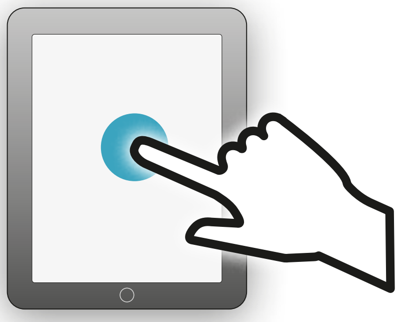
TOTALLY INTEGRATED POWER

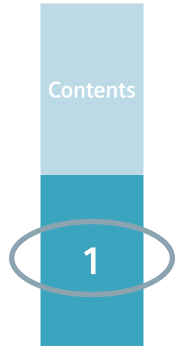
Industrial Plants
Applications for Electric Power Distribution

SIEMENS

Navigation tips



Touch screen
to navigate

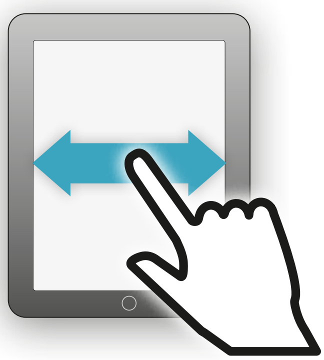


Navigation bar

On every page you will find a navigation bar.

Click on the chapter title/number in the navigation bar to move to the start page of the relevant chapter.

Click on “Contents” at the top to view the contents page.

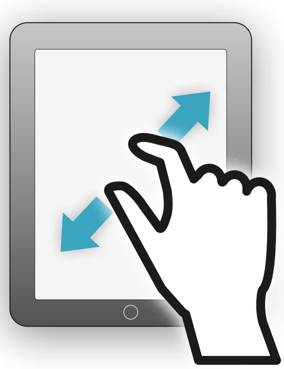


Scroll horizontally
to switch between
individual pages

Contents page

On the contents page you will find a listing of the subchapters.

Click on a subchapter to navigate to the relevant text section.



Pinch or stretch
to zoom

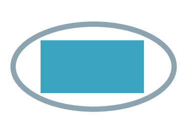
References to figures and tables

... standard EN 15232 can be used for the building management (see Tab. 2/9). However, note that ...

A figure (Fig.) or table (Tab.) that is referred to for the first time in the text and does not appear on the same page will be indicated by a blue background (button).

Click on the reference to skip to the corresponding Fig./Tab.

Fig. 2/3: Competitive situation during planning ...



You can navigate back from a figure or table to the page where it was first mentioned by clicking on the link with the blue background in the caption.

Editorial

Industrial plants constitute a system composed of production facilities, transport and storage possibilities, as well as office and infrastructure facilities. The electric power supply of such a heterogeneous system is a central component used jointly by all facilities and which can have an essential influence on their functionality. Therefore, the most diverse operational and organizational requirements must be taken into account for planning such a system.

Totally Integrated Power (TIP) by Siemens stands for consistent solutions in the planning of the electric power supply for infrastructure, facilities and buildings of industrial plants. Adjusted to the factory planning of Siemens, TIP provides the approach for a reliable and efficient operation of the plants.

Based on the TIP expertise, this manual points out the general outline to be observed for the design and layout of industrial projects during the first planning phases. The quality and functionality of the products and systems by Siemens specify a broad field of application, and can thus be dimensioned and configured in multiple respects. Nevertheless, the overall project and its framework conditions must never be left out of consideration.

This manual can give ideas and show what an industrial-specific procedure may look like. Further project-specific support beyond the contents of this manual will be provided by the TIP contact partners at Siemens.

Sebastian Büschel

Head of Consultant Support Totally Integrated Power

Contents

1
2
3
4
5
6
7

Contents

Chapter 1

Introduction
(Virtualization, Business Agility)

1 Introduction

The series of Siemens application manuals on electric power distribution is based on the general planning instructions as described in the planning manuals (such as [1.1]). The application manuals substantiate the general concepts and descriptions regarding the special requirements of the respective applications. In the present application manual, an outline of the requirements for industrial networks is created and implemented in sample networks, taking into account the digitalization and integration of embedded generation. The different framework conditions and task definitions lead to specific solution approaches. The analysis thereof and the optimization regarding common customer requirements such as for example
- cost efficiency (investment and operation)
- environmental friendliness
- future-proof design
- security of operation

constitute the main tasks of an electrical planner.

The conception, implementation and operation of industrial networks is comprehensively described in more detail in the document "Planning Guide for Power Distribution Plants" [1.2] for appropriate planning. This application manual takes up the facts in a more fundamental way and elucidates the procedure by means of two examples. In addition, recent developments regarding the integration of embedded generation and energy storage systems are introduced, and the extensive possibilities are outlined which Siemens offers for the planning and construction of industrial plants. This document points out a superordinate structure for the procedure to be followed when planning the electric power supply of industrial plants, for faster and easier integration of the statements made in [1.2] that are much more extensive and technically detailed. For an optimal procedure in the case of extensive planning projects, however, the statements in [1.2] should be taken as a basis.

This application manual can be used, on the one hand, for getting started in the electrical planning of industrial plants, and, on the other hand, serves as a kind of catalog for projects of enterprises, general contractors, and factory planners. The last aspect shows that the consistency of a project solution to be elaborated is also influenced by the consistency of the contractual partner's know-how.

These are some particularities of industrial networks (see [1.2]):
- High load and switchgear/switchboard density
- Simple network configurations enabling clear modes of operation
- High short-circuit power and comparably high short-circuit current stress
- High reliability of supply in the low-voltage distribution network
- Integration of embedded generation and energy storage
- Close connection of manufacturing/production processes and energy provision (generation, storage, distribution)
- Strong network feedbacks due to dynamic consumers
- High number of utilization hours for electrical equipment and systems.

For simplification, no difference is made in the following between manufacturing and production. In economics literature, a difference is usually made between:
- Discrete manufacturing = Irregular demand with single-item or volume production, and typically a change of the manufactured products from time to time.
- Repetitive manufacturing = Time- and quantity-related production of identical products; volume-related ordering
- Process manufacturing = Production = Batch and flow production; differentiation between batch processes (discontinuous) and continuous processes.

As the manufacturing/production capacity of an industrial plant is highly dependent on the power supply, and thus also on the electric power distribution, the planner must in turn urge the customer to supply specifications in as much detail as possible, or to procure these specifications independently, in order to find an optimally adjusted solution. Among other things, these specifications include:
- Definition of loads: Ideally, the planner receives a plan view containing the essential loads with their electrical data
- Process and operational specifications – space- and time-related
- Requirements on redundancy, availability and flexibility
- Placement and characteristic data of systems for embedded generation and energy storage including requested modes of operation
- Characteristic data related to power infeeds by transmission or distribution system operators.

In almost all cases, the coordination of the boundary conditions for planning will be an iterative process, in which the interaction between operator, factory planer, architect, production planner, electrical planner, and other parties involved should be as smooth as possible.

Contents

1

2

3

4

5

6

7

Beyond the scope of the "classical" additional knowledge in electrical engineering planning for industrial plants, such as experience in factory and production planning, plant engineering and mechanical engineering, automation and building technology, efficiency considerations, as well as environmental and quality management, the planner must nowadays keep track of the latest trends:
- Digitalization of the industry, and Industry 4.0
- Simulations and Building Information Modeling
- Business agility and sustainability.

These trends as well as the hardware- and software-related cross-linking of industrial process and production engineering with the information and communications technology drive the progress in all areas of industrial operation. For some time already, the industry has additionally started another step of cross-linking to adjust to the latest trends and requirements: the intelligent connection between power engineering and process/production engineering. In this context, energy management assumes an important part in order to optimize power supply, power generation, energy storage, and power distribution on the one hand, and availability, safety, efficiency, as well as flexibility and acceleration of the process flows on the other hand.

The interaction during the integration and implementation of the individual trends becomes the guide for the future viability of a project, no matter whether as a greenfield or brownfield. Translated to the planners' work, they will analyze their project based on
- the experience made in the past
- the current options and expectations
- the requirements of customers, authorities, the public, and the environment in the future, and determine their solutions in the present.

i) Industry 4.0

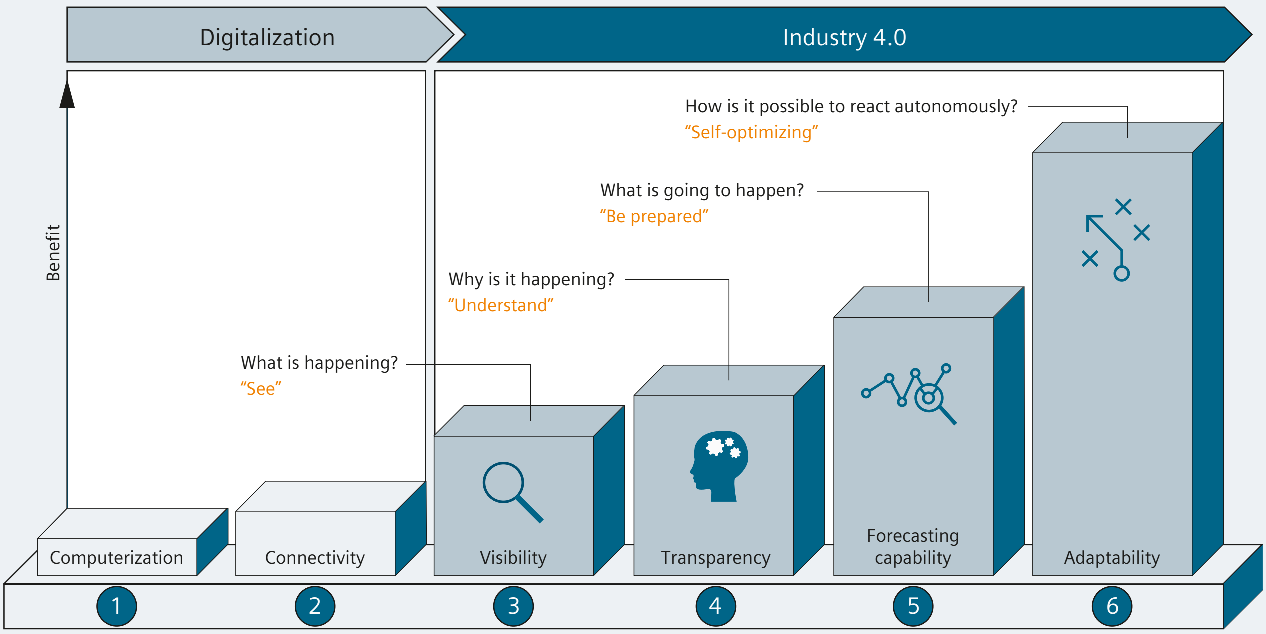
For companies, Industry 4.0 (abbrev.: I4.0) means going deeper step by step into digitalization and the industrial value chain:
- Digitized acquisition of parameters and process variables (use of sensors and measuring devices)
- Use of digital manufacturing and production technology (e.g. actuators, robotics, 3D printing)
- Cross-linking of devices and processes (Internet of Things: IoT, big data, and database concepts such as MindSphere)
- Virtualization of devices, plants and systems (digital twin)
- Simulation and analysis of processes and flows (management systems, production planning systems)
- Automation by control technology (control systems)
- Forecasting and self-regulation via algorithms and expert systems.

This is represented as a cascaded Industry 4.0 development path for the transition from Industry 3.0 (conventional digitalization for ICT utilization) to I4.0 (Fig. 1/1). Similar current keywords referred to factory planning are "advanced manufacturing", "factory of the future", "smart factory", or "smart industry". The term "Cyber Physical System" (CPS) stands for the technology and the engineering the I4.0 concept is based on [1)]. Digitalization, CPS, IoT, and cloud-based web services like MindSphere are elementary components of I4.0.

The objective of I4.0 is
- a cost-optimized flexibilization of all steps in the value chain (keyword: flexibilization)
- while preserving resources and the environment (keyword: efficiency and environmental awareness)
- in conjunction with a timely analysis of boundary conditions (keyword: rapidity)
- and the uncomplicated implementation of decisions (keyword: adaptability)
- while maintaining the requested quality (keyword: quality).

In the end, in the idealized world of full machine-to-machine communication (M2M), human actions concentrate, above all, on the planning phase as well as on the elimination of later failures in the flow of production or operation.

[1)] Note: Cyber Physical Systems not only play a decisive part for I4.0, but are also drivers of many future topics like Smart Grid, Smart Mobility, Active-Assisted Living (AAL), or E-Health.



1 Digital acquisition of parameters and process variables
2 Cross-linking of devices and processes
3 Virtualization and simulation (e.g. digital twin)
4 Analysis, dimensioning and automatic control
5 Forecasting for scheduling and resource planning as well as production control, among others
6 Automation, cloud-based web services and "M3" (Machine-Machine-Management)

Source: FIR e. V.,UdZPraxis, 2017

Fig. 1/1: **Development path of Industry 4.0 for the digital transformation of companies [1.3]**

ii) Building Information Modeling (BIM)

An important component for the planning of industrial plants for I4.0 is the integration of BIM in the factory planning process. The modeling has to observe the cross connections and overlaps between systems and processes, which in most cases have been completely planned in separate projects:

- Plant engineering
- Building technology
- Power engineering
- ICT systems
- Architecture
- Business processes
- Manufacturing or production processes
- Logistic processes.

BIM is a first step towards an integrated planning. Technical planners create separate, digital partial models, which then remain saved in a central model for further use. The virtual model accompanies the factory throughout the entire lifecycle: from planning through construction and operation to modification or retrofitting, and up to removal.

BIM goes far beyond the conventional 3D planning and is to be considered as a building- and process-overlapping coordination and optimization concept [1.4]. In addition to the 3D data for the geometry of the building models, it is necessary to collect the data for the other dimensions of the building information models [1.5]:

- 4D – Construction time planning
- 5D – Construction cost planning
- 6D – Lifecycle information that is characteristic for the operation.

The BIM objectives are as follows, in accordance with the VDI Guideline 2552 Sheet 1:

- Optimization of the planning quality
- Increase of the cost security
- Building efficiency and/or better lifecycle considerations
- Risk minimization through requirements management, construction process models, and integrated schedule models

- Better overview and control possibilities by data collection and data administration with a central data management
- Provision of a standardized tool with extended options for marketing and public relations.

The standardized and structured information exchange as well as the higher-level storage of the project data are basic advantages (like in Fig. 1/2, for example). Incompatibilities, coordination problems, intersections, redundancies, unacceptability, environmental impacts, and the problems of time, additional costs, and dissatisfaction resulting therefrom can be avoided in this way.

In line with this, the German VDI Guideline 2552 Sheet 1 defines the performance phases of the planning process according to HOAI (German Official Scale of Fees for Services by Architects and Engineers). While VDI 2552 Sheet 1 specifies that the establishment of the project basis and the preliminary planning (performance phases 1 and 2 according to HOAI) shall not take place before data drop 3 (project development), it would be desirable – in view of the advantages of an early possibility of coordination – to include the electrical planner already in the demand determination (Tab. 1/1).

It has to be observed that the consideration of the operational processes plays an important part in the factory planning (see Chapter 2). In consequence, the BIM model approach with time and costs as complementary decision factors is of particular interest for the planning of industrial plants. The demand for information multiplies according to the many factors to be taken into account. Moreover, inaccuracies or even missing information and estimations can lead to expensive iteration loops. For this reason, the planning expenditure for industrial plants should put a strong emphasis especially on the first three milestones from Tab. 1/1, for the sake of both time and costs. By increasing the degree of detailing, the planning expenditure for information, documentation, coordination, and integration will grow continuously, which means that the significance of a digital basis for diagrams, calculations, simulations, and vouchers – with BIM as the working tool – will gain importance.

iii) Business agility and sustainability

The term "business agility" refers to the quick response of an economic system to changes. This can be translated to the complete business environment and thus also to the planning of industrial plants. The intensive cooperation of the parties involved, the implementation and documentation of results for other parties included in the planning, as well as the creation of optimal solutions that do also consider other installations, can particularly provide an agile plus. Hereby, the electronic documentation as requested in the BIM is successfully applied.

Flexibility and dynamism are core concepts of business agility, which shall especially help in the context of increasing complexity and time-critical requirements of the planning. The growing data volume not only needs to be recorded and stored, but also processed and implemented in process updates and plant adjustments.

Important criteria for actions can be – as is always non-bindingly phrased – the cost-efficiency, environmental friendliness, and sustainability.

Data drop (milestone)	Project phase BIM	Performance phases of the HOAI
1	Concept study	
2	Demand determination	Establishment of the project basis
3	Project development	Preliminary planning
4	Design / Approval	Design planning and approval planning
5	Detailed design	Execution planning, site supervision
6	Project close-out	Site supervision, documentation, acceptance test
7	Operation / Utilization	

Tab. 1/1: **Milestones (data drops) for BIM planning (acc. to VDI 2552 Sheet 1) in relation to HOAI planning steps**

Contents
1
2
3
4
5
6
7

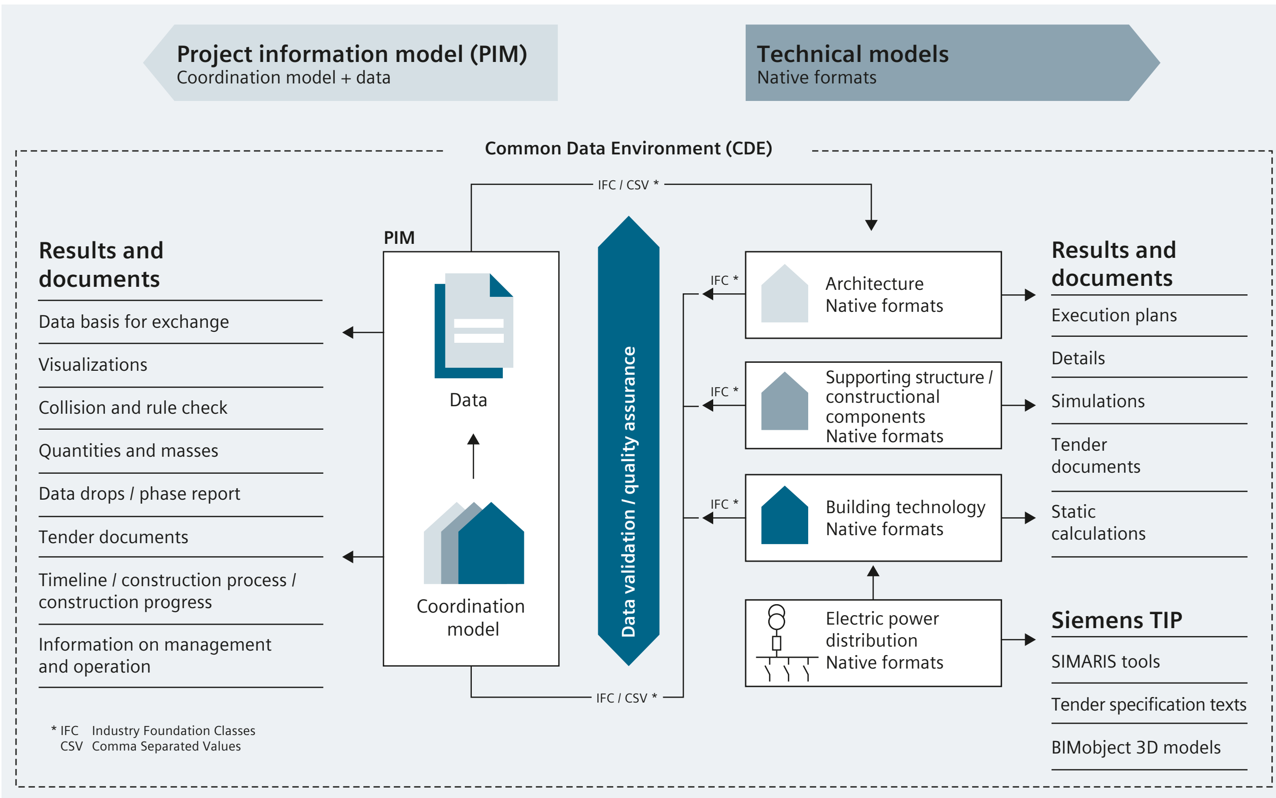


Fig. 1/2: **Schematic representation of a standardized data exchange in BIM [1.6]**

The actual dilemma of business agility is the apparent dropping of a clearly structured flow chart – as specified in the HOAI – in favor of overlapping phases in order to save time and possibly costs. While the current features of BIM direct the planning towards a standardized process guidance and the use of tools, the business agility accentuates the interaction and response to changes in planning projects. The significance of these points increases in the planning – particularly with regard to developments, improvements and coordination – from planning step to planning step.

However, if a builder has only a vague idea about a project, and if the planning target is only specified very roughly, agile methods support the progress of the project. In such cases, only iterative and incremental procedures will help: Many planning teams work in small steps, with full transparency between the individual teams. Transparency is important in order to develop an understanding for the customer requirements, the architect, and the planning colleagues. Planning targets are developed and translated into planning approaches. The results are reviewed and the targets and requirements are adjusted.

Business agility in the planning increases the significance of the first performance phases (see Tab. 1/1; HOAI: PP1 and PP2; BIM: concept study up to project development), and BIM can be an important component of agile planning, especially in view of another trend: A “disruptive” procedure shall divide complex tasks into small segments, or comprehensive models into partial models, with which the experts are able to work faster and with special technical competence. The linking of the individual technical results and the structured data exchange within a BIM project information model (see Fig. 1/2) enables automatic reviews and feedbacks. This facilitates and accelerates the analytics, coordination and documentation in the project planning.

Chapter 2

Factory Planning
(MindSphere, Production Process)

2 Factory Planning

Scientifically, factory planning is associated to an individual branch, the factory sciences. The multidisciplinarity is interesting here, which is not only limited to technical knowledge and commercial thinking, but is also influenced by progress (Fig. 2/1) in the social, natural and even human sciences [2.1].

In the VDI Guideline 5200 Sheet 1, factory planning is defined as follows: "Systematic, objective-oriented process for planning a factory, structured into a sequence of phases, each of which is dependent on the preceding phase, and makes use of particular methods and tools, and extending from the setting of objectives to the start of production." A distinction is made between:
- Development planning (greenfield)
- Replanning (brownfield), including for example remodeling, conversion, expansions, optimizations
- Clearance and demolition (shutdown)
- Site revitalization (greyfield).

Generally, factory planning is always based on an underlying corporate strategy decision, independently of whether it is prompted by internal or external causes, or the combination of both. As a general principle, the factory shall be cost-effective, flexibly adjustable, as well as socially and environmentally compatible.

Regarding the planning horizon of corporate decision-making, the following distinction can be made [2.2]:
- Strategic planning (time horizon of 5 years and more)
  – long-term corporate goal
- Tactical planning (time horizon of 2-3 years)
  – comparison of operation and goals with market conditions
- Operative planning (time horizon of 1 year)
  – actions and means for achieving targets.

Factory planning can be schematically arranged in a structural diagram (Fig. 2/2) according to [2.3].

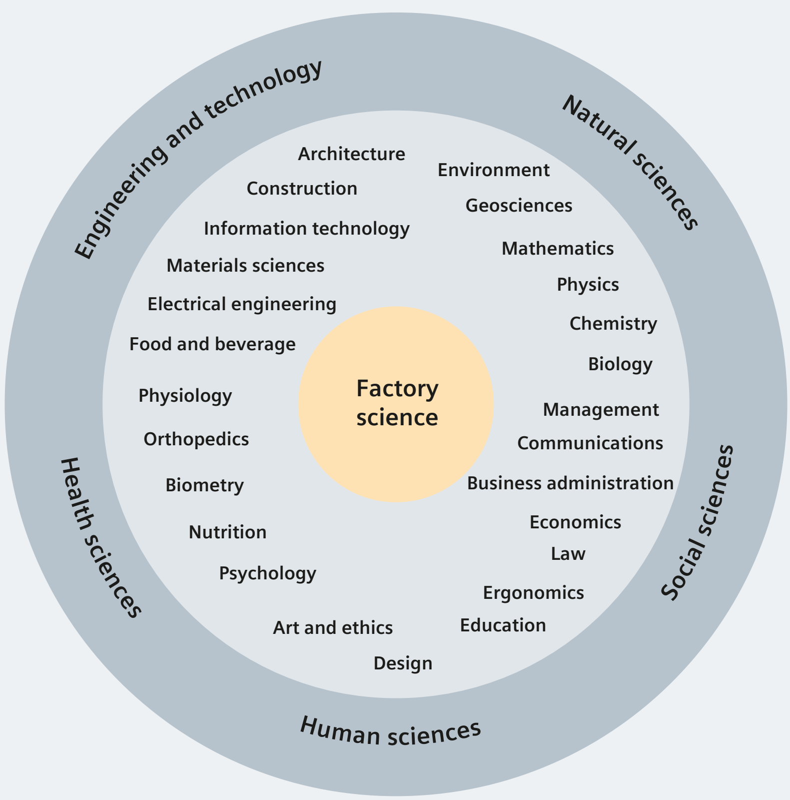


Fig. 2/1: **Multidisciplinarity of factory sciences according to the FOS categorization of the OECD [2.4]**

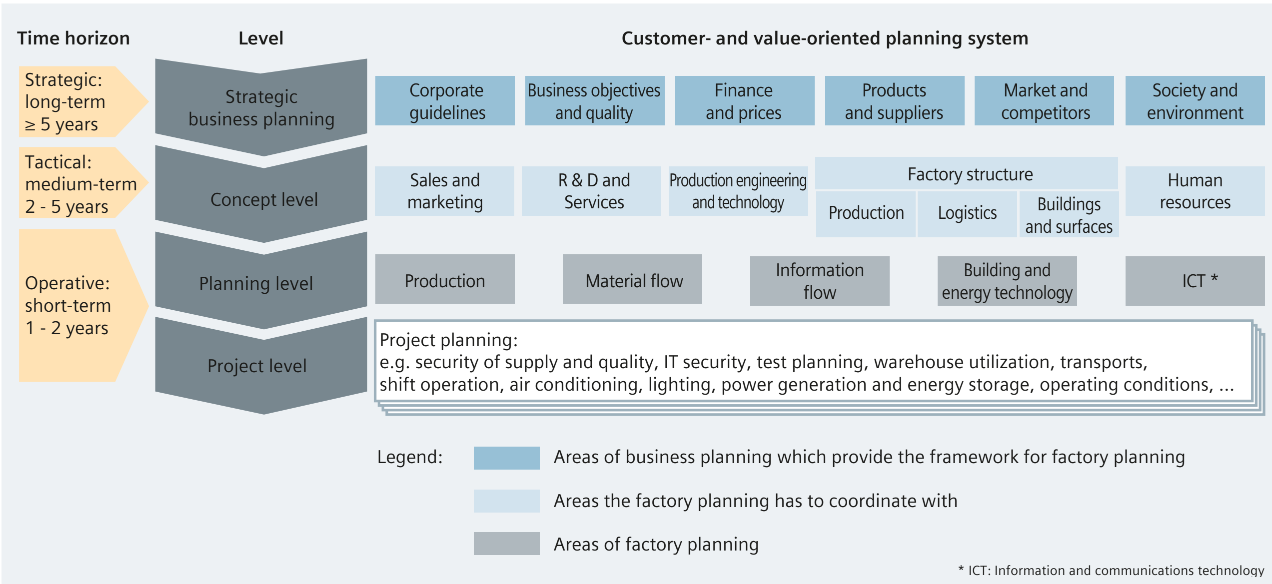


Fig. 2/2: **Structure of an integrated planning system similar to VDI 3637**

2.1 Structure of Factory Planning

As a rule, the company management (or at least their representatives in case of smaller replanning projects) will be the initiator for factory planning. The starting point are structural concepts that have to be approved by the company management. According to Guideline VDI 3637,

- the production-technical structural concept (technological),
- the logistical structural concept (related to process organization),
- and the constructional structural concept (as regards urban development)

provide the framework for factory planning (Fig. 2/2 depicts a detailed planning structure on the basis of Guideline VDI 3637). This clearly shows how important a BIM-conforming planning procedure with the help of a digital twin will be in the future.

Thanks to the standardization of planning processes, the advantages are, among others:

- Reusability of planning results
- Facilitation of documentation and archiving of data.

At the concept level, for example, decision papers shall be prepared that contain data on the intended budget and the cost-efficiency of investment and operation, as well as the expected time frame for implementation and for possibilities of future remodeling. Already in the concept phase, simple models and simulations can support the planners, thus relieving them of routine tasks. In the digital modelling with BIM (see VDI 2552-1 and Chapter 1), this is implemented by means of the concept of an increasing level of detail (LoD) for the planning phases. The level of detail LoD of the model is defined by the level of data depth required for the respective planning stage (level of development: LOD) with regard to economic, technical and geometric information:

$$LoD\ (= LOD) = LoI + LoG$$

Level of detail (LoD) = level of information (LoI) + level of geometry (LoG)

This means: For execution planning, the information must be further refined and the developed factory concept must be implemented with further details as realistically as possible. For these works, there is a high potential for the effective use of the tools of the “Digital Factory” (Chapter 2.3). The latter accelerate the planning process by pointing out workflows to the involved planners, for example with standardized sample solutions. Some examples for this are the quick modelling and arranging of production plants or of parts of the building technology, such as pipes for example, by means of libraries or features.

2.2 Phase Model of Factory Planning

Factory planning, especially for new constructions and conversions, can be divided into phases, too. A corresponding phase model is specified in the VDI Guideline 2552 Sheet 1. Compared with the performance phase structures of BIM and HOAI (Tab. 1/1), the requirements of the enterprise are taken into account in the planning process at an early stage (Fig. 2/3). Detailed explanations related to Fig. 2/3 would go beyond the scope here and can be looked up in the technical literature, for example [2.5] and [2.6].

In this process, an increasing level of detail is created for layout, organization and processes, as well as for the respective links to other planning disciplines. When corporate planning tasks are taken into account, the complexity of correlations between individual planning aspects increases. This generally leads to multiple iteration loops. According to VDI 5200 Sheet 1, the typical planning disciplines to be integrated include:
• Business planning
• Technology development
• Personnel planning
• Financial planning
• Factory operation.

Regarding the five planning levels in Fig. 2/3, a corresponding five-stage planning scheme can be developed:
• Ideal structure (network-oriented)
• Function and flow scheme (factory)
• Idealized layout presentation (rough layout)
• Real layout plan (fine layout)
• Arrangement (process and workstation).

Ultimately, the technical planning effort shall result in the creation and virtual operation of a digital twin already from the beginning of planning (Fig. 2/4) when developing a classical industrial enterprise into a "digital factory".

2.3 Digital Factory

In order to be able to systematically establish and analyze links and processes, a digitalized method of displaying and planning is the way to go. As a starting point for factory planning, the Guideline VDI 4499 Sheet 1 defines the term "digital factory" as a "generic term for a comprehensive network of digital models, methods and tools – including simulation and 3D visualization – integrated by a continuous data management system".

With database applications and simulation possibilities extending further into the production and work processes, digitalization pervades all phases and levels of factory planning. Advantages are, among others:
• Improvement of engineering and automation quality
• Briefer project preparation and execution
• Increase of plant availability and plant safety
• Optimization, training and testing possibilities before commissioning.

It must be noted that the VDI Guideline 4499 Sheet 1 brings the technical and economic aspects of digitalization to the fore. Apart from technology and cost-efficiency, however, the human being is the third, crucial focus area in planning, which must be integrated in all planning in its entirety, observing, among others, working hours, qualifications, and social bonds. The guideline refers to another VDI Guideline (VDI 3633 Sheet 6) that describes the way personnel is displayed in simulation models.

Generally, the influence of the public and civil society, and connected to that, the social and ecological linkages of the factory and production should be considered in the digitalization of factory planning, as mentioned before. In the following, however, the technically oriented planning of electric power distribution is examined, so that the social points of contact of the digital factory can only marginally be included here. Nevertheless, the ecological influence on the technical design of the electric power distribution and therefore on the planning process is becoming increasingly stronger.

Virtualization is a decisive aspect of the digital factory. The consistent digital twin has three characteristics: the product, the production, and the performance of product and production (Fig. 2/4), which shall be made available in one joint data model [2.7].

Planning characteristics	Influencing factors		
• Cost-efficiency • Acceptance • Changeability • Cross-linking, interfaces	Processes: • Process- and control technology • Mechanical engineering and plant engineering	Organization: • Personnel • Suppliers • Operational structure • Operational flows	Infrastructure: • Buildings and surfaces • Supply technology • Building technology

Planning phases

Phase 1	Phase 2	Phase 3	Phase 4	Phase 5	Phase 6	Phase 7
Setting of objectives	Establish-ment of the project basis	Concept planning	Detailed planning	Preparation for reali-zation	Monitoring realization	Ramp-up support

Project management → **Project close-out**

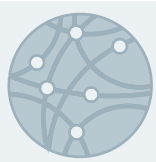
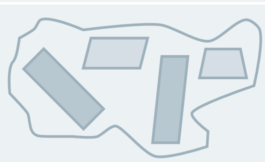
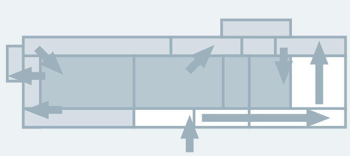
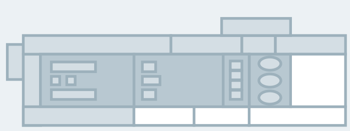
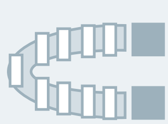
Planning levels		Characteristics
Production network layout		• Stipulations of infrastructure connections • Linking of locations • Influence of business relations
Factory layout		• Macro representation • Arrangement of buildings on the factory grounds and functional areas in the factory buildings
Rough layout		• Rough representation of the functional areas (e.g. production and logistic areas) • Representation of main transport and main material flow paths
Fine layout		• Fine representation with a high degree of detailing • Exact arrangement of operational equipment • Representation of building technologies and media supplies
Workstation layout		• Micro representation • Flow principles and concatenations • Fine arrangement of individual operational equipment in a workstation

Fig. 2/3: **Phases of the factory planning process**

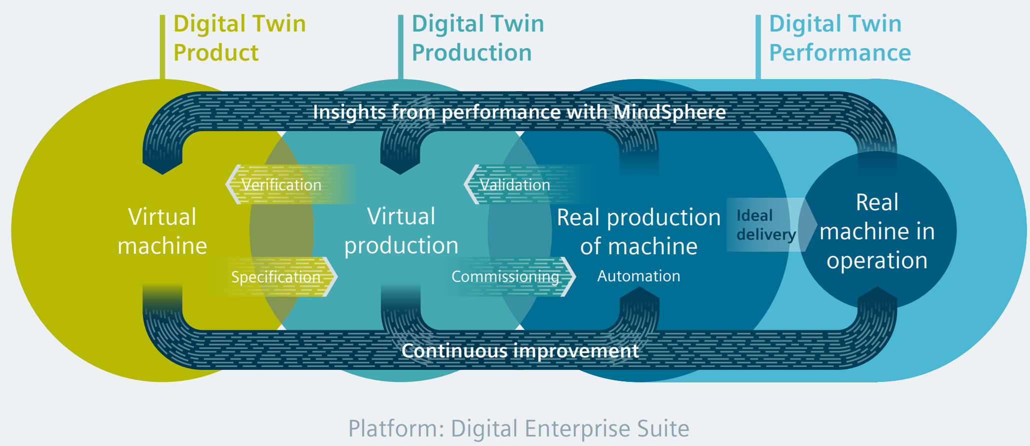


Fig. 2/4: **Virtualization with the Digital Enterprise Suite**

Siemens offers a complete software portfolio around the virtualization of the factory. The Digital Enterprise Suite can generate optimum solutions for the manufacturing operations management (MOM) from multiple components. Components of the Suite include, for example:

- Teamcenter – software for product data and product lifecycle management (PDM and PLM)
- NX – product design and engineering
- Simcenter – creation of a digital product twin and test simulations for performance
- Tecnomatix – manufacturing simulation and process optimization
- COMOS – engineering and asset management, comprehensive training opportunities for operating personnel
- SIMATIC – integration across operations and predictive process planning
- XHQ – KPI management and real-time performance for analytics and decision making support
- SIMIT – system virtualization and simulation of system states for optimizing process-engineering processes; virtual training environment
- TIA Portal – engineering platform, among others for automation and simulation of the automation logic.

MindSphere complements the range for implementing digital factory planning as a part of Industry 4.0. As an open and cloud-based platform (PaaS), MindSphere offers a secure, data-technological connection of devices, machinery and systems. By means of real-time data transmission, applications and services on the platform – for example – can be used for service and optimization purposes. The comparison of real data with the simulation results can point out problems like incorrect stress or delays. Fig. 2/5 roughly illustrates the architecture of the MindSphere platform. A closer description can be found in [2.8].

MindSphere offers a development environment into which own applications and services can be integrated. The platform developed as an open operating system for the Internet of Things allows improving the performance of systems by recording and analyzing large quantities of production data. Connectivity, tools for developers, applications for the collection, visualization, analysis, and further use of data, as well as industry-specific applications and services constitute the core components of MindSphere. The following are examples for the four core components (Fig. 2/5):

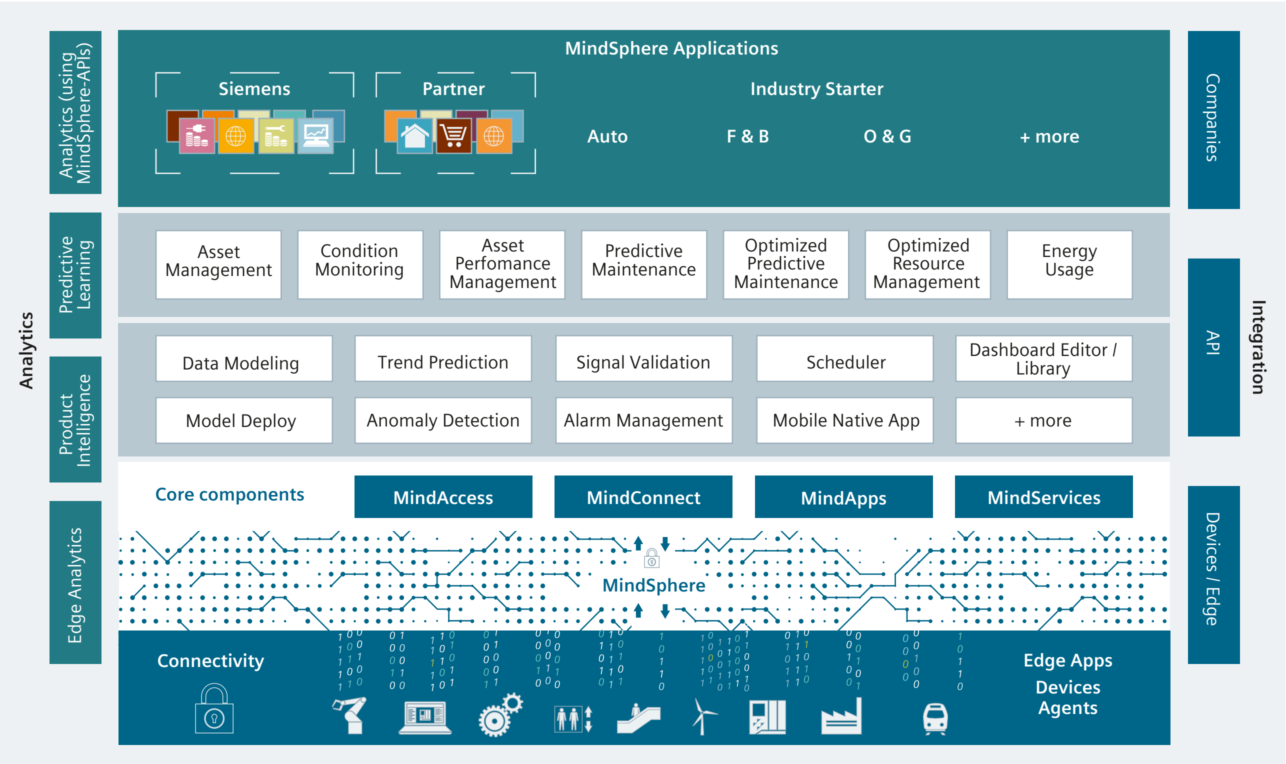


Fig. 2/5: **Overview of the MindSphere architecture [2.8]**

i. MindAccess

- *MindAccess Developer*
  allows access to the development system in order to develop and test applications, and make them available in the live system depending on the package

- *MindAccess User*
  provides an account by means of which the MindSphere platform can be accessed; it allows the use of MindSphere applications, the configuration of assets and users, as well as the storage of data

- *Fleet Manager*
  provides an overview of the assets configured in MindSphere, and enables quickly finding relevant assets based on different criteria and managing them

- *Fleet Manager Plus*
  adds additional functionalities to the Fleet Manager, such as rules with e-mail notification and asset information, as a Plus option

- *Visual Analyzer*
  provides an overview of the assets configured in MindSphere. While the Fleet Manager is a tool for managing the machinery, the Visual Analyzer serves as a tool for an in-depth data search with the option to create specific views of aspects

- *TIBCO Jaspersoft™ Service*
  simplifies the creation of dashboards and reports.

ii. MindConnect

- *Mindconnect Nano / MindConnect IoT2040*
  Hardware (devices) for connection of assets to MindSphere to enable data collection and data transmission

- *MindConnect FB 1500*
  TIA portal STEP 7 library which allows for the connection of the S7-1500 to MindSphere

- *CMS X-Tools PROFESSIONAL*
  Condition monitoring system (CMS), a tool for analytics, diagnostics, visualization, and archiving of dynamic processes in all industrial sectors.

iii. MindApps

- *Product Intelligence*
  automates the context-dependent evaluation of product performance data, thus increasing the transparency of the product and supply chain performance in order to avoid costly recalls, more swiftly solve quality issues, and deepen customer experiences

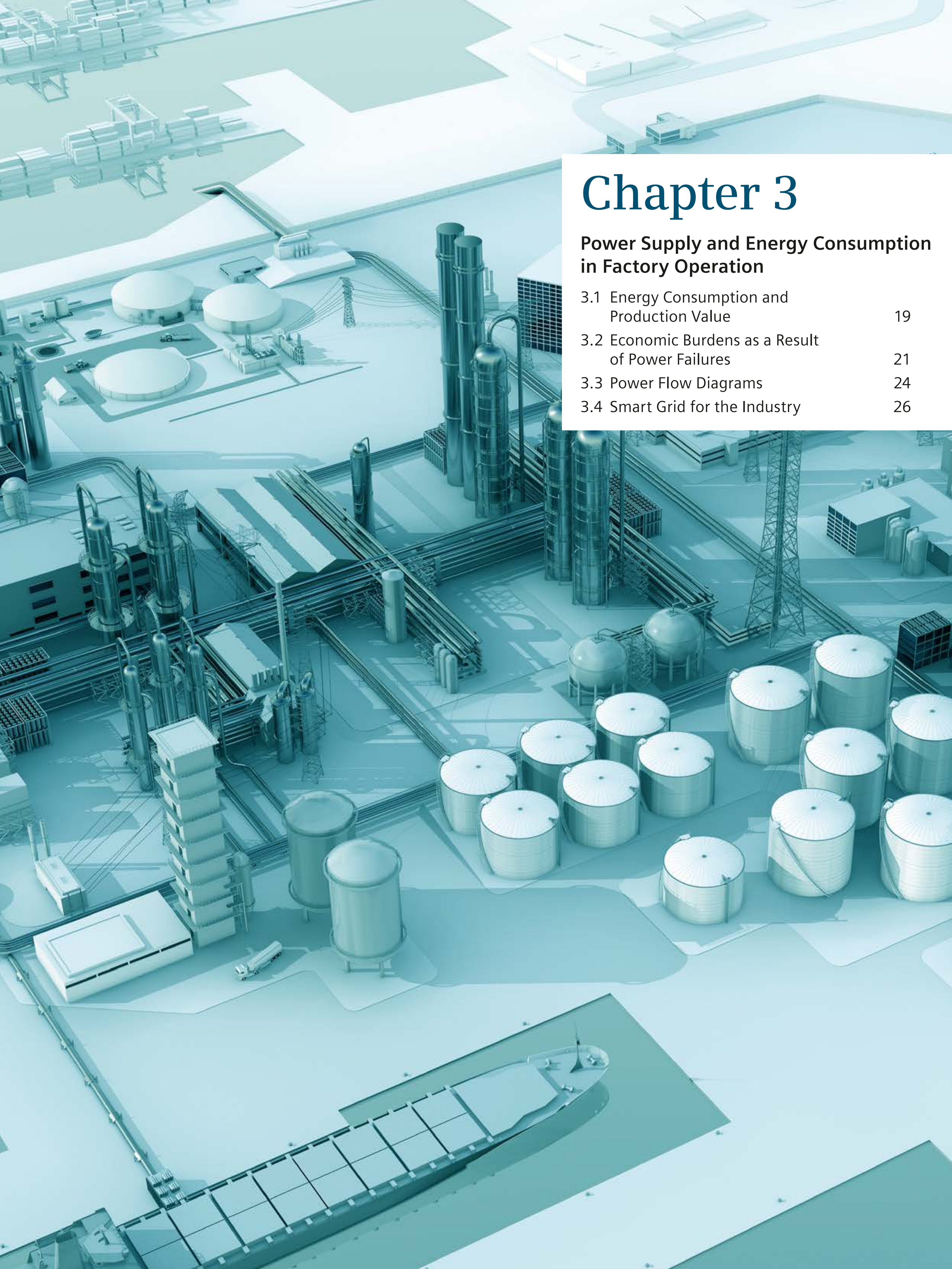
- *Manage MyMachines*
  with minimum effort, tool machinery can be monitored in small and large production facilities to increase their availability and productivity.

iv. MindServices

- *MindSphere Academy*
  stands for universal and diverse training opportunities on the topic of Industry 4.0. The focus is on digitalization in companies, the development of applications, technical possibilities and solutions with MindSphere, as well as the development and distribution of business solutions in the IoT market

- *MindSphere Consulting*
  provides insights and know-how to support and facilitate the implementation of MindSphere. The experience of our experts facilitates onboarding and supports the development of business cases and apps or customized solutions

- *MindSphere Security Service*
  for securing IoT data at any point. Siemens Plant Security Services detects threats early on so that weak points can be analyzed in detail. Appropriate, comprehensive safety measures are implemented to prevent future attacks.



Chapter 3

Power Supply and Energy Consumption in Factory Operation

Contents
1
2
3
4
5
6
7

3 Power Supply and Energy Consumption in Factory Operation

According to the aspects of factory planning described in Chapter 2, the stipulated objective of optimized planning should not only be an investment in systems and facilities that is as economical as possible. Next to the expenses for raw materials, personnel, supplies and services, exemplary cost and performance calculations for the planned industrial plant also take into account the power supply costs. In the future, economic and energy-relevant considerations will be shaped by political framework conditions and environmental aspects even more than today. Fig. 3/1 [3.1] depicts the development of end-use energy consumption classified by energy carriers.

Equally, regional differences have an impact in the usage of different energy carriers and the associated future development (Fig. 3/2). The energy consumption values to be expected up to the year 2050 in Fig. 3/1 and Fig. 3/2 are based on the EIA baseline scenario. For OECD countries, a mean growth of 1.5 % of gross domestic product (GDP) is assumed between 2018 and 2050. For non-OECD countries, this value is approx. 3.8 %, with the absolute value of GDP in non-OECD countries potentially reaching only about 45 % of that of the OECD countries by 2050.

As a detail, it remains to be noted that the increase of end-use energy consumption in OECD countries between 2018 and 2050 is largely caused by an increase in industrial oil and gas consumption in the USA. Electric energy consumption will not stand out in the future, either. Yet, the mean yearly increase of about 1.05 % of industrial electricity consumption exceeds the total energy increase of about 0.9 % per annum.

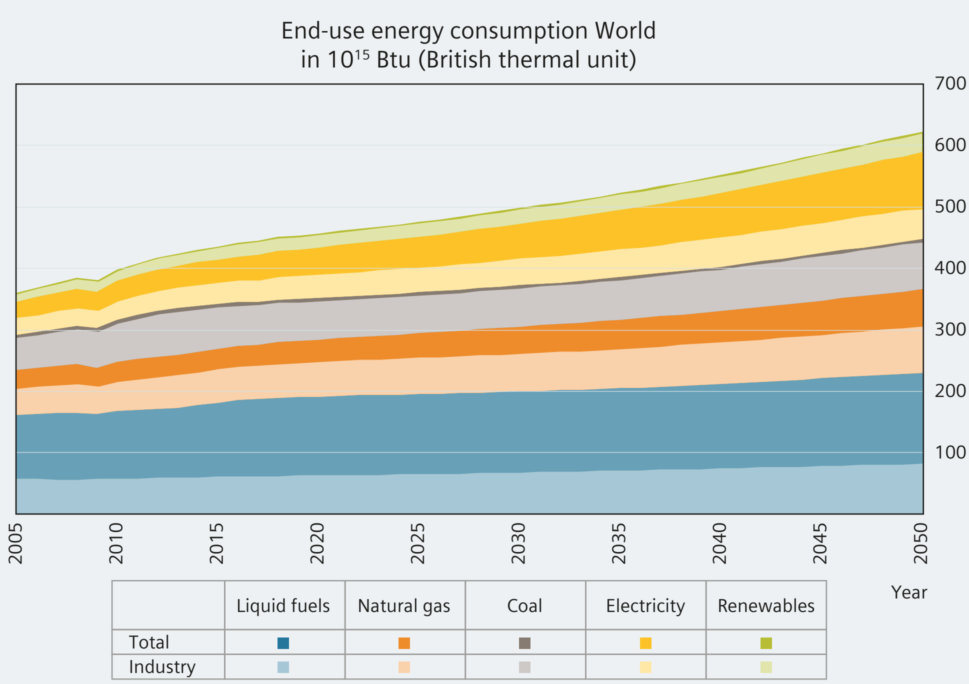


Fig. 3/1: **Development over time of end-use energy consumption worldwide (total consumption and share of industrial use), classified by energy carriers [3.1]**

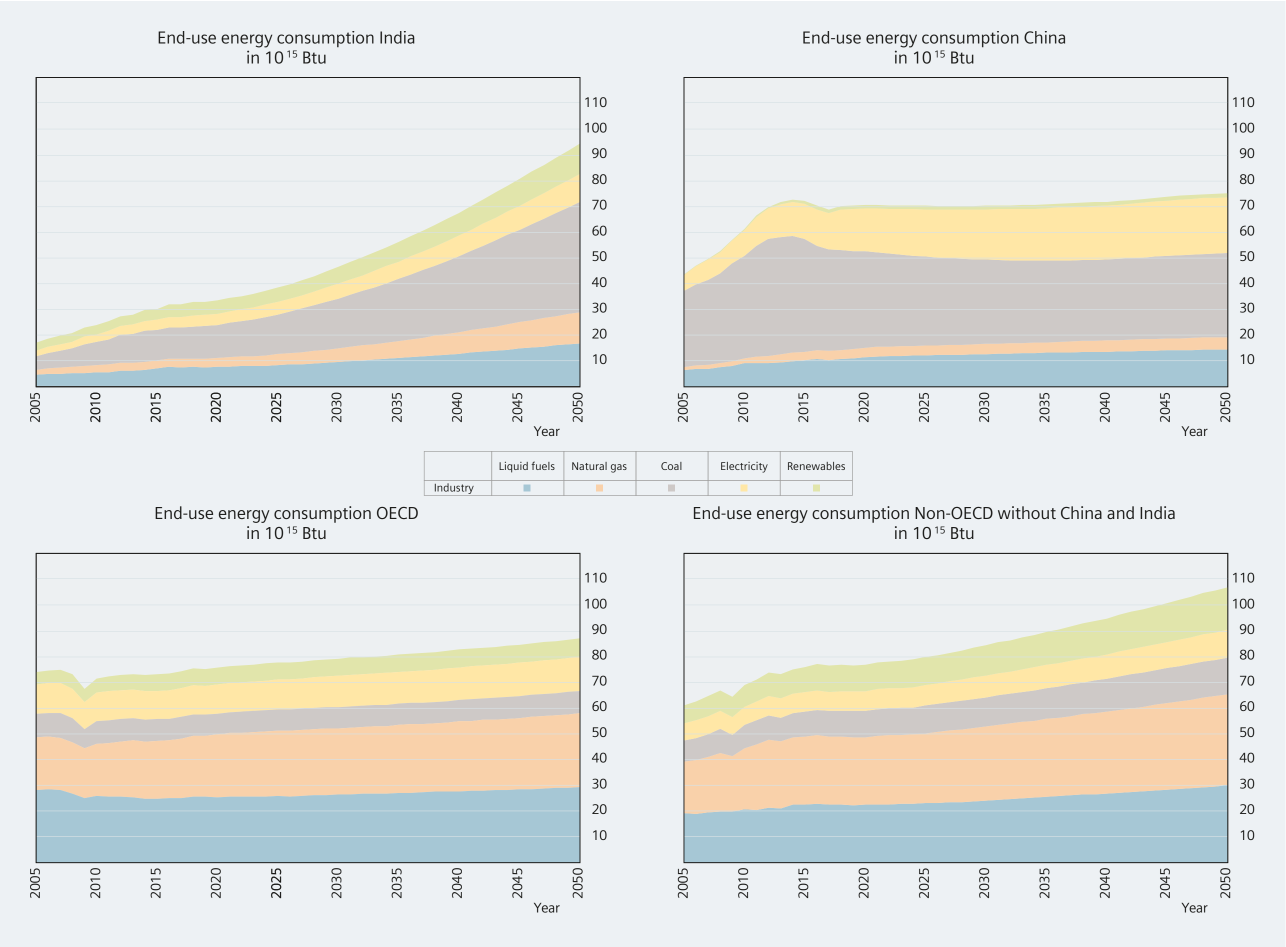


Fig. 3/2: **Development over time of end-use energy consumption for industrial use in various regions [3.1], classified by energy carriers**

3.1 Energy Consumption and Production Value

For a better assessment of the significance of end-use energy consumption for production plants, all associated costs must be considered in relation to other parts of the production value, such as labor costs and raw material prices. Based on statistical information, numerical sequences for economically significant countries and regions can be evaluated (Fig. 3/3). In this process, regional differences and the technical development in countries and regions noticeably affects the individual cost shares. The differences resulting from the cost allocation in different manufacturing sectors are noteworthy, too.

Energy costs can be allocated according to the energy carriers used for production (Fig. 3/4). To do this, energy consumption values are linked with average prices for the individual energy carriers for the sake of simplification; this is because the used technologies and the available resources play an important role in the consumption of the individual energy carriers. Furthermore, the prices of individual energy carriers differ significantly between countries and regions. The development of the individual components of the production costs over time, too, has a considerable influence on the resources, procedures and technologies used.

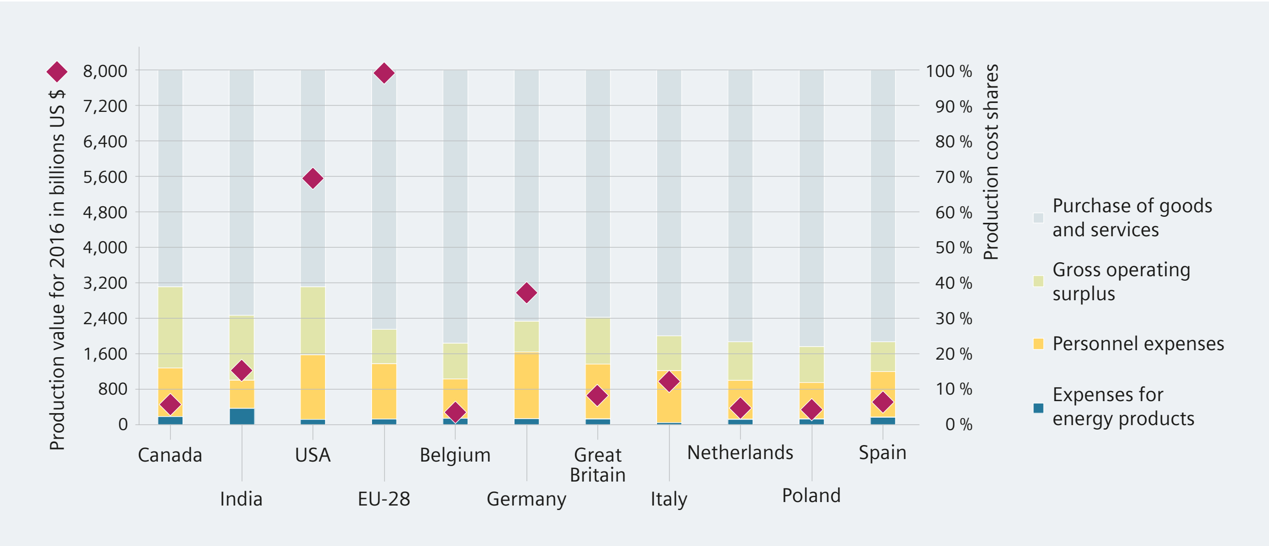


Fig. 3/3: **Percentage distribution of production costs (bars, see right) and of the total production value (hashes, see left) in selected countries / regions in 2016, averaged across the individual manufacturing sectors [3.2]**

Examples for price and therefore also cost differences among energy carriers:
- The allocation of specific costs of energy carriers between domestic production and imports in the different countries [3.3] leads to fundamental price differences
- Natural gas prices in Europe are currently on average about twice as high as in the USA, and even thrice as high as in Canada [3.4]
- Electricity prices for industrial users differ within the EU by a factor of about 2.5 [3.4]. In the USA, too, electricity prices are on average half the EU average
- Depending on the industrial plant's electricity and gas purchase volumes, prices can differ significantly (on EU average, the ratio in electricity prices between a "small" and a "large" plant is 1.75 to 1, and the gas price ratio is 1.3 to 1)
- Since demand charges and energy consumption prices for electricity and gas are linked, and different taxes and duties apply in different countries, fictitious electricity and gas prices have to be assumed anyway for an average industrial plant
- In India, practically only coal and oil products are currently used in industrial sectors like iron and steel, non-ferrous metals, chemicals, and mechanical engineering [3.5]. One possible reason is the embedded generation of companies using coal and oil due to the high level of insecurity in power supply.

For Fig. 3/4, the consumption data of the energy carriers according to Eurostat [3.6] are converted into cost shares for the individual energy carriers based on the specific energy carrier prices in Tab. 3/1.

Electricity	100 €/MWh (between approx. 50 and 150 €/MWh)
Natural gas	30 €/MWh (between approx. 3 and 50 €/MWh)
Coal	10 €/MWh (between approx. 6 and 15 €/MWh)
Crude oil	24 €/MWh (between 23.5 and 25.5 €/MWh)

Tab. 3/1: **Specific energy carrier prices, derived from data in [3.3, 3.4, 3.7]**

The electric energy consumption is the biggest cost factor in the European Union when procuring energy.
To highlight the importance of electric energy in the production, securing reliable operation must also be observed, which is briefly addressed in the following section.

