# Power Transmission and Distribution Solutions

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2 Power Transmission and Distribution Solutions

2.1 Overview of Technologies and Services

Feeding the power generated at different locations over long distances into power systems often calls for optimized power transmission and distribution solutions. Despite the challenges it poses, however, interconnecting of different regions, countries or even continents remains a viable option for providing these areas with economical access to power (fig. 2.1-1). As a solution provider with extensive experience in every aspect of power transmission and distribution, Siemens has already implemented a large number of projects linking power systems or connecting decentralized generating units to the grid. In each case, conditions were unique. And because Siemens strives to provide its customers with the most cost-efficient results, the implemented solutions using different technologies were also unique.

With Totally Integrated Power, Siemens offers a comprehensive low-voltage and medium-voltage portfolio which makes power distribution efficient, reliable, and safe – in cities, infrastructure, buildings, and industrial plants.

2.1.1 Solutions for Smart and Super Grids with HVDC and FACTS

The power grid of the future must be secure, cost-effective and environmentally compatible. The combination of these three tasks can be tackled with the help of ideas, intelligent solutions as well as advanced technologies.

Innovative solutions with HVDC (High-Voltage Direct-Current Transmission) and FACTS (Flexible AC Transmission Systems) have the potential to cope with the new challenges. By means of power electronics, they provide features which are necessary to avoid technical problems in the power systems, they increase the transmission capacity and system stability very efficiently and help to prevent cascading disturbances.

The vision and enhancement strategy for the future electricity networks are, for example, depicted in the program for “Smart Grids”, which was developed within the European Technology Platform.

Features of a future Smart Grid such as this can be outlined as follows:
• Flexible: fulfilling operator needs whilst responding to the changes and challenges ahead
• Accessible: granting connection access to all network users, particularly for Renewable Energy Sources (RES) and high-efficiency local generation with zero or low carbon emissions
• Reliable: assuring and improving security and quality of supply
• Economic: providing best value through innovation, efficient energy management and “level playing field” competition and regulation

Smart Grids will help achieve a sustainable development. It is worthwhile mentioning that the Smart Grid vision is in the same way applicable to the system developments in other regions of the world. Smart Grids will help achieve a sustainable development.

An increasingly liberalized market will encourage trading opportunities to be identified and developed. Smart Grids are a necessary response to the environmental, social and political demands placed on energy supply.

2.1.2 AC/DC Transmission and Distribution

HVDC and FACTS

Today’s power transmission systems have the task of transmitting power from point A to point B reliably, safely and efficiently. It is also necessary to transmit power in a manner that is not harmful to the environment. Siemens offers comprehensive solutions, technical expertise and worldwide experience to help system operators meet these challenges.

For each application and technical transmission stage, Siemens offers optimized solutions with HVDC transmission or FACTS for the most efficient operation of power systems.

Typical applications for FACTS include fast voltage control, increased transmission capacity over long lines, power flow control in meshed systems, and power oscillation damping. With FACTS, more power can be transmitted within the power system (section 2.3). When technical or economical feasibility of conventional three-phase technology reaches its limit, HVDC will be the solution (fig. 2.1-2). Its main application areas are economical transmission of bulk power over long distances and interconnection of asynchronous power grids. Siemens’ latest innovation in high-voltage direct-current technology is HVDC PLUS. The advantages of the new system, which employs voltage-sourced converters, include a compact layout of the converter stations, and advanced control features such as independent active and reactive power control and black start capability.
Power lines
Since the very beginning of electric power supply, overhead lines have constituted the most important component for transmission and distribution systems. Their portion of the overall length of electric circuits depends on the voltage level and on local conditions and practice. When environmental or structural factors make overhead lines impossible, Siemens’ “underground” transmission path is the ideal solution. Siemens gas-insulated transmission lines (GIL) can be an economically viable alternative to conventional power cables (section 2.4).

Grid access
Decentralized generating units are custom-engineered, which involves reconciling contrasting parameters, such as high reliability, low investment costs and efficient transmission, in the best possible solution. Specific attention is paid to intelligently designing the “collection systems” at the medium-voltage level, which is followed by the high-voltage transmission system providing the grid access. By relying on both transmission technologies, Siemens can offer AC as well as DC solutions at both the high- and medium-voltage levels (section 2.5).

Solar power
As an alternative power supply for rural electrification, Siemens integrates solar power in the low-voltage distribution system for private consumers, as stand-alone systems or even with grid connection (section 2.6).
2.1.3 Totally Integrated Power
We Bring Power to the Point – Safely and Reliably

Efficient, reliable, safe: These are the demands placed on electrification and especially power distribution (fig. 2.1-3). And our answer – for all application areas of the energy system – is Totally Integrated Power (TIP). It is based on our comprehensive range of products, systems and solutions for low and medium voltage, rounded out by our support throughout the entire lifecycle (fig. 2.1-4) – from planning with our own software tools to installation, operation and services.

Smart interfaces allow linking to industrial or building automation (fig. 2.1-4), making it possible to fully exploit all the optimization potential of an integrated solution. This is how we provide our customers around the world with answers to their challenges. With highly efficient, reliable and safe power distribution, we lay the foundation for sustainable infrastructure and cities, buildings and industrial plants. We bring power to the point – wherever and whenever it is needed.

Totally Integrated Power offers more:

- **Consistency:** For simplified plant engineering and commissioning, as well as smooth integration into automation solutions for building or production processes
- **One-stop-shop:** A reliable partner with a complete portfolio for the entire process and lifecycle – from the initial idea to after-sales service

Fig. 2.1-3: Comprehensive answers for power distribution in complex energy systems – from Siemens

- **Safety:** A comprehensive range of protection components for personnel safety, and line and fire protection, safety by means of type testing
- **Reliability:** A reliable partner who works with system operators to develop long-lasting solutions that meet the highest quality standards
- **Efficiency:** Bringing power to the point means greater plant availability and maximum energy efficiency in power distribution
- **Flexibility:** End-to-end consistency and modular design of Totally Integrated Power for any desired expansions and adaptation to future requirements
- **Advanced technology:** Reliable power distribution especially for applications in which supply is critical, continuous refinement of the technology.

Fig. 2.1-4: TIP is the perfect link to industrial and building automation
2.1.4 Consultant Support for Totally Integrated Power

Comprehensive services for the planning and concept drafting of electric power distribution systems

Experts – the Siemens TIP Consultant Support team – help electrical designers in many countries find holistic solutions for the fields of infrastructure, building and industry – even when it comes to critical power supply, for example, in hospitals and data centers.

All along the various planning phases, planners have recourse, to efficient software tools, online tender specification texts, and planning and application manuals.

The innovative SIMARIS® planning tools set standards in terms of planning efficiency. They support the planning process when dimensioning electric power distribution systems, determining the equipment and systems required, and preparing tender specification texts. The product portfolio of devices and systems required, ranging from the medium-voltage switchgear to modular installation devices in the distribution board, is mapped. This enables to plan entire power distribution systems from start to finish using the free-of-charge SIMARIS planning tools (fig. 2.1-5).

Siemens also provides qualified support for creating technical specification lists in the form of online tender specification texts within the framework of Totally Integrated Power. The fully integrated Siemens portfolio for electric power distribution can be found there. The clear tree structure in combination with a search function helps users find texts for the desired products. The text modules that were selected can be compiled in customized specifications (fig. 2.1-6).

The planning and application manuals will help you familiarize yourself with the technical background when planning power supply systems, and implementing it in product and systems solutions. In addition to the topical introduction provided by the planning manuals, the application manuals include solution criteria and approaches for planning power distribution to industry-specific buildings that meet our customers’ needs. Typical configurations and boundary conditions are presented in the form of examples, which are then turned into feasible concepts for the relevant building types, using specific products and system proposals. All manuals can be downloaded from our website as PDFs (fig. 2.1-7).

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For further information:
www.siemens.com/simarisis
www.siemens.com/specifications
www.siemens.com/tip-cs/planningmanuals

Fig. 2.1-5: The SIMARIS planning tools – easy, fast and safe planning of electric power distribution

Fig. 2.1-6: Text modules for tender specifications covering all Siemens products for electric power distribution

Fig. 2.1-7: Planning and application manuals impart specialized and up-to-date knowledge
2.1.5 Managing Entire Projects

Project management
Supplying power is more than just combining a number of individual components. It calls for large-scale projects, such as transmission systems or industrial complexes, especially in countries where the demand for power is growing at an accelerated pace. The best partner to handle such large projects is an expert who can carefully analyze the demand, take an integrated approach to project planning, and consider all the general conditions. A qualified project partner is one that can provide high-quality components and services for both power transmission tasks and power system management. Such a partner also can ensure that the systems are installed expertly.

Turnkey solutions
Siemens’ many years of experience allow to offer turnkey power transmission solutions that are tailored to individual requirements. Siemens supplies all components, including power plants, AC or DC transmission systems, and high-voltage interconnected power systems with high, medium and low voltage that finally reach the individual customers. What makes these turnkey solutions so attractive is that one party is responsible for coordinating the entire project, thereby reducing the number of interfaces between system operator and supplier to a bare minimum. Turnkey projects also reduce the operator’s own share in project risks, since Siemens is responsible for delivering a system that is ready for operation.

Engineering, procurement, production and construction
In addition to comprehensive planning and management services, engineering is one of Siemens’ special strengths. Siemens can produce or procure all necessary components and perform all construction work up to testing, commissioning and putting an entire system into operation. With Siemens as a partner, companies can benefit from Siemens’ extensive manufacturing expertise and from the work of experienced Siemens engineers who have already participated in a wide range of projects worldwide. Working on this basis, Siemens can provide the best technology for projects based on proprietary Siemens components and additional hardware purchased from reputable vendors. Siemens experts have the important task of determining which of the various technical options are best suited for implementing the project. They consider transmission capacity, transmission efficiency and the length of the transmission line, and after the best technical solution has been determined, they assess its long-term cost efficiency for the operator. Only then can the actual implementation begin for installation and on-time commissioning.

