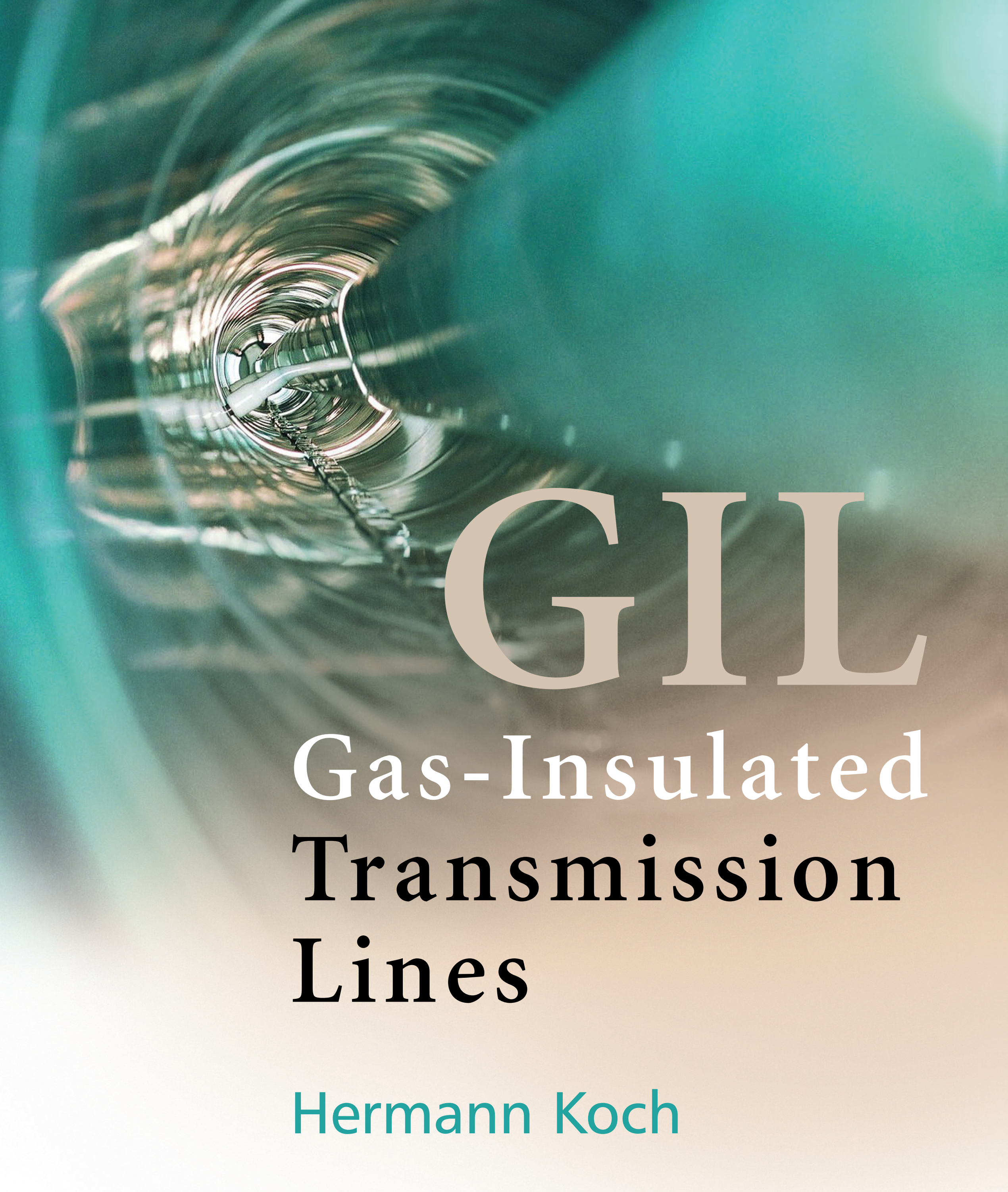
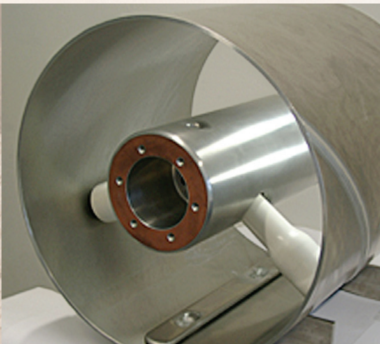


