

# 1

## Introduction

### 1.1

#### Reliability, Security, Economy

Power system engineering is the central area of activity for power system planning, project engineering, operation and rehabilitation of power systems for electrical power supply. Power system engineering comprises the analysis, calculation and design of electrical systems and equipment, the setup of tender documents, the evaluation of offers and their technical and financial assessment and contract negotiations and award. It is seen as an indispensable and integral part of the engineering activities for feasibility studies, for planning and operating studies, for project engineering, for the development, extension and rehabilitation of existing facilities, for the design of network protection concepts and protective relay settings and also for clearing up of disturbances e.g. following short-circuits.

The supply of electricity—as for other sources of energy—at competitive unit price, in sufficient quantity and quality, and with safe and reliable supply through reliable equipment, system structures and devices is of crucial importance for the economic development of industries, regions and countries. The planning of supply systems must take into account different boundary conditions, which are based on regional and structural consideration that in many cases have a considerable impact on the technical design. Given that, in comparison with all other industries, the degree of capital investment in electric utilities takes the top position, not only from the monetary point of view but also in terms of long-term return of assets, it becomes clear that each investment decision requires particularly careful planning and investigation, to which power system engineering and power system planning contribute substantially.

The reliability of the supply is determined not only by the quality of the equipment but also by careful planning and detailed knowledge of power systems, together with a consistent use of relevant standards and norms, in particular IEC standards, national standards and norms as well as internal regulations. Furthermore, the mode of system operation must conform to the conditions specified by standards, including the planning process, manufacturing of equipment and commissioning. Just as faults in equipment cannot be totally excluded because of technical or human failure, likewise the equipment and installations cannot be

designed to withstand any kind of fault: accordingly, the effects of faults must be limited. Thus, violation of or damage to other equipment must be prevented in order to ensure undisturbed system operation and reliable and safe supply to the consumers.

The security of the electrical power supply implies strict adherence to the conditions specified in standards, norms and regulations concerning the prevention of accidents. In low-voltage systems the protection of individuals is seen of primary importance; at higher voltage levels the protection of equipment and installations must also be considered.

## 1.2

### Legal, Political and Social Restrictions

Electrical power systems are operated with certain restrictions imposed by legal requirements, technical standards, political issues, financial constraints and social, political and environmental parameters which have a strong influence on the system structure, the design and the rating of equipment and thus on the cost of investment and cost of energy, without any justification in terms of aspects of security, reliability and economy. Some general areas pertaining to regulations, guidelines and laws for electrical power supply are simply stated below, without any elaboration at this stage.

- Concession delivery regulations
- Market guidelines for domestic electricity supply
- Electrical power industry laws
- Energy taxation
- Laws supporting or promoting “green-energy”
- Environmental aspects
- Safety and security aspects
- Right-of-way for overhead-line and cable routing.

Such regulations, laws and guidelines will have an impact on planning, construction and operation of power systems, likewise on the reliability of the power supply, the cost structure of equipment, the cost of electrical energy and finally on the attractiveness of the economic situation within the particular country.

- Generating plants will be operated in merit order, that is, the generator with lowest production cost will be operated in preference to operating generation with the highest efficiency.
- Criteria of profitability must be reevaluated in the light of laws supporting “green-energy.”
- Reduced revenues from energy sales will lead to a decrease in the investments, personnel and maintenance costs, with consequences of reduced availability and reliability.
- Increasing the proportion of “green-energy” generation plants that have low availability leads to an increase in the running reserve of conventional power

stations, with consequences of reduced efficiency of these plants and thus higher costs.

- Reduction of investment for the construction of new power stations leads to a decrease in reserve capabilities and thus to a decrease in the reliability of the power supply.
- Expenditures for coordination during normal operation and during emergency conditions are increased with rising numbers of market participants, with the consequence of an increased risk of failures.
- Power systems of today are planned for the generation of electrical energy in central locations by large power stations with transmission systems to the load centers. A change of the production structure, for example, by increase of “green-energy” production plants and development of small co-generation plants, mainly installed in distribution systems, requires high additional investment for the extension of the power system, resulting in rises in energy prices as well as reduced usage of existing plants.
- The power system structure up to now has been determined by connections of the load centers with the locations of power stations, which were selected on the basis of the availability of primary energy (e.g. lignite coal), the presence of cooling water (e.g. for nuclear power stations) or hydrological conditions (e.g. for hydro power stations). The construction of offshore wind energy parks requires substantial investment in new transmission lines to transmit the generated energy to the load centers.
- Increase of “green-energy” production plants, in particular photovoltaic, wind energy and fuel-cells, reduces the quality of the power supply (“Power quality”) due to the increased requirement for power electronics.
- The long periods for planning and investment of power stations and high-voltage transmission systems do not allow for fast and radical changes. Decisions on a different development, for example, away from nuclear power generation towards “green-energy” production, are to a certain extent irreversible if these decisions are not based on technical and economic background and detailed knowledge but are predominantly politically and ideologically motivated.

