\Delta u'} < \text{sec}$
8	Isolation of the fault location by protection equipment and dynamic compensation for voltage dips	$T_u = 0$ $t_{\Delta u'} = 0$ $150\,\text{msec} \le t_{DVR} \le 600\,\text{msec}$
9	Uninterrupted power supply with static or dynamic energy store	$T_u = 0$ $t_{\Delta u'} = 0$ $\text{h} \le t_{UPS/DUPS} < \text{d}$

d = day(s), h = hour(s), min = minute(s), sec = second(s), msec = millisecond(s), µsec = microsecond(s)

Class 1	Power supply of the process without transfer and instantaneous reserve
Class 2 to 6	Backed-up power supply of the process by switchover reserve (“cold standby“ redundancy for a single fault)
Class 7	Backed-up power supply of the process by the instantaneous reserve (“hot standby“ redundancy from the incoming supply to the distribution level)
Class 8	like Class 7 but with additional DVR system for the protection of critical loads from voltage dips $\Delta u'$
Class 9	Doubly backed-up power supply of the process by the instantaneous reserve that is independent of the power system (“hot“ standby for complete power system failure and highest power quality using static online UPS or dynamic DUPS systems)
$t_{\Delta u'}$	Duration of voltage dip $\Delta u'$ in case of short circuit
t_{DVR}	Compensation time of a DVR
$t_{UPS/DUPS}$	Backup time of a static online UPS or a DUPS
SR	Supply reliability
DVR	Dynamic Voltage Restorer
DUPS	Diesel UPS
UPS	Uninterruptible Power System

The interruption durations stated in Table A2.5 apply to a single fault and planning decisions made according to the $(n-1)$ criterion. With $(n-1)$-based planning decisions, the not improbable failure of an item of equipment must not result in an impermissible supply interruption. According to this planning principle, the supply reliability is taken into account as a technical constraint. However, optimum planning is achieved by financial evaluation of the supply reliability [2.12]. The financial evaluation of the supply reliability involves explicit consideration of the present value of investment, operating and outage costs and their aggregate minimization. A model for determining the failure costs due to supply interruptions incurred by industrial businesses is presented in [2.13]. Figs. A2.6 and A2.7 show the results of the model calculation.

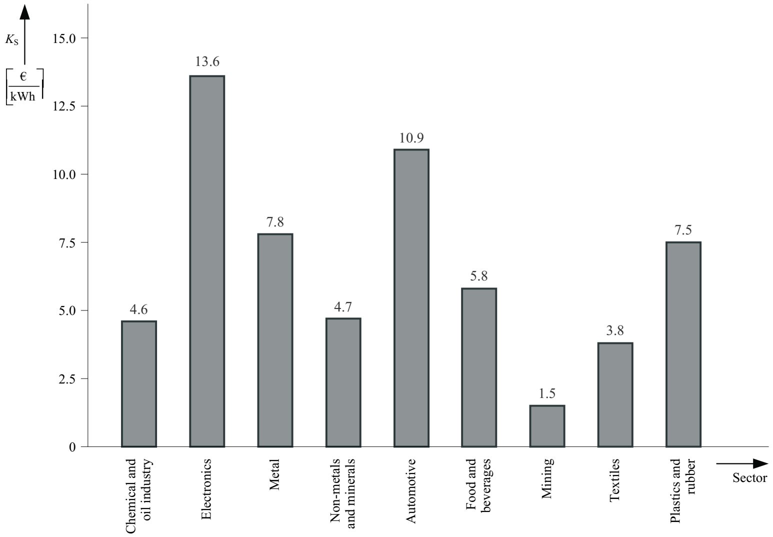


Fig. A2.6 Outage costs K_S due to supply interruptions for various German industries according to [2.13]

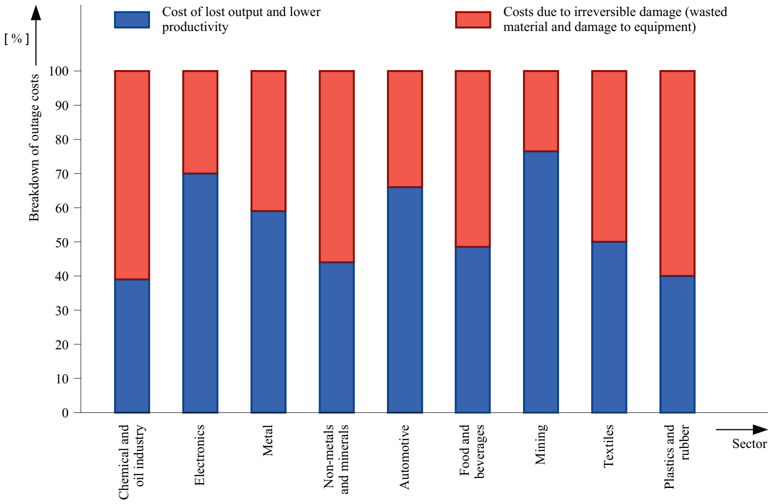


Fig. A2.7 Breakdown of the outage costs for various industries according to [2.13]

The outage costs determined according to the model [2.13] permit financial evaluation of the investment to avoid impermissible supply interruptions as compared with the risk of damage if the necessary *SR* requirements are not met. However, the outage costs stated in Figs. A2.6 and A2.7 are only guidance values. Damage costs due to interruptions are subject to great statistical variance and may differ greatly from one company to another within a single industry. To be precise and verifiable, an *SR* cost-efficiency study must apply the damage costs due to supply interruptions actually incurred by the industrial company.