GIL

Gas-Insulated Transmission Lines

Hermann Koch



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GAS-INSULATED TRANSMISSION LINES (GIL)

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Foreword

Environmental constrains have intensified the interest in underground transmission lines as an alternative solution to overhead lines. Nowadays, different options of underground transmission lines are available. The most common solution are cables, however, gas-insulated lines (GIL) are also applied as an alternative. GIL can be laid directly buried, in a passable or non-passable tunnel or on a gantry. In particular, the directly buried type of GIL is attractive because it can be verified over distances of some kilometres up to some tens of kilometres by adjustment to the landscape and to impediments. GIL solutions offer different advantages, such as high current-carrying capacity, low losses, low charging capacity etc.

Although GIL technology is mainly based on the experience with gas-insulated switchgear, a lot of specific features and criteria in design, installation and maintenance have to be considered. The present book written by Hermann Koch – who has been involved in this subject for nearly two decades – gives a broad overview on all issues of this technology, which was introduced in the 1970s and has since been applied more and more as an alternative to cable solutions. It differs between the first generation of GIL, filled with pure SF_6 and consisting of flanged sections, and the second generation of GIL, filled with a gas mixture (SF_6 and nitrogen) and comprising welded enclosures and conductors. After presentation of the dielectric properties and design features, the assembly and laying procedure is described and the quality assurance measures and testing methods – including diagnostic tools – are given. At this stage the special requirements of the different laying options are particularly taken into account. Furthermore, system and network issues, the environmental impact and economic aspects are considered. Finally, various worldwide GIL applications are illustrated and a comparison with other transmission systems regarding technical and site features as well as economical aspects and soft parameters like aesthetics, non-visibility and noises is presented.

This book will be invaluable for engineers involved in the special requirements of today's system layout. It should be of particular interest to students specializing in power system engineering, but also contains fruitful information for readers who want to get a general overview of the different underground transmission technologies.

Professor Claus Neumann
Essen, Germany

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This book reflects the information and experience gleaned from the development, manufacture, assembly and operation of gas-insulated transmission lines over the last 20 years. Contributions to this book have come from many sides, and many experts in the field have been involved.

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The material in this book is based on, and derived from, more than 130 publications – most of them written by the author together with many co-authors. Not everyone can be mentioned here who participated in the development of the second generation of gas-insulated transmission lines, which is the core content of this book. I would like to give thanks to those experts who have contributed in joint or own publications and with many persona discussions about gas-insulated technology:

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Hermann Koch

1

Introduction

This introduction explains the background reasons why the gas-insulated transmission line (GIL) will play an increasing role in the future of electric power supply and why this book is being written today.

1.1 Changing Electric Power Supply

The power transmission systems of today will see basic changes in the near future. The impact of global warming affects the structure of electric power generation. Regenerative energy sources will be used to a much greater extent than today. Onshore and offshore wind, solar thermal, photovoltaic, biomass, hydropower, geothermal and sea-based power generation using wave, tidal or under-sea current power generation are all regenerative resources to generate electric power.

The sources of regenerative electric power will enter the electric power market as large-scale generators or as distributed small-sized power installations. Large-scale electric power and generation locations are usually far away from the load centres, and need to be connected through the electric power grid [1].

To handle these new electric power resources, intelligent power flow control is needed – a so-called "smart grid". Smart energy consumption based on prices traded on the electricity market will require electric energy transmission from generator to consumer. Changing power flows caused by the availability of regenerative power sources such as wind, sun, waves, tides and all the other fluctuating regenerative energy sources will need power flow control and long-distance power transmission. Energy storage will play a much more important role if fluctuating regenerative energy is to be used efficiently. Storing regenerative energy when it is available and using the stored energy when regenerative energy generation is not available will balance the power supply. This is a requirement for the effective future use of regenerative energy.

There are several methods to store electric energy. The most common method is to pump water to a higher level when energy is available for a low price and use the pumped water to generate electric energy when the price is high. Today, such pumped storage power plants are designed to deliver peak energy for some hours a day. Large storage devices can deliver 1000 MVA for some hours, then they become empty and need water to be pumped again.