As an example, the structure of public tariffs for electrical energy in the Federal Republic of Germany is characterized by numerous measures initiated by the government. These taxes, concessionary rates, expenditures occasioned by the “green-energy” law, and so on amounted in the year 2011 to nearly 23.2 billion euro (€) according to data of the Bundesnetzagentur. Included in this are 0.2% for the support of combined cycle plants, 6.7% for concessionary rates for use of public rights of way, 14.1% for expenditures for the “green-energy” laws and 8.2% for energy taxes. Additionally, VAT (Value Added Tax) of 19% is added for private households. For the average electricity consumption of a private household of 3500kWh per year, these costs as a result of governmental actions amount to almost 35€ per household per month.

### 1.3

#### Needs for Power System Planning

Power system planning must take due consideration of the restrictions mentioned above and must develop concepts and structures which are technically and economically sound. This includes the planning and project engineering of generation systems, transmission and distribution networks, and optimization of systems structures and equipment, in order to enable flexible and economic operation in the long as well as the short term. Power system planning also has to react to changes in the technical, economic and political restrictions. Key activities are the planning and construction of power stations, the associated planning of transmission and distribution systems, considerations of long-term supply contracts for primary energy, and cost analysis.

The systematic planning of power systems is an indispensable part of power system engineering, but it must not be limited to the planning of individual system components or determination of the major parameters of equipment, which can result in suboptimal solutions. Power system engineering must incorporate familiar aspects regarding technical and economic possibility, but also those that are sometimes difficult to quantify, such as the following:

- Load forecast for the power system under consideration for a period of several years
- Energy forecast in the long term
- Standardization, availability, exchangeability and compatibility of equipment
- Standardized rated parameters of equipment
- Restrictions on system operation
- Feasibility with regard to technical, financial and time aspects
- Political acceptance
- Ecological and environmental compatibility.

Power system engineering and power system planning require a systematic approach, which has to take into account the financial and time restrictions of the investigations as well as to cope with all the technical and economic aspects for the analysis of complex problem definitions. Planning of power systems and project engineering of installations are initiated by:

- Demand from customers for supply of higher load, or connection of new production plants in industry
- Demand for higher short-circuit power to cover requirements of power quality at the connection point (point of common coupling)
- Construction of large buildings, such as shopping centers, office buildings or department stores
- Planning of industrial areas or extension of production processes in industry with requirement of additional power
- Planning of new residential areas
- General increase in electricity demand.

- Connection of “green-energy” generation, such as photovoltaic and biomass generation to LV and MV systems and wind energy plants in MV and HV systems.

Power system planning is based on a reliable load forecast which takes into account the developments in the power system mentioned above. The load increase of households, commercial and industrial customers is affected by the overall economic development of the country, by classification by land development plans, by fiscal incentives and taxes (for example, for the use or promotion of “green-energy”) and by political measures. Needs for power system planning also arise as a result of changed technical boundary conditions, such as the replacement of old installations and equipment, introduction of new standards and regulations, construction of new power stations and fundamental changes in the scenario of energy production, for example, by installation of photovoltaic generation. The objective of power system planning is the determination and justification of system topologies, schemes for substations and the main parameters of equipment considering the criteria of economy, security and reliability.

Further aspects must be defined apart from the load forecast:

- The information database of the existing power system with respect to geographical, topological and electrical parameters
- Information about rights-of-way, right of possession and space requirements for substations and line routes
- Information about investment and operational costs of installations
- Information about the costs of losses
- Knowledge of norms, standards and regulations.

The fundamental relations of power system planning are outlined in Figure 1.1.

## 1.4

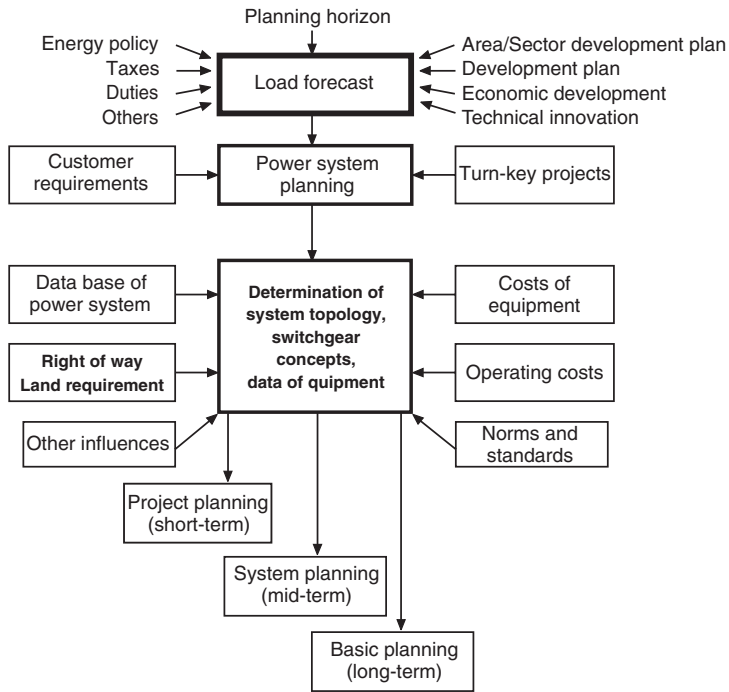
### Basic, Development and Project Planning

