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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.

1.2 Legal, Political and Social Restrictions

- 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.

1.3 Needs for Power System Planning

- 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.

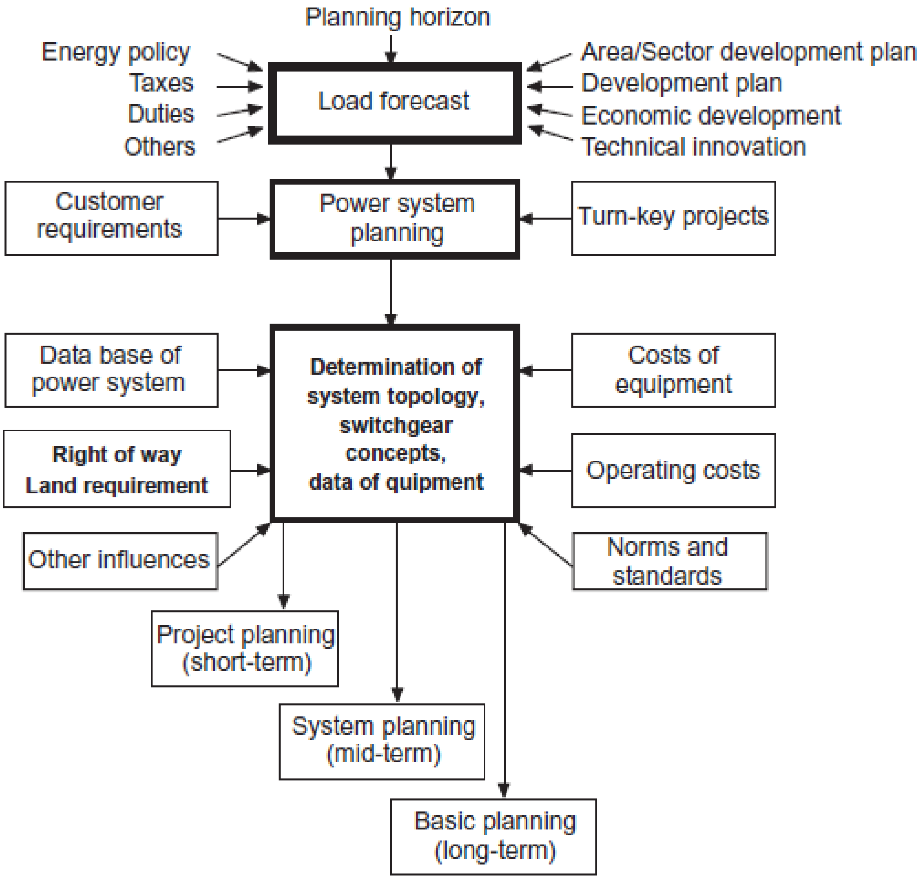


Figure 1.1 Fundamental relations of power system planning.

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 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.

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

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.

Power System Load

- 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.

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

Load Forecast with Standardized Load Curves

Another possibility for the determination of the system load is based on the annual energy consumption of the individual consumer or consumer groups, which can be taken from the annual electricity bill. The system load can be determined by means of standardized load curves or load profiles [4] for different consumer groups:

- Household consumers
- Commercial consumers of different kinds (24-hour shift, shop or manufacturing enterprise, opened or closed at weekends, seasonal enterprise, etc.)
- Agricultural enterprises of different kinds (dairy farming or water pumping)
- Other customers (schools, public buildings, etc.).

3.1
Planning Principles

The aim of planning electrical power systems is to fully serve the interests of the consumers to be supplied with electricity. The active and reactive power of the supply area to be expected in the long-range planning period are taken as basic parameters. In order to determine the configuration of power system in terms of technical, operational, economic, legal and ecological criteria, planning principles have to be defined and used. High priority is to be given to the supply of consumers with a defined need for supply reliability, which can be accomplished if sufficient data are available on system disturbances (faults, scheduled and unscheduled outages) or by means of quantitative and if necessary additional qualitative criteria.

The reliability of the electrical power supply system (power station, transmission and distribution system, switchgear, etc.) is influenced by:

- The fundamental structure of the power system configuration (topology)
  Example: The consumer is supplied only via one line (overhead line or cable) forming a radial supply system. In case of failure of the line, the supply is interrupted until the line is repaired.
- The selection of equipment
  Qualified and detailed specification and tendering of any equipment, consistent use of international norms for testing and standardization of equipment guarantee high-quality installations at favorable costs on an economic basis.
- The operational mode of the power system
  The desired reliability of supply can be guaranteed only if the power system is operated under the conditions for which it was planned.
- Earthing of neutral point
  A single-phase fault with earth connection (ground fault) in a system with resonance earthing does not lead to a disconnection of the equipment, whereas a single-phase earth fault in a system with low impedance neutral grounding (short-circuit) leads to a disconnection of the faulted equipment and in some cases to interruption of supply.
- Qualification of employees
  Apart from good engineering qualifications, continuing operational training of personnel obviously leads to an increase of employees' competence and through this to an increase of supply reliability.
- Regular maintenance
  Regular and preventive maintenance according to specified criteria is important to preserve the availability of equipment.
- Uniformity of planning, design and operation
  Operational experience must be included in the planning of power systems and in the specification of the equipment.
- Safety standards for operation
  The low safety factor for "human failure" can be improved by automation and implementation of safety standards, thus improving the supply reliability.

Reliability as high as necessary,
design and operation as economical as possible!

Prior to the definition of planning principles, agreement must be obtained concerning acceptable frequency of outages, their duration up to the reestablishment of the supply and the amount of energy not supplied and/or the loss of power due to outages. Outages include both planned or scheduled outages due to maintenance and unplanned or unscheduled outages due to system faults. Unscheduled outages result from the following:

- The equipment itself, the cause here being the reduction of insulation strength, leading to short-circuits and flash-over
- Malfunctioning of control, monitoring and protection equipment (protection relays), which can cause switch-off of circuit-breakers
- External influences, such as lightning strokes or earthquakes, which lead to the loss of equipment and installations
- Human influences, such as crash-accidents involving installations (overhead towers) or cable damage due to earthworks, followed by disconnection of the overhead line or the cable.

The duration of outages up to the reestablishment of the supply can be estimated as a maximum value and is determined by the following:

- Power system configuration and planning criteria
  If the power system is planned in such a way that the outage of one item of equipment or power system element does not lead to overloading of the remaining equipment, safe power supply is secured in case of failure of any piece of equipment, independently of the repair and reconnect duration.
- Design of monitoring, protection and switching equipment
  If switchgear in a power system can only be operated manually and locally, then the duration of the supply interruption is longer and thus the energy not supplied is larger than if the switches are operated automatically or from a central load dispatch center.
- Availability of spare parts
  A sufficient number of spare parts reduces the duration of supply interruption and the amount of energy not supplied, as the repair can be carried out much more quickly.
- Availability of personnel (repair)
  The timely availability of skilled and qualified personnel in sufficient number reduces the repair time significantly.
- Availability of personnel (fault analysis)
  The causes of failures and faults in the power system have to be analyzed and assessed carefully prior to any too-hasty reestablishment of the supply after outages, in order to avoid further failures due to maloperation and erroneous switching.
- Availability of technical reserves
  A sufficient and suitable reserve is needed to cover the outage of any equipment. This need not imply the availability of equipment of identical designed to the faulty equipment; for example, after the outage of a HV/MV-transformer the supply can be ensured temporarily by a mobile emergency power generator.

3.2 Basics of Planning

Power systems for electrical power supply must be planned and operated considering the loading of the equipment in such a way as to achieve the following:

- A reasonable and/or suitable relation between the maximal thermal stress (acceptable load current) and the actual load in the final stage of system voltage and/or until restructuring measures become effective and
- No inadmissible thermal loadings (load current) arise, except those which are permitted under certain operating and ambient site conditions.

- Material properties
- Ambient temperature
- Other site conditions, for example, wind and sun exposure
- Number of load cycles
- Preloading conditions of the equipment in case of variable load
- Duration of the additional load arising after the preloading conditions
- Past total actual time under operation.

The permissible loads are to be taken from standards or manufacturers' data or can be determined with suitable computer programs.

Power systems must be planned and operated with regard to short-circuit currents in such a way that

- The thermal strength of equipment and installations is always higher than the prospective thermal effects of the short-circuit currents.
- The electromagnetic effects of short-circuit currents are lower than the associated mechanical strength of the equipment and installations.
- The short-circuit and fault currents through earth do not cause any impermissible step or touch voltages or impermissible voltages at earthing electrodes.

Power systems must be planned and operated with regard to the generation, transmission and distribution of electrical power and energy in such a way that

- Sufficient generation capacity is available to supply the expected (forecast) load as well as the power system losses and to cover the internal consumption under normal operating conditions and in case of outages of power stations and any other equipment in the power system.

- Transmission and distribution systems have sufficient capacity to supply the power system load under normal operating conditions and under defined outage conditions.

Power systems must be planned and operated with regard to the system voltage in such a way that

- A suitable and internationally standardized voltage level is selected for transmission and distribution systems.
- The voltage is within a suitable bandwidth as defined by international standards or by planning criteria under normal operation and under outage conditions.
- The power factor of the system is on the lagging side and the generators can run in the over-excited mode.

- No inadmissible frequency fluctuations shall be initiated due to disconnections of loads or due to short-circuits in the power system. (Load-shedding by frequency relays is seen only as the last measure to secure the stability of the power system).
- The frequency range shall remain within the limits defined for the operation of synchronous and asynchronous machines.

A stable frequency under steady-state conditions represents an essential condition for the regulation of the exchange of electricity between different supply

- The type and topology of the system allow supply to some extent even for load developments different from those forecast.
- The system losses are minimal under normal operating conditions.
- Different schedules of operation of power stations are possible.
- The generation of energy is possible in economic priority sequence (merit order), and ecological and environmental conditions are taken into account.
- A suitable and favorable relation between design and rating of equipment and the actual load, in particular their thermal permissible loading, is achieved in the final system development stage.
- Standardization of the equipment is possible, without impairment of operational flexibility.

Read Page 31 Planning Criteria

4

Economic Consideration and Loss Evaluation

4.1
Present Value and Annuity Method

In the context of power system planning and project engineering, economic aspects must be considered, compared and assessed for different alternatives and scenarios, such as investment costs of the project as well as an evaluation of the losses resulting from system operation. Various methods are available; the most common ones – present value and annuity method – are explained in the context of this book [8].

The present value takes account of all incomes and expenditures of the period under review, which are referred to one reference time instant t_0, usually the time of project commissioning. Payments K_{Bi} resulting during the project engineering, building and commissioning phase of the project will be cumulated to the time instant t_0 in accordance with Equation 4.1a.

$$K_{B0} = \sum_i K_{Bi} \cdot q^i \tag{4.1a}$$

The present value method for investment cost is well-suited for the comparison of different financing scenarios of projects and also for the comparison of different prices of equipment. The present value method is also suitable for the comparison of loss costs during the foreseeable operating time and for comparison of annual costs of different project concepts and/or equipment resulting from the loss costs. One includes the costs K_{Ri} (e.g. for maintenance and repair), arising during the operation time, into the present value method according to Equation 4.1b and the expected incomes K_{Vi} according to Equation 4.1c.

$$K_{R0} = \sum_i \frac{K_{Ri}}{q^i} \tag{4.1b}$$

$$K_{V0} = \sum_i \frac{K_{Vi}}{q^i} \tag{4.1c}$$

Costs are to be set as negative values, incomes as positive values. The project is profitable if the total present value becomes positive over the expected lifespan.

Read Page 38 Evaluation of losses

For the evaluation of the losses in the context of power system planning over the entire long-range planning period, the losses are usually determined for each year and will be represented as present value, discounted on the time of the investment decision or commissioning. The losses in one year i are calculated using Equation 4.18.

$$K_{Vi} = W_{Vi} \cdot \left(\frac{k_P}{\vartheta_i \cdot T_Z} + k_{wi} \right) \tag{4.18}$$

The present value of the costs of losses are calculated from Equation 4.19

$$K_{V0} = \sum_{i=1}^{n} \frac{K_{Vi}}{q^i} \tag{4.19}$$

with the interest factor $q = 1 + p$. If future load increase with an annual growth rate g is taken into account, the annual losses and the annual cost of losses are increased in accordance with Equation 4.20a,

$$K_{V0} = \sum_{i=1}^{n} \frac{K_{Vi}}{q^i} \cdot \frac{1}{(1+g)^{2(i-1)}} \tag{4.20a}$$

and for continuous annual costs of losses K_V according to Equation 4.20b with the increase factor $r = 1 + g$,

$$K_{V0} = K_V \cdot \frac{q^n - r^{2n}}{q^n \cdot (q - r^2)} \tag{4.20b}$$

If the load of the equipment under investigation or the power system does not increase continuously from the initial loading S to the final loading $k \times S$ over the long-range planning period, but rather experiences several load cycles (number j) of S on $k \times S$ during n years, then the present value of the cost of losses is given by Equation 4.21.

$$K_{V0} = K_V \cdot \frac{q^{jn} - 1}{q^{jn} \cdot (q-1)} \cdot \frac{(q^n - r^{2n}) \cdot (q-1)}{(q - r^2) \cdot (q^n - 1)} \tag{4.21}$$

with

K_V = cost of losses
j = number of load cycles
n = number of years
q = interest factor: $q = 1 + p$
r = load increase factor $r = 1 + g$
p = interest rate
g = load increase rate.