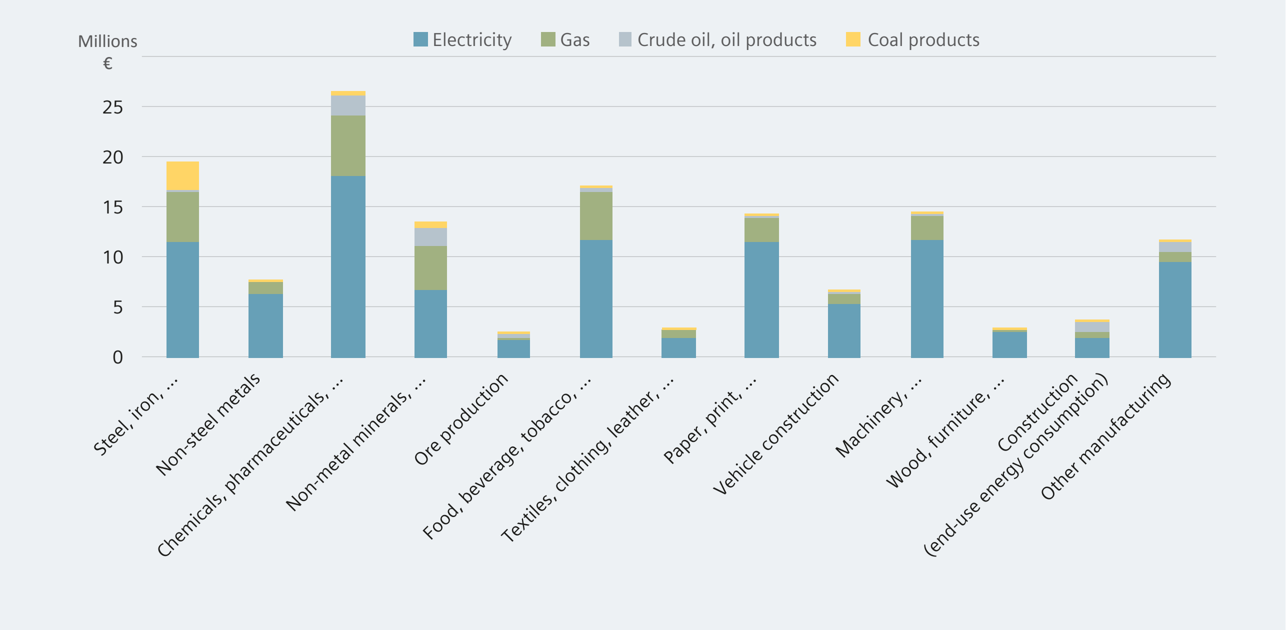


Fig. 3/4: **Distribution of energy costs in the EU (EU-28 for 2016) for different manufacturing sectors**

3.2 Economic Burdens as a Result of Power Failures

If the directly influenceable factors on the cost side of a production plant, like personnel and energy costs, are considered, the electricity consumption costs do make up a significant share. In addition to that, there are the effects of power supply failures on the production flow, which are caused by external (failure of grid infeed) or internal events (operational accident with destruction of lines, or as a result of fire). Even small failures can lead to production downtimes or even to system damages. A typical example for the serious consequences of a failure is the cooling and hardening of melts, making it necessary to remove and exchange entire system components. External problems can be caused by, for example, natural disasters, by cyberattacks, or by maloperation in the transmission and distribution grids. In a liberalized market, "non-technical" threats due to speculations in electricity trading must not be underestimated [3.8]. When grid supply is affected by such external influences, the corporate problem management must be ready for the task. This is because the coverage of damages by external system operators is usually much too low.

Value of Lost Load (VoLL)

For the economic evaluation of a power failure, or rather for the costs of electric energy not supplied, a characteristic value has been introduced: VoLL. This value is defined by the EU Regulation 2019/943 as the amount consumers are willing to pay for uninterrupted electricity supply, in order to avoid, for example, an interruption of production due to a power failure. In electricity trading, this amount yet to be determined must be taken into account in the clearing prices (the clearing price defines the intersection of supply and demand, and is determined according to 2015/1222/EU by comparing purchase and sell offers in the electricity market). Using the simple VoLL definition according to the report of the European Commission [3.9]:

$$VoLL = \frac{Operating\ surplus}{Electricity\ consumption\ of\ the\ company}$$

Contents
1
2
3
4
5
6
7

and with statistical values from Eurostat, IEA, Canada Statistics, and Klems India, a number of estimations can be calculated that reflect the economic loss in Euro or in another currency which might accrue from the lack or failure of one kilowatt hour or megawatt hour of electric energy (see Fig. 3/5). In Fig. 3/6 and Fig. 3/7, production plants are distinguished by multiple industrial sectors, so that the dependency on the used technology and energy carriers in the production processes as well as regional differences reflect, to some extent, the economic significance of a reliable electricity supply.

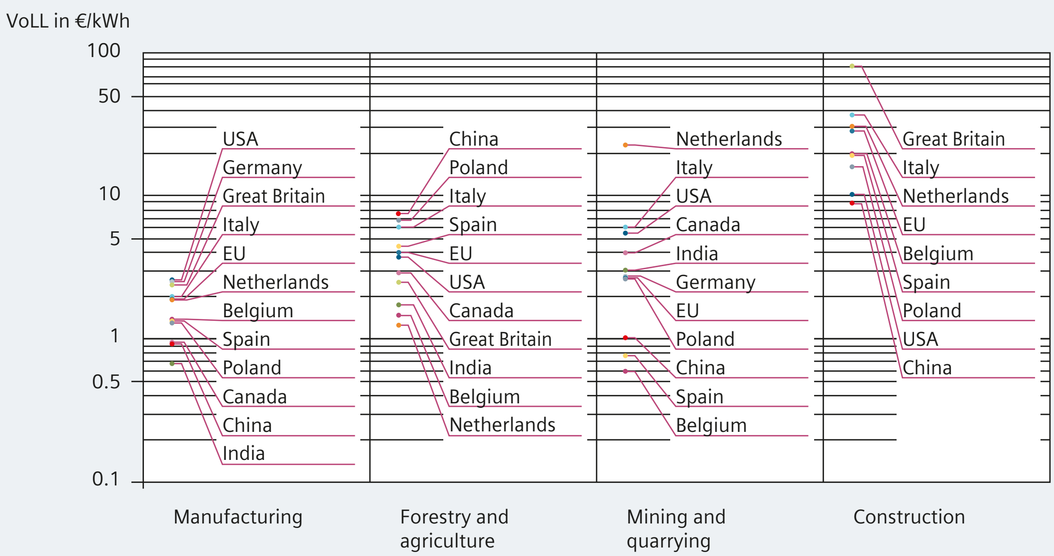


Fig. 3/5: **Calculated values for the Value of Lost Load (VoLL) of individual industries for some countries and regions in 2016**

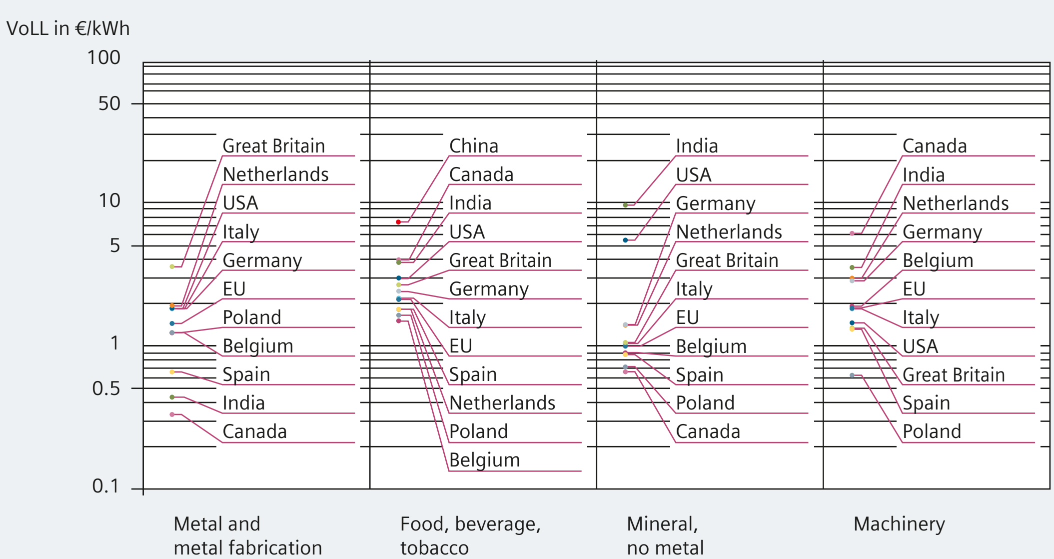


Fig. 3/6: **Part 1 of the calculated values for the Value of Lost Load (VoLL) in individual production industries for some countries and regions in 2016**

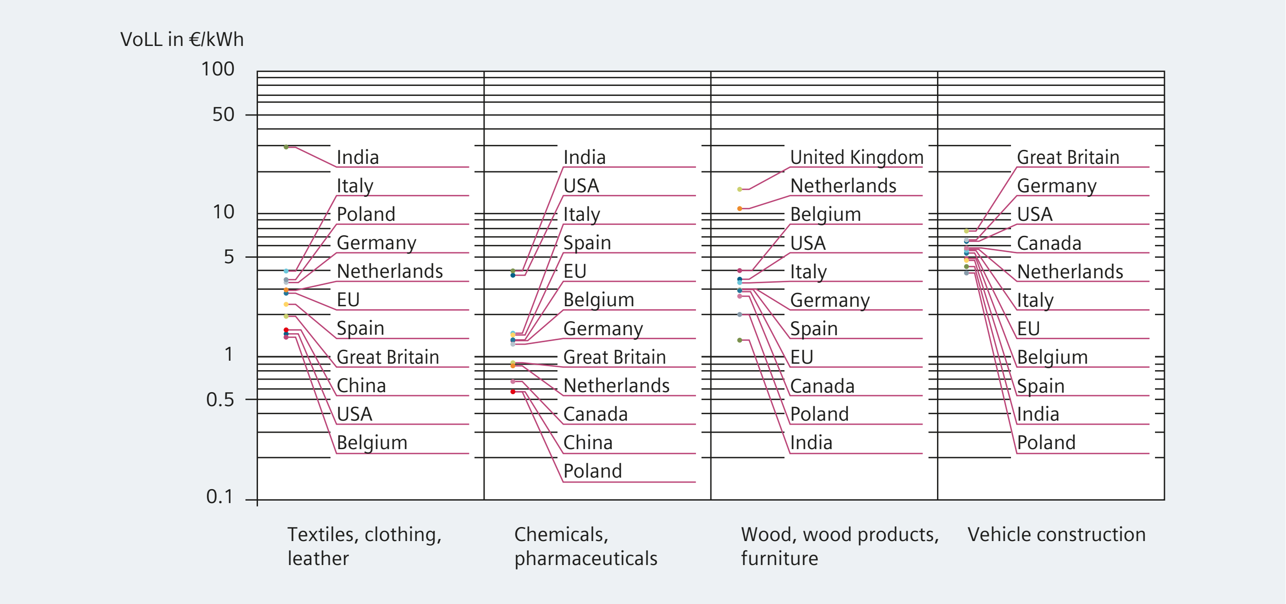


Fig. 3/7: **Part 2 of the calculated values for the Value of Lost Load (VoLL) in individual production industries for some countries and regions in 2016**

It becomes clear from the spreading of the values for individual economic sectors and production industries that the simply calculated values can only be a starting point for the economic significance of a secure electric power supply. Furthermore, a dependency on the duration of the power failure is to be expected. Additionally, there will be a correlation of the values with the point of time of the electricity supply failures (season and time of day, as well as weekday).

From the statistically determined worldwide creation of value and the global electricity consumption in the production sector [3.10, 3.11], a global VoLL quotient of about 1.30 € per kWh is calculated for 2016. This value is considerably lower than the VoLL value between 11 and 26 € per kWh specified for many EU countries in [3.9]. Similar values as in Fig. 3/5 to Fig. 3/7 are mentioned in the CEPA study [3.12] conducted by ACER (see Fig. 3/8).

Due to the development of the underlying statistical data, it is likely that the VoLL values will increase in the future. Increases in productivity on the numerator side and progress in efficiency on the denominator side will change the ratio in this direction. In the EU, the Directive 2018/2002/EU on energy efficiency stipulates annual savings in end-use energy consumption of 0.8 % p.a. (between 2021 and 2030, and possibly beyond). The power supply of an industrial plant should already be an issue today that combines cost, efficiency, environmental and security aspects, the future viability of which will be considered accordingly in the planning.

The legal framework for the importance of this task is provided by the Regulation on the internal market for electricity of the European Union (Regulation 2019/943/EU replaces Regulation 2009/714/EC). To implement Regulation 2019/943/EU, in December 2019 ENTSO-E published a draft for calculating the VoLL [3.13] for public review. It must be noted that “other costs” that are specific to the industrial sector are added to the costs for the production loss in the industry. This includes, for example, costs for damages, re-commissioning, material scraps, social impacts, customer impression, and many more. [3.13] defines VoLL for an industrial sector as follows:

$$VoLL = Lost\ production + other\ costs$$

Contents
1
2
3
4
5
6
7

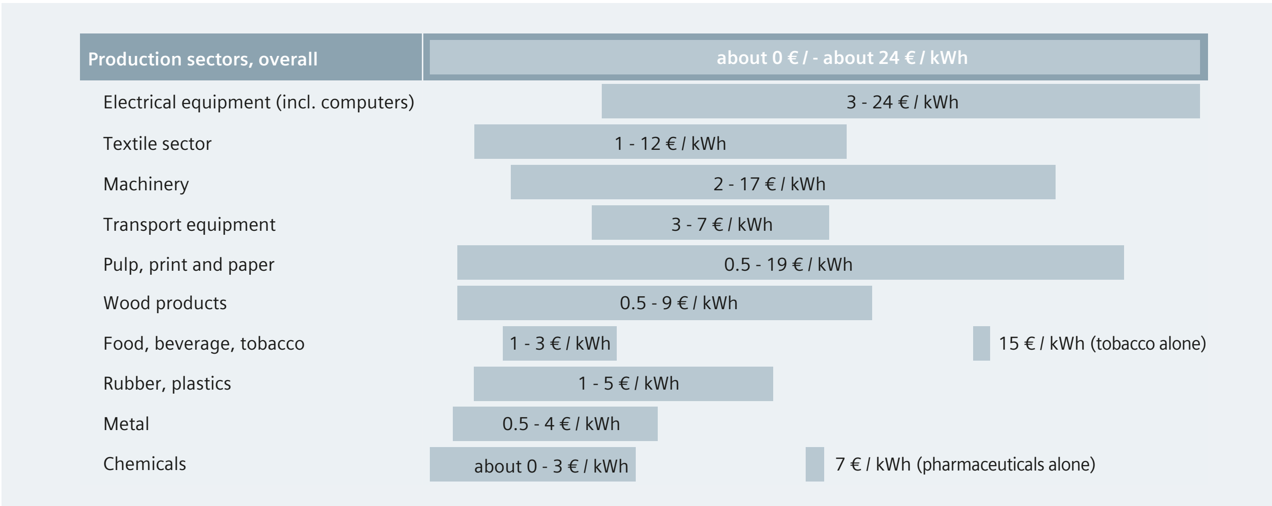


Fig. 3/8: **Estimate of VoLL values of individual industrial sectors according to the CEPA study [3.12]**

There, the value of *Lost production* is estimated as:

$$\text{Lost production} = \frac{PNF \times SF \times \text{annual gross value added}}{\text{annual electricity consumption}}$$

With:

PNF = Pre-notification factor; indicates to what extent an announcement of electricity supply problems can reduce production problems, for example, by increasing embedded generation or by short-term purchase; without pre-notification, the *PNF* is 100 %; [3.13] recommends either an internal monitoring by the authorities or alternatively calculating with *PNF* = 79 % for all industrial sectors (except *PNF* = 62 % for agriculture)

SF = Substitutability factor; marks the portion of gross value added that depends on electricity supply. ACER stipulates a value of 0.68 for agriculture/forestry and fishery, and a value of 0.80 for all other industrial sectors [3.12].

Regulation 2019/943/EU establishes that, in the face of ecological and economic challenges and objectives, the regulation of the electricity market with an extension and improvement of value systems and price calculation methods is indispensable. For this reason, the following was written down for the EU's internal market in electricity in Article 10 of the Regulation 2019/944/EU:

"Final customers shall have the right to a contract with their supplier that specifies: ...

f) any compensation and the refund arrangements which apply if contracted service quality levels are not met, ..."

It must be noted that the price-cap for electricity sale defined by EU countries [3.9], such as 3 €/kWh (Belgium, Denmark, France, Germany, Italy, Sweden) or 1 €/kWh (Ireland) or 0.18 €/kWh (Portugal, Spain), is not very suitable for making emergency and peak load supply cost-efficient. These prices reflect the current state of in-house securing of electricity supply in production plants by means of uninterruptible power supply (UPS) and in-house generators for safety power supply. Along with the preference for volatile power-generating technologies, they lead to increasingly challenging problems for peak load supply and intensified requirements for the integration of embedded generating plants into the distribution networks (see next chapter).

3.3 Power Flow Diagrams

Another important step towards basic planning of the electric power distribution is a rough estimation of the power demand for the most important parts of a production plant. In addition, boundary conditions are defined around the provision of the required electric power. In a simplified manner, Fig. 3/9 depicts the correlations between the basic components grid infeed/self-supply/consumers and the connecting elements.

To some extent, Fig. 3/9 points out that this is usually not a stringent, one-way process flow. Instead, planning the electric power distribution is usually an iterative process – in which multiple iteration loops may become necessary in the ongoing planning process due to new specifications and adjustments of details – in order to take feedbacks and interactions into account. Practically all over the world, for example, distribution and transmission system operators demand, or at least wish, an ever increasing access to high-performance generation, storage and consumer elements in order to be able to ensure the stabilization of grid conditions in view of fluctuating grid infeeds. Also, different contributions and directions of power flows must be considered during power generation with respect to consumer self-supply, when recharging storage elements, or when intentionally feeding energy into the supply grid.

Power flow diagrams are suitable for roughly describing classical supply relationships in normal operation, with a power flow from power generation to consumers. Statistics generally reflect mean values across a typical interval of time. Interest for the direction-dependent shares of power flows will increase. Peak and maximum values are required for the design and dimensioning of the plant.

Currently, embedded generation and storage of electric energy and process heat/steam in cogeneration plants mainly serve in-house usage. Regenerative feedback into the supply grid still plays a subordinate role and is accordingly not yet taken into account in statistics and flow diagrams.

Flow diagrams are frequently used to illustrate statistics and as a basis for the analyses derived from them. In principle, the energetic input and output values are linked with the power demand for the main and ancillary processes of production. During data aggregation, the consumers are classified into groups by means of collective terms such as heating, cooling, mechanical energy of motors, compressed air, or lighting.

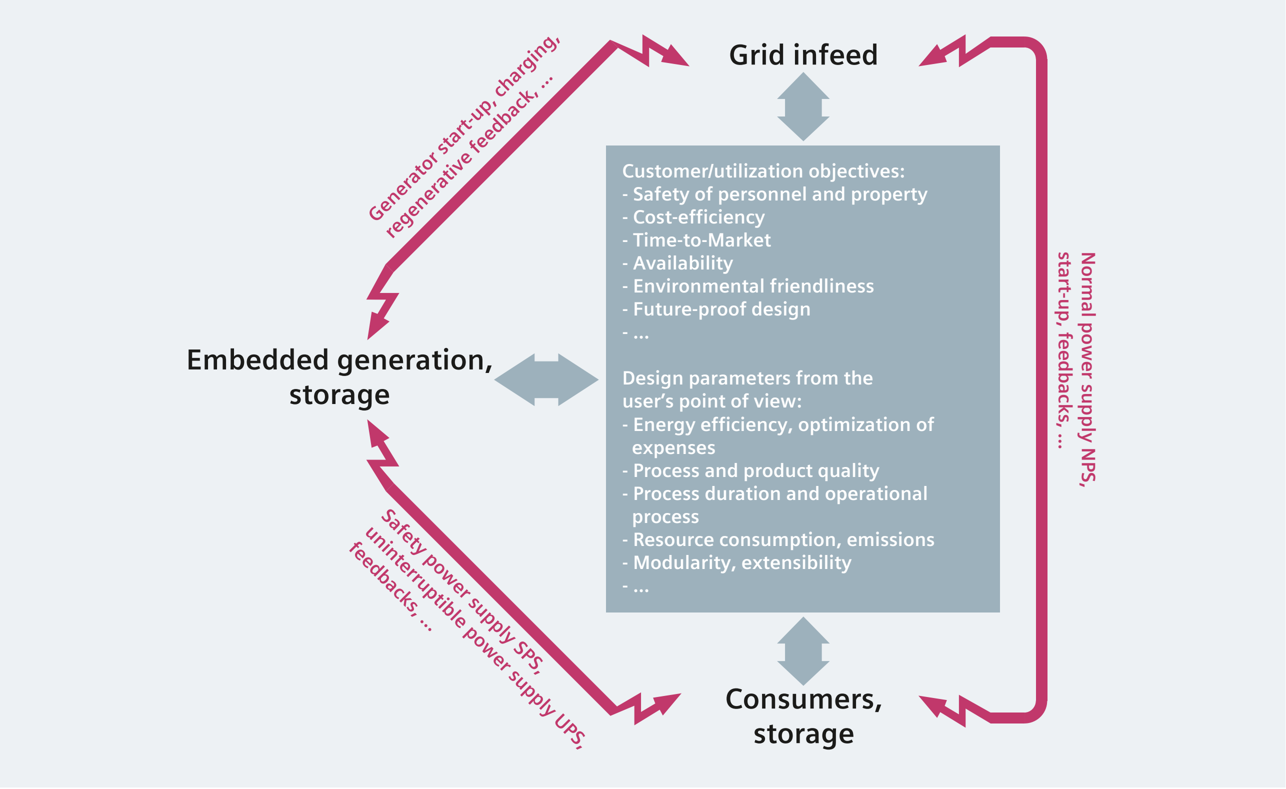


Fig. 3/9: **Cornerstones for basic planning**

Contents

1

2

3

4

5

6

7

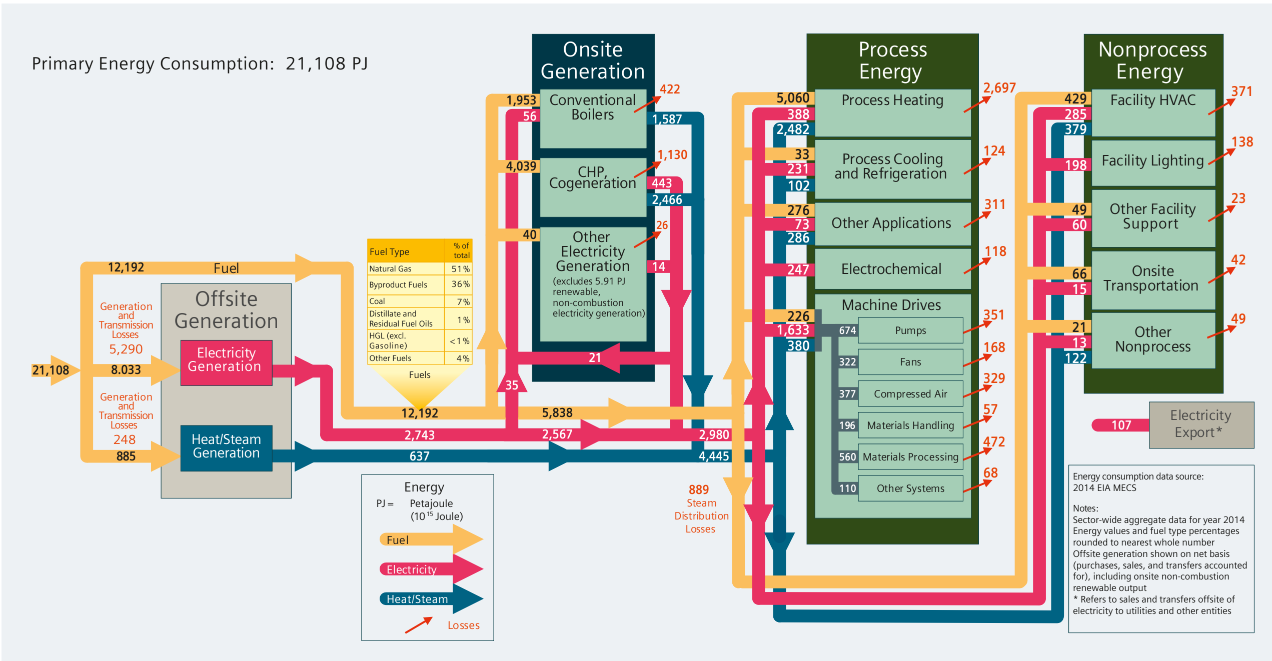


Fig. 3/10: **Power flow diagram for the industry in the USA in 2014 [3.14]**

Fig. 3/10 shows a power flow diagram created on the basis of statistical data for industrial production in the United States of America [3.14]. It is to be noted that all statistics currently only reproduce the power flow from generation to the consumer. In face of the importance of energy management and smart grids, it will likely not take much longer until further reaching evaluations are made possible and increasing regenerative network feedbacks by embedded generating plants can be taken into account in statistics. For the individual industrial plants with the respective contracts, this is already normal practice today.

3.4 Smart Grid for the Industry

Power flow diagrams only display the conditions in the annual average, as shown in the previous section. The increasing use of volatile energy sources such as wind and photovoltaics, the application possibilities of storage technologies, additional electricity applications such as charging battery storages in electric vehicles, as well as the requirements and possibilities that energy markets are offering to larger prosumers can no longer be described via one-way power flows. Rather, the interconnection of generation and consumption of electric energy, and the flexibility this requires from the grids, consequently lead to the demand for Smart Energy Systems and Solutions. For industrial production, this means that the electric power supply and distribution of industrial facilities is considered for all points of time during operation, that it is integrated into the production process chain, and that it should be "smart", which means, intelligent and controlled with specific objectives.

This approach must be taken into account in the planning by depicting and analyzing the energetic requirements of the industrial processes and accompanying processes, as well as the framework conditions of supply chains and markets, while considering social, societal and ecological influences – as schematically indicated in Fig. 3/9. This, however, must not only be about considering an average, stationary condition at the start of operations of the production plants. On the contrary, the time dependencies throughout the entire operational lifetime must already be considered in the planning phase. The operations management cycle is displayed in Fig. 3/11 in a circular arrangement, similar to other management cycles, as is customary for ISO 9001, ISO 14001 and ISO 50001. The evaluation in the planning phase and the setup of the associated installations form the basic prerequisites for the economically and ecologically sustainable usage of Smart Energy Systems and Solutions.

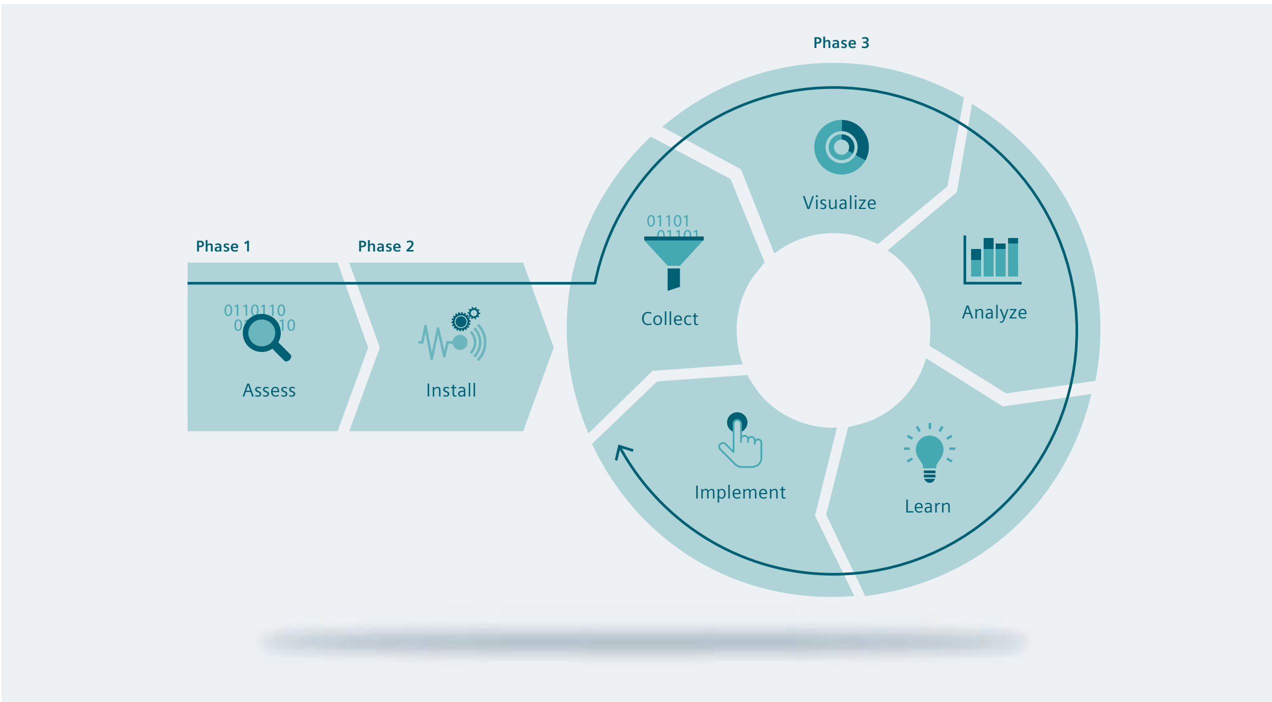


Fig. 3/11: **Fundamental management process as a basis for Smart Energy Systems and Solutions**

The underlying management process (Fig. 3/12) is fully supported:

- Already in the early planning phases, Siemens creates analyses and feasibility studies as a support, or basis, for decision-making. In this process, concepts and models for distributed energy systems (DES) are developed and simulations are calculated for all project phases on the basis of modular simulation software (PSS®), and the results are compared
- The Microgrid Control product range, based on the SICAM product platform, provides a comprehensive offer of hardware and software for monitoring, and for local control of power flows and KPIs around Smart Energy Systems and Solutions
- Via cloud-based services, as they are used in DEOP, the energy and power demand can be monitored and managed in the operational cycle in Fig. 3/11. In addition, DEOP facilitates analyses and forecasts for energy provision and consumption, and creates links with other participants in the energy market.

i) Concept finding and simulations (on the basis of PSS® software)

Time is a critical factor in the planning. For this reason, the number of iteration loops during concept finding for the electric power distribution and supply should be kept to a minimum, as suggested in Fig. 3/9. However, it is important to take different development scenarios for the industrial plant into account when creating the concept, as those scenarios help determine the individual optimum and can thus have a significant influence on the basic design of the concept. With the help of simulations, specific scenarios can be run through.

To examine the feasibility, key items are stipulated regarding the usage of the industrial plant and the associated infrastructure, and time schedules are defined. The concept for electric power distribution, which is adapted to the user’s expectations, is deduced from the analysis of simulation results. The use of specific PSS® software tools (PSS®DE and PSS®SINCAL) for performing simulations makes it possible to run through various versions and make a techno-economical comparison of different supply scenarios.

Contents

1

2

3

4

5

6

7

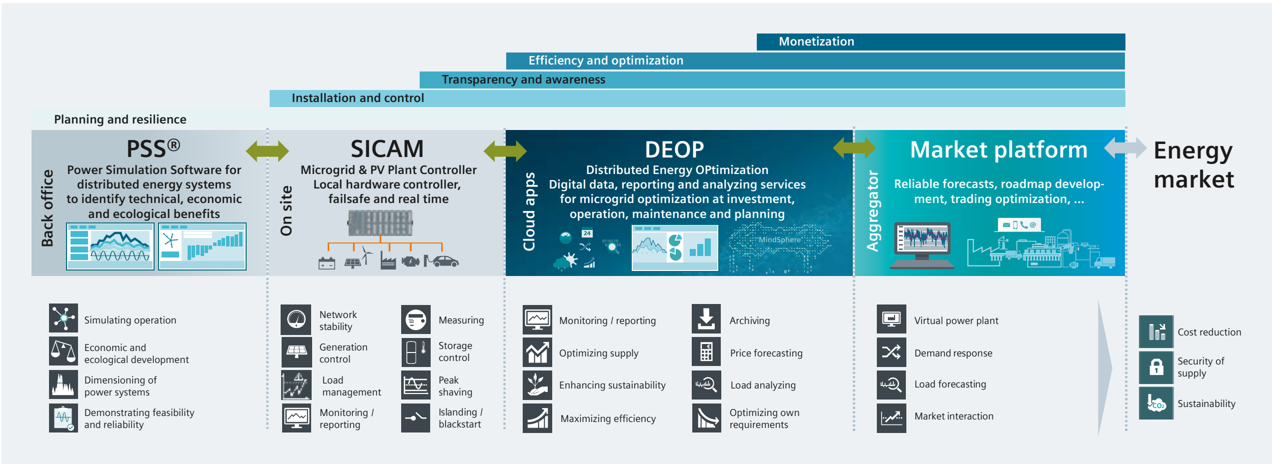


Fig. 3/12: **Integrated approach by Siemens for Smart Energy Systems and Solutions**

The analysis of the latter leads to the desired, specific optimization of the power supply based on the stipulated objectives and prioritizations. For example, a trade-off is carried out between:
- Safety, availability and reliability
- Technical feasibility and implementation
- Cost-efficiency (OPEX and CAPEX)
- Operability and flexibility
- Sustainability and efficiency
- Independence from suppliers
- Environmental compatibility.

For the simulations, a digital twin of the generating plants and, if applicable, the storage systems of the project is created in PSS®DE (PSS® software for simulating the implementation schedule for generating plants – the so-called "generation dispatch"). Beyond that, PSS®SINCAL facilitates the construction and inspection of the energy infrastructure, such as for example that of the electric power supply grid. Based on that, scenarios of the planned energy system can be developed, analyzed and evaluated. The following aspects play a significant role in this:
- Project-specific time series, for example: load profiles, environmental data for sun and wind, temperature characteristics, labor and demand prices
- Data on the medium- and long-term usage behavior for the plants, as well as intended corporate development
- Estimates on possibilities of variations and their prioritization in order to generate assessment criteria and establish a financial comparability on this basis.

In PSS®-based planning projects, a large number of versions is calculated in an automated way, and the selected configurations are considered throughout the anticipated service life, whereby specific boundary conditions such as operational reserves, redundancies, start-up and run-down scenarios, conversion or modification limitations, extensions, and many more can be defined and taken into account. Fig. 3/13 depicts the three phases:
- Project definition (system definition, power-generating systems, loads, prosumers, ambient conditions)
- Simulation (digital twin, runtimes, operating conditions)
- Analysis, financial evaluation, and optimizations (network and resilience analyses, prioritizations and comparison of versions, technical assessment criteria, and business KPIs).

Ultimately, the tests serve
- a better understanding of the correlations in the planned energy system and an accordingly optimized system design
- the assessment of important technical, economic and ecological parameters, which form the basis for the energy concept, as well as their dependency on different scenarios
- as stipulation for tender priorities, taking into consideration possible monitoring and management options for Smart Energy Systems and Solutions
- the identification and evaluation of alternatives in order to make the smart industrial grid future-proof.

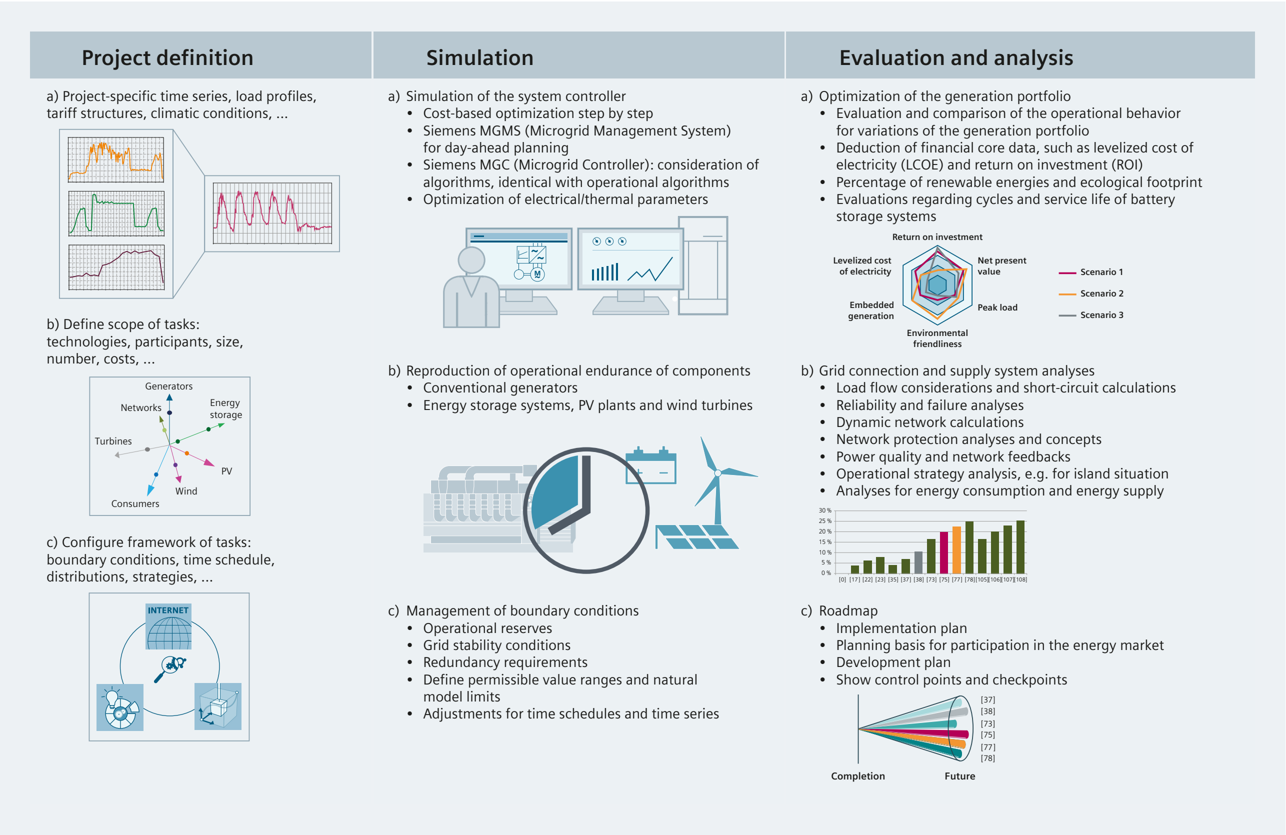


Fig. 3/13: **Process steps in PSS®-based planning projects**

ii) Setup of control and monitoring options for Smart Energy Systems and Solutions

The technical implementation for monitoring, data collection and evaluation, as well as the comparison between operational data and calculation/study results follows in the second phase of Fig. 3/11 and Fig. 3/12. Already during the planning, the design of the associated hardware and software must be taken into account. By using uniform algorithms and structures in the previously conducted studies with PSS®DE as well as in installations using SICAM, systematic deviations are avoided.

The Microgrid Control product range, a SICAM application, allows for an optimal control of locally available generating plants and consumers in order to ensure that agreed objectives, such as a high availability, power quality, or self-sufficiency, are achieved. As an example for monitoring and communication connection by means of Microgrid Control with the user interface Microgrid HMI, a corresponding screen view is shown in Fig. 3/14.

The Microgrid system supports the monitoring and control of operational equipment such as:
- Conventional generators with piston drive (e.g. for CHP plants)
- Turbines
- Battery storage systems
- Switchable electrical loads
- Point of common coupling (PCC)
- Photovoltaic plants
- Wind turbines.

In order to comply with the customers' requirements of achieving their economic and technical objectives, Microgrid Controller provides, among others, readily available and comprehensively tested features (see Tab. 3/2).

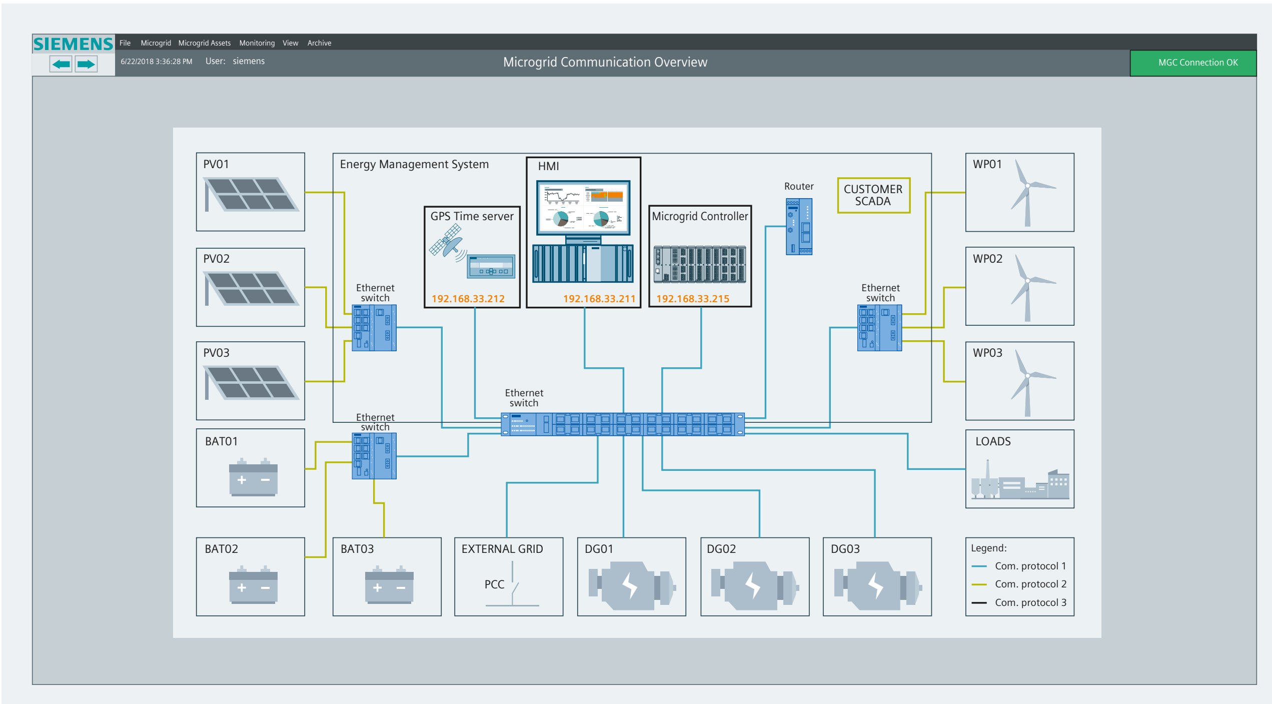


Fig. 3/14: **Overview screen in the Microgrid HMI for the communication status**

Functions
Blackout detection
Island detection
Load Frequency Control (LFC)
Automatic Voltage Control (AVC)
Re-synchronization
Generator control / monitoring
CHP control / monitoring
Battery storage control / monitoring
Intentional islanding
Load flow control (from / to grid)
Tariff monitoring & supervision
SMS messaging
Operation modes
Peak shaving
Demand charge reduction
Reserve monitoring
Load shedding & manual restoration
Photovoltaic control / monitoring
Autostart sequencing
Load forecasting
Generation forecasting
Scheduling

Tab. 3/2: **Readily available features of the Microgrid Controller**

The entire control system is based on tested, readily available functions. Furthermore, these functions are scalable in all their parts, and can therefore be used flexibly.

iii) Support in operation by means of DEOP

After installing the flexible, secure and reliable Microgrid Control products, it will be possible during operation to compress, among others, data, values, notifications, alarms, or automated switching and control operations (see Fig. 3/12) hierarchically and pass them on with the help of the energy optimization software DEOP – from the indication at the plant and the human-machine interface through the communication via web interface up to the control room in the monitoring center. Examples for functionality are:

- Monitoring / control of all system parts (SCADA)
- Performance and energy management (balance between consumption, generation, storage and procurement of energy)
- Managing blackout situations (e.g. restart plan after shutdowns)
- Frequency stabilization and voltage stability (management of dynamic processes in Smart Energy Systems and Solutions)
- Controlling the link with energy markets (e.g. power control, spinning reserves, virtual power plant (VPP))
- Managing between island operation and grid supply (synchronization).

DEOP serves as a web portal as well as for remote monitoring and benchmarking of plant parameters (energy). The cloud application is integrated into Microgrid Control via a web interface. Functions of the cloud application are:

- Benchmark for system power and performance
- Optimization of operational planning
- Optimization of setpoint stipulations
- Integration of web and mobile applications
- Monitoring and reporting
- Optimization of energy use
- Improvement of sustainability
- Maximization of efficiency
- Archiving
- Price forecasting
- Load forecasting.

The advantages that can be derived from this compared with conventional data processing are displayed schematically in Fig. 3/15.

The HMI of DEOP is designed as a dashboard / cockpit to provide information at a higher level via an intuitive user interface. Decisions at different hierarchical levels in the company can be supported in this way. Especially the linkage to energy markets with requirements that greatly change depending on the situation illustrates the advantages of an automated control system for resources and plants.

An important element of DEOP is the creation of virtual power plants (VPP) and the exemplary description of energetically, economically and ecologically relevant processes. Of course, DEOP can create a link with supplier and consumer markets as well as with distribution system and transmission system operators (Fig. 3/15).

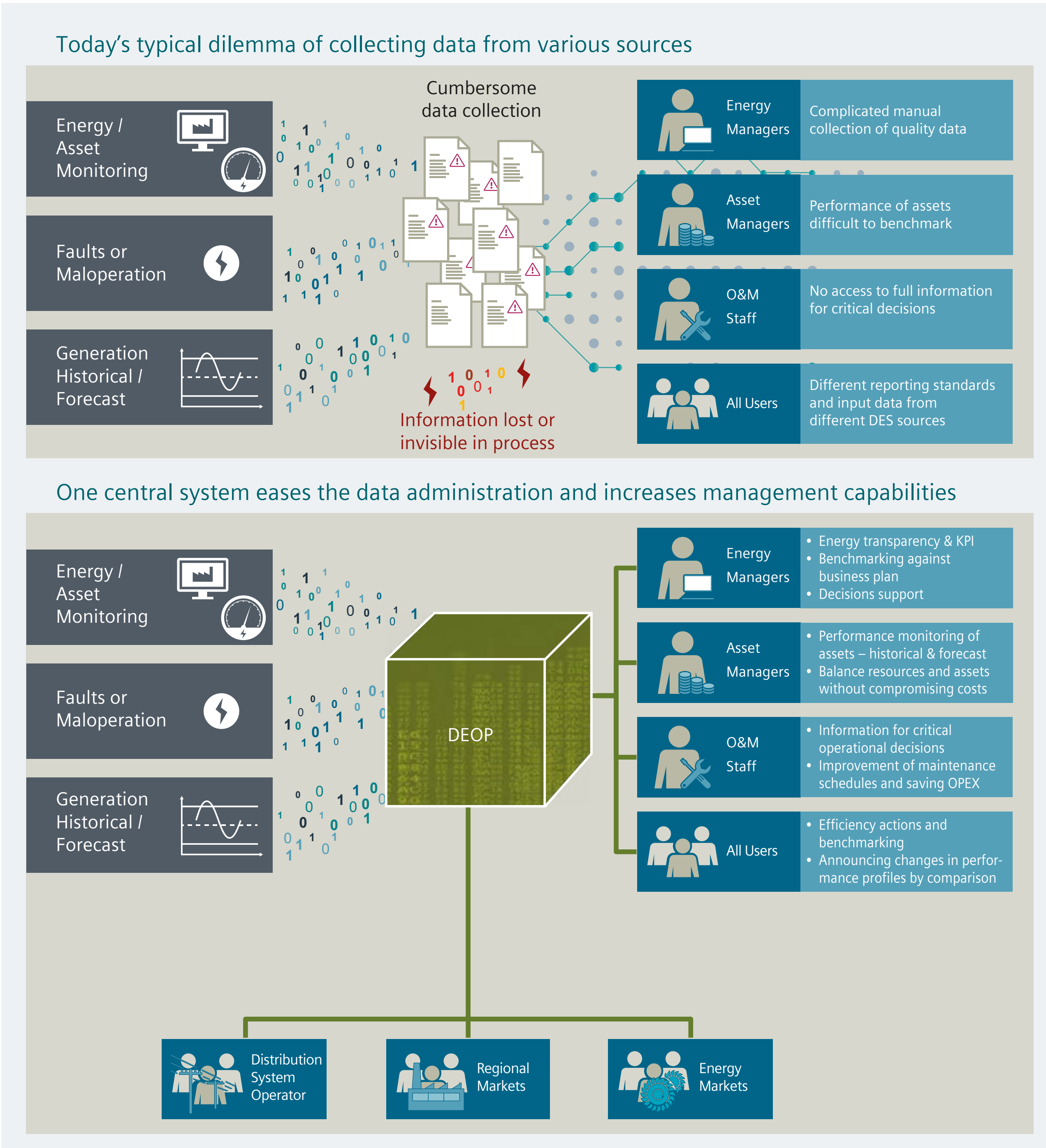


Fig. 3/15: **Comparison between conventional data collection and a centralized data cube[1] such as DEOP**

[1] The data cube is a multi-dimensional form of data organization as it is used, for example, in merchandise management systems. This way, the possibilities to combine and analyze data are simplified and improved.

Chapter 4

Creation of a Planning Concept

Contents

1

2

3

4

5

6

7

4 Creation of a Planning Concept

The project- and process-specific requirements make it practically impossible to find a universally applicable concept for planning the electric power distribution of an industrial plant. This applies to a new construction (greenfield) as much as to a conversion or expansion (brownfield) or even a reconstruction (greyfield).

The basic planning phases for factory planning in Fig. 2/3 must be implemented considering the boundary conditions defined by the customer regarding the development, update and refinement of a power distribution concept. Even for a first rough planning overview, fundamental user requirements are needed as a basis in order to take location conditions into account while establishing the project basis, and to be able to incorporate an estimate of the required budget. This also includes the development of a basic scheme for the electric power distribution. A cost estimate merely on the basis of the floor area size and an average power demand is usually inaccurate. Connection conditions, environmental influences, safety requirements, the time schedule, process- and system-related parameters, as well as user expectations – for example, regarding operational stipulations, expansion possibilities, and embedded generation of electricity and heat/steam –, all significantly influence the concept and thus the cost situation.

The North American standard IEEE 141-1993 [4.1], created under former preconditions, assumes for a so-called "preliminary estimate" that a miscalculation of the actual costs of up to 40 % (see box) is possible. New developments such as, among others,

- Smart Energy Systems and Solutions (see Chapter 3.4)
- Energy transparency for a constant adaptation of the factory
- Substitution of fossil fuel-based technology by electrical consumers
- Heat recovery

will rather increase the insecurity of cost estimates of an area-based power demand. From today's point of view, it therefore only makes limited sense to specify area-based power values, such as for example in [1.1], even more so if they are subjected to large fluctuation ranges. For preliminary estimates, at least a concept draft should be created. To do this, one usually falls back on empirical values and concepts from similar projects. Via plausibility checks and coordination with the customer, a draft for the supply structure is created.

In the standard IEEE 141-1993 ("Red book", [4.1]), the following three approximation steps are defined:

1. An estimate based on area specifications as well as on number and ratings of motors, or by comparison with similar projects: The actual cost will range from 15 % below or 40 % above the estimate.
2. An engineering estimate based on a one-line diagram [4.1] – hereafter called single-line diagram: The actual cost will range from 10 % below or 20 % above the estimate.
3. A detailed estimate that is already based on manufacturer offers and detailed drawings of the plant: The actual cost will range from 5 to 10 % below or above the estimate.

Simple power demand and cost estimates for basic planning should be built on simple data based on the three pillars of electric power distribution in Fig. 3/9 – infeed, embedded generation, and consumers (storage systems act both as producers and consumers). Accordingly, it is one of the first tasks of a planner to design a concept based on user requirements as a starting point for planning and configuration of the network (Fig. 4/1).

Contents
1
2
3
4
5
6
7

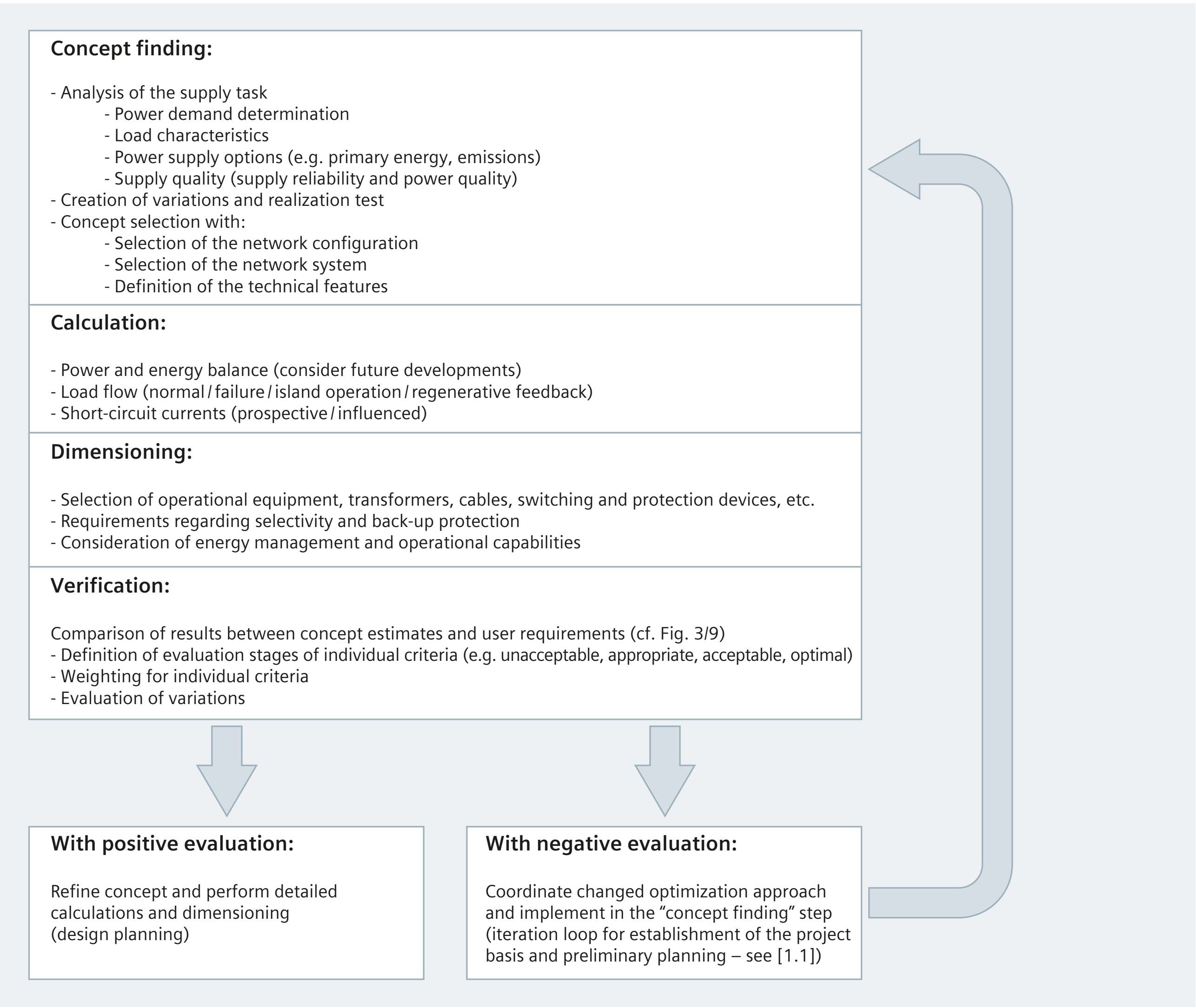


Fig. 4/1: **Flow chart of concept finding**

Especially when creating a concept, the development and assessment of different variations is crucial for the quality of planning and feasibility. Process- and operation-related design parameters, external boundary conditions, and known equipment specifications are already to be considered in the concept finding phase. For those variations that seem suitable, calculations and dimensionings are performed in order to be able to, for example, estimate the costs and space requirements, or test the feasibility of other user requirements (as detailed in Fig. 3/9).

A structural diagram (Fig. 4/2) is helpful for illustrating the process of concept finding. The fundamental decision-making levels for a rough concept are structured in a simplified way:

1. Infeed
2. Infeed distribution and network configuration
3. Embedded generation
4. Medium-voltage switchgear and load centers at process level
5. Consumer and load distribution.

In Fig. 4/2, the possible variety of alternatives and options for the individual levels does not become clear yet. A possible procedure is sketched in the following subitems. Further focal points for the design, which, however, depend on a more detailed knowledge of the project, include:

- Supply quality of the infeed by the distribution system operator (DSO)
- Short-circuit stress in the medium- and low-voltage network (besides the DSO infeed, larger motorized loads and generators must be taken into account)
- Neutral earthing and protection layout for the infeed distribution level
- Evaluation of power quality (e.g. influence from load changes or start-up of large drives)
- Network system (earthing) for the low-voltage network in the process distribution level
- Network feedbacks and compensation in the entire network
- Protection layout in the process distribution level.

The above-mentioned points do not have a direct influence on the general procedure in creating the rough concept, but each piece of information on it can influence the created concept. In the following, the fundamental elements and boundary conditions are described that must be taken into account during concept finding for a reliable electric power distribution in industrial plants. However, due to changes and/or extensions of the framework knowledge, or by focusing on other planning areas, the concept finding can be refined, varied, or structured in a completely different way. The TIP contact partners from Siemens can provide support for a project-specific concept finding (www.siemens.com/tip-cs).

4.1 Infeed

Two characteristics are decisive for the selection of the DSO infeed:

a) The existing infrastructure of the DSO
b) Customer requirements concerning the current and future power demand.

An infeed concept can be selected with the help of a simple decision diagram (Fig. 4/3):

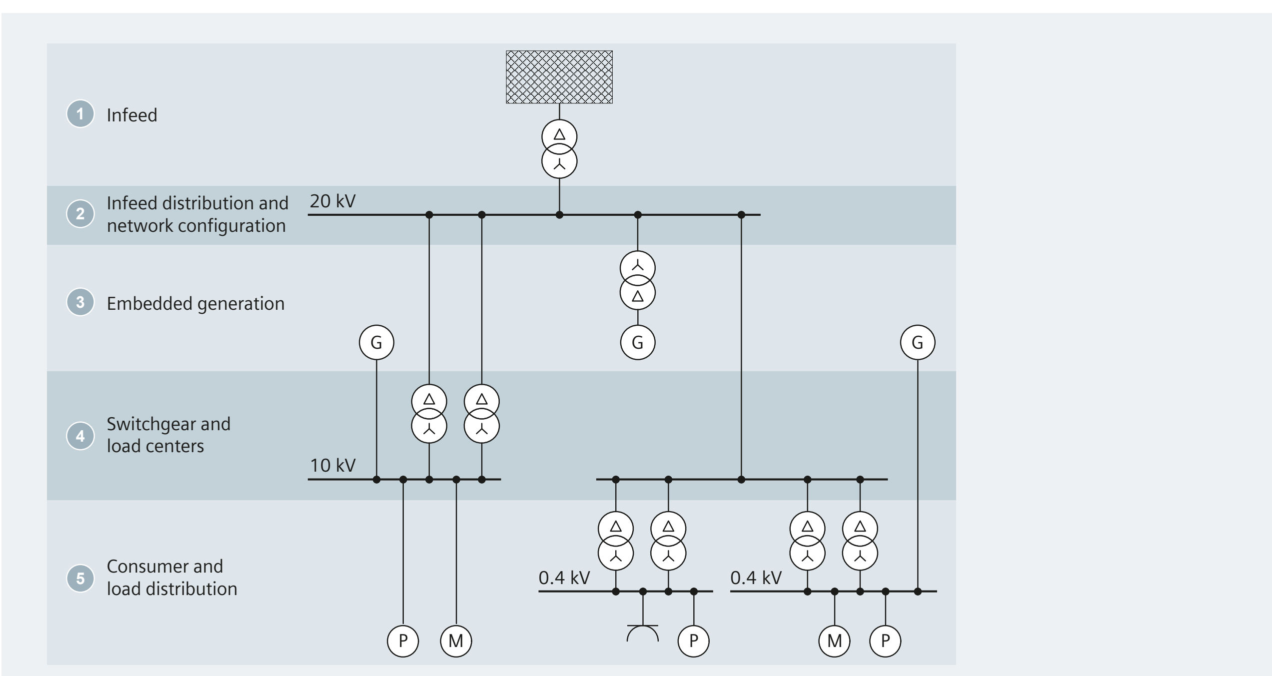


Fig. 4/2: **Structural diagram to illustrate the levels of a rough concept**

Contents

1

2

3

4

5

6

7

- Looping into an existing medium-voltage ring[1], typically for smaller industrial plants with the maximum connected load:

  $S_{max} \leq 3$ MVA
  at nominal system voltage $U_{nS} = 10$ kV

  $S_{max} \leq 5$ MVA
  at nominal system voltage $U_{nS} = 20$ kV

- Supply directly from the main transformer substation[2], typically via a double radial line with two cable connections:

  3 MVA $< S_{max} \leq 14$ MVA
  at nominal system voltage $U_{nS} = 10$ kV

  5 MVA $< S_{max} \leq 20$ MVA
  at nominal system voltage $U_{nS} = 20$ kV

- Supply from the high-voltage grid (nominal connection voltage $U_{nDSO} = 110$ kV) via one or multiple in-house transformers[3]:

  14 MVA $> S_{max}$
  at nominal system voltage $U_{nS} = 10$ kV

  20 MVA $> S_{max}$
  at nominal system voltage $U_{nS} = 20$ kV

Of course, it is important to coordinate the connection options with the distribution system operator (see, for example, Chapter 4.3 for technical connection conditions). In this process, further boundary conditions such as distances, short-circuit currents, use and behavior of motors or motor starters and generators, as well as the required supply quality must be observed (see Chapter 4.4).