Gas-Insulated Transmission Lines (GIL), First Edition. Hermann Koch.

Large storage devices can only be built in remote and sparsely populated areas, which are far away from the consumers of electricity. In Europe, for example, this would mean Norway. The available space in the Alps or Pyrenees is very limited. And lower-altitude storage does not provide the required energy capacity. Remote storage will require additional transmission lines to connect the storage with consumers.

Compressed air in large volumes in mines or underground caverns offers another possibility to store large amounts of electrical energy. Here, air will be pumped into the mine or cavern in cases when a surplus of regenerative energy is available. When no regenerative energy is available the compressed air is released through turbines to generate electricity. Today, prototype mines are under investigation in Europe and the USA, and the expectation is that this could be a relatively low-cost storage solution close to consumers where mines or caverns are available [223].

A very large storage capacity is available when the surplus of wind and solar power is used to produce hydrogen (H_2) by the electrolytic process, and store it at high pressure (about 30 MPa) in a large storage cavern in the salt layer – about 4000 to 5000 m under ground. This technology is being used today to store large quantities of natural gas. These storage capacities can be used to bridge long periods of no wind, which can occur for example in January in the North Sea for several days. The stored hydrogen can then be used with burned-in turbines to generate electricity.

Cooling or heating of residential houses or commercial cool houses is another possibility to store electric energy. Cooling or heating can be adapted to the availability of regenerative energy. When regenerative energy is available, the heating or cooling is done up to higher or down to lower temperatures. The building stores the energy using the time constant of the building. This can be part of the pricing of energy, and heating or cooling of buildings plays a role in balancing energy consumption.

Storage of regenerative energy in batteries of electric vehicles is another opportunity to balance the electric power supply. Electric vehicles stand still most of the time (80–90% of a car's lifetime is spent stationary). The batteries of electric vehicles are widely distributed and offer a large storage capacity for electric energy. Connected to the network, electric vehicles can be controlled by a smart grid to take electric energy from the network or to deliver electric energy to the network. Batteries can be used in short cycles to change from charging to delivering and can make an important contribution to a stable electric power supply based on regenerative energy sources, which are fluctuating.

Storage of surplus regenerative energy will be a key feature in the regenerative electricity market. In times when more wind or sunshine is available then the electricity market can take electric energy. This will be stored and sold later at higher prices when the electricity market requires more energy.

Small and large-scale storage facilities will be used and needed. A typical distributed small-scale storage facility is formed by the e-car batteries, as explained above. In terms of time, it covers short and mid-term sequences of minutes and hours. If the sequence of non- or low levels of regenerative energy generation reaches days or even weeks, large-scale storage facilities are needed.

Large-scale regenerating power installations installed in the near future will be far away from power consumption in metropolitan areas. Regenerative generation in offshore wind farms or desert-located solar power generation will be located in areas with low power consumption. Metropolitan areas and large cities cover only a very small part on the earth, and their density and electric power consumption is growing. Large power storage facilities will only be available far away from consumers [2, 3].

This will lead to long-distance, high-power transmission lines to connect power generation with power consumption. To balance regenerative energy sources it will be necessary to interconnect large distances, for example from the North Sea and Baltic Sea to the French or Spanish Atlantic coast; or the North East of the USA with the South East to take advantage of different wind situations in distant areas [4].

The power transmission system of today does not offer an optimized long-distance, high-power transmission network. Only relatively weak interconnections between regions are installed to cover emergency situations after the loss of large power generation (e.g., 1500 MVA) in one region when power from another region is needed.

Today, thermal power plants are located close to consumers and provide the required electric energy in a region. The future of regenerative energy generation is different, and requires an overlay network for continuous transmission of high power over longer distances, a so-called "super grid", or overlay network. The super grid will bring energy from the power generation locations to the consumers of electric power in the load centres and to the locations where electric power can be stored (e.g., hydropower pumping storage).

For other reasons, such high-power, long-distance electric power transmission has been and will be installed in China and India. Both emerging countries are building up their electric power supply by using large resources of hydropower when building dams, for example the Three Gorges in China or Tehri in India. Electric power of several gigawatts is transmitted over very long distances of 1000 km or more into the metropolitan areas of, for example, Shanghai or Mumbai.