The second term in Equation 4.21 indicates the annuity factor for discounting of the constant cost of losses K_V and the last term takes account of the increase of load in the load cycles described.

5.2
Recommended Voltage Levels

Nominal voltages in power systems are recommended in IEC 60038. Table 5.1 outlines the appropriate voltage levels as applicable in Germany. In addition to the nominal voltage, typical application and supply tasks are mentioned as well.

Table 5.1 Recommended system voltages according to IEC 60038 as applicable in German power systems.

Common name	Nominal system voltage	Supply task	Remarks
Low-voltage (LV)	400V/230V	Household customers Small industrial consumers	IEC 60038 Table I
	500V	Supply of motors in industry	Not mentioned in IEC 60038
Medium-voltage (MV)	6kV	HV-motors in industry and power stations	IEC 60038 Table III
	10kV	Urban supply, industrial power systems	
	20kV	Rural supply, industrial power systems	
	30kV	Industrial supply (electrolysis, thermal processes) Rural power supply	Not mentioned in IEC 60038
High-voltage (HV)	110kV	Urban transport and sub-transmission systems	IEC 60038 Table IV
	220kV	Transmission systems (decreasing importance)	
	380kV (400kV)	UCTE transmission system	IEC 60038 Table V Definition of highest voltage of equipment U_{bmax} = 420kV

5.3
Topology of Power Systems

Power systems are constructed and operated as

- Radial systems or
- Ring-main systems or
- Meshed systems.

Additional criteria for distinction can be defined, such as the number and kind of feeders from supplying system level, the number and arrangement of lines and the reserve capability of the system to cover loss of load. The three system topologies are constructed and operated at all voltage levels. In the context of the sections below, the following definitions are used:

Feeder	Outgoing connection of any overhead line or cable from a MV or LV substation
Gridstation	Switchyard including busbars, transformers and outgoing feeders to the EHV level
Substation	Switchyard including busbars, transformers and outgoing feeders to the HV level
Station	Switchyard including busbars, transformers and outgoing feeders to the MV level
Primary	Switchyard including busbars, transformers and outgoing feeders to the LV level
Line	Any overhead line or cable of any voltage level.

Read details Page 48

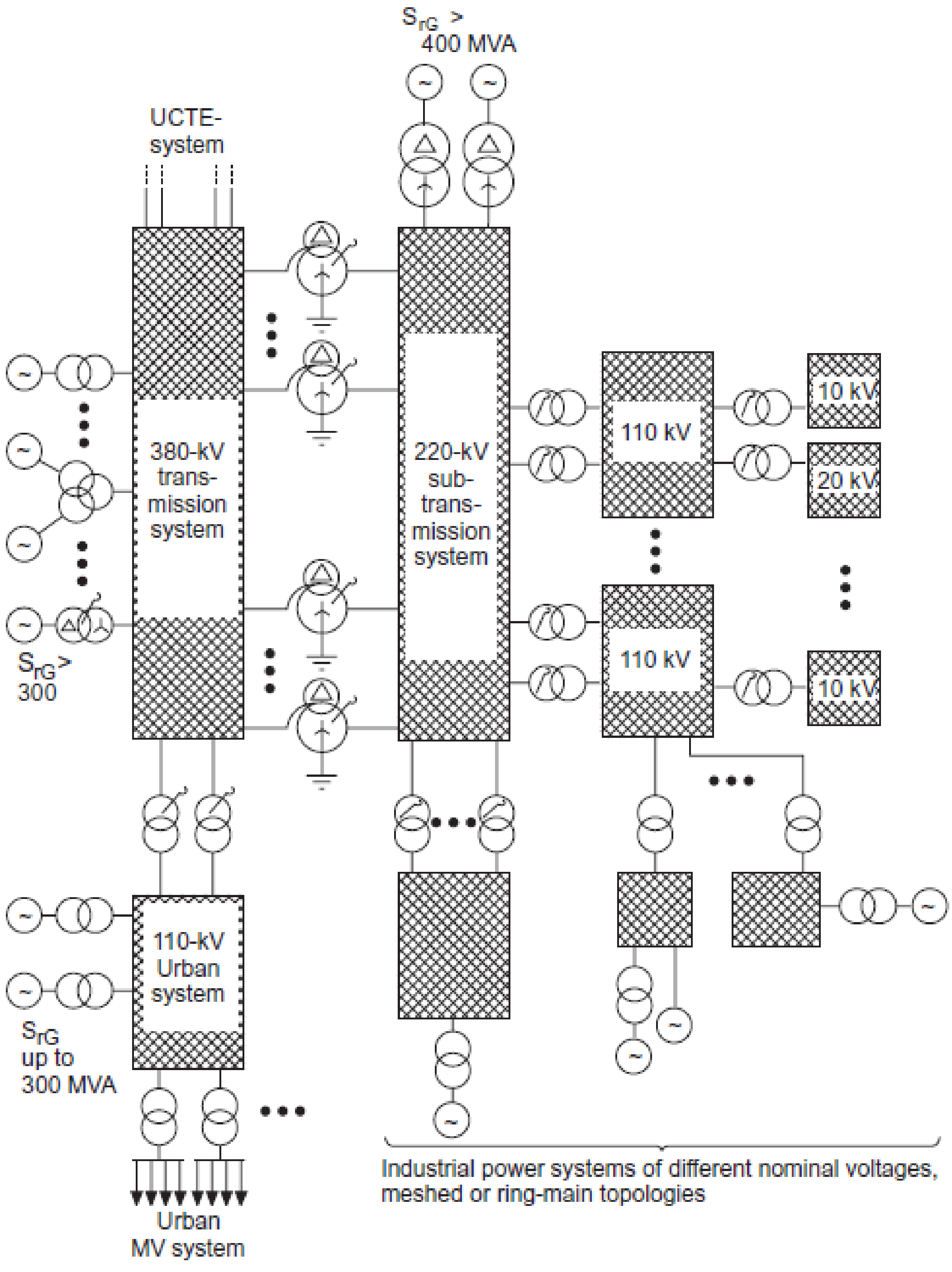


Figure 5.13 Diagram of a high-voltage transmission system with different voltage levels.

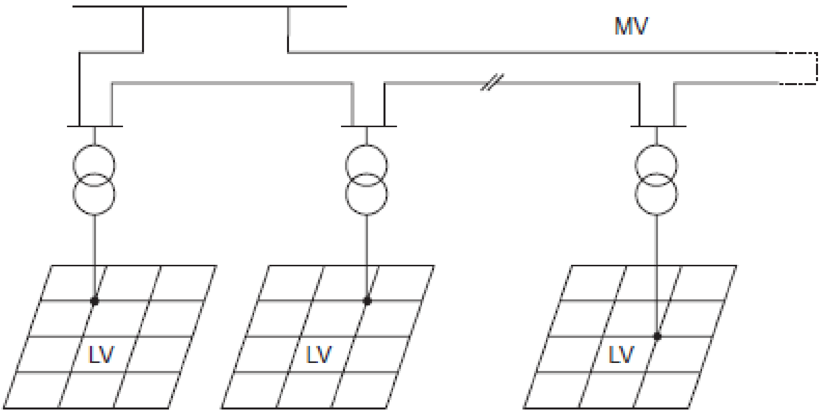


Figure 5.15 Structure of a meshed LV system supplied station-by-station.

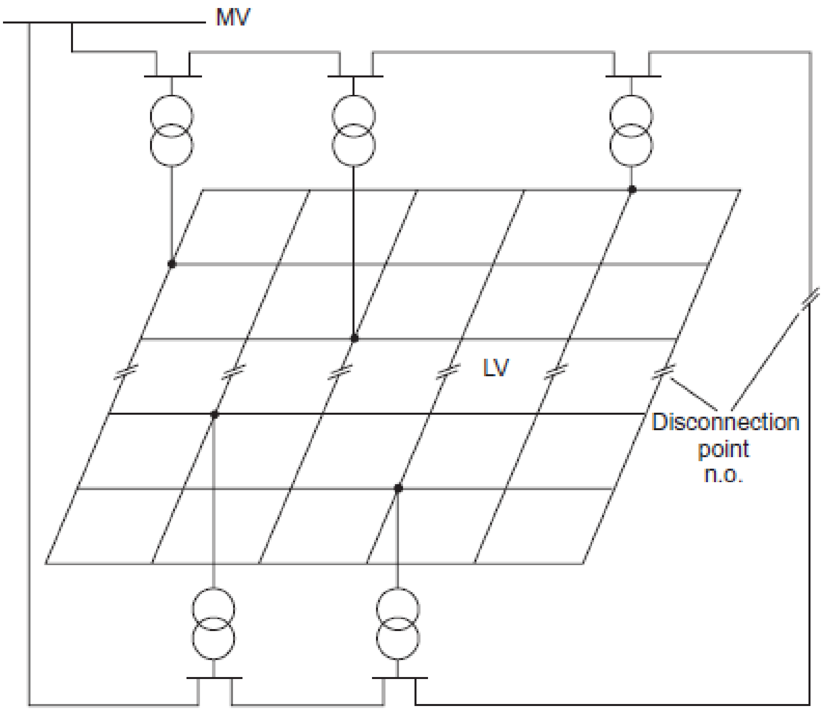


Figure 5.16 Structure of a meshed LV system with single-line supply.

Table 5.2 Aspects for combination of different system topologies on different voltage levels.

Feeding system HV/MV	Supplied system MV/LV	Loading	Reliability	Remarks
Meshed HV system	Meshed HV or MV system	Load-flow calculation	Very high according to planning criteria	Common combination
Meshed MV system	Meshed LV system	Simulation of loading	Very high in both MV and LV systems	Back-power relay necessary in LV-system
	Radial LV system	Simulation of loading	High in MV system, low in LV system	No special considerations for planning and operation
Ring-main system with open disconnection point in MV system	Meshed LV system	Simulation of loading	Fair in MV system, very high in LV system	Back-power relay necessary in LV-system
	Radial LV system	Simulation of loading	Fair in MV system, low in LV-system	Common combination, no special considerations for planning and operation

6
Arrangement in Gridstations and Substations

6.1
Busbar Arrangements

6.1.1
General

The arrangement and connection of incoming and outgoing feeders in gridstations and substations and the number of busbars have an important influence on the supply reliability of the power system. Gridstations and substations and the topology of the power system must be designed in a similar way and must therefore be included in the context of planning as a single task.

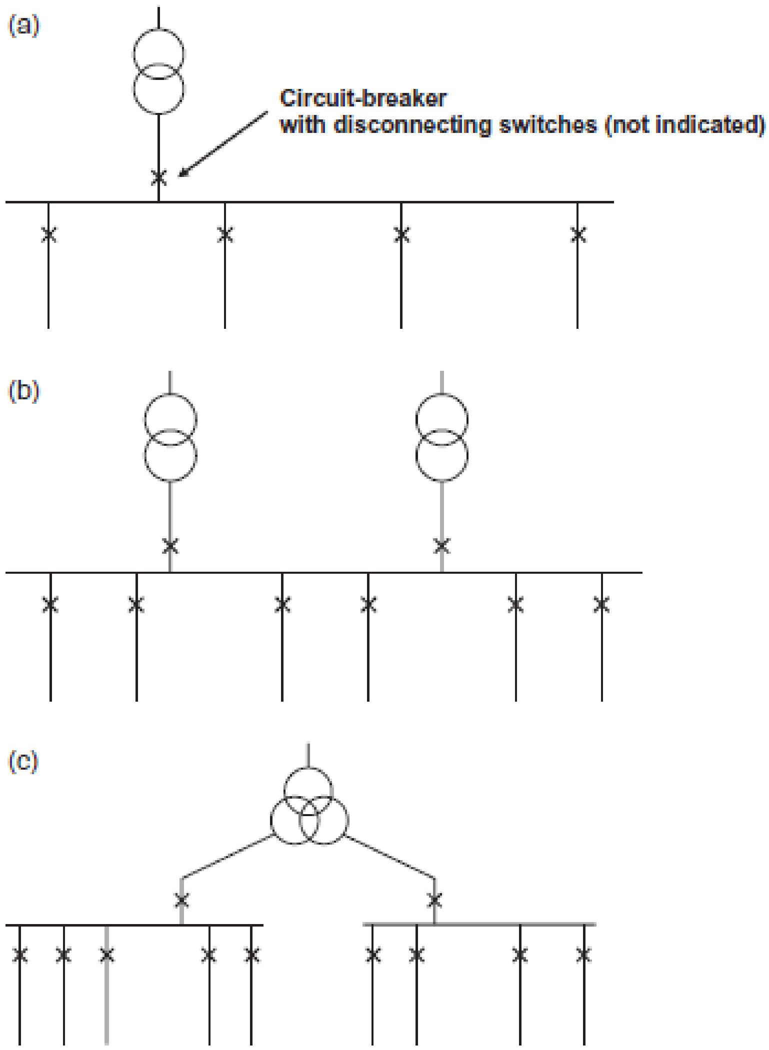


Figure 6.1 Substation single busbar on load-side. (a) Supply by one transformer; (b) supply by two transformers; (c) block arrangement to supply two MV systems.

