Juergen Schlabbach and Karl-Heinz Rofalski

Power System Engineering

Planning, Design, and Operation of Power Systems and Equipment

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The Authors

Prof. Dr.-Ing Jürgen Schlabbach
University of Applied Sciences
Bielefeld

Dipl.-Ing. Karl-Heinz Rofalski
Bad Homburg

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Contents

Foreword

The supply of electrical energy at competitive prices, in sufficient quantity and quality, and under the aspect of safe supply through reliable equipment, system structures and devices is of crucial importance for the economic development of countries and for the well-being of each individual. When planning power systems different boundary conditions must be considered, which are based on regional, structural, technical, environmental and financial facts, having a considerable impact on the technical design in many cases. Each investment decision requires a particularly careful planning and investigation, to which power system engineering and power system planning contribute substantially.

This book deals with nearly all aspects of power system engineering starting from general approach such as load estimate and the selection of suitable system and substation topology. Details for the design and operational restrictions of the major power system equipment, like cables, transformers and overhead lines are also dealt with. Basics for load-flow representation of equipment and short-circuit analysis are given as well as details on the grounding of system neutrals and insulation coordination. A major chapter deals with the procedures of project definition, tendering and contracting.

The purpose of this book is to serve as a reference and working book for engineers working in practice in utilities and industry. However, it can also be used for additional information and as a hand-book in post-graduate study courses at universities. The individual chapters include theoretical basics as far as necessary but focus mainly on the practical application of the methods as presented in the relevant sections. Carrying out engineering studies and work moreover requires the application of the latest edition of standards, norms and technical recommendations. Examples are given based on projects and work carried out by the authors during the last years.

The preparation of this book was finalised in *March 2008* and reflects the actual status of the techniques, norms and standards. All comments stated in this book are given to the best of knowledge, based on the comprehensive technical experience of the authors.

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juergen.schlabbach@fh-bielefeld.de   rofalski-hg@gmx.de

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 2006 to nearly 12.43 billion euro (€)according to data of the VDEW (the association of public utilities in Germany). Included in this are 6.5% for the support of combined cycle plants, 16.8% for concessionary rates for use of public rights of way, 25.6% for expenditures for the “green-energy” laws and 50.4% 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 4600 kWh per year, these costs as a result of governmental actions amount to almost 100€ per household per year.

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.

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.

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,

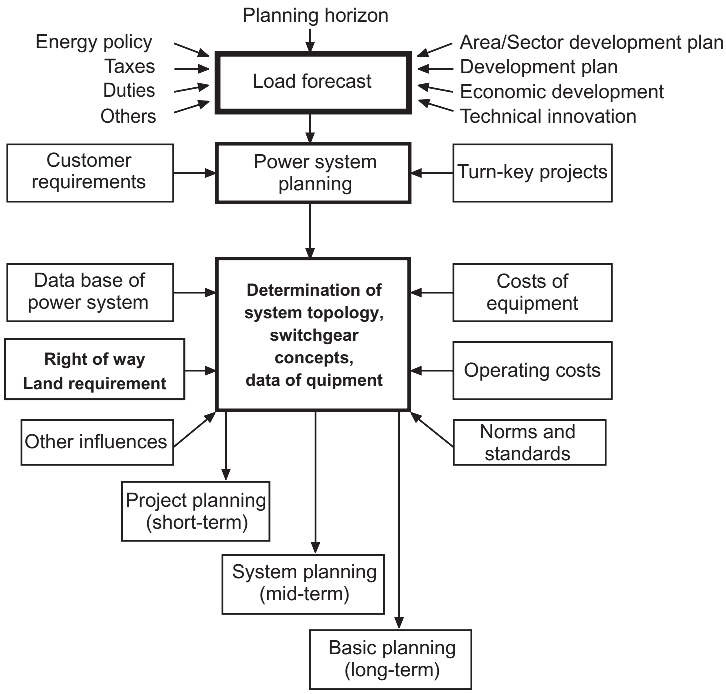

Figure 1.1 Fundamental relations of power system planning.