1) For looping into a public medium-voltage cable ring, an upper reference power value is common, which constitutes about 50 % of the maximum transmission capacity of the normally open ring.

2) The power limitation in case of direct connection to a main transformer substation is usually determined by its transformer. Frequently, 31.5 MVA transformers (secondary voltage 10 kV) or 63 MVA transformers (secondary voltage 20 kV) are used, so that a limitation to a third of these ratings results in upper limits of about 14 MVA and 20 MVA. Many consumers use the earth-fault compensation for neutral earthing.

3) If an embedded supply network is created with in-house transformers, the neutral earthing can be designed specifically for the requirements of the embedded network (this is an advantage compared with the other two previous versions). For details, see [1.2]. In case of a secondary-side delta winding of the transformers, this neutral point cannot be created at the transformer, but must be created via a neutral earthing transformer on the infeed distribution level. The Consultant Support of Siemens TIP provides assistance for the selection and dimensioning of the neutral earthing transformer and the earthing resistance.

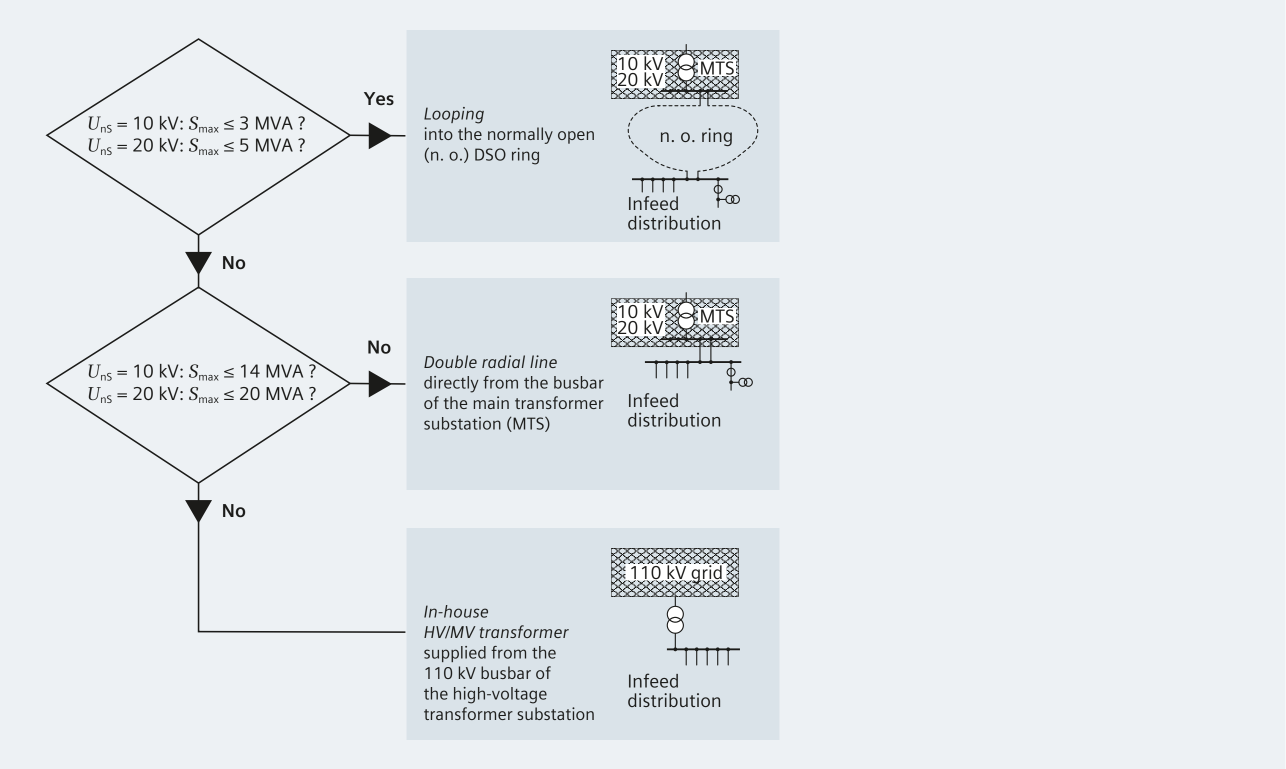


Fig. 4/3: **Decision diagram for the selection of the grid infeed of industrial plants**

If there is no detailed information for basic planning, the simple approach is continued and adjusted based on Fig. 4/1 with changed parameters, if needed.

4.2 Infeed Distribution and Network Configuration

The nominal system voltage of the infeed distribution is selected according to the supply voltage in Chapter 4.1. IEC 60038 stipulates standard voltages in medium voltage (1 kV < U_{nS} ≤ 35 kV) and high voltage (35 kV < U_{nS} ≤ 230 kV). IEC 60038 notes that new public distribution grids should no longer use a voltage level of 6 kV. In industrial applications, the following reasons speak for higher voltage levels (10, 20 or 30 kV) compared with 6 kV:

- Lower rated short-circuit making and breaking currents (assuming the same short-circuit power; I_{ma} and I_{sc} at 6 kV are higher by a factor of 1.67 / 3.33 / 5 at 10 / 20 / 30 kV)
- Smaller cable cross-sections (smaller by approx. a factor of 2 to 3 for 10 kV, and up to approx. a factor of 6 to 10 at 30 kV compared with 6 kV; assuming the same power or short-circuit power to be transmitted)
- Higher energy efficiency (due to lower network losses)
- Sufficiently long grading times for definite time-overcurrent protection as main and back-up protection due to lower short-circuit currents[4].

Three basic types (Fig. 4/4) of network configurations can be differentiated:

- Radial network
- Ringed network
- Meshed network.

From this, versions or combinations (Fig. 4/4) can be derived, such as for example:

- Line/bus network
- Tree network
- Double radial line network.

It must be noted that Fig. 4/4 only shows structures and does not provide details on infeed, generation and consumption. The tree network represents a concatenation of radial networks. If there is a coupler between the two infeed distributions, the double radial line network can be considered a simple combination of individual ringed networks.

[4] Lower short-circuit currents cause a lower thermal let-through energy (I^2t) and a smaller peak short-circuit current (i_p). The longer disconnection times resulting therefrom have a positive influence on the possible grading levels of the definite time-overcurrent protection.

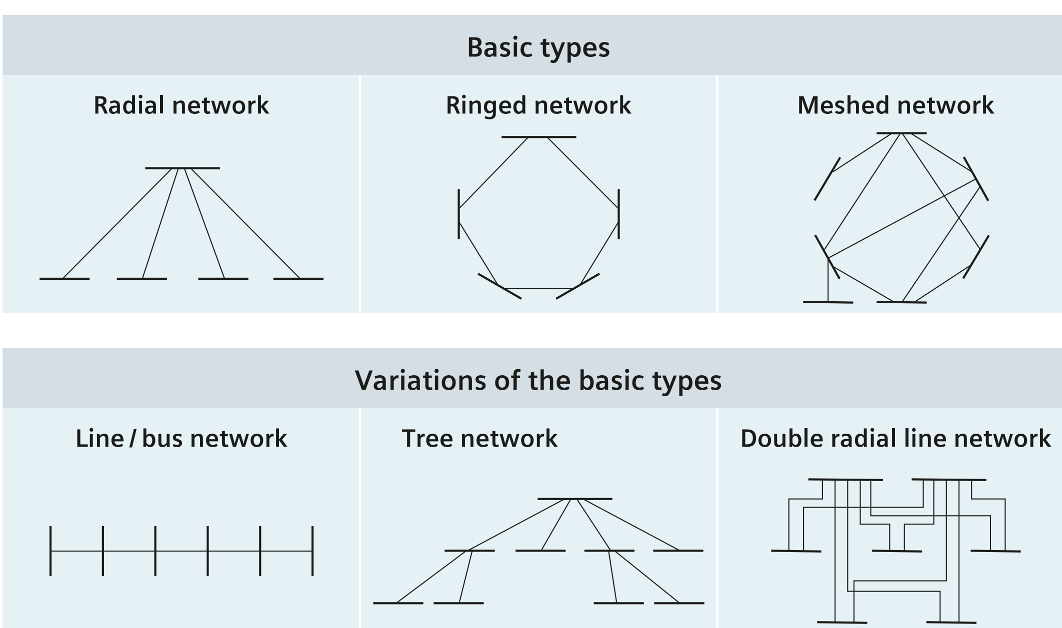


Fig. 4/4: **Network configurations for power distribution**

Operationally required versions of the ringed and double radial line network which differ in normal operation can be divided into "open" and "closed" modes of operation. The "open ring" corresponds to a line/bus network. In "open double radial line", each individual ring is accordingly open in normal operation.

Attention: The basic principle is that a "closed" operation is not possible in case of infeed from two separate sources of energy providers. SIPLINK from Siemens offers a possibility to couple separate sources. Thanks to the converter technology, the grids can be adjusted accordingly, for example for frequency adjustments as they are necessary in South America when a 50 Hz grid (Argentina, Paraguay) is to be coupled with a 60 Hz grid (Brazil), or for the supply of US American industrial plants (chemicals, oil & gas) operated in Asia. Parallel operation of supply grid and generator is possible if the generator is synchronized.

When selecting the network type, it must be observed that the project-specific framework stipulates the individual weighting of individual criteria and, if applicable, defines specific criteria in order to prefer or exclude a network type. Since the medium-voltage infeed network in industrial plants is typically designed as a radial, ringed or double radial line network, Tab. 4/1 shows important criteria for comparing these three network configurations. The estimation of the criteria can support decision making during project planning.

4.3 Embedded Generation

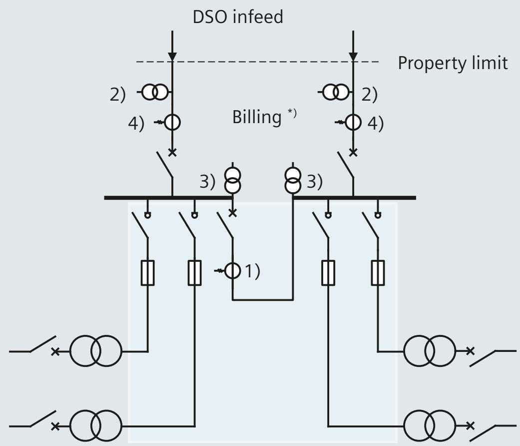
There are various reasons for operating an embedded generating plant in parallel with a distribution grid:

- If process heat is required, electric energy can be produced simultaneously when energy carriers are transformed by cogeneration
- In case of insufficient public electric power supply that can impair production processes
- For emergency power supply of safety-relevant applications as described in IEC 60364-5-56 (electricity sources for safety services[5)]), for example
- To avoid or reduce energy consumption costs, especially of apportionments, taxes or similar additional charges (e.g. system usage charges) in connection with energy consumption and peak load demand
- To improve a company's ecological footprint
- To use energetically recyclable production residues, such as for example in the wood and paper industry, or so-called coupling gases in the steel industry.

Due to an increasing interest in embedded generation in the industry, with cogeneration or regenerative energy consumption of wind, sun and biomass, the distribution and transmission grids are impacted, too. Large power plants which significantly contribute to network support are becoming rarer. Volatile, small energy producers which are partially connected to the grid via inverters are supposed to replace such large power plants in increasingly distributed grids. Therefore, greater emphasis must be placed on sufficient functionality in terms of grid stabilization for smaller generating plants as well.

For parallel operation of embedded generating plants with the public grids, an automatically controlled integration of the plants is required both for normal operation and in case of failure. Commonly, the transmission and distribution system operators specify the connection requirements in their grid codes. As a general rule, national and international standards as well as directives and empirical values form the basis for these codes (Tab. 4/2). It is important to know that, due to the larger restructuring which is underway in the global electricity market, there is a constant process of adjustment in laws, standards, specifications, directives, stipulations, and conditions. For this reason, when these documents are referred to, the latest version at the time must be consulted.

[5)] Note: According to IEC 60364-5-56, two separate infeeds which are independent of each other are permissible as a safety power supply source when it is unlikely that both infeeds fail at the same time.

Legend	Radial network	
1) Current transformer for protection 2) Voltage transformer for measuring 3) Voltage transformer for protection (optional) 4) Combined current transformer with 2 cores for measuring and protection 5) Voltage transformer for protection *) Switchgear-specific “system instrument transformers” for billing		

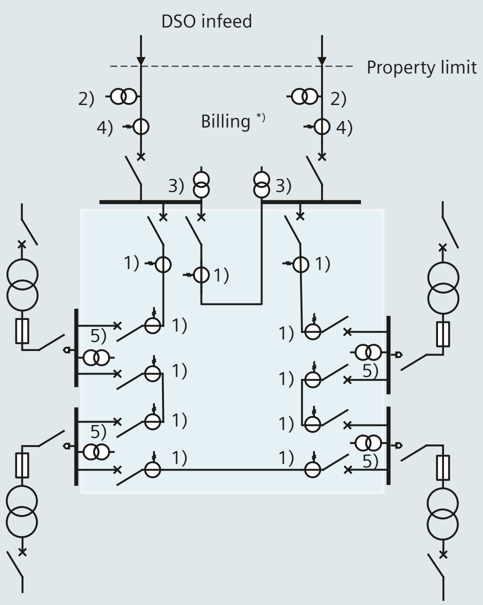
Design features for medium-voltage network configuration	Radial network	
Cable fault, medium-voltage side (marked areas)	The faulty cable run is removed / disconnected by the switching and protection device. There is no switchover possibility to the other source → Connected transformers and associated consumers are no longer supplied	
Protection technology	Low expenditure (outgoing feeder protection with switch-disconnector/fuse combination)	
Network monitoring in operation	Separate expenditure with current and/or voltage transformers as well as measuring / indicating devices	
Voltage dip in case of short circuit	Low for feeders not affected by the fault, in case of protection with HV HRC fuses and correspondingly brief disconnection times (< 10 ms)	
Danger to persons	Low, as the arc energy released in the event of a short circuit is mostly low due to the short disconnection time (< 10 ms) and the current-limiting effect of HV HRC fuses [1.2]	
Availability	No redundancy, therefore low availability for the affected feeder in case of fault	
Installation of the switchgear	Under certain circumstances, the switchgear may be installed directly in the production hall (e.g. consideration of ambient conditions like temperature, dust, humidity, and many more)	

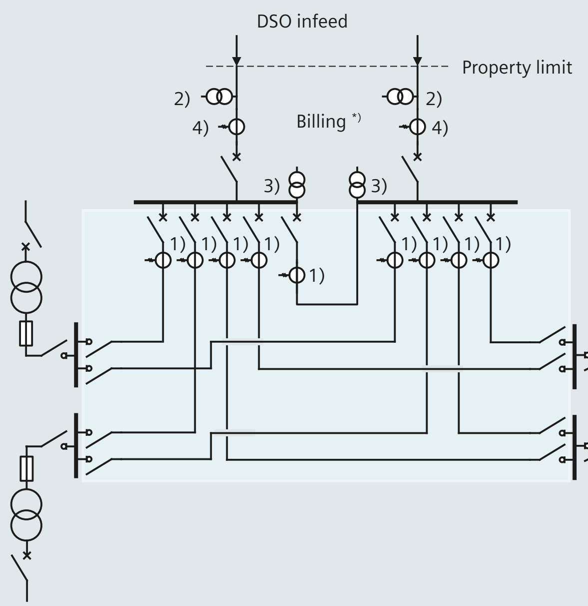
Note: Due to the planning complexity, no generally valid estimates can be made in the above table. All specifications refer to generalized empirical values. As described in Fig. 4/1, the draft of a concept must be substantiated with data and specifications, and must be further verified and refined (or, if required, also completely changed) on the basis of calculations and dimensioning.

Tab. 4/1: **Features of medium-voltage network configurations**

Contents
1
2
3
4
5
6
7

	Ringed network	Double radial line network





	Ringed network, normally closed (n. c.)	Double radial line network, normally open (n. o)
	Protection technology with direction detection is required to selectively separate / disconnect the faulty cable run → Connected transformers and associated consumers are supplied without interruption thanks to the ringed concept (n. c.)	The faulty cable run is selectively separated / disconnected by the switching and protection device → From fault occurrence to fault clearance, including switchover in the double radial line network, connected transformers and associated consumers are not supplied; consumers might have to restart again then
	High expenditure (circuit-breaker plus protection device with current and voltage transformers including direction detection)	Medium expenditure (circuit-breaker plus protection device with current transformers)
	Easily possible thanks to the functionality integrated in protection devices (e.g. SIPROTEC)	Easily possible thanks to the functionality integrated in protection devices (e.g. SIPROTEC)
	Can be considerably higher, as a disconnection time of 70 up to 120 ms has to be taken into account in case of protection via circuit-breaker for fault detection, tripping, internal time of the circuit-breaker, arcing time, plus the set time delay (typically 0 to 1 s)	Can be considerably higher, as a disconnection time of 70 up to 120 ms has to be taken into account in case of protection via circuit-breaker for fault detection, tripping, internal time of the circuit-breaker, arcing time, plus the set time delay (typically 0 to 1 s)
	Higher, as the disconnection time of 70 to 120 ms with circuit-breakers can lead to more than 7 times the arc energy values compared with HV HRC fuses (for an example, see [1.1]); accordingly, higher expenditure for protection is required (e.g. dimensioning of the switchgear design)	Higher, as the disconnection time of 70 to 120 ms with circuit-breakers can lead to more than 7 times the arc energy values compared with HV HRC fuses (for an example, see [1.2]); accordingly, higher expenditure for protection is required (e.g. dimensioning of the switchgear design)
	Redundancy without interruption of supply (n. c. ring); voltage dip (see above) is to be observed	Redundancy given, but gap in supply due to switchover from one radial line to the other
	Separate electrical service room required for the switchgear to prevent hazards due to high short-circuit energy – or other constructional measures	Separate electrical service room required for the switchgear to prevent hazards due to high short-circuit energy – or other constructional measures

Standards		
Regions	**Organization**	**Standard**
Worldwide	CENELEC	IEC/TS 62786
Europe	CENELEC	EN 50549-1/-2
Australia / New Zealand	Standards AS / NZ	AS/NZS 3010
North America	IEEE	IEEE 1547, IEEE 2030
China	State Grid Corporation	Q/GDW 480-2015
Rules, directives, regulations		
Regions	**Organization**	**Directive, regulation**
European interconnected system	ENTSO-E	e.g. NC RfG, NC DCC
North America	NERC	e.g. BAL-001, BAL-003, MOD-027
Australia	AEMC	e.g. NER V132

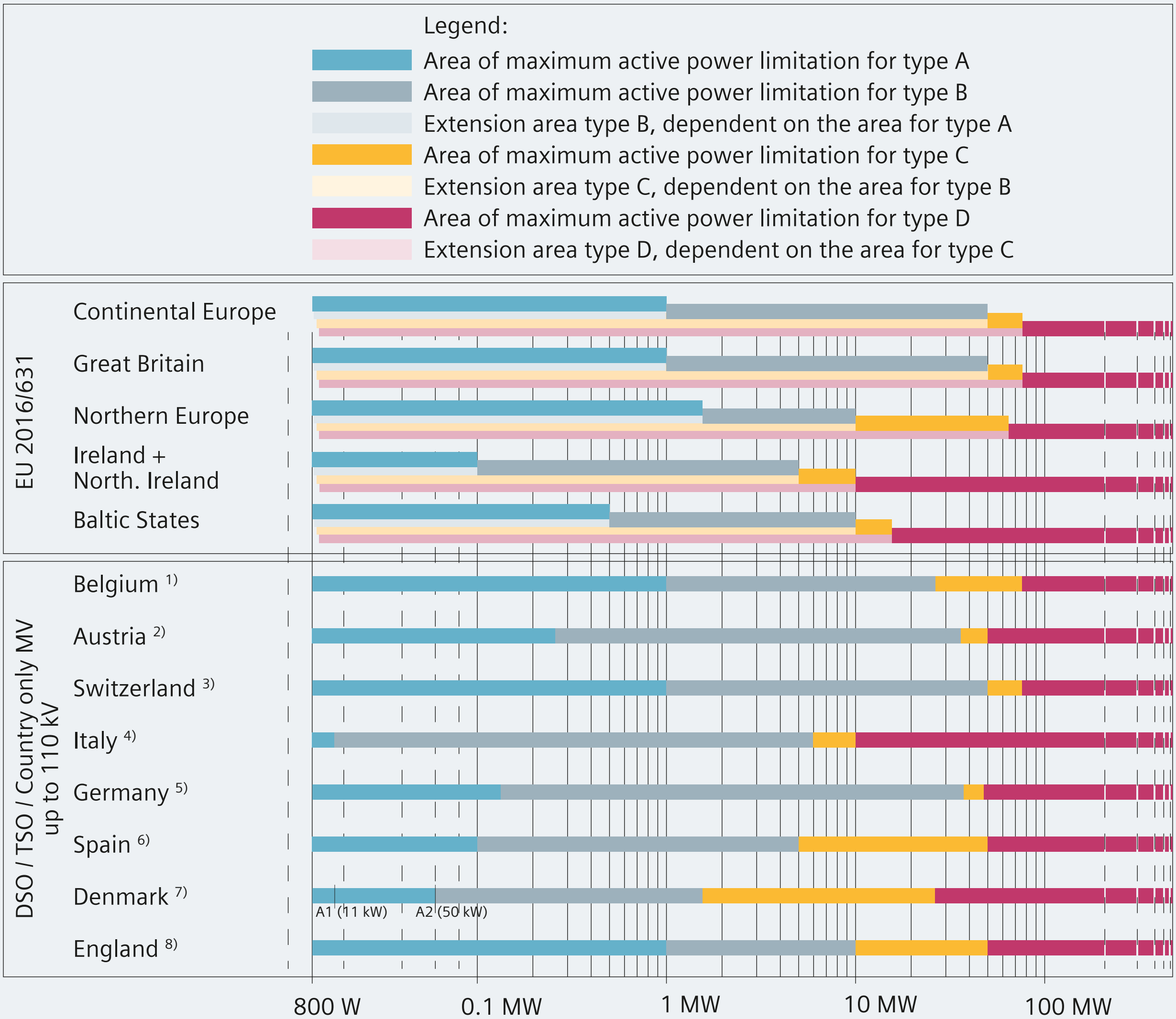
Tab. 4/2: **Examples of international standards and specifications as well as directives and regulations for the connection of power-generating plants in parallel with the public electricity grids**

4.3.1 Standards, Specifications

The international Technical Specification IEC/TS 62786 is broadly formulated, as it not only includes 50 Hz grids, 60 Hz grids, and low-voltage systems, but also medium-voltage systems without power limitations. Accordingly, in the required values for designing embedded generating plants, value ranges are frequently specified which must then be narrowed down based on the national or local situation. Additionally, further limitations, requirements and instructions are stipulated in the national and international transpositions of the Technical Specification. In the European transposition, for example, a series of standards (EN 50549) is drawn up which normatively takes into account a subdivision regarding system voltage and performance classification according to the European Regulation 2016/631/EU (known as NC RfG = Network Code on Requirements for Generators).

The Regulation 2016/631/EU defines a typification for the requirements on power-generating plants regarding the voltage level for grid connection and the maximum electrical active power output (type A, B, C and D; see Fig. 4/5 and Chapter 4.3.2). For a system voltage of 110 kV and more at the point of connection, the requirements for type D must always be fulfilled. Additionally, type D is also to be used for lower system voltages when the stipulated power threshold values of the maximum capacity of power-generating modules are exceeded (see Fig. 4/5).

The Regulation stipulates individual value ranges for the typification in the different European regions (Continental Europe, Great Britain, Northern Europe, Ireland and Northern Ireland, Baltic States). It is remarkable that the margins for the typification in the directives and regulations of the DSO and TSO are used by the different countries according to their specific conditions.



[1] RfG Requirements of General Application; 2019; Elia (Belgium)
[2] TOR Erzeuger (TOR Generator; one edition each for type A, type B, type C, type D); 2019, E-CONTROL (Austria)
[3] Empfehlung Netzanschluss für Energieerzeugungsanlagen (Recommendation for grid connection of power-generating plants); 2014; VSE/AES (Switzerland)
[4] CEI 0-16; 2019; Norma Italiana CEI (Italian standard)
[5] VDE AR-N 4110 (TAR Medium Voltage); 2018; VDE/FNN (Germany)
[6] Norma técnica de supervisión de la conformidad de los módulos de generación de electricidad segun el Reglamento UE 2016/631 (Technical supervision standard for conformity of power-generating modules according to Regulation EU 2016/63); 2019; Red Eléctrica (Electricity grid) (Spain)
[7] Technical Regulation 3.2.3; 2017 and Technical Regulation 3.2.5; 2016; Energinet (Denmark)
[8] Engineering Recommendation G99; 2019; ENA (England)

Fig. 4/5: **Power-specific categorization for power-generating modules at a grid connection voltage of less than 110 kV in Europe**

4.3.2 Requirements for Grid Connection of Power-Generating Plants

Regulation 2016/631/EU differentiates the requirements for grid connection of a power-generating plant regarding this typification, and also for synchronous and non-synchronous grid connection. For CHP plants, the maximum electrical active power output is used as a way for typification. The fundamental requirements for the different types can be roughly summarized as follows:

Type A:
- General requirements to secure the power-generating capacity
- Limited automated response
- Minimum system operator control
- Avoiding larger generating capacity dips in wide parts of network operation
- Minimizing critical events and determining intervention measures if system-critical events do actually take place.

Type B:
- Broader range of automated, dynamic responses for higher resilience to operational events, and limitation of the effects of network events
- Requirements for ensuring dynamic response options
- More extensive control options for the system operator and accordingly required information.

Type C:
- Precise, stable and highly controllable dynamic response of important system services in real time to ensure security of supply
- Enabling coordinated operator action in overall power-generating facilities in different situations during trouble-free operation as well as in case of grid disturbances.

Type D:
- Higher voltage level of the grid connection of generating plants (according to EU Regulation 2016/631: ≥ 110 kV) for ensuring a stable interconnected system operation in Europe.

On the basis of the typification in the Regulation 2016/631/EU, the standards EN 50549-1 and -2 take the modules of type A and type B in low-voltage systems (EN 50549-1) and medium-voltage systems (EN 50549-2) into account.

Exception: Power-generating modules with an apparent power output of up to 150 kVA can also be connected to the medium-voltage grid according to the requirements of EN 50549-1. It is always possible to make agreements with the DSO, and the country-, DSO- or TSO-specific provisions, directives, conditions, and regulations (examples in Fig. 4/5) must be observed.

If different requirements interfere with each other, protection and automatic control must be applied hierarchically according to EN 50549-1 and -2 (decreasing significance from 1. to 7.):

1. Generating unit protection (e.g., the protection equipment of the generating unit must not trip before the interface protection when a) the DSO does not agree or b) foreseeable operating conditions do not require it), including the driving engine, if applicable
2. Interface protection and protection against faults within the generating plant
3. Voltage support during faults and step changes in voltage
4. Active power response by remote control for distribution grid support or due to local overfrequency in the grid
5. Active power response to underfrequency in the grid
6. Control of reactive power and active power
7. Other control commands for active power regulation, for example due to self-optimization stipulations, for economic reasons, or according to local market conditions.

For CHP plants embedded in industrial plants, active power requirements shall be agreed between the producer and the system operator. The above priority list can be adapted accordingly.

In the European interconnected system, the requirements for the high-voltage grid of 110 kV and beyond are homogenized. IEC/TS 62786 and EN 50549-1 and -2 stipulate a common framework for the medium- and low-voltage systems. In detail, these may differ from the characteristics requested by national or local transmission and distribution system operators.

The requirements according to EN 50549-1 and -2, which can only briefly be discussed in here, include:

1. In normal operation:
   a. Permissible minimum operating periods with grid connection for defined frequency ranges[6)] → see Tab. 4/3
   b. Permissible minimum active power at underfrequency → see Fig. 4/6
   c. For the minimum requested range of nominal voltage U_n, the following applies for the agreed system connection voltage U_c:
   EN 50549-1: $0.85\ U_c \leq U_n \leq 1.1\ U_c$
   EN 50549-2: $0.9\ U_c \leq U_n \leq 1.1\ U_c$
   (IEC/TS 62786: $0.9\ U_c \leq U_n \leq 1.1\ U_c$)

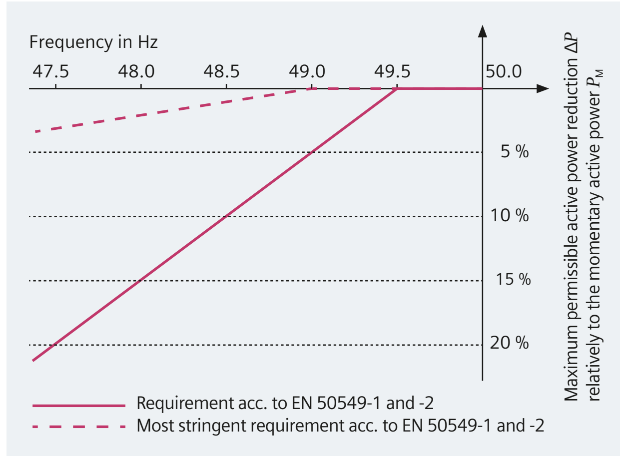


Fig. 4/6: **Maximum permissible active power reduction at underfrequency**

6) The requirement for frequency support in the European interconnected system was triggered by experiences with the increasing energy provision from photovoltaic plants in the low-voltage network (50.2 Hz problem) as well as from wind power and embedded generating plants (49.5 Hz problem) [4.3]

	Frequency in Hz	47.0	47.5	48.0	48.5	49.0	49.5	50.0	50.5	51.0	51.5	52.0
EN 50549-1/-2	Minimum requirements		30 min			Unlimited				30 min		
	More stringent requirements	20 s	90 min			Unlimited				90 min	15 min	
EU 2016/631	Continental Europe		30 min			Unlimited				30 min		
	Northern Europe		30 min			Unlimited				30 min		
	Great Britain	20 s	90 min			Unlimited				90 min	15 min	
	Ireland / Northern Ireland		90 min			Unlimited				90 min		
	Baltic States		30 min			Unlimited				30 min		

IEC/TS 62786	Frequency in Hz	45.0	47.0	49.5	50.0	50.5	52.0	57.0
	Power frequency 50 Hz		Unlimited operation possible	Unlimited		Unlimited operation possible		
		Frequency for a limited operating time (0.5 s to 90 min)				Frequency for a limited operating time (0.5 s to 90 min)		

IEC/TS 62786	Frequency in Hz	57.0	59.5	60.0	60.5	61.8
	Power frequency 60 Hz	Unlimited operation possible	Unlimited		Unlimited operation possible	
		Frequency for a limited operating time (0.5 s to 90 min)			Frequency for a limited operating time (0.5 s to 90 min)	

Tab. 4/3: **Frequency-dependent time stipulations for grid operation of power-generating plants according to EN 50549-1 and -2, 2016/631/EU and IEC/TS 62786**

Contents
1
2
3
4
5
6
7

2. For grid-critical states:
   a. Voltage support by means of reactive power provision [7)]
      → see Fig. 4/7

   b. Control modes for voltage control according to EN 50549-1 and -2, out of which only one may be active exclusively:
      - Mode of setting point for Q (setpoint for reactive power output)
      - Mode of setting point for cos φ (setpoint for cos φ)
      - $Q(U)$ (reactive power output as a function of voltage)
      - $Q(P)$ (reactive power output as a function of active power); not possible for power-generating plants according to EN 50549-1
      - cos φ (P) (power-related control of cos φ)

[7)] Voltage support can be requested from the DSO according to IEC/TS 62786 or EN 50549-1 and -2. In 2016/631/EU, voltage support by means of reactive power is only described for type B, C and D. In EN 50549-1 and -2, the requirements for low or medium voltage at nominal voltage are illustrated as a P/Q diagram respectively (active power as a function of reactive power), and, in case of deviations from this, as a power-voltage diagram (ratio of voltage U to nominal voltage U_n as a function of the ratio of reactive power Q to design active power P_D).

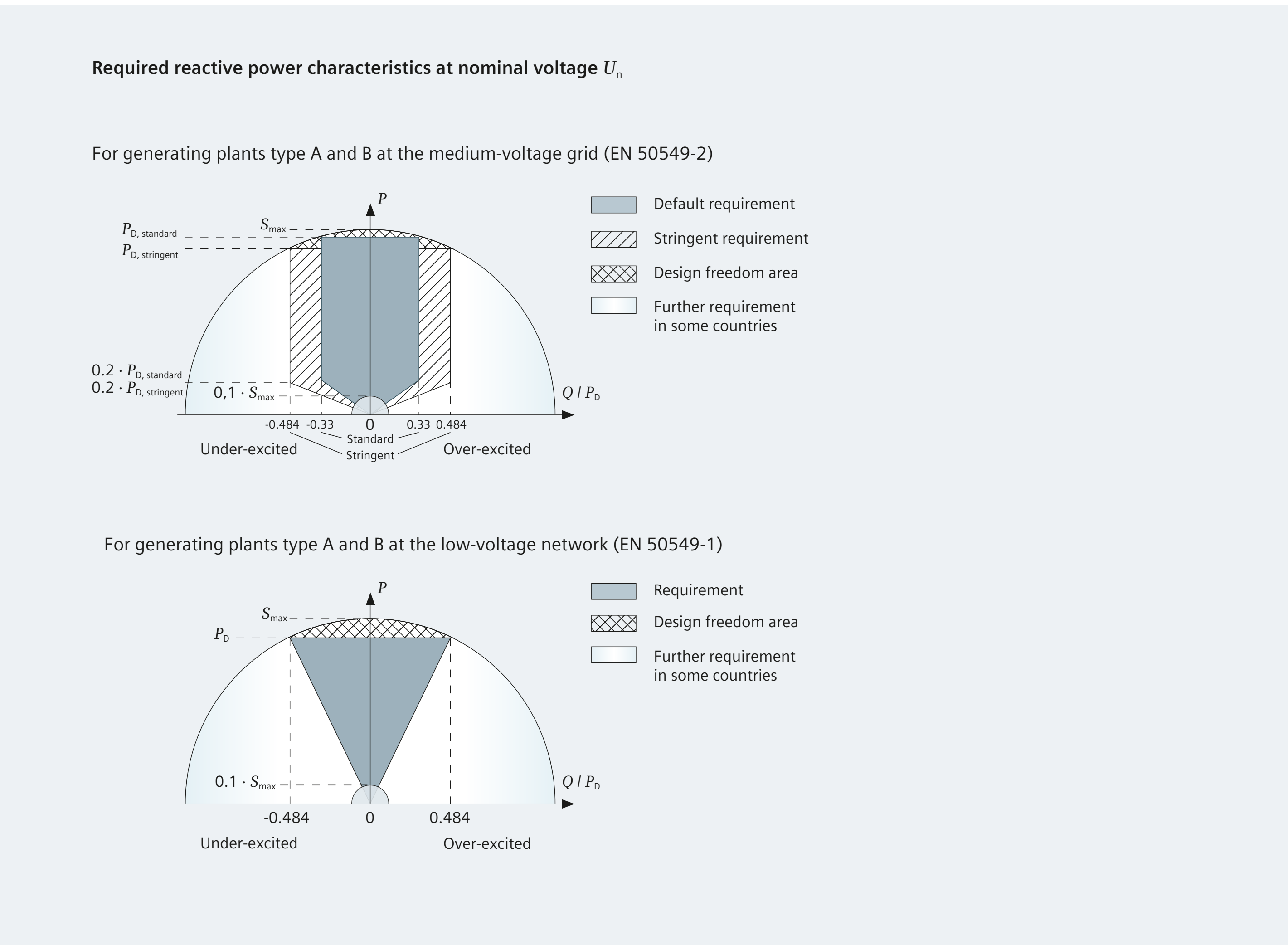


Fig. 4/7: **Reactive power behavior of power-generating plants for grid support according to EN 50549-1 and -2**

c. Voltage-related active power reduction
→ At critical overvoltage, the speed of power reduction may only be 33 % per second as a maximum for a 100 % change

d. Permissible rate of change of frequency (ROCOF):

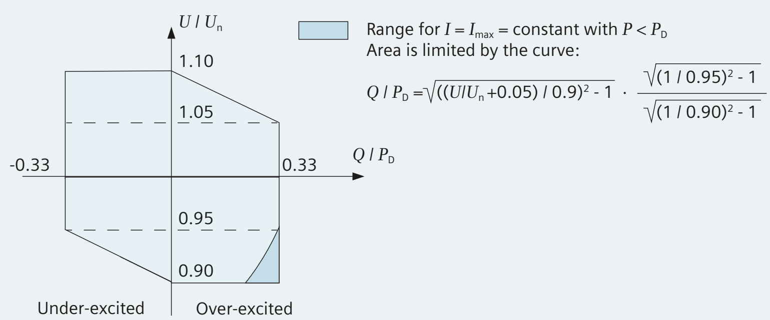
IEC/TS 62786:	Agreement of individual countries (note: 2.5 Hz/s is requested in some countries)
EN 50549-1 and -2:	At least 2 Hz/s for non-synchronous generators At least 1 Hz/s for synchronous generators

e. Frequency support by means of active power response[8]
→ see Fig. 4/8

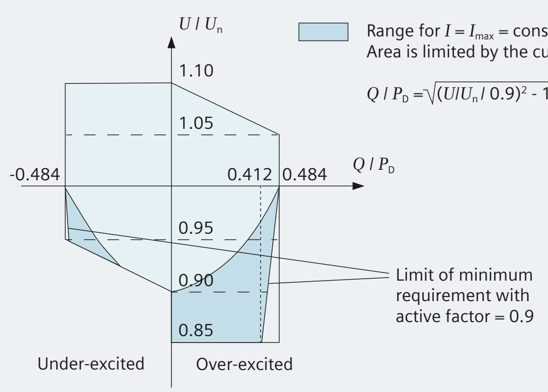
[8] The active power provision at underfrequency (LFSM-U) is not a "must" requirement for power-generating plants according to EN 50549-1 and -2 ("must" applies to electric energy storages and, according to 2016/631/EU, only for power-generating plants of type C and type D. For power-generating plants type C and D, there can additionally be an agreement according to 2016/631/EU for the frequency-sensitive mode FSM for $\Delta P / P_{ref}$ between 1.5 % and 10 %). The requested changes in active power at underfrequency/overfrequency are described by providing information on parameters such as delay, threshold frequency, droop/slope, dead band of frequency, and relative active power range.

Required reactive power characteristics at active power P_D and deviations from the nominal voltage U_n

For generating plants type A and B at the medium-voltage grid (EN 50549-2)



For generating plants type A and B at the low-voltage network (EN 50549-1)



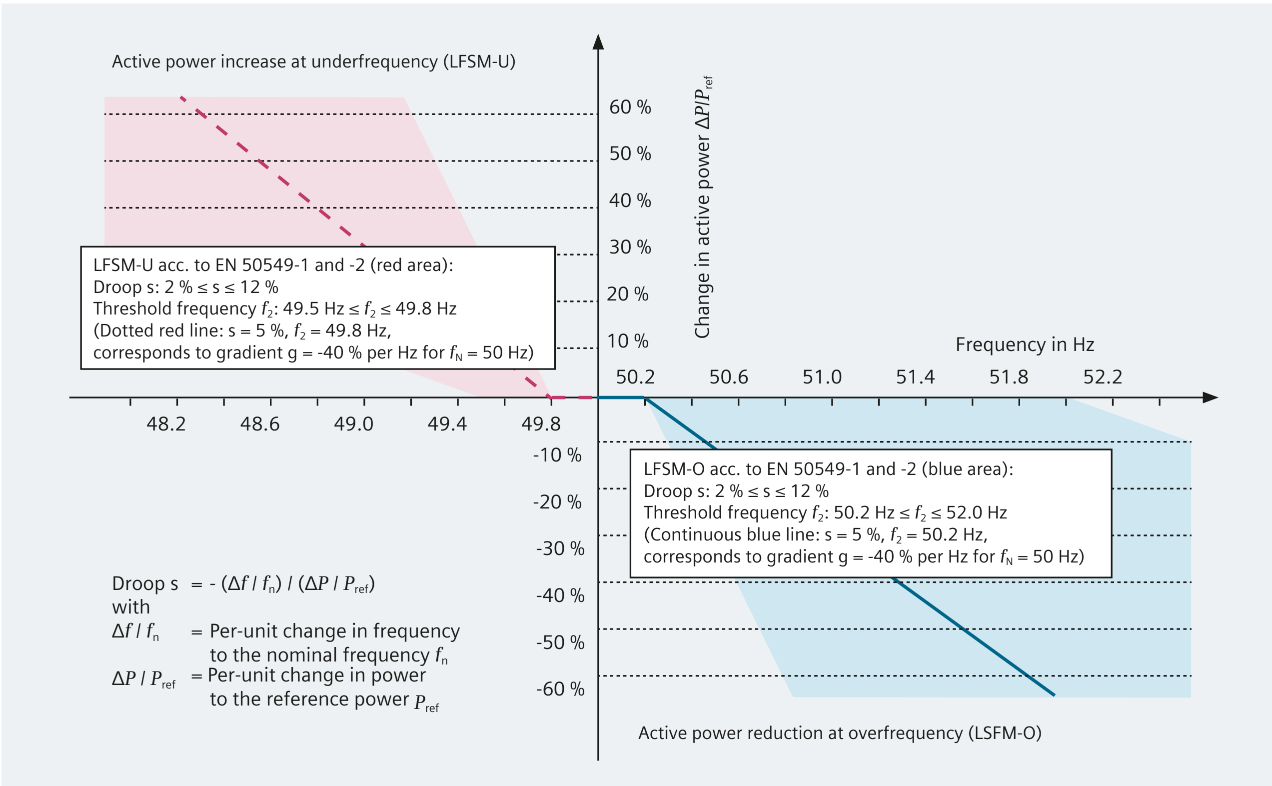


Fig. 4/8: **Frequency-dependent active power response according to EN 50549-1 and -2 (- - - - LFSM-U; ______ LFSM-O)**

f. Dynamic grid support
→ In case of failures and step changes in voltage (typically caused by short circuits), the unwanted disconnection of the power-generating plant and a potential grid instability resulting from this are to be avoided:
   i) Voltage-time profiles in case of failures
   FRT capability (to maintain a stable operation with design-conforming failures) → see Fig. 4/9
   ii) Reactive current infeed
   In case of short-term step changes in voltage, a dynamic reactive current provision has to occur beyond the previously described voltage support. For power-generating plants in the low-voltage distribution network, this is generally not required, but it can be agreed on. Synchronous generators offer sufficient support by system design. Normative requirements for non-synchronous power-generating plants are described in EN 50549-2. The additional reactive current is to be supplied at least up to the level of the rated current. However, no electricity infeed is required at $U < 0.15 \cdot U_c$ (declared supply voltage U_c)
   iii) Current reduction in converter connected power generating plants
   As an additional requirement at critical voltage, converter connected power-generating plants must be able to reduce their current as quickly as technically possible to 10 % of rated current (or below) (see EN 50549-1 and -2).

[4.4] provides an overview of all the differences among European countries when it comes to the implementation of the RfG network code. Especially in Europe, the topic of grid connection of embedded generating plants is highly dynamic, so that short-term changes must be observed.

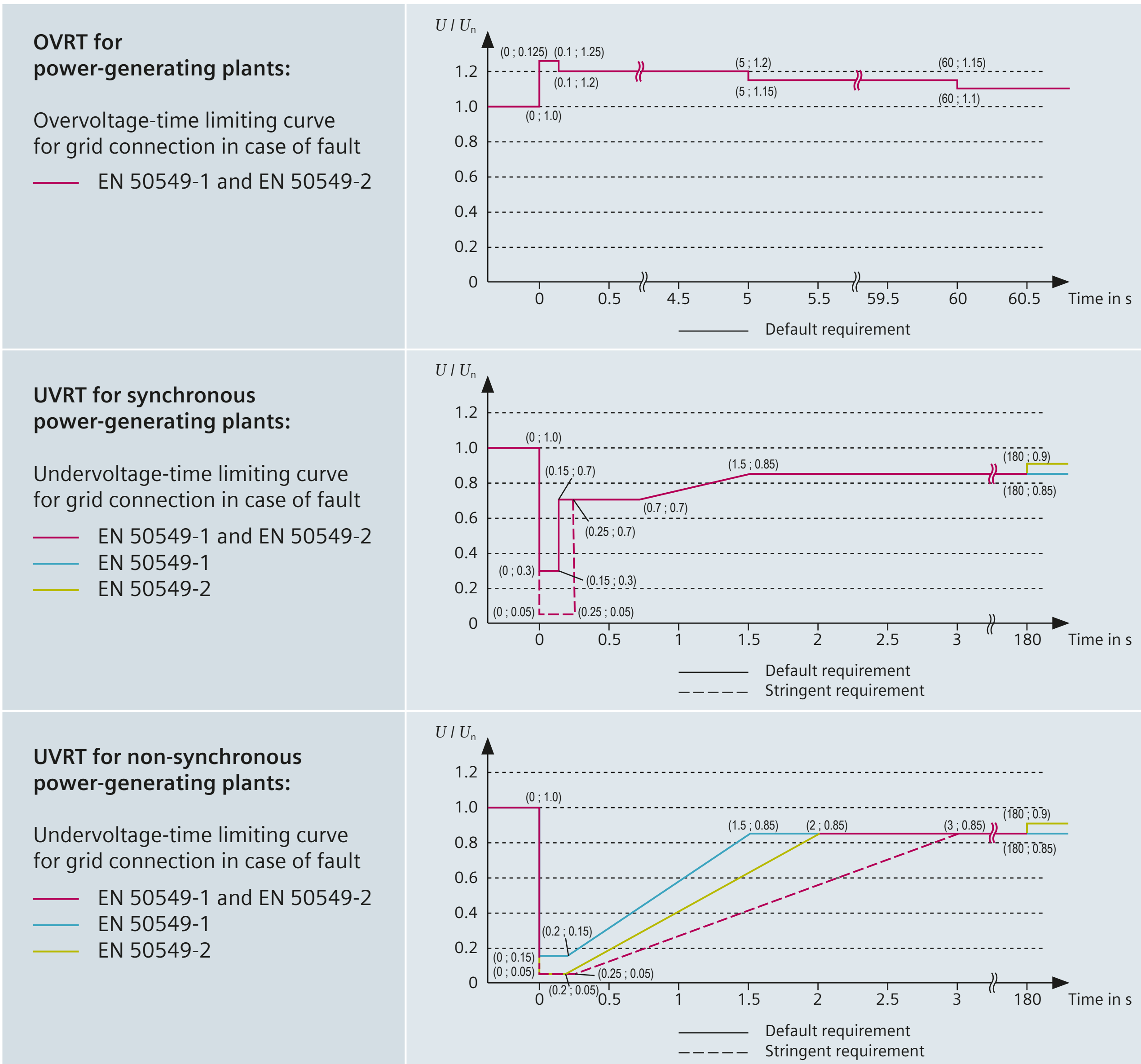


Fig. 4/9: **Voltage-time characteristics according to EN 50549-1 and -2* (also called FRT characteristics) for describing the voltage behavior in case of fault**

* Remark: 2016/631/EU and EN 50549-1 and -2 do not fully coincide. For example, the behavior in case of underfrequency (UVRT in Fig. 4/9) is only required in 2016/631/EU for types B, C and D. EN 50549-1 and -2 recommend this for type A as well. The same is true for the reactive power provision for voltage support. In EN 50549-1 and -2, LFSM-U (Fig. 4/8) is also proposed for type A and type B.

This also becomes evident when it comes to electromagnetic compatibility (EMC). According to IEC/TS 62786, power-generating plants must comply with the basic requirements of the standard series IEC 61000. EN 50549-1 and -2 point out how the latest IEC 61000 series is oriented towards consumers. The standard series IEC 61000 is currently being revised and, if required, adjusted to include power-generating plants.

In EN 50549-1 and -2, the conformity with the relevant requirements of the Directives 2014/30/EU and 2014/53/EU as well as with the requirements of EN 50160 on power quality are determined. With respect to power quality, IEC/TS 62786 and EN 50549-1 and -2 agree that local requirements must be taken into account. They also agree that power-generating plants must not feed any direct currents into the grid.

Contents

1

2

3

4

5

6

7

4.3.3 Interface Protection

Switching and protection equipment may be used to ensure that the requirements on power-generating plant operation are met, as illustrated schematically in Fig. 4/10. The interface protection relay (IPR) acts on the interface switch. The IPR responds to

- Faults in the distribution grid
- Unintentional islanding
- Voltage and frequency conditions outside of the set limit values.

On the DSO's request, the IPR may act on another switching device with an adequate delay in case the interface switch fails. In the same way, the DSO can request a UPS for the interface protection to ensure a delay or to deal with UVRT behavior.

The interface protection system (IPS) must be an independent facility which is not integrated in the generating units. Exceptions are converter connected power-generating plants according to IEC/TS 62786, and so-called micro-generating plants according to EN 50549-1 (low-voltage connection and maximum rated current of 16 A of the power-generating plant; above that, the DSO is permitted to determine a threshold value), in which an interface protection and a measuring point can be integrated in the generating units of the power-generating plant.

The protection measures for the IPR, listed in Tab. 4/4, can be derived from the requirements for voltage and frequency protection (according to EN 50549-1 and -2).

4.4 Medium-Voltage Switchgear and Low-Voltage Load Centers at Process Level

The terms "load centers" and "switchgear" make it clear that, next to the energy- and power-specific criteria of the loads, especially the spatial framework conditions of the industrial plant must be taken into account during concept finding for the electric power supply. In a first step, it must be clarified – based on the existing technical data and the installation or arrangement of loads and consumers – which voltage levels should be preferably provided. Generally, it is frequently more cost-efficient to install and operate only few voltage levels.

Apart from the supply voltage of 230/400 V for typical low-voltage consumers – such as lighting, information and communication technology, safety and automation applications, as well as smaller drives – larger motorized loads of more than 250 kW should be connected to a medium-voltage distribution of 10 kV.

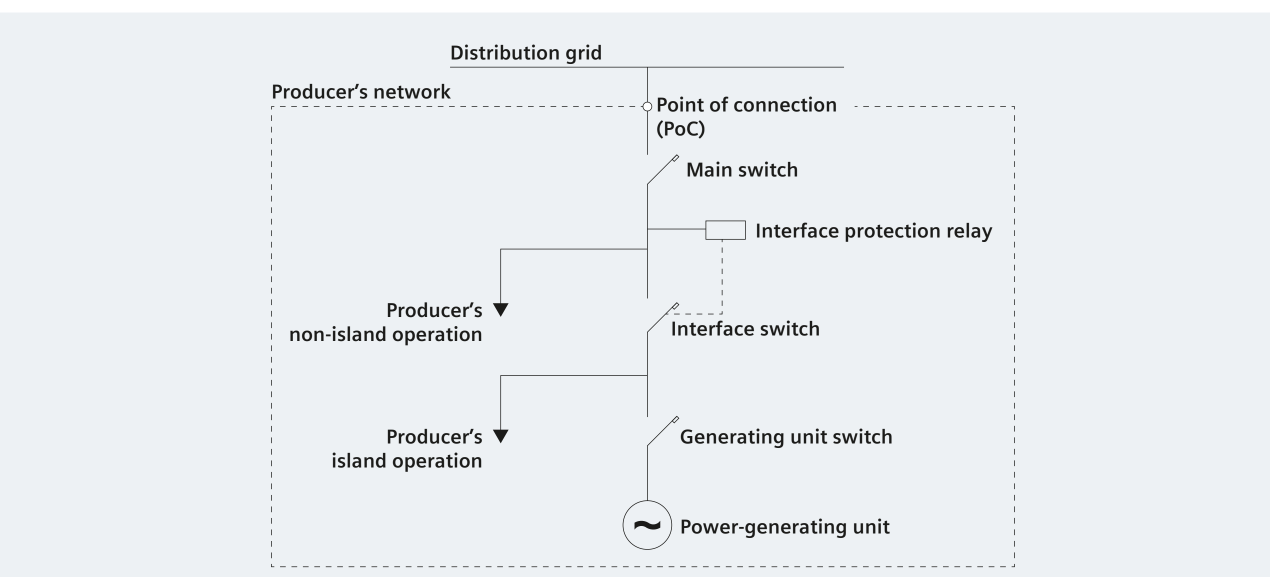


Fig. 4/10: **Schematic example for the connection of a power-generating plant to a distribution grid based on IEC/TS 62786 or EN 50549-1 and -2**

Protection function	EU standard	ANSI code	Setting ranges	
			Threshold value range	Pickup time range
Undervoltage protection	EN 50549-1/-2	27 <	$0.2\ U_c \leq U \leq 1.0\ U_c$	0.1 up to 100 s
		27 <<	$0.2\ U_c \leq U \leq 1.0\ U_c$	0.1 up to 5 s
Overvoltage protection	EN 50549-1/-2	59 >	$1.0\ U_c \leq U \leq 1.2\ U_c$	0.1 up to 100 s
		59 >>	$1.0\ U_c \leq U \leq 1.3\ U_c$	0.1 up to 5 s
10-minute mean value for overvoltage protection	EN 50549-1/-2		$1.0\ U_c \leq U \leq 1.15\ U_c$	
Underfrequency protection	EN 50549-1/-2	81 <	47 Hz to 50 Hz	0.1 up to 100 s
		81 <<	47 Hz to 50 Hz	0.1 up to 5 s
Overfrequency protection	EN 50549-1/-2	81 >	50 Hz to 52 Hz	0.1 up to 100 s
		81 >>	50 Hz to 52 Hz	0.1 up to 5 s
Positive phase-sequence undervoltage protection	EN 50549-2	27D	$0.2\ U_c \leq U \leq 1.0\ U_c$	0.2 up to 100 s
Negative phase-sequence overvoltage protection	EN 50549-2	47	$0.01\ U_c \leq U \leq 1.0\ U_c$	0.2 up to 100 s
Zero-sequence overvoltage protection	EN 50549-2	59N	$0.01\ U_c \leq U \leq 1.0\ U_c$	0.2 up to 100 s

Tab. 4/4: **Protection settings for the interface protection according to EN 50549-1 and -2**

The short-circuit currents of large motors must be observed, which additionally stress the infrastructure of electric power distribution in case of short circuit. The higher the operating voltage, the lower the short-circuit current at equal short-circuit power. The short-circuit current at 6 kV, for example, is 67 % higher than at 10 kV. Further advantages of a higher voltage are:

- Reduction of cable cross-sections (cost-efficiency of the switchgear)
- Lower network losses
- Advantages in terms of protection technology by extending the grading time ranges[9].

4.4.1 Low-Voltage Load Centers

The advantages of a distributed low-voltage supply of load centers regarding short-circuit currents and voltage drop as compared with a centralized supply are illustrated qualitatively in [1.1]. The standard IEC 60364-8-1 basically only describes in a qualitative way that the number of load center substations depends on criteria such as the load distribution and the associated area in the building. The background of the load center determination described in IEC 60364-8-1 is a reduction of losses by minimizing distances between transformer substations and loads. Further boundary conditions that are important for the structural concept of the load center are not taken into account.

The load center determination is an iterative process for which numerous detailed pieces of information should be available and adjustments should additionally be possible, such as for example shifting the consumers, and thus the load center. To create a first concept draft for the supply of the load centers for low-voltage consumers, it is sufficient to consider the voltage drop in the low-voltage system and the line lengths associated with it, as well as the requirements for the short-circuit power on the low-voltage side.

i) **Line lengths and voltage drop**
When dimensioning cables and lines in the low-voltage network, the permissible current-carrying capacity in dependency of the installation conditions is decisive for determining the cross-section. For the cross-section determined in this way, the result is a line length of 100 m as a maximum in order to keep the voltage drop less or equal to 2 % [1.2].

This can be verified by means of two simple estimations:

a) When checking with SIMARIS design, a 100 m connection cable is dimensioned for a low-voltage motor with a maximum power of 250 kW. With cos φ = 0.9 and an efficiency of 0.95, the result is a maximum current of about 422 A. In case of installation type C,

9) Lower short-circuit currents cause a lower thermal stress for the operational equipment (let-through energy I^2t and dynamic peak short-circuit current i_p). For this reason, longer disconnection times are permissible which, in turn, positively influence the possible grading levels of the definite time-overcurrent protection.

this means a cable cross-section of 300 mm² for a PVC-insulated copper cable, and the voltage drop remains below 2 %.

b) Estimation according to equation 63 in DIN VDE 0100 Supplement 5:

$l_{perm} = l_{stand} \cdot U_n / I_B \cdot \Delta u$

with: l_{perm} = permissible line length
l_{stand} = standardized value for the permissible line length according to DIN VDE 0100 Supplement 5; the unit of l_{stand} is (m · A)/(V · %)
U_n = nominal voltage
I_B = maximum operational current
Δu = percentage for voltage drop

Example: U_n = 400 V; I_B = 422 A; multi-core cable 300 mm²

→ stipulation: line l = 100 m

l_{stand} = 53.9 m (according to DIN VDE 0100 Supplement 5 for PVC copper multi-core cables of 300 mm², results in:
$\Delta u = l_{perm} / l_{stand} \cdot I_B / U_n$ = 100 m / 53.9 m · 422 / 400 = 1.96 %)

For placing one or more load centers, the distance must not be assumed as a line length of 100 m. The line routing in the room must rather be taken into account, with rectangular layouts and bypassing of obstacles.

ii) **Short-circuit power and voltage stability**
Voltage dips behave inversely proportional to the short-circuit power at the point of connection or common coupling. Commonly, the devices become more expensive if a higher short-circuit power is requested. Furthermore, in case of fault, the severity and the extent of damage can increase due to the higher currents. The relative impedance voltage u_{kr} of the transformers is crucial for this. The following key issues should be considered when designing the load centers:

– For a cost-effective design, the initial symmetrical short-circuit current capacity of a load center's transformers S''_k (transformer) should be less than approx. 45 MVA (I''_k = 66 kA) at 400 V. $u_{kr} = \sum S_{rT} / S''_k$ (transformer) gives the following maximum total rated power of the transformers for an individual substation in the load center, depending on u_{kr}:

  $\sum S_{rT}$ (u_{kr} = 4 %) ≤ 1.8 MVA

  $\sum S_{rT}$ (u_{kr} = 6 %) ≤ 2.7 MVA

– A higher total short-circuit power of the transformers from about 60 MVA to 90 MVA (corresponds to I''_k from 85 kA to 130 kA) mitigates the voltage dips which are caused, for example, by the direct-on-line start of large motors. For the range from 60 MVA to 90 MVA with u_{kr} equaling 4 % and 6 %, the respective range of the total transformer power for an individual substation in the load center results as follows:

  2.4 MVA ≤ $\sum S_{rT}$ (u_{kr} = 4 %) ≤ 3.6 MVA

  3.6 MVA ≤ $\sum S_{rT}$ (u_{kr} = 6 %) ≤ 5.4 MVA

Requested short-circuit withstand strength I''_k of the switching and protection devices		**55 kA**	**66 kA**	**85 kA**	**100 kA**	**130 kA**
$S''_k = \sqrt{3} \cdot 400\ \text{V} \cdot I''_k$						
Corresponding short-circuit withstand strength S''_k of the transformers		**38 MVA**	**45 MVA**	**60 MVA**	**70 MVA**	**90 MVA**
S_{max}(transformer) = $S''_k \cdot u_{kr}$						
Maximum total power S_{max}(transformer) for transformers with u_{kr} = 4 %	1 busbar / substation	1.5 MVA	1.8 MVA	2.4 MVA	2.8 MVA	3.6 MVA
	2 busbars / substations	3.0 MVA	3.6 MVA	4.8 MVA	5.6 MVA	7.2 MVA
	3 busbars / substations	4.5 MVA	5.4 MVA	7.2 MVA	8.4 MVA	10.8 MVA
Maximum total power S_{max}(transformer) for transformers with u_{kr} = 6 %	1 busbar / substation	2.3 MVA	2.7 MVA	3.6 MVA	4.2 MVA	5.4 MVA
	2 busbars / substations	4.6 MVA	5.4 MVA	7.2 MVA	8.4 MVA	10.8 MVA
	3 busbars / substations	6.9 MVA	8.1 MVA	10.8 MVA	12.6 MVA	16.2 MVA

Tab. 4/5: **Maximum total power of transformers depending on the requirements for the short-circuit behavior and the number of load centers (number of substations or connection busbars)**

At a total power in the load center of more than 2.7 MVA or 5.4 MVA, the power is distributed to several substations (or separate connection busbars).