Read Arrangements Page 71

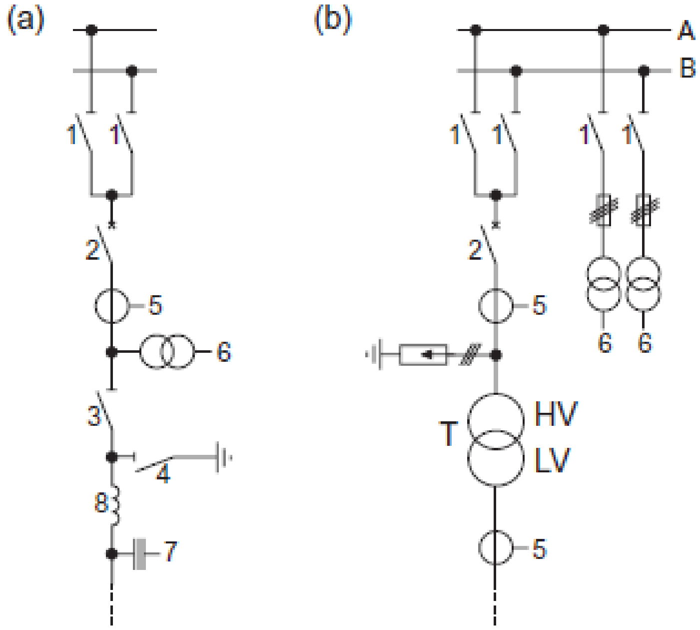


Figure 6.5 Typical feeder arrangement in a HV switchyard [12]. (a) Overhead line feeder with double busbar; (b) transformer feeder with double busbar. **1**, Busbar disconnecting switch; **2**, circuit-breaker; **3**, feeder disconnecting switch; **4**, earthing switch; **5**, current transformer; **6**, voltage transformer; **7**, capacitive voltage transformer with coupling for frequency carrier signal; **8**, blocking reactor against frequency carrier signals.

Table 6.1 Categories of current transformers and their parameter according to VDE 0414 part 7.

Category	Implementation	F_i	δ_i	K_r	T_s
P	• Iron closed core • Total error defined for symmetrical current on primary side • Remanence flux not limited	–	–	–	–
TPS	• Iron closed core • Low residual flux • Remanence flux not limited • To be used for differential protection	±0.25%	–	–	Some seconds
TPX	• Iron-closed core • Defined limits for error in magnitude and phase-angle • Remanence flux not limited • Suitable for automatic reclosure	±0.5%	±30′	~0.8	Some seconds
TPY	• Small air-gap to limit remanence flux • Remanence flux ≤10% of saturation flux • Suitable for automatic reclosure only if time-constant is smaller than reclosing time	±1.0%	±60′	~0.1	0.1 s up to 1 s
TPZ	• Large air-gap (linear core) • Remanence flux negligible • Protective devices remain in excitation for a long time	±1.0%	±18′	~0	60 ms

Read Page 81 Transformers

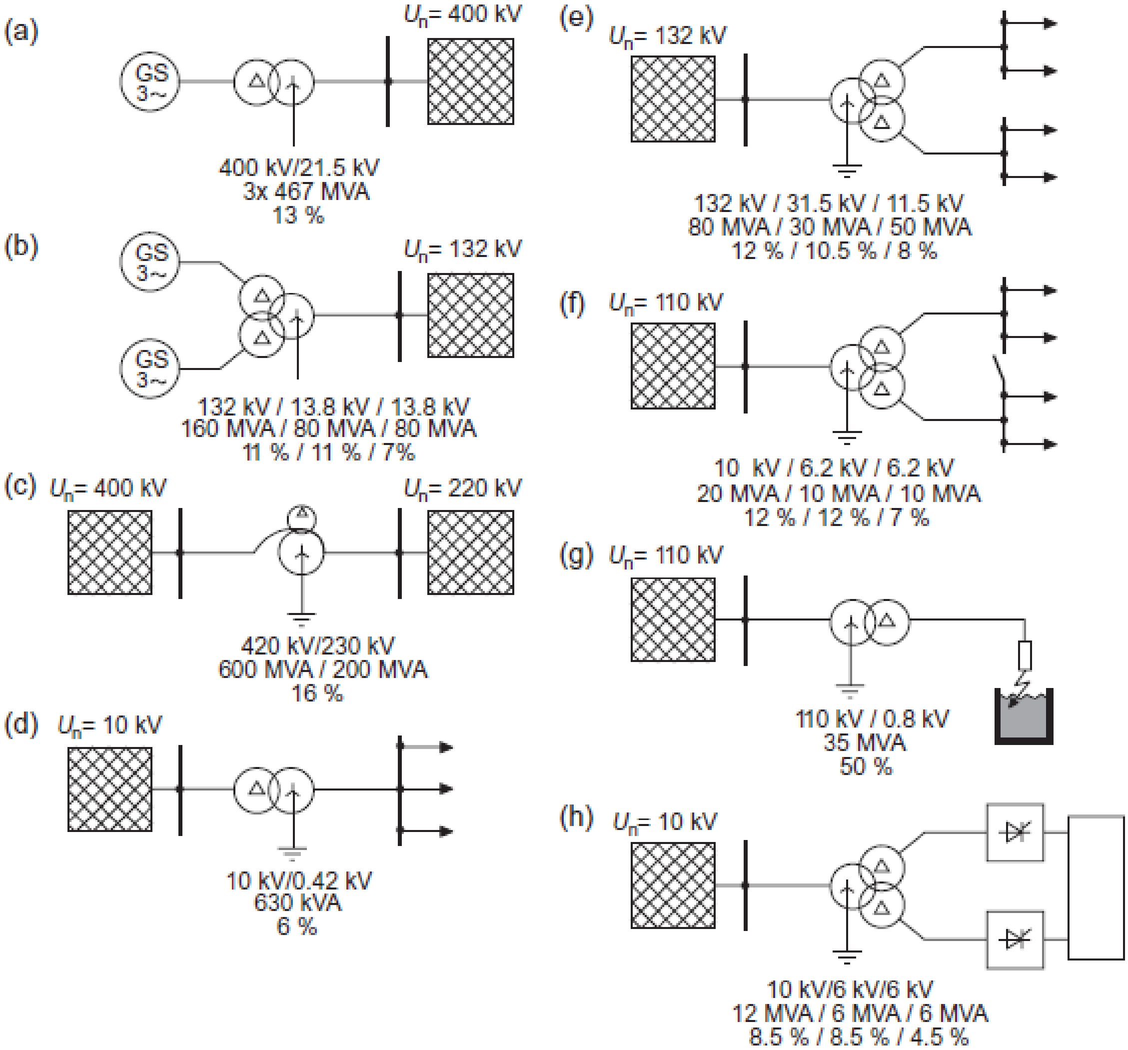


Figure 7.2 Arrangements of transformers in power systems. (a) Generator transformer (transformer bank of three single-phase transformers); (b) three-winding block transformer in a gas-turbine power station; (c) high-voltage autotransformer coupling two power systems; (d) low-voltage transformer; (e) three-winding transformer for the supply of two rural MV-systems; (f) three-winding transformer in an industrial power system; (g) transformer for the supply of a three-phase alternating-current arc furnace; (h) static inverter transformer for the connection of two static frequency inverters.

Table 7.1 Types of cooling and insulation of transformers.

	Internal cooling agent		External cooling agent	
	Type	**Circulation**	**Type**	**Circulation**
Oil-immersed transformers	O Mineral oil or synthetic fluid with flame temperature ≤300 °C	N Natural circulation of cooling agent	A Air	N Natural convection
	K Insulation fluid with flame temperature >300 °C	F Forced circulation by cooler	W Water	F Forced movement by ventilation
	L Insulation fluids without measurable flash point	D Forced circulation by cooler and through windings		
	G Gas			
Dry-type transformers	G Gas	N Natural circulation	A Air	F Forced circulation
	A Air	F Forced circulation		

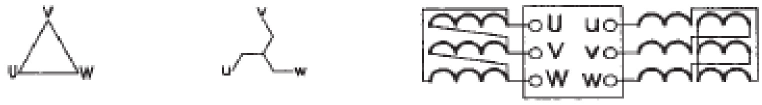
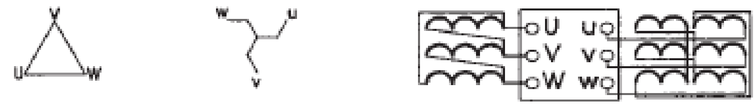
Dd0	
Yy0	
Dz0	
Dy5	
Yd5	
Yz5	
Dd6	
Yy6	
Dz6	
Dy11	
Yd11	
Yz11	

Table 7.4 Thermal classes of insulation materials of transformers acc. to VDE 0301 part 1 [17].

Thermal class	Temperature (°C)	Example of insulation material
Y	90	Organic fibers (paper, molded wood, wood, cotton) not impregnated PVC
A	105	Organic fibers (paper, molded wood, wood, cotton) impregnated Nitrile-rubber
E	120	Foils and shaped parts of polyester Varnish made from polyvinylformal, polyvinyl acetate or epoxy resin
B	130	Shaped parts of epoxy resin and polyester resin with inorganic filler Foils from polyethersulfon Varnish with higher temperature-resistance
F	155	Molded shaped parts of epoxide-isocyanate resin Varnish made from polyterephthalate Polyamide foils Glass fiber-reinforced insulation made from modified silicone resin
H	180	Glass-fabric with silicon or silicone-rubber Varnish made from polyamide, silicone-rubber or aramid fibers

$$V = e^{\left(\frac{15000}{110+273} + \frac{15000}{\vartheta_{HS}+273}\right)} \tag{7.2b}$$

with

V_{HS} = aging rate at actual hot-spot temperature
V_{98} = aging rate at hot-spot temperature of 98 °C
ϑ_{HS} = hot-spot temperature in degrees.

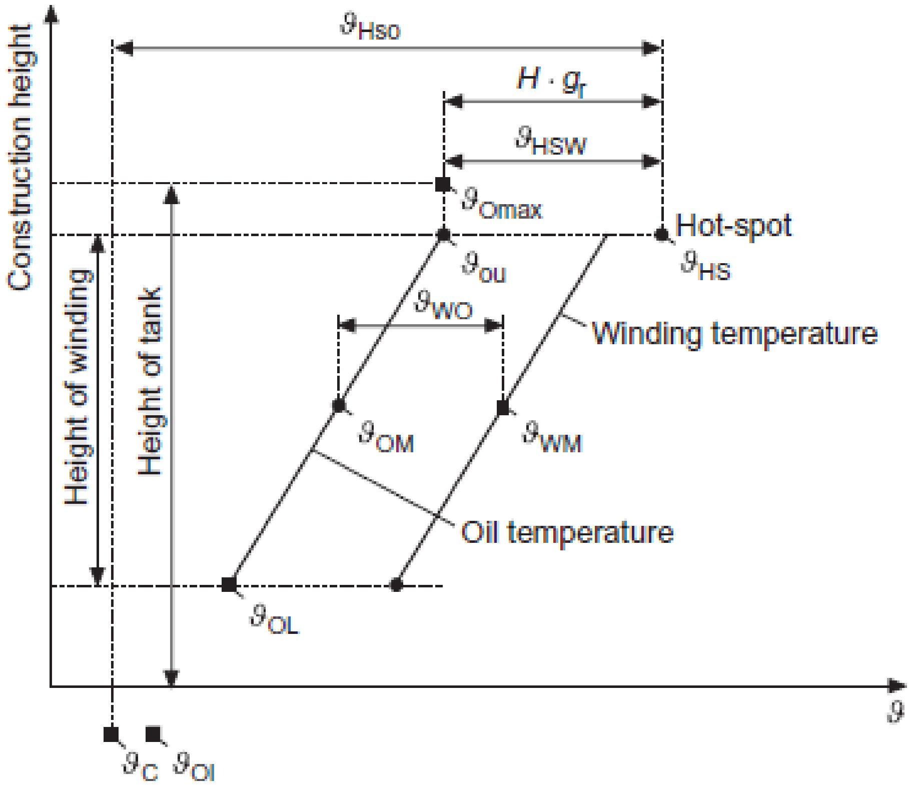


Figure 7.5 Temperature rise within the transformer for consideration of the maximum thermal loading; see text for explanation.