Maintenance
Systems will operate at their best when equipment lasts a long time and provides continuous trouble-free operation. The Siemens maintenance service ensures that all components are always running safely and reliably. Siemens continuously maintains operator systems through regular inspections including all switchgear and secondary technology. If a malfunction occurs during operation, Siemens is immediately on the job; support is available 24 hours a day, 365 days a year. And with the increased use of state-of-the-art online monitoring and remote diagnosis systems, Siemens offers additional possibilities for keeping operating costs to a minimum.

Optimization and modernization
Technological evolution leads to equipments and systems which are continuously improving. Siemens offers retrofit and upgrade services for existing schemes. This fast and economical solution allows customers to invest their capital wisely and take full advantage of Siemens’ experience in adapting older systems to new technical standards.

2.1.6 Partners throughout the System Life Cycle

Siemens is with system operators every step of the way to help them develop their projects, to create financing solutions and to provide project management (fig. 2.1-8), and supports them beyond engineering, production and construction. This support continues as the system is commissioned, as customers need maintenance services and even when it is time to modernize. The partnership between Siemens and the system operators does not stop when a turnkey job is finished: Siemens accompanies the system operators throughout the entire life cycle of their systems, offering a wide range of services with products of the highest quality that are always based on the most durable technologies.
2.2 High-Voltage Direct-Current Transmission

Siemens HVDC transmission is used when technical and/or economical feasibility of conventional high-voltage AC transmission technology have reached their limits. The limits are overcome by the basic operation principle of an HVDC system, which is the conversion of AC into DC and vice versa by means of high power converters.

Featuring its fast and precise controllability, a Siemens HVDC can serve the following purposes:
- Transmission of power via very long overhead lines or via long cables where an AC transmission scheme is not economical or even not possible
- Transmission of power between asynchronous systems
- Exact control of power flow in either direction
- Enhancement of AC system stability
- Reactive power control and support of the AC voltage
- Frequency control
- Power oscillation damping.

2.2.1 Siemens HVDC Technologies

Depending on the converter type used for conversion between AC and DC, two technologies are available:
- Line Commutated Converter technology (LCC) based on thyristor valves
- Voltage Sourced Converter technology (VSC) based on IGBT valves, also known as HVDC PLUS.

Both technologies enable Siemens to provide attractive solutions for most challenging transmission tasks ranging from extra-high-voltage bulk power transmission to the connection of systems in remote locations to main grids; from long distance overhead line or cable to interconnection of two systems at one location.

2.2.2 Main Types of HVDC Schemes

The main types of HVDC converters are distinguished by their DC circuit arrangements (fig. 2.2-1), as follows:

Back-to-back:
Rectifier and inverter are located in the same station. These converters are mainly used:
- To connect asynchronous high-voltage power systems or systems with different frequencies
- To stabilize weak AC links
- To supply more active power where the AC system already is at the limit of its short-circuit capability
- For grid power flow control within synchronous AC systems.

Cable transmission:
DC cables are the most feasible solution for transmitting power across the sea to supply islands/offshore platforms from the mainland and vice versa.

Long-distance transmission:
Whenever bulk power is to be transmitted over long distances, DC transmission is the more economical solution compared to high-voltage AC.
2.2.3 LCC HVDC – The “Classical” Solution

After more than 50 year’s history with Siemens constantly contributing to its development, LCC HVDC is still the most widely used DC transmission technology today.

Technology

Thyristor valves
The thyristor valves are used to perform the conversion from AC into DC, and thus make up the central component of the HVDC converter station. The valves are described by the following features:

- Robust design
- Safe with respect to fire protection due to consequent use of fire-retardant, self-extinguishing material
- Minimum number of electrical connections and components avoiding potential sources of failure
- Parallel cooling for the valve levels using de-ionized cooling water for maximum utilization of the thyristors
- Earthquake-proof design as required (fig. 2.2-2)
- Direct Light-Triggered Thyristors (LTT) with wafer-integrated overvoltage protection – the standard solution for transmission ratings up to 5,000 MW
- Electrically triggered thyristors for bulk power transmission up to 7,200 MW and above.

Filter technology
Filters are used to balance the reactive power of HVDC and power system and to meet high harmonic performance standards.

- Single-tuned, double-tuned and triple-tuned as well as high-pass passive filters, or any combination thereof, can be installed depending on the specific requirements of a station
- Active AC and DC filters are available for highest harmonic performance
- Wherever possible, identical filters are selected maintaining the high performance even when one filter is switched off.

Applications
The primary application areas for LCC HVDC are:

- Economical power transmission over long distances
- Interconnection of asynchronous power grids without increase in short-circuit power
- Submarine DC cable transmission
- Hybrid integration of HVDC into a synchronous AC system for stability improvement
- Increase in transmission capacity by conversion of AC lines into DC lines.

Power ratings
Typical ratings for HVDC schemes include:

- Back-to-back: up to typically 600 MW
- Cable transmission: up to 1,000 MW per HVDC cable
- Long-distance transmission: up to typically 7,200 MW.
2.2.4 Ultra-HVDC Transmission (UHV DC) Bulk Power

UHV DC from Siemens is the answer to the increasing demand for bulk power transmission from remote power generation to large load centers. After having been awarded the contract in 2007, Siemens has successfully commissioned the world’s first ±800 kV UHV DC system with 5,000 MW in China Southern Power Grid in 2010 (fig. 2.2-3).

Technology
The high DC voltage imposes extreme requirements to the insulation of the equipment and leads to huge physical dimensions (fig. 2.2-4). The capability to withstand high electrical and mechanical stresses is thoroughly investigated during the design. All components are extensively tested to assure that they withstand most severe operating conditions and meet highest quality standards.

The thyristor valves are equipped with either 5” or 6” thyristors depending on the transmission rating (fig. 2.2-5).

Applications
UHV DC transmission is the solution for bulk power transmission of 5,000 MW or higher over some thousand kilometers. Compared to a 500 kV LCC HVDC system, the Siemens 800 kV UHV DC reduces line losses by approx. 60 % – an important aspect with respect to CO₂ reduction and operational cost.

Special attention has to be paid to the corresponding AC networks that have to supply or absorb the high amounts of electric power.

Power ratings
The Siemens 800 kV HVDC systems are designed to transmit up to 7,200 MW over long distances.

2.2.5 HVDC PLUS – One Step Ahead

VSC technology offers unique advantages for HVDC transmission which become more and more important for applications like connecting remote renewable energy sources, oil and gas platforms or mines to an existing grid.

Using the latest modular IGBT (Insulated Gate Bipolar Transistor) technology in a pioneering Modular Multilevel Converter (MMC) design, Siemens engineers have developed HVDC PLUS as a landmark product in the evolution of HVDC transmission.

The high power ratings available today make HVDC PLUS increasingly attractive also for projects where LCC HVDC could be used from a technical perspective.

Features
HVDC PLUS provides important technical and economical advantages compared to LCC:
• HVDC technology in the smallest possible space:
  An HVDC PLUS station does typically not require any harmonic...
2.2 High-Voltage Direct-Current Transmission

filters (fig. 2.2-6). The MMC design allows to realize nearly perfect sinusoidal AC-side converter terminal voltages which are virtually free from harmonics. Together with a compact design of the MMC, this makes HVDC PLUS perfectly suitable for offshore platforms or stations with limited space (fig. 2.2-7).

- Independence from short-circuit capacity: HVDC PLUS can operate in networks with very low short-circuit capacity or even in isolated systems with or without own generation using its black-start capability.

- Unipolar DC voltage
  The DC voltage polarity is fixed independently from the direction of power flow. This allows integration into multi-terminal systems or DC grids. HVDC PLUS can operate with extruded XLPE or mass-impregnated DC cables.

- Economical design and standardization:
  The modularly designed HVDC PLUS converter stations can be perfectly adapted to the required power rating.

- For symmetrical monopolar configurations, standard AC transformers can be used, whereas LCC transformers require special design due to additional stresses from DC voltage and harmonics.

Applications
HVDC PLUS can be applied in all fields of HVDC transmission – there are no technical restrictions. The advantages of HVDC PLUS will be most apparent in circumstances that require the following capabilities:

- Black start of AC networks
- Operation in AC networks with low short-circuit capacity
- Compact design, e.g., for offshore platforms
- Operation in DC multi-terminal systems or in a DC grid.

Power ratings
The design of HVDC PLUS is optimized for power applications in the range from 30 MW up to 1,000 MW or higher, depending on the DC voltage.

Topologies (fig. 2.2-8)
Different topologies are available in order to fit best for the project specific requirements:

- Half-bridge (HB) topology
  The DC voltage is always controlled in one polarity only. Such a configuration is preferred for DC circuits with pure cable configurations. The risk of DC-side faults are small and typically lead to a permanent shutdown of the link

- Full-bridge (FB) topology
  The DC voltage can be controlled in a wide range including both polarities. Such a topology is predestinated for DC circuits with overhead lines, and provides the same features as known from HVDC Classic: DC line faults (e.g. due to lightning strikes) are cleared safely by a short-time reversion of the voltage. Furthermore, operation at reduced DC voltage levels is possible, which is often specified in case of pollution problems of line insulators.
2.2.6 DC Compact Switchgear DC CS

Business drivers for the development of DC compact switchgear

The changing generation and load structure in existing power grids requires increased transmission capacity. Longer transmission distances and increased loading tend to reduce the AC grid’s static and dynamic stability. To amend this, HVDC systems can be integrated into existing AC grids to provide the required transmission capacity, and at the same time increase grid stability.