As an overview for the different short-circuit withstand strengths of the switching and protection devices and the associated short-circuit power of the transformers, a table (Tab. 4/5) can be created.

It becomes evident that the calculated values of the maximum total power of the transformers reflect the simple dependency on the number of load centers (substations or connection busbars) as well as on the impedance voltage u_{kr} of the transformers. Additionally, Fig. 4/11 illustrates the correlations between the short-circuit withstand strength of the operational equipment and the transformers at a connection busbar.

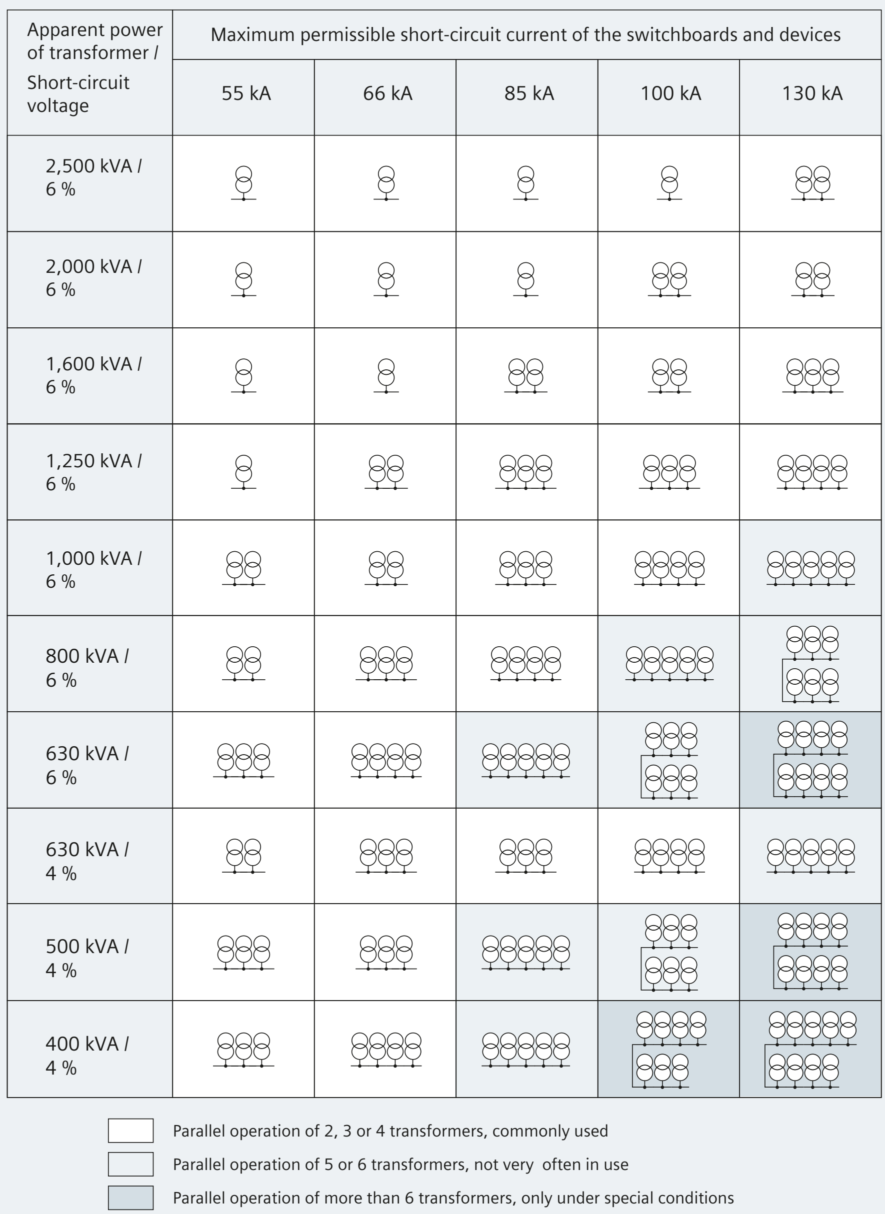


Fig. 4/11: **Overview of short-circuit requirements on low-voltage switchboards and devices depending on different transformer configurations**

iii) **Maximum output of the individual transformers in the load center**
If switch-disconnectors with HV HRC fuses are preferred as transformer protection on the medium-voltage side (advantages being the limitation of short-circuit current and short-circuit duration in case of fault), a maximum transformer rating is recommended as follows:

800 kVA at 10 kV

1,250 kVA at 20 kV

By using HV HRC fuses for transformer protection, smaller cable cross-sections for the transformer feeders result in the event of short circuit thanks to the lower let-through energy (lower I^2t values) (advantages compared with circuit-breakers: limitation of let-through current as well as faster fault clearance). If, however, a selective fault clearance is requested between the HV HRC fuse (on the medium-voltage side) and the transformer circuit-breaker (on the low-voltage side), the fuse-link must be analyzed more closely, as the HV HRC fuses typically are not fully selective with the transformer circuit-breaker on the low-voltage side.

The procedure for concept finding with the help of table Tab. 4/5 is explained by means of an example (Fig. 4/12). In this process it is demonstrated that different concepts can be created for one or multiple load centers depending on the requirements. The following is stipulated:

- A service room with a floor area of 100 m x 100 m
- In this room, 12 low-voltage motors of 250 kW power each are almost evenly distributed (with active power factor cos φ = 0.9 and efficiency η = 0.95, the result is a total apparent power of about 3.5 MVA)
- The motors should be supplied via one or multiple load substations with transformers (primary voltage U_{prim} = 20 kV / secondary voltage U_{sec} = 0.4 kV).

It is required that the relative voltage drop Δu of the supply line between the load center(s) and the motors remains below 2 %. As described in item i), this can be achieved if the line length is shorter than 100 m. For using the HV HRC fuses according to the above item iii), a power of 1,000 kVA or 1,250 kVA per transformer is selected for the medium-voltage supply with 20 kV. This way, the total power of the minimum four or three transformers required is higher than 3.5 MVA, in line with the total power of the motors. The two selected concepts are:

1. One load center substation:
   In order to comply with the 100 m line length, the load center substation must be installed centrally. Two versions can be selected here. On the one hand, all transformers – with 4 times 1,000 kVA or 3 times 1,250 kVA – are connected to a common busbar. In this case, operational equipment with a short-circuit withstand strength of I''_k = 100 kA (4 times 1,000 kVA) or I''_k = 85 kA (3 times 1,250 kVA) are to be used according to Tab. 4/5 and Fig. 4/11 (Fig. 4/12 illustration a). For a low short-circuit withstand strength of I''_k = 55 kA, not all transformers are operated in parallel: For the 1,000 kVA transformers, it is two that are operated at two busbars each, or one transformer each at three busbars for the 1,250 kVA transformers (Fig. 4/12 illustration b).
2. Two load center substations:
   If a central installation is not possible for spatial reasons and the transformers shall be installed close to the wall, the solution involving the four 1,000 kVA transformers is appropriate, as at least two separate load centers must be established (Fig. 4/12 illustration c). Depending on the requirements, the short-circuit withstand strength of the operational equipment can then be selected with I''_k = 55 kA or more. The line length of 100 m is also accomplished in case of corner installation.

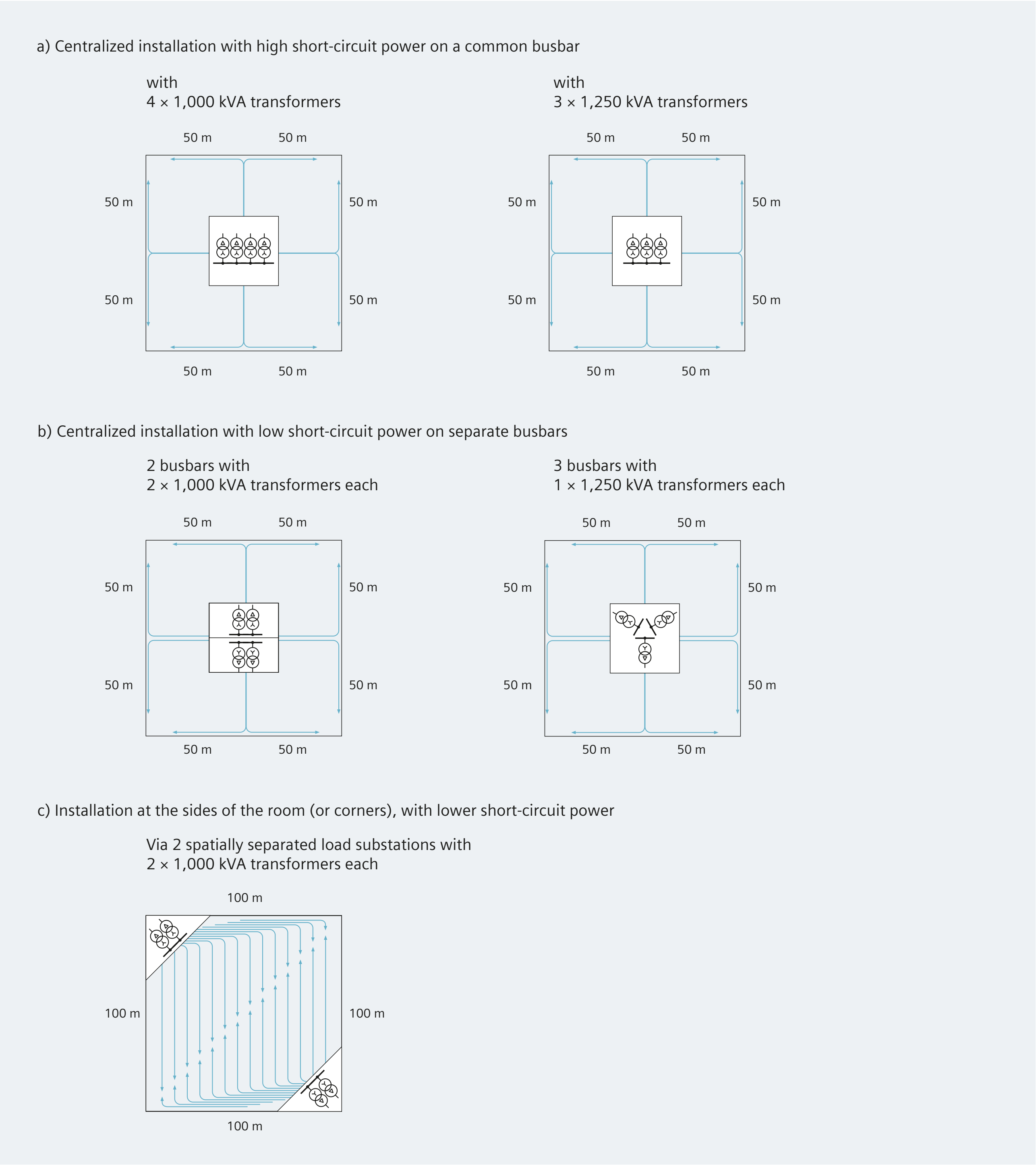


Fig. 4/12: **Placement of load centers depending on the low-voltage cable length and the installation options**

4.4.2 Medium-Voltage Switchgear

In case of larger motorized loads (commonly above 250 kW), it is reasonable to connect to a medium-voltage level. As opposed to electric power distribution for low-voltage loads, the line length is negligible in medium-voltage distribution systems when considering the voltage drop. For the connection of 10 kV motors to a medium-voltage switchgear, for example, the line length (with the same conductor cross-section) can be 25 times longer than in the low-voltage network – with all assumptions previously made for the voltage drop, this means 2.5 km.

Typical loads which should be directly connected to the medium-voltage distribution system are large-scale three-phase asynchronous motors. During connection, the voltage drop caused by the start of the motors must be taken into account. The arising starting currents in direct-on-line starts can amount up to 5 to 7 times the rated value, and can therefore be the cause for critical voltage dips in the higher-level distribution grid. It must be checked whether the starting currents can cause a voltage drop of more than 10 % [1.2].

For a simple verification, the short-circuit power provided by the transformer is compared with the power required at motor start.

Transformer short-circuit power:

$$S''_{kT} = S_{rT} \cdot 100 / u_{kr}$$

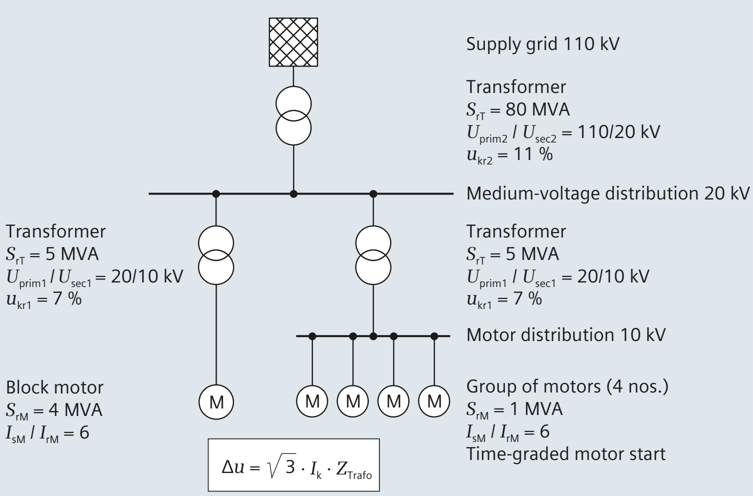
Motor starting power:

$$S_{sM} = S_{rM} \cdot (I_{sM} / I_{rM})$$

Voltage drop:

$$\Delta u = S_{sM} / S''_{kT}$$

Single-line diagram:



Impedances for voltage drop estimation:

$$Z_{Trafo} = \frac{U_{sec2}^2 \cdot u_{kr}}{S_{rT}}$$

$$Z_{Trafo}(80\ \text{MVA}) = (20\ \text{KV})^2 \cdot 0.125 / 80\ \text{MVA} = 0.625\ \Omega$$

$$Z_{Trafo} = \frac{U_{sec1}^2 \cdot u_{kr}}{S_{rT}}$$

$$Z_{Trafo}(5\ \text{MVA}) = (10\ \text{KV})^2 \cdot 0.07 / 5\ \text{MVA} = 1.4\ \Omega$$

$$Z_{Motor} = \frac{U_{sec1}^2}{S_{rM} \cdot I_{sM} / I_{rM}}$$

$$Z_{Motor}(1\ \text{MVA}) = (10\ \text{KV})^2 / (1\ \text{MVA} \cdot 6) = 16.7\ \Omega$$

$$Z_{Motor}(4\ \text{MVA}) = (10\ \text{KV})^2 / (4\ \text{MVA} \cdot 6) = 4{,}17\ \Omega$$

Voltage drop at motor terminals:

$$I_{rM} = \frac{S_{rM}}{\sqrt{3} \cdot U_{sec1}}$$

and therefore

$$I_k = I_{sM} = (I_{sM} / I_{rM}) \cdot \frac{S_{rM}}{\sqrt{3} \cdot U_{sec1}}$$

resulting in

$$\Delta u_M = (I_{sM} / I_{rM}) \cdot \frac{S_{rM}}{U_{sec1}} \cdot Z_{Trafo}(5\ \text{MVA})$$

Δu_M (4 MVA) = 6 · 4 MVA / 10 kV · 1.4 Ω = 3.36 kV = 33.6 %
Δu_M (1 MVA) = 6 · 1 MVA / 10 kV · 1.4 Ω = 0.84 kV = 8.4 %

Voltage drop in the medium-voltage distribution 20 kV:

$$I_k = I_{s\,20\,kV} = I_{sM} \cdot \frac{U_{sec1}}{U_{prim1}}$$

resulting in

$$\Delta u_{Tr} = \sqrt{3} \cdot I_{sM} \cdot \frac{U_{sec1}}{U_{prim1}} \cdot Z_{Trafo}(80\ \text{MVA}) =$$

$$= (I_{sM} / I_{rM}) \cdot \frac{S_{rM}}{U_{prim1}} \cdot Z_{Trafo}(80\ \text{MVA})$$

Δu_{Tr} (4 MVA) = 6 · 4 MVA / 20 kV · 0.625 Ω = 750 V = 3.75 %
Δu_{Tr} (1 MVA) = 6 · 1 MVA / 20 kV · 0.625 Ω = 187.5 V = 0.94 %

Fig. 4/13: **Comparison of a staging motor start with the direct-on-line start of a large medium-voltage motor**

With

S''_{kT}	Transformer initial short-circuit power
S_{rT}	Transformer rated apparent power
u_{kr}	Transformer impedance voltage in percent
S_{sM}	Short-circuit power contribution due to motor start
S_{rM}	Motor rated apparent power
I_{sM} / I_{rM}	Ratio of starting current to rated current of motor

The more precise determination of the voltage drop via impedances is described in IEC 60909-0. In Fig. 4/13, it is shown based on a simple example how a time-graded motor start (also called "staging" start) of multiple smaller asynchronous motors affects the voltage drop compared with a direct-on-line start of a large motor (cable impedances are disregarded so that a maximum feedback is assumed). For both cases in Fig. 4/13, the voltage drop in the medium-voltage distribution grid (U_{prim1} = 20 kV) remains below 5 %, so that the effects on the power quality and thus on other consumers stay within acceptable limits.

It must also be observed that the voltage drop at the motor does not become too high, as the torque of an asynchronous motor is square dependent on the voltage. This, in turn, leads to an extension of the starting time (Fig. 4/14). For the starting duration t_s, the following applies approximately:

Starting duration $t_s = J \cdot n / (9.55 \cdot M_{acc})$

with

J	Total moment of inertia which must be accelerated (in kgm²)
n	Operating speed (in revolutions per minute: rpm)
M_{acc}	Acceleration torque (in Nm),

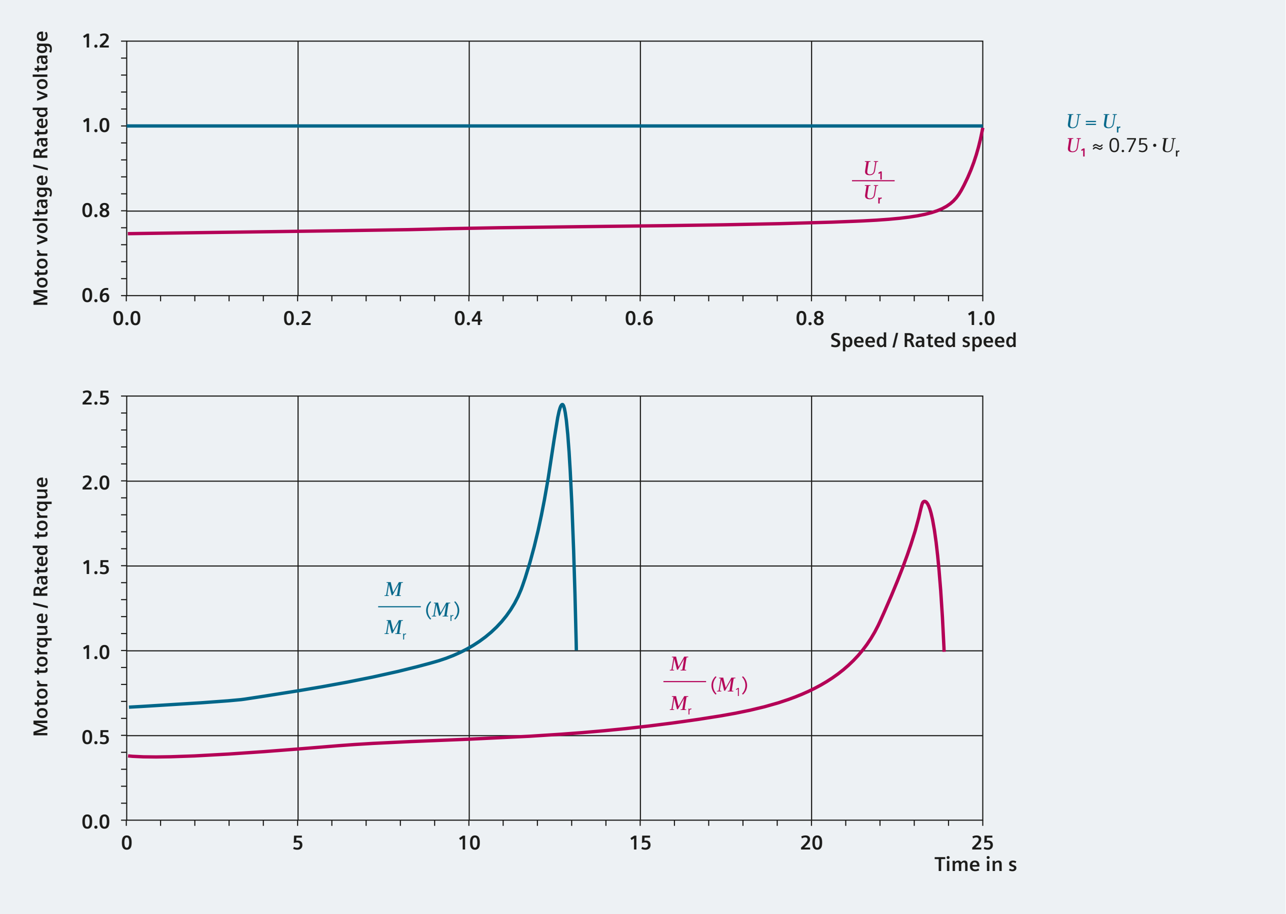
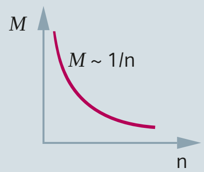
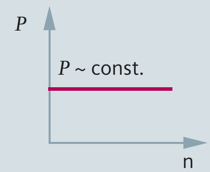
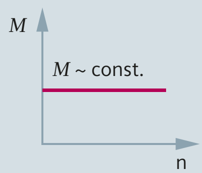
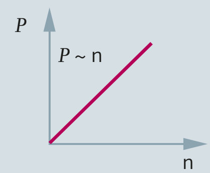
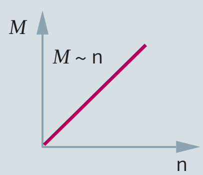
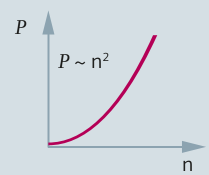
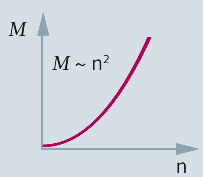
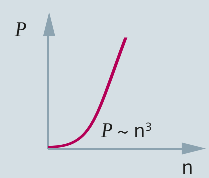


Fig. 4/14: **Example for the extension of the motor starting time by means of a voltage reduction**

Applications	Torque M over speed n	Power P over speed n
Winding motor, spinning machines, facing lathe	 $M \sim 1/n$	 $P \sim$ const.
Conveyor belts, cranes, elevators, rolling mills, planing machines	 $M \sim$ const.	 $P \sim n$
Eddy current brakes, calenders, printing machines, smoothening, embossing	 $M \sim n$	 $P \sim n^2$
Fans, centrifuges, centrifugal pumps	 $M \sim n^2$	 $P \sim n^3$

Power at the shaft P = Torque M · Speed n / 9,550

Fig. 4/15: **Starting behavior of different motor applications**

with the acceleration torque itself being square dependent on the voltage. Overall, the acceleration moment which is important for motor ramp-up must be sufficient to accelerate the drive to rated speed in the time permissible for the starting type. Under certain circumstances, the requirements might also increase regarding the stress of the operational equipment in the electric distribution network, such as for example in the design of feeders with contactor-fuse combinations.

Furthermore, the starting time depends on the starting class and the mode of operation (see [1.1]). The different starting characteristics of the motor applications also play a role (Fig. 4/15) in selecting the motor starter (see Chapter 4.5).

For a staging operation of several motors, suitable SINAMICS frequency converters can be used (Fig. 4/16). Pumps and compressors are typical applications for which the pressure or flow rate must be variable. Above all, efficiency advantages and operating time optimizations of the motors can be achieved by switching on and off as well as regulating individual motors.

Regarding feedback in the higher-level medium-voltage grid, the impedances of the network components as well as the starting currents of the relevant drives are decisive, as shown in Fig. 4/13. The voltage dip at the relevant point in the network can be determined from this. The technical possibilities of limiting an excessively high voltage drop at motor start (as in the example of Fig. 4/13) are shown in the next section.

Note: When smaller motors are connected to the low-voltage network, many power suppliers only permit direct-on-line start, meaning that, as a general rule, different starting types must be selected in order not to stress the upstream and the feeding grid excessively (Chapter 4.5). In most cases, when using larger medium-voltage motors, it is advisable for both the user and the planner to coordinate with the power supply company.

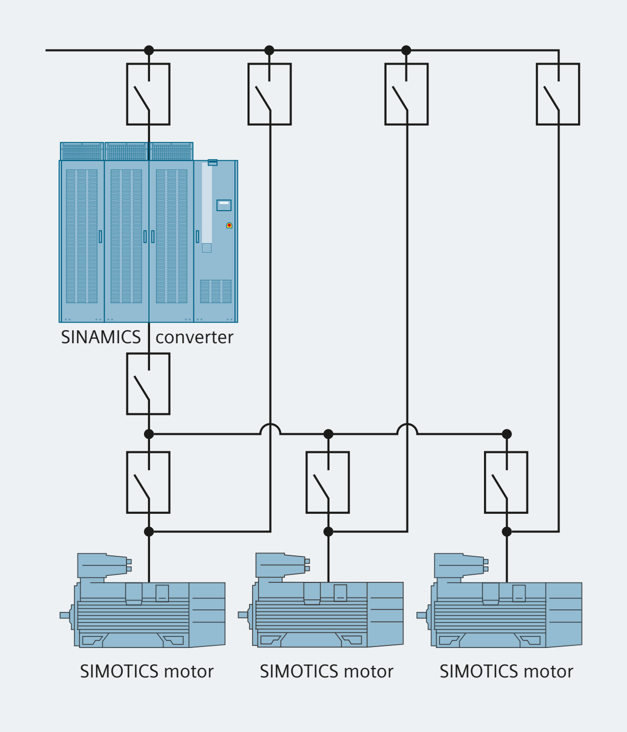


Fig. 4/16: **Motor staging for graded start and regulated operation by means of control via a frequency converter**

4.5 Influences on Motor Starting

About two thirds of electrical industrial consumers are three-phase asynchronous motors. Generally, a starter combination consisting of a switching and protection device is used as a motor feeder in electric power distribution. According to the requirements of the motor application and the electrical network, a starting method (Fig. 4/17) is selected:
- Direct-on-line start
- Star-delta combination [10)]
- Soft starter
- Frequency converter.

Important device standards are, for example, IEC 60947-4-1 and -2 for low voltage, as well as the standard series IEC 62271 for medium voltage (e.g. IEC 62271-100, IEC 62271-106, IEC 62271-110 and the basic standard IEC 62271-1). According to the standard series IEC 61800 as well as IEC/TS 60034-25, frequency converters as variable frequency drives offer the great advantage of a flexible motor control with optimum use of torque across the entire operating range of the motor.

Furthermore, a design advantage of converters without energy recovery (so-called "2-quadrant converters"; under certain circumstances, the network feedbacks of diode rectifiers are to be observed and filters to be installed) is that they do not contribute to the short-circuit current. In converters with energy recovery (so-called "4-quadrant converters"; use of transistors for input and output switching operations), the current limitation can also intervene to limit the short-circuit current. However, it must be observed to protect the converter electronics (see Fig. 4/17). When using frequency converters, the technical requirements for the connected motors (pulse-width modulated output voltage with high-frequency harmonics) must absolutely be observed, such as for example for the shaft fan, the winding, and the bearing insulation.

As frequency converters have only low but continuous losses during operation (for many drive systems consisting of motor and frequency converter, a range of ratings between 40 and 70 percent of the rated power is efficient), it should be considered in the planning that a base load is operated without frequency converters.

Other important assessment criteria for the selection of a suitable motor starter are:
- Breakaway and starting torque for the application
- Mechanical stresses and wear for movable drive components (bearings, axes, shafts, gears, worms, belts, wheels, chains, etc.)
- Switching frequency in operation
- Problems with abrupt starting and stopping, such as for example water hammer in pipes
- Sensitivity regarding network feedbacks, like the voltage dip due to a high starting current
- Operational and/or efficiency-enhancing speed control
- Short-circuit withstand strength of components.

In Tab. 4/6 (see also [4.5]), the main features of the four starter types (specifications for low-voltage application) are listed.

[10)] Other "classical" starting methods are auto-transformer starters and block transformers as well as the use of reactors

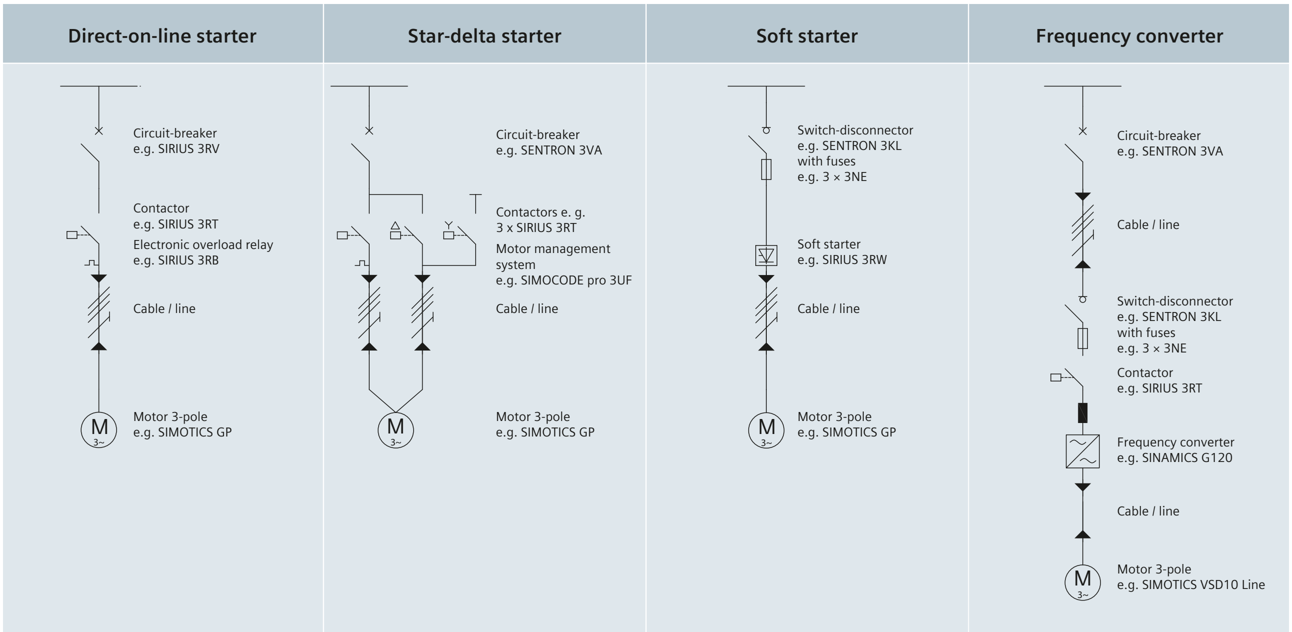
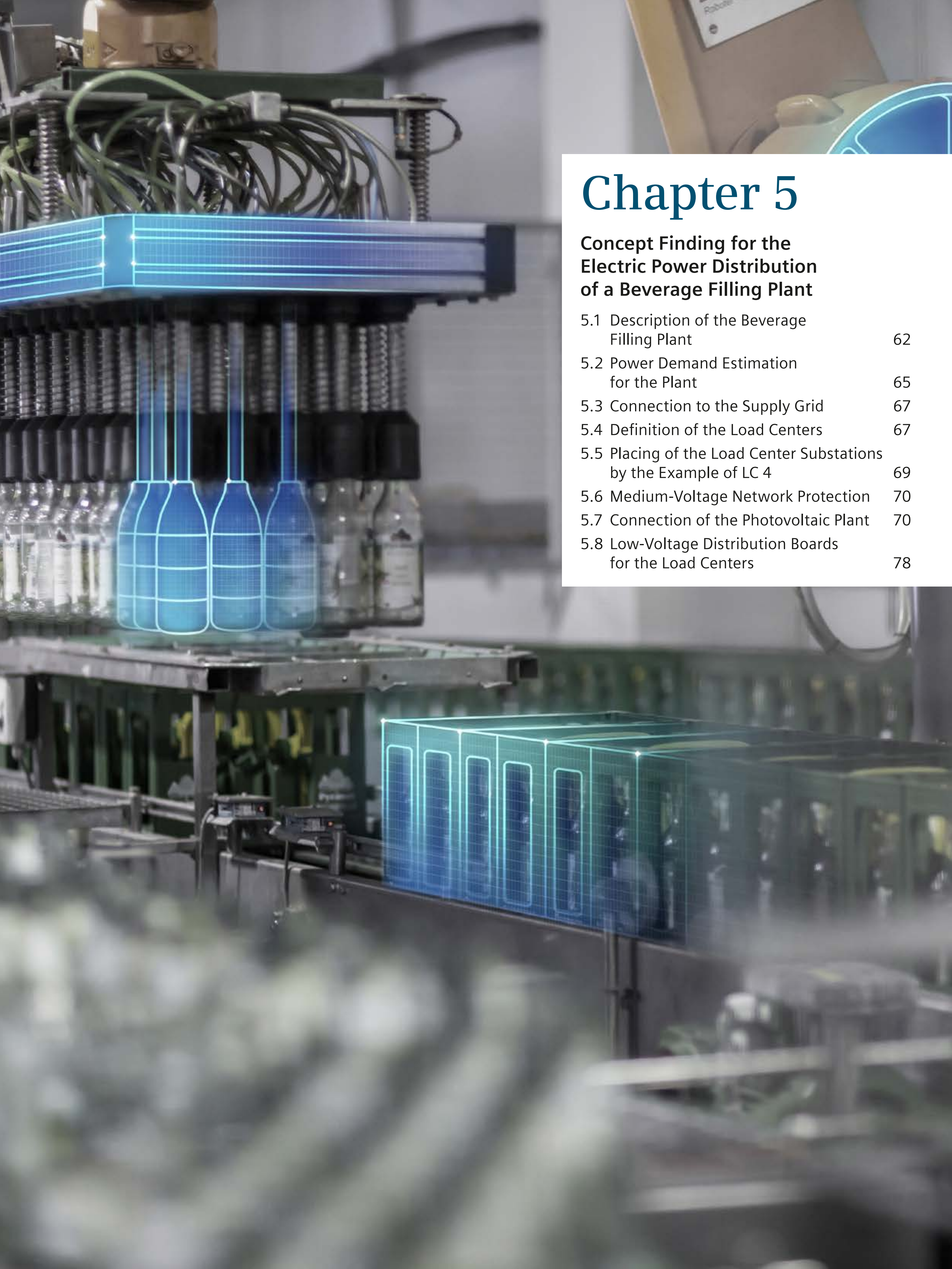


Fig. 4/17: **Switching and protection systems of the different motor starting methods**

	Direct-on-line / reversing start	Star-delta combination	Soft starter	Frequency converter
Speed control	No	No	Limited	Yes
Starting current	5 to 7 times I_n	2 to 2.5 times I_n	1 to 3 times I_n	Approx. I_n (motor adaptation)
Typical range of ratings	Up to 4 kW	4 kW up to approx. 250 kW	From 4 kW	Universal use
Reduction of current peaks	No	Yes	Yes	Yes
Starting moment / ramp-up	Maximum torque	Low starting moment; problematic for some applications	Continuous increase of torque without impulses	Full motor moment in the entire speed range
Start / stop	Abrupt	Small jerk while switching over during start (star → delta); abrupt stop	Smooth start and partially also stop	Optimum adjustment
Space requirements	Low	High	Medium	High
Mechanical stress of the switchgear	High	Medium	Low	Low
Device wear	Mechanical wear in the switchgear	Present	Low	Not present
Communication capability	Optional	Optional	Optional	Optional
Safety functions	Integrated optionally	Additional hardware required	Optional	Integrated optionally
Investment costs	Low	Medium	Medium	High
Power loss	Low	Low	Thyristor losses during start, and possibly during braking	Transistor losses, partially energy recovery capability

Tab. 4/6: **Features of typical low-voltage starters**



Chapter 5

Concept Finding for the Electric Power Distribution of a Beverage Filling Plant

5 Concept Finding for the Electric Power Distribution of a Beverage Filling Plant

To illustrate the basic considerations of Chapter 4, the two following chapters describe examples for the concept finding of an electric power distribution of industrial production plants. This chapter focuses on the low-voltage distribution for a beverage filling plant, and Chapter 6 on the medium-voltage distribution of a chemical plant. For the beverage filling plant, a photovoltaic plant is intended to be used for power supply.

5.1 Description of the Beverage Filling Plant

The beverage filling plant for soft drinks described in here is a new construction. Soft drinks are usually made from a syrup based on sugar, which is processed in the mixing plant together with treated water and additives. Before filling, carbonic acid may be added. In the sample plant, separate lines are used for filling glass bottles (content 0.3 l), PET bottles (content 0.5 l), and cans (content 0.33 l) (Fig. 5/1). Some initial information for the plant is given in Tab. 5/1. To reduce energy costs and improve the ecological footprint of the plant, photovoltaic modules are installed on the roof of the plant, which shall feed a power of about 3 MVA into the network (see Chapter 5.7). Island operation without grid supply is not intended.

For filling, the glass bottles must be previously cleaned and checked for damages. Cans must also be checked for manufacturing residues before filling. In disposable systems, the PET bottles are delivered as blanks and blown to the required size under heat and pressure in the blow molder. This process is called stretch blow molding.

After that, all lines direct to the next process step for filling with the exact amount of liquid depending on the size of the bottle or can. Carbonic acid is added in the filling process. Then, the bottles are closed with a top, or the cans with a lid. The filled bottles go through a testing machine again which shall ensure that no foreign objects are enclosed in the product.

At the end of the actual filling plant, the bottles or cans are transported to the labeling machine to get their labels. The packaging machines follow, which either place the cans in cardboard boxes or the bottles in boxes, or, as in the case of the PET bottles, just provide a plastic wrap including tape handle. Subsequently, the ready and packaged products are stacked on pallets and transported to the warehouse or depot, or they are directly loaded for transport.

Production information	
Production period	5 days a week around the clock
Annual production period	48 weeks a year
Plant operating time	15 years
Use of water	1.9 liters of water for 1 liter of soft drink
Annual water consumption	526 million liters
Annual soft drink production	277 million liters

Plant information	
Building floor area	19,600 m^2
Extension area	9,800 m^2
Throughput of PET bottles	50,000 nos. per hour
Throughput of glass bottles	50,000 nos. per hour
Throughput of cans	50,000 nos. per hour
PV plant infeed	3.0 MVA

Tab. 5/1: **Basic data of the beverage filling plant**

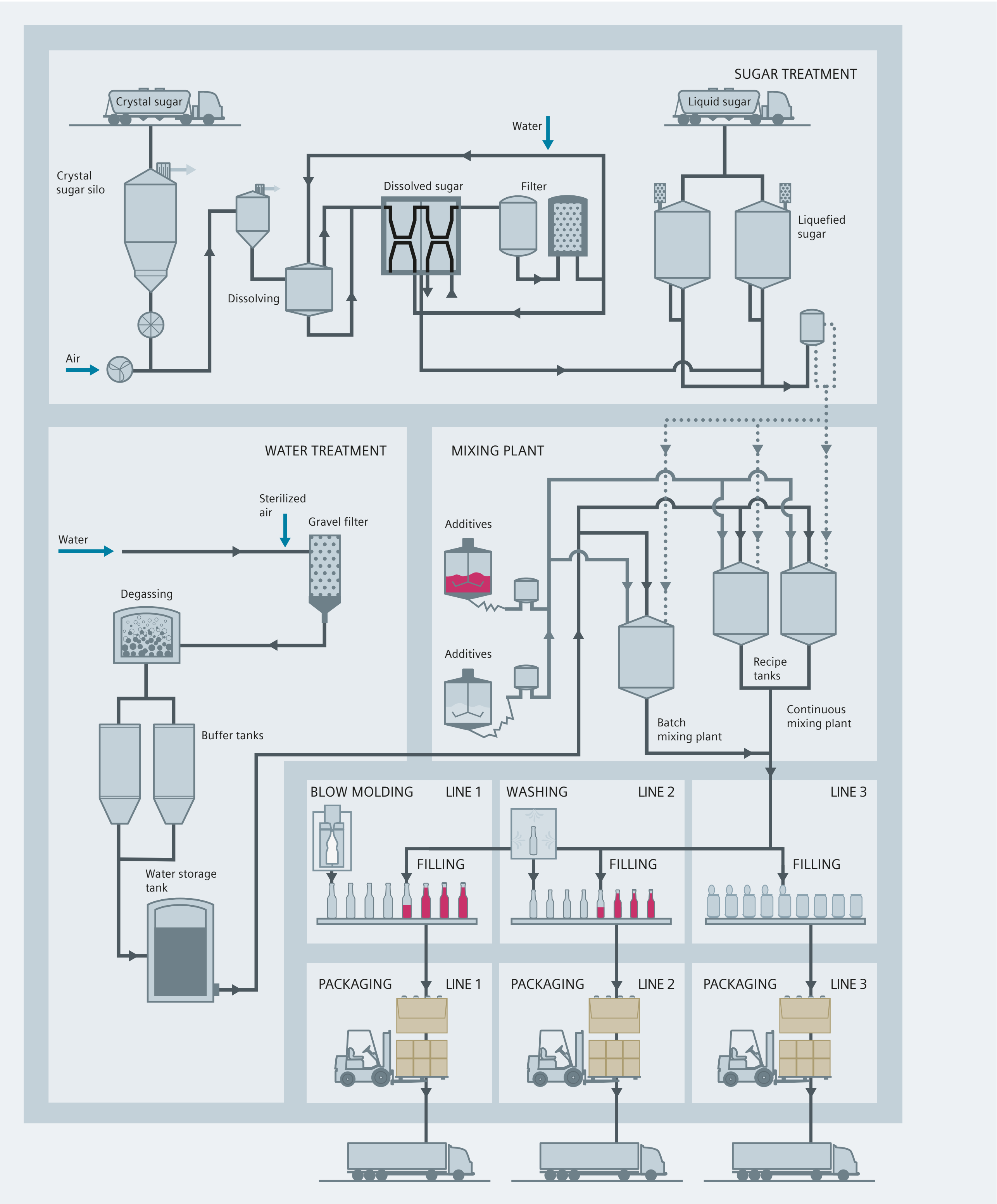


Fig. 5/1: **Process scheme for a beverage filling plant**

Contents
1
2
3
4
5
6
7

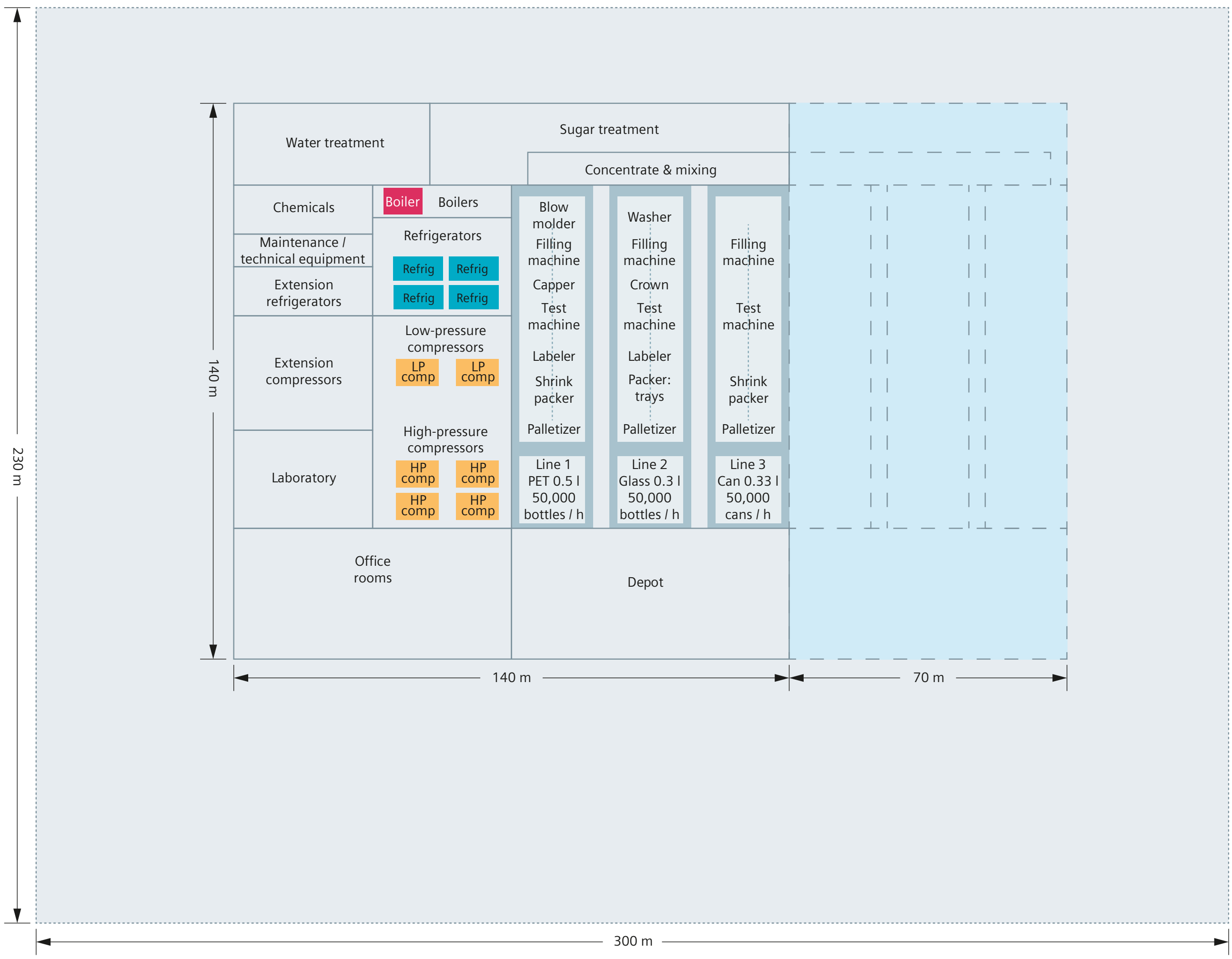


Fig. 5/2: **Simplified plan view of the building for the sample plant (the optional extension by three filling lines is marked with dotted lines)**

To illustrate a planned, future extension with three new filling lines, the additional space is shown in dotted lines on the floor area (Fig. 5/2). Furthermore, the floor area strongly depends on the requested storage capacities on the grounds. The degree of automation and the conditions for charging the electrical forklifts and conveyors also play an important part. The information in Fig. 5/2 is therefore only to be considered as a rough assumption for the total area (dotted limiting line).

For starting operations with three filling lines, a building floor area of 140 by 140 meters is taken as a basis. To add three new filling lines, the building section has to be expanded by 70 meters (light blue area in Fig. 5/2). When the filling plant is extended, the photovoltaic plant shall also be upgraded from 3 MVA to 4.5 MVA.

Contents

1

2

3

4

5

6

7

5.2 Power Demand Estimation for the Plant

When a plant is planned, the information status on the boundary conditions will constantly change. For example, a rough estimation based on a simple area consideration can be done first. In the course of project development, a load list will be available in most cases.

5.2.1 Area-Dependent Power Demand Estimation

With the plan view and the area distribution for the plant, the power demand can be estimated based on the information given in [1.1]. When estimating with 600 to 1,000 W/m^2 for the food and beverage industry, two items should be taken into account:

1. For office buildings, dispatch areas, laboratories, chemical production processes (hereafter called "chemicals"), and maintenance, considerably lower values are assumed according to [1.1].
2. For compressors, cooling devices and boilers, the areas required for the extension are planned right from the beginning. This means that the extension areas have to be left free.

Without considering these two items, the resulting power demand for a building area of 19,600 m^2 with 600 up to 1,000 W/m^2 and a simultaneity factor of 0.8 would range between 9 MW and 16 MW. If the extension with an area of 9,800 m^2 is included, the resulting total power demand would range between 13.5 MW and 24 MW.

If the area utilization is examined in more detail, the power demand (with a simultaneity factor of 0.8) for the extension with 3 filling lines at the beginning of production is reduced to an approximate value between 5.9 MW and 9.8 MW [1)]. For the complete plant with 6 filling lines, the calculated power ranges between 10.2 MW and 17 MW [2)].

5.2.2 Power Demand Determination with Load List

Normally, the load lists are provided along with the definitions of the spatial divisions and the production requirements. They will anyway be required later on during dimensioning with the planning tool SIMARIS design. In the load overview Fig. 5/3, only some special consumers are shown in the individual rooms – without lighting and socket outlets, for example – or summarized as consumer groups.

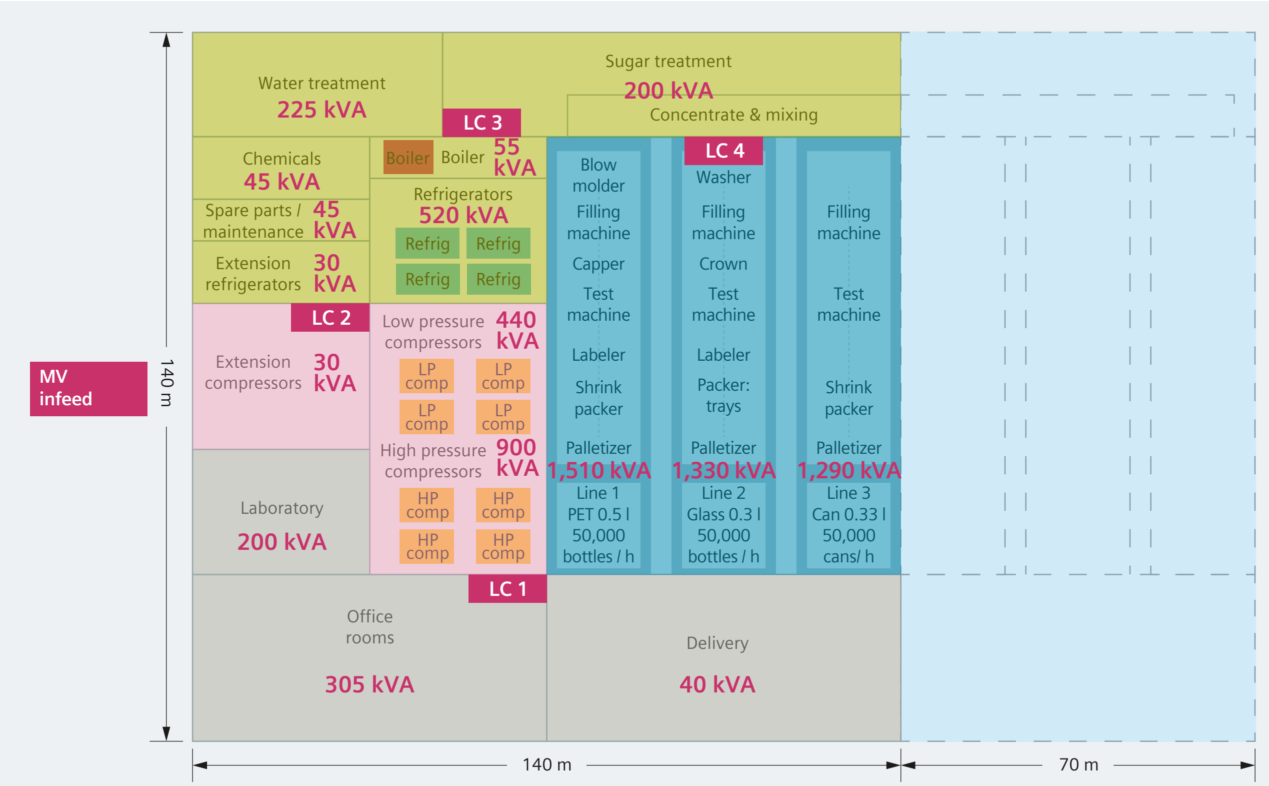
Based on the load lists stipulated by the customer and on the summary of all consumers, a total load of about 7.2 MVA or 12.8 MVA results in the final state. All loads can be supplied via low-voltage connections.

1) According to the information given in [1.1], the following is assumed at the beginning of production:

- Office buildings	approx. 2,300 m^2	→ 20 to 40 W/m^2
- Laboratory and chemicals	approx. 1,300 m^2	→ 100 to 200 W/m^2
- Maintenance/services, depot	approx. 2,590 m^2	→ 5 to 15 W/m^2
- Extensions for refrigerators, compressors	approx. 1,450 m^2	→ 5 to 15 W/m^2
- Production areas	approx. 11,960 m^2	→ 600 to 1,000 W/m^2

2) For the final state, the following is assumed:

- Office buildings	approx. 2,300 m^2	→ 20 to 40 W/m^2
- Laboratory and chemicals	approx. 1,300 m^2	→ 100 to 200 W/m^2
- Maintenance/services, depot	approx. 4,900 m^2	→ 5 to 15 W/m^2
- Production areas	approx. 20,900 m^2	→ 600 to 1,000 W/m^2



Power demand of individual parts of the plant

	Room	Application	Power demand in kVA
Load center LC 1	Office section	Computer room	65
		Air conditioning	100
		Fire alarm / fire protection	50
		Lighting / socket outlets	90
	Laboratory rooms	Safety system	120
		Lighting / socket outlets	80
	Dispatch	Lighting / socket outlets	40
Load center LC 2	Low-pressure compressors	Compressors	440
	High-pressure compressors	Compressors	900
	Extension*	Compressors	30
Load center LC 3	Water treatment	Treatment plants	225
		Boiler	55
	Mixing plant	Sugar treatment	150
		Mixer	50
	Cooling facility	Refrigerators	550
	Chemicals	Laboratory connections	15
		Lighting / socket outlets	30
	Maintenance / technical equipment	Lighting / socket outlets	45

	Line	Application	Power demand in kVA
Load center LC 4	Filling line 1 (PET)	Conveyor belts	360
		Packaging	400
		Cleaning (Cip)	40
		PET stretch blow machine	250
		Filling and closing	240
		Light, air conditioning, control	220
	Filling line 2 (glass)	Conveyor belts	425
		Packaging	135
		Cleaning (Cip)	40
		Bottle rinsing	240
		Filling and closing	270
		Light, air conditioning, control	220
	Filling line 3 (can)	Conveyor belts	240
		Packaging	330
		Can cleaning	240
		Cleaning (Cip)	40
		Filling and closing	230
		Light, air conditioning, control	210

* For the extension rooms, the first power demand estimation is for lighting and socket outlets only.

Fig. 5/3: **Load overview and load centers for the production plant from Fig. 5/2**

5.3 Connection to the Supply Grid

A comparison of the requirements from the previously made power demand estimation with the evaluations in Fig. 4/3 shows that a double radial line connection from the busbar of a main transformer substation is suitable. According to IEC 60038, 10 kV (11 kV) or 20 kV (22 kV) are the nominal system voltages which are preferred for three-phase systems today (the specifications are voltage values between phase conductors; IEC 60038 indicates two series for nominal system voltages – the values in brackets belong to the second series). Due to the advantages of higher system voltages described in Chapter 4.2, power systems with a nominal voltage of 30 kV (33 kV) will become increasingly important in the future. Since the 20 kV voltage levels still prevails significantly, the connection on the medium-voltage side is done with U_n = 20 kV.

Attention: The nominal system voltages for North America, 13.8 kV for example, are specified in "Series II" of Table 3 of the standard.

In the medium-voltage grids of the power suppliers, the neutral point is usually earthed via an arc suppression coil (resonance-earthed neutral). The selection of the neutral point earthing influences the design of the protection concept and the selection of the protection instrument transformers [1.2].

According to IEC 60909-0, the required short-circuit withstand strength for the switchgear and switching devices in the medium-voltage distribution can be determined in a simplified way via the short-circuit impedance Z_k and the short-circuit current I_k:

$$Z_k = (c \cdot U_n^2) \,/\, S_k'' \qquad (1)$$

$$I_k = (c \cdot U_n) \,/\, (\sqrt{3} \cdot Z_k) \qquad (2)$$

Equation (1) is inserted in (2), so that the voltage factor c is cancelled and the short-circuit current I_k can be calculated from the nominal system voltage U_n and the initial symmetrical short-circuit power S_k'':

$$I_k = S_k'' \,/\, (\sqrt{3} \cdot U_n)$$

If the symmetrical short-circuit power S_k'' is not known, a symmetrical short-circuit power of 500 MVA – at a highest voltage for the equipment of 7.2 kV, 12 kV, 17.5 kV and 24 kV – can be used according to IEC 60076-5 in conformity with European and North American practice:

$$I_k'' = 500 \text{ MVA} \,/\, (\sqrt{3} \cdot 20 \text{ kV}) = 14.45 \text{ kA}$$

This value and also the symmetrical short-circuit power match well with the values I_k'' = 14.6 kA and S_k'' = 505.2 MVA (see Tab. B4.5 in [1.2]) stipulated in [1.2]. The differences can be explained by means of the above simplified estimation. A more exact specification, where the ratio of resistance to reactance (R/X) is taken into account, is described in IEC 60909-0. In order to consider reserves for motor feedbacks, a short-circuit withstand strength of I_{sc} = 20 kA is requested for the operational equipment. Due to the power demand of 7.2 MVA or 12.8 MVA, a rated busbar current of 630 A (I_b = 12.8 MVA / (√3 · 20 kV) = 370 A) is sufficient for medium-voltage switchgear at a nominal system voltage of 20 kV.

5.4 Definition of the Load Centers

The individual load centers (Fig. 5/3) are determined by means of the load overview and the plan view of the building. When determining the total transformer power for supplying the load centers, the following is taken into account according to Chapter 4.4.1:
- Limitation of line lengths between the low-voltage load center substations and the consumers
- Ensuring the n-1 redundancy
- Selection of the initial symmetrical short-circuit power
  – regarding cost optimization when there are no particular requirements
  – regarding the power quality (e.g. start-up of powerful motors or impulse load due to large consumers).

If only the line lengths are considered, three load centers might suffice. In this process, one common load center would have to be established for the office section and the high-performance compressors. If the function and feedback behavior of the compressors is additionally taken into account, Fig. 5/3 suggests a division into four load centers. This way, the ICT consumers in the office section are better separated from disturbances by the production area. The four areas marked in color in Fig. 5/3 identify the supply areas of the individual load center substations:

- Load center substation LC 1: 545 kVA
- Load center substation LC 2: 1,370 kVA
- Load center substation LC 3: 1,120 kVA
- Load center substation LC 4: 4,130 kVA

For the filling area, a further subdivision according to the 3 filling lines on the low-voltage side (with 1,510 kVA, 1,330 kVA and 1,290 kVA for the individual lines) would be appropriate from a performance and process perspective.