7.4.2
Maximum Permissible Loading of Oil-Immersed Transformers

General

The maximum permissible loading of oil-immersed transformers with rated apparent power up to 100 MVA can be determined according to IEC 60354 [18]. For higher rated apparent power, the recommendations of the manufacturer are to be used. The VDE standard 0536 is replaced at international level by the revised version of IEC 60354 "Loading guide for oil-immersed transformers" dated 1991 [19]. A revised version is published as IEC 60076-7 (Power Transformers– part 7: Loading guide for oil-immersed power transformers). Differences between IEC 60354:1991 and VDE 0532:1977 are not completely dealt with in the context of this book, however; details can be found in [17]. In this book the determination of the permissible loading is explained on the basis of IEC 60354:1991 with references to IEC 60076-7.

Different types of transformers, such as distribution transformers, medium-sized transformers and large power transformers have to dealt with separately.

Distribution Transformers The maximal permissible loading of distribution transformers with rated apparent power ≤2.5 MVA and with natural oil-cooling, without on-load tap-changer, is determined only by the hot-spot temperature and the thermal aging.

Medium-sized Transformers Medium-sized transformers have rated apparent power ≤100 MVA and an impedance voltage u_k according to Equation 7.6. The influence of the leakage flux is comparatively low.

$$u_k \leq \frac{\left(25 - 0.1 \cdot \frac{3 \cdot S_r}{W}\right)}{100} \tag{7.6}$$

S_r = rated apparent power in MVA
W = number of legs with windings.

Different methods of cooling are considered. For autotransformers an equivalent apparent power S_t and/or an equivalent impedance voltage u_{kt} must be determined according to Equations 7.7 and 7.8.

$$S_t = S_r \cdot \left(\frac{U_{rHV} - U_{rLV}}{U_{rOS}}\right) \leq 100 MVA \tag{7.7a}$$

$$u_{kt} = u_{kr} \cdot \left(\frac{U_{rHV}}{U_{rLV} - U_{rHV}}\right) \leq 0.25 - \frac{S_t}{1000} \tag{7.7b}$$

For other types of autotransformers the rated power per phase (per leg) is important. Equivalent apparent power and equivalent impedance voltage are calculated according to Equation 7.8.

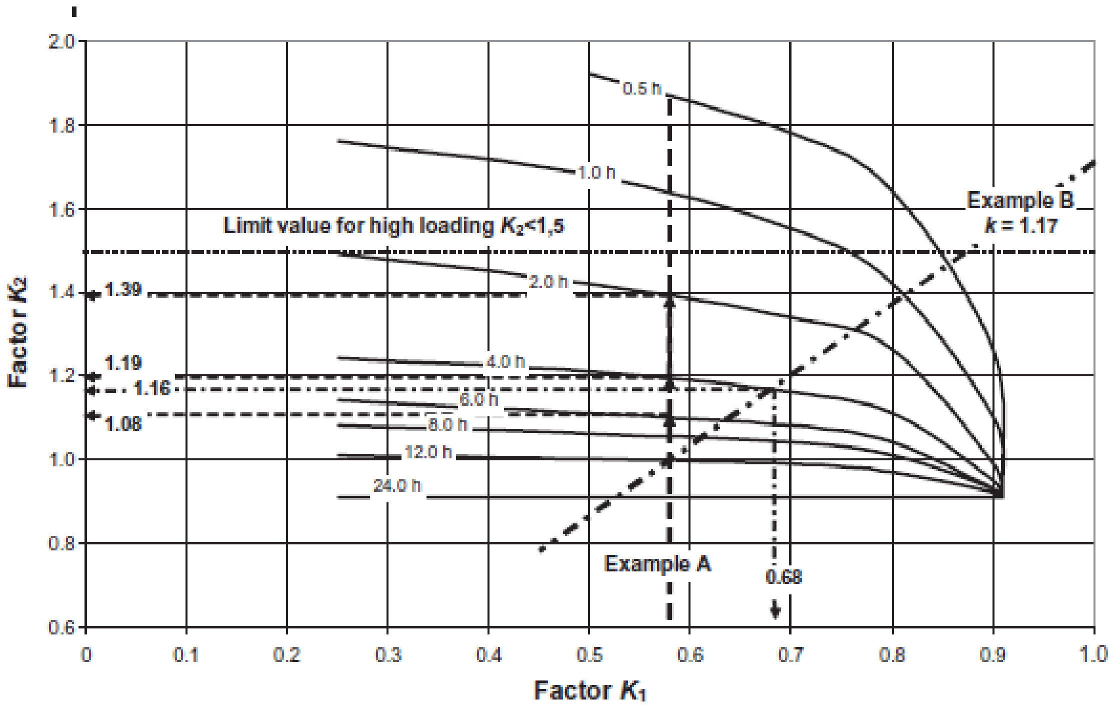


Figure 7.7 Determination of the maximal permissible loading of oil-immersed transformers according to IEC 60354 with sample application. Example A: determination of the maximal permissible loading (normal cyclic load) as a function of the loading period, Example B: determination of the rated apparent power with given load cycle.

8
Cable Systems

8.1
General

Cables are used for the transmission and distribution of electrical energy in public and industrial power systems. The permissible loading of the cables is determined by different parameters such as environmental conditions, type of laying (in ground or in air), cable design and type of insulation, operating conditions and so on. Conductors are made of aluminum or copper. The insulation is of various materials: PVC (polyvinyl chloride) and PE (polyethylene) are used as standard used in LV and MV cables; oil-insulation and gas-pressure cables can still be found in HV systems ($U_n > 110\,kV$), whereas XLPE (cross-linked polyethylene)-insulated cables are today standard in power systems with nominal voltages of 110 kV and above. Mass-impregnated paper-insulated cables are still in use in the medium-voltage range, but are found only on older cable routes; this type will no longer be installed.

Cable abbreviation codes are used that indicate the material of the cable from the inner layer to outer layers. Copper conductors, mass-impregnated paper-insulated cables, and internal protection shields are not specially indicated. In addition to the coding of the inner construction, the number of conductors, the cross-section and the shape of the conduct as well as the nominal voltage (line-to-ground / line-to-line) is indicated. Special coding is defined in the specific cable standards or can be found in [22]. Abbreviation codes for impregnated paper-insulated cables and cables with PVC or XLPE insulation are listed in Tables 8.1 and 8.2.

Conductor shape and type are identified as

RE Solid round conductor
RM Stranded round conductor
SE Solid sector-shape conductor
SM Stranded sector-shape conductor
RF Flexible stranded round conductor.

Table 8.7 Influence of cable parameters on the permissible loading of cables and on the cost of trenches and installations.

Parameter	Cable cost	Cost of transport	Cost of trench	Assembly cost at site	Permissible loading	Remarks
Cross-bonding of sheaths	—	—	—	+	++	Necessary in case of large cross-section
Flat or triangle formation	—	—	+	(+)	+	No influence with low spacing
Cable distance	—	—	+	(+)	+	With MV cables up to 300 mm^2
Laying depth	—	—	++	—	(–)	Standardized laying depth
Thermally stabilized soil	—	—	+	(+)	++	Recommended in all case
Cross-section	+	(+)	—	—	+	Together with cross-bonding
Outside diameter	+	(+)	—	—	(+)	Only in combination with increased dielectric strength

—, no influence; (+), low influence; (–) small reduction; +, increase; ++, significant increase.

The thermally equivalent short-time current I_{th} is calculated according to Equation 8.9a based on the amount of heat Q generated in a conductor with resistance R during the short-circuit duration T_k.

$$I_{th} = \sqrt{\frac{Q}{R \cdot T_k}} = \sqrt{\frac{\int_0^{T_k} i_k^2(t)\,dt}{R \cdot T_k}} \tag{8.9a}$$

The thermally equivalent short-time current can also be determined taking account of the heat dissipation factors m and n according to Figures 7.10 and 7.11, considering the thermal effect of the DC and the AC component of the short-circuit current as in Equation 8.9b,

$$I_{th} = I_k'' \cdot \sqrt{m + n} \tag{8.9b}$$

with the initial short-circuit current I_k''. The thermally equivalent short-circuit current in case of several short-circuits with different time durations T_{ki} and currents I_{thi} are calculated with Equation 8.10a.

$$I_{th} = \sqrt{\frac{1}{T_k} \sum_{i=1}^{n} I_{thi}^2 \cdot T_{ki}} \tag{8.10a}$$

$$\text{with} \quad T_k = \sum_{i=1}^{n} T_{ki} \tag{8.10b}$$

Based on the current density given by Equation 8.11,

$$J_{th} = \frac{I_{th}}{q_n} \tag{8.11}$$

$$J_{\text{thz}} = \sqrt{\frac{Q_c \cdot (\beta + 20°\text{C})}{\rho_{20}} \cdot \ln\left(\frac{\delta_e + \beta}{\delta_b + \beta}\right) \cdot \frac{1}{T_{\text{kr}}}} \qquad (8.13a)$$

$$I_{\text{thz}} = J_{\text{thz}} \cdot q_n \qquad (8.13b)$$

with

Q_c = specific heat in J K mm^{-2}
α_0 = temperature coefficient in K^{-1}
β = parameter $\beta = 1/\alpha_0 - 20\,°\text{C}$
δ_e = permissible short-circuit temperature
δ_b = permissible temperature before short-circuit
ρ_{20} = specific resistance at 20 °C in Ω mm^{2}m^{-1}
q_n = cross-section of sheaths or screen in mm^2
T_{kr} = rated short-circuit duration.

Other short-circuit durations and several short-circuits with different duration T_{ki} can considered using Equation 8.10.

9
Overhead Lines

9.1
General

Various aspects have to be considered during the design and project engineering of overhead lines.

- Determination of the permissible thermal loading (permissible current) in the context of the project planning period
- Design and determination of the tower arrangement and in special cases the placement of the towers along the route of the line route for project realization (and possibly in the tendering period)
- Mechanical design of the overhead line towers, again in the context of project realization.

9.2
Permissible Loading (Thermal) Current

9.2.1
Design Limits

The tensile strength and the modulus of elasticity of conductors for overhead lines are reduced by thermal stresses originating from the load current and from external heating by solar radiation. Additionally, the wind speed has an influence on the required mechanical parameters of the conductor. The reduction of the tensile strength and the modulus of elasticity result in an irreversible increase of the sag and finally in rupture of the line conductor. This effect depends on the temperature and the time of exposure. As an example, the tensile strength of an Aldrey conductor decreases non reversible by approximately 7% when heated to 75 °C over 12 months; when it is heated to 100 °C for the same period, the reduction is 21%. The tensile strength of pure aluminum conductors (99.5% Al) is reduced by approximately 8% for heating to 75 °C over 12 months; when it is heated to 100 °C during for same period, the reduction is approximately 9% and remains at this value even for longer loading periods. Copper conductors are less favorable in terms of the

Page 147 Heating effect/ Thermal loading

9.4
Sag, Tensions and Minimum Distances

9.4.1
Minimal Length of Insulation

The mechanical design of overhead lines is determined by

- Minimum distances of the conductors to earth, to other conductors and to the tower
- Minimum clearances and minimum length of insulators, depending on the pollution class
- Sag, taking account of conductor and ambient conditions
- Tensile stress of the conductor
- Wind forces on the conductor, insulators and towers.

Minimum distances for nominal system voltage $U_n \geq 110\,\text{kV}$ as indicated in Table 9.4 are defined in IEC 60071-1 (VDE 0111-1). The length of the insulators is determined by the minimum length of insulators and the specific creepage distance for different pollution classes according to IEC 60071-2 (VDE 0111-2).

The contamination classes are defined as follows below, whereas the specific creepage distance refers to the highest voltage for equipment U_m.

- Class 1 Lightly polluted areas without industry and with spread settlement (houses with exhaust from heating devices to be considered); areas with small industrial density or small populated areas, which are exposed to frequent wind and rain; areas far from sea shores or on large heights above sea level. The specific creepage distance can be kept at $1.6\,\text{cm}\,\text{kV}^{-1}$.
- Class 2 Medium polluted area, industrial areas without any particular emissions, areas with medium population density with exhaust from heating devices to be considered; areas with high population density and/or industrial areas, which are exposed to frequent wind and rain; areas which are more than 1 km distant from the sea shore. The specific creepage distance shall be $2.0\,\text{cm}\,\text{kV}^{-1}$.
- Class 3 Heavily polluted areas with high industrial density and suburbs of larger cities with considerable exhaust gases from heating; areas near sea shores

9.5
Short-Circuit Thermal Withstand Strength

The thermal withstand strength against short-circuits of any equipment is determined by the short-circuit duration, the initial short-circuit current and the conductor temperature prior to the short-circuit. The maximal permissible conductor temperatures during short-circuit are determined by VDE 0201, see Table 9.5. Manufacturers' specific data on the permissible conductor temperature are to be considered. The permissible temperature during short-circuits applies to a maximum short-circuit duration of $t_k = 5\,\text{s}$ and the heating of the conductor is assumed to be adiabatic. Skin effect and proximity effect are generally neglected, the specific heat capacity is assumed constant, and the resistance temperature dependence is assumed linear.