What is more, the global trend towards decarbonization of power generation calls for an increased use of renewable energy sources (RES). While RES like offshore wind are typically found at great distances from the load centers, HVDC provides an effective (and in some cases the only) technical solution for power transmission.

The compact 320 kV DC switchgear DC CS is needed for HVDC cable connections to remote offshore wind farms, as well as for onshore HVDC projects. Thanks to its compact design, the DC CS helps to reduce the HVDC system’s space requirements. Hence it is predestinated for applications where space is limited or expensive, e.g. offshore HVDC platforms for remote windfarms, as well as close to city centers.

Using the DC CS outdoors even in rough climates adds to this effect. In the near future, DC compact switchgear and transmission solutions facilitate the realization of multi-terminal arrangements or DC grids, backing up the existing AC networks.

Fig. 2.2-11: Standardized modules of the DC CS product line

Fig. 2.2-12: 320 kV DC switchyard in/out bay
Modular structure
The 320 kV Direct-Current Compact Switchgear (DC CS) (without circuit-breaker) is developed based on proven BDQ1 550 kV AC GIS design and a new DC insulator following the well-established resin-impregnated-paper design which is used in wall bushings for decades.

The DC CS is a highly modularized product line, with standardized and predefined modules (fig. 2.2-11) which minimize the required interface engineering complexity between the DC CS modules as well as interfaces to e.g. control and protection systems. Examples of a 320 kV converter pole feeder arrangements are given in fig. 2.2-12 and fig. 2.2-13.

The range of modules like 0°/90° disconnector and earthing switch modules, 45°/90° angle modules grant flexibility to adapt to complex arrangements such as designs with a single or double busbar.

The module catalog is completed by an RC divider for voltage measurement, the zero flux compensated current measurement system, surge arrester and compensation modules required for service access, and both axial and lateral heat dilatation.

Application and special arrangements
DC compact switchgear can be applied at various locations with an HVDC system as displayed in fig. 2.2-13. An important application option for DC CS is between the converter transformer and the converter valves. With bipolar arrangements where 2 or more converters are arranged in a line with neutral in between, the section between the secondary connection of a converter transformer and the respective converter valves is stressed with a DC voltage offset resulting in a mixed voltage stress AC/DC requiring dedicated DC equipment. On the DC terminal, the DC switchyard, transition stations (enabling compact transition from cable to overhead line) along the line and finally future multi-terminal stations can be planned with DC CS.

The most important benefit of 320 kV DC compact switchgear is its inherent size advantage compared to air-insulated DC switchyard equipment.

Furthermore, the option for outdoor installation, even under extreme environmental conditions, is an advantage of DC CS. If for technical reasons, like temperature below -30 °C, a housing is required, the DC CS fits into pre-fabricated, containerized building modules (fig. 2.2-14). Containerized arrangements further have the advantage to pre-assemble and test whole switchyard/substation layouts locally at the manufacturer’s or the container builder’s plant, cutting short remote erection and commissioning efforts and costs, as well as simplifying the interface to civil works. Layouts with identical design which are repetitively used in a HVDC scheme can be planned and executed likewise, e.g. cable transition stations. Building and foundation costs can therefore be greatly reduced.

Finally, an underground installation hidden from view and public access is possible thanks to the encapsulation and compact design.

Regarding planned projects in densely populated areas, with critical points which are already occupied by traffic junctions and AC overhead lines as well as by natural barriers like rivers, huge potential for compact DC transmission solutions is existent.
Fig. 2.2-15: Application for DC compact switchgear, between transformer and valves, DC switchyard, transition station and multi-terminal station

<table>
<thead>
<tr>
<th>Technical data for switchgear type ±320 kV DC CS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated voltage</td>
</tr>
<tr>
<td>Rated current</td>
</tr>
<tr>
<td>Rated short-circuit current</td>
</tr>
<tr>
<td>Max. continuous operating voltage</td>
</tr>
<tr>
<td>Lightning impulse voltage to earth/ across terminals</td>
</tr>
<tr>
<td>Switching impulse voltage to earth/ across terminals</td>
</tr>
<tr>
<td>DC withstand voltage</td>
</tr>
<tr>
<td>Ambient temperature</td>
</tr>
<tr>
<td>Application</td>
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</tbody>
</table>

Table 2.2-1: Technical data of ±320 kV DC CS

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09131 / 7-43518
2.2.7 Siemens HVDC Control System: Win-TDC

The control and protection system is an important element in an HVDC transmission. The Siemens control and protection system for HVDC has been designed with special focus on high flexibility and high dynamic performance, and benefits from the knowledge gained from over 30 years of operational experience in HVDC and related fields of other industries (fig. 2.2-16).

High reliability is achieved with a redundant and robust design. All control and protection components from the human-machine interface (HMI), control and protection systems down to the measuring equipment for DC current and voltage quantities have been designed to take advantage of the latest software and hardware developments. These control and protection systems are based on standard products with a product lifecycle of 25 years or more.

The name Win-TDC reflects the combination of the PC-based HMI system SIMATIC WinCC and the high-performance industrial control system SIMATIC TDC for Microsoft Windows.

SIMATIC WinCC (Windows Control Centre) is used for operator control and monitoring of HVDC systems.

SIMATIC TDC (Technology and Drive Control) is a high-performance automation system which allows the integration of both open-loop and high-speed closed-loop controls within this single system. It is especially suitable for HVDC (and other power electronics applications) demanding high-performance closed-loop control. For extremely fast control functions as required in HVDC PLUS systems, SIMATIC TDC is complemented by the dedicated PLUSCONTROL comprising the fast Current Control System (CCS) and the Module Management System (MMS).

SIMATIC WinCC and SIMATIC TDC are used in a wide range of industrial applications including power generation and distribution.

In Siemens LCC HVDC systems, the DC currents and voltages are measured with a hybrid electro-optical system: DC current with a shunt located at HV potential, DC voltage with a resistive/capacitive voltage divider. Both systems use laser-powered measuring electronics so that only optical connections are made to the ground level controls – this provides the necessary HV isolation and noise immunity.

For HVDC PLUS, the DC currents are measured with a zero flux measuring system, which provides the required accuracy and dynamic response for fast control during grid transients. The zero flux cores are located at ground level on suitable locations, e.g., converter hall bushings or cable sealing ends.

Siemens provides proven hardware and software systems built around state-of-the-art technologies. Their performance and reliability fulfills the most demanding requirements for both new installations and control system replacement (fig. 2.2-17).
2.2.8 Services

The following set of services completes the Siemens HVDC portfolio.

**Turnkey service**
Experienced staff designs, installs and commissions the HVDC system on a turnkey basis.

**Project financing**
Siemens is ready to assist customers in finding proper project financing.

**General services**
Extended support is provided to customers of Siemens from the very beginning of HVDC system planning, including:
- Feasibility studies
- Drafting the specification
- Project execution
- System operation and long-term maintenance
- Consultancy on upgrading/replacement of components/redesign of older schemes, e.g., retrofit of mercury-arc valves or relay-based controls.

Studies during contract execution are conducted on system engineering, power system stability and transients:
- Load-flow optimization
- HVDC systems basic design
- System dynamic response
- Harmonic analysis and filter design for LCC HVDC
- Insulation and protection coordination
- Radio and PLC interference
- Special studies, if any.

For further information:
- [www.siemens.com/energy/hvdc](http://www.siemens.com/energy/hvdc)
- [www.siemens.com/energy/hvdc-plus](http://www.siemens.com/energy/hvdc-plus)
- [www.energy.siemens.com/IHqIen/powrr-transmission/hvdc/innovations.htm](http://www.energy.siemens.com/IHqIen/powrr-transmission/hvdc/innovations.htm)
2.3 Flexible AC Transmission Systems

Flexible AC Transmission Systems (FACTS) have been evolving to a mature technology with high power ratings. The technology, proven in numerous applications worldwide, became a first-rate, highly reliable one. FACTS, based on power electronics, have been developed to improve the performance of weak AC systems and to make long distance AC transmission feasible and are an essential part of Smart Grid and Super Grid developments (refer to chapter 1).

FACTS can also help solve technical problems in the interconnected power systems. FACTS are available in parallel connection:
- Static Var Compensator (SVC)
- Static Synchronous Compensator (STATCOM)

or in series connection:
- Fixed Series Compensation (FSC)
- Thyristor Controlled/Protected Series Compensation (TCSC/TPSC).

2.3.1 Parallel Compensation

Parallel compensation is defined as any type of reactive power compensation employing either switched or controlled units that are connected in parallel to the transmission system at a power system node.

Mechanically Switched Capacitors/Reactors (MSC/MSR)
Mechanically switched devices are the most economical reactive power compensation devices (fig. 2.3-1a).
- Mechanically switched capacitors are a simple but low-speed solution for voltage control and network stabilization under heavy load conditions. Their utilization has almost no effect on the short-circuit power but it increases the voltage at the point of connection.
- Mechanically switched reactors have exactly the opposite effect and are therefore preferable for achieving stabilization under low load conditions.
- An advanced form of mechanically switched capacitor is the MSCDN. This device is an MSC with an additional damping circuit for avoidance of system resonances.

Static Var Compensator (SVC)
Static var compensators are a fast and reliable means of controlling voltage on transmission lines and system nodes (fig. 2.3-1b).
2.3 Flexible AC Transmission Systems

fig. 2.3-2). The reactive power is changed by switching or controlling reactive power elements connected to the secondary side of the transformer. Each capacitor bank is switched ON and OFF by thyristor valves (TSC). Reactors can be either switched (TSR) or controlled (TCR) by thyristor valves.

When system voltage is low, the SVC supplies capacitive reactive power and rises the network voltage. When system voltage is high, the SVC generates inductive reactive power and reduces the system voltage.