Experience with state-of-the-art high-voltage transmission technology in China and India shows that long distances are operated over with high reliability and high efficiency – power transmission lines of ultra high voltage (UHV) for AC systems with 1000 kV AC and DC systems using ±800 kV DC. Since the year 2010 in China, ±800 kV DC is also in operation to connect large power generation stations to metropolitan areas. These long transmission lines are built as overhead lines using very high towers (typical 70–80 m) and also large bundles of conductor wires (8–10 wires in a bundle of about 500 mm to 800 mm diameter). Such large overhead lines may not be possible everywhere, and underground solutions for at least sections of the transmission line may be needed. The need for high-power transmission and the possibility of combining overhead transmission lines with underground solutions make the GIL a good candidate for an overall solution, or at least part of the solution [217].

Today, large-scale wind farms onland and offshore are in planning or under construction. Large-scale photovoltaic generation or solar thermal generation is in planning and the first pilot projects are proving feasible. While wind is mostly best at sea and sun shines best in deserts, long-distance transmission is needed to compensate for fluctuation and to bring the regenerative energy to the consumers.

When overhead lines cannot be built, then the GIL offers an alternative solution to going underground with the same amount of energy as the overhead line can transmit (e.g., at 400 kV the transmitted power is 2000 MVA).

More than 40 years' experience of first-generation gas-insulated technology is an excellent basis for using GIL as a high-power transmission system underground. The gas-insulated technology was introduced to substations in the late 1960s and is widely used today with high reliability. The introduction of second-generation GIL in 2001 using N_2/SF_6 gas mixtures and pipeline laying methods to reduce costs makes the GIL a long-distance, high-power underground transmission system with high reliability and availability for the future [168].

1.2 Advantages of GIL

GIL offers several advantages for high capacity power transmission, as listed below [9, 10].

Low Transmission Losses Resistive losses are low because of the large cross-section of the conductor and enclosure pipes. Typical GIL resistances are 6–8 mΩ/km depending on the outer diameter (500 mm or 600 mm) and the wall thickness of the enclosure and conductor pipe (6 mm to 15 mm). The transmission losses are related to the square of the transmitted current as $P_\mathrm{v} = I^2 \cdot R$ (I = current, R = resistance). When the current rating is high – as it is for GIL (e.g., 3000 A) – then the effect of low transmission losses is high. The losses through the insulating gas are negligibly small.

Low Capacitive Load Electric phase-angle compensation is only needed at very long lengths, because the capacity of the GIL is low, typically 55 μF/km. Therefore, no or low compensation coils are needed under most network conditions for transmission lengths of about 100 km. This also reduces the thermal operation losses.

Power Rating Like an Overhead Line The GIL is the ideal alternative or supplement to overhead lines. The high power transmission capability of the GIL (up to 3000 MVA per system at 550 kV rated voltage) allows it to go directly underground in series with an overhead line without power reduction. The GIL also allows the use of protection and control systems in the same way as with overhead lines. No differential protection is needed for failure location when a GIL is combined with overhead lines. The GIL has a low capacitance and, therefore, the inrush current is low.

High Level of Personnel Safety The outer enclosure pipe is solid grounded and no access to high-voltage parts is possible (gas-tight enclosure). Personnel safety is also guaranteed in case the GIL has to carry a short-circuit current (50, 63 or 80 kA up to 1 or 3 s). Even in case of internal failure and an arc between the enclosure and conductor pipes, tests have shown that no external impact occurs on the surroundings.

High Reliability The only purpose of the GIL is electric power transmission. No internal switching or breaking capability is needed. Based on this, the GIL can be seen as a passive high-voltage gas-insulated system with no active moving parts (e.g., switches). Today, more than 300 km of single-phase lengths has been in operation world-wide for more than 35 years. So far, no major failure (arc fault in the system) has been reported. This makes the GIL the most reliable power transmission system known.

No Electric Ageing Gas insulations do not age. The best example is an overhead line with ambient air as insulating gas. The electric field strength of the insulators and the maximum temperature of the GIL are too low to start the process of electrical or thermal ageing. This has been proven using long-term measurements in independent laboratories and also by extensive experience with the equipment in the network. The first GIL installations have been in operation since 1974, and the results are reported by the CIGRE [71, 224].