For installing fuse-switch-disconnectors as described in Chapter 4, individual transformers smaller or equal to 1,250 kVA are to be selected (U_{prim} = 20 kV or 800 kVA at U_{prim} = 10 kV). Fig. 5/4 shows a single-line diagram for the medium-voltage distribution with the transformer connections for the load center substations.

Due to the customer requirements and the given design of the production plants, the medium-voltage distribution network is to be set up as a ringed network (see Tab. 4/1). Since there are no specific requirements regarding the short-circuit power or dielectric strength, and a cost-efficient system design is intended (with a short-circuit withstand strength of the operational equipment of $I_k'' \leq 66$ kA), the total power of the transformers in the individual load center substations (LC 2 to LC 4, according to Tab. 4/5 for u_{kr} = 6 %) may amount to a maximum of 2.7 MVA per substation.
In order to additionally ensure the n-1 availability, 3 x 800 kVA transformers each are selected for the supply of the low-voltage distribution boards.
As shown in Fig. 5/4, the filling lines for LC 4 are to be supplied separately. Two 630 kVA transformers with adequate reserve are sufficient for the load center substation LC 1.

For power supply in industrial plants, dry-type transformers are preferably used according to IEC 60076-11. GEAFOL cast-resin transformers are characterized by:
- Low fire load
- No requirement for special fire protection measures
- No risks that might intensify a fire

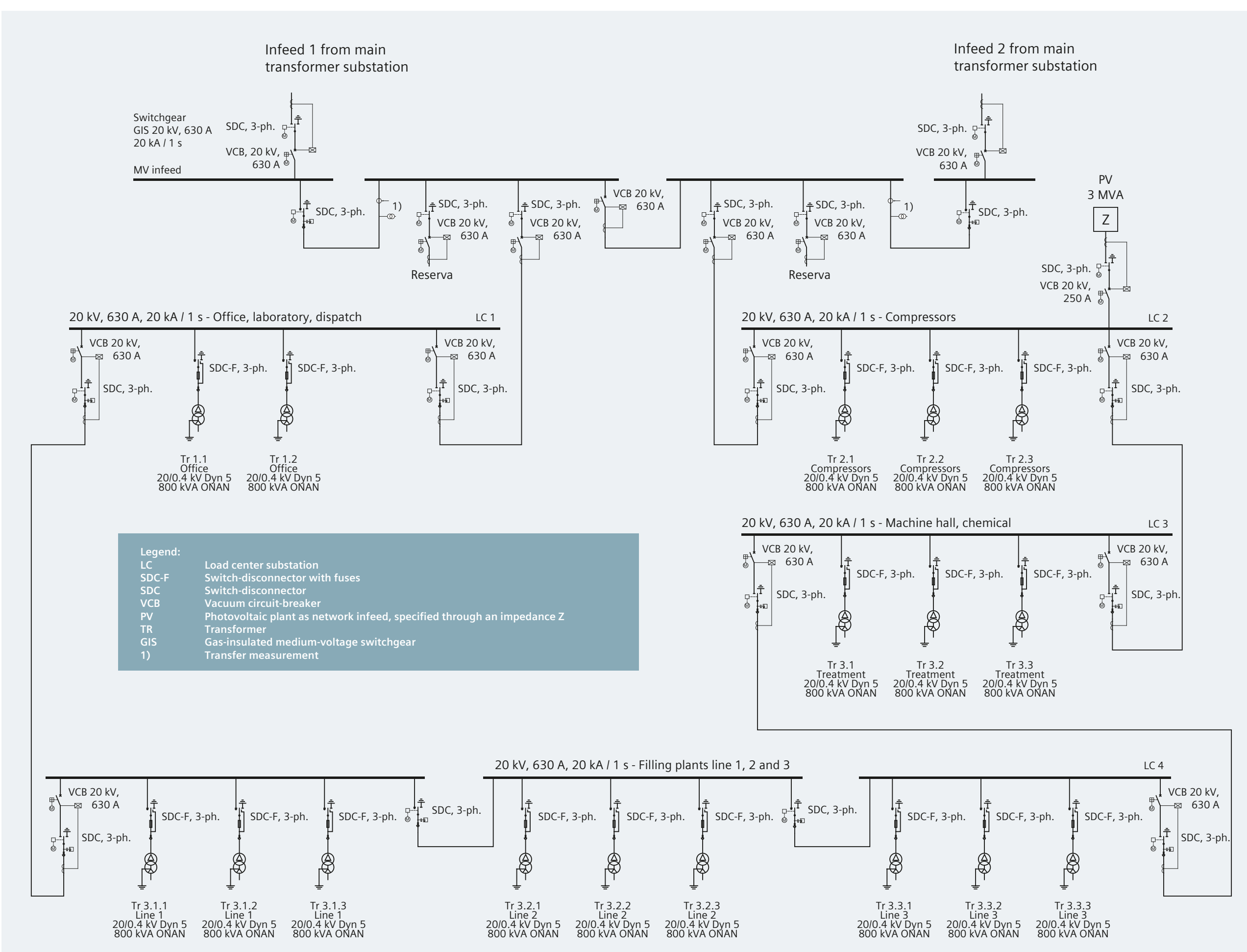


Fig. 5/4: **Single-line diagram for the medium-voltage ring of the filling plant**

- Measures for groundwater protection
- Power increase up to 140 % of rated power (GEAFOL transformers with $S_r \geq 500$ kVA) by means of installed, temperature-dependently controlled radial-flow fans
- Utilization of overload capability as a "hot" redundancy to increase the supply reliability
- No loss of service life when utilizing the overload capability
- No danger of impermissible switching overvoltages due to resonance excitation of the windings when switching on or off using a vacuum circuit-breaker.

5.5 Placing of the Load Center Substations by the Example of LC 4

When placing the LC 4 substation, the following has to be observed:

- Low voltage drop
- Low material costs
- Good heat dissipation and pressure relief
- Easy accessibility of the equipment (e.g. during maintenance and replacement of components).

From an electrotechnical perspective, the placement of the electrical service rooms (for the transformers and low-voltage distribution boards) at the core of the load center is ideal. The distances to the individual consumers are minimized in this way, thereby also keeping the voltage drop in the network as low as possible. The protection of the transformers by means of HV HRC fuses is advantageous in this context; their current-limiting effect mitigates the released energy between the medium-voltage switchgear and the transformer in the event of a short circuit. This way, personnel and equipment risks are reduced.

If there is no space at the core of the production level for installing the equipment, and there is no possibility to create an intermediate level above or below the area to be supplied, LC 4 can at least be installed at the edge of the production area (or at the building wall) as the distance to the consumers permits to do so here. It is a good compromise to place the medium-voltage switchgear including the medium-voltage ring cabling outside of the production area, and install the transformers (supplied via medium-voltage radial lines and protected by HV HRC fuses, Fig. 5/4) as well as the low-voltage distribution boards for the production lines at the room wall near the individual lines. Frequently, they are, however, concentrated at the edges of the room (Fig. 5/5).

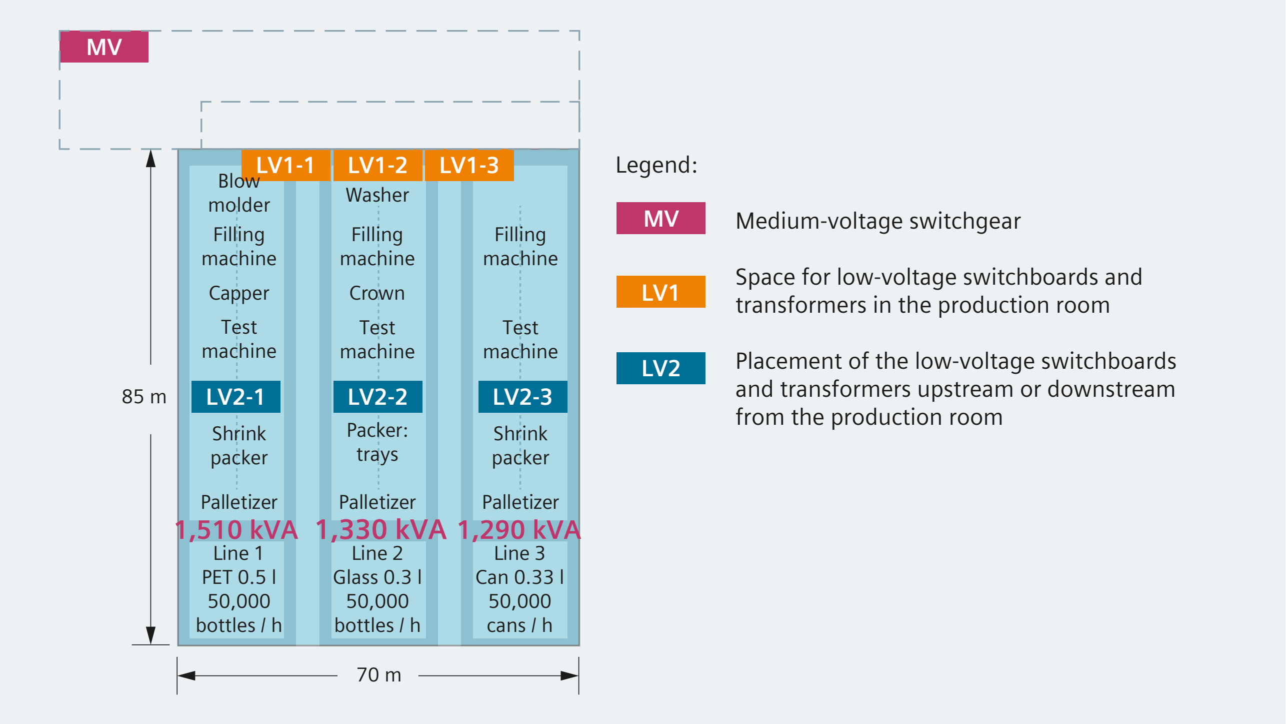


Fig. 5/5: **Placement of the power distribution boards for LC 4**

Contents

1

2

3

4

5

6

7

5.6 Medium-Voltage Network Protection

Since the medium-voltage network spans the entire filling plant, and the infeed from the power supplier as well as the connection of the embedded generating plant to the medium-voltage network takes place here, protection is particularly important.

The objectives of protection are:
- Disconnection of a fault in the network as quickly as possible to minimize personal injuries and equipment damages
- Selective shutdown of faulty parts of the network to prevent impacts on system parts not affected by the fault.

This is achieved by means of digital protection devices, such as for example the SIPROTEC devices from Siemens.

Differential protection relays (e.g. 7SD82, 7SD85) are used for the protection of cable runs (primary protection, red arrows in Fig. 5/6) in the network. Faults on the cable runs are detected and cleared instantaneously (in less than 0.1 s) by the differential protection. The back-up protection with definite time-overcurrent protection devices (e.g. 7SJ82, 7SJ85; green arrows in Fig. 5/6) provides a high level of safety. As a back-up protection, the definite time-overcurrent protection clears faults on the cable runs in reserve time (< 0.3 s). Parameterized as a directional and interlocked protection, the definite time-overcurrent protection devices additionally take over the protection of switchgear (purple arrows in Fig. 5/6), "outside" of the coverage for the primary protection. This way, a quick and selective fault clearance can be realized within the switchgear in case of a fault.

As shown in Fig. 5/6, the definite time-overcurrent protection devices 7SJ82 are suitable for the selective fault clearance of the incoming cables. According to the grid connection conditions for embedded generating plants (Chapter 4.3.2), the devices can be installed for the interface protection of the photovoltaic plant (description of the PV plant in Chapter 5.7). According to EN 50549-2, the accuracy requirements must be observed for the voltage transformers for interface protection (marked blue in Fig. 5/6):
- Minimum accuracy class 3P according to IEC 61869-3 (for the overvoltage protection, zero-sequence system 59N, class 3P/0.5 is requested)
- Rated voltage factor (rated time according to IEC 61869-3 and IEC 60044-7):
  - 1.9 for voltage transformers between earth and phase conductor
  - 1.2 for voltage transformers between phase conductors
- The rated output power of the voltage transformer corresponds to the intended load of the protection winding.

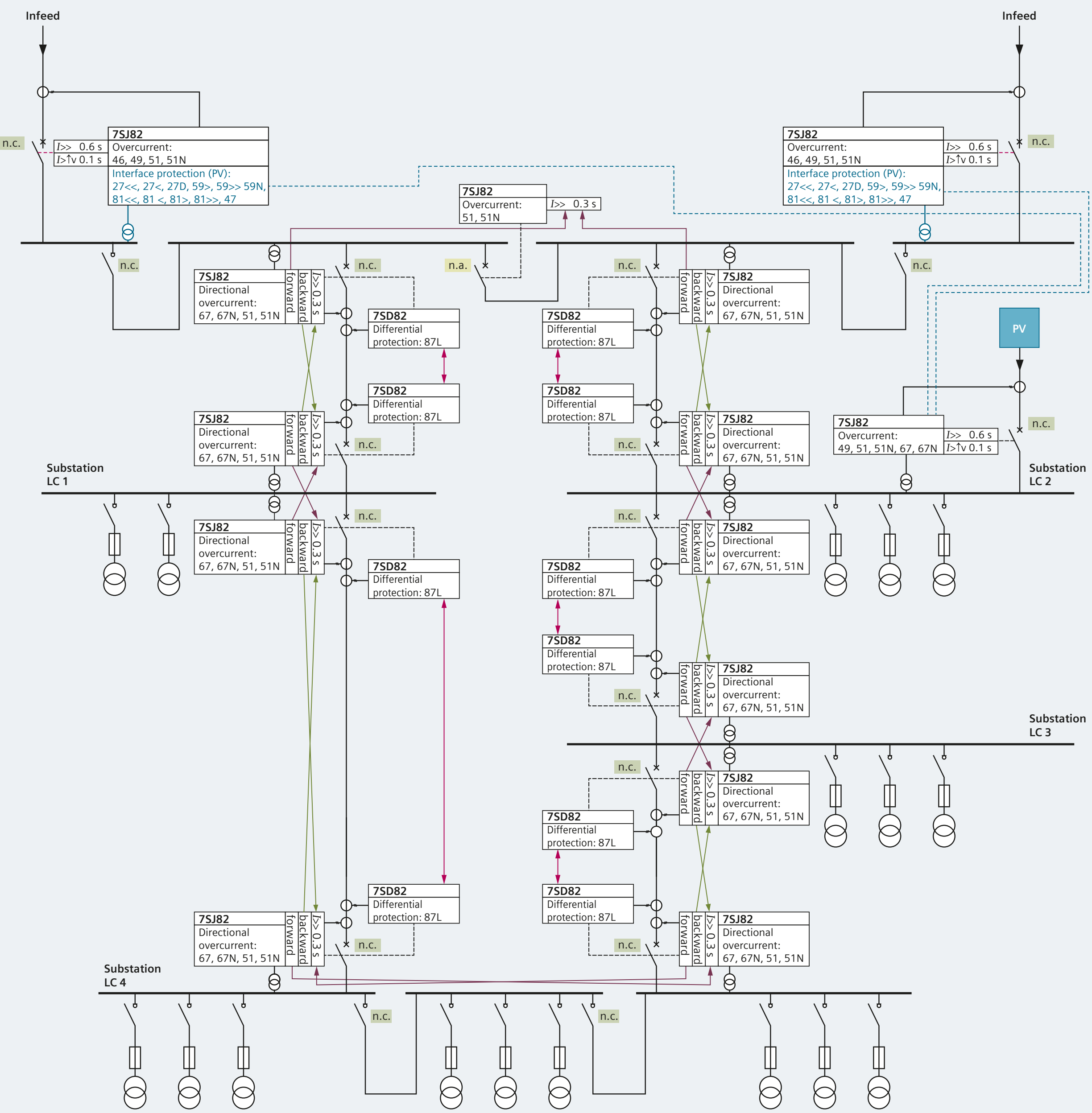
No island operation is intended in this protection concept. Protection concepts for island operation are briefly addressed in Chapter 5.7.3. In Fig. 5/6, the switching device assumes the function of the interface switch in the supply line of the PV plant to LC 2 (see Chapter 4.3.3). The blue dotted lines mark the connection between the two interface protection relays 7SJ82 and the interface switch.

The two medium-voltage spare feeders shown in Fig. 5/4 are not significant for the protection concept of the medium-voltage ring without extension, and are therefore not represented in Fig. 5/6. Today, fiber-optic connections are commonly used for the communication between the protection devices. Besides the protection concept for the power distribution, a measurement concept for monitoring and diagnostics must be created. The procedure is illustrated in the application manual on energy transparency [5.1], and the use of the product families SICAM, SENTRON and SIMATIC is described.

5.7 Connection of the Photovoltaic Plant

An embedded generating plant with photovoltaic modules (PV modules) is to be integrated into the supply concept (Fig. 5/6) to reduce the energy and power procurement from the supply grid and, at the same time, minimize the ecological footprint of the production plant by using renewable power-generating technology. For grid connection, the requirements described in Chapter 4 must be observed. The protection concept must especially fulfill the requirements of IEC/TS 62786 or EN 50549-2 for the medium-voltage interface protection.

For the example, an energy storage is not provided, so that the size of the PV plant is essentially limited by the installation conditions, the roof area, and an appropriately covered share of the power demand of the production plant. Due to the volatility of solar utilization, a partial island operation without energy storage is not reasonable either. The PV plant will therefore not be able to replace a generator for continuing with production.



n.c.	Normally closed
n.a.	Normally open
I>↑v	Short-circuit tripping in the forward direction; this means in the direction of the line
backward	Short-circuit direction determination backward; this means in the direction of the busbar
forward	Short-circuit direction determination forward; this means in the direction of the line
	Blocking
	Interface protection

ANSI device numbers (IEEE/ANSI C37.2):

27	Undervoltage protection	59	Overvoltage protection
27D	Undervoltage protection, positive phase-sequence system	59N	Overvoltage protection, zero-sequence system
47	Overvoltage protection, negative phase-sequence system	67	Directional time-overcurrent protection
49	Thermal overload protection	67N	Directional earth-fault detection
51	Inverse time-overcurrent protection	81<	Underfrequency protection
51N	Earth-fault detection	81>	Overfrequency protection
		87L	Line differential protection

Note: Consider adding grading times for faults at the beginning of the ring!

Fig. 5/6: **Protection concept for the medium-voltage ring**

Contents

1

2

3

4

5

6

7

Currently, PV modules with an area of approx. 2 m^2 supply a solar electric power of 400 to 500 W_{peak} under ideal conditions of use (peak value; i.e. power peak value for defined standard test conditions (STC) per square meter of module area). For an electric total rated output of 3 MVA[3)], the roof of the production building would be enough. When extending the production, the PV plant shall be expanded to a total electric power of 4.5 MVA[3)].

For network connection, the electric energy supplied by the PV modules must be converted from DC voltage to AC voltage. Two known solar inverter types are string inverters and central inverters. In the case of the string inverter, multiple PV modules are connected in series to a smaller inverter. Thanks to the parallel connection of the string inverters, higher ratings can be achieved. For the central inverter, the PV modules are connected to a large converter on the DC voltage side.

For connection to the distribution network, Siemens offers both string inverters and central inverters to suit the different application profiles. Siemens technical consultants offer support for the selection of appropriate types. For the use in the considered range of ratings between 3 and 4.5 MVA, both types of inverters are suitable. Both Siemens device families (KACO blueplanet 150 TL3 and SINACON PV) have a very high efficiency of up to 99 % and, moreover, low harmonic distortion factors of less than 3 %.

In the selected range of ratings, the usage focus areas of the two inverter types overlap. For smaller ratings, systems with string inverters are generally more cost-efficient:
• Easier adjustment to different solar radiation conditions
• Easier expansion possibilities
• Usually only partial failure of the plant in case of fault.

In larger plants, in contrast, the advantages of central inverters prevail:
• Easier installation
• Lower troubleshooting effort.

For an infeed power of the PV plant of more than 2 MVA, the usual way is to connect it to the medium-voltage distribution system. The infeed is done via the substation LC 2.

5.7.1 PV Plant with String Inverters

The inverters KACO blueplanet 150 TL3, devices with an AC power of 150 kVA, are suitable for the intended PV plant. For a total PV power of 3 MVA, each ten of these inverters are connected in parallel to two sections (Fig. 5/7a). The connection to the 20 kV medium-voltage ringed network is done via a transformer to the switchgear for the load center LC 2. When extending the PV plant to 4.5 MVA, an additional transformer for a power of 1.5 MVA must be installed (Fig. 5/7b). The installation of a 4.5 MVA transformer is also imaginable in the initial installation phase (3 MVA power), so that in case of an extension of the PV plant, only the systems on the low-voltage side of the transformer are extended by the additional section with ten inverters (Fig. 5/7c).

5.7.2 PV Plant with Central Inverter

In case of a central inverter SINACON, the DC cables of the PV generating modules are led to the four so-called power stack converter modules (Fig. 5/8). Thanks to the liquid cooling and optional heating, the PV central inverter SINACON can also be used in an extremely wide range of ambient air temperatures (from -40 °C to +60 °C).

3) The rating information corresponds to the electric apparent power at the inverter output of the PV plant. The maximum possible input power of the solar modules installed in the PV plant (direct voltage DC) must be greater, and is commonly indicated as peak power of the solar modules in "W_{peak}". The area of 140 × 140 m would, if fully equipped, enable a PV module peak power of more than 3.9 MW_{peak}.

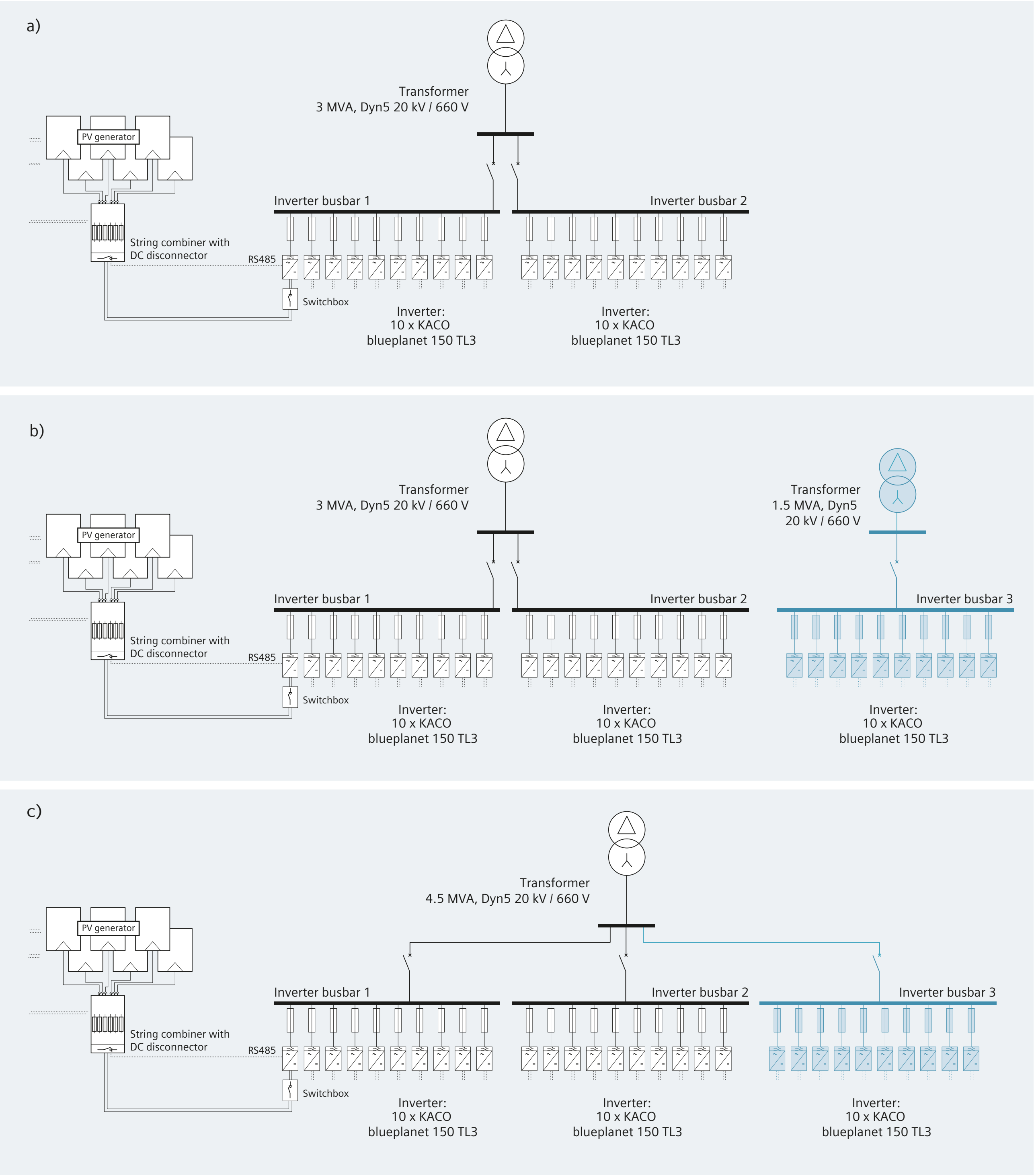


Fig. 5/7: **PV power-generating plant with string inverters**
a) For initial installation with PV plant with 3 MVA apparent power
b) For PV plant with 4.5 MVA apparent power: Extension of the initial installation (3 MVA PV plant) by a separate transformer feeder of 1.5 MVA
c) For PV plant with 4.5 MVA apparent power: The 4.5 MVA transformer already considered during initial installation (3 MVA PV plant) is expanded by a 1.5 MV PV feeder

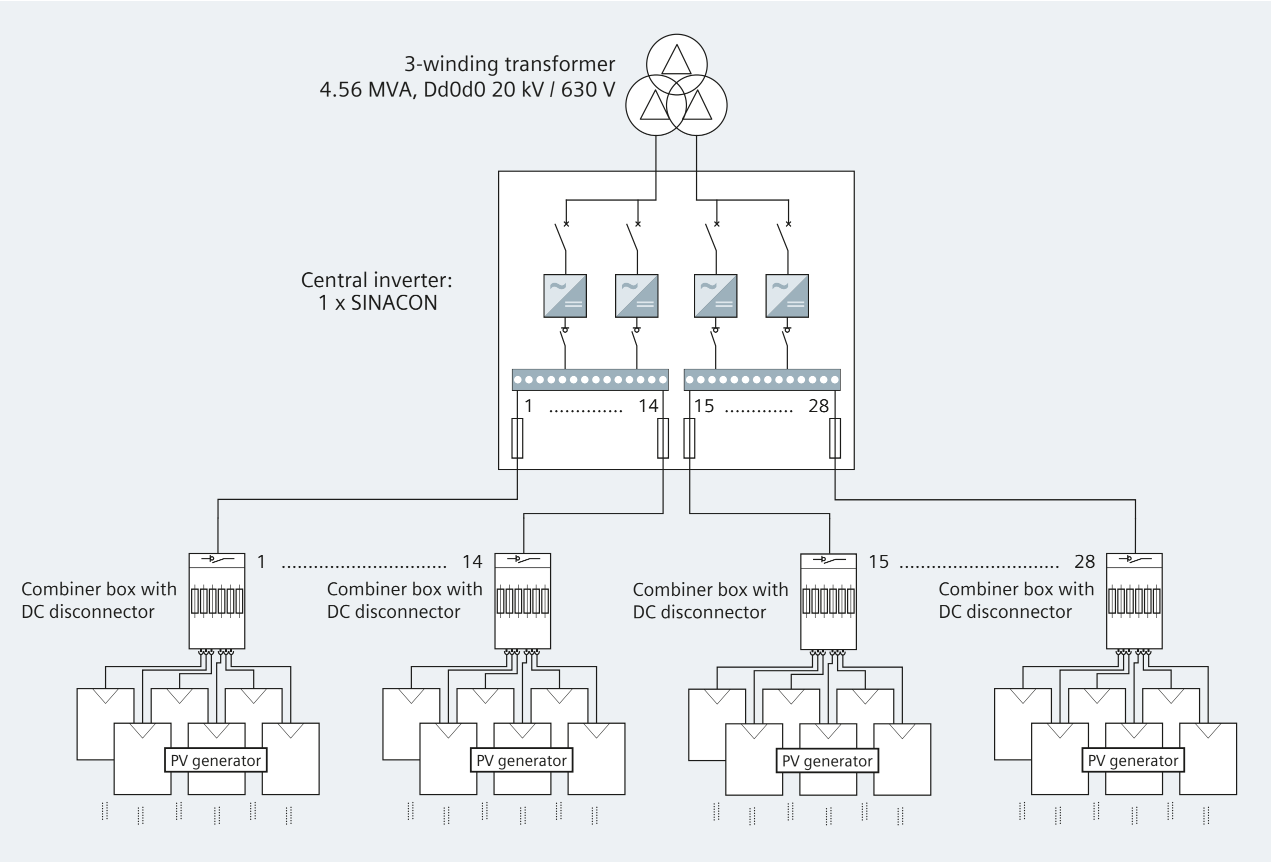


Fig. 5/8: **PV power-generating plant with central inverter**

5.7.3 Protection-Technological Integration of Embedded Generating Plants in Island Operation

Based on the protection concept shown in Fig. 5/6, the requirements for the network connection of power-generating plants (see Chapter 4.3.2) can also be pointed out if island operation is requested. This is realistic for production plants in which energy is economically recovered from residual products, and thus only a small portion of the total energy amount required for operation must be provided by additional energy sources and energy storages. From the wood processing in paper manufacturing, for example, organic residual products accrue which can be used in CHP plants in an energetically similar way to fossil fuels.

Fig. 5/9 illustrates the integration of power-generating plants with a protection concept for island operation. In this process, not the entire network of the plant operator must be able to switch over to island operation. This is illustrated by the two versions in Fig. 5/9 (option 1: partial network substation LC 2, and option 2: overall network). There are multiple other options which are not further specified. It is also remarkable that, in island operation, the switching device for interface protection (PV) of Fig. 5/6 can then be used as a switching device of the generating unit.

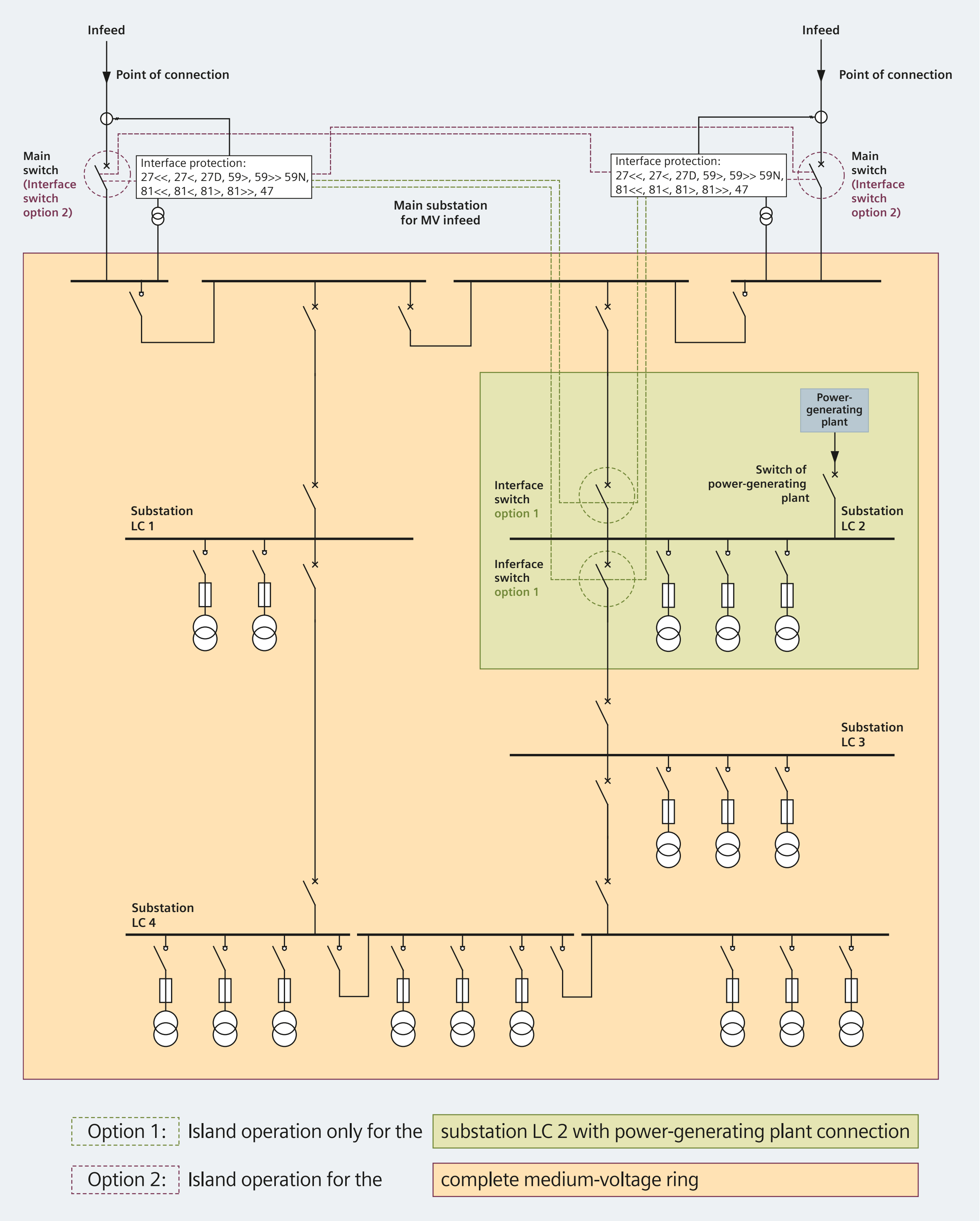


Fig. 5/9: **Examples for protection concepts to enable island operation with embedded generating plants**

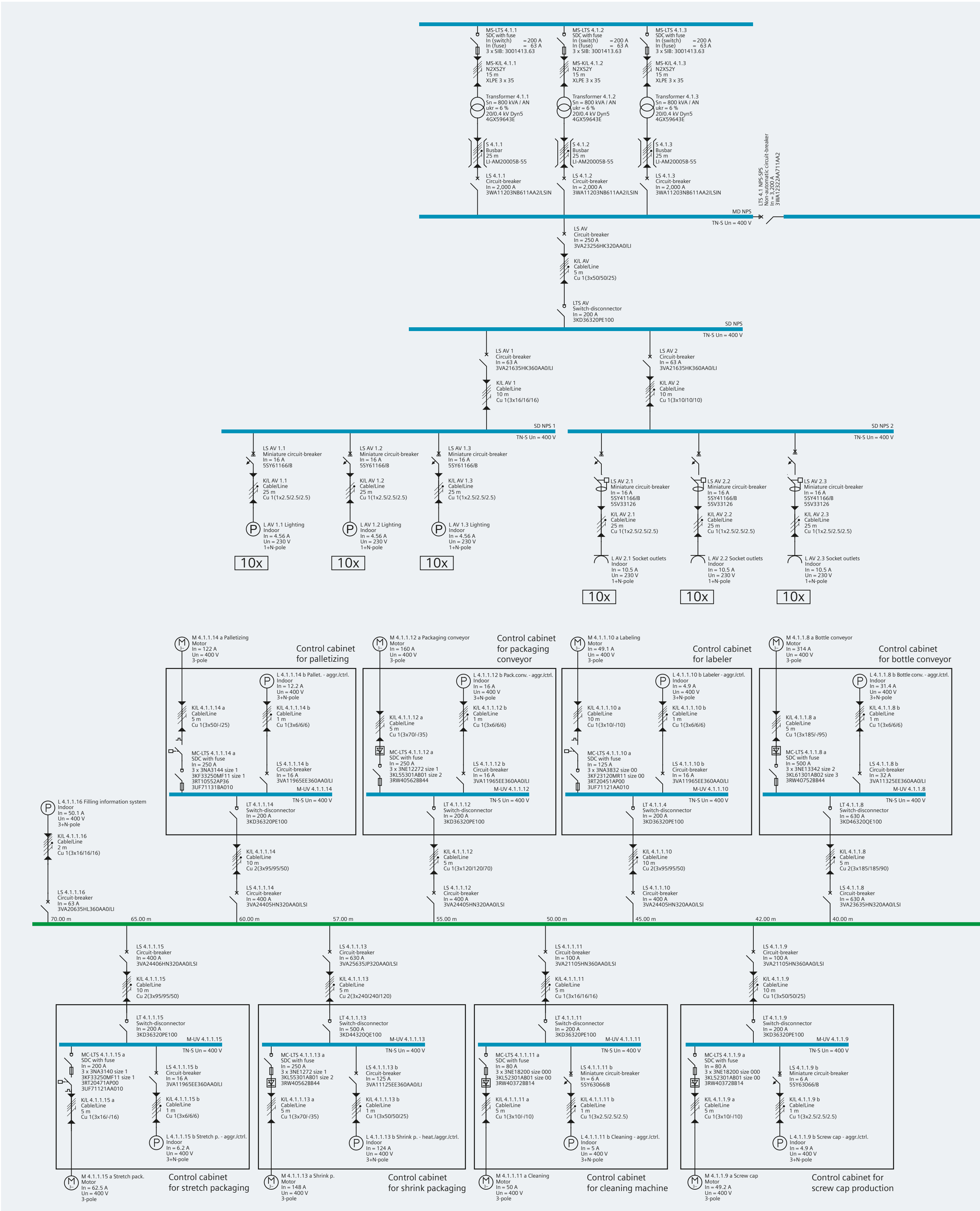
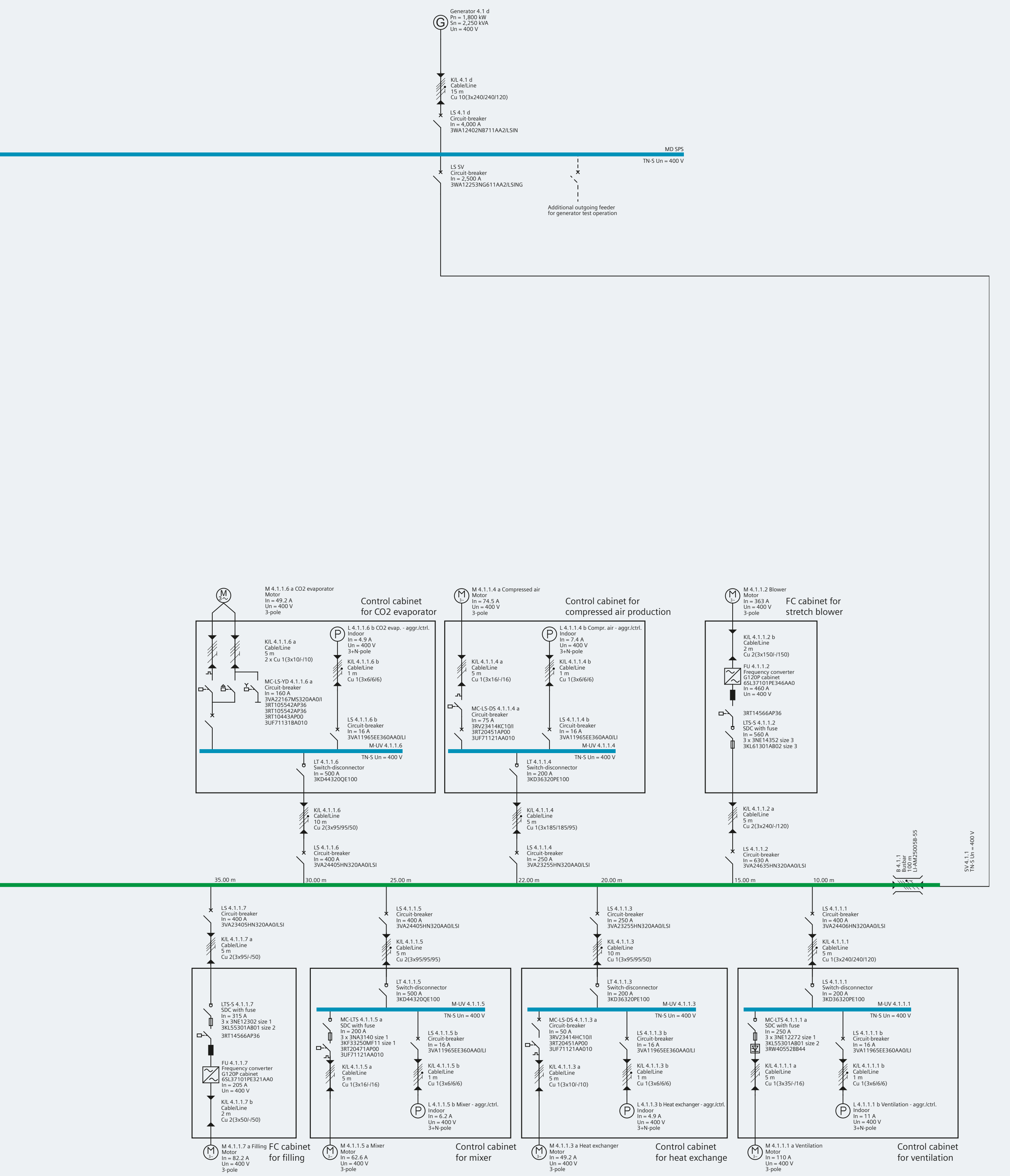


Fig. 5/10: **Single-line diagram of the electric power distribution for filling line 1 according to the dimensioning with SIMARIS design**



Generator 4.1 d
Pn = 1,800 kW
Sn = 2,250 kVA
Un = 400 V
K/L 4.1 d
Cable/Line
15 m
Cu 10(3x240/240/120)
LS 4.1 d
Circuit-breaker
In = 4,000 A
3WA12402NB711AA2/LSIN
MD SPS
TN-S Un = 400 V
LS SV
Circuit-breaker
In = 2,500 A
3WA12253NG611AA2/LSING
Additional outgoing feeder
for generator test operation
M 4.1.1.6 a CO2 evaporator
Motor
In = 49.2 A
Un = 400 V
3-pole
Control cabinet
for CO2 evaporator
L 4.1.1.6 b CO2 evap. - aggr./ctrl.
Indoor
In = 4.9 A
Un = 400 V
3+N-pole
K/L 4.1.1.6 a
Cable/Line
5 m
2 x Cu 1(3x10/-/10)
K/L 4.1.1.6 b
Cable/Line
1 m
Cu 1(3x6/6/6)
MC-LS-YD 4.1.1.6 a
Circuit-breaker
In = 160 A
3VA22167MS320AA0/I
3RT105542AP36
3RT105542AP36
3RT10443AP00
3UF71131BA010
LS 4.1.1.6 b
Circuit-breaker
In = 16 A
3VA11965EE360AA0/LI
M-UV 4.1.1.6
TN-S Un = 400 V
LT 4.1.1.6
Switch-disconnector
In = 500 A
3KD44320QE100
K/L 4.1.1.6
Cable/Line
10 m
Cu 2(3x95/95/50)
LS 4.1.1.6
Circuit-breaker
In = 400 A
3VA24405HN320AA0/LSI
M 4.1.1.4 a Compressed air
Motor
In = 74.5 A
Un = 400 V
3-pole
Control cabinet for
compressed air production
L 4.1.1.4 b Compr. air - aggr./ctrl.
Indoor
In = 7.4 A
Un = 400 V
3+N-pole
K/L 4.1.1.4 a
Cable/Line
5 m
Cu 1(3x16/-/16)
K/L 4.1.1.4 b
Cable/Line
1 m
Cu 1(3x6/6/6)
MC-LS-DS 4.1.1.4 a
Circuit-breaker
In = 75 A
3RV23414KC10/I
3RT20451AP00
3UF71121AA010
LS 4.1.1.4 b
Circuit-breaker
In = 16 A
3VA11965EE360AA0/LI
M-UV 4.1.1.4
TN-S Un = 400 V
LT 4.1.1.4
Switch-disconnector
In = 200 A
3KD36320PE100
K/L 4.1.1.4
Cable/Line
5 m
Cu 1(3x185/185/95)
LS 4.1.1.4
Circuit-breaker
In = 250 A
3VA23255HN320AA0/LSI
M 4.1.1.2 Blower
Motor
In = 363 A
Un = 400 V
3-pole
FC cabinet for
stretch blower
K/L 4.1.1.2 b
Cable/Line
2 m
Cu 2(3x150/-/150)
FU 4.1.1.2
Frequency converter
G120P cabinet
6SL37101PE346AA0
In = 460 A
Un = 400 V
3RT14566AP36
LTS-S 4.1.1.2
SDC with fuse
In = 560 A
3 x 3NE14352 size 3
3KL61301AB02 size 3
K/L 4.1.1.2 a
Cable/Line
5 m
Cu 2(3x240/-/120)
LS 4.1.1.2
Circuit-breaker
In = 630 A
3VA24635HN320AA0/LSI
B 4.1.1
Busbar
100 m
LI-AM25005B-55
SV 4.1.1
TN-S Un = 400 V
35.00 m
30.00 m
25.00 m
22.00 m
20.00 m
15.00 m
10.00 m
LS 4.1.1.7
Circuit-breaker
In = 400 A
3VA23405HN320AA0/LSI
K/L 4.1.1.7 a
Cable/Line
5 m
Cu 2(3x95/-/50)
LTS-S 4.1.1.7
SDC with fuse
In = 315 A
3 x 3NE12302 size 1
3KL55301AB01 size 2
3RT14566AP36
FU 4.1.1.7
Frequency converter
G120P cabinet
6SL37101PE321AA0
In = 205 A
Un = 400 V
K/L 4.1.1.7 b
Cable/Line
2 m
Cu 2(3x50/-/50)
M 4.1.1.7 a Filling
Motor
In = 82.2 A
Un = 400 V
3-pole
FC cabinet
for filling
LS 4.1.1.5
Circuit-breaker
In = 400 A
3VA24405HN320AA0/LSI
K/L 4.1.1.5
Cable/Line
5 m
Cu 2(3x95/95/95)
LT 4.1.1.5
Switch-disconnector
In = 500 A
3KD44320QE100
M-UV 4.1.1.5
TN-S Un = 400 V
MC-LTS 4.1.1.5 a
SDC with fuse
In = 200 A
3 x 3NA3140 size 1
3KF33250MF11 size 1
3RT20471AP00
3UF71121AA010
LS 4.1.1.5 b
Circuit-breaker
In = 16 A
3VA11965EE360AA0/LI
K/L 4.1.1.5 a
Cable/Line
5 m
Cu 1(3x16/-/16)
K/L 4.1.1.5 b
Cable/Line
1 m
Cu 1(3x6/6/6)
L 4.1.1.5 b Mixer - aggr./ctrl.
Indoor
In = 6.2 A
Un = 400 V
3+N-pole
M 4.1.1.5 a Mixer
Motor
In = 62.6 A
Un = 400 V
3-pole
Control cabinet
for mixer
LS 4.1.1.3
Circuit-breaker
In = 250 A
3VA23255HN320AA0/LSI
K/L 4.1.1.3
Cable/Line
10 m
Cu 1(3x95/95/50)
LT 4.1.1.3
Switch-disconnector
In = 200 A
3KD36320PE100
M-UV 4.1.1.3
TN-S Un = 400 V
MC-LS-DS 4.1.1.3 a
Circuit-breaker
In = 50 A
3RV23414HC10/I
3RT20451AP00
3UF71121AA010
LS 4.1.1.3 b
Circuit-breaker
In = 16 A
3VA11965EE360AA0/LI
K/L 4.1.1.3 a
Cable/Line
5 m
Cu 1(3x10/-/10)
K/L 4.1.1.3 b
Cable/Line
1 m
Cu 1(3x6/6/6)
L 4.1.1.3 b Heat exchanger - aggr./ctrl.
Indoor
In = 4.9 A
Un = 400 V
3+N-pole
M 4.1.1.3 a Heat exchanger
Motor
In = 49.2 A
Un = 400 V
3-pole
Control cabinet
for heat exchange
LS 4.1.1.1
Circuit-breaker
In = 400 A
3VA24406HN320AA0/LSI
K/L 4.1.1.1
Cable/Line
5 m
Cu 1(3x240/240/120)
LS 4.1.1.1
Switch-disconnector
In = 200 A
3KD36320PE100
M-UV 4.1.1.1
TN-S Un = 400 V
MC-LTS 4.1.1.1 a
SDC with fuse
In = 250 A
3 x 3NE12272 size 1
3KL55301AB01 size 2
3RW40552BB44
LS 4.1.1.1 b
Circuit-breaker
In = 16 A
3VA11965EE360AA0/LI
K/L 4.1.1.1 a
Cable/Line
5 m
Cu 1(3x35/-/16)
K/L 4.1.1.1 b
Cable/Line
1 m
Cu 1(3x6/6/6)
L 4.1.1.1 b Ventilation - aggr./ctrl.
Indoor
In = 11 A
Un = 400 V
3+N-pole
M 4.1.1.1 a Ventilation
Motor
In = 110 A
Un = 400 V
3-pole
Control cabinet
for ventilation

5.8 Low-Voltage Distribution Boards for the Load Centers

Apart from the load center substations LC 1 (office section and dispatch), LC 2 (compressors), and LC 3 (cooling and treatment), the electrical consumers of the three filling lines are separately supplied via substation LC 4 (Fig. 5/3), through one transformer substation with a low-voltage main distribution board each. The dimensioning of the switching and protection devices for the six individual low-voltage distribution boards of the load centers LC 1 to LC 4 is done using the SIMARIS tools. The starting point is the load overview in Fig. 5/3.

A similar procedure applies to all six low-voltage distribution boards, starting from the distribution structure (network systems, redundancies, transformer arrangements, cables and/or busbar trunking system, observance of consumer specifics, etc.) through the calculations and dimensioning up to the exact determination of the suitable product types, so that it is sufficient to perform any further considerations for two low-voltage distribution boards.

On one hand, the different motor starter combinations are addressed based on filling line 1. On the other hand, it can be shown for the load center LC 1 (office section and dispatch) how circuit-breakers with electronic characteristic tripping curve that come close to a fuse (SENTRON 3VA with ELISA release) optimize the power distribution regarding cable and busbar cross-sections as well as selectivity, and thus contribute to the cost-efficient design and increase of system availability.

5.8.1 Motor starter Combinations for Filling Line 1

The loads connected in the filling line 1 must be supplied via a low-voltage distribution which allows for a power transmission of at least 1,510 kVA. Due to the requested redundancy, an infeed in the normal power supply (NPS in Fig. 5/10) via three 800 kVA GEAFOL transformers would be appropriate. The safety power supply (SPS in Fig. 5/10) is connected to the NPS through a coupler. In case of failure through the transformers, the SPS busbar continues to be supplied from a generator connected to it. This is a specialty of the sample plant, which reflects that frequent interruptions in power supply by the distribution system operator (DSO) can occur in the system environment.

For industrial applications, a linear power distribution system with a busbar trunking system is typically planned along the production line. An individual busbar run is drawn as a sub-distribution for each filling line. As an example, it is sufficient to look at filling line 1 in Fig. 5/10 more closely, as the same procedure can be followed for the other low-voltage distribution circuits. Fig. 5/10 shows the single-line diagram as it is used for the billing, dimensioning, and project planning with the SIMARIS tools. The switchgear assemblies are shown as examples for the individual results. The low-voltage switchboard SIVACON S8 from Fig. 5/11 corresponds to the main distribution board with the three transformer infeeds, the two outgoing feeders for the NPS and SPS, as well as the associated longitudinal coupler. In the medium-voltage switchgear 8DJH in Fig. 5/12, the entire load center LC 4 is shown according to Chapter 5.4 for the three filling lines.

Tab. 5/2 contains the load data of the consumers of filling line 1 and the respective intended starter type for the motors. The individual applications are divided into motor loads and resistive loads, such as for example auxiliary power units, control modules, and heating. Approximately 10 % of the required motor power are assumed for the resistive loads. For heating the packaging film to create a shrink-wrapped packaging, an additional resistive load of about 75 kVA is taken into account.

Fig. 5/10 also illustrates that combinations are selected which are typical for a requirement-conforming motor start. During selection, energizing and de-energizing of the motor, the starting and stopping behavior, as well as the operational behavior and the motor protection in case of overload are considered. When planning the electric power distribution, the short-circuit protection and the overload protection of the supply line must be designed, apart from the motor protection.

The overload and short-circuit protection of the motor feeders can be executed in both non-fused and fused technology:

- Non-fused technology
  - with circuit-breaker for short-circuit and overload protection
  - with circuit-breaker (for short-circuit protection) and overload relay (thermal or electronic) or a motor management device as well as contactors for tripping (for overload protection)
- Fused technology with fuse-switch-disconnector (the fuses take on the short-circuit protection) and overload relay (thermal or electronic) or a motor management device as well as contactors for tripping (for overload protection).

Fig. 5/11: **Low-voltage switchboard SIVACON S8 for the main distribution of filling line 1 (dimensions in mm)**

To determine the load behavior at motor start, four different combinations are used in filling line 1, which serves as an example:

- Direct-on-line start with overload relay/control unit and contactor
- Star-delta start with overload relay/control unit and three contactors
- Start with soft starters that limit, protect and switch
- Start with frequency converters that limit and protect.

In this process, soft starters and frequency converters can take over the overload protection. When using soft starters and frequency converters with fused technology, semiconductor fuses are used.

It must be observed that the motor protection contained in the converter cannot be used in case of multi-motor operation with frequency converters. In Tab. 5/3, the combinations of starters and protection devices stored in SIMARIS design are specified with the corresponding Siemens device series for the four different motor start types. Additional devices and possible combinations can be found in the respective catalogs [5.3], [5.4] and [5.5], as well as in the white paper [4.5] and in guidelines such as [1.1] and [1.2].

According to IEC 60204, a protection of the motors against overheating is mandatory as from a power of 0.5 kW. The protection can be provided by means of overload protection, overtemperature protection, or current limiting.

Contents
1
2
3
4
5
6
7

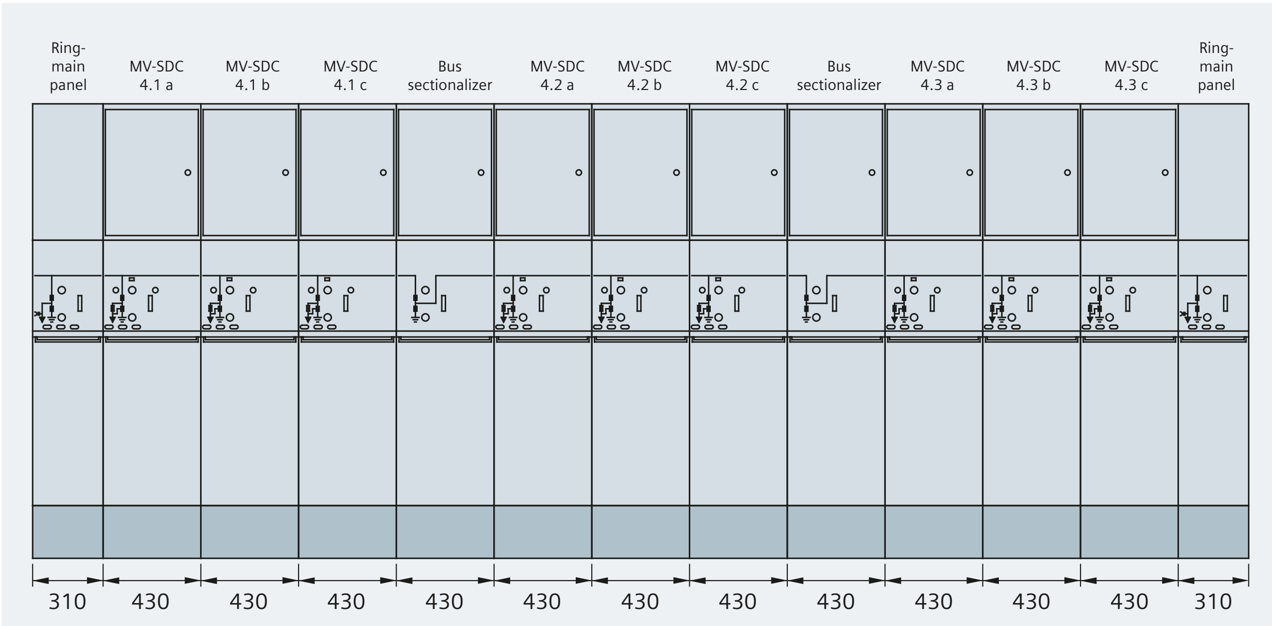


Fig. 5/12: **Medium-voltage switchgear 8DJH of the load center LC 4 for the three filling lines (dimensions in mm)**

Application	Load type	Motor start	SIMARIS no.	Position of tap-off unit	Nominal current	NPS - SPS / Voltage	Quantity
Ventilation	Motor	Soft starter	M 4.1.1.1 a	10 m	110.0 A	SPS / 400 V	1
	Aggr. / control system		L 4.1.1.1 b		11.0 A		1
Stretch blower	Motor	Frequency converter	M 4.1.1.2	15 m	363.0 A	SPS / 400 V	1
Heat exchange	Motor	Direct (non-fused)	M 4.1.1.3 a	20 m	49.2 A	SPS / 400 V	1
	Aggr. / control system		L 4.1.1.3 b		4.9 A		1
Compressed air production	Motor	Direct (non-fused)	M 4.1.1.4 a	22 m	74.5 A	SPS / 400 V	1
	Aggr. / control system		L 4.1.1.4 b		7.4 A		1
Mixer	Motor	Direct (fused)	M 4.1.1.5 a	25 m	62.6 A	SPS / 400 V	1
	Aggr. / control system		L 4.1.1.5 b		6.2 A		1
CO_2 evaporator	Motor	Star-delta	M 4.1.1.6 a	30 m	49.2 A	SPS / 400 V	1
	Aggr. / control system		L 4.1.1.6 b		4.9 A		1
Filling	Motor	Frequency converter	M 4.1.1.7	35 m	82.2 A	SPS / 400 V	1
Bottle conveyor	Motor	Soft starter	M 4.1.1.8 a	40 m	314.0 A	SPS / 400 V	1
	Aggr. / control system		L 4.1.1.8 b		31.4 A		1
Screw cap production	Motor	Soft starter	M 4.1.1.9 a	42 m	49.2 A	SPS / 400 V	1
	Aggr. / control system		L 4.1.1.9 b		4.9 A		1
Labeling	Motor	Direct (fused)	M 4.1.1.10 a	45 m	49.1 A	SPS / 400 V	1
	Aggr. / control system		L 4.1.1.10 b		4.9 A		1
Automatic cleaning unit	Motor	Soft starter	M 4.1.1.11 a	50 m	50.0 A	SPS / 400 V	1
	Aggr. / control system		L 4.1.1.11 b		5.0 A		1
Packaging conveyor	Motor	Soft starter	M 4.1.1.12 a	55 m	160.0 A	SPS / 400 V	1
	Aggr. / control system		L 4.1.1.12 b		16.0 A		1
Shrink packaging	Motor	Soft starter	M 4.1.1.13 a	57 m	148.0 A	SPS / 400 V	1
	Heat. / Aggr. / Ctrl.		L 4.1.1.13 b		124.0 A		1
Palletizing	Motor	Direct (fused)	M 4.1.1.14 a	60 m	122.0 A	SPS / 400 V	1
	Aggr. / control system		L 4.1.1.14 b		12.0 A		1
Stretch film wrapping machine	Motor	Direct (fused)	M 4.1.1.15 a	65 m	62.5 A	SPS / 400 V	1
	Aggr. / control system		L 4.1.1.15 b		6.2 A		1
Filling information system			L 4.1.1.16	70 m	50.1 A	SPS / 400 V	1
Lighting			UV 4.1.2.1		4.6 A	NPS / 230 V	10
Socket outlets			UV 4.1.2.2		10.5 A	NPS / 230 V	10

Tab. 5/2: **Load list for filling line 1 for dimensioning with SIMARIS design according to Fig. 5/10**

	Short-circuit protection		Overload protection		Max. mech. power	Device protection [1]
	Fused / non-fused	**Switching / protection device**	**Release**	**Switching device**		**Fuses / circuit-breaker**
Direct-on-line start	Fused	Fuses SENTRON 3NA [2]	Overload relay, thermal SIRIUS 3RU	Contactor SIRIUS 3RT	45 kW	
			Overload relay, electronic SIRIUS 3RB	Contactor SIRIUS 3RT	250 kW [3]	
			Motor management device SIMOCODE Pro C 3UF7	Contactor SIRIUS 3RT	250 kW [3]	
	Non-fused	Circuit-breaker SIRIUS 3RV, SENTRON 3VA		Contactor SIRIUS 3RT	250 kW	
		Circuit-breaker SIRIUS 3RV, SENTRON 3VA	Overload relay, electronic SIRIUS 3RU	Contactor SIRIUS 3RT	22 kW	
			Overload relay, electronic SIRIUS 3RB	Contactor SIRIUS 3RT	250 kW [3]	
			Motor management device SIMOCODE Pro C 3UF7	Contactor SIRIUS 3RT	250 kW [3]	
Star-delta starter	Non-fused	Circuit-breaker SIRIUS 3RV, SENTRON 3VA	Overload relay, thermal SIRIUS 3RU	3 contactors SIRIUS 3RT	15 kW	
			Overload relay, electronic SIRIUS 3RB	3 contactors SIRIUS 3RT	200 kW	
			Motor management device SIMOCODE Pro C 3UF7	3 contactors SIRIUS 3RT	200 kW	
Soft starter	Fused	Fuses SENTRON 3NA [2]	Soft starter SIRIUS 3RW30	Contactor SIRIUS 3RT	18.5 kW	
		Fuses SENTRON 3NE	Soft starter SIRIUS 3RW40 [4]		250 kW	
Frequency converter	Fused	Fuses SENTRON 3NA [2]	Freq. converter SINAMICS (decentralized devices)	G110M G110D, G120D	4 kW 7.5 kW	
			Freq. converter SINAMICS G120, G120X (built-in devices)	Contactor SIRIUS 3RT	250 kW	
			Freq. converter SINAMICS G120P, G150 (cabinet units)	Contactor SIRIUS 3RT	250 kW	Fuses SENTRON 3NE
	Non-fused	Circuit-breaker SENTRON 3VA	Freq. converter SINAMICS G120, G120X (built-in devices)	Contactor SIRIUS 3RT	250 kW	
		Circuit-breaker SENTRON 3VA, 3WA	Freq. converter SINAMICS G120P, G150 (cabinet units)	Contactor SIRIUS 3RT	400 kW	Fuses SENTRON 3NE
		Circuit-breaker SENTRON 3VA, 3WA	Freq. converter SINAMICS G120P, G150 (cabinet units)		> 400 - 560 kW	Circuit-breaker SENTRON 3WA

[1] Device protection in the frequency converter cabinet
[2] In combination with a switch-disconnector, such as e.g. Siemens 3KF, 3NJ, 3NP
[3] The contactor SIRIUS 3TF6 can be designed for motor ratings up to 450 kW (in low-voltage distribution networks, it is recommended to limit the motor rating to about 250 kW during direct-on-line start)
[4] Type-tested device combination in which the soft starter takes over the function of the contactor; other soft starters in the SIRIUS program are, for example, 3RW50, 3RW52 and 3RW55 [IC10]

Tab. 5/3: **Device combinations stored in SIMARIS design for the start and protection of low-voltage motors**

Contents

1

2

3

4

5

6

7

Protection of the motor for	Motor protection		
	only current-dependent, e.g. with overload relay	only temperature-dependent, e.g. with thermistor motor protection relay	current- and temperature-dependent
overload in continuous operation	✓	✓	✓
long starting and braking processes	❍	✓	✓
irregular intermittent periodic duty	❍	✓	✓
too high switching rate	❍	✓	✓
single-phase operation and current asymmetry	✓	✓	✓
voltage and frequency fluctuations	✓	✓	✓
application of the brakes on the rotor	✓	✓	✓
connection with locked rotor in case of stator-critical motor	✓	✓	✓
connection with locked rotor in case of rotor-critical motor	✓	❍	✓
increased ambient air temperature	–	✓	✓
hindered cooling	–	✓	✓

✓ full protection
❍ conditional protection
– no protection

Tab. 5/4: **Comparison of the motor protection methods**

The use of a SIRIUS 3RN2 thermistor motor protection device as a direct motor protection is appropriate

- for motors which frequently start and brake
- at high ambient air temperatures or in environments in which cooling might be impaired (e.g. due to dust)
- in case of very long starting and braking processes
- in combination with frequency converters at low speeds.