Static var compensators perform the following tasks:
- Improvement in voltage quality
- Dynamic reactive power control
- Increase in system stability
- Damping of power oscillations
- Increase in power transfer capability
- Unbalance control (option).

The design and configuration of an SVC, including the size of the installation, operating conditions and losses, depend on the system conditions (weak or strong), the system configuration (meshed or radial) and the tasks to be performed.

SVC PLUS – new generation of STATCOM

SVC PLUS is an advanced STATCOM which uses Voltage-Sourced Converter (VSC) technology based on Modular Multilevel Converter (MMC) design.
- MMC provides a nearly ideal sinus-shaped waveform on the AC side. Therefore, there is only little – if any – need for harmonic filtering
- MMC allows for low switching frequencies, which reduces system losses.
- SVC PLUS uses robust, proven standard components, such as typical AC power transformers, reactors and switchgear.
- Using containerized SVC PLUS solutions with small operating ranges will result in significant space savings in comparison to a conventional SVC installation.

Applications

SVC PLUS with its superior undervoltage performance fulfills the same task as conventional SVCs. Due to the advanced technology, SVC PLUS is the preferred solution for grid access solutions (e.g., wind parks).

Modular system design

The modular SVC PLUS is equipped with industrial class IGBT (Insulated Gate Bipolar Transistors) power modules and DC capacitors.
- A very high level of system availability, thanks to the redundancy of power modules
- Standard WinCC and SIMATIC TDC control and protection hardware and software are fully proven in practice in a wide range of applications worldwide.

Portfolio

- Standardized configurations are available: ±25, ±35, and ±50 MVar as containerized solutions. Up to four of these units can be configured as a fully parallel operating system
- Easily expandable and relocatable
- Open rack modular system configuration (in a building) allows for operating ranges of ±250 MVar and more.
- Hybrid SVCs comprise a combination of both, multilevel STATCOM and conventional thyristor based SVC technology. This solution combines the benefits of the SVC PLUS, especially the undervoltage performance, with the flexibility of unsymmetrical operating ranges by TSR and TSC.
2.3.2 Series Compensation

Series compensation is defined as insertion of reactive power elements into transmission lines. The most common application is the fixed series capacitor (FSC). Thyristor-valve controlled systems (TCSC) and thyristor-valve protected systems (TPSC) may also be installed.

**Fixed Series Capacitor (FSC)**

The simplest and most cost-effective type of series compensation is provided by FSCs. FSCs comprise the actual capacitor banks, and for protection purposes, parallel arresters (metal-oxide varistors, MOVs), spark gaps and a bypass switch for isolation purposes (fig. 2.3-6a).

Fixed series capacitor provides the following benefits:
- Increase in transmission capacity
- Reduction in transmission angle.

**Thyristor-Controlled Series Capacitor (TCSC)**

Reactive power compensation by means of TCSCs can be adapted to a wide range of operating conditions. In this configuration, a TCR is connected in parallel to the capacitor bank. This allows to tune the overall system impedance of the TCSC according to the varying system operation conditions during dynamic disturbances. Spark gaps and major part of the arresters can be omitted in this configuration.

Additional benefits of thyristor-controlled series capacitor:
- Increase in system stability
- Damping of power oscillations (POD)
- Load flow control
- Mitigation of sub-synchronous torsional interaction (SSTI).

**Thyristor-Protected Series Capacitor (TPSC)**

An enhanced configuration of the FSC is the TPSC. In this case, high-power thyristors in combination with a current-limiting reactor are installed in parallel to the limiting series capacitors, and substitute the spark gap as well as the MOVs as protection devices. The protection of the power capacitor is performed by firing a bypass of the thyristors valves. Due to the very short cooling-down times of the special thyristor valves, TPSCs can be quickly returned to service after a line fault, allowing the transmission lines to be utilized to their maximum capacity. TPSCs are the first choice whenever transmission lines must be returned to maximum carrying capacity as quickly as possible after a failure (fig. 2.3-6c).

For further information:
www.siemens.com/energy/facts
2.3.3 Synchronous Condenser

Synchronous condenser solutions are being "reintroduced" worldwide to support today's transmission system requirements. The addition of renewables-based power generation to the energy mix, phase-out of conventional power plants, new HVDC systems, and the extension of power supply systems to remote areas influence the stability of transmission systems. Hence, the installation of synchronous condenser solutions has become necessary to provide sufficient support to the transmission systems.

The benefits of synchronous condensers
• Provision of short-circuit power and inertia
• Steady-stage and dynamic voltage control
• Reactive power control of dynamic loads.

A synchronous condenser solution generally consists of a synchronous generator connected to the high-voltage transmission system via a step-up transformer. The synchronous generator is started up and braked with a frequency-controlled electric motor (pony motor) or a starting frequency converter. When the generator has reached operating synchronous speed depending on the system frequency, it is automatically synchronized with the transmission system, and the machine is operated as a motor providing reactive and short-circuit power to the transmission system.

The generator is equipped with either a brushless exciter or with a conventional static exciter with brushes. The two solutions have different characteristics with respect to dynamic behaviors, and are selected according to the project requirements. Contrary to power-electronics-based static var compensators (SVCs), a synchronous condenser features the major advantages of injecting large amounts of short-circuit power and providing inertia due to its rotating mass.

Synchronous condensers offered as tailor-made turnkey solutions are based on proven, reliable in-house equipment, extensive know-how on transmission system requirements, and project execution experience. Siemens supplies a broad range of generators up to 1,300 MVA at nominal frequency. The generators are based on air, hydrogen or water-cooled technologies.

Applications
1. Stabilization of grids with high amounts of wind energy infeed
The synchronous condenser provides the transmission system with short-circuit power and reactive power control to operate the transmission system including an infeed of large amounts of wind power.

2. Support of HVDC Classic under weak system conditions
The synchronous condenser can increase the short-circuit power of weak systems. Furthermore it can improve the phase angle stability of the AC system by providing an additional rotating mass (increase in inertia time constant).

Fig. 2.3-7: Synchronous generator
Fig. 2.3-8: Synchronous condenser in Bjaeverskov, Denmark
Fig. 2.3-9: Synchronous condenser building of the HVDC Black Sea Transmission Network, Georgia
2.4 Power Transmission Lines

2.4.1 Gas-Insulated Transmission Lines

For high-power transmission systems where overhead lines are not suitable, alternatives are gas-insulated transmission lines (GIL). GIL exhibit the following differences to cables:

- High-power ratings (transmission capacity up to 3,700 MVA per system)
- High overload capability
- Auto-reclosing functionality without overheating risk
- Suitable for long distances (70 km and more without compensation of reactive power)
- High short-circuit withstand capability (even in the theoretical case of internal arc faults)
- Possibility of direct connection to gas-insulated switchgear (GIS) and gas-insulated arresters without cable entrance fitting
- Non-flammable; no fire risk in case of failures
- Lowest electromagnetic field.

History/Siemens’ experience
When SF₆ was introduced in the 1960s as an insulating and switching gas, it became the basis for the development of gas-insulated switchgear. On basis of the experience collected with GIS, Siemens started to develop SF₆ gas-insulated lines to transmit electrical energy. The aim was to create alternatives to air insulated overhead lines with decisively smaller clearances. In the early 1970s initial projects were implemented. More installations in tunnels and above ground followed. In the course of product optimization, the initially used insulating medium SF₆ was replaced by a gas mixture where the majority of the insulating gas is nitrogen, a non-toxic natural gas. Only a comparatively small portion of sulfur hexafluoride (SF₆) is still needed. Thus, the way was free for environmentally friendly long transmission projects with GIL. The latest innovation of Siemens GIL is the directly buried laying technique, which was a further milestone for long distance transmission with GIL.

Challenges now and in the future
Continuously growing world population and urbanization lead to a strongly increased demand for bulk power transmission at extra high voltage, right into the heart of cities. At the same time, the available space for transmission systems has been restricted more and more, and environmental requirements such as EMC and fire protection have gained increased importance. GIL fulfill these requirements perfectly. Meanwhile power generation is undergoing a conceptual change as well. As natural resources are limited, regenerative power generation is becoming more important. Offshore wind parks and solar power plants are being installed, providing a huge amount of energy at remote places. Consequently, transmission systems are needed which allow to transport this bulk power with utmost reliability and with the least possible losses.

The transmission systems of the future will be measured by their overall CO₂ balance, asking for the minimum possible environmental impact from production of the equipment through
operational while in service until its end of service life. Due to its properties and low losses, the overall CO₂ impact of GIL is clearly lower than that of traditional overhead-lines, proving the GIL’s environment friendliness.

**Reliable technology**
The gas-insulated transmission line technique is highly reliable in terms of mechanical and electrical design. Experience over the course of 35 years shows that after a GIL system is commissioned and in service, it runs safely without dielectrical or mechanical failures. Consequently, Siemens GIL – in service for decades – did not have to undergo their initially planned revision after 20 years of operation. Instead, a mere inspection was sufficient as there was no sign of any weak point. From the operational experience gained with Siemens GIL and GIB, the Mean Time Between Failure (MTBF) was estimated > 213 years for a 1-km-long GIL system.

**Basic design**
In order to meet electrical and mechanical design criteria, gas-insulated lines have considerable cross-sections of enclosure and conductor, which ensures high-power transmission ratings and low losses. Because of the geometry and the gaseous insulating medium, the systems create only low capacitive loads, so that compensation of reactive power is not needed, not even for longer distances. The typical technical data of the GIL are shown in table 2.4-1.

**Testing**
GIL systems are tested according to the international standard IEC 62271-204 “Rigid high-voltage, gas-insulated transmission lines for voltages of 72.4 kV and above” (fig. 2.4-4, fig. 2.4-5).