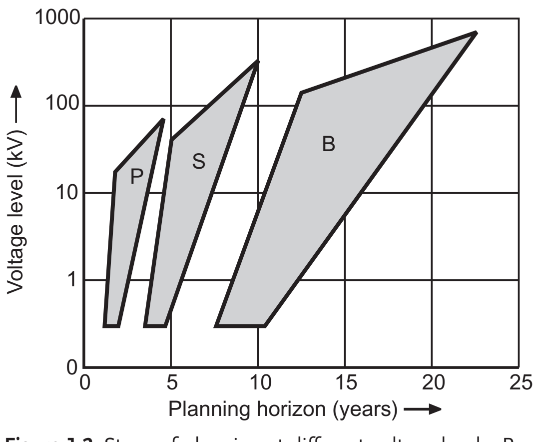

Figure 1.2 Steps of planning at different voltage levels. P, project planning; S, system development planning; B, basic planning.

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 capacitative, 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.

2
Power System Load

2.1
General

The forecasting of power system load is an essential task and forms the basis for planning of power systems. The estimation of the load demand for the power system must be as exact as possible. Despite the availability of sophisticated mathematical procedures, the load forecast is always afflicted with some uncertainty, which increases the farther the forecast is intended to be projected into the future. Power systems, however, are to be planned in such a way that changing load developments can be accommodated by the extension of the system. Long-term planning is related either to principal considerations of power system development or to the extra-high voltage system, so that no irrevocable investment decisions are imposed. These investment decisions concern the short term, as they can be better verified within the short-term range, for which the load forecast can be made with much higher accuracy. One thinks here, for example, of the planning of a medium- and a low-voltage system for a new urban area under development or the planned connection of an industrial area.

If the three stages of the planning process, explained in Chapter 1, are correlated with the required details and the necessary accuracy of the load forecast, it is clear that planning procedures are becoming more detailed within the short-time range and less detailed within the long-time range. Accordingly, different methods of load forecast have to be applied, depending on the planning horizon and thus on the voltage level and/or task of planning. From a number of different load forecasting procedures, five methods are described below.

– Load forecast with load increase factors
– Load forecast based on economic characteristic data
– Load forecast with estimated values
– Load forecast based on specific load values and extend of electrification
– Load forecast with standardized load curves.

The precise application of the different methods cannot be determined exactly and combinations are quite usual.

2.2
Load Forecast with Load Increase Factors

This method is based on the existing power system load and the increase in past years and estimates the future load increase by means of exponential increase functions and trend analyses. The procedures therefore cannot consider externally measured variables and are hardly suitable to provide reliable load and energy predictions. On the basis of the actual system load P_0 the load itself in the year n is determined by an annual increase factor of $(1 + s)$ according to Equation 2.1.

$$P_n = P_0 \cdot (1+s)^n \tag{2.1}$$

Assuming a linear load increase instead of exponential growth, the system load in the year n is given by Equation 2.2.

$$P_n = P_0 \cdot \left(1 + n \cdot \frac{\Delta P}{P_0}\right) \tag{2.2}$$

An increase in accuracy is obtained if the load forecast is carried out separately for the individual consumption sectors, such as households, trade, public supply and so on. The individual results are summed for each year to obtain the total system load.

Another model for load forecasting is based on the phenomenological description of the growth of electrical energy consumption [1]. The appropriate application for different regions must be decided individually for each case. The change of the growth of system load P with time is calculated from Equation 2.3.

$$\frac{\mathrm{d}P}{\mathrm{d}t} = c \cdot P^k \cdot (B-P)^l \tag{2.3}$$

where

k = growth exponent
c = growth rate
B = saturation level of the growth process as standardization value
l = saturation exponent.

With this model, adjustments can be combined with the process of load development of the past with different increases and saturation effects for the future. Experience indicates that, if l can be set $l > k$, the load increase follows the growth processes in the saturation phase at the limiting external conditions. Figure 2.1 shows typical load developments, calculated with the load development model [2]. The load development was standardized at the saturation level $B = 1$ at the end of the period under investigation; the growth rate was set equal to unity.