The thermal equivalent short-time current I_{th} as reference value for the heat-production Q in a conductor with resistance R during the short-circuit duration T_k is calculated with Equation 9.17.

$$I_{th} = \sqrt{\frac{Q}{R \cdot T_k}} = \sqrt{\frac{\int_0^{T_k} i_k^2(t)\,\mathrm{d}t}{R \cdot T_k}} \tag{9.17}$$

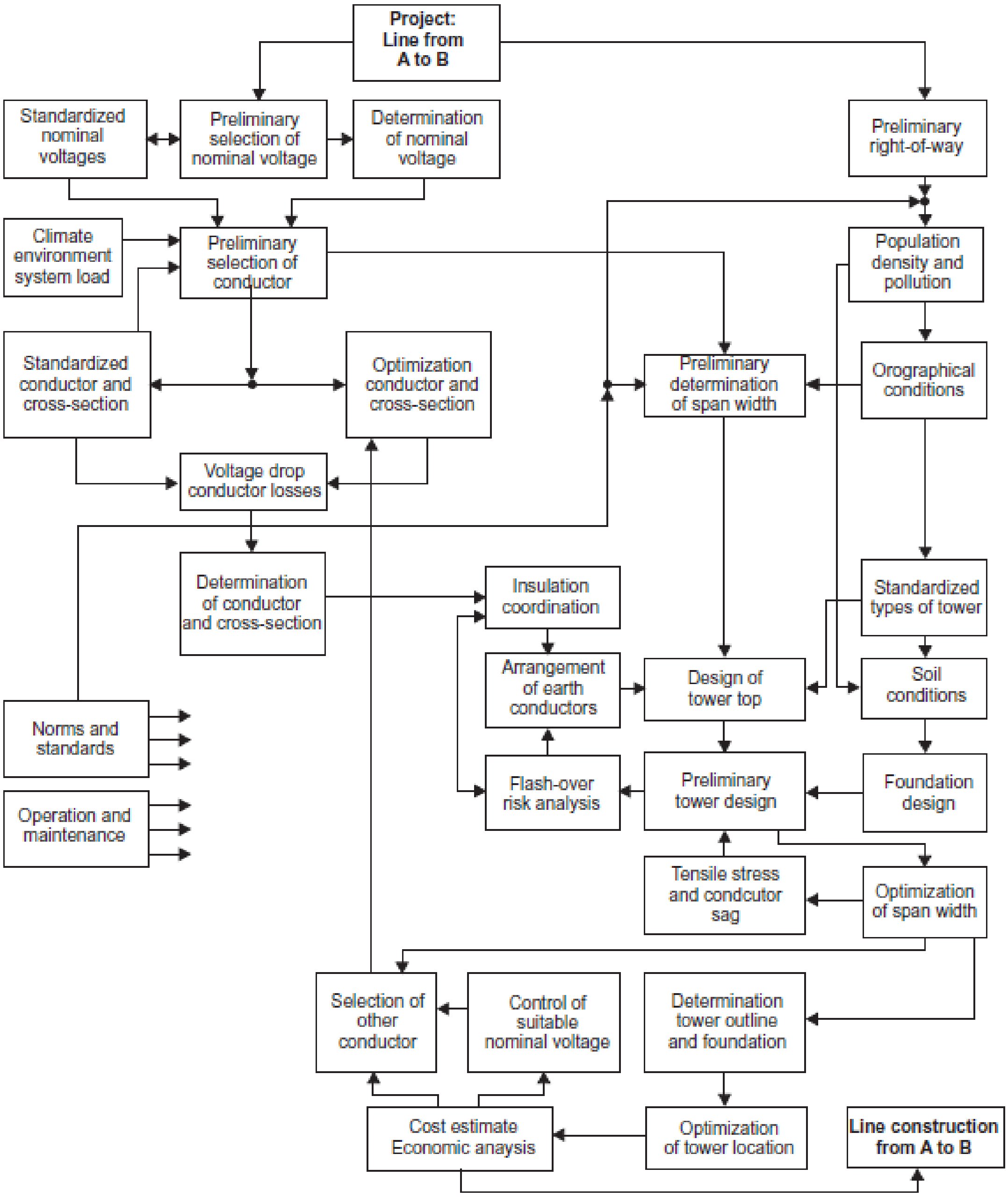
The short-time current density can also be calculated on the basis of an operating temperature of 20 °C in accordance with IEC 60865-1 (VDE 0103) according to Equation 9.22. If other temperatures are considered, Equation 9.22 must be modified accordingly.

$$J_{thr} = \frac{\sqrt{\frac{\kappa_{20} \cdot c \cdot \gamma}{\alpha_{20}} \cdot \ln \frac{1 + \alpha_{20} \cdot (\delta_e - 20\,°\text{C})}{1 + \alpha_{20} \cdot (\delta_b - 20\,°\text{C})}}}{\sqrt{T_{kr}}} \tag{9.22}$$

c = specific thermal capacity
γ = specific density
κ_{20} = conductivity (20 °C)
α_{20} = temperature coefficient (20 °C)
δ_e = permissible short-circuit temperature
δ_b = permissible temperature before short-circuit.

Parameter values are given in Table 9.6.

I


Project:
Line from
A to B
Standardized nominal voltages
Preliminary selection of nominal voltage
Determination of nominal voltage
Preliminary right-of-way
Climate environment system load
Preliminary selection of conductor
Population density and pollution
Standardized conductor and cross-section
Optimization conductor and cross-section
Preliminary determination of span width
Orographical conditions
Voltage drop conductor losses
Determination of conductor and cross-section
Insulation coordination
Standardized types of tower
Arrangement of earth conductors
Design of tower top
Soil conditions
Norms and standards
Operation and maintenance
Flash-over risk analysis
Preliminary tower design
Foundation design
Tensile stress and condcutor sag
Optimization of span width
Selection of other conductor
Control of suitable nominal voltage
Determination tower outline and foundation
Cost estimate
Economic anaysis
Optimization of tower location
Line construction from A to B

9.7
Cost Estimates

Costs of overhead transmission lines consist of the annual capital costs and the annual cost of losses. The annual capital costs involve voltage-dependent and cross-section-dependent components and a fixed part according to Equation 9.25.

$$K_i = \left[a + b \cdot U + c \cdot \sqrt[4]{n} \cdot n_S \cdot q\right] \cdot e \cdot (r_n + \Delta k) \tag{9.25}$$

with

a, b, c = cost factors
e = factor for the consideration of cost increases
n = number of conductors per phase (subconductors)
n_S = number of AC systems per tower
q = cross-section of a conductor and/or sub-conductor
U_n = nominal voltage
r_n = annuity factor
Δk = additional cost per year.

The cost of losses are given by Equation 9.26.

$$K_V = 3 \cdot I_{max}^2 \cdot \frac{\rho}{q} \cdot \frac{n_S}{n} \cdot [k_F + k_W \cdot \vartheta \cdot T_Z] \cdot \mu \tag{9.26}$$

with μ and r as in Equations 9.27a and 9.27b:

$$\mu = \frac{q^n - r^{2n}}{q^n \cdot (q - r^2)} \tag{9.27a}$$

$$r = 1 + g \tag{9.27b}$$

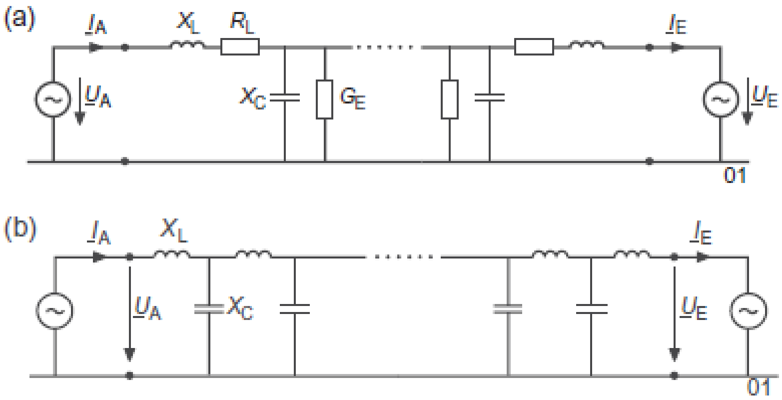


Figure 10.1 Equivalent circuit diagram of a line for quasi-stationary conditions. (a) Diagram with impedances and admittances; (b) simplified circuit diagram of the lossless line.

the reactive power of the line is balanced, as the reactive power produced by the capacitances (proportional to the square of the voltage) is equal to the reactive power needed by inductances (proportional to the square of the current). During higher loading the inductive voltage drop along the line becomes larger and thus the reactive (inductive) power becomes larger as compared with the reactive (capacitive) power produced by the capacitances, and the resulting voltage decreases.

The required reactive power must be made available or absorbed by the connected power systems at both ends of the line. In the circuit diagram of Figure 10.1 the voltage reaches its minimum in the middle of the line with same voltages at the sending and receiving ends of the line. When the line is loaded below the natural power, the capacitive part exceeds the inductive part and the voltage rises along the line length and reaches its maximum in the middle of the line. The unbalanced capacitive part of the reactive power in this case must be absorbed by the connected power systems.

If the line is assumed electrically short, then Equation 10.4 applies

$$\sin\theta \approx \theta = \omega \cdot \sqrt{L \cdot C} \cdot a \tag{10.4}$$

With this approximation Equation 10.5 is applicable.

$$Z_S \cdot \theta = \sqrt{\frac{L}{C}} \omega \cdot \sqrt{L \cdot C} \cdot a = \omega \cdot L \tag{10.5}$$

As a consequence Equation 10.1 is converted into Equation 10.6:

$$P = \frac{U_A \cdot U_E}{X_L} \cdot \sin\delta \tag{10.6}$$

10.2 Parallel Compensation of Lines

Parallel compensation is the standard means of reactive power compensation in the MV and LV systems. The aim is to achieve a defined power factor of the load, limitation of the supplied reactive energy and a decrease of the voltage drop. Parallel compensation within the high-voltage range uses the same principle to increase the transferable power through lines. The system diagram of Figure 10.4 is employed. The lossless compensation (capacitor) is placed in the middle of the line. The voltage at the capacitor U_M is equal the voltages at the sending and receiving end of the line, U_A and U_E, if the maximal power is transmitted.

Similarly to Equation 10.7c, the voltages between the middle and the sending and receiving ends of the line are given by Equation 10.10:

$$U_{M1} = U_{M2} = U \cdot \cos\frac{\delta}{4} \tag{10.10}$$

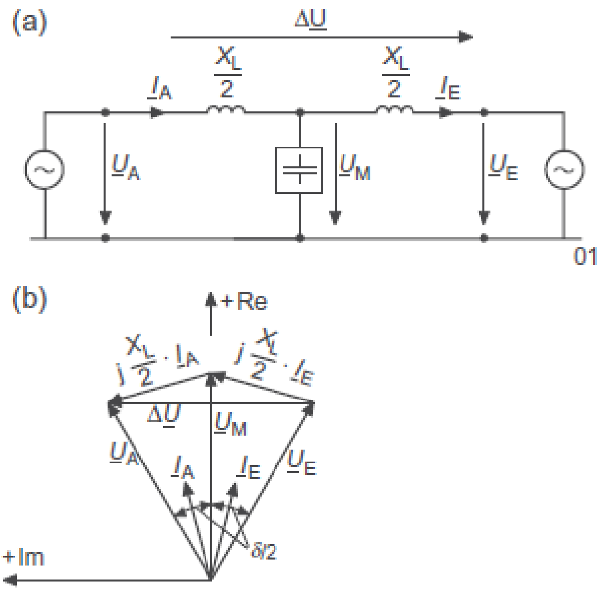


Figure 10.4 Simplified equivalent circuit diagram of the lossless line with parallel compensation in the middle of the line. (a) Equivalent circuit diagram; (b) vector diagram of the voltages and the current.

10.4
Phase-Shifting Equipment

If the transferable power of a line is to be increased by changing of the phase-angle of the line, phase-shifting equipment– for example, a quadrature or phase-shifting transformer–has to be installed. The aim of phase-shifting is to decrease the angle between the voltages at the sending and the receiving ends by addition of an auxiliary voltage U_Z with a defined phase-angle $\delta_Z > 0°$ related to the voltage U_A at the sending end of the line according to Equation 10.15 and represented in Figure 10.8. With the installation at the receiving end of the line, the phase-angle has to be related to the voltage U_E at the receiving end of the line. The voltage at the sending end of the line, relevant for the phase-angle of the line, can be tuned and thus the phase-angle of the line can be adjusted by changing either the angle or the magnitude of the auxiliary voltage.

$$\underline{U}_Z = U_Z \cdot e^{j\alpha} \tag{10.15}$$

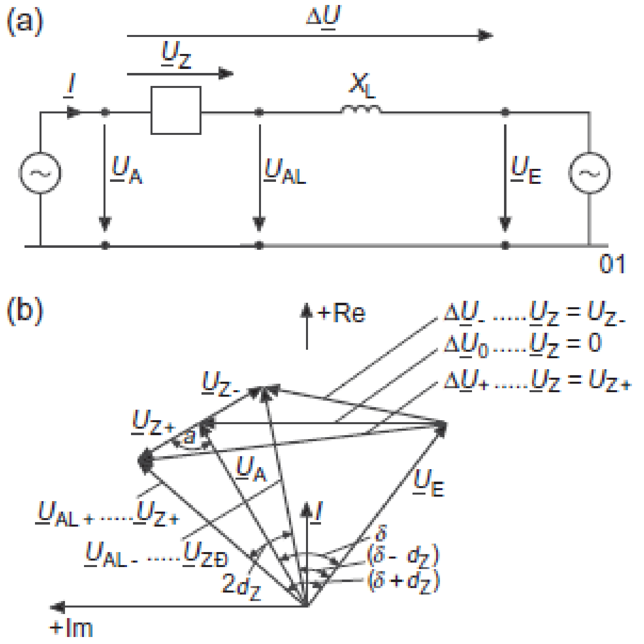


Figure 10.8 Equivalent circuit diagram of the lossless line with phase-shifting (quadrature booster) transformer. (a) Equivalent circuit diagram; (b) vector diagram of the voltages and the current.

angle of 90 is added, as the phase-angle is changed substantially in this case without affecting the magnitude of the voltage.