The long-term performance of GIL has been proven by tests at the independent test laboratory IPH, Berlin, Germany, and the former Berlin power utility BEWAG (now ELIA). The test pattern was set by adopting long-term test procedures for power cables. The test procedure consisted of load cycles with doubled voltage and increased current as well as frequently repeated high-voltage tests. The results confirmed the meanwhile more than 35 years of field experience with GIL installations worldwide. The Siemens GIL was the first in the world to have passed these long-term tests without any problems. Fig. 2.4-6 shows the test setup arranged in a tunnel of 3 m diameter.

**Fault containment**
Tests have proven that the arcing behavior of GIL is excellent. It is even further improved by using mixed-gas insulations. Consequently there would be no external damage or fire caused by an internal fault.

**Electromagnetic compatibility allows flexible route planning**
The construction of the GIL results in much smaller electromagnetic fields than with conventional power transmission systems. A reduction by a factor of 15 to 20 can be achieved. This makes GIL suitable to follow new routings through populated areas (e.g., next to hospitals or residential areas, in the vicinity of flight monitoring systems, etc.). GIL can be laid in combined

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**Technical data short-circuit capacity 63 kA**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated voltage</td>
<td>Up to 550 kV</td>
</tr>
<tr>
<td>Rated current</td>
<td>up to 5,000 A</td>
</tr>
<tr>
<td>Transmission capacity</td>
<td>up to 3,700 MVA</td>
</tr>
<tr>
<td>Capacitance</td>
<td>≈ 60 nF/km</td>
</tr>
<tr>
<td>Length</td>
<td>up to 70 km</td>
</tr>
<tr>
<td>Gas mixture SF₆/N₂</td>
<td>20%/80% (400 kV), 60%/40% (500 kV)</td>
</tr>
<tr>
<td>Laying</td>
<td>Directly buried</td>
</tr>
<tr>
<td></td>
<td>In tunnels, sloping galleries, vertical shafts</td>
</tr>
<tr>
<td></td>
<td>Open-air installation, above ground</td>
</tr>
</tbody>
</table>

**Table 2.4-1: Technical data of GIL**
infrastructure tunnels together with foreign elements (e.g., close to telecommunication equipment and similar). Thus, GIL provides maximum flexibility for the planning of transmission systems, in EMC-sensitive environments, where magnetic fields have to be avoided. Siemens GIL systems can satisfy the most stringent magnetic flux density requirements, for example, the Swiss limit of 1 μT (fig. 2.4-4, fig. 2.4-5).

Jointing technique
In order to perfectionize gas tightness and to facilitate laying of long straight lines, flanges may be avoided as a jointing technique. Instead, welding the various GIL construction units ensures highest quality (fig. 2.4-6). Siemens’ welding process is highly automated by using orbital welding machines. This as well contributes to high productivity in the welding process and a short overall installation time. To ensure quality, the welds are controlled by a new sophisticated ultrasonic testing system which exceeds even X-ray test standards.

Laying
During the installation process, climatic influences such as rain, dust, seasons of the year, etc. need to be taken into account. To meet Siemens’ requirements for cleanliness and quality, the laying techniques of GIL differ from pipeline technology. To protect the assembly area against dust, particles, humidity and other environmental factors, a temporary installation tent is set up for the installation period. In this way, working conditions are created which meet the standards of modern GIS factories. After the GIL is installed, these supporting installations are removed completely, and the entire area is re-naturalized. Thus, GIL are well suitable for use in environmentally protected areas. Due to the small width of GIL routes, the system is specifically compatible with the landscape.

Above ground installation
GIL installation above ground are a trouble-free option for use in properties with restricted public access. The open air technology is proven under all climatic conditions in numerous installations all over the world. GIL are unaffected by high ambient temperatures, intensive solar radiation or severe atmospheric pollution (such as dust, sand or moisture). Due to the use of corrosion resistant alloys, corrosion protection can be omitted in most application cases (fig. 2.4-7).

Tunnel installation
Tunnels made up of prefabricated structural elements provide a quick and easy method of GIL installation especially in densely populated areas. The tunnel elements are assembled in a dig-and-cover trench, which is backfilled immediately. The GIL is installed once the tunnel has been completed. Thus, the open trench time is minimized. With this method of installation, the land above the tunnel can be fully restored to other purpose of use (fig. 2.4-8).

Vertical installation
Gas-insulated tubular lines can be installed without problems at any gradient, even vertically. This makes them a top solution especially for cavern power plants, where large amounts of
energy have to be transmitted from the bottom of the cavern (e.g., the machine transformer / switchgear) to the surface (overhead line). As GIL systems pose no fire risk, they can be integrated without restriction into tunnels or shafts that are accessible to man, and can also be used for ventilation at the same time. Thus, cost for tunnelling works can be reduced clearly.

The use of GIL in hydropower plant projects with the highest demand on reliability transporting electricity of 3900 MVA of power safely and efficiently from the dam to the population centers is becoming of more importance.

**Direct burying**
Especially when used in lesser populated areas, directly buried GIL are a perfect solution. For that purpose, the tubes are safeguarded by a passive and active corrosion protection. The passive system comprises a HDPE coating which ensures at least 40 years of protection. The active system additionally provides cathodic DC protection potential for the aluminum tubes. Magnetic fields measured at the surface above the line are minimal. The high transmission power of GIL minimizes the width of trench. The land consumption is lower by approx. 1/3 related to comparable cable installations (fig. 2.4-9).

**References**
Siemens has gained experience with gas-insulated transmission lines at rated voltages of up to 550 kV, and with phase lengths totalling more than 90 km (2014). Implemented projects include GIL in tunnels, sloping galleries, vertical shafts, open-air installations, as well as directly buried. Flanging as well as welding has been applied as jointing technique.

The first GIL stretch built by Siemens was the connection of the turbine generator pumping motor of the pumped storage power plant of Wehr in the Black Forest in Southern Germany with the switchyard. The 420 kV GIL is laid in a tunnel through a mountain and has a single-phase length of ~4,000 m (fig. 2.4-1). This connection was commissioned in 1975. One of the later installations is the Limberg II pumped-storage power plant in Kaprun, Austria, which was commissioned in 2010. Here a GIL system was laid in a shaft with a gradient of 42°. It connects the cavern power plant with the 380 kV overhead line at an altitude of about 1,600 meters. The GIL tunnel is used for ventilation purposes, and serves for emergency exit as well. That resulted in substantial cost reduction by eliminating the need for a second shaft in this project (fig. 2.4-11).

A typical example for a city link is the PALEXPO project in Geneva, Switzerland. A GIL system in a tunnel substitutes 500 meters of a former 300 kV double circuit overhead line, which had to move for the raised exhibition centre building. The line owner based his decision to opt for a GIL over a cable solution on the GIL’s much better values with respect to EMC. Thus, governmental requirements are met, and high sensitive electronic equipment can be exhibited and operated in the new hall without any danger of interference from the 300 kV connection located below it (fig. 2.4-12).
A typical example for a directly buried GIL is the reference project at Frankfurt Airport in Kelsterbach, which was commissioned in April 2011. The GIL solution allows to continue one phase of the OHL in one phase of GIL, thus reducing the size of both trench and transition area at the connection points (fig. 2.4-9).

Typical examples for vertically installed GIL are the hydro power plant projects Xiluodu and Jinping in China energized in 2013. Xiluodu (fig. 2.4-13) is the longest vertically installed GIL having an average vertical distance of more than 460 meters from turbines in the power cavern to the overhead transmission lines on top of the dam. In total 12 kilometers of welded GIL were installed divided on 7 GIL systems.

At Jinping (fig. 2.4-14), the world’s tallest HPP dam, three GIL Systems from Siemens span 230 meters vertical shafts. For this project, Siemens had to demonstrate its capability of mastering extremely difficult site conditions, and at the same time accelerate the installation to meet the energization target for the HPP.

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Fig. 2.4-13: Vertically installed GIL in Xiluodu, China

Fig. 2.4-14: Jinping, China, the world’s tallest HPP dam
### 2.4.2 High-Voltage Power Cables

Cables intended for the transmission and distribution of electrical energy are mainly used in power plants, in distribution systems and substations of power supply utilities, and in industry. Standard cables are suitable for most applications. They are preferably used where overhead lines are not suitable. Cables exhibit the following differences to gas-insulated transmission lines (GIL):

- For operating voltages up to 220 kV, as well as where the rated design current is below ~2500A, the investment costs for the primary cable equipment are lower than for other underground transmission systems.
- The installation time at site is comparatively short, as long cable lengths (e.g., up to 800m – or even higher depending on cable design) can be delivered on one drum, which significantly reduces jointing and installation times.
- During cable laying, the open-trench-times for earth-buried systems are comparatively short.
- Cables do not contain any unbound climate-damaging SF$_6$ gas.
- The costs of de-installation of a cable plant are significantly lower; a high level of recycling is possible.

#### Basic design

There is a variety of high-voltage cables with different design and voltage levels (fig. 2.4-15).

Cable joints connect lengths of cables in long transmission routes or at points of repair (example see fig. 2.4-17).

Sealing ends form the termination points of a cable, and serve as a connection to switchgear, transformers and overhead lines. Fig. 2.4-16 shows the different types of cable accessories, fig. 2.4-18 an example of an outdoor sealing end.

Siemens offers vendor-neutral consulting and evaluation of cable manufacturers, and procurement of high-voltage cables and accessories, adapted in case of application. The factories of the cable manufacturers are audited by Siemens chief engineers taking under consideration all relevant DIN VDE and IEC standards. In addition, the following engineering tasks can be performed by specialists from Siemens.

#### Engineering

For operation, cable and accessories must comply with electrical requirements, and have to satisfy ambient conditions which can differ significantly depending on location, ground, indoor or outdoor.