Operation Like an Overhead Line Overhead lines in the transmission network are operated with the so-called autoreclosure function. This means that in case of a ground fault detected on the line, the circuit breaker will automatically break the lines, wait some seconds (depending on the network condition) and then switch on again. In most cases the reason for the fault current detection will be gone and the transmission line will go back to normal operation (for example, if a tree branch gets too close to an overhead line, the branch will be burned away or if a lightning strike causes the fault current, that will also be gone after some seconds).

Electromagnetic Fields To protect the public and the operational personnel international regulations require electromagnetic field limitations. These values vary across regions and countries depending on laws and regional regulations. A trend can be seen worldwide that limiting values are getting lower and the restrictions harder. In densely populated areas and cities these electromagnetic field requirements are defining the allowed design of transmission lines.

The GIL is operated as a solid grounded installation and the inductive loop is closed through the ground connection. The coupling factor is about 95%. This means that the superposition of the two reverse currents reduces the outside magnetic field by 95%, and only 5% of the magnetic field of the conductor current is effective outside the GIL.

Because of the induction law, the current in the conductor will induce a current in the enclosure of the same size and with 180° phase shift. The superposition of both electromagnetic fields is close to zero. In case of limitation of the magnetic field in the surroundings, this solid grounded GIL can fulfil even very low magnetic field requirements. With a current rating of 3000 A, within a few metres' distance a magnetic field strength of 1 μT can be reached (as required in some countries).

The advantage of a low magnetic field is important when residential areas are close to the transmission line – for airports with their sensitive instruments, hospitals with their sensitive imagining systems, or all kinds of sensitive electronic equipment in private or business use.

In Italy, electromagnetic field requirements for new installations go down to magnetic flux values of only 0.2 μT. When residential areas are involved, the GIL can reach such low values over a distance of a few metres.

No Thermal Ageing The GIL is designed for maximum operational temperatures given by the surrounding conditions – maximum 60 or 70°C touching temperature in a tunnel, or 40 or 50°C when directly buried. The different temperature values depend on individual countries and their applied standards and regulations.

In all cases the maximum allowed temperature of the conductor of 100 to 120°C is not reached by far. Therefore, no practical ageing of the system can be expected under these operating conditions.

2

History

In this chapter the historical background of electric power supply and the development stages of the gas-insulated transmission line will be explained.

2.1 Transmission Network Development

2.1.1 General

When electrification started in the mid-1800s, electric power generation was installed close to the consumers. At voltages of about 100 V DC, generators delivered electric power to the consumers – for electric lights and electric drives. The generators were driven by hydropower at rivers, and the consumers were households, farms, offices and small industry (e.g., sawmills).

When cities started using electric street lights and manufacturers started using electric machines for production, electrification grew quickly. Electric generators used running water at rivers or steam engines in power houses transmitted the electricity using DC. Point-to-point connection was the normal case, mainly because it was difficult to switch DC currents. During these early periods of electrification, discussion was rife over the relative advantages of DC vs AC. Arguments led to two main positions:

- Tesla position – favoured AC, because it can be transferred to other voltage levels and is easy to switch.
- Edison position – favoured DC, because of its low transmission losses and higher transmission efficiency.

Today we know that AC won the battle in this first development stage of the electrical network, and the main reason was the transformer for higher voltage levels and the availability of AC switching devices. When AC was transformed to higher voltage levels of some kilovolts, and switches and circuit breakers managed to operate reliably, the extent of electricity use increased. Larger power generation units were possible to serve more consumers in a switched distribution network of high AC voltages.

Gas-Insulated Transmission Lines (GIL), First Edition. Hermann Koch.

With AC technology developing new materials, higher voltage levels were introduced and could be managed. With improvements in reliability and service life of electric light bulbs and electric motors, the number of installations and with that the electric power consumption increased. The voltage levels went to higher values and reached some kilovolts in the late 1800s. At this time, the first central power stations using steam engines to operate AC generators were installed in cities like New York, London, Paris and Berlin.