Conclusion

No stipulations for supply reliability are provided by standards. Consequently, ($n-1$)-based planning decisions are standard practice. To plan the supply reliability according to the ($n-1$) criterion, the interruption durations divided into classes provided in Table A2.5 can be used. Non-restrictive consideration of the supply reliability is only possible if the damage costs due to interruptions are known.

2.3.2.2 Voltage quality

Like the supply reliability (*SR*), the voltage quality (*VQ*) is an essential component of the quality of supply (*QS*). Indeed, the direct dependence of the quality of supply on the voltage quality has become more pronounced than in the past. This new dependency is most noticeable from the more stringent requirements that modern industrial plants make of the voltage quality in all industries. Above all, sensitive production processes and the industrial application of high technologies such as

- continuous production processes in the plastics and chemical industries (e.g. injection moulding processes),
- microprocessor-controlled automation (computer technology),
- nanotechnological processes (nanotechnology),
- semiconductor technology (e.g. wafer production) and
- photolithography and electron beam lithography (e.g. production of lithographic screens for exposing wafers)

call for solutions specially tailored to the specific *VQ* requirements.

The production processes performed in modern industrial plants make very high demands on the voltage quality but production processes performed in such plants may themselves have an adverse effect on the voltage quality because of their non-linear and fluctuating loads.

The negative effect on the voltage quality caused by the process is evaluated using continuous-time characteristic quantities. Such quality characteristics include flicker, harmonics, voltage unbalance and voltage fluctuations. Event-driven quality characteristics include voltage dips, short interruptions of the voltage and overvoltages. These discrete-time characteristic quantities are used to assess the negative impact of faults in the power system on voltage quality. The relevant characteristics of the power quality are explained in Table A2.8 and shown in Fig. A2.9.

To verify the internal compatibility of all loads of a process and the external compatibility of this process with the supply system, precisely defined limit values and compatibility levels are required for the voltage quality. The most important definitions for voltage quality are to be found in the following standards and guidelines:

- DIN EN 50160 (EN 50160): 2008-04 [2.15] (Voltage characteristics of electricity supplied by public distribution networks),
- DIN EN 61000-2-2 (VDE 0839-2-2): 2003-02 [2.16] or IEC 61000-2-2: 2002-03 [2.17] (Compatibility levels for low-frequency conducted disturbances and signalling in public low-voltage power supply systems),
- DIN EN 61000-2-4 (VDE 0839-2-4): 2003-05 [2.18] or IEC 61000-2-4: 2002-06 [2.19] (Compatibility levels in industrial plants for low-frequency conducted disturbances),
- D-A-CH-CZ Guideline 2007 [2.20] (Technical Rules for Assessing System Perturbations).

Table A2.8 Discrete-time and continuous-time characteristics of the voltage quality

Causes of the reduction in voltage quality	Quality characteristic quantities	
	discrete-time	continuous-time
Faults and similar events in the system	Voltage dips 1)	
	Short interruptions of the voltage 2)	
	Overvoltages/surges 3)	
System perturbations		Flicker 4)
		Harmonics 5)
		Voltage unbalances 6)
		Voltage fluctuations 7)

1) Short circuits in the system are not the only cause of voltage dips. Closing operations and connection of large machines (motors, transformers) and loads also cause voltage dips.

2) Voltage interruptions are a special case of voltage dips. They are typical, for example, in 110-kV overhead systems in operation with automatic reclosure.

3) A distinction is made between external and internal overvoltages. External overvoltages include, for example, lightning surges. Typical internal overvoltages include switching and fault surges.

4) Flicker is low-frequency fluctuation of the voltage amplitude ($f < 25$ Hz). It is caused by the intermittent operation of impulse loads (e. g. welding machines). The human eye perceives flicker in the form of fluctuations in luminance, which are found to be extremely irritating. Flicker can also be caused by the so-called stroboscopic effect, which resembles a slowing or stopping rotary machine.