In rotor-critical motors, the overtemperature detection in the stator windings can lead to a delayed and thus insufficient protection. In this case, an additional protection, for example via an overload relay, is to be provided according to the standard. In Tab. 5/4, the effectiveness of different motor protection methods is compared. Due to the I^2t detection contained in the SINAMICS firmware, the SINAMICS frequency converters provide a simple protection against thermal overload as standard. A more precise motor protection can be achieved by means of temperature detection with additional temperature sensors.

The Siemens portfolio for motor protection is completed by, for example, the current monitoring relays SIRIUS 3RR and the non-fused compact starters SIRIUS 3RA6, which are installed in the control cabinet in a space-saving design as a unit including circuit-breaker, contactor and electronic overload relay. For more on this and on other components around motor starters and motor protection devices, see [5.3]. It should be noted again at this point that for the planning of drive powers as from 250 kW at 400 V, medium-voltage motors are the preferred choice, as the dynamic voltage drop and the high starting currents can otherwise lead to problems in the low-voltage network.

In SIMARIS design, the values for typical motor data of standard-compliant Siemens low-voltage motors are stored for preselection. However, the corresponding tested starter combination can also be dimensioned for any other motor. The white paper [4.5], the planning manual [1.1] and the configuration manual [5.6] provide more information on motor start.

5.8.2 Selectivity by Means of Appropriate Selection of Circuit-Breaker Types in Sub-Distribution Circuits and Integration of a Static UPS System

The design of the switching and protection equipment for the low-voltage distribution board of the load center LC 1 not only takes into account the supply of office workplaces, but also the protection of a server rack with single-phase supplied servers (current demand I_n = 26.8 A per rack) as well as the fire detection and fire protection equipment by means of a static UPS system. The lighting and socket outlets for the office rooms are distributed to three sub-distribution boards with separate circuits for lighting and socket outlets (Fig. 5/13).

According to [5.7], the UPS system is reproduced in SIMARIS design using three components. The UPS rectifier with battery charge is simulated by an equivalent load and supplied via the SPS. The inverter output corresponds to an infeed which supplies the consumers connected to the UPS. As the considered UPS has a separate input for the internal bypass, this input is connected to the NPS. It must be noted that no internal UPS connections are reproduced in Fig. 5/13, and that the circuit-breakers for the internal bypass and the inverter as well as the distribution board busbars “USP-Out” and “USP-In” are fictitious and only required for the simulation in SIMARIS design. More information on the UPS simulation with SIMARIS design can be found in [5.7] or inquired via the responsible TIP contact partner.

Since there should not occur a total shutdown of all lighting facilities and all consumers connected to the socket outlets in the office section in the event of a fault in any of the end circuits, full selectivity is required for the NPS sub-distribution boards in the office section. In Fig. 5/13, the suitable protection devices are already arranged in the network. This, however, needs some readjustments in the dimensioning with SIMARIS design.

As a starting point for the readjustments, Fig. 5/14 shows the result of a fully “automated” dimensioning with SIMARIS design. To do this, the network configuration is set up and the boundary conditions for infeeds and consumers are stipulated. The switching and protection devices marked yellow in Fig. 5/14 identify partial selectivity, and the switching and protection devices marked green identify full selectivity. Even if the switching and protection devices of the main distribution board MD NPS are fully selective, it does not suffice to only adjust the switching and protection devices of the sub-distribution boards in order to achieve full selectivity for them, too. In fact, the experience of technical planners is essential here, as they know how to use tools like SIMARIS and are able to evaluate the results.

This application manual can provide important information on what to keep in mind during the design.
By no means is it a general instruction for how to proceed to achieve full selectivity in a given project. Moreover, the described example confirms that software tools can contribute to facilitating the task of planning, but the technical competence of the user actually determines the quality of the results significantly.

As a first intervention, the load protection for the socket outlets and lighting facilities is permanently increased up to a rated current I_r of 16 A. This way, the cable cross-sections change as well.

The comparison between Fig. 5/13 and Fig. 5/14 illustrates how the entire chain from the infeed up to the consumers must be contemplated for selectivity considerations. The more distribution steps there are between the infeed and the consumers, the more complex it can get to design the protection grading selectively. Moreover, modifications in one circuit can also have consequences for the other circuits, which must be taken into account.

The new electronic overcurrent tripping unit ETU340 (ELISA) for the molded-case circuit-breakers SENTRON 3VA2 from Siemens features an easily adjustable tripping characteristic that resembles the one of fuses and with the help of which selective gradings can perhaps be achieved more easily. The outgoing feeder circuit-breakers LS AV 1 (between sub-distribution board SD NPS and sub-distribution board SD NPS 1; as well as SD NPS 2 and 3, analogously) and LS AV 1.1 or LS AV 1.2 to the sub-distribution boards SD NPS 1.1 or SD NPS 1.2 (the circuit-breakers for SD NPS 2.1 and 2.2, as well as SD NPS 3.1 and 3.2, analogously) are such 3VA2 circuit-breakers with ETU340 according to Fig. 5/13. In Fig. 5/15, the curves of the circuit-breaker LS AV 1.1 and LS AV 1.2 from the selectivity-optimized SIMARIS calculation (see Fig. 5/13) are compared with the “automated” SIMARIS calculation (see Fig. 5/14).

Nevertheless, additional solutions could possibly be found, and the comparison is only meant to illustrate as an example how diverse the starting points for project planning can be. More information on the correlation between selectivity and design of a distribution network structure, especially when it comes to the molded-case circuit-breaker 3VA, can be found in the selectivity manual [5.8].

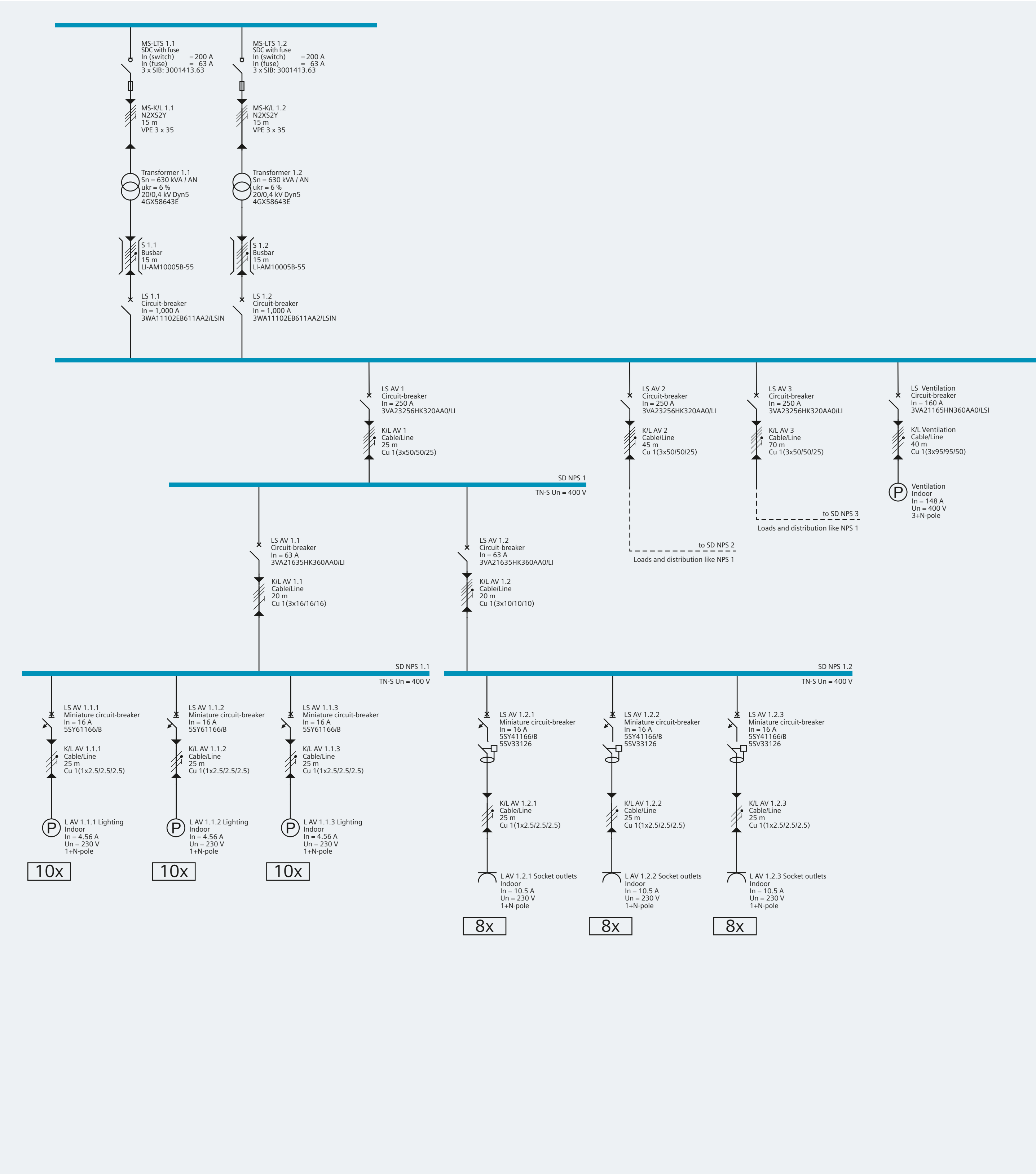
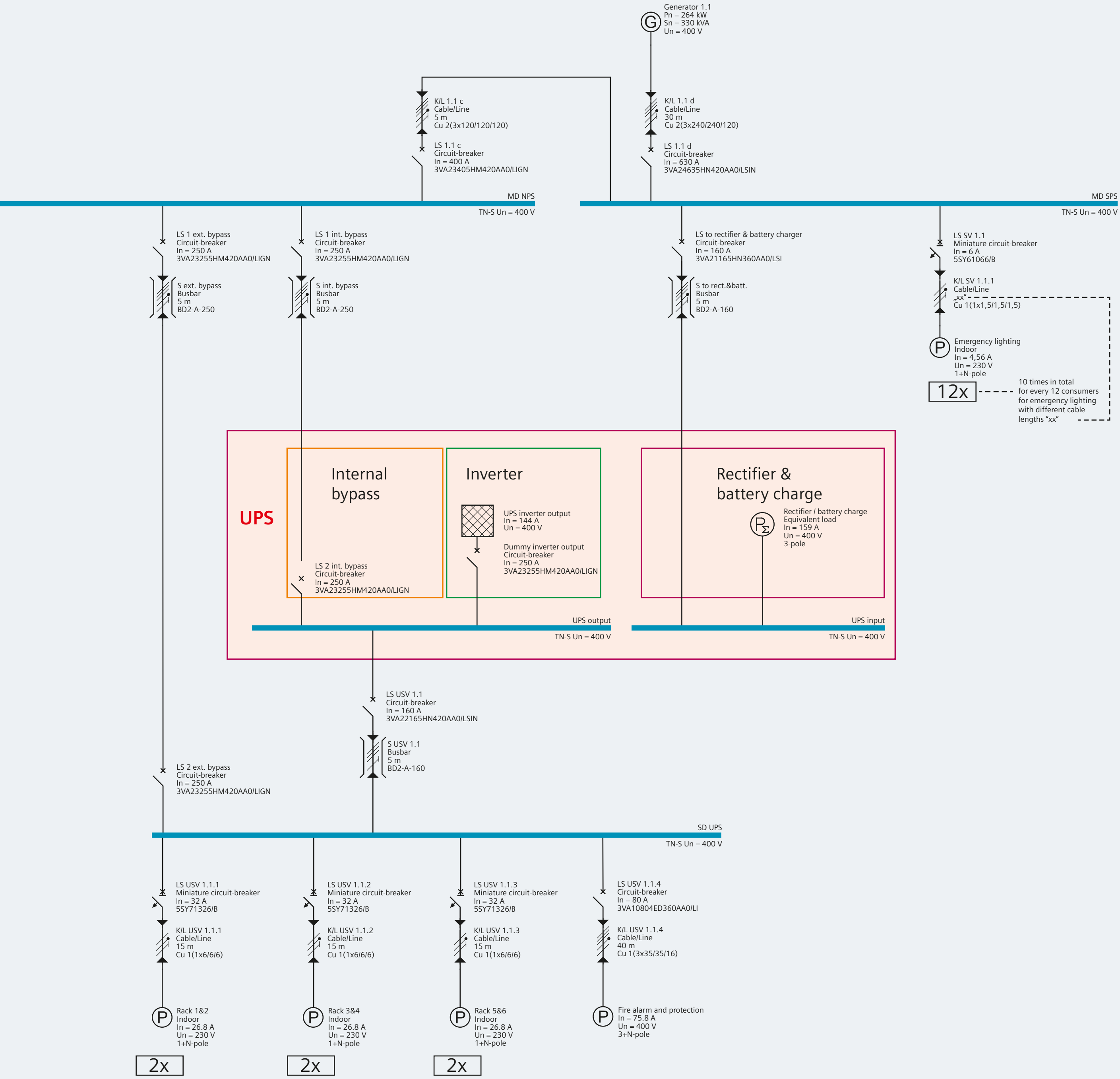


Fig. 5/13: **Single-line diagram for the office section of the load center substation LC 1**


Generator 1.1
Pn = 264 kW
Sn = 330 kVA
Un = 400 V
K/L 1.1 c
Cable/Line
5 m
Cu 2(3x120/120/120)
LS 1.1 c
Circuit-breaker
In = 400 A
3VA23405HM420AA0/LIGN
K/L 1.1 d
Cable/Line
30 m
Cu 2(3x240/240/120)
LS 1.1 d
Circuit-breaker
In = 630 A
3VA24635HN420AA0/LSIN
MD NPS
TN-S Un = 400 V
MD SPS
TN-S Un = 400 V
LS 1 ext. bypass
Circuit-breaker
In = 250 A
3VA23255HM420AA0/LIGN
LS 1 int. bypass
Circuit-breaker
In = 250 A
3VA23255HM420AA0/LIGN
LS to rectifier & battery charger
Circuit-breaker
In = 160 A
3VA21165HN360AA0/LSI
LS SV 1.1
Miniature circuit-breaker
In = 6 A
5SY61066/B
S ext. bypass
Busbar
5 m
BD2-A-250
S int. bypass
Busbar
5 m
BD2-A-250
S to rect.&batt.
Busbar
5 m
BD2-A-160
K/L SV 1.1.1
Cable/Line
„xx"
Cu 1(1x1,5/1,5/1,5)
Emergency lighting
Indoor
In = 4,56 A
Un = 230 V
1+N-pole
12x
10 times in total
for every 12 consumers
for emergency lighting
with different cable
lengths "xx"
UPS
Internal bypass
Inverter
Rectifier & battery charge
UPS inverter output
In = 144 A
Un = 400 V
Dummy inverter output
Circuit-breaker
In = 250 A
3VA23255HM420AA0/LIGN
Rectifier / battery charge
Equivalent load
In = 159 A
Un = 400 V
3-pole
LS 2 int. bypass
Circuit-breaker
In = 250 A
3VA23255HM420AA0/LIGN
UPS output
TN-S Un = 400 V
UPS input
TN-S Un = 400 V
LS USV 1.1
Circuit-breaker
In = 160 A
3VA22165HN420AA0/LSIN
S USV 1.1
Busbar
5 m
BD2-A-160
LS 2 ext. bypass
Circuit-breaker
In = 250 A
3VA23255HM420AA0/LIGN
SD UPS
TN-S Un = 400 V
LS USV 1.1.1
Miniature circuit-breaker
In = 32 A
5SY71326/B
LS USV 1.1.2
Miniature circuit-breaker
In = 32 A
5SY71326/B
LS USV 1.1.3
Miniature circuit-breaker
In = 32 A
5SY71326/B
LS USV 1.1.4
Circuit-breaker
In = 80 A
3VA10804ED360AA0/LI
K/L USV 1.1.1
Cable/Line
15 m
Cu 1(1x6/6/6)
K/L USV 1.1.2
Cable/Line
15 m
Cu 1(1x6/6/6)
K/L USV 1.1.3
Cable/Line
15 m
Cu 1(1x6/6/6)
K/L USV 1.1.4
Cable/Line
40 m
Cu 1(3x35/35/16)
Rack 1&2
Indoor
In = 26.8 A
Un = 230 V
1+N-pole
Rack 3&4
Indoor
In = 26.8 A
Un = 230 V
1+N-pole
Rack 5&6
Indoor
In = 26.8 A
Un = 230 V
1+N-pole
Fire alarm and protection
In = 75.8 A
Un = 400 V
3+N-pole
2x
2x
2x

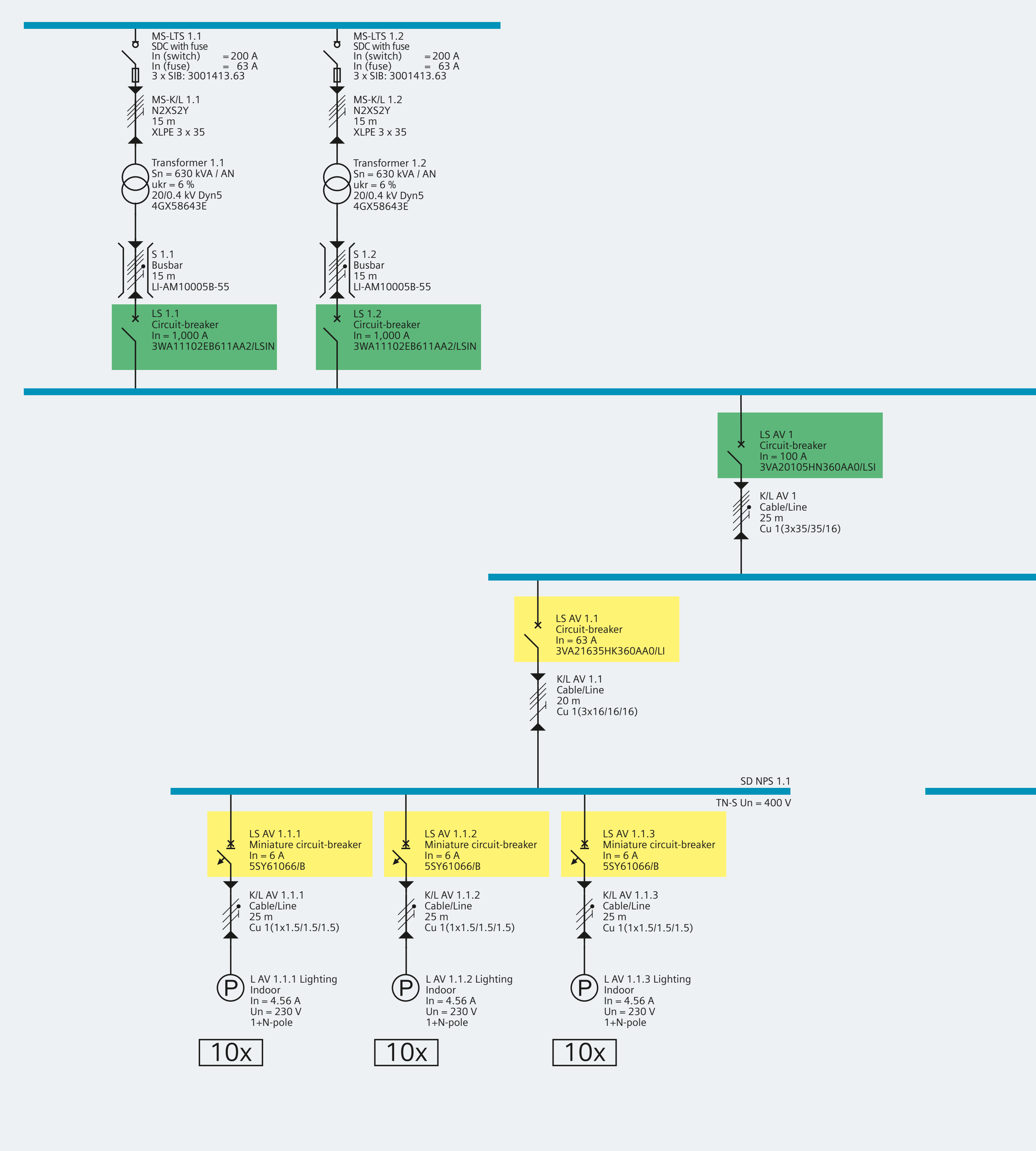
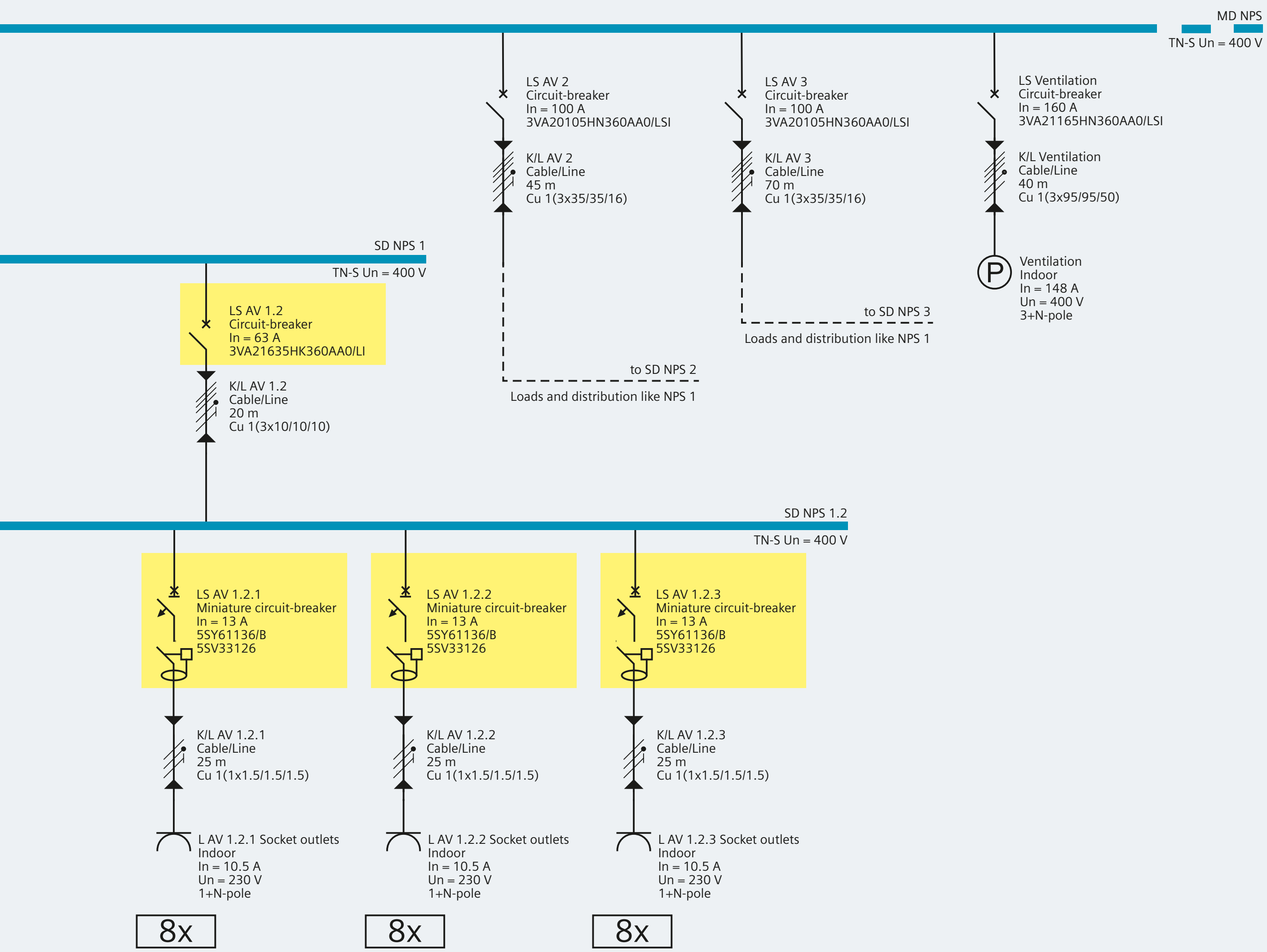
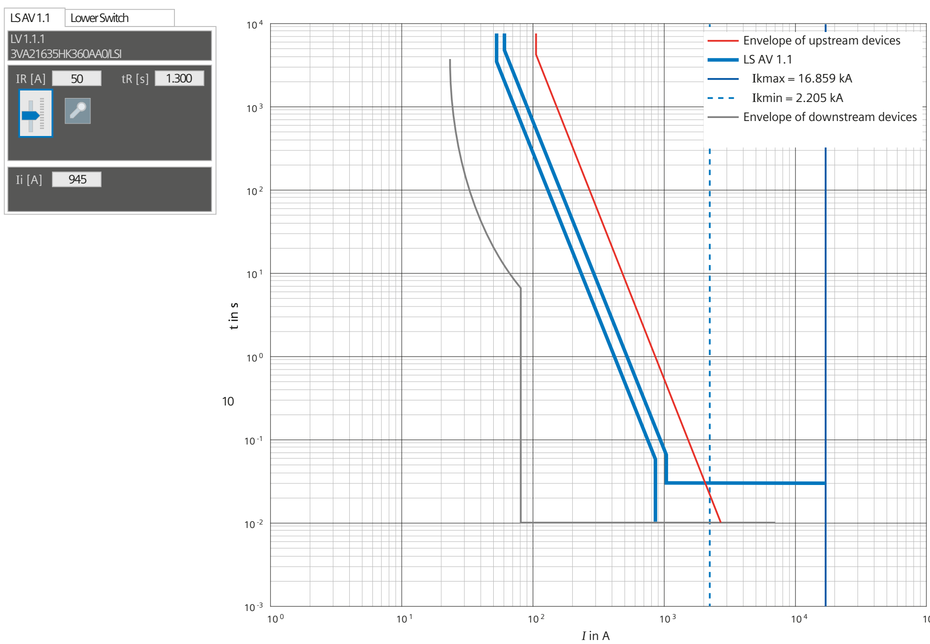


Fig. 5/14: **Simplified single-line diagram with selectivity marking (yellow = partially selective; green = fully selective) for the office section according to an automated dimensioning with SIMARIS design**


MD NPS
TN-S Un = 400 V
LS AV 2
Circuit-breaker
In = 100 A
3VA20105HN360AA0/LSI
K/L AV 2
Cable/Line
45 m
Cu 1(3x35/35/16)
LS AV 3
Circuit-breaker
In = 100 A
3VA20105HN360AA0/LSI
K/L AV 3
Cable/Line
70 m
Cu 1(3x35/35/16)
LS Ventilation
Circuit-breaker
In = 160 A
3VA21165HN360AA0/LSI
K/L Ventilation
Cable/Line
40 m
Cu 1(3x95/95/50)
P
Ventilation
Indoor
In = 148 A
Un = 400 V
3+N-pole
SD NPS 1
TN-S Un = 400 V
to SD NPS 3
Loads and distribution like NPS 1
LS AV 1.2
Circuit-breaker
In = 63 A
3VA21635HK360AA0/LI
to SD NPS 2
Loads and distribution like NPS 1
K/L AV 1.2
Cable/Line
20 m
Cu 1(3x10/10/10)
SD NPS 1.2
TN-S Un = 400 V
LS AV 1.2.1
Miniature circuit-breaker
In = 13 A
5SY61136/B
5SV33126
LS AV 1.2.2
Miniature circuit-breaker
In = 13 A
5SY61136/B
5SV33126
LS AV 1.2.3
Miniature circuit-breaker
In = 13 A
5SY61136/B
5SV33126
K/L AV 1.2.1
Cable/Line
25 m
Cu 1(1x1.5/1.5/1.5)
K/L AV 1.2.2
Cable/Line
25 m
Cu 1(1x1.5/1.5/1.5)
K/L AV 1.2.3
Cable/Line
25 m
Cu 1(1x1.5/1.5/1.5)
L AV 1.2.1 Socket outlets
Indoor
In = 10.5 A
Un = 230 V
1+N-pole
L AV 1.2.2 Socket outlets
Indoor
In = 10.5 A
Un = 230 V
1+N-pole
L AV 1.2.3 Socket outlets
Indoor
In = 10.5 A
Un = 230 V
1+N-pole
8x
8x
8x

Fully selective sub-distribution circuit with 3VA2 circuit-breakers and ETU 340 (ELISA)



Partially selective sub-distribution circuit with 3VA2 circuit-breakers and ETU 350 (LSI)

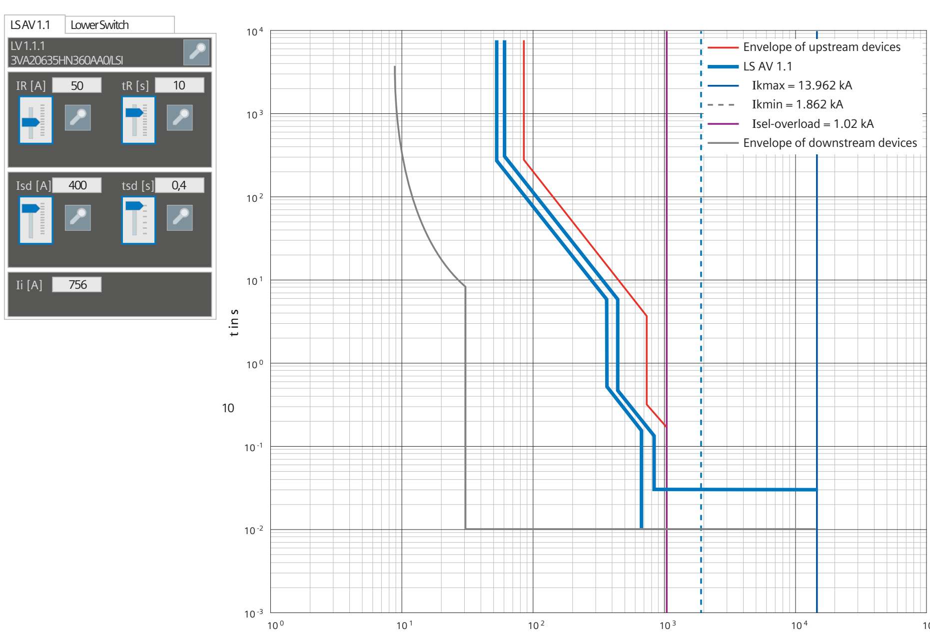


Fig. 5/15: **Comparison of the selectivity outputs of SIMARIS design for circuit-breakers LS AV 1.1 and LS AV 1.2: top, "optimized" according to Fig. 5/13; bottom, "automated" according to Fig. 5/14**

5.8.3 Concept Examples for Low-Voltage Distribution Boards by the Example of Filling Lines 1 to 3

Due to the adjacent arrangement of three filling lines in one production hall, the distribution concept in Fig. 5/10 is only one of many possible options in the industrial environment. An adjustment or change of requirements can lead to different focal points and concepts in planning. As some basic concepts for the low-voltage main distribution boards of the three filling lines are briefly addressed in the following as examples, the consumers of the three individual lines can be joined as equivalent loads and the generator infeeds can be disregarded. Design-specific characteristics of the concepts can be found in Tab. 5/5 and in the single-line diagrams in Fig. 5/16. Characteristics of the examples are:

1. Three supply substations (with three 800 kVA transformers each) for the separate supply of the individual lines
2. Three supply substations (with two 1,000 kVA transformers each) for the supply of the lines, with couplers between the parts of the low-voltage switchboard
   2.1 When a transformer fails: Coupling of two lines (3 × 1,000 kVA for two lines + 2 × 1,000 kVA for the third line)
   2.2 When a transformer fails: Coupling of the five remaining transformers (5 × 1,000 kVA for three lines)
3. Three supply substations to supply the lines: The coupling through a bypass busbar enables a separate installation of the low-voltage switchboards
   3.1 With 2 × 1,000 kVA transformers with fans (a power increase to 1,400 kVA is possible with fan operation) per substation, which are coupled through the bypass busbar when a transformer fails
   3.2 With 2 × 1,250 kVA transformers per substation, which are coupled through the bypass busbar when a transformer fails
4. Supply of the three lines through a busbar trunking system ring with four individual infeeds from one 1,250 kVA transformer each with fans for the (n-1) failure supply with only three transformers.

Rough calculations are performed for the considered basic concepts. The maximum short-circuit currents I''_k are calculated without taking into account the upstream network influences and line impedances (the overview in Fig. 4/11 is a graphical implementation of the values):

$$I''_k = \frac{S_{Tr}}{\sqrt{3} \cdot u_{kr} \cdot 400\ V}$$

The results are verified by means of SIMARIS design calculations. In SIMARIS design, the line impedances are taken into account, which explains the differences in the values in Tab. 5/5.

In concept 1., the supplies of the individual filling lines remain separate in all operating states. On the one hand, switching operations are avoided, but on the other hand, a larger number of components (e.g. nine 800 kVA transformers in total) must be accepted for (n-1) availability. The lowest maximum value of the short-circuit currents (rough calculation: 58 kA; SIMARIS: 55 kA) is advantageous regarding the short-circuit withstand strength of the devices.

In normal operation, the concepts 2.1, 2.2 and 3.1 are more convenient regarding the protection of persons and equipment, as the maximum short-circuit currents are lower than in concept 1. Since the maximum short-circuit currents in case of failure are higher than in concept 1., a higher short-circuit withstand strength of the switching and protection devices is required as well. The concepts 2.1 and 2.2 might not differ in their general design, but different (n-1) failure actions are performed. It becomes apparent that it is more advantageous to not close all couplers between the substations when a transformer fails, and thus switching all remaining five transformers in parallel (concept 2.2). It is sufficient to close one coupler in order to supply two lines with three transformers and to continue to supply one line separately with two transformers (concept 2.1). The resulting short-circuit currents are therefore lower.

The transformer configuration and the treatment in case of failure of concept 3.1 largely corresponds to that of concept 2.1. The difference in concept 3.1 is the bypass busbar which, compared with concepts 2.1 and 2.2, allows for a spatially separate installation of the low-voltage switchboards (closer to the individual filling lines) and also enables the right-hand and left-hand substation to be coupled (Fig. 5/15: "3.1" and "3.2") even if the intermediate substation fails completely. Thus, in case of such a (n-2) availability, only four transformers are required to supply the total load of about 4,350 kVA.

Contents

1

2

3

4

5

6

7

Distribution concept for the low-voltage supply	One substation per filling line – separated	One substation per filling line – couplers between the substations		One substation per filling line – substations coupled through bypass busbar		Four substations in the busbar trunking system ring supply three filling lines
Example / single-line diagram (Fig. 5/16)	**1.**	**2.1**	**2.2**	**3.1**	**3.2**	**4**
Transformers in normal operation and main switchboards	3 × 800 kVA in 3 substations	3 × 2 × 1,000 kVA with open couplers in a substation	3 × 2 × 1,000 kVA with open couplers in a substation	2 × 1,000 kVA with fan in 3 substations, connected through an open bypass busbar	2 × 1,250 kVA in 3 substations, connected through an open bypass busbar	1 × 1,250 kVA each with fan in 4 substations
Transformers at (n-1) failure operation and main switchboards	3 × 800 kVA in non-affected substations 2 × 800 kVA in affected substation	3 × 1,000 kVA coupled for 2 lines 2 × 1,000 kVA for the third line	5 × 1,000 kVA coupled for 3 lines	3 × 1,000 kVA (fan) coupled for 2 lines 2 × 1,000 kVA (fan) for the third line	3 × 1,250 kVA coupled for 2 lines 2 × 1,250 kVA for the third line	1 × 1,250 kVA each with fan in 3 substations
Ventilation of the transformers in (n-1) failure operation	Natural ventilation (AN)	Natural ventilation (AN)	Natural ventilation (AN)	With fan (AF)	Natural ventilation (AN)	With fan (AF)
Rough calculation without considering line lengths (cables / busbars)						
Maximum theoretical short-circuit stress: Normal operation / (n-1) failure	approx. 58 kA / 38.5 kA	approx. 48 kA / 72 kA	approx. 48 kA / 120 kA	approx. 48 kA / 72 kA	approx. 60 kA / 90 kA	approx. 120 kA / 90 kA
Validation by means of calculation with SIMARIS design considering line lengths (cables / busbars)						
Short-circuit stress from simplified calculation: Normal operation / (n-1) failure	approx. 55 kA / 38 kA	approx. 47 kA / 68 kA	approx. 47 kA / 108 kA	approx. 48 kA / 66 kA	approx. 58 kA / 79 kA	approx. 98 kA / 80 kA

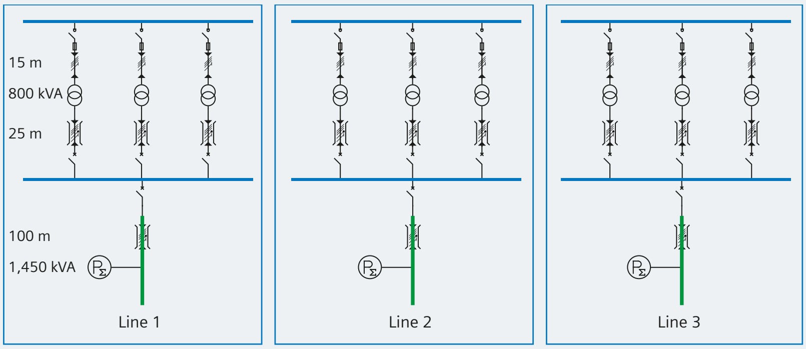
Tab. 5/5: **Typification and some characteristics of the low-voltage concept examples for the three filling lines**

With the fans being installed on the transformers, a power increase for the 1,000 kVA transformers up to 1,400 kVA [4)] can be achieved in case of failure. Alternatively, as shown in concept 3.2, transformers can be used without installed fans, but with a power increase up to 1,250 kVA. In doing so, however, the maximum short-circuit currents increase compared with concept 3.1.

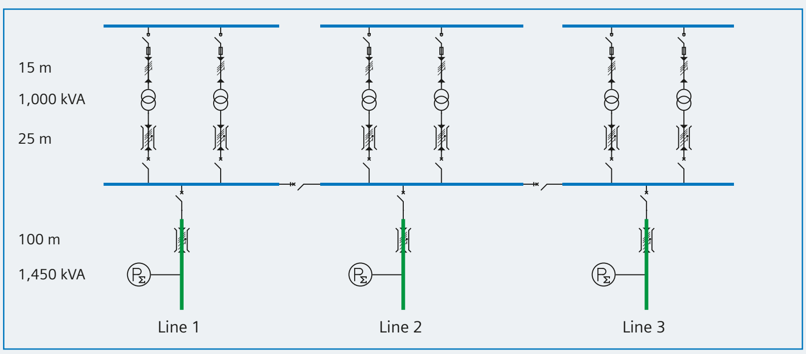
It must absolutely be observed that other values result for the concepts 3.1 and 3.2 regarding switching and protection devices, cables, and busbar trunking systems. The calculation of the short-circuit currents of the transformers is based on the rated values, regardless of fan installation. The short-circuit current to be expected is therefore independent of the power increase provided by fan installation.

Even with the limitation to the failure of only one transformer, and if a bypass busbar is used, it is not possible to do without the power increase of the transformers in the concepts 3.1 and 3.2, compared with concept 2.1. The dimensioning with SIMARIS design shows that the additional line lengths of the bypass busbar between the transformers lead to an unequal distribution of currents to the transformers, and thus three 1,000 kVA transformers no longer suffice to provide the power for two filling lines.

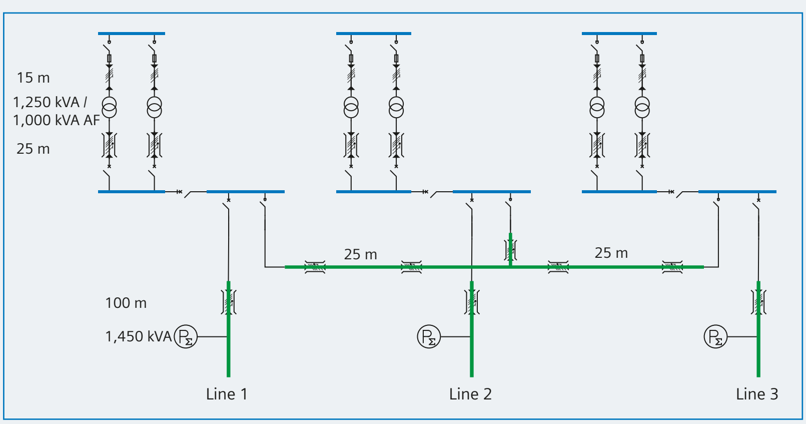
4) By means of forced ventilation, the maximum output of a transformer in failure situations can be increased by about 40 %. Besides the energy consumption for fan operation, the power losses due to the transformer increase squarely with the power increase, which must also be taken into account for room ventilation. The Windows PC tool SITRATO provides support in determining the ventilation parameters, and can be installed using the SIMARIS Suite from Siemens. It applies generally that the distribution transformers can be operated efficiently when they are utilized at 40 to 50 % capacity. It can thus easily become uneconomical when larger transformers or a redundant transformer are not used because of the installation of fans, which is especially true if the transformers are constantly highly utilized in normal operation [5.9].



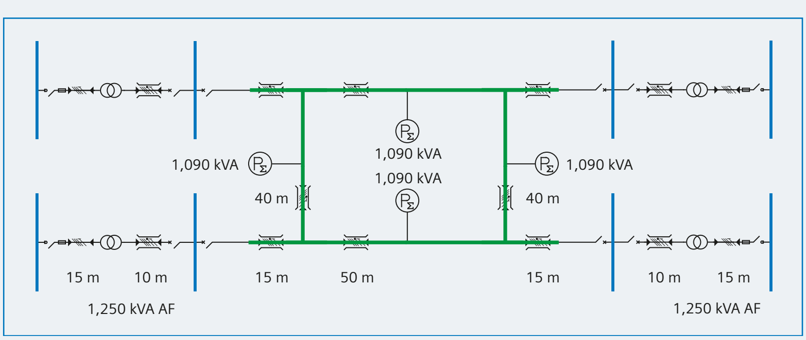
1.
Three separate infeeds and distributions via 3 switchboards with 3 × 800 kVA GEAFOL transf. each



2.1 + 2.2
Separate infeeds with 3 × 2 × 1,000 kVA GEAFOL transf., via a common low-voltage switchboard with open couplers



3.1 + 3.2
Separate infeeds with
(3.1) 3 × 2 × 1,000 kVA GEAFOL transf. with fans (AF),
(3.2) 3 × 2 × 1,250 kVA GEAFOL transf., coupled through a bypass busbar (normally open)



4.
Busbar trunking system ring with four infeeds with one 1,250 GEAFOL transf. each, with fan

Fig. 5/16: **Examples for low-voltage concepts for (n-1) supply of the three filling lines**

Contents

1

2

3

4

5

6

7

The busbar trunking system ring in concept 4 prevents a "one-sided" supply that can be interrupted in case of failure. All loads of the three filling lines are simulated by means of a simplified distribution to a busbar trunking system ring. The transformers indeed are installed individually (four substations), but are coupled among themselves from two sides through busbar trunking systems. This way, in the busbar trunking system ring it is not necessary to switch on through couplers, other than in the case of individual supply. At the same time, a compensation of the currents occurs, and the maximum short-circuit currents are determined by the quantity and power of the coupled transformers. When a transformer fails, the availability for all filling lines is achieved by increasing the transformer power by means of fan installation. When dimensioning cables and busbar trunking systems as well as switching and protection devices, the higher short-circuit currents in case of parallel connection of the transformers in normal operation must be taken into account.

Beyond these four concepts, there are innumerable other possibilities and versions. Here, only some few aspects and variations of the concepts could be briefly addressed. More exact evaluations must be undertaken project-specifically. The technical consultants of Siemens provide support in this.

Chapter 6

Concept Finding for the Electric Power Distribution of a Chemical Plant

6 Concept Finding for the Electric Power Distribution of a Chemical Plant

Other than for the beverage filling plant in Chapter 5, the example considered in here for an air separation plant (ASP) uses many powerful electric motors, which are usually supplied directly with medium voltage. Therefore, the electric power supply of low-voltage consumers is not described in detail in the sample plant.

6.1 Description of the Air Separation Process

The primary task of the ASP is gaining liquid oxygen from the ambient air. Three gas components can be extracted from the earth atmosphere, with a mass percentage of

75.5 % nitrogen (N_2) - 23.1 % oxygen (O_2) - 1.3 % argon (Ar) [1)]

Air separation according to the low-pressure process is the most common procedure for oxygen production, and it is also known as cryogenic rectification. This term characterizes essential process steps:
- "Cryogenic" characterizes the temperature reduction for liquefaction of gases
- "Rectification" means countercurrent distillation of liquefied gases.

The process is schematically shown in Fig. 6/1.

First, the air sucked in from the environment is cleaned, compressed to a pressure of about 6 bar and cooled down afterwards. The multi-step separation process uses the boiling point differences of the individual gases (O_2: -183 °C; Ar: -186 °C; N_2: -196 °C). The liquefied air is then separated in a double-column rectification system, consisting of a high-pressure column (approx. 6 bar) and a low- pressure column (approx. 1.5 bar). Pre-separation of oxygen (column sump), argon (middle section) and nitrogen (column top) takes place in the high-pressure column according to the boiling point differences. The liquefied gases are led into the low-voltage column, where still unseparated oxygen shares are largely separated. The pure liquefied gases are supplied by pipeline to large industrial customers near the production plant, or transferred to tanks for storage or transportation. For the sample plant, the following output is estimated:

- 650 tons of liquid oxygen daily
- 2,000 tons of liquid nitrogen daily
- 40 tons of liquid argon daily.

For their generation, an ASP with two parallel operating process units is designed. Since the process units are set up identically, only one line is shown in the following, as well as the additional links between the two lines. Unless stated otherwise, the data in the tables and the graphics are referred to one line.

6.2 Consumers and Requirements

Besides the industrial processes, the electric power distribution of the ASP must also consider the operational facilities, such as control rooms, staff rooms, office rooms, meeting rooms, as well as installation rooms for air conditioning, fire protection, and electronic infrastructure. In addition to the two product lines, the operational facilities are combined in four factory buildings (Fig. 6/2). Each building is supplied by a separate transformer. The block diagram of the ASP in Fig. 6/2 roughly shows the spatial conditions and does not represent a site plan with exact positions or dimensions.

For the process control room in Fig. 6/2, it is stipulated that two medium-voltage switchgear assemblies separated by a fire protection wall are connected via a sectionalizer circuit-breaker. Possible installation versions reflect the safety requirements for the separation of the two process lines:
- Functional separation: One switchgear assembly with bus sectionalizer in one room
- Fire protection separation: Two switchgear assemblies, coupled through a connection, are separated from each other by a fire protection wall / fire protection facility; close proximity
- Spatial separation: Separate installation of two (electrically interconnected) switchgear assemblies in individual rooms, which are not next to one another.

Two buildings for the control system, which are set up redundantly, must be assigned to the product lines. The load list in Tab. 6/1 combines one of these two buildings with the consumers of one of the two production trains.

1) Note: Volume percentage: 78 % nitrogen (N_2) - 21 % oxygen (O_2) - 1 % argon (Ar)

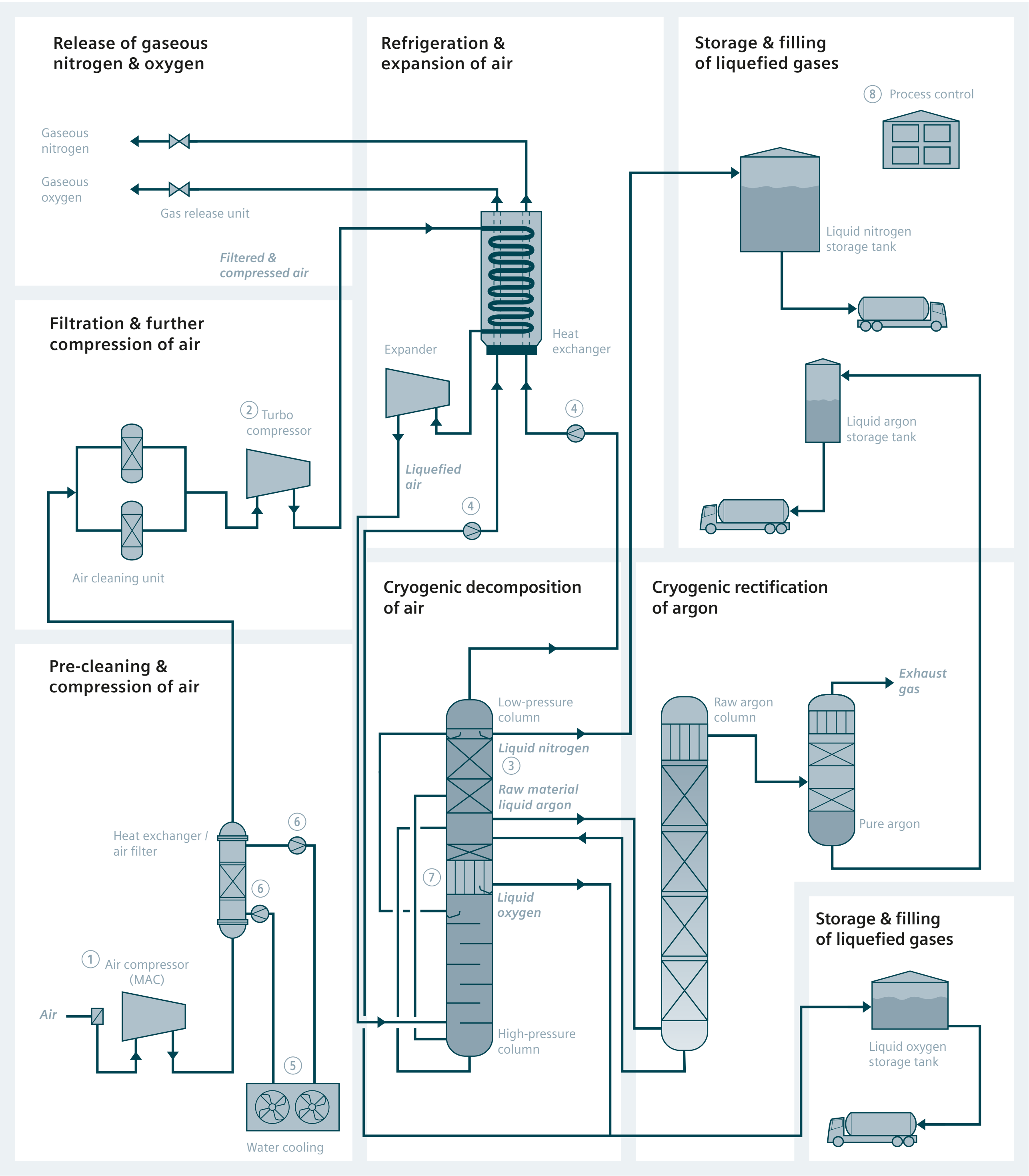


Fig. 6/1: **Schematic process representation of air separation** (the numbers 1 to 8 of the components identify the assignment for **Tab. 6/1**)

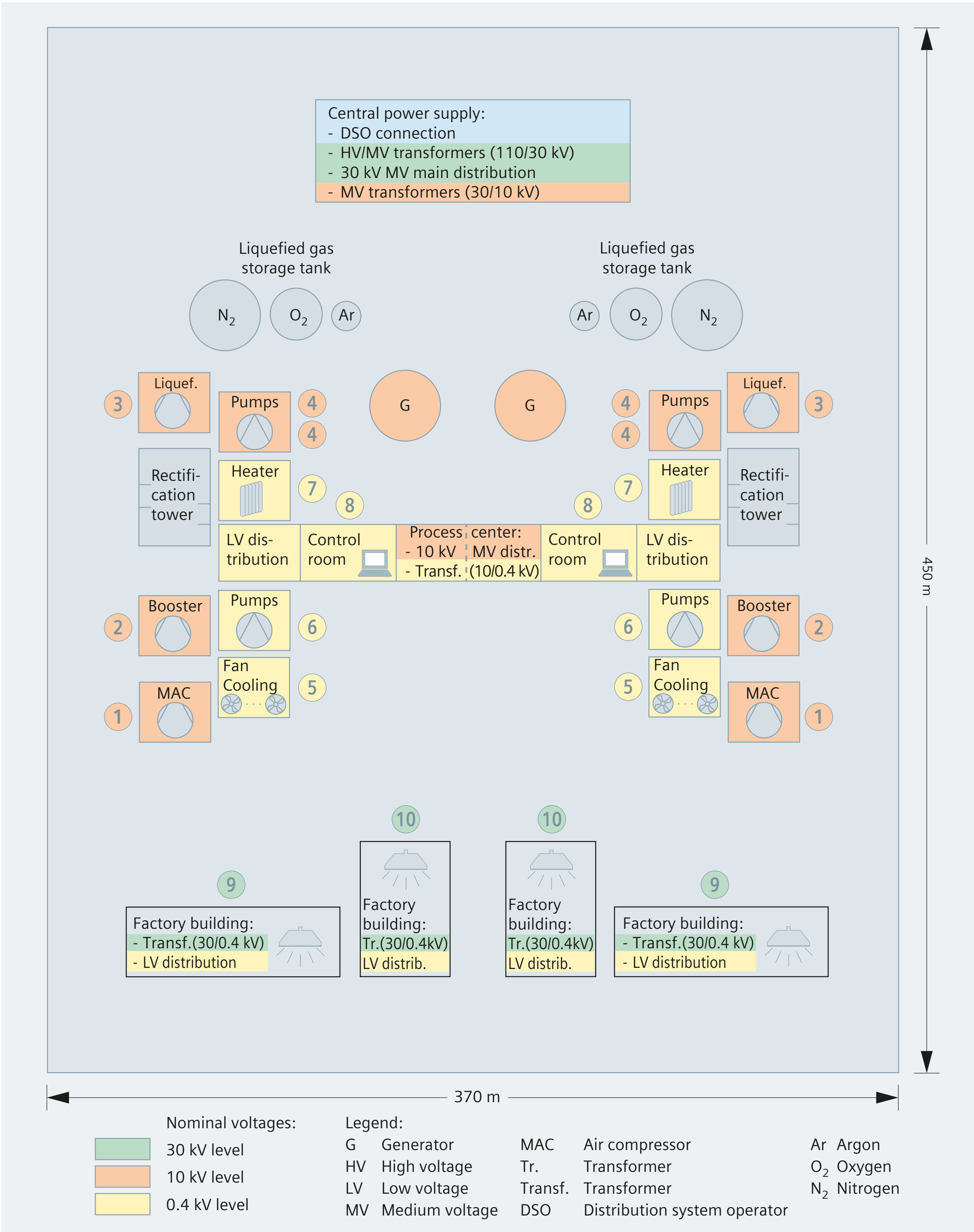


Fig. 6/2: **Block diagram for the ASP ground sketch** (numbers correspond to the identification in **Fig. 6/1** and **Tab. 6/1**)

No.	Quantity	Description	Load type	Voltage	Active power	Total apparent power	Current	Starter
1	1	Air compressor (MAC)	Motor 1)	10 kV	11,200 kW	13,397.10 kVA	773.50 A	VFD 3)
2	1	Turbo compressor (booster)	Motor 1)	10 kV	5,800 kW	6,937.80 kVA	400.60 A	VFD 3)
3	1	Liquefaction	Motor 1)	10 kV	4,840 kW	5,789.50 kVA	334.30 A	Soft
4	2	Pump	Motor 1)	10 kV	2 × 300 kW	717.70 kVA	41.44 A	Direct
5	11	Fan for cooling	Motor 1)	0.4 kV	11 × 40 kW	526.30 kVA	759.70 A	VFD 3)
6	2	Cooling water pump	Motor 1)	0.4 kV	2 × 175 kW	418.70 kVA	604.30 A	VFD 3)
7	4	Electric process heater	Resistive load 2)	0.4 kV	4 × 287 kW	1,148.00 kVA	1,657.00 A	-
8	1	Process control	Others 2)	0.4 kV	200 kW	227.30 kVA	328.05 A	-
9	1	Factory building 1.1	Others 2)	0.4 kV		2 MVA		-
10	1	Factory building 1.2	Others 2)	0.4 kV		1.6 MVA		-

1) The mechanical power of the motors is specified. The following applies: cos φ = 0.88 and efficiency η = 0.95
2) Resistive load: cos φ = 1; other loads: cos φ = 0.88
3) VFD starter without feedback

Tab. 6/1: **Consumer list for a single product line and two of the four factory buildings as starting point for the electric power distribution concept of the ASP**

In addition, the following has to be observed when designing the electric power distribution:

- International design of the basic concept according to IEC standards
- The two trains of the ASP can be operated separately from each other; the electric power supply shall accordingly be set up separately
- In case of a failure of one of the two grid infeeds, the remaining infeed must be able to continue supplying the two process lines including the factory buildings without restrictions
- The process loads on the low-voltage side must be able to continue to operate also in case of maintenance work or a power failure at the transformer
- In case of a power failure of the associated infeed, the power supply of the control cabinets and the operator interfaces (HMI) of an ASP train must remain in operation
- As embedded generating plants, a generator with an apparent power of 16 MVA shall be planned for each of the two process lines. In case of a failure of the DSO infeed, each of the two generators can supply the process consumers of the 0.4 kV level (5, 6, 7, 8) of both lines
- Two infeeds from the high-voltage grid (nominal system voltage 110/220 kV) are assumed as linkage to the power supply
- The simultaneity factors (sf) for the loads are estimated with the typical values for industrial plants:
  sf (medium-voltage motor) = 0.9
  sf (low-voltage load) = 0.75
- For future extensions / power increases, a reserve of at least 20 % has to be provided for the transformers
- In order to ensure the power quality of the network (total voltage drop < 10 %) and a reliable motor start, the voltage drop for the motor start is to be limited to approximately 25 % (at the motor terminals).