For save project planning of cable installations, the cross-section of conductor shall be determined such that the requirement current-carrying capacity $I_C \geq$ loading $I_L$ is fulfilled for all operating conditions which can occur. A distinction is made between the current-carrying capacity:

- for normal operation
- and for short circuit (operation under fault conditions).
For high-voltage cables, the current-carrying capacity is to be examined by means of special calculation tools for each special case of application. First of all, the laying and installation conditions have to be taken in consideration. Fig. 2.4-19 shows different laying arrangements.

**Laying in ground**
The depth of laying a high-voltage cable in ground is generally taken as 1.20 m, which is the distance – below the ground surface – to the axis of the cable or the center of a bunch of cables. To lay cables in the ground, calculations show that the load capacity of the cable decreases as depth increases, assuming the same temperature and thermal resistivity of the soil. On the other hand, the deeper regions of the ground are normally moister and remain more consistent than the surface layers.

Crossing of cable runs can cause difficulties especially when these are densely packed (hot spot). At such points, the cables must be laid with a sufficiently wide vertical and horizontal spacing. In addition to this, the heat dissipation must be assisted by using the most favorable bedding material (fig. 2.4-20). A calculation of conductor heat output and temperature rise is absolutely necessary because the maximum conductor temperature of XLPE cable must not exceed 90 °C (fig. 2.4-21).

---

**Example:** Current rating for cable 2XS(FL)2Y 1 x 630RM/50 64/110 kV at different laying conditions

<table>
<thead>
<tr>
<th>Laying Condition</th>
<th>Current (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Free in air</td>
<td>1082</td>
</tr>
<tr>
<td>In air-filled channel</td>
<td>970</td>
</tr>
<tr>
<td>In pipes in ground</td>
<td>543</td>
</tr>
<tr>
<td>Direct in ground</td>
<td>560</td>
</tr>
<tr>
<td>In ground in thermally stabilized backfill</td>
<td>681</td>
</tr>
<tr>
<td>In pipes in ground in thermally stabilized backfill</td>
<td>598</td>
</tr>
</tbody>
</table>

**Conditions:** Cables in trefoil formation, cable screens bonded at both ends, air temperature 30°C, ground temperature 20°C, spec. thermally resistivity of natural 1.0/2.5 km/W, spec. thermal resistivity of thermal stabilized backfill 1.2 km/W, PVC pipes 150 x 5 mm, laying depth 1200 mm, dimensions of cable channel width x height x cover: 1000 x 600 x 150 mm, thermally stabilized backfill in ground 600 x 600 mm, thermally stabilized backfill for pipes 700 x 700 mm

---

Fig. 2.4-19: Laying arrangements

Fig. 2.4-20: Heat dissipation from cables

Temperature distribution for 2 parallel 110 kV cable circuits with different load currents

**Fig. 2.4-21: Temperature distribution for 2 parallel 110 kV cable circuits**
In case of using different laying arrangements in ground for a cable system, the chain principle “The weakest link determines the strength of the whole chain” applies. This means that the thermally most critical section determines the current-carrying capacity of the whole cable circuit (fig. 2.4-22).

**Laying free in air**
The highest load capacity is given when laying the cables free in air on cable trenches with an unhindered heat dissipation by radiation and convection.

When cables are installed directly on a wall or on the floor, the load capacity has to be reduced by using a factor of 0.95.

However, other heat inputs, e.g. solar radiation must be considered or prevented by use of covers. The air circulation must be secured, and a calculation of the load capacity is recommended.

The same applies to laying cables in air-filled channels.

When cables are laid in air, the effects of thermal expansion in normal operating mode and in cases of being subjected to short-circuit currents have to be considered.

According to DIN VDE standards, cables have “to be installed in such a way that damage, e.g., by pressure points caused by thermal expansion, are avoided”. This can be achieved by installing the cables in an approximate sine-wave form (snaking) and fixing as shown in fig. 2.4-23.

### Cable deflection caused by thermal expansion

<table>
<thead>
<tr>
<th>Project:</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Plant:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cable type: N2XS(FL)2Y 1x630 RM/50 64/110 kV</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Input data**

| Minimum ambient temperature | \( \theta_{0 \text{min}} \) | 0°C |
| Maximum ambient temperature | \( \theta_{0 \text{max}} \) | 40°C |
| Maximum conductor temperature | \( \theta_{L \text{max}} \) | 90°C |

| Minimum deflection (at minimum ambient temperature) | \( \delta_{\text{min}} \) | 100 mm |
| Fixing distance in longitudinal direction | \( l_S \) | 3.00 m |
| Additional reduction of fixing distance (i.e. expansion gap) | \( \Delta l_S \) | 0.00 mm |
| Conductor material | | Kupfer |
| Linear expansion coefficient of conductor material | \( \alpha_l \) | 0.0000162 K\(^{-1}\) |

**Cable expansion and deflection**

| Maximum thermal expansion of conductor | \( \Delta l (\theta_{L \text{max}}) \) | 4.39 mm |
| Deflection at maximum conductor temperature | \( \delta_{\text{max}} (\theta_{L \text{max}}) \) | 124 mm |
| Deflection at max. cond. temperature and reduced fixing distance | \( \delta_{\text{max}} (\theta_{L \text{max}}; -\Delta l_S) \) | 124 mm |

![Fig. 2.4-22: Different laying arrangements in ground](image-url)

![Fig. 2.4-23: Snaking of cables](image-url)
Concerning short-circuit currents, DIN VDE stipulates that “Single-core cables must be safely fixed to withstand the effects of peak short-circuit currents”, which means they must withstand the stresses caused under short circuit, and remain in position such that neither the cable or the fixing element get damaged.

**Earthing**

Due to electromagnetic induction, a voltage is induced in the outer conductor and metallic screen, which depends on the operating or short-circuit current level. In order to handle all induced voltages and to guarantee a good earth connection during a short circuit, the outer conductor and the metallic sheath must be sufficiently connected to the external earthing system. Depending on the calculations of the induced voltage, several different types of earthing can be applied (fig. 2.4-24).

The above-mentioned engineering works and calculations which are necessary for safe operation of cable systems can completely carried out by Siemens engineering specialists.

**Both-end bonding**

For both-end bonding, both ends of the cable screen are connected to the ground. The advantage of the method is that no standing voltages occur at the cable ends.

The disadvantage is that circulating currents may flow inside the screen as the loop between the two earthing points is closed through the ground. As these circulating currents can be as high as the conductor current itself, they can reduce the cable ampacity significantly.

The losses incurred by both-end bonding means that this is the most disadvantageous earthing system method as far as economic issues are concerned. It is therefore mainly applied in selected cases and for short distances.

**Single-end bonding**

For single-end bonding, only one end of the cable screen is connected to earth while the other end is left floating. The voltage is induced linearly along the whole cable length, and at the “open end” a standing voltage occurs. The open end should be protected with a sheath voltage limiter. This diminishes the chance of overvoltages occurring inside the cable screen, protects the cable system, and ensures that relevant safety requirements are upheld.

The advantage of single-end bonding is that losses caused by circulating currents cannot occur, and the current carrying capacity is higher.

The disadvantage is the voltage which occurs at one end of the termination.

**Cross bonding**

Cross bonding is necessary for long cable segments with joints. The cross-bonding system consists of three sections, each followed by a cyclic sheath crossing. At the terminations, earthing must be solidly bonded to the ground. In an ideal cross-bonding system, the three sections are of equal length.

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**Variants of bonding metal sheaths/screens of single cor HV-cables**

<table>
<thead>
<tr>
<th>Bonding at both sides</th>
<th>+ no induced sheath voltage + simple cost saving design – circulating sheath currents – additional sheath losses – reduced current carrying capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bonding at single sides</td>
<td>+ no circulating currents + increased current carrying capacity – induced voltages at sealing ends – sheath voltage limiters and parallel earth continuity conductor required</td>
</tr>
<tr>
<td>Cross bonding</td>
<td>+ no circulating currents + increased current carrying capacity – induced voltages at joints – sheath voltage limiters and sheath interruption joints required</td>
</tr>
</tbody>
</table>

*Fig. 2.4-24: Different types of earthing*
The advantage of cross bonding is the absence of residual voltages at the end of the three sections. With no driving voltages, the sheath currents and therefore the losses in the system are zero. In reality, some minor differences between each section and a low current-flow in the sheath do actually cause some losses. However, with a good cross-bonding system, the sheath losses can be kept very low. Another advantage of regular cross bonding is that at the earthed termination ends the voltage is zero.

The disadvantages of cross bonding are the increased amount of additional equipment needed, and the fact that in reality three sections of equal length cannot always be realized.

Project management
In addition to sales and engineering tasks, Siemens is able to provide certified project managers for execution of all kind of high-voltage cable projects. The main competences are:
• Elaboration of turnkey proposals, interface clarifications
• Support of high-voltage cable projects
• Planning of installation (schedule, material, manpower)
• Procurement of high-voltage cable components
• Order processing in turnkey projects
• Commissioning of high-voltage cable systems according to national and international standards
• Fault locations, inspections, modernization of plants
• Service, maintenance for high-voltage cable systems.

Installation
The installation of high-voltage cable systems can be carried out by Siemens installation specialists. All site managers, supervisors and fitters are certified regarding SCC and EHS. It can be taken for granted that the fitters are trained on various accessories directly by main manufacturers. The competences are:
• Surveillance of civil and underground works
• Turnkey installation of high-voltage cable systems, cable laying and assembly of accessories up to rated voltages level 500 kV
• Commissioning of high-voltage cable systems
• Supervision of high-voltage tests at site
• After-sales service
• Fault repair and retrofitting of plants.