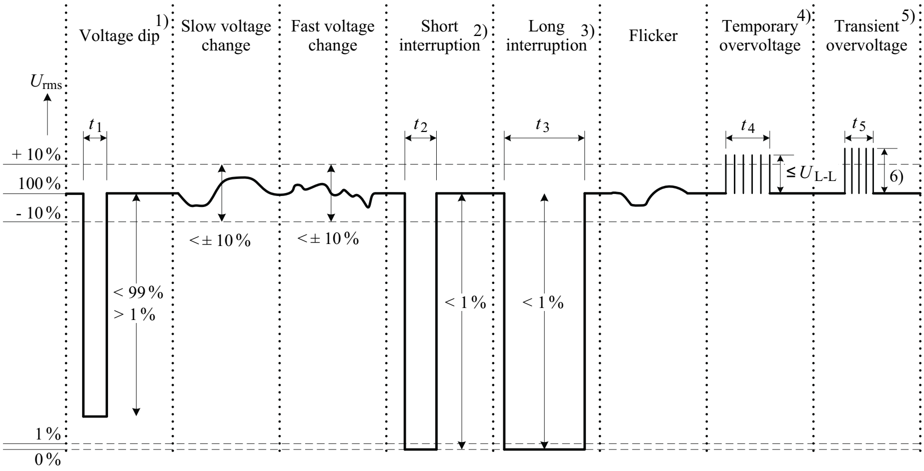
5) Harmonics are currents or voltages whose frequencies are an integer multiple of the sinusoidal 50(60)-Hz fundamental. They are caused by non-linear loads (e. g. static converter equipment, equipment with electronic power supply units, energy-saving lamps, etc.).

6) Voltage unbalance is a state in the three-phase system in which the RMS values of the three voltages or the angles between two consecutive phases are not of equal magnitude. Voltage unbalances can occur transiently (e. g. asymmetrical fault) or temporarily (e. g. load unbalance).

7) Voltage fluctuations are a sequence of voltage changes that are caused by operation of large fluctuating loads (e. g. arc furnaces)

The standard DIN EN 50160 (EN 50160): 2008-04 [2.15] defines the quality characteristics of the voltage for the supply of electrical energy from the public supply system (Table A2.10).

The standards DIN EN 61000-2-2 (VDE 0839-2-2): 2003-02 [2.16] / IEC 61000-2-2: 2003-03 [2.17] and DIN EN 61000-2-4 (VDE 0839-2-4): 2003-05 [2.18] / IEC 61000-2-4: 2002-06 [2.19] and the D-A-CH-CZ Guideline [2.20], on the other hand, define the *VQ* requirements to be observed in the consumption of electrical energy. The essential difference between the above-stated *VQ* standards is the compliance with the limit values or the permissible compatibility level over the stipulated times. The standard DIN EN 50160 (EN 50160): 2008-04 [2.15] states a large number of limit values that only apply to 95 % of each weekly interval (see Table A2.10). However, the standard limits the validity duration to 95 %, which means that the defined limit values can be violated throughout 5 % of a weekly interval, i.e. 8.4 h.



1) 10 msec $\leq t_1 <$ 1 min

2) 0.3 sec $< t_2 \leq$ 3 min for automatic reclosures in 110-kV overhead systems (special case of a voltage dip)

3) $t_3 >$ 3 min (Long interruptions are not a characteristic quantity of the voltage quality. They are a characteristic of the supply reliability)

4) sec $\leq t_4 <$ 1 min

5) 1 µsec $< t_5 \leq$ msec

6) Max. 6 kV at the LV level

Fig. A2.9 Graphical representation of the characteristics of the voltage quality [2.14]

The standards DIN EN 61000-2-2 (VDE 0839-2-2): 2003-02 [2.16] / IEC 61000-2-2: 2002-03 [2.17] and DIN EN 61000-2-4 (VDE 0839-2-4): 2003-05 [2.18] / IEC 61000-2-4: 2002-06 [2.19] do not permit such a mitigation of voltage quality. For more specific evaluation of the voltage quality for consumption of electrical energy, DIN EN 61000-2-4 (VDE 0839-2-4): 2003-05 [2.18] / IEC 61000-2-4: 2002-06 [2.19] have also introduced environment classes. In terms of compliance with the process-related *VQ* requirements, these environment classes have the significance of supply or system classes.

A total of three different supply or system classes are described in Table A2.11. For sound system planning, the process to be supplied with power must be assigned to one of the three system classes. The limit values and compatibility levels that are essential to comply with the voltage quality requirements are derived from correct assignment of the process to a certain class. Table A2.12 provides a selection of the most important limit values and compatibility levels of the voltage quality for consumption of electrical energy.

All system perturbations and faults in the system that result in violation of the compatibility levels in Table A2.12 obtained from DIN EN 61000-2-4 (VDE 0839-2-4): 2003-05 [2.18] / IEC 61000-2-4: 2002-06 [2.19] adversely affect the required voltage quality.

In the LPQI study [2.21], an analysis and evaluation of the annual financial loss in Europe due to adverse effects on the voltage quality were conducted separately for the various industries and quality characteristics. Fig. A2.13 shows the most important result of this study.