On the basis of a power demand estimation by means of the building surfaces and taking into account the critical loads in the buildings, two transformers (30 kV/0.4 kV) each with a rating of 1.6 MV and 2 MVA (connections 9 and 10 in Tab. 6/1) are considered when designing the medium-voltage distribution, as stipulation for the four factory buildings in Fig. 6/2.

For rating the apparent power demand of the entire plant ($S_{r,ASP}$), the apparent power data of the consumers 1 to 8 from Tab. 6/1 are multiplied with the associated simultaneity factor sf (for consumers 1 to 4, sf = 0.9, and for consumers 5 to 8, sf = 0.75), and are summed up afterwards. This sum of the loads is supplemented with a reserve of 20 %. For this, the rated apparent power of the two transformers for the supply of the factory buildings 9 and 10 is added, and finally the resulting sum total is doubled (for two process lines):

$$S_{r,ASP} = [(\Sigma S_{10\,kV} \cdot 0.9 + \Sigma S_{0.4\,kV} \cdot 0.75) \cdot 1.20 + \Sigma S_{Factory\ building}] \cdot 2 = [(26.84\ MVA \cdot 0.9 + 2.32\ MVA \cdot 0.75) \cdot 1.20 + 3.6\ MVA] \cdot 2 = 69.4\ MVA$$

6.3 Network Layout and Basic Concept Parameters

According to the decision diagram in Fig. 4/3, a connection to the high-voltage grid should be aimed at, preferably at the 110 kV level of the distribution system operator (DSO), with in-house feeding transformers. In case of an infeed from the high-voltage grid, the voltage of the distribution level can be freely selected.
For economic reasons, a higher voltage is desirable when using several large motors. On the one hand, the influence of the motor starting currents on the voltage stability at the point of connection is reduced in this way. On the other hand, lower normal currents stand for a more cost-effective design of the switchgear outgoing feeders. The following nominal voltage levels are taken into account in the design:

- 110 kV grid infeed
- 30 kV distribution level
- 10 kV consumer/process level for individual ratings greater than 250 kW
- 0.4 kV consumer/process level for individual ratings with a maximum of 250 kW.

i) **Network configuration**
The following criteria matter when selecting the network configuration:
- Continuous operation of both process lines (even if one of the two grid infeeds fails)
- Selective shutdown in case of fault
- Simple network monitoring and network control
- Optimization of expenses regarding the protection system.

The following features of the process level also exert an influence on the selection of the network configuration:
- Relatively short distances between medium-voltage consumers (< 500 m; see Fig. 6/2)
- Requirements on the power quality
- Number and physical location of the load centers
- Short switching interruptions are permissible for the work processes (control rooms, automation and similar must of course be protected without interruptions).

The comparison of the network types in Tab. 4/1 makes clear that the double radial line network offers the most advantages due to the mentioned boundary conditions.

ii) **Neutral earthing at the medium-voltage level**
The type of neutral earthing [1.2] can also be selected in coordination with the distribution system operator in accordance with the grid infeed from the high-voltage level and the in-house 110/30 kV transformers. In the industrial power supply, the low-impedance neutral earthing has proven itself, since no great risk is expected by too high touch voltages during operation of an impedance-earthed neutral if the short-circuit-to-earth current I''_{k1} is limited to values below 2,000 A. The limitation of the short-circuit-to-earth current is additionally important to restrict the impact on the voltage of the low-voltage network in case of short circuit (e.g. voltage band -10 % $\leq \Delta U / U_{nN} \leq$ +10 %). For the 30 kV level, low-impedance neutral earthing is selected with a limitation of the short-circuit-to-earth current I''_{k1} to 1,000 A [1.2].

For neutral earthing of the 10 kV process level, the medium-voltage motors have to be paid attention to. In order to avoid core burning, the single-phase short-circuit current must be limited to values lower than 200 A [1.2]. Fault clearance must then occur without time delay.

iii) **Transformers for the 10 kV intermediate substation of the process loads**
A 10 kV switchgear each is provided for supplying the two process lines, whereby a sectionalizer (open in normal operation) ensures the connection between the two lines. However, in case of failure with closed sectionalizer, the two 30/10 kV infeed transformers must be sufficient for the total load of the two lines. Consequently, the rated apparent power of the two transformers must be at least 63 MVA each.

iv) **Transformers for the low-voltage process level**
The loads of the 0.4 kV-process level are supplied by two transformers of 1.6 and 1 MVA on each line. The transformers as well as the associated low-voltage switchboards are installed near the loads, but they are spatially separated from the 10 kV substations for the medium-voltage consumers.

v) **Transformers of the 30 kV level**
Apart from the two transformers for the supply of the 10 kV process level, two 30/0.4 kV transformers of 1.6 MVA and 2 MVA are provided on each line at the 30 kV level to supply the factory buildings.

vi) **Transformers for the infeed level**
Since each infeed should be sufficient to supply the two process lines and all of the four factory buildings ($S_{n,ASP}$ = 69.4 MVA), 110/30 kV infeed transformers with a rated apparent power of 80 MVA each are selected.

vii) **Operating modes**
To create a distribution concept, the following operating modes are considered:
- Normal operation:
  - Both grid infeeds are in operation
  - The two process lines are supplied and operated separately from each other
  - The two factory buildings (9, 10) are supplied by in-house transformers of the 30 kV voltage level
  - One generator each with a rating of 16 MW can feed into the 10 kV voltage level separately for each process line
- Failure operation with only one infeed
  - The grid infeed ready for operation supplies the two process lines and all of the factory buildings
  - One generator each with a rating of 16 MW feeds into the 10 kV voltage level separately for each process line
- Failure operation without public supply
  - The two generators are operated separately from each other (no parallel operation)
  - The consumers of the 10 kV and 30 kV voltage level are not supplied
  - The generators supply the loads of the 0.4 kV level [2)]
- Failure operation for the low-voltage process consumers in case of a failure on a connection between the central 10 kV process distribution and the process-line-specific 10 kV sub-distribution board
  - The direct connection to the process infeed is interrupted
  - Consumers are supplied through the power distribution of the second process line.

viii) **Single-line diagram for the power distribution concept**
Based on the data, positionings and assignments made before, a first draft of a power distribution structure can be created; however, the more detailed dimensioning and specification of individual components follow later. In the case of the single-line diagram in Fig. 6/3, the medium-voltage consumers of the two process lines are supplied through a medium-voltage switchgear with sectionalizer. For the low-voltage process consumers, separate substations with medium-voltage switchgear, transformer, and low-voltage switchboard are installed, so that the line lengths of the low-voltage system remain below 100 m (see Chapter 4). Cross-connection between the two switchgear sections at the 10 kV level for the supply of the low-voltage process consumers ensures redundancy in case of failure on the supply line belonging to the process line of the 10 kV medium-voltage switchgear in the process control room.

6.4 Design of the Medium-Voltage Switchgear

Based on the single-line diagram in Fig. 6/3, the suitable medium-voltage switchgear assemblies are selected. For this, the ratings of the operational equipment for the eligible switchgear types [1.2] must be compared with the expected loads. The following requirements are to be clarified:
- Rated voltage $U_r \geq$ nominal system voltage U_n
- Rated current of the busbar and the feeders $I_r \geq$ maximum expected normal current I_b
- Rated short-circuit breaking current $I_{sc} \geq$ initial symmetrical short-circuit current I''_k
- Rated short-circuit making current $I_{ma} \geq 2.5 \cdot I''_k$ (the factor 2.5 is set for peak withstand currents according to IEC 62271-1 [3)]).

A precondition for determining the above-mentioned ratings of the medium-voltage switchgear is the calculation of the initial symmetrical short-circuit currents I''_k for the different short-circuit events. For this, the impedances of transformers, generators and motors are calculated and concatenated as described in IEC 60909-0.

2) Since one of the generators is sufficient to supply the low-voltage consumers of both lines, a redundant supply is ensured.

3) Note: The factor 2.5 (for 50 Hz grids; for 60 Hz grids, factor 2.6) is set for determining the rated peak withstand currents of a medium-voltage switchgear tested according to the series of standards IEC 62271 (peak factors of the rated short-circuit making current are to be selected according to IEC 62271-100).
The initial symmetrical short-circuit current as well as the peak short-circuit-current at the respective mounting location of the switchgear are calculated according to IEC 60909-0.

In Tab. 6/2, the formulas for the individual components and for the concatenations in case of series and parallel connection of the components are stated. The use of the formulas is shown more clearly with the sample calculations for short-circuit events at the 30 kV level and at the 10 kV level.

Motors with a variable frequency drive (VFD) without feedback (braking operation) as motor starter can be neglected in the calculations according to IEC 60909-0. For the following calculations, the worst case is considered. For selecting the switchgear of the 30 kV level and the 10 kV level, the maximum short-circuit currents at both voltage levels must be determined.

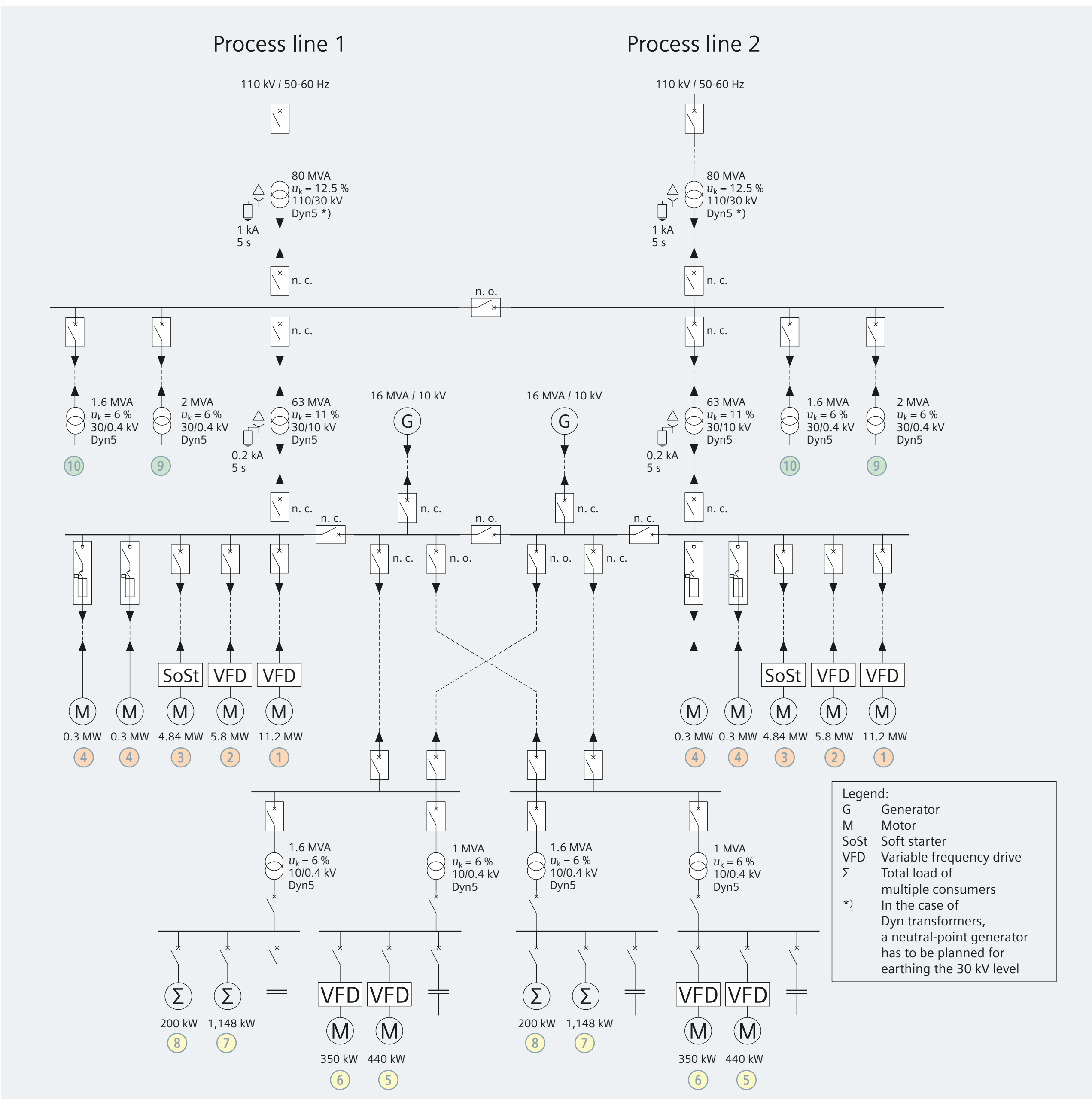


Fig. 6/3: **Single-line diagram for the ASP power supply concept** (the numbers 1 to 10 comply with the identification in **Fig. 6/1** and **Tab. 6/1**)

	Motor	Generator [1]	Transformer [2]
Impedance Z	$Z_M = \dfrac{U_{rM}^2 \cos\varphi \cdot \eta}{s_M \cdot P_{rM}}$	$Z_G = \dfrac{U_{rG}^2 \cdot x''_d}{S_{rG}}$	$Z_T = \dfrac{u_{kr} \cdot U^2_{rT}}{S_{rT}}$
Initial short-circuit current I''_k	$I''_k = \dfrac{c \cdot U_n}{\sqrt{3} \cdot Z_K}$		
Associated values	c — Voltage factor (according to IEC 60909-0, the following applies: c = 1.10 for maximum short-circuit currents and high voltage greater than 1 kV) U_n — Nominal voltage cos φ — Power factor η — Efficiency s_M — Motor starting factor $s_M = I_{sM} / I_{rM}$ (see Chapter 4.3) P_{rM} — Rated active power of the motor U_{rM} — Rated voltage of the motor x''_d — Subtransient generator reactance in percent (100 % = 1) S_{rG} — Rated apparent power of the generator U_{rG} — Rated voltage of the generator u_{kr} — Short-circuit impedance of the transformer in percent (100 % = 1) S_{rT} — Rated apparent power of the transformer U_{rT} — Rated voltage of the transformer		
	Parallel connection	**Series connection**	**Transformer ratio**
Calculation steps	$\dfrac{1}{Z_{tot}} = \dfrac{1}{Z_1} + \dfrac{1}{Z_2} + \ldots + \dfrac{1}{Z_n}$	$Z_1 + Z_2 + \ldots + Z_n = Z_{tot}$	Ratio $t_r = U_{prim} / U_{sec}$ $Z_2 = Z_1 \cdot t_r^2$

[1] For direct connection of a generator, a correction factor is stated in IEC 60909-0 for the calculation of Z_G: $Z_{GK} = Z_G \cdot K_G$ with $K_G = (U_n / U_{rG}) \cdot [c / (1 + x''_d \cdot \sqrt{1 - \cos^2 \varphi_{rG}})]$; whereby U_n = nominal system voltage, U_{rG} = rated generator voltage, $\cos \varphi_{rG}$ = rated power factor of the generator at rated operation; here, $K_G = 1$ is set for concept finding

[2] In IEC 60909-0, a correction factor for the calculation of Z_T is stated for two-winding transformers: $Z_{TK} = Z_T \cdot K_T$ with $K_T = 0.95 \cdot c / (1 + 0.95 \cdot x_T)$; whereby x_T = relative reactance of the transformer; here, $K_T = 1$ is set for concept finding

Tab. 6/2: **Formulas for initial short-circuit currents and impedances of transformers, generators, and motors feeding back, as well as their interconnection in distribution concepts**

6.4.1 Short-Circuit Current Calculation for a Short Circuit at the 30 kV Level

Based on the design of Fig. 6/4, a short circuit is assumed in one of the 30 kV supply lines to the factory buildings (e.g. to the transformer for building ⑨ in Fig. 6/3). The worst case that only one infeed supplies both process lines is assumed, and that the sectionalizer in the 30 kV switchgear is closed. In this case, not only the grid infeed through the 80 MVA transformer contributes to the short circuit, but also the two generators and the motor consumers at the 10 kV level.

For the short-circuit calculation, it is easier to calculate with the impedances, as described in Tab. 6/2.
To illustrate the calculations with the component impedances, Tab. 6/3 shows the input variables for the calculations, a simple equivalent diagram, as well as the individual partial steps. To determine the motor starting currents, a typical value of $s_M = 6$ is set for the starting factor [6.1]. This value must also be set for the soft starter, as it has to be assumed that the motor has switched over to direct operation after the start and that the soft starter is therefore bridged when a short circuit occurs, so that there will be a direct feedback through the line.

The calculated initial symmetrical short-circuit current $I''_{k\,tot}$(30kV) of 19.2 kA is a maximum, as both process lines are supplied through one infeed transformer (in case of a short circuit in normal operation, the contributions of the motors and the generator from the second line would not feed back. In this case, $I''_{k\,tot}$(30 kV) is 16.4 kA).

With the formula for the initial symmetrical short-circuit current according to IEC 60909-0, the following results for the calculation with the impedances:

$$I''_{k\,tot}(30\text{ kV}) = \frac{c \cdot U_n}{\sqrt{3} \cdot Z_{tot}(30\text{ kV})} = 19.2\text{ kA}$$

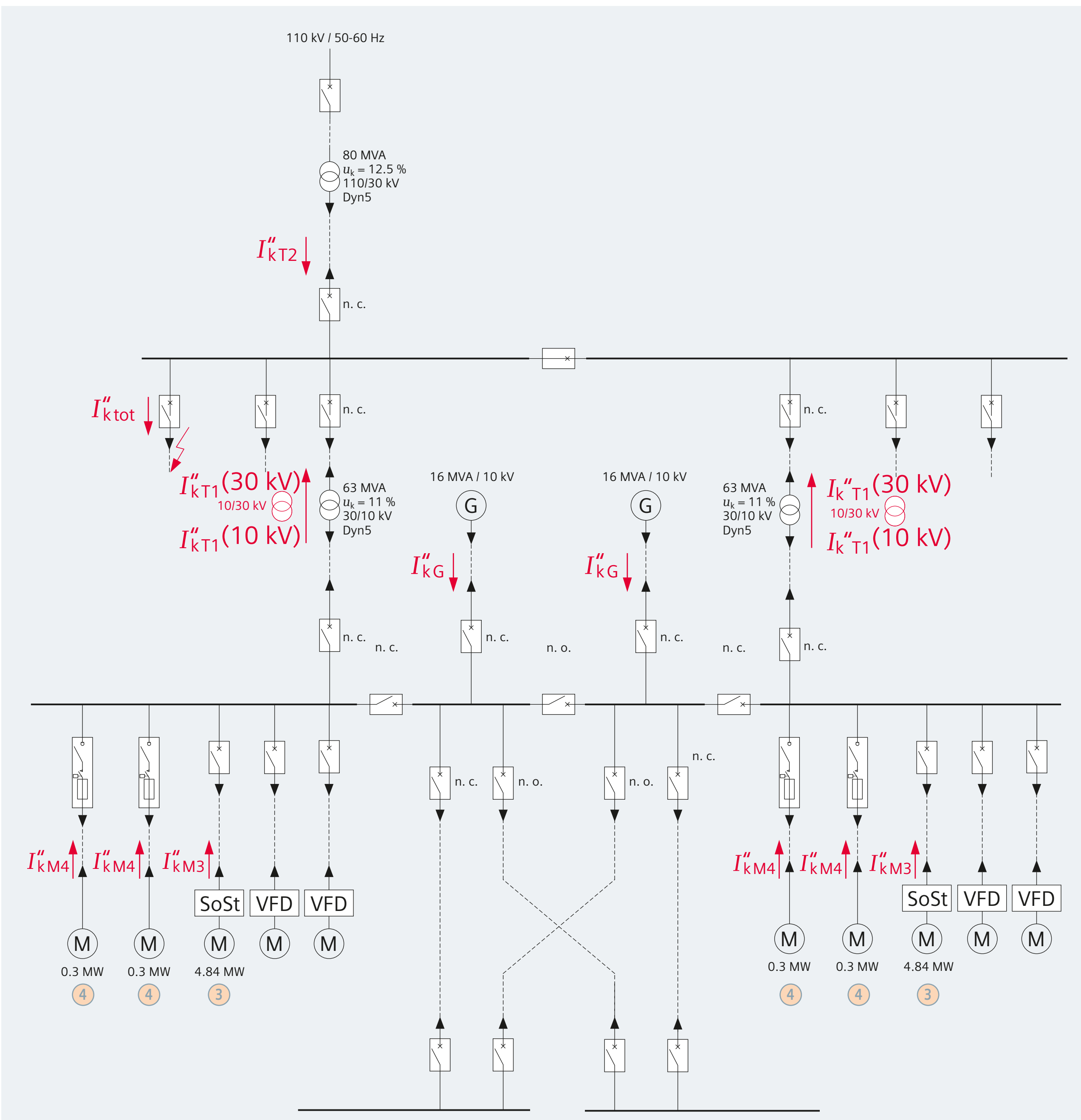


Fig. 6/4: **Simple single-line diagram for illustration of the short-circuit situation at the 30 kV level**

Contents
1
2
3
4
5
6
7

Parameters	Motor M4	Motor M4	Motor M3	Generator G	Transformer T1	Transformer T2
Voltage factor c	1.1	1.1	1.1	1.1	1.1	1.1
Rated voltage U_r	10 kV	10 kV	10 kV	10 kV	30 / 10 kV	110 / 30 kV
Efficiency η	0.95	0.95	0.95			
Power factor cos φ	0.88	0.88	0.88			
Motor starting factor s_M	6	6	6			
Active power P_r	300 kW	300 kW	4,840 kW			
Rated apparent power S_r				16 MVA	63 MVA	80 MVA
Subtransient generator reactance x''_d				11.9 %		
Short-circuit impedance of the transformer u_{kr}					11 %	12.5 %
Transformer ratio t_r					3	3

Short-circuit current calculation through concatenation of impedances	
Step 1	Impedances of the loads at the 10 kV level: $Z_{M3} = (10\text{ kV})^2 \cdot 0.88 \cdot 0.95 / (6 \cdot 300\text{ kW}) = 46.44\ \Omega$ $Z_{M4} = (10\text{ kV})^2 \cdot 0.88 \cdot 0.95 / (6 \cdot 4{,}840\text{ kW}) = 2.879\ \Omega$ $Z_G = (10\text{ kV})^2 \cdot 0.119 / 16\text{ MVA} = 0.7438\ \Omega$
Step 2	Impedances of the loads at the 30 kV level: $Z'_{M3} = Z_{M3}(30\text{ kV}) = 46.44\ \Omega \cdot 9 = 418.0\ \Omega$ $Z'_{M4} = Z_{M4}(30\text{ kV}) = 2.879\ \Omega \cdot 9 = 25.91\ \Omega$ $Z'_G = Z_G(30\text{ kV}) = 0.7438\ \Omega \cdot 9 = 6.694\ \Omega$
Step 3	Impedances of the transformers at the 30 kV level: $Z'_{T1} = 0.11 \cdot (30\text{ kV})^2 / 63\text{ MVA} = 1.571\ \Omega$ $Z'_{T2} = 0.125 \cdot (30\text{ kV})^2 / 80\text{ MVA} = 1.406\ \Omega$
Step 4	Concatenation of individual impedances for total impedance Z_{tot}: $Z_{tot} = \dfrac{1}{\dfrac{2}{\dfrac{1}{\dfrac{1}{25.91\ \Omega} + \dfrac{2}{418.0\ \Omega} + \dfrac{1}{6.694\ \Omega}} + 1.571\ \Omega} + \dfrac{1}{1.406\ \Omega}} =$ $= 0.9930\ \Omega$
Step 5	Short-circuit current determination with Z_{tot} at the 30 kV level: $I''_k = 1.1 \cdot 30\text{ kV} / (1.732 \cdot 0.9930\ \Omega) = 19.2\text{ kA}$

Equivalent diagram

Step 5

$$I''_k = \frac{c \cdot U_n}{\sqrt{3} \cdot Z_{tot}}$$

Step 4

$$Z_{tot} = \frac{1}{\dfrac{2}{\dfrac{1}{\dfrac{1}{Z'_{M3}} + \dfrac{2}{Z'_{M4}} + \dfrac{1}{Z'_G}} + Z'_{T1}} + \dfrac{1}{Z'_{T2}}}$$

Step 3

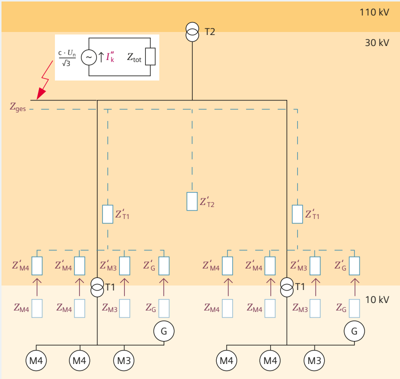
$$Z'_{Tx} = \frac{u_{kr} \cdot U^2_{rTx}}{S_{rTx}}$$

Step 2

$$Z'_x = Z_x \cdot t_r^2$$

Step 1

$$Z_x = \frac{U_n^2 \cdot \cos\varphi \cdot \eta}{s \cdot P_r}$$



Tab. 6/3: **Short-circuit current and impedance calculations as well as equivalent diagram for illustration of a short circuit at the 30 kV level of the ASP**

6.4.2 Short-Circuit Current Calculation for a Short Circuit at the 10 kV Level

Based on the design of Fig. 6/3 (normal operation, sectionalizer at 30 kV level open), a short circuit is assumed in one of the 10 kV supply lines to one of the switchgear assemblies for the low-voltage process supply (Fig. 6/5).

For the total impedance, the shares from the infeed via the transformers T1 and T2 and that from the feedback of the three motors M3 and M4 as well as of the generator G must be considered. The impedances for M3, M4 and G have already been calculated for the 10 kV level. Only the values Z'_{T1} and Z'_{T2} must be converted with the ratio factor $t_r = 30\text{ kV}/10\text{ kV}$ to Z_{T1} and Z_{T2}. After that, the concatenation at the 10 kV level can be calculated. On the following page, Tab. 6/4 shows the equivalent diagram, the data taken from Tab. 6/3, and the associated calculations.

The formula for the initial symmetrical short-circuit current according to IEC 60909-0 results in:

$$I''_{k\,tot}(10\text{ kV}) = \frac{c \cdot U_n}{\sqrt{3} \cdot Z_{tot}(10\text{ kV})} = 30.2\text{ kA}$$

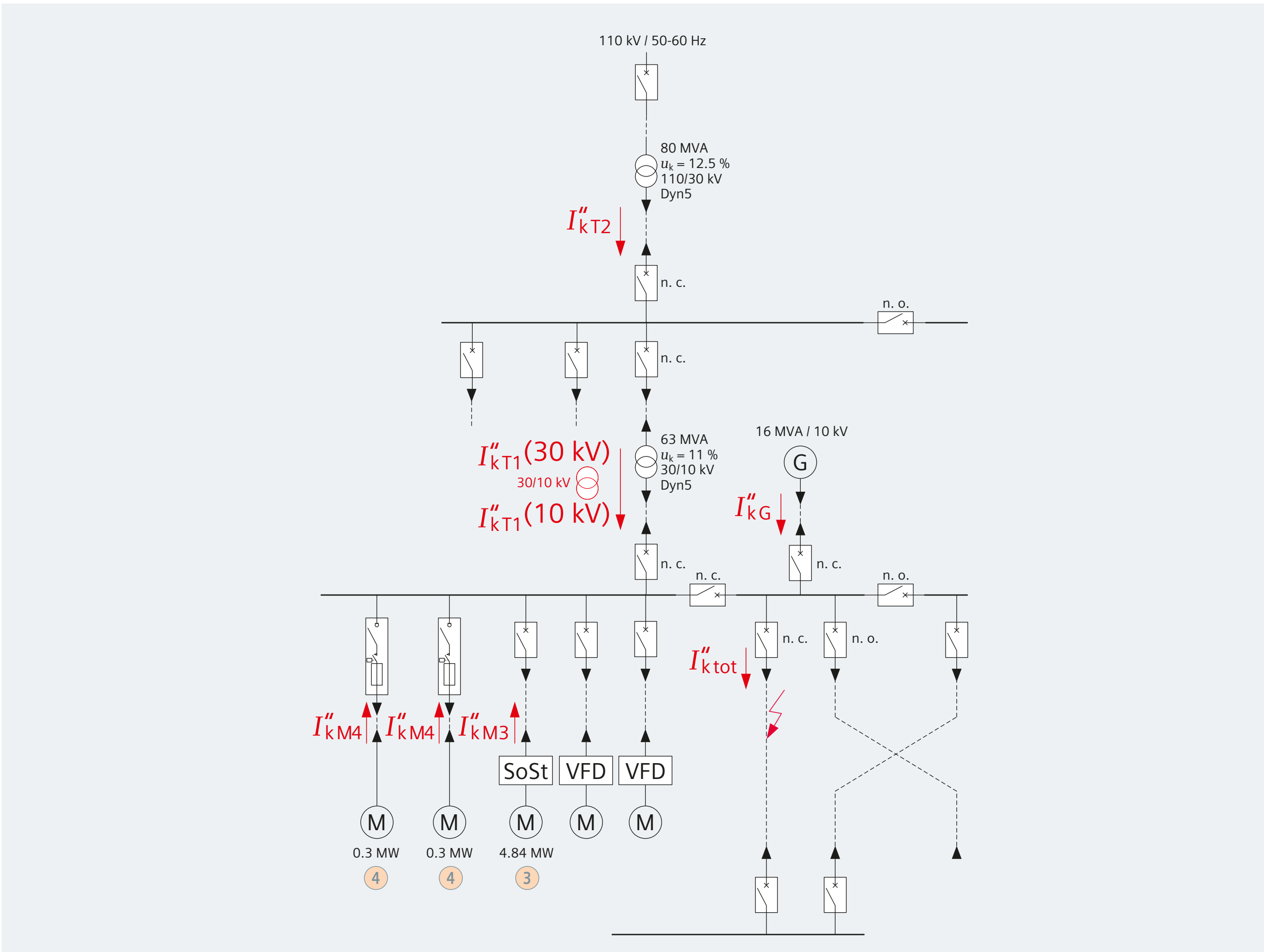
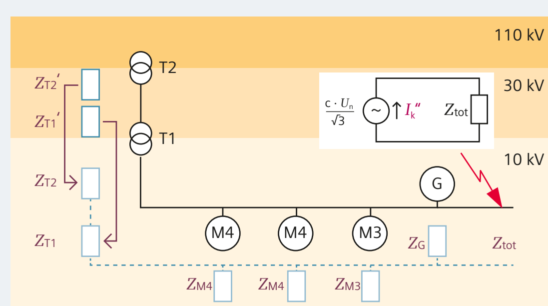


Fig. 6/5: **Simple single-line diagram for illustration of the short-circuit situation at the 10 kV level**

Short-circuit current calculation through concatenation of impedances		**Equivalent diagram**
Step 1	Impedances of the transformers at the 10 kV level: $Z_{T1} = Z'_{T1} / t^2_r = 1.571\ \Omega / 9 = 0.1746\ \Omega$ $Z_{T2} = Z'_{T2} / t^2_r = 1.406\ \Omega / 9 = 0.1562\ \Omega$	
From Tab. 6/3	Impedances of the loads at the 10 kV level: Z_{M3} = (10 kV)^2 · 0.88 · 0.95 / (6 · 4,840 kW) = 2.879 Ω Z_{M4} = (10 kV)^2 · 0.88 · 0.95 / (6 · 300 kW) = 46.44 Ω Z_G = (10 kV)^2 · 0.119 / 16,000 MVA = 0.7438 Ω	Step 1 $Z_{Tx} = Z_{Tx}' / t_r^2$
Step 2	Total impedance: Z_{tot}(10 kV) = $= 1 / [1 / Z_{M3} + 2 / Z_{M4} + 1 / Z_G + 1 / (Z_{T1} + Z_{T2})] = 0.2102\ \Omega$	Step 2 $Z_{tot} = \frac{1}{\frac{1}{Z_{M3}} + \frac{2}{Z_{M4}} + \frac{1}{Z_G} + \frac{1}{Z_{T1} + Z_{T2}}}$
Short-circuit current	I''_k(10 kV) = 1.1 · 10 kV / (1.732 · 0.2102 Ω) = 30.2 kA	Step 3 $I''_k = \frac{c \cdot U_n}{\sqrt{3} \cdot Z_{tot}}$

Tab. 6/4: **Short-circuit current and impedance calculations as well as equivalent diagram for illustration of the short-circuit current calculation for a short-circuit at the 10 kV level of the ASP**

6.4.3 Selection of the Medium-Voltage Switchgear Types

The basis for switchgear selection are the rated voltage and the rated current of the feeding transformers, as well as the short-circuit currents resulting from the previous sections. From the overviews of possible switchgear types in Tab. 6/5 and Tab. 6/6, as well as from the parameters relevant for selection, a switchgear with the matching design values is then selected.

i) Conditions for the design values and selection of the switchgear at the 30 kV level:

$U_r \geq 30$ kV

$I_r(30 \text{ kV}) \geq S_{rT2} / (\sqrt{3} \cdot U_r) =$
80 MVA / ($\sqrt{3} \cdot 30$ kV) = 1,540 A

With $I''_{k\,tot}(30 \text{ kV}) = 19.2$ kA follows

$I_{sc} \geq 19.2$ kA

$I_{ma} \geq 2.5 \cdot 19.2 \text{ kA} = 48$ kA

Therefore, the types NXPLUS and 8DA or 8DB can be selected from Tab. 6/5. For the 30 kV distribution level of the ASP, the type 8DA is selected. Due to the hermetic enclosure, the 8DA can be used independently from the site altitude, and it is especially safe for operation and suitable for use in aggressive ambient conditions thanks to the single-phase metal-enclosed busbar layout.

Technical data of the 8DA switchgear used:

Busbar system:	Single busbar
Rated voltage:	36 kV
Operating voltage:	30 kV
Rated normal current:	2,000 A
Rated short-time withstand current:	25/3 kA/s

ii) Conditions for the design values and selection of the switchgear at the 10 kV level:

$U_r \geq 10$ kV

$I_r(10 \text{ kV}) \geq S_{rT1} / (\sqrt{3} \cdot U_r) =$
63 MVA / ($\sqrt{3} \cdot 10$ kV) = 3,637 A

$I''_{k\,tot}(10 \text{ kV}) = 30.2$ kA results in

$I_{sc} \geq 30.2$ kA

$I_{ma} \geq 2.5 \cdot 30.2 \text{ kA} = 75.6$ kA

For the medium-voltage switchgear of the 10 kV level, it has additionally to be observed that, independently from the project-specific boundary conditions, different starter combinations are required for the various motor starter types (Tab. 6/5):

- Direct-on-line starter (motor M4)
  - Vacuum circuit-breaker
  - Vacuum circuit-breaker and vacuum contactor
  - Switch-disconnector with HV HRC fuses (maximum 250 A) and vacuum contactor
- Soft starter (motor M3)
  - Vacuum circuit-breaker and vacuum contactor
- Frequency converter (motor M1 and M2)
  - Vacuum circuit-breaker in combination with the converter (e.g. SINAMICS).

According to the selection table Tab. 6/5, only the NXAIR remains as switchgear type for the 10 kV distribution level. The NXAIR with a rated short-circuit breaking current of 40 kV is selected for the ASP.
Apart from the flexibility of the feeder selection for motorized consumers and a good suitability for installation near the chemical processes, air insulation and the high reliability of the well-proven switchgear also play an important part when selecting the NXAIR.

iii) At the 10 kV level, the switchgear type NXPLUS C is used for supplying the two transformers of the 0.4 kV process level. This switchgear type stands out for its robustness, modularity and flexibility in case of operational extensions.

6.5 Dimensioning the Medium-Voltage Motor Feeders

As already stated in the consumer list in Tab. 6/1, the mechanical performance, rated voltage, efficiency, and the power factor are important data for dimensioning the motor feeders in the medium-voltage switchgear. Apart from this motor data, the following information is additionally required:

- Data of the feeding transformer, such as for example primary and secondary voltage, apparent power, and short-circuit impedance
- Short-circuit power of the feeding grid
- Starting current and starting frequency of the motors
- Permissible voltage drop at the busbars during motor start (typically 5 % as a maximum).

Consumer / feeder	Protection function	Switching function	Rated voltage	Rated short-circuit breaking current	Rated current of busbar	Rated current of feeders	Siemens switchgear type [1]	Typical applications
General medium-voltage consumers	Vacuum circuit-breaker (IEC 62271-100)	Directly to consumer (switching only via circuit-breaker)	12 kV	20 kA / 1 s	630 A	630 A	8DJH 12 blue GIS	Medium-voltage switchgear for primary and secondary distri-bution, as well as medium-voltage Motor Control Centers (MCC); motor feeders: soft starter or frequency converter in separate housing
				25 kA / 1 s	630 A	630 A	8DJH	
					1,250 A	1,250 A	SIMOSEC	
					2,000 A	2,000 A	NXAIR C	
				31.5 kA / 1 s	2,500 A	2,500 A	NXPLUS C / NXPLUS	
				40 kA / 1 s	5,000 A	3,150 A	8DA/B	
				50 kA / 1 s	4,000 A	4,000 A	NXAIR	
			24 kV	20 kA / 1 s	630 A	630 A	8DJH	
				25 kA / 1 s	1,250 A	1,250 A	SIMOSEC	
					2,000 A	2,000 A	NXAIR C	
					2,500 A	2,500 A	NXPLUS C / NXAIR M	
				31.5 kA / 1 s	2,500 A	2,500 A	NXPLUS	
				40 kA / 1 s	5,000 A	3,150 A	8DA/B	
			36 kV	25 kA / 1 s	630 A	630 A	8DJH 36	
					1,250 A	1,250 A	NXPLUS C	
				31.5 kA / 1 s	2,500 A	2,500 A	NXPLUS	
				40 kA / 1 s	5,000 A	3,150 A	8DA/B	
	Switch-disconnector with HV HRC fuses (IEC 62271-105)	Directly to the transf. via the SDC, without contactor	12 kV	25 kA / 1 s	630 A	200 A [2]	8DJH	Transformers
					1,250 A	200 A [2]	SIMOSEC	
					2,000 A	200 A [2]	NXAIR C	
				31.5 kA / 1 s	2,500 A	200 A [2]	NXPLUS C	
					4,000 A	200 A [2]	NXAIR	
			24 kV	20 kA / 1 s	630 A	200 A [2]	8DJH	
				25 kA / 1 s	1,250 A	200 A [2]	SIMOSEC	
					2,000 A	200 A [2]	NXAIR C	
					2,500 A	200 A [2]	NXPLUS C / NXAIR M	
			36 kV	20 kA / 1 s	630 A	200 A [2]	8DJH36	
		With vacuum contactor [2]	12 kV	31.5 kA / 1 s	2,500 A	450 A [2]	NXPLUS C	- Medium-voltage motors - Compensation systems
				50 kA / 1 s	4,000 A	400 A [2]	NXAIR	
			24 kV	25 kA / 1 s	2,500 A	450 A [2]	NXPLUS C	

[1] The switchgear from Siemens meet the safety integrity level SIL 2 according to IEC 61508-1 (corresponds to the performance level PL = d according to ISO 13849-1)

[2] The maximum permissible rated current depends on the HV HRC fuse used

Tab. 6/5: **Selection table of medium-voltage switchgear for general consumers**

At first, it is checked whether the type of motor start (direct-on-line start, soft start, or frequency converter) selected respectively for the four motor types (feeders no. 1, 2, 3 and 4 in Fig. 6/3) is suitable to limit the voltage drop at the motor terminals to approximately 25 %. For the NXAIR, and due to the required normal currents, vacuum circuit-breakers are selected for line protection of the motor feeders 1, 2 and 3. A numerical protection device SIPROTEC 5 (7SJ8 or 7SK8) is selected for monitoring and tripping (Fig. 6/6). The motor is protected via the motor starter (soft starter or frequency converter).

When starting motors with starting currents less than or equal to 600 A are switched, high switching overvoltages can arise. To limit these overvoltages to harmless values, surge arresters or surge limiters are installed. Single motors with reactive power compensation are an exception. These motors do not require a protection circuit if the capacitors are permanently connected to the motor and no series-connected reactor is used for compensation. Accordingly, a surge arrester is necessary for feeder 2, whereas it is only recommended for feeders 1 and 3.

Consumer / feeder	Protection function	Switching function	Rated voltage	Rated short-circuit breaking current	Rated current of busbar	Typical motor rating of the feeders	Siemens switchgear type [1]	Typical applications
Motor direct-on-line start or via block transformer	Vacuum circuit-breaker (Siemens 3AE/3AH/3AK)	Without contactor	6 kV	31.5 kA / 1 s	2,500 A	< 7.5 MW [3]	NXPLUS C	- Pumps - Compressors - Conveyor and elevator systems - Fans - Transformers - Compensation systems Typical motor starting current: 5 to 7 × I_n [2]
				50 kA / 1 s	4,000 A		NXAIR	
			10 kV	31.5 kA / 1 s	2,500 A	< 12.5 MW [3]	NXPLUS C	
				50 kA / 1 s	4,000 A		NXAIR	
	HV HRC fuses	With vacuum contactor 3TM	6 kV	31.5 kA / 1 s	2,500 A	< 1.3 MW	NXPLUS C	
				50 kA / 1 s	4,000 A	< 2.1 MW	NXAIR	
			10 kV	31.5 kA / 1 s	2,500 A	< 2 MW	NXPLUS C	
				50 kA / 1 s	4,000 A	< 1.7 MW	NXAIR	
Soft starter	Vacuum circuit-breaker (Siemens 3AE/3AH/3AK)	SIMOVAC-AR vacuum contactor 12SVC4/8 (in separate housing)	2.3 - 6.9 kV	50 kA / 1 s	720 A	< 6 MW	SIMOVAC-AR	- Pumps - Compressors - Fans Typical motor starting current: 3 × I_n [2]
Frequency converter	Vacuum circuit-breaker (Siemens 3AE/3AH/3AK)	SINAMICS PERFECT HARMONY GH180	2.3 - 11 kV	25 kA / 1 s	2,000 A	< 10 MW	NXAIR C	- Pumps - Compressors - Fans Typical motor starting current: 1 × I_n [2]
				31.5 kA / 1 s	2,500 A		NXPLUS C / NXPLUS	
				50 kA / 1 s	4,000 A		NXAIR	
		SINAMICS PERFECT HARMONY GH150	4.16 - 13.8 kV	25 kA / 1 s	2,000 A	4 - 35 MW	NXAIR C	
				31.5 kA / 1 s	2,500 A		NXPLUS C / NXPLUS	
				50 kA / 1 s	4,000 A		NXAIR	
		SINAMICS GL150	1.4 - 10.3 kV	25 kA / 1 s	2,000 A	1.4 - 30 MW	NXAIR C	
				31.5 kA / 1 s	2,500 A		NXPLUS C / NXPLUS	
				50 kA / 1 s	4,000 A		NXAIR	

[1] The switchgear from Siemens meet the safety integrity level SIL 2 according to IEC 61508-1 (corresponds to the performance level PL = d according to ISO 13849-[1])

[2] For motor starting currents less than 600 A, an overvoltage protection is required (exception: motors with internal reactive power compensation)

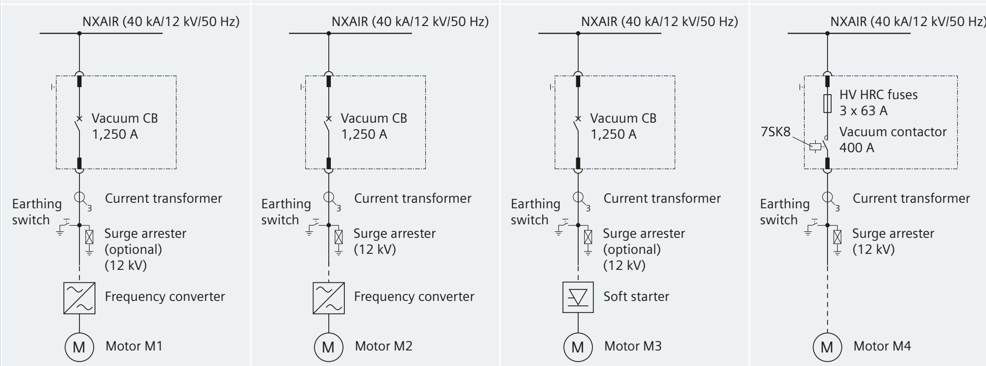
[3] See [1.2] figure C8.3

Tab. 6/6: **Selection table of medium-voltage switchgear for more special consumer connections**

Depending on the neutral earthing, minimum rated voltages can be determined based on IEC 60099-4 to dimension the surge arresters (Tab. 6/8). As an impedance-earthed neutral is given, a rated voltage of 12 kV is selected for the surge arresters.

For the smaller motors in feeders 4, surge arresters must be provided for. Furthermore, HV HRC fuses and vacuum contactors are the best choice as switching and protection devices in the NXAIR switchgear with regard to the rated motor currents and the starting conditions. For the motor feeders with direct-on-line starting, vacuum contactor/fuse combinations are installed to ensure a high number of operating cycles. In connection with the high-quality numerical protection devices SIPROTEC 5 (7SK8, see Fig. 6/6) and the matching current and voltage transformers, this combination ensures both line and motor protection. Alternatively, the Reyrolle devices 7SR1 can be used, which are especially suitable for motor protection. As overload protection devices, they detect an overload situation and trip the feeder by means of the vacuum contactor.

In motor feeders, the HV HRC fuses in charge of short-circuit protection protect the switching devices (here for example, the vacuum contactors) that do not feature a short-circuit breaking capacity, and also the cables. HV HRC fuses for the protection of high-voltage motors are used in combination with vacuum contactors for rated voltages U_r in the range of 7.2 kV ≤ U_r ≤ 12 kV. Vacuum contactors are switching devices which are suitable for switching currents in the range of their

	Feeder 1	Feeder 2	Feeder 3	Feeder 4
Active power P_{rM}	11.2 MW	5.8 MW	4.84 MW	0.3 MW
Starting factor s_M	1	1	3	6
Starting current I_{sM}	773.5 A	400.6 A	1002.8 A	124.3 A
Calculation of voltage drop	$\Delta u = S_{sM} / S''_{kT} = (\sqrt{3} \cdot U_n \cdot I_{sM}) / (S_{rT} / u_{kr})$			
Voltage drop Δu	2.34 %	1.21 %	3.03 %	0.38 %
Line protection	Protection device: SIPROTEC 7SJ8 Tripping: vacuum CB	Protection device: SIPROTEC 7SJ8 Tripping: vacuum CB	Protection device: SIPROTEC 7SJ8 Tripping: vacuum CB	HV HRC fuse
Motor protection	VFD	VFD	Soft starter	Protection device: SIPROTEC 7SK8 Tripping: vacuum contactor
Overvoltage protection	recommended	required	recommended	required
Single-line diagram for the design				
Common motor data	Rated voltage U_r = 10 kV; efficiency of motors = 0.95; cos φ = 0.88			
Transformer data	S_{rT} = 63 MVA; u_{kT} = 11 %			

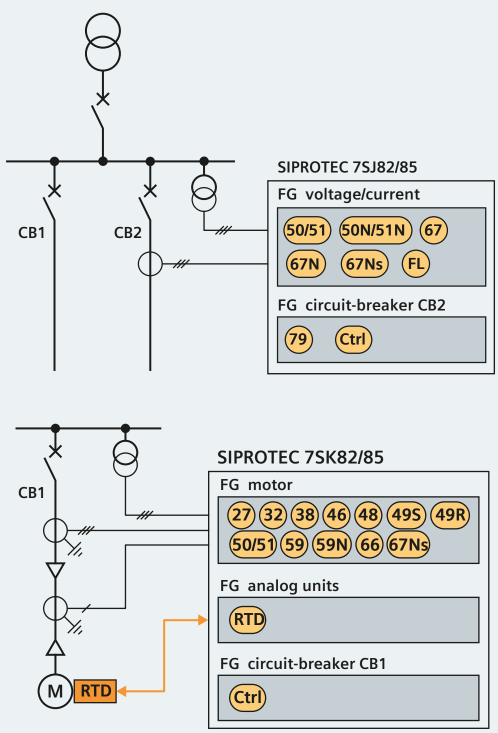
Tab. 6/7: **Data and selection of the switching and protection devices for the motor feeders at the 10 kV level**

rated current. When switching normal currents, they feature a high number of operating cycles (1,200 operating cycles per hour when using the Siemens vacuum contactor 3TM). The end of the mechanical endurance is not reached until after approximately 10^6 operating cycles at rated current. Therefore, vacuum contactors are especially suitable for switching high-voltage motors. Due to the low breaking capacity (rated short-circuit breaking current of 3TM up to I_{sc} = 5,000 A), however, they cannot break high short-circuit currents. The protection of the vacuum contactor in case of short circuit must be taken over by the current-limiting HV HRC fuses. In all, a coordination of the motor protection between fuse and contactor is necessary, taking the motor start requirements into account. Depending on the switchgear type and voltage level, the motor protection combination of vacuum contactor and fuse can be used up to a rated short-circuit breaking current of 50 kA.

To prevent the fuse from being impermissibly tripped or pre-damaged, the HV HRC fuses that are exclusively used for the short-circuit protection of the motor circuit are selected according to:
- Rated voltage U_r and rated motor current I_{rM}
- Motor starting current I_{sM}
- Motor starting time t_{sM}
- Starting frequency (motor starts per hour)
- Ambient air temperature[4].

For selection of the numerical overload protection relay as well as the motor protection combination of HV HRC fuse and vacuum contactor, the following has to be checked (Fig. 6/7 shows curves and points for the 300 kW motors for feeder 4 in Tab. 6/8):

[4] The increased temperature results in a worse heat dissipation to the environment of the HV HRC fuse, so that a reduction of the rated current has to be considered; manufacturer information is to be observed.



FG	Function group
Crtl	Control
CB	Circuit-breaker
RTD	Indications from RTD box
27	Undervoltage protection
32	Power protection, active power
38	Temperature supervision
46	Unbalanced-load protection
48	Starting time supervision
49R/49S	Thermal overload protection, rotor/stator
50/51	Time-overcurrent protection, phases
50N/51N	Time-overcurrent protection, earth
59/59N	Overvoltage protection: "3-phase", or "zero-sequence component U0", or "positive phase-sequence system U1", or "universal Ux"
66	Restart inhibit for motors
67	Directional time-overcurrent protection, earth
67Ns	Sensitive earth-fault detection for resonant-earthed and isolated systems
79	Automatic reclosing

Fig. 6/6: **Examples for line and motor protection as well as for motor control (with abbreviations and ANSI device designation numbers)**

1. The current-time characteristic of the HV HRC fuse must be above the motor starting current characteristic I_{sM} and the motor starting time t_{sM}
2. The tripping characteristic of the overcurrent protection must be above the characteristic for I_{sM} and t_{sM} (the overload relay has an impact on the vacuum contactor)
3. The take-over current I_B (intersection of the current-time characteristic of the HV HRC fuse with the tripping characteristic of the overcurrent protection, point B in Fig. 6/7) must be greater than the minimum short-circuit breaking current I_{sHHmin} of the HV HRC fuse (I_{sHHmin} can be found in the data sheets of the HV HRC fuses $I_B > I_{sHHmin}$)
4. A tested combination of HV HRC fuse and vacuum contactor that is suitable for the required stress values (particularly regarding thermal and dynamic short-circuit currents) must be installed in the switchgear. This is usually verified for the intended combination by the switchgear manufacturer. The permissible values can mostly be found in the technical data of the corresponding switchgear.

	Maximum system voltage U_s					
Minimum rated voltage U_r in kV for	3.6 kV	7.2 kV	12 kV	17.5 kV	24 kV	36 kV
Solidly earthed neutral system	3	6	9	15	18	27
System with isolated neutral or for delta winding	6	9	15	24	30	45
Impedance earthed neutral system	3	9	12	15	21	33
System with earth-fault compensation	6	9	15	24	30	45

Tab. 6/8: **Design of the rated voltage U_r for surge arresters according to IEC 60099-4**

Fuses with a current-time characteristic that is especially designed for a motor should be preferred due to their low heat loss. To select suitable fuses, the manufacturers of switchgear with a vacuum contactor/fuse combination provide curves or tables which take the starting time, starting frequency and motor starting current of the motor feeder to be protected into account.

Number of starts per hour	*K* factor
2	0.59
4	0.53
8	0.48
16	0.43
32	0.39

Tab. 6/9: ***K* factors for motor HV HRC fuses from SIBA [6.1]**

To show the correlations, no HV HRC fuse is selected from a table given by the manufacturer, but the characteristics are entered in a time-current diagram. In this process, however, the influence of the motor starting time and the starting frequency still needs to be considered. In IEC 60644, the K factor is defined accordingly, which describes this influence on the current-carrying capacity of the HV HRC fuse (according to IEC 60644, a permissible pre-arcing characteristic of a fuse-link is specified by multiplication of the current values from the current characteristic with the K factor).

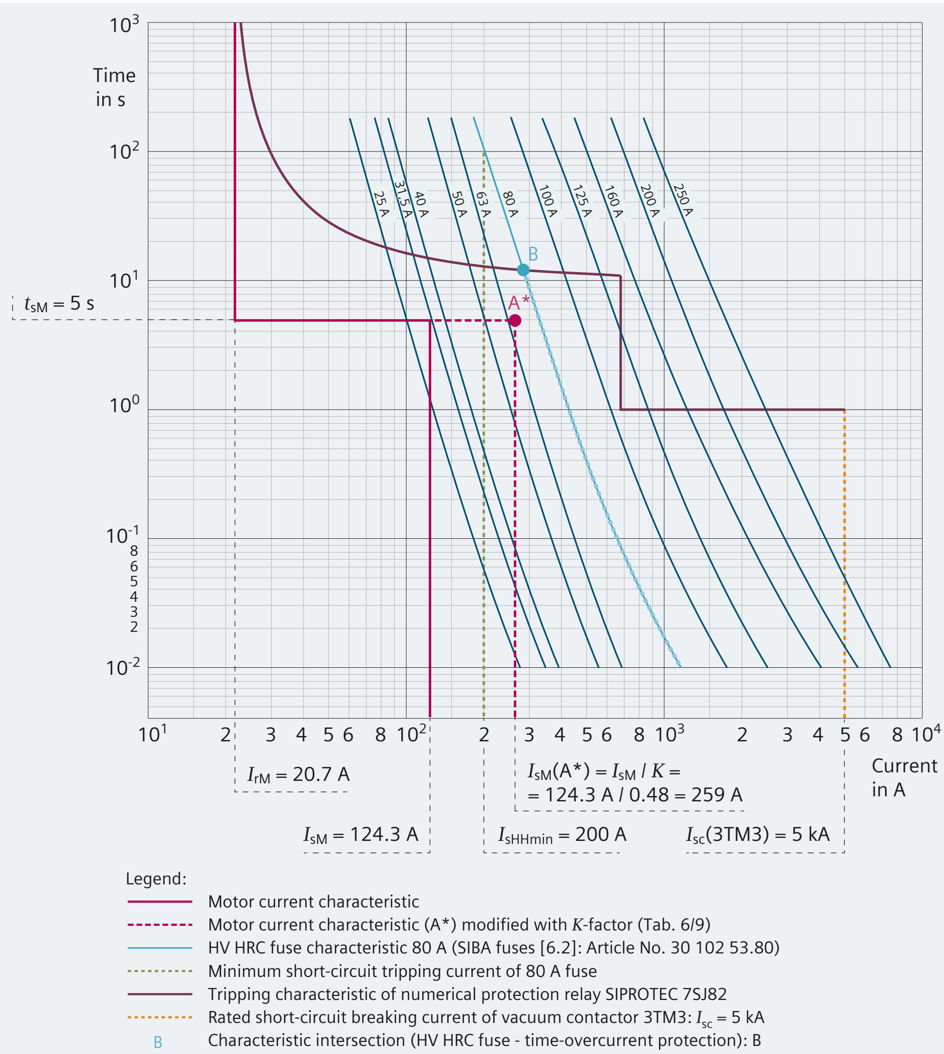


Fig. 6/7: **Characteristics diagrams for selecting a suitable combination of protection devices for motor M4**

In Tab. 6/9, K factors are stated for HV HRC fuses make SIBA [6.1].

For the K factors or the motors M4, the following applies:

- Motor starting time less than 10 s
- Starting frequency maximum 6 starts per hour
- Maximum 2 starts in immediate succession.

To illustrate the interaction of motor start, HV HRC fuse, and overcurrent protection when dimensioning a suitable combination for the motor feeder M4, in Fig. 6/7, the characteristics of motor, HV HRC fuse, overcurrent protection, and vacuum contactor are entered, and important points for the selection are marked. The associated device parameters and calculations for the selection matching with motor M4 are likewise stated in Fig. 6/7.

6.6 Motor Start with Block Transformer

Under certain circumstances, the use of a soft starter or a frequency converter can be omitted for individual medium-voltage motors by connecting the motor to a block transformer as a more cost-effective motor starter version. This can be done, for example, if no automatic motor control is necessary during normal operation.
If, during the start, there is a lower voltage applied than the rated motor voltage, the starting current that must be provided by the feeding grid is also reduced.
Due to the block transformer ratio, the current on the high-voltage side at the transformer is reduced by the square, and thus also the feedbacks of the motor start on the network. It has to be checked whether the block transformer is sufficient to limit the voltage drop during the start to the desired extent.