References
Siemens looks back on more than 100 years of experience with design and installation of high-voltage cable systems. Our worldwide references of oil cable projects reach back to the 1950, and the references concerning XLPE-cable projects to the 1980.
2.4 Power Transmission Lines

2.4.3 Overhead Lines

Since the very beginning of electric power generation, overhead transmission lines (OHL) have constituted the most important component for transmission and distribution of electric power. The portion of overhead transmission lines within a transmission and distribution system, depends on the voltage level as well as on local conditions and practice. In densely populated areas like Central Europe, underground cables prevail in the distribution sector, and overhead power lines in the high-voltage transmission sector. In other parts of the world, for example, in North America, overhead lines are often also used for distribution purposes within cities. Siemens has planned, designed and erected overhead power lines for all important voltage levels in many parts of the world.

Selection of line voltage

For the distribution and transmission of electric power, standardized voltages according to IEC 60038 are used worldwide. For 3-phase AC applications, three voltage levels prevail:

- **Low voltage** (up to 1 kV AC)
- **Medium voltage** (between 1 kV and 36 kV AC)
- **High voltage** (between 52 kV and 765 kV AC) and higher.

Low-voltage lines serve households and small business consumers. Lines on the medium-voltage level supply small settlements, individual industrial plants and large consumers; the transmission capacity is typically less than 10 MVA per circuit. The high-voltage circuits up to 145 kV serve for subtransmission of the electric power regionally, and feed the medium-voltage grid. This level is often chosen to support the medium-voltage level even if the electric power is below 10 MVA. Moreover, some of these high-voltage lines also transmit the electric power from medium-sized generating stations, such as hydro plants on small and medium rivers, and supply large-scale consumers, such as sizable industrial plants or steel mills. They constitute the connection between the interconnected high-voltage grid and the local distribution systems. The bandwidth of electrical power transported corresponds to the broad range of utilization, but rarely exceeds 100 MVA per circuit, while the surge impedance load is 35 MVA (approximately).

In Central Europe, 245 kV lines were used for interconnection of power supply systems before the 420 kV level was introduced for this purpose. Long-distance transmission, for example, between the hydro power plants in the Alps and consumers, was done by 245 kV lines. Nowadays, the importance of 245 kV lines is decreasing due to the existence of the 420 kV transmission system. The 420 kV level represents the highest operation voltage used for AC transmission in Central Europe. It typically interconnects the power supply systems and transmits the energy over long distances. Some 420 kV lines connect the national grids of the individual European countries enabling interconnected network operation (UCTE = Union for the Coordination of Transmission of Electricity) throughout Europe. Large power plants such as nuclear stations feed directly into the 420 kV grid. The thermal capacity of the 420 kV circuits may reach 2,000 MVA, with a surge impedance load of approximately 600 MVA and a transmission capacity up to 1,200 MVA.

Overhead power lines with voltages higher than 420 kV AC will be required in the future to economically transmit bulk electric power over long distances, a task typically arising when utilizing hydro, wind and solar energy potentials far away from consumer centers. Fig. 2.4-26 depicts schematically the range of application for the individual AC voltage levels based on the distance of transmission and the power rating. The voltage level has to be selected based on the task of the line within the network or on the results of network planning. Siemens has carried out such studies for power supply companies all over the world.

High-voltage direct current

However, when considering bulk power transmission over long distances, a more economical solution is the high-voltage direct-current (HVDC) technology. Siemens is in the position to offer complete solutions for such interconnections, starting with network studies and followed by the design, assistance in project development and complete turnkey supply and construction of such plants. For DC transmission no standard is currently available. The DC voltages vary from the voltage levels recommended in the above-mentioned standardized voltages used for AC.

HVDC transmission is used for bulk power transmission and for system interconnection. The line voltages applied for projects worldwide vary between ±300 kV, ±400 kV, ±500 kV, ±600 kV and recently (2007), ±800 kV. The selection of the HVDC line voltage is ruled by the following parameters:

- Amount of power to be transferred
- Length of the overhead power line
- Permissible power losses
- Economical conductor size.

The advantages of DC transmission over AC transmission are:

- A DC link allows power transfer between AC networks with different frequencies or networks that cannot be synchronized.
- Inductive and capacitive parameters do not limit the transmission capacity or the maximum length of a DC overhead transmission line.
- The conductor cross-section can be more or less fully utilized because there is no skin effect caused by the line frequency.
- DC overhead power lines are much more economical to built and require less right-of-way.

Economical considerations/evaluation of DC voltages

Fig. 2.4-27 shows the economical application of DC voltages in relation to overhead transmission line length and transmitted power. This graph must be seen as a general guideline. Any project should be separately evaluated on a case-by-case basis. The budgets established for this evaluation are based on 2007 figures.
Conclusions:

• **300 kV voltage level:**
The range of 750 and 1,000 km with a power transfer of 600 MW has been evaluated. The line and converter costs have been added, and transferred into a cost factor per MW power and km of transmission line. The result shows that for long-distance HVDC transmission, the 300 kV voltage level is not the optimal solution (refer to 400 kV below). However, this voltage level is useful in short HVDC interconnectors such as the Thailand-Malaysia Interconnector, which has a line length of 113 km.

• **400 kV voltage level:**
The range 750, 1,000 and 1,500 km with a power transfer of 600, 1,000 and 2,000 MW has been evaluated. The line and converter costs have been added, and transferred into a cost factor per megawatt power and kilometer of transmission line length. The result shows that the 400 kV voltage level is a suitable solution for line lengths of 750 to 1,000 km with transmitted power of 600 to 1,000 MW.

• **500 kV voltage level:**
The range 1,000 and 1,500 km with a power transfer of 1,000, 2,000 and 3,000 MW has been evaluated. The line and converter costs have been added, and transferred into a cost factor per megawatt power and kilometer of transmission line length. The result shows that the 500 kV voltage level is a suitable solution for the line lengths of 1,000 km to 1,500 km with transmitted power of 1,000 to 2,000 MW. However, the 400 kV voltage level can also be competitive in this range of power and line length.

• **600 kV voltage level:**
The range 1,500, 2,000 and 3,000 km with a power transfer of 2,000 and 3,000 MW has been evaluated. The line and converter costs have been added, and transferred into a cost factor per megawatt power and kilometer of transmission line length. The result shows that the 600 kV voltage level is a suitable solution for the line lengths of 1,500 km to 3,000 km with transmitted power of 2,000 MW, and 3,000 MW for lines up to 2,000 km. However, the 500 kV voltage level can still be competitive in parts of this range.

• **800 kV voltage level:**
The range 2,000, 3,000 and 4,000 km with a power transfer of 2,000 and 3,000 MW has been evaluated. The line and converter costs have been added, and transferred into a cost factor per megawatt power and kilometer of transmission line. The result shows that the 800 kV voltage level is a suitable solution for the line lengths of 2,000 km and above with transmitted power of 2,000 and 3,000 MW. However, shorter line lengths of 1,500 to 3,000 km with power rating of 3,000 to 7,000 MW can be economically covered with an 800 kV solution.
2.4 Power Transmission Lines

Selection of conductors and earth wires
Conductors represent the most important component of an overhead power line because they have to ensure economical and reliable transmission and contribute considerably to the total line costs. For many years, aluminum and its alloys have been the prevailing conducting materials for power lines due to the favorable price, the low weight and the necessity of certain minimum cross-sections. However, aluminum is a very corrosive metal. But a dense oxide layer is formed that stops further corrosive attacks. Therefore, up to a certain level, aluminum conductors are well-suited for areas in which corrosion is a problem, for example, a maritime climate.

For aluminum conductors, there are a number of different designs in use. All-aluminum conductors (AAC) have the highest conductivity for a given cross-section; however, they possess only a low mechanical strength, which limits their application to short spans and low tensile forces. To increase the mechanical strength, wires made of aluminum-magnesium-silicon alloys are adopted. Their strength is approximately twice that of pure aluminum. But single-material conductors like all-aluminum and aluminum alloy conductors have shown susceptibility to oxications. Compound conductors with a steel core, so-called aluminum conductor, steel-reinforced (ACSR), avoid this disadvantage. The ratio between aluminum and steel ranges from 4.3:1 to 11:1. An aluminum-to-steel ratio of 6.0 or 7.7 provides an economical solution. Conductors with a ratio of 4.3 should be used for lines installed in regions with heavy wind and ice loads. Conductors with a ratio higher than 7.7 provide higher conductivity. But because of lower conductor strength, the sags are bigger, which requires higher towers.

Experience has shown that ACSR conductors, just like aluminum and aluminum alloy conductors, provide the most economical solution and offer a life span greater than 40 years. Conductors are selected according to electrical, thermal, mechanical and economic aspects. The electric resistance as a result of the conducting material and its cross-section is the most important feature affecting the voltage drop and the energy losses along the line and, therefore, the transmission costs. The cross-section has to be selected so that the permissible temperatures will not be exceeded during normal operation as well as under short-circuit condition. With increasing cross-section, the line costs increase, while the costs for losses decrease. Depending on the length of the line and the power to be transmitted, a cross-section can be determined that results in the lowest transmission costs. The heat balance of ohmic losses and solar radiation against convection and radiation determines the conductor temperature. A current density of 0.5 to 1.0 A/mm² based on the aluminum cross-section has proven to be an economical solution in most cases.

High-voltage results in correspondingly high-voltage gradients at the conductor’s surface, and in corona-related effects such as visible discharges, radio interference, audible noise and energy losses. When selecting the conductors, the AC voltage gradient has to be limited to values between 15 and 17 kV/cm. Since the sound of the audible noise of DC lines is mainly caused at the positive pole and this sound differs from those of AC lines, the subjective feeling differs as well. Therefore, the maximum surface voltage gradient of DC lines is higher than the gradient for AC lines. A maximum value of 25 kV/cm is recommended. The line voltage and the conductor diameter are one of the main factors that influence the surface voltage gradient. In order to keep this gradient below the limit value, the conductor can be divided into subconductors. This results in an equivalent conductor diameter that is bigger than the diameter of a single conductor with the same cross-section. This aspect is important for lines with voltages of 245 kV and above. Therefore, so-called bundle conductors are mainly adopted for extra-high-voltage lines. Table 2.4-2 shows typical conductor configurations for AC lines.