Load forecast, power system planning and project engineering are assigned to special time intervals, defining partially the tasks to be carried out. Generally three steps of planning are to be considered—basic planning, development planning and project planning—which cover different time periods as outlined in Figure 1.2.

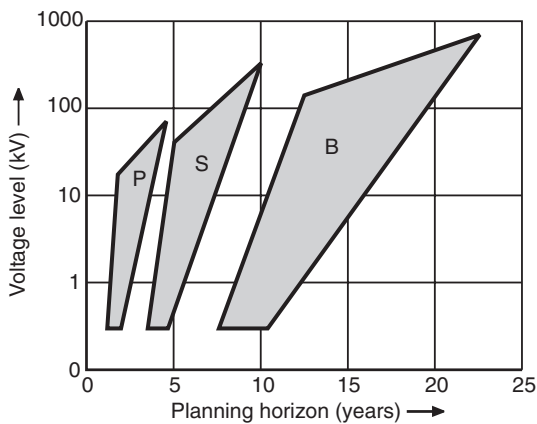
#### 1.4.1

##### Basic Planning

For all voltage levels the fundamental system concepts are defined: standardization of equipment, neutral earthing concepts, nominal voltages and basics of power system operation. The planning horizon is up to 10 years in low-voltage systems and can exceed 20 years in high-voltage transmission systems.



**Figure 1.1** Fundamental relations of power system planning.



**Figure 1.2** Steps of planning at different voltage levels. P, project planning; S, system development planning; B, basic planning.

## 1.4.2

**System Development Planning**

Detailed planning of the system topology is carried out based on the load forecast. Alternative concepts are analyzed technically by load-flow calculations, short-circuit analysis and stability computations. Cost estimates are also carried out. Disturbance and operational statistics are evaluated and locations for installations are determined. The main parameters of equipment, such as cross-section of overhead lines and cables, short-circuit impedance of transformers are defined. The planning horizon is approximately five years in a low-voltage system and up to 10 years for a high-voltage transmission system.

## 1.4.3

**Project Planning**

The projects defined in the system development planning stage are implemented. Typical tasks of the project engineering are the connection types of new customers, connection of new substations to the power system, restructuring measures, evaluation of information on system loading, preparation of tender documents and evaluation of offers, supervising construction contracts, cost calculation and cost control. Project planning covers a time range of one year in the low-voltage system and up to four years in the high-voltage system.

## 1.5

**Instruments for Power System Planning**

The use of computer programs as well as the extent and details of the investigations are oriented at the desired and/or required aim of the planning process. The fundamental investigations that must be accomplished by power system planning are explained below.

The load-flow analysis (also named power-flow calculation) is a fundamental task for planning and operation of power systems. It serves primarily to determine the loading and the utilization of the equipment, to calculate the active and reactive power-flow in the branches (lines, transformers, etc.) of the power system, to determine the voltage profile and to calculate the power system losses. Single or multiple outages of equipment can be simulated in the context of the investigations for different preloading conditions. The required setting range of the transformer tap-changer and the reactive power supply by generators or compensation devices are determined.

Short-circuit current calculations are carried out for selected system configurations, defined by load-flow analysis. For special applications, such as protection coordination, short-circuit current calculation should consider the preloading conditions as well. Symmetrical and unsymmetrical faults are simulated and the results are taken as a basis for the assessment of the short-circuit strength. Calculations of short-circuit current for faults between two systems are sometimes

necessary to clarify system disturbances. Faults between two systems may occur in cases of multiple-circuit towers in overhead-line systems.

The results obtained by calculation programs are as exact as the main parameters of the equipment. If those data are not available, the parameters must be determined by calculation. In the case of overhead-lines and cables, the reactances, resistances and capacitances in the positive-sequence and zero-sequence component are calculated from the geometrical arrangement of the conductors and from the cable construction. Subsequent calculation may determine the permissible thermal loading, the surge impedance, natural power and, in case of overhead lines, additionally the electric field strength at the conductor as well as the electric and magnetic field strengths in the surrounding of the line for certain applications.