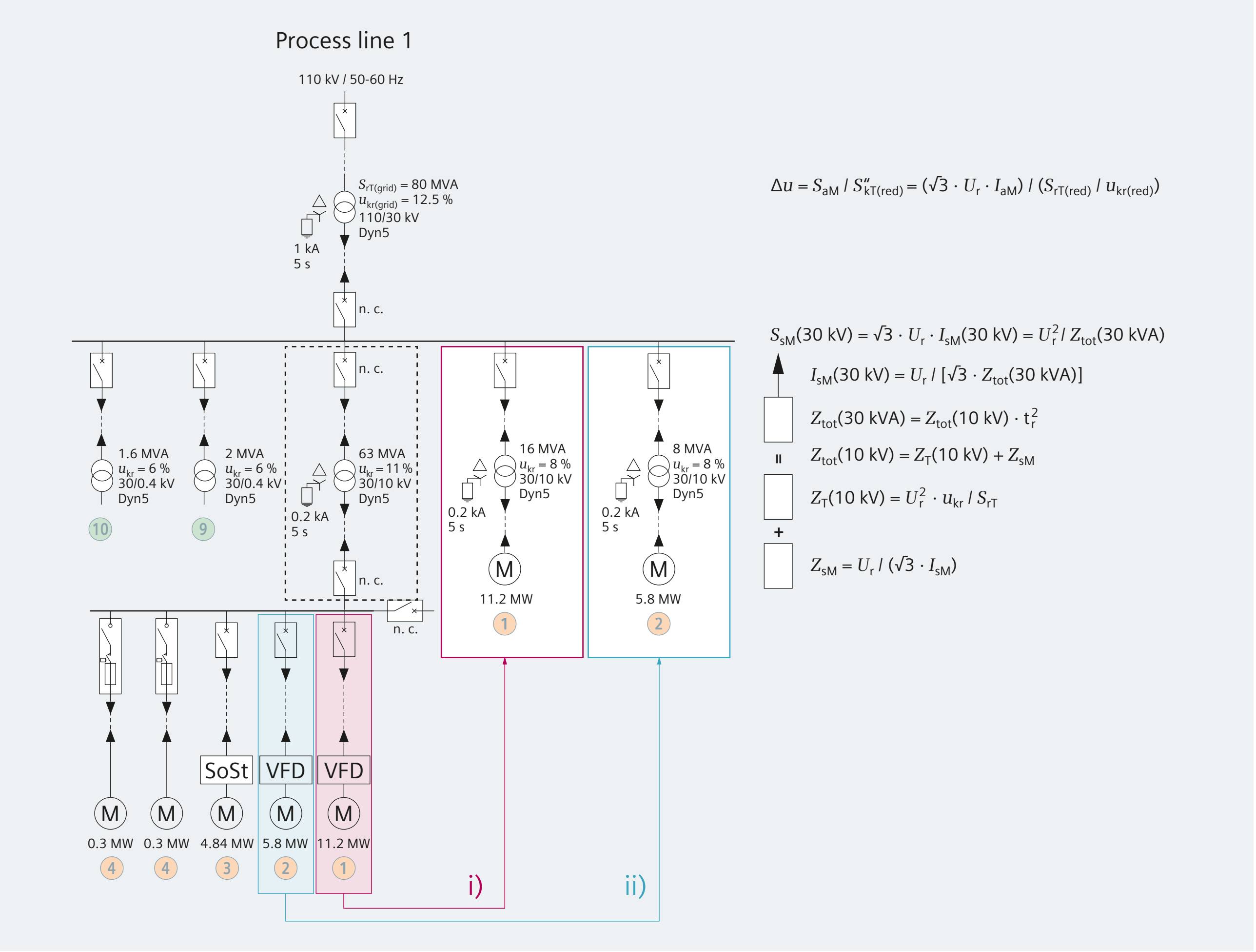


Fig. 6/8: **Single-line diagram for connecting the two sample motors, and equivalent diagram for determination of impedances and voltage drop in Tab. 6/10**

	i) Motor 1	ii) Motor 2
Active power P_{rM}	11.2 MW	5.8 MW
Starting factor s_M	6	6
Rated current I_{rM}	773.5 A	400.6 A
Motor impedance Z_{sM}	1.244 Ω	2.402 Ω
Data of block transformer	S_{rT} = 16 MVA; u_{kr} = 8 %	S_{rT} = 8 MVA; u_{kr} = 8 %
Transformer impedance Z_T	0.5 Ω	1 Ω
Total impedance (secondary side) Z_{tot}(10 kV)	1.744 Ω	3.402 Ω
Total impedance (primary side) Z_{tot}(30 kV)	15.70 Ω	30.62 Ω
Motor starting power (primary side) S_{sM}(30 kV)	57.32 MVA	MVA29.39 MVA
Data of grid transformer	$S_{rT(grid)}$ = 80 MVA; $u_{kr(grid)}$ = 12.5 %	
Short-circuit power of grid transformer $S''_{kT(grid)}$	640 MVA	
Calculation of voltage drop	$\Delta u = S_{sM} / S''_{kT} = (\sqrt{3} \cdot U_r \cdot I_{sM}) / (S_{rT} / u_{kr})$	
Voltage drop Δu	8.96 %	4.59 %
Calculation of motor starting voltage with block transformer U_{sM}(10 kV)	$I_{sM}(10\text{ kV}) = U_r / [\sqrt{3} \cdot Z_{tot}(10\text{ kV})] \rightarrow U_{sM}(10\text{ kV}) = \sqrt{3} \cdot I_{sM}(10\text{ kV}) \cdot Z_{sM}$	
Motor starting voltage U_{sM}(10 kV)	7,133 V	7,061 V
Relative torque ΔM ~ $[U_{sM}(10\text{ kV}) / U_r]^2$	51 %	50 %

Tab. 6/10: **Results of the sample calculations for the use of a block transformer**

It is likewise to be observed that the starting torque is reduced by the square with the motor current or the motor voltage. If the voltage drop is accomplished, it must therefore be checked whether the starting torque and the starting duration are sufficient to ensure normal motor operation without any problems.

For the sample calculations of the block transformer, the two large motors are considered, which shall be operated via frequency converters. For verification of the motor starting torque, it is assumed that 50 % of the maximum starting torque are sufficient. Due to the square dependence (torque M ~ motor starting voltage $U_{sM}{}^2$), the terminal voltage at the motor must not drop below 71 % of the rated voltage.

Fig. 6/8 schematically shows the connection of the two sample motors 1 and 2 at the 30 kV level via a block transformer. The impacts on further network setup (e.g. in Fig. 6/8, in dotted lines, for the 63 MVA transformer 30 kV/10 kV) are not considered. The results are stated in Tab. 6/10.

Regarding the stipulation that the motor starting torque must exceed at least 50 % of the nominal operating torque, both motors could be started via a block transformer. However, the network feedback of 8.96 % due to the start of the large motor 1 (main air compressor MAC) is too large for the voltage drop at the 30 kV level, compared to the stipulation of a maximum of 5 %. In contrast, motor 2 can be started via a block transformer with the data from Fig. 6/8 with a permissible voltage drop of 4.59 %. In the following, however, the original concept with the connection of these two motors via frequency converters is taken as a basis again.

6.7 Generator Protection

Type tests as specified in IEC 62271-100 are performed as a rule for all Siemens circuit-breakers. The generator circuit-breakers are additionally tested according to IEC/IEEE 62271-37-013. This standard for generators above 10 MVA takes into account the increased requirements to which the circuit-breakers are subjected when switching generators (Fig. 6/9):
- For generator-source faults: high DC components and the missing current zeros resulting therefrom
- For system-source faults: higher TRV rates of rise (edge steepness of the transient recovery voltage)
- Higher test voltage levels.

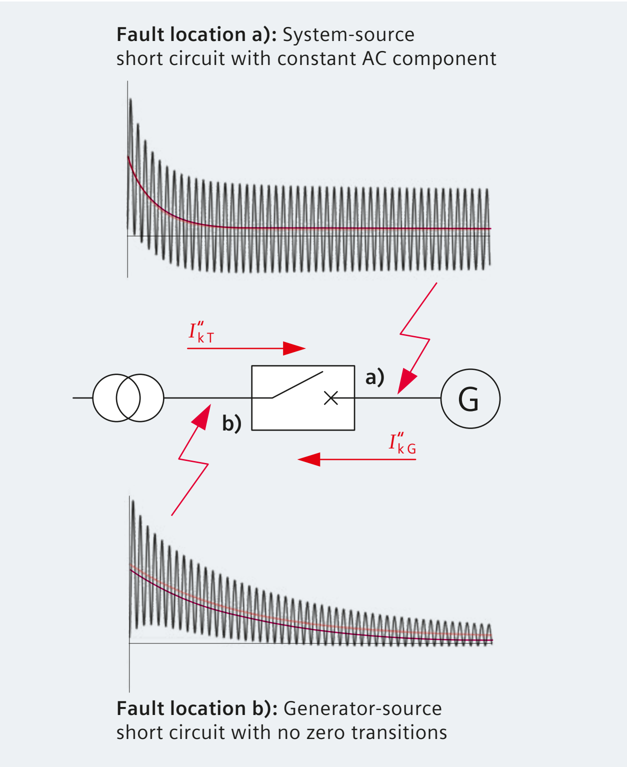


Fig. 6/9: **Short-circuit stress of a generator breaker for a) supply via transformer b) supply via generator**

The particular requirements lead to a special construction and design of the generator breakers. Conventional circuit-breakers usually cannot meet these requirements. Selection criteria for the generator breaker are:
- Rated voltage
- Rated current
- Behavior in case of system-source short circuit
- Behavior in case of generator-source short circuit.

For this, a calculation of the short-circuit currents is carried out taking into account the two fault locations (system-side – generator-side) and the operating states of the plant. Coordination preferably takes place between the generator manufacturer and the circuit-breaker manufacturer. Essential circuit-breaker characteristics to be tested are:
- DC component of the short-circuit breaking current
- Asymmetrical breaking current.

Depending on the type, the capability of the vacuum circuit-breakers for generator switching applications is sufficient for rated currents up to 14 kA, apparent power up to 500 MVA, rated voltages up to 24 kV, and rated short-circuit breaking current I_{sc} up to 110 kA. Type SION 3AE2185 circuit-breakers are used for the two 16 MVA generators of the ASP. The technical data is given in the brochure [6.3], also for further circuit-breaker types.

6.8 Network Protection Concept and Energy Management

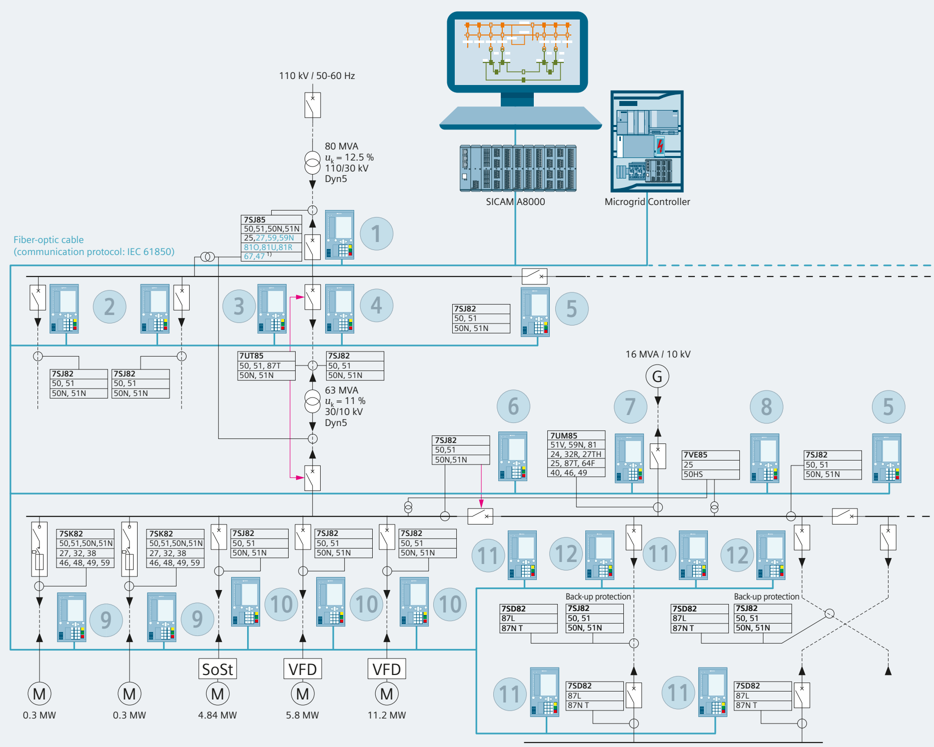
Measuring devices, digital protection devices, current and voltage transformers, as well as evaluation and control units must be adjusted to each other. For this, both the grid connection conditions (see Chapter 4) and the corporate requirements have to be observed. For a better overview, the network protection concept and the measurement concept for the energy management are described separately. The SICAM A8000 process controller together with the Microgrid Controller are provided as a central connection point for controlling the embedded generating plants for both ASP process lines. The facilities are mirrored for the two process lines and, thanks to the communication linking, the redundancy for controlling these important components can be ensured.

i) **Network protection concept**
To develop the protection concept, the procedure is as follows:

1. Specification of protection targets, which result from the design of the distribution system as well as from the project-specific and operational requirements (e.g. switch positions for stipulated modes of operation of the plant, generator operating modes)
2. Selection of the protection devices according to the individual protection targets (e.g. transformer, generator, motor, line) and the most appropriate degree of protection (e.g. definite time-overcurrent protection, differential protection, distance protection)
3. Dimensioning and selection of suitable protection current transformers.

Additionally, the neutral earthing has an essential influence on the protection concept, the protection functions to be selected (e.g. sensitive earth-fault detection, direction detection), the selection and design of the protection current transformers (for example, zero-sequence current transformers for detecting small earth-fault currents in isolated and compensated networks, voltage transformers for direction detection).

For the medium-voltage side network protection in the electric power distribution concept, numerical protection relays are used. Depending on the use case, SIPROTEC 5 devices are provided, as shown in Fig. 6/10. The protection functions of the individual devices are listed in Tab. 6/11 according to the numbering in Fig. 6/10.



	Protection application	Protection function	Protection device
1	Infeed from DSO	Time-overcurrent and feeder protection	SIPROTEC 7SJ85
2	Transformer feeders 30/0.4 kV	Transformer differential protection	SIPROTEC 7SJ82
	Transformer feeders 30/10 kV:		
3	Primary protection	Transformer differential protection	SIPROTEC 7UT85 2)
4	Back-up protection	Time-overcurrent and feeder protection	SIPROTEC 7SJ82
5	Interface 3)	Time-overcurrent and feeder protection	SIPROTEC 7SJ82
6	Interface switch	Time-overcurrent and feeder protection	SIPROTEC 7SJ82
7	Generator	Generator protection	SIPROTEC 7UM85
8		Paralleling device	SIPROTEC 7VE85
9	Motor feeders (motor and line)	Paralleling device	SIPROTEC 7SK85
10	Motor feeders (line)	Time-overcurrent and feeder protection	SIPROTEC 7SJ85
	Connecting lines10 kV:		
11	Primary protection	Differential protection	SIPROTEC 7SD82
12	Back-up protection	Time-overcurrent and feeder protection	SIPROTEC 7SJ82

1) Functions for the interface protection are marked in blue
2) For transformer feeders with line lengths of more than 500 m, a differential protection relay SIPROTEC 7SD82 is recommended
3) The protection device ⑥ protects the interface and serves for tripping the interface protection (measurement and decision are made in protection device ①)

Fig. 6/10: **Main components, protection functions, and links in the network protection concept for the ASP**
(red arrows identify the circuit-breakers that can be tripped by the protection device)

The basics for dimensioning and selection of the protection current transformers are the standard IEC 61869-2 and the application guidance IEC/TR 61869-100.
The requirements on the protection current transformers are stipulated by the corresponding protection device, and can be found in the respective manuals (e.g. for SIPROTEC 5).

In order not to damage the connected protection device, the current transformer must reach saturation in due time. However, it must not reach saturation too early, so that the linear ratio is not lost too early, causing impermissible errors (Fig. 6/11). Since the current transformer dimensioning quickly becomes complex, Siemens offers the PC tool CTDim for this. Additionally, the TIP technical consultants will be pleased to provide support in designing the current transformer.

ANSI	Function	Abbrev.
24	Overexcitation protection	U/f
25	Synchrocheck, synchronizing function	Sync
27	Undervoltage protection	U<
27TH	Stator earth-fault protection with 3rd harmonic	U03.H<
32R	Reverse-power protection	-P<
40	Underexcitation protection	1/xd
46	Negative phase-sequence system overcurrent protection, unbalanced-load protection	I2>, I2^{2}t>
47	Overvoltage protection, negative phase-sequence system	U2>
49	Thermal overload protection	θ, I^2t
50/51	Time-overcurrent protection, phases	I1>
50N/51N	Time-overcurrent protection, earth	IN>
51V	Voltage-dependent time-overcurrent protection	t=f(I,U)
59/59N	Overvoltage protection "3-phase", or "zero-sequence system U0", or "positive phase-sequence system U1", or "universal Ux"	U>
64F	Rotor earth-fault protection	IRE>, RRE<
67	Directional time-overcurrent protection, phase	I>, <(U,I)
81	Frequency protection: "f>" or "f<" or "df/dt"	f<>; df/dt<>
81O	Overfrequency protection	f>
81R	Rate-of-frequency-change protection	df/dt<>
81U	Underfrequency protection	f<(AFE)
87N T	Earth-fault differential protection	ΔIN
87T	Transformer differential protection	ΔI

Tab. 6/11: **Protection functions of the SIPROTEC devices for the ASP protection concept with ANSI code (IEEE C37.2) and abbreviations of functions (IEC 60617); further device functions and more details are given in [6.4] and [6.5]**

ii) **Measurement concept and energy management system**

For energy transparency in the distribution network, measured values are acquired at the following three levels:

- Infeed
- Distribution
- Consumer feeders.

At the infeed – the point of connection (PoC) to the customer –, the measuring point operator measures the energy procured from or, if applicable, fed back into the distribution grid [5.1]. No regenerative feedback of the embedded generating plants into the grid is intended for the ASP.

In order to check the data made available by the measuring point operator to the plant operator, and to receive more detailed information, the customer can carry out additional control measurements. Measuring devices with network analysis functions are suitable for such control measurements. The measuring devices can deliver the following values:

- Sum energy across the three phases
- Energy values per phase: active and reactive component
- Power values per phase: active and reactive component
- Active factors per phase and as sum
- Power factors per phase and as sum
- Harmonic content of voltage (THDU) and current (THDI) per phase and as sum
- Flicker, etc. (depending on device).

Due to the in-house medium-voltage network after the DSO infeed, the control measurement can of course also be done at the medium-voltage level of the user.

For the measurement concept shown in Fig. 6/12, the measuring devices SICAM Q100, P850 and P50 from Siemens are used according to the requirements of the different levels.

Typical measured values of the three acquisition levels [5.1] are:

1. Infeed – transfer/control measurement: Active/reactive energy, active/apparent/reactive power, frequency, voltages, currents, active factors (cos φ), power factors (lambda), harmonics (THD), and further power quality factors

Contents
1
2
3
4
5
6
7

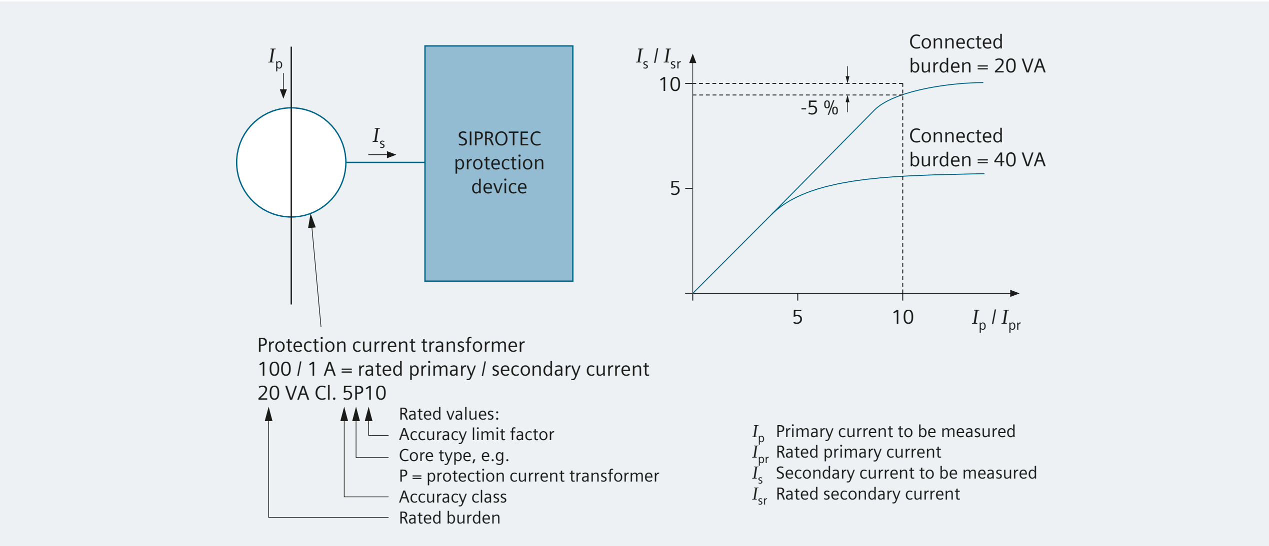


Fig. 6/11: **Classification of current transformers according to IEC 61869-2 and current transformer saturation for various burdens**

2. Infeed – embedded generation:
   Active energy, active/reactive power, voltages, currents, frequency, active factors
3. Distribution levels and transformers:
   Currents, active factors, power factors, harmonics of currents
4. Consumer level:
   Measurements depend on the load requirements (see [5.1]); at least, active/reactive power and currents are usually measured.

In addition, the evaluation, analysis and assessment of the measured values, especially for power quality, must always be considered. By detecting anomalies at an early stage, failures and damages can be avoided. Therefore, the measuring devices should be able to provide the basic data for a power quality analysis. With Power Quality Analytics (PQA), Siemens offers a corresponding service, for which a discussion of experts with the customer is the essential feature for assessment.

The multifunction measuring device SICAM Q100 is used for acquisition, visualization, analysis, and transmission of electrical measuring variables, such as for example alternating current, alternating voltage, frequency, power, harmonics. The acquisition, processing, and accuracy of measuring variables and events correspond to the standard IEC 61000-4-30 Class A for power quality measurement. Besides the monitoring function, the device offers a combined recording and analysis function: Measured values can be recorded in programmable time intervals by means of various recorders (e.g. power quality and fault recorders). Long-time data and events are evaluated directly in the device, and are shown as a report according to the power quality standards (e.g. EN 50160).

The SICAM P850 are multifunctional devices for acquisition, display and transmission of measured electrical variables such as alternating current, alternating voltage, power types, harmonics, etc. The measuring variables can be transmitted to a PC and to the control and protection system via the communication interfaces, or they can be shown on an optional display.

As an all-in-one device with an internal 2 GB storage, SICAM P850 offers new recording functionalities in addition to the monitoring function:
- Sine recording and acquisition with voltage and current trigger settings in COMTRADE
- Recording of mean, minimum and maximum values of different network parameters in flexible intervals in CSV
- Flexible data export in CSV and/or COMTRADE formats.

With the web server integrated in the device, parameterization and measured-value output is carried out via HTML pages on the connected PC/notebook. In case of devices with display, parameterization via the function keys on the front, as well as measured-value output via the display are also possible.

SICAM P50 is a power meter with a graphical display and background illumination for flush mounting or standard rail mounting for acquiring and/or displaying measured values in electrical power supply systems. More than 100 values can be measured, including r.m.s. values of voltages (phase-to-phase and/or phase-to-earth), currents, active/reactive/apparent power and energy, power factor, phase angle, harmonics of currents and voltages, total harmonic distortion (THD) per phase plus frequency and symmetry factor, energy output, as well as external signals and states.

Other device characteristics are:

- Easy parameterization with the parameterizing software SICAM P Manager as well as via the front keys.
- Graphical display with background illumination with up to 20 programmable screens
- Real-time clock, so that measured values and states can be recorded with time stamp
- 1 MB memory including memory management
- Recording and display of limit-value violations and log entries

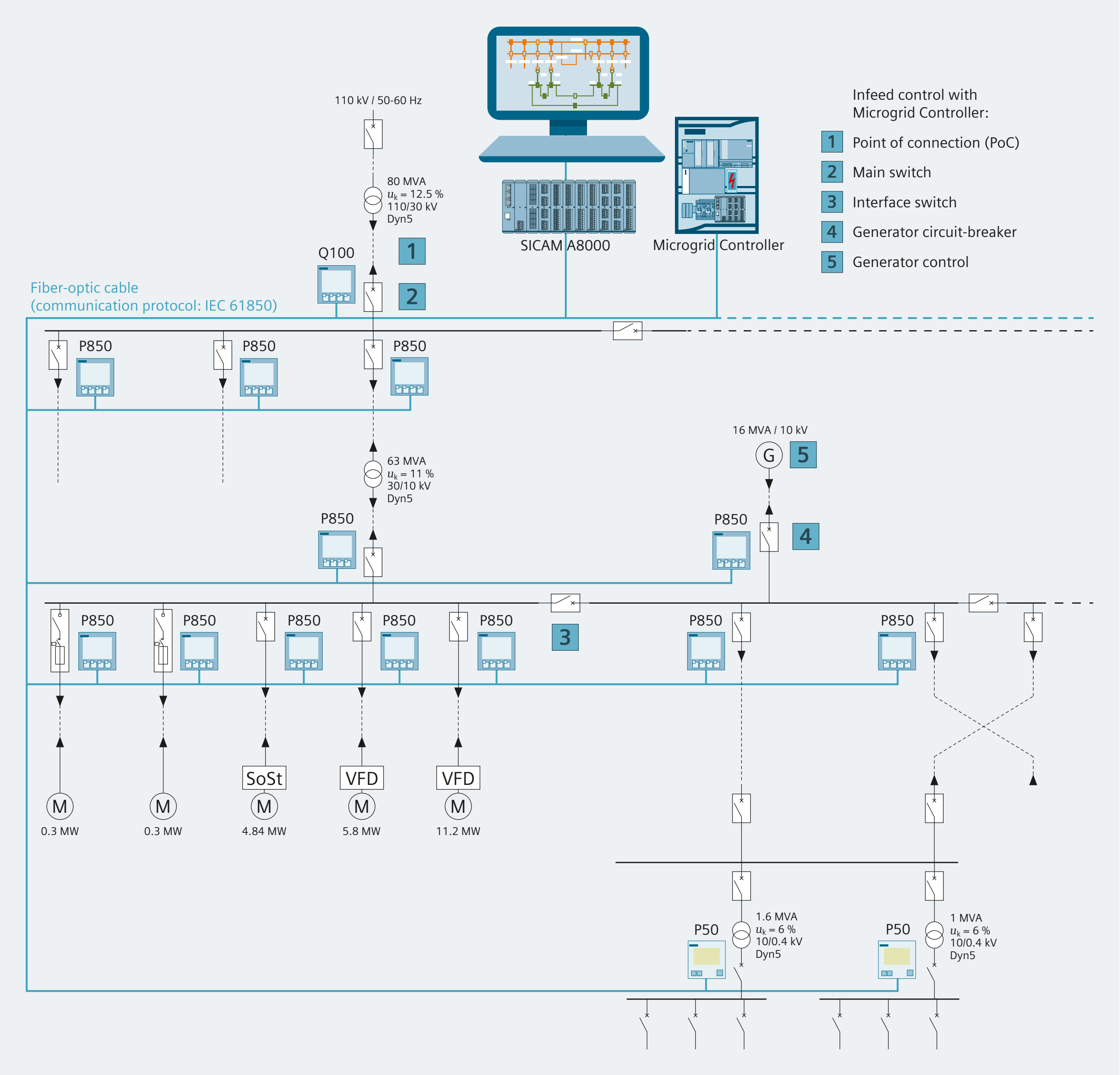


Fig. 6/12: **Measurement concept for energy management of the ASP and infeed control with the Microgrid Controller**

• Integrated battery for records: Limit-value violations or energy values (meter values), for example, are not lost even in case of failure of auxiliary power, but they remain available in the measurement memory up to 3 months.

Further technical data and features of the SICAM devices are given in the product catalog [6.6].

The Microgrid Controller (Fig. 6/13), as a power management system (PMS) application, monitors and controls the electric power distribution system at the various voltage levels, including the DSO infeed, on the customer side at the 30 kV transformer secondary side, and the generators at the 10 kV level, both during normal operation and in case of fault states. In case of a power supply interruption in the infeed or the generators, the system must initiate a fast changeover of the prioritized consumers to the available power supply. Thus, the impacts on the normal production processes in the plant shall be minimized. The PMS must functionally enable both automatic operation and user-led operation.

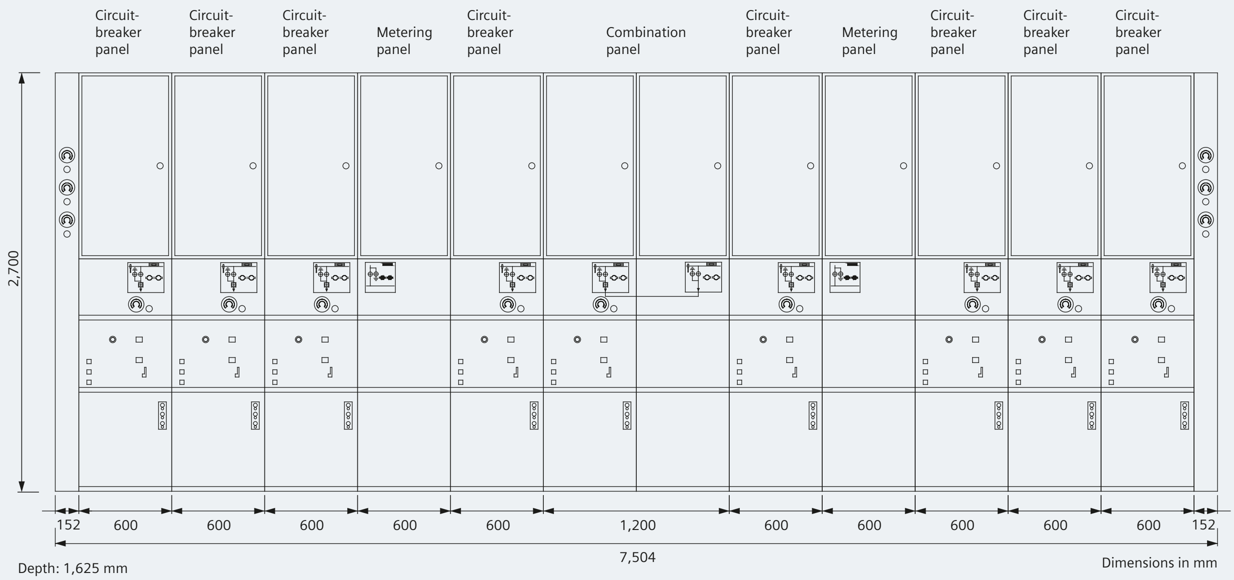
For the ASP, the Microgrid Controller must automatically ensure that no regenerative feedback of the generators occurs in the feeding grid, and that the generator infeed is optimally controlled according to the operating conditions. The grid connection conditions of the DSO must be complied with. As described in Chapter 4.3, these conditions follow national stipulations, standards, laws or guidelines (see Fig. 4/5). The basis for this are international regulations and standards (Chapter 4.3), which reflect the recognized state of the art.

For infeed control via the Microgrid Controller, the measuring points and switching devices marked with blue boxes in Fig. 6/12 are selected in the network protection and measurement concept of the ASP – in accordance with Fig. 4/10. The connection of the Microgrid Controller with the automatic generator control is schematically shown as separate box (5). The Microgrid Controller can, of course, be accessed via a user interface (HMI).

Fig. 6/13: **Automation box as a system application of the Microgrid Controller**

6.9 Front Views and Room Planning of the Medium-Voltage Switchgear

Following the dimensioning of the switching and protection devices for medium-voltage switchgear assemblies at the 30 kV level and the 10 kV level, the dimensions, weights and installation conditions can be determined. An important help for this is the engineering tool SIMARIS project. Whereas the front view of the medium-voltage switchgear 8DA for the 30 kV level is shown including all the panels in Fig. 6/14, only about half of the medium-voltage switchgear NXAIR for the process distribution at the 10 kV level is shown in Fig. 6/15, since the panels marked by dotted lines are mirrored. The smaller medium-voltage switchgear assemblies NXPLUS C of the two process lines are identically designed, so that showing of one of them is sufficient (Fig. 6/16).

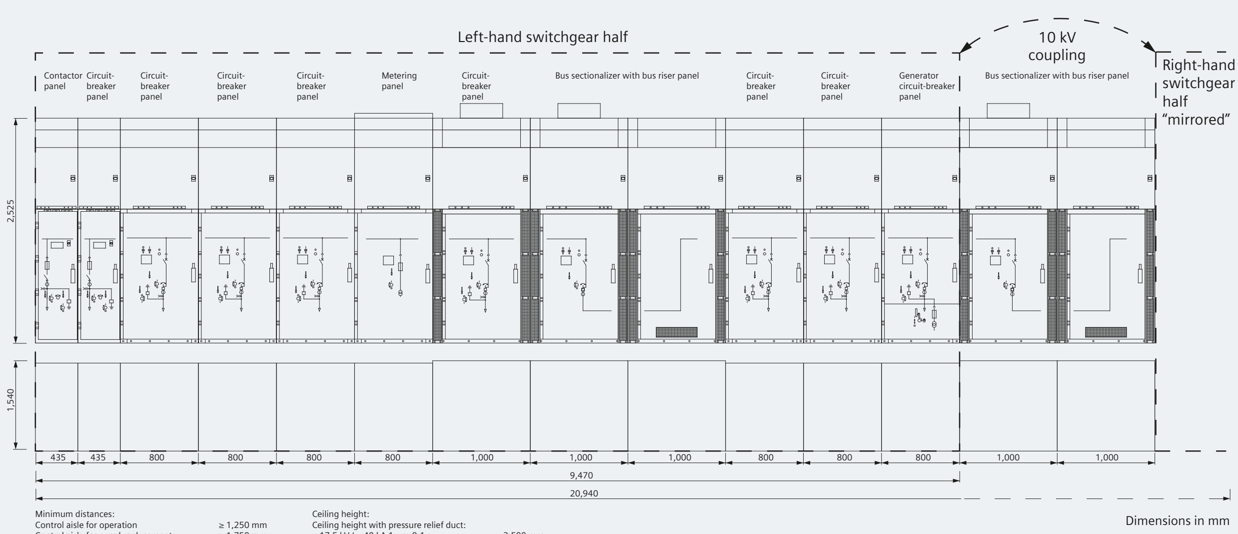


Depth: 1,625 mm

Minimum distances:
Control aisle ≥ 800mm
Wall distance on the right for operation ≥ 100 mm
Wall distance on the right for replacement ≥ 500 mm
Wall distance on the left for operation ≥ 100 mm
Wall distance on the left for replacement ≥ 500 mm
Wall distance to the rear
for wall-standing arrangement ≥ 100 mm
for free-standing arrangement ≥ 800 mm
Ceiling height ≥ 2,850 mm

This information does not correspond to any construction execution data and drawings.
Further planning instructions for switchgear installation can be found in Catalog HA 35.11 [6.7].

Fig. 6/14: **Front view and data for installation of the 30 kV switchgear 8DA**



Minimum distances:
Control aisle for operation ≥ 1,250 mm
Control aisle for panel replacement ≥ 1,750 mm
Wall distance on the right ≥ 150 mm
Wall distance on the left ≥ 150 mm

Wall distance for contactor panel:
Wall distance on the right ≥ 150 mm
Wall distance on the left ≥ 150 mm

Wall distance with pressure relief duct on the opposite side of the switchgear:
Wall distance on the right ≥ 500 mm
Wall distance on the left ≥ 500 mm

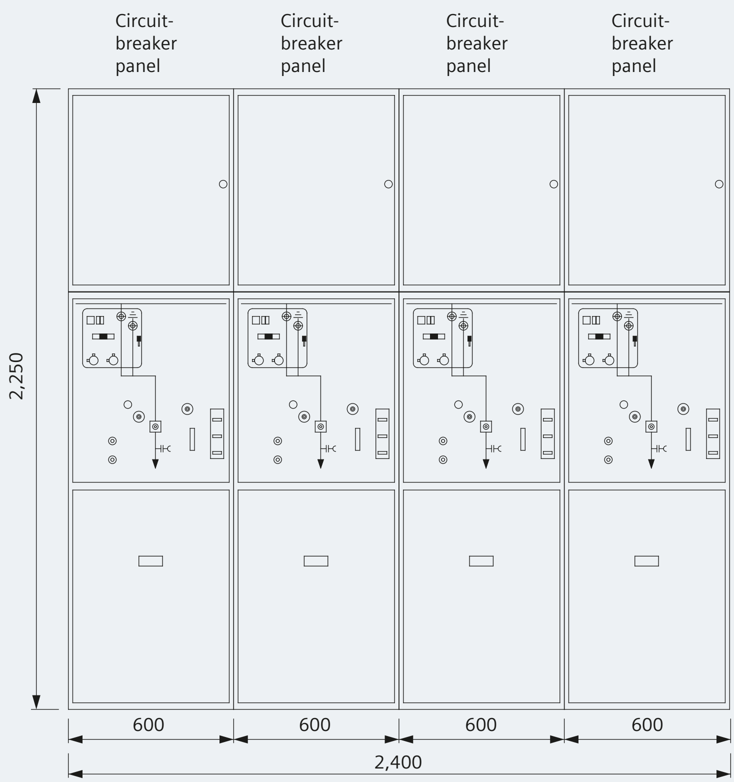
Wall distance at the rear:
for cable connection at the front ≥ 150 mm
for cable connection at the rear ≥ 500 mm

Ceiling height:
Ceiling height with pressure relief duct:
≤ 17.5 kV / ≤ 40 kA 1 s or 0.1 s ≥ 2,500 mm

Ceiling height without pressure relief duct:
≤ 12 kV / ≤ 25 kA 1 s or 0.1 s ≥ 2,800 mm
≤ 12 kV / 31.5 kA 1 s or 0.1 s ≥ 3,000 mm
≤ 12 kV / 40 kA 1 s or 0.1 s ≥ 3,500 mm
≤ 17.5 kV / ≤ 31.5 kA 1 s or 0.1 s ≥ 3,500 mm
≤ 17.5 kV / 40 kA 1 s or 0.1 s ≥ 3,500 mm

This information does not correspond to any construction execution data and drawings.
Further planning instructions for switchgear installation can be found in Catalog HA 25.71 [6.8].

Fig. 6/15: **Front view of one half of the switchgear assembly including bus sectionalizer, as well as data for installation of the 10 kV switchgear NXAIR**



Depth: 1,225 mm

Dimensions in mm

Wall distances:

Wall distance at the rear	≥ 50 mm
Wall distance on the right	≥ 50 mm
Wall distance on the left	≥ 50 mm
Control aisle	≥ 800 mm
Control aisle for extension (600 mm panels)	≥ 1,400 mm
Control aisle for extension (900 mm panels)	≥ 1,600 mm

Ceiling height: ≥ 2,500 mm

Minimum door openings for transport:

Panel width	Switchgear depth	Switchgear height	Door clearance [W x H]
600 mm	1,100 mm - 1,225 mm	2,250 / 2,650 mm	900 mm x 2,500 mm
900 mm	1,225 mm	2,250*) / 2,650 mm	1,200 mm x 2,500 mm

*) Spoiler is delivered loosely

This information does not correspond to any construction execution data and drawings.
Further planning instructions for switchgear installation can be found in Catalog HA 25.71 [6.8].

Fig. 6/16: **Front view and data for installation of a medium-voltage switchgear NXPLUS C**

Chapter 7

Annexes

7 Annexes

7.1 List of Standards Cited

Standards, guidelines, regulations	Year	Title
2009/714/EU	2009	Conditions for access to the network for cross-border exchanges in electricity (Predecessor of 2019/943/EU)
2014/30/EU	2014	Harmonisation of the laws of the Member States relating to electromagnetic compatibility
2014/53/EU	2014	Harmonisation of the laws of the Member States relating to the making available on the market of radio equipment
2015/1222/EU	2015	Establishing a guideline on capacity allocation and congestion management
2016/631/EU	2016	Network code on requirements for grid connection of generators
2018/2002/EU	2018	Energy efficiency
2019/943/EU	2019	Internal market for electricity
2019/944/EU	2019	Common rules for the internal market for electricity
AS/NZS 3010 (Australia / New Zealand)	2017	Electrical installations – Generating sets
CEI 0-16 (Italy)	2016	Regola tecnica di riferimento per la connessione di utenti attivi e passivi alle reti AT ed MT delle imprese distributrici di energia elettrica (Reference technical rules for the connection of active and passive consumers to the HV and MV electrical networks of distribution companies)
DIN VDE 0100 Sup. 5	2017	Errichten von Niederspannungsanlagen – Beiblatt 5: Maximal zulässige Längen von Kabeln und Leitungen unter Berücksichtigung des Fehlerschutzes, des Schutzes bei Kurzschluss und des Spannungsfalls (Erection of low-voltage systems – Supplement 5: Maximum permissible lengths of cables and lines in consideration of fault protection, protection in case of short circuit, and voltage drop)
EN 50549-1	2019	Requirements for generating plants to be connected in parallel with distribution networks – Part 1: Connection to a LV distribution network – Generating plants up to and including Type B
EN 50549-2	2019	Requirements for generating plants to be connected in parallel with distribution networks – Part 2: Connection to a MV distribution network – Generating plants up to and including Type B
EN 50160	2010	Voltage characteristics of electricity supplied by public electricity networks
ENA G99 (England)	2019	Engineering recommendation: Requirements for the connection of generation equipment in parallel with public distribution networks
IEC 60038	2012	CENELEC standard voltages
IEC 60044-7	1999	Instrument transformers – Part 7: Electronic voltage transformers
IEC 60076-5	2007	Power transformers – Part 5: Ability to withstand short-circuit
IEC 60076-11	2018	Power transformers – Part 11: Dry-type transformers
IEC 60099-4	2014	Surge arresters – Part 4: Metal-oxide surge arresters without gaps for a.c. systems
IEC 60204-1	2016	Safety of machinery – Electrical equipment of machines – Part 1: General requirements

Standards, guidelines, regulations	Year	Title
IEC 60364-5-56	2018	Low-voltage electrical installations – Part 5-56: Selection and erection of electrical equipment – Safety services
IEC 60364-8-1	2019	Low-voltage electrical installations – Part 8-1: Functional aspects – Energy efficiency
IEC 60617	2011	Graphical symbols for diagrams
IEC 60644 ed. 2.1	2019	Specification for high-voltage fuse-links for motor circuit applications
IEC 60870-5-103	1997	Telecontrol equipment and systems – Part 5-103: Transmission protocols – Companion standard for the informative interface of protection equipment
IEC 60909-0	2016	Short-circuit currents in three-phase a.c. systems – Part 0: Calculation of currents
IEC 60947-4-1	2018	Low-voltage switchgear and controlgear – Part 4-1: Contactors and motor-starters – Electromechanical contactors and motor-starters
IEC 60947-4-2	2020	Low-voltage switchgear and controlgear – Part 4-2: Contactors and motor-starters – Semiconductor motor controllers, starters and soft-starters
IEC 61000		Series of standards: Electromagnetic compatibility (EMC)
IEC 61000-4-30	2015	Electromagnetic compatibility (EMC) – Part 4-30: Testing and measurement techniques – Power quality measurement methods
IEC 61800		Series of standards: Adjustable speed electrical power drive systems
IEC 61850		Series of standards: Communication networks and systems
IEC 61869-2	2012	Instrument transformers – Part 2: Additional requirements for current transformers
IEC 61869-3	2011	Instrument transformers – Part 3: Additional requirements for inductive voltage transformers
IEC 62271		Series of standards: High-voltage switchgear and controlgear
IEC 62271-1	2017	High-voltage switchgear and controlgear – Part 1: Common specifications for alternating current switchgear and controlgear
IEC 62271-100	2008	High-voltage switchgear and controlgear – Part 100: Alternating-current circuit-breakers
IEC 62271-106	2011	High-voltage switchgear and controlgear – Part 106: Alternating current contactors, contactor-based controllers and motor-starters
IEC 62271-110	2018	High-voltage switchgear and controlgear – Part 110: Inductive load switching
IEC/TR 61869-100	2017	Instrument transformers – Part 100: Guidance for application of current transformers in power system protection
IEC/TS 60034-25	2014	Rotating electrical machines – Part 25: A.C. electrical machines when used in power drive systems – Application guide
IEC/TS 62786	2017	Distributed energy resources connection with the grid
IEC/IEEE 62271-37-013	2015	High-voltage switchgear and controlgear – Part 37-013: Alternating-current generator circuit-breakers
IEEE 141	1993	Recommended practice for electric power distribution for industrial plants

Standards, guidelines, regulations	Year	Title
IEEE 1547	2018	IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces
IEEE 2030	2011	Guide for smart grid interoperability of energy technology an information technology operation with the Electric Power Systems (EPS), end-use applications, and loads
IEEE C37.2	2008	Electrical power system device function numbers, acronyms, and contact designations
ISO 9001	2015	Quality management systems – Requirements
ISO 14001	2015	Environmental management systems – Requirements with guidance for use
ISO 50001	2015	Energy management systems – Requirements with guidance for use
NTS v1.0 (Spain)	2019	Norma técnica de supervisión de la conformidad de los módulos de generación de electricidad según el Reglamento UE 2016/631 (Technical supervision standard to harmonize electricity generating modules with 2016/631/EU)
Q/GDW 480-2015 (China)	2015	Technical rule for distributed resources connected to power grid
Technical regulation 3.2.1 (Denmark)	2016	Technical regulation 3.2.1 for power plants up to and including 11 kW
Technical regulation 3.2.2 /.3 /.5 (Denmark)	2016/17	Technical regulation 3.2.2 / 3.2.3 / 3.2.5 for PV / thermal / Wind power plants above 11 kW
VDE AR-N 4110 (Germany)	2018	Technical rules for the connection and operation of customer installations to the medium-voltage grid (TCR medium voltage)
VDI 2552 Sheet 1	2020	Building information modeling – Fundamentals
VDI 3633 Sheet 6	2001	Simulation of systems in materials handling, logistics and production – Representation of human resources in simulation models
VDI 3637	1996	Data collection for long term factory planning
VDI 4499 Sheet 1	2008 / bestätigt 2015	Digital factory – Fundamentals
VDI 5200 Sheet 1	2011	Factory planning – Planning procedures

7.2 List of Abbreviations

3G	Mobile radio standard 3rd generation

A

AAL	Active-assisted living
ACER	Agency for the Cooperation of Energy Regulators
AEMC	Australian Energy Market Commission
ANSI	American National Standards Institute
API	Application programming interface
ASP	Air separation plant
AVC	Automatic voltage control

B

BIM	Building information modeling
Btu	British thermal unit

C

CAPEX	Capital expenditure
CB	Circuit-breaker
CDE	Common data environment
CENELEC	Comité Européen de Normalisation Électrotechnique (European Committee for Electrotechnical Standardization)
CEPA	Cambridge Economic Policy Associates Ltd
CHP	Combined heat and power
Cip	Cleaning in place
CMS	Condition monitoring system
CPS	Cyber-physical system
CSV	Comma separated values

D

DEMS	Distributed energy resource management system
DEOP	Distributed energy optimization
DES	Distributed energy systems
DSO	Distribution system operator

E

EIA	U.S. Energy Information Administration
ENA	Energy Networks Association
ENTSO-E	European Network of Transmission System Operators for Electricity
EU	European Union

F

FOS	Field of science and technology
FRT	Fault-ride-through
FSM	Frequency-sensitive mode

G

GB	Gigabyte
GDP	Gross domestic product
GPS	Global positioning system

H

HGL	Hydrocarbon gas liquids
HMI	Human-machine interface
HOAI	German Official Scale of Fees for Services by Architects and Engineers
HTML	Hypertext markup language
HV	High voltage
HV HRC	High-voltage high-rupturing capacity
HVAC	Heating - ventilation - air conditioning

I

I4.0	Industry 4.0
ICT	Information and communications technology
IEA	International Energy Agency
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IFC	Industry foundation classes
IPR	Interface protection relay
IPS	Interface protection system
IoT	Internet of things
IT	Information technology

K

KPI	Key performance indicator

L

LCOE	Levelized cost of electricity
LFC	Load frequency control
LFSM-O	Limited frequency sensitive mode – overfrequency
LFSM-U	Limited frequency sensitive mode – underfrequency

LoD	Level of detail
LOD	Level of development
LoG	Level of geometry
LoI	Level of information
LV	Low voltage

M

M2M	Machine-to-machine
M^3	Machine-machine-management
MAC	Main air compressor
MCC	Motor control center
MOM	Manufacturing operations management
MTS	Main transformer substation
MV	Medium voltage

N

NC RfG	Network code requirements for generators
NERC	North American Electric Reliability Corporation

O

O & M	Operation and maintenance
OECD	Organisation for Economic Co-operation and Development
OPEX	Operational expenditure
OVRT	Overvoltage-ride-through

P

PaaS	Platform as a service
PCC	Point of common coupling
PDM	Product data management
PET	Polyethylene
PIM	Project information model
PL	Performance level
PLM	Product lifecycle management
PMS	Power management system
PNF	Pre-notification factor
PoC	Point of connection
PP	Performance phase
PQA	Power quality analytics
prim	Primary voltage
PSS®	Power system simulation software
PV	Photovoltaic
PVC	Polyvinylchloride

R

R & D	Research and development
ROCOF	Rate of change of frequency
ROI	Return on investment
RPM	Revolutions per minute
RTD	Resistance temperature detector

S

SCADA	Supervisory control and data acquisition
sf	Simultaneity factor
SF	Substitutability factor
SI	Système International d´Unités (International units system)
SIL	Safety integrity level
SMS	Short message service
SoSt	Soft starter
STC	Standard test conditions

T

THD	Total harmonic distortion
THDI	Total harmonic distortion current I
THDU	Total harmonic distortion voltage U
TIA	Totally Integrated Automation
TIP	Totally Integrated Power
TRV	Transient recovery voltage
TSO	Transmission system operator

U

UPS	Uninterruptible power supply
UVRT	Undervoltage-ride-through

V

VCB	Vacuum circuit-breaker
VDI	Association of German engineers
VFD	Variable frequency drive
VoLL	Value of lost load
VPP	Virtual power plant

Contents

1

2

3

4

5

6

7

7.3 Bibliography

	Author	Year	Title
1.1	Siemens AG	2018	Planning of Electric Power Distribution: Technical Principles (EMMS-T10007-00)
1.2	Kiank, Fruth	2011	Planning Guide for Power Distribution Plants (ISBN: 978-3-89578-371-5)
1.3	acatech – Deutsche Akademie der Technikwissenschaften	2017	Industrie 4.0 Maturity Index (ISSN 2192-6174)
1.4	Siemens AG	2019	Intelligent Power Distribution (SIDS-T10003-00-7600)
1.5	BIMpedia	Download 2021	https://www.bimpedia.eu/-/1347-dimensionen-der-bim-planung
1.6	Bauen digital Schweiz	2018	BIM Workbook – Verständigung (BIM Workbook – Understanding)
2.1	Schenk, Wirth, Müller	2014	Fabrikplanung und Fabrikbetrieb (Factory planning and factory operation)
2.2	M. Bergholz	2005	Dissertationsschrift: Objektorientierte Fabrikplanung (Object-oriented factory planning)
2.3	E. Uhlmann	2011	Vorlesungsfolien Produktionstechnik I (PT1-VL 9) (Lecture slides for production technology)
2.4	OECD (Organisation for Economic Co-operation and Development)	2007	Revised field of science and technology (FOS) classification (JT03222603)
2.5	Aggteleky	1987	Fabrikplanung – Werksentwicklung und Betriebsrationalisierung (Factory planning – Factory development and rationalization of operations)
2.6	Wiendahl, Reichardt, Nyhuis	2014	Handbuch Fabrikplanung: Konzept, Gestaltung und Umsetzung wandlungsfähiger Produktionsstätten (Manual for factory planning: concept, design and implementation of adaptable production plants)
2.7	Siemens AG	2019	Realize your digital transformation now (DICM-B00002-01-7600)
2.8	Siemens AG	2018	White Paper: Mindsphere (69993-A21)
3.1	U.S. Energy Information Administration	2018	International Energy Outlook 2019
3.2	Eurostat	Download 2020	https://ec.europa.eu/eurostat/de/data/database
	EIA	Download 2020	https://www.eia.gov/outlooks/aeo/
	Reserve Bank of India	Download 2020	The India KLEMS database
	Statistics Canada	Download 2020	Principal statistics for manufacturing industries, by North American Industry Classification System (Table: 16-10-0117-01)
3.3	Heat Roadmap Europe	2019	EU28 fuel prices for 2015, 2030 and 2050
3.4	Trinomcs B.V.	2018	Study on Energy Prices, Costs and Subsidies and their Impact on Industry and Households
3.5	Government of India – Central Statistics Office – Ministry of Statistics and Programme Implementation	2018	Energy Statistics 2019
3.6	Simplified energy balances – annual data [nrg_100a]	2018 [Download 30.07.2020]	https://db.nomics.world/Eurostat/nrg_100a (Download am 30.07.2020)
3.7	BP p.l.c.	2018	BP Statistical Review of World Energy 2019
3.8	D. Röhrlich	2019 [Download 30.07.2020]	Unsichere Stromversorgung in Zeiten der Energiewende (Insecure power supply in times of energy transition) [www.deutschlandfunk.de/ruesten-gegen-den-blackout-unsichere-stromversorgung-in.724.de.html?dram:article_id=456306]
3.9	European Commission	2016	Interim Report of the Sector Inquiry on Capacity Mechanisms [SWD(2016) 119 final]
3.10	IEA	Download 30.07.2020	Auswertung von Sankey-Diagrammen (Evaluation of Sankey diagrams) [https://www.iea.org/sankey/]

Contents

1

2

3

4

5

6

7

	Author	Year	Title
3.11	The World Bank Group	Download 30.07.2020	Datenzusammenstellung von (Data compilation of) [https://databank.worldbank.org/source/world-development-indicators]
3.12	Agency for the Cooperation of Energy Regulators (ACER)	2018	Study on the Value of Lost Load of Electricity Supply in Europe
3.13	ENTSO-E	2018	Draft: Proposal for a Methodology for calculating the Value of Lost Load, the Cost of New Entry for generation, or demand response, and the Reliability Standard in accordance with Article 23 of the Regulation (EU) 2019/943 of the European Parliament and of the Council of 5 June 2019 on the internal market for electricity (recast)
3.14	U.S. (DOE) Office of Energy Efficiency and Renewable Energy	Download 30.07.2020	Manufacturing Energy and Carbon Footprints (2014 MECS) [https://www.energy.gov/sites/prod/files/2019/06/f64/Manufacturing%20Energy%20Footprint-2014_Latest_compliant.pdf]
4.1	The Institute of Electrical and Electronics Engineers, Inc.	1993	IEEE 141-1993: IEEE Recommended Practice for Electric Power Distribution for Industrial Plants
4.2	NERC (North American Electric Reliability Corporation)	2020	Reliability Standards for the Bulk Electric Systems of North America
4.3	International Renewable Energy Agency (IRENA)	2016	Scaling up variable renewable power: the role of grid codes
4.4	Bründlinger, Schaupp, Graditi, Adinolfi	2018	Implementation of the European Network Code on Requirements for Generators on the European national level (Conference: Solar Integration Workshop at Stockholm)
4.5	Siemens AG	2020	White Paper: Starting motors – Technical principles and selection criteria
5.1	Siemens AG	2017	Applications for power distribution – Energy transparency
5.2	European Commssion JRC	2010	Guidelines for PV Power Measurement in Industry
5.3	Siemens AG	2021	Catalog IC10: SIRIUS – Industrial Controls (E86060-K1010-A101-B2-7600)
5.4	Siemens AG	2021	Catalog LV10: Low-Voltage Power Distribution and Electrical Installation Technology (E86060-K8280-A101-B3-7600)
5.5	Siemens AG	2018	Catalog D31.1: SINAMICS Inverters for Single-Axis Drives – Built-In Units (E86060-K5531-A111-A1-7600)
5.6	Siemens AG	2017	Configuration Manual – Load Feeders – Configuring the SIRIUS Modular System (A8E56203880102A/RS-AB/006)
5.7	Siemens AG	2020	Technical Series Edition 3 - Modeling of systems for Uninterruptible Power Supply (UPS) in SIMARIS®design for application in data centers
5.8	Siemens AG	2016	3VA selectivity configuration manual (3ZW1012-0VA20-0AC1)
5.9	Siemens AG	2016	Technical Series Edition 16 - Transformer Selection according to Utilisation Profiles
6.1	SIBA GmbH	2011	Handbuch Hochspannnungs-Sicherungen (Manual for high-voltage fuses)
6.2	SIBA GmbH	2020	HV-Catalogue
6.3	Siemens AG	2020	Vacuum circuit breakers for generator switching applications (EMLP-B10161-00-7600)
6.4	Siemens AG	2020	SIPROTEC 5 Catalog, Edition 7 (SIDG-C10059-00-7600)
6.5	Siemens AG	2017	Planning of Electric Power Distribution: Products & Systems Medium Voltage (EMMS-T10099-00-7600)
6.6	Siemens AG	2017	SICAM Power Quality and Measurement – Catalog. Edition 6 (EMDG-C10026-01-7600)
6.7	Siemens AG	2017	Catalog HA 35.11 (EMMS-K1435-A101-B5-7600)
6.8	Siemens AG	2019	Air-Insulated Medium-Voltage Switchgear NXAIR and NXAIR M – Catalog HA 25.71 (EMMS-K1425-A811-B5-7600)

7.4 Units System

SI basic units			
Size	**Unit**	**Symbol / abbreviation**	
Length	Meter	m	
Weight	Kilogram	kg	
Time	Second	s	
Electric current	Ampere	A	
Temperature	Kelvin	K	
Luminous intensity	Candela	cd	

SI units			
Size	**Unit**	**Symbol / abbreviation**	**Derived**
Frequency	Hertz	Hz	1 Hz = 1 s^{-1}
Force	Newton	N	1 N = 1 kg · m/s^2
Pressure, tension	Pascal	Pa	1 Pa = 1 N/m^2
Energy, quantity of heat	Joule	J	1 J = 1 N · m = 1 kg · m^2/s^2
Power, heat flow	Watt	W	1 W = 1 J/s = 1 kg · m^2/s^3
Electric charge	Coulomb	C	1 C = 1 A · s
Electric voltage	Volt	V	1 V = 1 J/C = 1 kg · m^2 / (A · s^3) = 1 W/A
Electric resistance	Ohm	Ω	1 Ω = 1 V/A
Electric conductivity	Siemens	S	1 S = 1 Ω^{-1} = 1 A/V
Magnetic flux	Weber	Wb	1 Wb = 1 V · s
Magnetic flux density	Tesla	T	1 T = 1 Wb/m^2
Inductance	Henry	H	1 H = 1 Wb/A
Luminous flux	Lumen	lm	1 lm = 1 cd · sr [1)]
Illuminance	Lux	lx	1 lx = 1 lm/m^2

1) sr = steradian (measuring unit for the solid angle *sr*, so that an area A is enclosed on a sphere with a radius r: $sr = A/r^2$)

Notes

Notes

Contents

1

2

3

4

5

6

7

Contents

1

2

3

4

5

6

7

We would like to thank the following persons for their technical support in the preparation of this manual:

Braga, Rodrigo
Englert, Ingo
Erschen, Benjamin
Gemsjäger, Ben
Glas, Johannes
Kapinosova, Kateryna
Maschek, Jürgen
Ramirez Jordan, Saul
Shamim, Taiyab
Weber, Ralf
Wegehaupt, Klemens

Imprint

Totally Integrated Power – Consultant Support
Applications for Electric Power Distribution
Industrial Plants

Published by

Siemens AG
Smart Infrastructure
Distribution Systems

Editor

Siemens AG
Dr. Siegbert Hopf
E-mail: siegbert.hopf@siemens.com

Publishing House

Saatchi & Saatchi GmbH
Arnulfstraße 60
80335 Munich, Germany

Siemens AG

Smart Infrastructure
Distribution Systems

Mozartstr. 31c
91052 Erlangen
Germany

E-Mail: consultant-support.tip@siemens.com