The active power P_S transferable through the line and the reactive power Q_S at the sending and receiving end of the line are calculated according to Equation 10.16,

$$P_S = \frac{U^2}{X_L} \cdot \sin(\delta - \delta_Z) \tag{10.16a}$$

10.5
Improvement of Stability

The mode of operation of phase-shifting equipment for increasing the transferable power as described in the previous sections can be applied to improve the stability of the generators and the power system. The stability limit of a synchronous generator under changing loading conditions, for example, by short-circuits, can be determined graphically in accordance with Figure 10.10. The generator is operated in the quasi-stationary mode with active power P_1 followed by a stepwise change in load (active power P_2). If the system voltage is assumed to be constant, the phase-angle δ_1 corresponds to the rotor phase-angle. The active power P_1 and P_2 are therefore related to the rotor phase-angle δ_1 and δ_2. In case of a load change from P_1 to P_2 the rotor phase-angle will attune with a damped oscillation to the new operating point δ_2 with an overshoot up to the rotor phase-angle δ_3 corresponding to an active power P_3. The maximal attainable rotor angle is determined from the equal-area criterion, that is, the balance of the accelerating and the decelerating torques as represented in Figure 10.10.

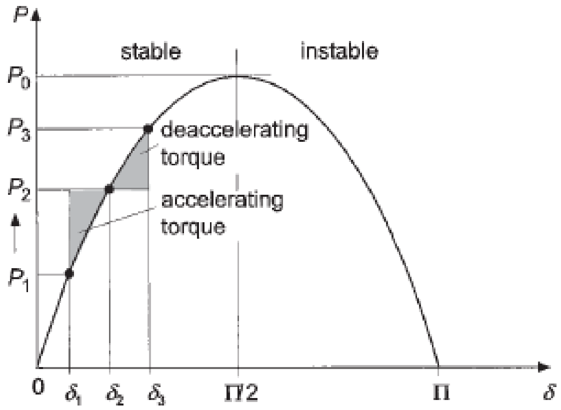
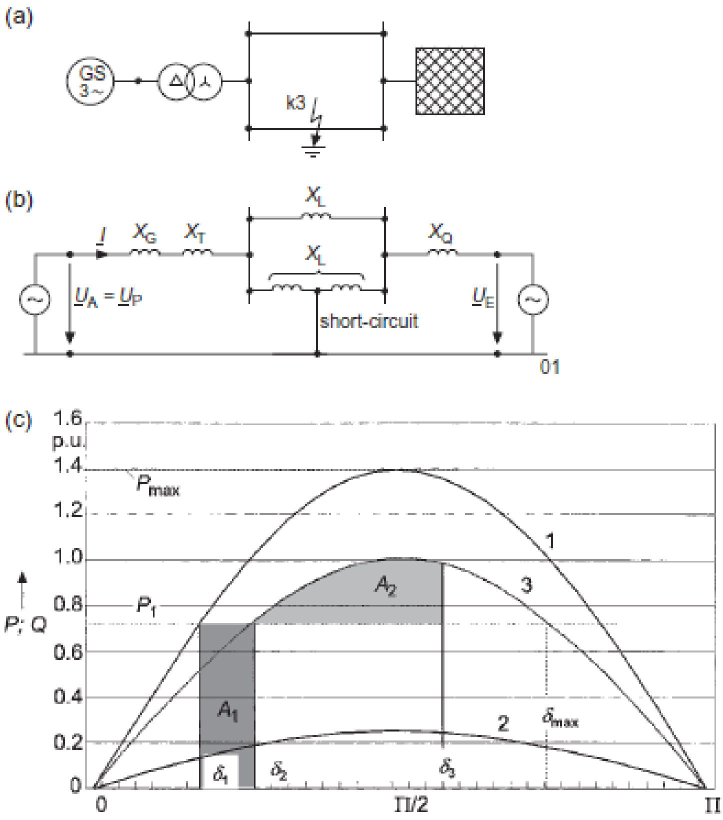


Figure 10.10 Graphic determination of the stability of a synchronous generator during stepwise load change in the power system using the equal-area criterion [49].



11.1
Load-Flow Calculation

An important tool for the planning of electrical power systems is the load-flow analysis or load-flow calculation. The objective is the determination of significant parameters of the power system for normal operation and under emergency conditions, such as

- Voltages at grid-stations, substations and busbars in terms of kilovolts or percent of nominal voltage and in terms of phase angle
- Currents and/or active and reactive power-flow on overhead lines, in cables and through transformers and other equipment, as well as the resultant relative loading
- Active and reactive power losses of equipment, power systems and subsystems
- Exchange of active and reactive power between power systems or between groups of power systems
- Balance of generation and load in subsystem areas
- Power transfer through power systems or subsystems
- Required voltage control range of transformers and generators
- Reactive power needs and/or compensation needs at busbars, made available by generators, compensation equipment or flexible AC transmission systems (FACTS)
- Further characteristics, which can be determined from the knowledge of current and voltages in the power system.

Generally load-flow calculation assuming symmetrical, three-phase operation is adequate. On the basis of the equations for admittance Y and power S according to Equation 11.1,

$$\underline{Y} = \frac{\underline{I}}{\underline{U}} \tag{11.1a}$$

$$\underline{S} = \sqrt{3} \cdot \underline{U} \cdot \underline{I}^* \tag{11.1b}$$

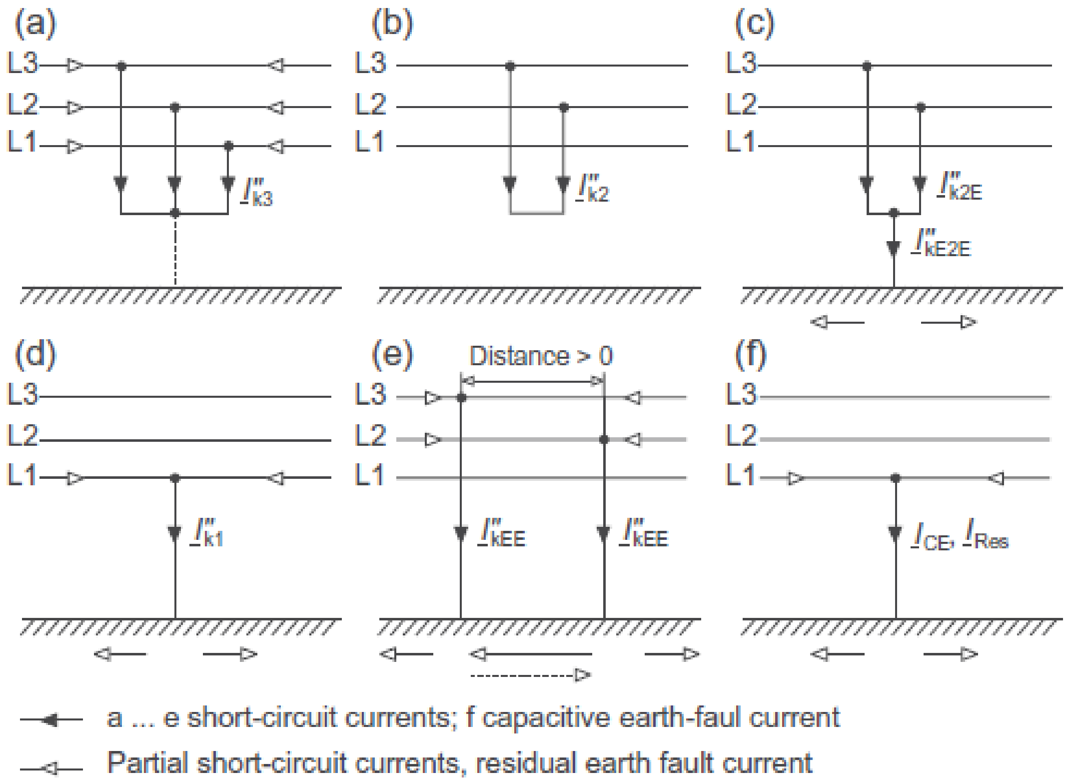


Figure 11.1 Types of short-circuits in three-phase AC systems. (a) Three-phase short-circuit; (b) two-phase (double-phase) short-circuit without earth connection; (c) two-phase short-circuit with earth connection; (d) single-phase (line-to-ground) short-circuit; (e) double-earth fault (only in systems with isolated neutral or with resonance earthing; (f) line-to-ground fault (only in systems with isolated neutral or with resonance earthing).

Table 11.2 Calculation equations for initial short-circuit current.

Type of short-circuit	Equation	Remark
Three-phase	$I''_{k3} = \frac{cU_n}{\sqrt{3}\lvert\underline{Z}_1\rvert}$	
Two-phase without earth connection	$I''_{k2} = \frac{cU_n}{\lvert 2\underline{Z}_1\rvert}$	
Two-phase with earth connection		
General	$I''_{k2EE} = \left\lvert\frac{-\sqrt{3}cU_n\underline{Z}_2}{\underline{Z}_1\underline{Z}_2 + \underline{Z}_1\underline{Z}_0 + \underline{Z}_2\underline{Z}_0}\right\rvert$	Current through earth
	$I''_{k2EL2} = \left\lvert\frac{-jcU_n(\underline{Z}_0 + \underline{a}\underline{Z}_2)}{\underline{Z}_1\underline{Z}_2 + \underline{Z}_1\underline{Z}_0 + \underline{Z}_2\underline{Z}_0}\right\rvert$	Current in phase L2
	$I''_{k2EL3} = \left\lvert\frac{jcU_n(\underline{Z}_0 - \underline{a}^2\underline{Z}_2)}{\underline{Z}_1\underline{Z}_2 + \underline{Z}_1\underline{Z}_0 + \underline{Z}_2\underline{Z}_0}\right\rvert$	Current in phase L3
Far-from-generator ($Z_1 = Z_2$)	$I''_{k2EE} = \frac{\sqrt{3}cU_n}{\lvert\underline{Z}_1 + 2\underline{Z}_0\rvert}$	Current through earth
	$I''_{k2EL2} = \frac{cU_n\left\lvert\frac{\underline{Z}_0}{\underline{Z}_1} - \underline{a}\right\rvert}{\lvert\underline{Z}_1 + 2\underline{Z}_0\rvert}$	Current in phase L2
	$I''_{k2EL3} = \frac{cU_n\left\lvert\frac{\underline{Z}_0}{\underline{Z}_1} - \underline{a}^2\right\rvert}{\lvert\underline{Z}_1 + 2\underline{Z}_0\rvert}$	Current in phase L3
Single-phase		
General	$I''_{k1} = \frac{\sqrt{3}cU_n}{\lvert\underline{Z}_1 + \underline{Z}_2 + \underline{Z}_0\rvert}$	
Far-from-generator ($Z_1 = Z_2$)	$I''_{k1} = \frac{\sqrt{3}cU_n}{\lvert 2\underline{Z}_1 + \underline{Z}_0\rvert}$	

Table 11.3 Impedance correction factors for short-circuit current calculation according to IEC 60909.