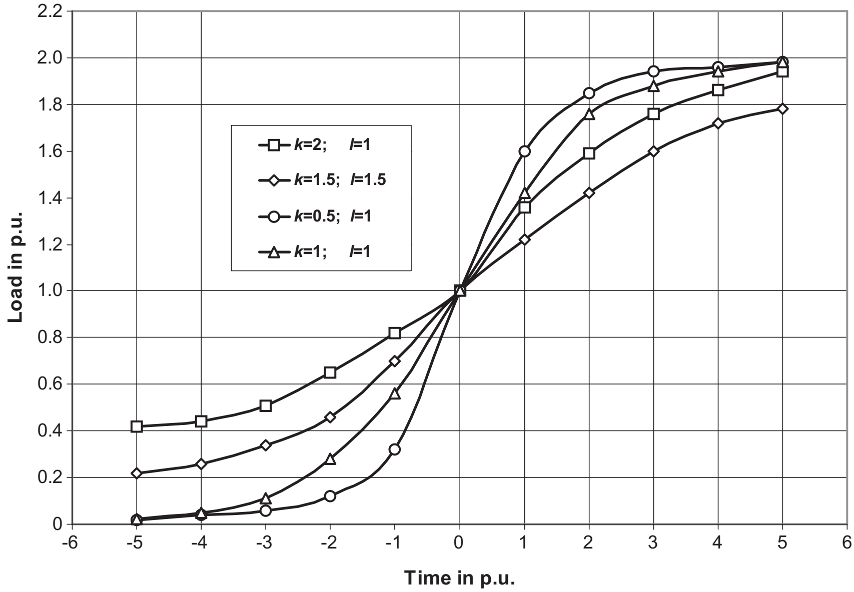

Figure 2.1 Load forecast calculated with the load development model (curves for various values of *k* and *l*).

2.3 Load Forecast with Economic Characteristic Data

Load forecast with economic characteristic data obtained from energy statistics assumes different relations between economic growth, availability of energy resources, energy consumption and requirements in general, such as the increase in energy consumption due to growth of population, and in special applications, such as energy requirements of industry. The requirement for electrical energy per capita of the population is determined to a large extent by the standard of living and the degree of industrialization of a country. However, it has to be considered that high consumption of energy can be also an indicator of the waste of energy, for example, in the case of high numbers of buildings with air conditioning or where there are comparatively low energy prices arising from differences in generation structure, as seen in countries with a high proportion of electrical heating because of cheap energy production in hydro plants.

In the past the increase of electrical energy consumption in industrialized countries was less affected by the growth of population and predominantly by the growth of the gross domestic product (GDP) and/or the gross national product (GNP). The economic ascent of Germany in the years 1950 to 1980 resulted in a rise of primary energy needs and demand for electrical energy. Growth rates of the so-called gross electrical consumption (GEC) amounted to about 7% per year until the end of the 1960s. Thus, doubling of the annually generated electricity every ten years was observed. The average rise of the GEC amounted to approximately 2%

in the 30 years upto 2004, during which economic recession caused decreases in the years 1975, 1982 and 1992. In this context it is not to be assumed that higher energy consumption automatically leads to an increase in the economic indicators GDP or GNP. Uncoupling of economic growth and electrical power requirement for industrialized countries today appears possible. We do not in this book discuss energy predictions based on various economic characteristics in more detail.

2.4
Load Forecast with Estimated Values

The aim of power system planning is to develop structures and concepts for the secure and reliable supply of electricity to the various types of consumers. For the load forecast, land development plans and land registers of town and regional planning authorities can be used. In the case of connection of bulk loads and industrial customers, the system load to be supplied must be determined via the owner of the industrial installation on the basis of the industrial processes operated and the installed number and types of devices and machinery.

Land development plans contain general information about the area development and use of land, and the size, location and types of residential, industrial and commercial areas, without allowing one to be able to derive detailed individual measures from them. The plans are suitable for the preliminary estimation of the future power system load, however. The need for construction of new substations and transformer stations, for example, from the 110-kV system to feed the distribution system, and area requirements needed for it can be justified using them. Estimated values for load densities of different type of land usage are illustrated in Table 2.1.

Larger industrial plants and special large consumers, such as shopping centers, are usually considered with their actual load based on internal planning.