With the technical development of insulating materials, the production of insulators and the better understanding of high-voltage electric fields, higher operating voltages were introduced and with the availability of switches and circuit breakers the point-to-point electric power transmission system developed into an electrical network with high-voltage power transmission and medium-voltage distribution. Transmission voltages went into the 100 kV range and small local power producers cooperated and connected their electrical systems to develop city-sized power producers and distributors. They formed the first distribution companies and became known as public utilities.

Based on the growth of these public utilities the units of electric power generation increased in size, and in cooperation with other utilities larger areas were served with electric power supply. Larger power plants of 100 MW to 500 MW, and later 1000 MW, were developed and installed. With this larger power generation the power transmission voltages also increased, with new transmission voltages of 220 kV typically in Europe or 242 kV typically in North America. These transmission voltage levels came into use at the beginning of the 1920s. The next step increase in transmission voltages came in the 1960s, with 380 kV in Europe and 345 kV/550 kV systems in North America and Japan. Over the following years, transmission voltage levels of 345 kV up to 550 kV were installed all over the world. The highest voltage levels for transmission networks occurred in North and South America, South Africa and Russia – reaching 735 kV, 765 kV and 1000 kV. Today, activities on UHV transmission lines can be found in China (1100 kV) and India (1200 kV). Plans are also underway in North America and Europe to connect distant regenerative energy sources to the load centres by UHV lines [12].

2.1.2 Power Transmission Levels

The electric power system of today can be assigned to five levels: local, regional, national, international and intercontinental, as shown in Table 2.1 [13, 14].

Local Level The local level (level 1) of the electric power system has close reach to the consumers, with a typical distance of 1–5 km. The local level represents the origin of electric power supply, when 100 V DC was used in the first place. Then, the development was from DC to AC with typical house connection phase-to-ground voltages of 110 V AC in, for example, the USA and Japan and 240 V AC in, for example, Europe and some Asian and South American countries. Three-phase electric systems of 400 V AC are used today. These voltage levels are in wide use and cannot easily be changed because of the high cost of replacing all the installed equipment.

Regional Level The regional level (level 2) can be identified as covering a region, typically a city and the surrounding area. The reach of such a region is typically up to 100 km. The

Table 2.1 Power transmission levels

Level	Type	Example	Typical distances	Typical voltage levels	Typical current
1	local	small power producer city, e.g. Berlin, London, New York, Paris	1–5 km	up to 500 V	500 A
2	regional	utility city, e.g. Metropolitian areas of Berlin, London, New York or Paris; region, e.g. Bavaria	100 km	1–52 kV	2000 A
3	national	utility country, e.g. France, Italy; larger region, e.g. North East USA	1000 km	up to 400 kV* and 550 kV**	4000 A
4	international/ interregional	interconnected network, e.g. UCTE, NORDEL, MAGHREB, Itaipu, Cabora Bassa	2000 km	400 kV* 550 kV** 800 kV** 1100 kV***	5000 A
5	intercontinental	intercontinental networks, e.g. Europe/Africa, Europe/Asia	3000 km	1200 kV****	6000 A (expected)

* Europe, Middle East, India, Africa.
** North/South America, Asia.
*** China, Japan.
**** India.

voltage levels are below 100 kV and large power generation units are installed inside this region. Power producers in a region may be private or public entities owned by the city or regional organization. These larger companies, compared with the local power producers, own larger power generation units and operate higher voltage level transmission and distribution lines to serve more customers in a larger area. At the regional level several voltage levels have been introduced: 1 kV, 3 kV, 4.5 kV, 12 kV, 15 kV, 20 kV, 33 kV, 42 kV, 52 kV, and some more voltage levels between these values can be found around the world. These many steps in voltage levels represent the technical development of insulating materials. Today, the international standardization defines distribution voltages as 1–52 kV.

Many private companies and public-owned utilities were formed when the regional power transmission and distribution structure was built, and these companies are still in operation today – serving individual cities or regions. The typical reach of such a regional electric power supplier is about 100 km. Today, the deregulation of the power market has the goal of unbundling the monopolistic structures of the past, changing ownership and creating new structures of regional power supply under competition. The goal is for electric power users to have a choice of different power deliverers, with regulations and laws set in place. This will bring new players into the electricity market, and more companies will offer and trade with electricity. Trading with electricity was never in the mind of engineers when the power transmission and distribution network of today was designed. This means a basic change in the design and use of the power network.