Equipment	Correction factor	Remark
Synchronous generator	$K_G = \frac{U_{nQ}}{U_{rG}(1+p_G)} \cdot \frac{c_{max}}{1+x''_d \cdot \sin\varphi_{rG}}$	If the voltage is kept constant at U_{rG}, $p_G = 0$ To be applied for positive-, negative- and zero-sequence components
Generators and unit transformers without tap-changer in power stations	$K_{KWo} = \frac{U_{nQ}}{U_{rG}(1+p_G)} \cdot \frac{U_{rTLV}}{U_{rTHV}} \cdot (1 \pm p_T) \cdot \frac{c_{max}}{1+x''_d \cdot \sin\varphi_{rG}}$	To be applied for positive-, negative- and zero-sequence components
Generators and unit transformers with tap-changer in power stations	$K_{KWs} = \frac{U^2_{nQ}}{[U_{rG}(1+p_G)]^2} \cdot \frac{U^2_{rTLV}}{U^2_{rTHV}} \cdot \frac{c_{max}}{1+\lvert x''_d - x_T \rvert \cdot \sin\varphi_{rG}}$	If the voltage is kept constant at U_{rG}, $p_G = 0$ To be applied for positive-, negative- and zero-sequence components only in case of over-excited operation (leading power factor)
Transformers installed in the power system	$K_T = \frac{U_{nQ}}{U_{bmax}} \cdot \frac{c_{max}}{1+x_T \frac{I_{bmaxT}}{I_{rT}} \sin\varphi_{bT}}$ Approximation $K_T = 0.95 \cdot \frac{c_{max}}{1+0.6x_T}$	In case of lagging power factor at transformer and $U_{bLV} > 1.05\,U_n$ To be applied for positive-, negative- and zero-sequence components

11.2.5
Steady-State Short-Circuit Current

In case of near-to-generator short-circuits, the steady-state short-circuit current I_k depends on (among other things) the saturation of the generator and the operating status of the power system (tripping of circuits due to protection during the time elapsed of the short-circuit) and can only be calculated with some inaccuracy. The method proposed in IEC 60909 therefore indicates upper and lower limit values for those cases where the short-circuit is fed by one synchronous generator only. Maximal excitation of the generator leads to the maximal steady-state short-circuit current I_{kmax} according to Equation 11.9a. For the calculation of the minimal steady-state short-circuit current, a constant no-load excitation of the generator is assumed. The minimal steady-state short-circuit current I_{kmin} is calculated according to Equation 11.9b.

$$I_{kmax} = \lambda_{max} \cdot I_{rG} \tag{11.9a}$$

$$I_{k\,min} = \lambda_{min} \cdot I_{rG} \tag{11.9b}$$

The factors λ_{max} and λ_{min} for turbo and salient-pole type generators are to be taken from Figures 11.4 and 11.5 with x_{dsat} the reciprocal of the short-circuit ratio. The remarks to be found in IEC 60909 should to be noted.

For far-from-generator short-circuits, the steady-state short-circuit current I_k is equal to the initial short-circuit current I_k'' for all types of short-circuits.

11.2.6

Read other topics in Chapter 11

12
Connection of "Green-Energy" Generation to Power Systems

12.1
General

Power plants must be connected to the power system in such a way as to avoid negative effects on the operation of the power system and equipment. The following should be noted:

- The rated power of equipment in the power system must be sufficient to enable the transfer of the produced power from the generation plant into the power system and to the consumers.
- The short-circuit currents of the power system must not be inadmissibly increased by the power plants.
- The voltage rise at the connection point (point of common coupling PCC) and in the power system must remain below the permissible limits.
- Voltage changes by switching of the generation must remain within permissible limits.
- The power quality with respect to harmonics, interharmonics, asymmetry and flicker must be properly maintained and not degraded by the connection of the generating system.

12.2.2
Short-Circuit Currents and Protective Devices

All installations must be able to withstand the foreseeable short-circuit stress and the proof has to be documented in a suitable way. If the short-circuit level in the system is increased by the connection of the generation, which is generally the case, suitable measures to limit the short-circuit current have to be planned and installed by the contractor. If data concerning the expected short-circuit current are not known, multiples of the generator rated current are to be used as the contribution to the short-circuit current:

- Synchronous generators $I''_{kG} = 8 \times I_{rG}$
- Asynchronous generator $I''_{kG} = 6 \times I_{rG}$
- Inverter $I''_{kG} =$ up to $1.4 \times I_{rG}$.

12.2.4
Voltage Fluctuations and Voltage Increase

Voltage changes due to the connection of generation must be limited to 2% of the nominal system voltage for connection to MV and HV systems or 3% in the case of LV connection, taking account of the number of switching operations per minute (switching frequency). With high-voltage transmission systems it is imperative that during switching of individual generation units – for example, one generator of a wind park – the voltage change remains below 0.5%. The maximal voltage change can be estimated according to Equation 12.1.

$$\Delta u_{max} = k_{i\,max} \frac{S_{nE}}{S''_{kPCC}} \tag{12.1}$$

with

S''_{kPCC} = initial short-circuit power at point of common coupling
S_{nE} = nominal apparent power of the generation unit
k_{imax} = maximal switching factor as ratio of starting current to rated current $k_{imax} = I_a/I_r$

- $k_{imax} = 1$: synchronous generator with exact synchronization, inverter
- $k_{imax} = 4$: asynchronous generator, switching with 95–105% of synchronous speed
- $k_{imax} = I_a/I_r$: asynchronous generator with direct start method
- $k_{imax} = 8$: in case I_a/I_r is unknown.

12.2.5 Harmonic and Interharmonic Currents and Voltages

The connection of generation units must not cause any system disturbances in the higher frequency range. Special care has to be taken of this in the case of connection of generation equipped with power electronic converters, such as used in photovoltaic and wind energy installations. The harmonic emissions are to be proved by conformity certificate of the manufacturer or by any independent certification agency in accordance with the different parts of IEC 61000.

For connection to the LV system, the standards in IEC 61000-3-2 (VDE 0838-2) and IEC 61000-3-12 (VDE 0838-12) are to be taken into account. For the connection to the MV system as well as in the case of missing electromagnetic compatibility, the permissible harmonic and interharmonic currents $I_{\nu per}$ and $I_{\mu per}$ must be determined from Equations 12.5,

$$I_{\nu per} = i_{\nu per} \cdot S''_{kPCC} \quad \text{harmonics} \tag{12.5a}$$

$$I_{\mu per} = i_{\mu per} \cdot S''_{kPCC} \quad \text{interharmonics} \tag{12.5b}$$

Read other topics in Chapter 12

Protection of Equipment and Power System Installations

13.1
Faults and Disturbances

Electrical equipment has to be designed and constructed in such a way as to withstand the foreseeable loading during its lifetime under normal and emergency conditions. Generally it is economically not meaningful and technically not realistic to design equipment for all loadings and disturbances. Among others factors, the following should be mentioned:

- Unforeseeable site and ambient conditions such as flooding of basements where cables are laid
- External influences such as mechanical damage by construction work
- Atmospheric influences such as lightning strokes in line conductors and structures
- Aging and loss of dielectric strength of non-self-healing insulation, for example, oil-impregnated paper
- Internal influences such as short-circuits due to insulation failure.

It is therefore necessary to install devices for the protection of equipment which limit the effects of unforeseeable faults and loading on the equipment and protect it against cascading damage. These protection devices must be capable of differentiating between normal and disturbed operating conditions and they must operate reliably to isolate the damaged or endangered equipment as soon as possible from the power supply. It is not the task of the protective devices to avoid errors and disturbances. This can be achieved only by careful planning of the power system, by thorough project engineering of the equipment and by appropriate operation. Protective devices are to fulfill the following four conditions ("Four S criteria"):

- *Selectivity:* Protective devices shall switch-off only that equipment affected by the system fault or impermissible loading condition, the nonfaulted equipment shall remain in operation.
- *Sensitivity:* Protective devices must be able to distinguish clearly between normal and impermissible operating conditions or faults. Permissible high loading of equipment during emergency operation and small short-circuit currents are to be handled in a different way.
- *Speed:* Protective devices are to switch-off the faulted equipment from the power supply as soon as possible in order to limit the effects of the short-circuit or impermissible loading.
- *Security:* Protective devices with all their associated components such as transducers, cable connections, wiring and trip circuits must operate safely and reliably. As faults in power systems are comparatively rare, protective devices must continue to be able to fulfill their function after many years of stand-by operation.

Table 13.1 Criteria, faults and operation criteria for protective devices [67].

Criteria	Operation criteria	Fault, disturbance	Protection of equipment
Current	Overcurrent	Short-circuit Overload	Overcurrent protection of lines, transformers, motors and generators
	Differential current	Short-circuit	Differential protection of lines, transformers and generators
Voltage	Voltage increase	Load-shedding	Overvoltage protection of lines, transformers and generators
	Neutral voltage	Earth-fault	Earth-fault protection of lines, transformers and generators
	Voltage dip	Motor start-up Short-circuit	Undervoltage protection of motors and generators
Impedance	Low impedance Ratio R/X	Short-circuit Short-circuit	High-impedance protection of busbars Distance protection of lines, transformers and generators
Power	Direction of power flow	Short-circuit	Directional overcurrent protection of lines Reverse power of generators
	Active power in zero-sequence component	Earth-fault	Earth-fault protection of lines
Frequency	Change of frequency	Short-circuit Loss of load Increase of load	Protection of generators General task of system protection
	Under-/over-frequency	Loss of load Increase of load	Protection of generators General task of system protection
Phase-angle	Change of phase-angle	Short-circuit	Vector relay of generators
Harmonics and high frequencies		Power electronic Short-circuit Earth fault	Protection of capacitors Rush stabilization Earth-fault protection
Temperature	Increase or decrease of temperature	Overload Short-circuit	Overload protection of transformers and cables
Arc	Radiation	Short-circuit	Protection of switchgear cubicles and switchgear rooms
Pressure	High pressure Low pressure	Short-circuit Leakage	Protection of switchgear cubicles and switchgear rooms Protection of gas-insulated cables and switchgear
Speed	Change of oil-flow in transformers	Overload Short-circuit	Oil-stream protection of transformers (pressure switch or Buchholz-protection)
Volume	Decrease	Leakage	Protection of equipment with oil-insulation

Read other topics in Chapter 13

Read Chapter 14

15
Influence of Neutral Earthing on Single-Phase Short-Circuit Currents

15.1
General

Currents and voltages in case of short-circuits with earth connection (e.g. single-phase short-circuits) depend on the positive-sequence and zero-sequence impedances Z_1 and Z_0. If the ratio of zero-sequence to positive-sequence impedance is $k = Z_0/Z_1$ the voltages in the non-faulted phases and the single-phase short-circuit current are calculated according to Equation 15.1.

$$|\underline{U}_{L2}| = |\underline{U}_{L3}| = E_1 \cdot \sqrt{3} \cdot \frac{\sqrt{k^2+k+1}}{2+k} \qquad (15.1a)$$

$$I''_{k1} = \frac{E_1}{Z_1} \cdot \frac{3}{2+k} \qquad (15.1b)$$

If the voltage E_1 is set to $E = U_n/\sqrt{3}$, similar to the equivalent voltage at the short-circuit location, then

$$|\underline{U}_{L2}| = |\underline{U}_{L3}| = U_n \cdot \frac{\sqrt{k^2+k+1}}{2+k} \qquad (15.1c)$$

$$I''_{k1} = \frac{U_n}{\sqrt{3} \cdot Z_1} \cdot \frac{3}{2+k} \qquad (15.1d)$$

15.2
Power System with Low-Impedance Earthing

Low-impedance earthing is applied worldwide in medium-voltage and high-voltage systems with nominal voltages above 10 kV. Power systems having nominal voltages $U_n \geq 132$ kV are generally operated with low-impedance earthing. In order to realize a power system with low-impedance earthing, it is not necessary that the neutrals of all transformers are earthed, but the criterion should be fulfilled that the earth-fault factor (ratio of the line-to-earth voltages of the non-faulted phases to the line-to-earth voltage prior to the fault) remains below $k \leq 0.8\sqrt{3}$. The disadvantage of earthing all neutrals is seen in an increased single-phase short-circuit current, sometimes exceeding the three-phase short-circuit current. The neutral of unit transformers in power stations should not be earthed at all, as the single-phase short-circuit current will then depend on the generation dispatch. As the contribution of one unit transformer is in the range of some kiloamps, the influence on the single-phase short-circuit currents is significant.

Based on Figure 15.1 and assuming a far-from-generator short-circuit with positive-sequence impedance equal to negative-sequence impedance, $\underline{Z}_1 = \underline{Z}_2$, the single-phase short-circuit current is calculated by

$$\underline{I}''_{k1} = \frac{c \cdot \sqrt{3} \cdot U_n}{2 \cdot \underline{Z}_1 + \underline{Z}_0} \tag{15.1}$$

with voltage factor c according to Table 11.1. If the single-phase short-circuit current is related to the three-phase short-circuit current as

$$\underline{I}''_{k3} = \frac{c \cdot U_n}{\sqrt{3} \cdot \underline{Z}_1} \tag{15.2}$$

it follows that

$$\frac{\underline{I}''_{k1}}{\underline{I}''_{k3}} = \frac{3 \cdot \underline{Z}_1}{2 \cdot \underline{Z}_1 + \underline{Z}_0} \tag{15.3}$$

Table 15.1 Characteristics of different types of neutral handling in power systems.