2.5
Load Forecast with Specific Loads and Degrees of Electrification

More exact planning is possible using development plans available from town planning authorities, from which data can be taken concerning the structural use of the areas. Land usage by houses of different types and number of storeys, infrastructure facilities such as schools, kindergartens and business centers, as well as roads and pathways are included in the development plans. Thus a more exact determination of the system load can be achieved. The bases of the load forecast are the loads of typical housing units, which may vary widely depending on the degree of electrification. For the calculation of the number of housing units N_{WE}, the relationship of floor space (floor area) A_W to the housing estate surface A_G, the so-called floor space index G indicated in the development plan is used, see Equation 2.4 [3].

Table 2.1 Estimated values of load densities for different types of land usage (European index).

Type of usage	Load density	Remarks
Individual/single plot	$1\,\mathrm{MW\,km^{-2}}$	Free-standing single-family houses, two-family houses
Built-up area	$3\,\mathrm{MW\,km^{-2}}$	Terrace houses, small portion of multiple-family houses with maximum of three stories
Dense land development	$5\,\mathrm{MW\,km^{-2}}$	Multiple-story buildings, multifamily houses
Business	$5\,\mathrm{MW\,km^{-2}}$	Manufacturing shops, small business areas
	$0.2\,\mathrm{kW\,m^{-2}}$	Warehouses
	$0.3\,\mathrm{kW\,m^{-2}}$	Supermarkets and shopping malls
Industry	Up to $15\,\mathrm{MW\,km^{-2}}$	Medium-size enterprises, not very spatially expansive
General consumption	$2\,\mathrm{MW\,km^{-2}}$	Schools, kindergartens, street lighting

$$G = \frac{A_{\mathrm{W}}}{A_{\mathrm{G}}} \tag{2.4}$$

If the sizes of the housing estates are not yet well known, the total area must be reduced by about 25–40% for roads, pathways and green areas. The inhabitant density E (capita per km^2) is derived from the empirical value of a gross floor space of 20–22 m^2 per inhabitant (German index) according to Equation 2.5.

$$E \approx 25.000 \times G \tag{2.5}$$

In the case of only two persons per housing unit the housing density D is derived from Equation 2.6.

$$D \approx 13.000 \times G \tag{2.6}$$

The number of the housing units N_{WE} for given land development surface A_{G} is derived from Equation 2.7.

$$N_{\mathrm{WE}} \approx 13.000 \times A_{\mathrm{G}} \times G \tag{2.7}$$

The increase of gross floor space per inhabitant as well as the trend to more one-person households in industrialized countries leads to a reduced number of housing units N_{WE} for the area under investigation. The type of residential area must therefore be considered in the estimation of load forecast.

Table 2.2 Degree of electrification and load assumptions for households, authors' index.

Degree of electrification	Peak load of one household (kW)	Portion of peak load per household P_W (kW)	Degree of simultaneous usage g_∞	Remarks
EG1	5	0.77–1.0	0.15–0.2	Low electrification (old buildings, lighting only), today of less importance
EG2	8	1.0–1.2	0.12–0.15	Partial electrification (lighting, cooking)
EG3	30	1.8–2.1	0.06–0.07	Complete electrification (without electrical heating or air-conditioning
EG4	15	10.5–12	0.7–0.8	Total electrification (with electrical heating and air-conditioning)

Households have different grades of usage of electrical appliances. Usage depends on differing attitudes of individual groups within the population to the use of electrical energy, on the age of the house and also on the ages and the incomes of the inhabitants. As indicated in Table 2.2, one can divide the different household appliances in terms of the degree of electrification of the household or building. As not all appliances within one household are in operation at the same time and as not all households have the same consumption habits at the same time, the respective portion of the peak load P_W has to be set for the total load determination, which for increasing number of housing units reaches the limit value g_∞.

The degree of simultaneous usage g_n for the number of households N_{WE} (denoted n in Equation 2.8) can be calculated according to Equation 2.8, whereas values for g_∞ are taken from Table 2.2.

$$g_n = g_\infty + (1 - g_\infty) \cdot n^{-0.75} \tag{2.8}$$

The proportion of peak load to be taken for the load forecast P_{tot} for households with different degrees of electrification ($I = 1, \ldots, 4$) can be calculated using Equation 2.9.

$$P_{tot} = \sum_{i=1,4} g_{ni} \cdot P_{Wi} \cdot n_i \tag{2.9}$$

The loads for commercial, industrial and common consumers are added to the load of the housing units.