National Level The national level (level 3) of electric power supply can often be identified with national borders of countries (e.g., France) or parts of countries (e.g., California in the USA). In some countries, the electric power supply was seen as a national task and public or government-owned power companies have been formed with governmental regulations. In Europe, such national level power suppliers have been established with, for example, EDF in France or ENEL in Italy. In other countries, with a more federal structure, the development of electric utilities was via private entities. These private entities grew to the same size in terms of generated megawatts or number of served customers as the public utilities. In Europe, such power supply companies can be found, for example, in Germany (e.g., RWE, PreussenElektra, Bayernwerk). In North America, regional utilities can reach the same area as whole countries in Europe (e.g., New York Edison in the Northeast, Bonville Power Association [BPA] in the Northwest, or Tennessee Valley Authority [TVA] in the Southeast).

The typical reach of a national power supply level has distances up to 500 to 1000 km and in consequence, voltage levels reached values of 420 kV in Europe, the Middle East, Africa and parts of South America and Asia and 550 kV in North America, Japan, parts of South America, Asia and Africa.

International Level The international or interregional level (level 4) can be identified with an area of several countries or larger regions. The level 4 network is used to stabilize the power transmission network in total and to offer network stability. Historically, the development of level 4 was meant to connect regions with high-voltage lines for emergency situations when power generation was lost in one country or region. In case of power losses because of interruptions in generation or interruption of transmission lines, the connection to the neighbouring region supports the network and keeps it stable. The UCTE in Europe developed the rule that the power of two 1500 MW nuclear power units can be compensated by international or interregional power reserves of 3000 MW. At each point in the network the concentration of electric power is limited to this value. The typical reach of this international or interregional level is about 3000 km, considering networks in Europe and North America.

In Europe, the northern NORDEL, the central UCTE and the eastern Baltic networks are synchronized in connection. In the USA, independent system operators (ISOs) have been established. These ISOs are operated with fixed frequencies and have interregional connections for relatively low power capacities.

Intercontinental Level The intercontinental level (level 5) does not really exist today but is on the way to being developed following the need for long-distance power supply when regenerative energy sources are in use world-wide. This layer needs even higher voltages to cover the long distances of up to 3000 km of electric reach for such intercontinental power transmission. These very long distances require the advantages of high-voltage DC power transmission, which offers low power transmission losses. As part of this future intercontinental power transmission level, the first installations are already in place in different parts of the world. The intercontinental level is certainly 30 years or more into the future, but current projects in China and India show that it is technically and economically feasible.

2.1.3 Long-Distance Power Transmission

In Africa, Cahora Bassa was installed in 1977–1979 to connect the hydropower resources of the Sambesi River to industrialized South Africa with a length of 1420 km. The power transmitted is at 1920 MW and the operational voltage is ±533 kV DC (see Table 2.2).

Table 2.2 Main data of Cahora Bassa, South African Development Zone [8]

Commissioning	1979, upgraded 2008
Power rating	1920 MW
DC transmission voltage	±533 kV
Length of overhead line	1420 km

In Figure 2.1 a large hydro dam and in Figure 2.2 a small hydro dam is shown. Large dams are often located in remote areas and need connection to the load centres by high-voltage AC or DC transmission lines. Small dams are usually located closer to load centres and are connected by lower high-voltage levels.

In Itaipu in South America, hydropower generated in the Argentina/Uruguay border area is delivered to the region of Sao Paulo in Brazil over 800 km away. The hydropower station at