The permissible thermal loading of equipment under steady-state conditions and under emergency conditions is based on ambient conditions, for example, ambient temperature, thermal resistance of soil, wind velocity, sun exposure and so on. The calculation of the maximum permissible loading plays a larger role with cables than with overhead lines because of the poorer heat dissipation and the lower thermal overload capability.

The investigation of the static and in particular transient stability is a typical task when planning and analyzing high-voltage transmission systems. Stability analysis is also important for the connection of industrial plants with their own generation to the public supply system. Stability analysis has to be carried out for the determination of frequency- and voltage-dependent load-shedding schemes. The stability of a power system depends on the number and type of power stations, the type and rating of generators, their control and excitation schemes, devices for reactive power control, and the system load as well as on the voltage level and the complexity of the power system. An imbalance between produced power and the system load results in a change of frequency and voltage. In transient processes, for example, short-circuits with subsequent disconnection of equipment, voltage and frequency fluctuations might result in cascading disconnections of equipment and subsequent collapse of the power supply.

In industrial power systems and auxiliary supply systems of power stations, both of which are characterized by a high portion of motor load, the motors must start again after short-circuits or change-overs with no-voltage conditions. Suitable measures, such as increase of the short-circuit power and time-dependent control of the motor starts, are likewise tasks that are carried out by stability analyses.

The insulation of equipment must withstand the foreseeable normal voltage stress. It is generally economically not justifiable and in detail not possible to design the insulation of equipment against every voltage stress. Equipment and its overvoltage protection, primarily surge arresters, must be designed and selected with regard the insulation and sensitivity level, considering all voltage stresses that may occur in the power system. The main field of calculation of overvoltages and insulation coordination is for switchgears, as most of the equipment has non-self-restoring insulation.



Equipment in power systems is loaded, apart from currents and voltages at power-frequency, also by those with higher frequencies (harmonics and interharmonics) emitted by equipment with power electronics in common with the industrial load, in the transmission system by FACTS (flexible AC transmission systems) and by generation units in photovoltaic and wind-energy plants. Higher frequencies in current cause additional losses in transformers and capacitors and can lead to maloperation of any equipment. Due to the increasing electronic load and application of power electronics in generation plants, the emission of harmonics and interharmonics is increasing. Using frequency-dependent system parameters, the statistical distribution of the higher-frequency currents and the voltage spectrum can be calculated as well as some characteristic values, such as total harmonic distortion (THD), harmonic content, and so on.

Equipment installations, communication circuits and pipelines are affected by asymmetrical short-circuits in high-voltage equipment due to the capacitive, inductive and conductive couplings existing between the equipment. Thus, inadmissible high voltages can be induced and coupled into pipelines. In power systems with resonance earthing, unsymmetry in voltage can occur due to parallel line routing with high-voltage transmission lines. The specific material properties and the geometric outline of the equipment must be known for the analysis of these interference problems.

Electromagnetic fields in the vicinity of overhead lines and installations must be calculated and compared with normative specified precaution limit values, to assess probable interference of humans and animals exposed to the electric and magnetic fields.

Earthing of neutrals is a central topic when planning power systems since the insulation coordination, the design of the protection schemes and other partial aspects, such as prospective current through earth, touch and step voltages, depend on the type of neutral earthing.

In addition to the technical investigations, questions of economy, loss evaluation and system optimization are of importance in the context of power system planning. The extension of distribution systems, in particular in urban supply areas, requires a large number of investigations to cover all possible alternatives regarding technical and cost-related criteria. The analysis of all alternative concepts for distribution systems cannot normally be carried out without using suitable programs with search and optimization strategies. Optimization strategies in high-voltage transmission systems are normally not applicable because of restrictions, since rights of way for overhead lines and cables as well as locations of substations cannot be freely chosen.

The conceptual design of network protection schemes determines the secure and reliable supply of the consumers with electricity. Network protection schemes must recognize incorrect and inadmissible operating conditions clearly and separate the faulty equipment rapidly, safely and selectively from the power system. An expansion of the fault onto other equipment and system operation has to be avoided. Besides the fundamental design of protection systems, the parameters of voltage and current transformers and transducers must be

defined and the settings of the protective devices must be determined. The analysis of the protection concept represents a substantial task for the analysis of disturbances.

## 1.6

### Further Tasks of Power System Engineering

Project engineering is a further task of power system engineering. Project engineering follows the system planning and converts the suggested measures into defined projects. The tasks cover

- The evaluation of the measures specified by the power system planning
- The design of detailed plans, drawings and concept diagrams
- The description of the project in form of texts, layout plans, diagrams and so on
- The definition of general conditions such as test provisions, conditions as per contract, terms of payment and so on
- The provision of tender documents and evaluation of offers of potential contractors
- The contacts with public authorities necessary to obtain permission for rights of way and so on.
- The setup of project team to carry out the specific tasks of the project.