	Isolated neutral	**Low-impedance earthing**	**Earthing with current limitation**	**Resonance earthing**
Single-phase fault current (short-circuit current)	Capacitive earth-fault current $\underline{I}_{CE} = j\omega\sqrt{3}C_E U_n$	Single-phase (earth-fault) short-circuit current $\underline{I}''_{k1} = \frac{\omega\sqrt{3}U_n}{(2\underline{Z}_1 + \underline{Z}_0)}$	Single-phase (earth-fault) short-circuit current $\underline{I}''_{k1} = \frac{\omega\sqrt{3}U_n}{(2\underline{Z}_1 + \underline{Z}_0)}$	Residual earth-fault current $\underline{I}_{Res} = j\omega\sqrt{3}C_E U_n \cdot (\delta_0 + j\nu)$
Increase of voltages at non-faulted phases	Present $U_{0max}/U_n \approx 0.6$	No increase $U_{0max}/U_n < 0.3$–0.45	No increase $U_{0max}/U_n \approx 0.45$–$0.6$	Present $U_{0max}/U_n \approx 0.6$
Earth-fault factor δ	$\approx\sqrt{3}$	<1.38	$1.38 \ldots \sqrt{3}$	$\approx\sqrt{3}$ to $1.1\times\sqrt{3}$
Ratio of impedances Z_0/Z_1	Generally high	2–4	>4	→ infinity
Extinguishing of fault arc	Self-extinguishing (see Figure 15.7)	Not self-extinguishing	Self-extinguishing in rare cases	Self-extinguishing (see Figure 15.11)
Repetition of faults	Double earth-fault Re-ignition of earth-fault	None	None	Double earth-fault
Voltage at earthing electrode U_E	$U_E \leq 125\,V$	$U_E > 125\,V$ permitted	$U_E > 125\,V$ permitted	$U_E \leq 125\,V$
Touch voltage U_B	$U_B \leq 65\,V$	see VDE 0141	see VDE 0141	$U_B \leq 65\,V$

U_n = nominal system voltage.
U_{0max} = maximal voltage in the zero-sequence system, that is, at neutral of transformer.
ω = angular velocity of the power system.
C_E = line-to-earth capacitance of the power system.
$\underline{Z}_0$, $\underline{Z}_1$ = zero-sequence and positive-sequence impedance of the system, respectively.
δ_0 = damping of the power system, see Section 15.5.
ν = Detuning factor, see Section 15.5.

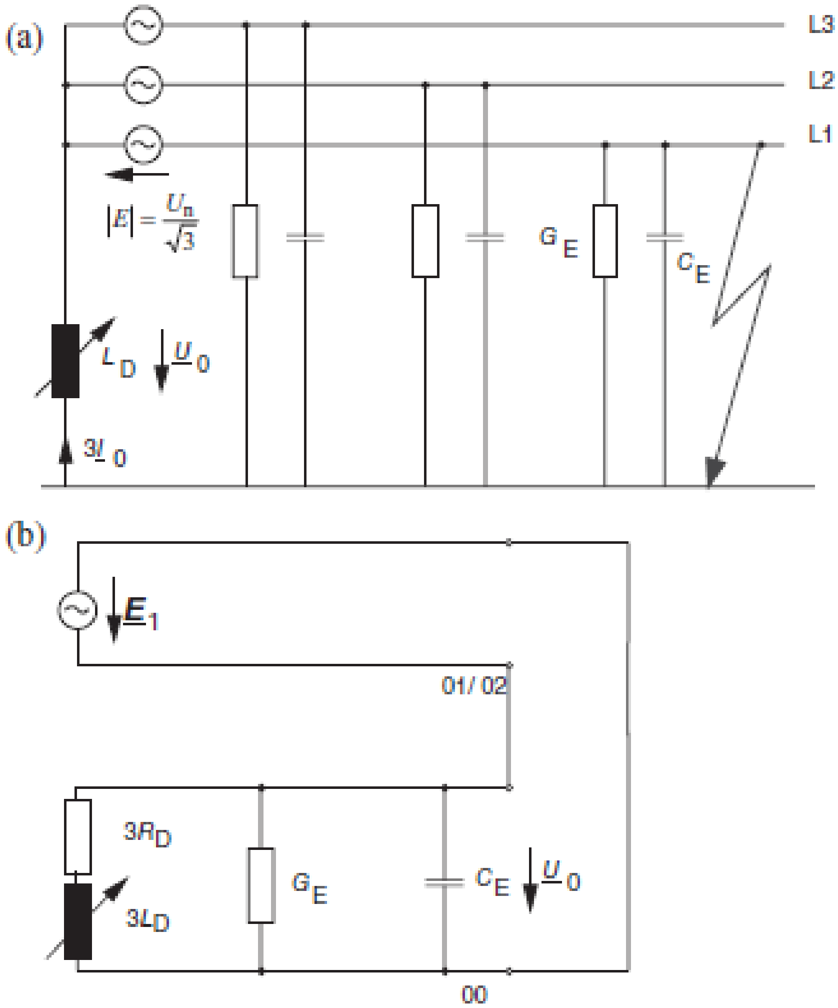


Figure 15.10 System with resonance earthing, earth-fault in phase L1. (a) Equivalent circuit diagram in the three-phase system; (b) equivalent diagram in the system of symmetrical components.

will be set in resonance to the line-to-earth capacitances of the system. The principal of the arrangement of a power system with resonance earthing is outlined in Figure 15.10.

The impedances of transformers and lines of the positive-sequence component can be neglected compared with those of the zero-sequence component due to the order of magnitude of the impedances. The admittance of the zero-sequence component is given by Equation 15.12

$$\underline{Y}_0 = \mathrm{j}\omega \cdot C_E + \frac{1}{3 \cdot R_D + \mathrm{j}3 \cdot X_D} + G_E \qquad (15.12)$$

with

C_E = line-to-earth capacitances of the system
ω = angular frequency of the system
R_D = resistance of the Petersen coil
X_D = reactance of the Petersen coil, $X_D = \omega L_D$
G_E = admittance representing the conductive line losses.

After some conversions, Equation 15.13 follows:

$$\underline{Y}_0 = j\omega \cdot C_E \cdot \left(1 - \frac{1}{3 \cdot \omega^2 \cdot L_D \cdot C_E \cdot \left(1 - j\frac{R_D}{X_D}\right)}\right) + G_E \tag{15.13}$$

The impedance of the Petersen coil appears with its threefold value in the zero-sequence component [80]. It is assumed that $R_D << X_D$ and that the losses of the Petersen coil are summed with the line-to-earth losses and are represented as admittance G_E of the line. The admittance in the zero-sequence component is then given by Equation 15.14a.

$$\underline{Y}_0 = j\omega \cdot C_E \cdot \left(1 - \frac{1}{3 \cdot \omega^2 \cdot L_D \cdot C_E}\right) + G_E \tag{15.14a}$$

The maximal impedance is obtained if the imaginary part according to Equation 15.13 is equal to zero and the current of the Petersen coil I_D is equal to the capacitive current I_{CE} of the system. As indicated in Figure 15.10, the line-to-earth capacitance C_E, the reactance $3L_D$ and the ohmic losses $R_0 = 1/G_E$ form a parallel resonance circuit with resonance frequency according to Equation 15.15.

$$\omega = \frac{1}{\sqrt{3 \cdot L_D \cdot C_E}} \tag{15.15}$$

The resonance frequency in case of resonance earthing is to be the nominal frequency $f = 50$ Hz or $f = 60$ Hz. Defining the detuning factor ν according to Equation 15.16a,

$$\nu = \frac{I_D - I_{CE}}{I_{CE}} = 1 - \frac{1}{3 \cdot \omega^2 \cdot L_D \cdot C_E} \tag{15.16a}$$

and the system damping δ_0 according to Equation 15.16b,

$$\delta_0 = \frac{G_E}{\omega \cdot C_E} \tag{15.16b}$$

the admittance of the zero-sequence component is given by Equation 15.14b.

$$\underline{Y}_0 = \omega \cdot C_E \cdot (j\nu + \delta) \tag{15.14b}$$

The admittance will be minimal and the impedance will be maximal in case of resonance tuning ($\nu = 0$). The earth-fault current I_{Res} in general is obtained with Equation 15.17a.

$$\underline{I}_{\text{Res}} \approx \sqrt{3} \cdot U_{\text{n}} \cdot \omega \cdot C_{\text{E}} \cdot (\text{j}\nu + \delta_0) \tag{15.17a}$$

In case of resonance tuning ($\nu = 0$) the earth-fault current is a pure ohmic current and is calculated according to Equation 15.17b.

$$\underline{I}_{\text{Res}} \approx \sqrt{3} \cdot U_{\text{n}} \cdot \omega \cdot C_{\text{E}} \cdot \delta_0 \tag{15.17b}$$

The line-to-earth voltages of the non-faulted phases increase to the value of the line-to-line voltage in case of a single-phase earth-fault, which is further increased due to asymmetrical system voltages, resulting in a higher displacement voltage between neutral and earth. In order to avoid the high voltages in case of exact resonance tuning, a small detuning of 8–12% is chosen in practice.

The task of resonance earthing is to reduce the earth-fault current at the fault location to the minimum or nearly to the minimum by adjusting the Petersen coil to resonance or nearly to resonance with the line-to-earth capacitances. The ohmic part of the residual current I_{Res} cannot be compensated by this. If the residual current is small enough, self-extinguishing of the arc in air at the fault location is possible. VDE 0228 part 2:12.87 defines the limits for self-extinguishing of residual currents I_{Res} (and capacitive earth-fault currents I_{CE}) for different voltage levels as outlined in Figure 15.11. It can be seen from Figure 15.11 that the limit for ohmic currents is nearly twice the limit for capacitive currents.

The Petersen coil can only be tuned for one frequency (nominal frequency) in resonance. Harmonics that are present in the system voltage increase the residual current at the fault location.

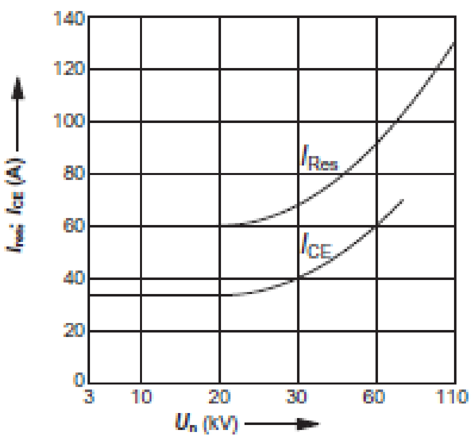


Figure 15.11 Limits for self-extinguishing of ohmic currents I_{Res} and capacitive currents I_{CE} according to VDE 0228-2:1987.

16
Tendering and Contracting

16.1
General (Project Definition)

The preceding chapters have dealt with the needs and basics of power system planning and principles as well as focusing on basic design aspects of main power system components. Based on recommendations resulting from various studies, the project engineering phase, as the next step, mainly covers the design, tendering and contracting/project implementation phases.

In this chapter the focus is set upon the general procedures and activities during the project engineering phase up to contracting/project implementation, after the project has been approved for realization and execution.

The creation of projects in the field of power and energy may be required for various reasons (refer also to Chapter 3), such as:

- Construction of new substations, overhead transmission lines or power cable systems as a result of power system planning
- Extension of existing power systems due to expansion of the supply areas, increase in power demand, addition of new supply point(s)
- Re-configuration of existing power network(s) to cope with developments and requirements in cities, regions or countries
- Interconnection between power systems
- Development of new power supply network(s) for new industrial complexes, newly created cities, resorts
- Addition of new or extension of existing power plants
- Improvement of existing power supply or electrical networks to increase reliability, operation flexibility, reduce network losses
- Rehabilitation or refurbishment of existing plants, substations, lines or components to meet the increasing requirements of power system development and expansion.

The engineering activities required to realize the planned project are carried out by the engineering divisions of the client (e.g. a utility), or are assigned to an engineering company.

16.2
Terms of Reference (TOR)

Terms of reference for a defined project are issued by clients/authorities and describe the services, supplies and work requested for the execution of the project under its terms and relevant regulations. Eligible or short-listed companies are invited to offer the work and services.

The terms of reference (TOR) are normally prepared by the client. The TOR serve to give a comprehensive overview of the client and its organization, the nature and status of the project, the requirements for services, engineering services, hardware and software, implementation schedule and commercial conditions and to outline the objective (such as to construct new high-voltage substations and overhead lines to meet the continuing growth in power demand, or to investigate the power interconnection with an industrial company to improve the reliability of power supply).

Formally the terms of reference are structured as detailed below.

16.2.1
Background

The functions and areas of responsibility of the client and the organization of the power sector are outlined, for example, responsibility for generation and transmission of bulk power throughout the country, or responsibility for distribution of electric power. Data and information relevant to the power system and system composition are stated, for example, radial distribution and transmission system.

16.2.2
Objective

Under this section three examples of projects are selected which are defined e.g. by utilities or power supply companies under development or power system expansion programs, or part thereof, with the aim to cope with the requirements of increasing power demand or changes in the power network structure.

– The client (e.g. in south-east Asia) plans to expand the existing 115/22 kV supply system with new 115/22 kV substations and switching stations in order to cope with the continuing growth in demand. Engineering services are needed to design the substations and switching stations and prepare turnkey solicitation followed by the tendering procedures.
– The client (e.g. in a Middle Eastern country) intends to carry out conceptual and engineering design, including preparation of tender packages for the reinforcement of electrical power supply at a large industrial complex. The engineering tasks include the conceptual and front end engineering design, preparation of tender packages, and identification of connection options with the required power system studies to support the selected option.

Read other topics in Chapter 16