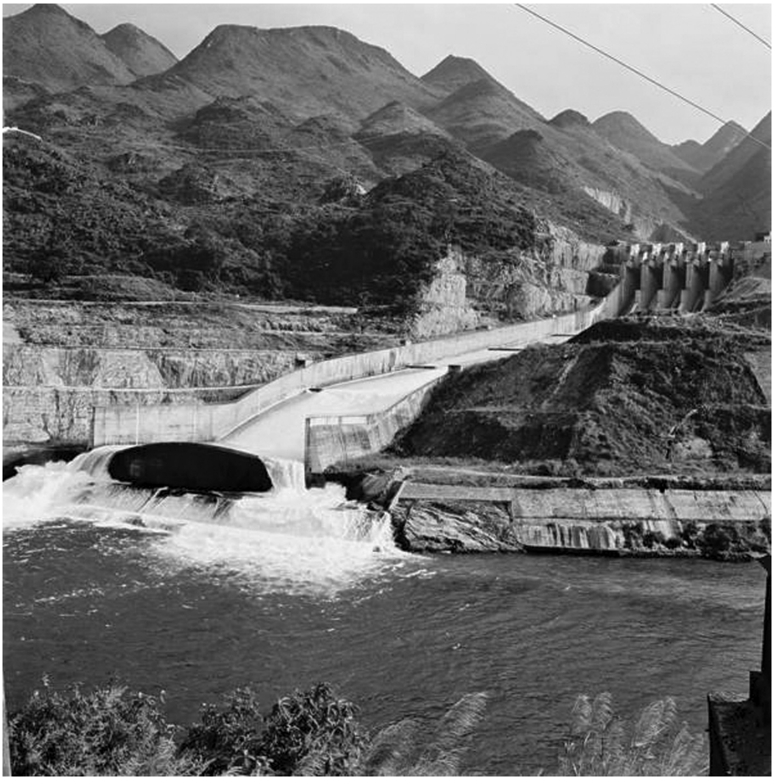

Figure 2.1 Example: Large hydro dam. Reproduced by permission of © Siemens AG

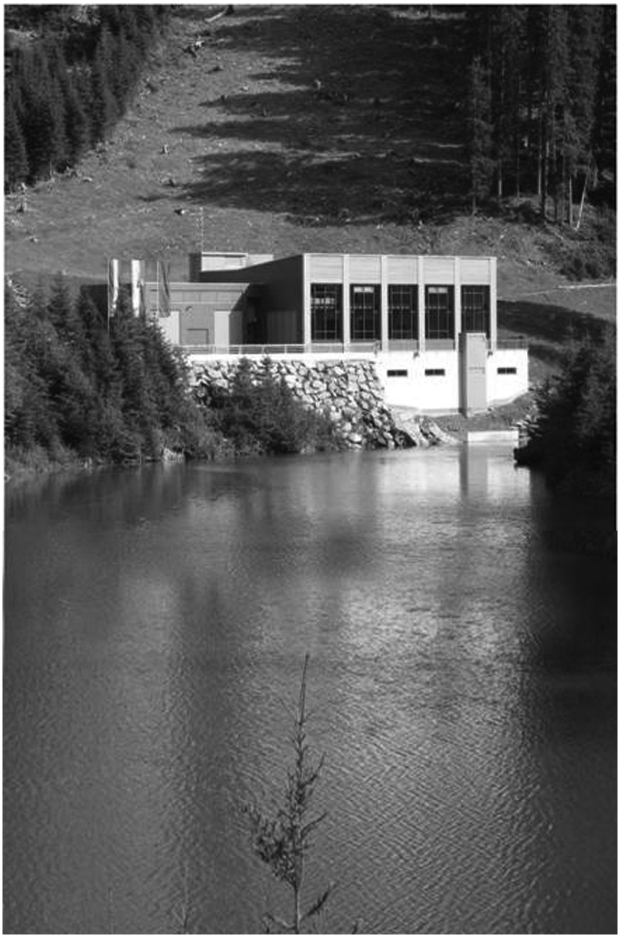

Figure 2.2 Example: Small hydro dam. Reproduced by permission of © Siemens AG

Itaipu went into operation in 1987, and with two high-voltage DC systems a total of 6300 MW is transmitted to the electric load centre in and around Sao Paulo (Technical data of the Itaipu project is shown in Table 2.3. Figure 2.3 shows the 735 kV AC gas-insulated switchgear [GIS] inside the dam).

One of the early projects in the USA was the Pacific Inter-Tie, which transmits a total of 3100 MW from Oregon's water dams to the metropolitan area of Los Angeles. The distance is about 1360 km, see Table 2.4.

Table 2.3 Main data of Itaipu, Brazil/Argentina [16]

Commissioning	1984–1987
Power rating	6300 MW
DC transmission voltage	±600 kV
Length of overhead line	Line 1: 685 km Line 2: 805 km