From a mechanical point of view, the conductors have to be designed for everyday conditions and for maximum loads exerted on the conductor by wind and ice. As a rough figure, an everyday stress of approximately 20% of the conductor rated tensile stress can be adopted, resulting in a limited risk of con-

<table>
<thead>
<tr>
<th>Rated voltage [kV]</th>
<th>20</th>
<th>110</th>
<th>220</th>
<th>380</th>
<th>700</th>
</tr>
</thead>
<tbody>
<tr>
<td>Highest system voltage [kV]</td>
<td>24</td>
<td>123</td>
<td>245</td>
<td>420</td>
<td>765</td>
</tr>
<tr>
<td>Nominal cross-section [mm²]</td>
<td>50</td>
<td>120</td>
<td>150</td>
<td>300</td>
<td>bundle 2x240</td>
</tr>
<tr>
<td>Conductor diameter [mm]</td>
<td>9.6</td>
<td>15.5</td>
<td>17.1</td>
<td>24.5</td>
<td>28.8</td>
</tr>
<tr>
<td>Ampacity (at 80 °C conductor temperature) [A]</td>
<td>210</td>
<td>410</td>
<td>470</td>
<td>740</td>
<td>900</td>
</tr>
<tr>
<td>Thermal capacity [MVA]</td>
<td>7</td>
<td>14</td>
<td>90</td>
<td>140</td>
<td>340</td>
</tr>
<tr>
<td>Resistance at 20 °C [Ω/km]</td>
<td>0.59</td>
<td>0.24</td>
<td>0.19</td>
<td>0.10</td>
<td>0.067</td>
</tr>
<tr>
<td>Reactance at 50 Hz [Ω/km]</td>
<td>0.39</td>
<td>0.34</td>
<td>0.41</td>
<td>0.38</td>
<td>0.4</td>
</tr>
<tr>
<td>Effective capacitance [nF/km]</td>
<td>9.7</td>
<td>11.2</td>
<td>9.3</td>
<td>10</td>
<td>9.5</td>
</tr>
<tr>
<td>Capacitance to earth [nF/km]</td>
<td>3.4</td>
<td>3.6</td>
<td>4.0</td>
<td>4.2</td>
<td>4.8</td>
</tr>
<tr>
<td>Charging power [kVar/km]</td>
<td>1.2</td>
<td>1.4</td>
<td>35</td>
<td>38</td>
<td>415</td>
</tr>
<tr>
<td>Earth-fault current [A/km]</td>
<td>0.04</td>
<td>0.04</td>
<td>0.25</td>
<td>0.25</td>
<td>0.58</td>
</tr>
<tr>
<td>Surge impedance [Ω]</td>
<td>360</td>
<td>310</td>
<td>375</td>
<td>350</td>
<td>365</td>
</tr>
<tr>
<td>Surge impedance load [MVA]</td>
<td>–</td>
<td>–</td>
<td>32</td>
<td>35</td>
<td>135</td>
</tr>
</tbody>
</table>

Table 2.4-2: Electric characteristics of AC overhead power lines (data refer to one circuit of a double-circuit line)
ductor damage. The maximum working tensile stress should be limited to approximately 40 % of the rated tensile stress.

Earth wires, also called shieldwire or earthwire, can protect a line against direct lightning strikes and improve system behavior in the event of short circuits; therefore, lines with single-phase voltages of 110 kV and above are usually equipped with earth wires. Earth wires made of ACSR conductors with a sufficiently high aluminum cross-section satisfy both requirements.

Since the beginning of the 1990s, more and more earth wires for extra-high-voltage overhead power lines have been executed as optical earth wires (OPGW). This type of earth wire combines the functions just described for the typical earth wire with the additional facility for large data transfer capacity via optical fibers that are integrated into the OPGW. Such data transfer is essential for the communication between two converter stations within an HVDC interconnection or for remote controlling of power plants. The OPGW in such a case becomes the major communication link within the interconnection. OPGW are mainly designed in one or more layers of aluminum alloy and/or aluminum-clad steel wires. One-layer designs are used in areas with low keraunic levels (small amount of possible lightning strikes per year) and small short-circuit levels.

Selection of insulators
Overhead line insulators are subject to electrical and mechanical stresses, because they have to isolate the conductors from potential to earth and must provide physical supports. Insulators must be capable of withstanding these stresses under all conditions encountered in a specific line.

The electrical stresses result from:
- The steady-state operating power-frequency voltage (highest operation voltage of the system)
- Temporary overvoltages at power frequency
- Switching and lightning overvoltages.

Insulator types
Various insulator designs are in use, depending on the requirements and the experience with certain insulator types:
- Cap-and-pin insulators (fig. 2.4-28) are made of porcelain or pre-stressed glass. The individual units are connected by fittings of malleable cast iron or forged iron. The insulating bodies are not puncture-proof, which is the reason for a relatively high number of insulator failures.
- In Central Europe, long-rod insulators made from aluminous porcelain (fig. 2.4-29) are most frequently adopted. These insulators are puncture-proof. Failures under operation are extremely rare. Long-rod insulators show superior behavior, especially in polluted areas. Because porcelain is a brittle material, porcelain long-rod insulators should be protected from bending loads by suitable fittings.
- Composite insulators are the third major type of insulator for overhead power line applications (fig. 2.4-30). This insulator type provides superior performance and reliability, particularly because of improvements over the last 20 years, and has been in service for more than 30 years.
The composite insulator is made of a glass fiber reinforced epoxy rod. The glass fibers applied are ECR glass fibers that are resistant to brittle fracture (ECR = electrical grade corrosion resistant glass fibers). In order to avoid brittle fracture, the glass fiber rod must additionally be sealed very carefully and durably against moisture. This is done by application of silicone rubber. Nowadays, high temperature vulcanized (HTV) silicone is used.

The silicone rubber has two functions within this insulator type:
- Sealing the glass fiber rod
- Molding into insulator sheds to establish the required insulation.

Metal fittings are compressed onto the glass fiber rod at both ends of the insulator, either with a ball socket or clevis connection fitting. Since the 1980s, compression fittings have been the prevailing type. The sealing of the area between fitting and silicone housing protecting the rod is most important, and is nowadays done with special silicone elastomer, which offers after vulcanization the characteristic of a sticky solid, similar to a fluid of high viscosity.

Advantages of the composite long-rod insulator are:
- Light weight, less volume and less damages
- Shorter string length compared to cap-and-pin – and porcelain long-rod – insulator strings
- Up to 765 kV AC and 600 kV DC, only one unit of insulator (practical length is only limited by the ability of the production line) is required
- High mechanical strength
- Vandalism resistance
- High performance in polluted areas, based on the hydrophobicity (water repellency) of the silicone rubber.

Advantages of hydrophobicity are:
- Silicone rubber offers outstanding hydrophobicity over the long term; most other polymeric housing material will loose this property over time
- Silicone rubber is able to recover its hydrophobicity after a temporary loss of it
- The silicone rubber insulator is able to make pollution layers on its surface water-repellent, too (hydrophobicity transfer)
- Low surface conductivity, even with a polluted surface and very low leakage currents, even under wetted conditions.

**Suspension string sets**

Suspension insulator sets carry the conductor weight, including additional loads such as ice and wind, and are arranged more or less vertically. There are I-shaped (fig. 2.4-31a) and V-shaped sets in use. Tension insulator sets (fig. 2.4-31b, fig. 2.4-31c) terminate the conductors and are arranged in the direction of the conductors. They are loaded by the conductor tensile force and have to be rated accordingly. Multiple single, double, triple or more sets handle the mechanical loadings and the design requirements.

**Design of creepage distance and air gaps**

The general electrical layout of insulation is ruled by the voltages to be withstood and the pollution to which the insulation is subjected. The standards IEC 60071-1 and IEC 60071-2 as well as the technical report IEC 60815, which provides four pollution classes (the new version will have five classes), give guidance for the design of the insulation.

Because IEC 60815 is applicable to AC lines, it should be noted that the creepage distances recommended are based on the phase-to-phase AC voltage \( U_{L-L} \). When transferring these creepage distances recommended by IEC 60815 to a DC line, it should be noted that the DC voltage is a pole-to-earth value \( U_{L-E} \). Therefore, these creepage distances have to be multiplied by the factor \( \sqrt{3} \). Furthermore, it should be noted that the AC voltage value refers to a mean value, while the DC voltage is comparable to a peak value, which requires a further multiplication with factor \( \sqrt{2} \).

Insulators under DC voltage operation are subjected to a more unfavorable conditions than they are under AC, due to a higher collection of surface contamination caused by the constant unidirectional electric field. Therefore, a DC pollution factor has to be applied. Table 2.4-3 shows specific creepage distances for different insulator materials under AC and DC application, and is based on industry experience published by power supply companies in South Africa and China. The results shown were confirmed by an experienced insulator manufacturer in Germany. The correction factors shown are valid for porcelain insulators only. When taking composite insulators into consideration, an additional reduction factor of 0.75 can be applied. The values for a DC system must be seen as a guideline only, that must be verified on a case-by-case basis for new HVDC projects.

To handle switching and lightning overvoltages, the insulator sets have to be designed with respect to insulation coordination according to IEC 60071-1 and IEC 60071-2. These design aspects determine the gap between the earthed fittings and the live part. However, for HVDC application, switching impulse levels are of minor important because circuit-breaker operations from AC lines do not occur on DC Back-to-back lines. Such lines are controlled via their valve control systems. In order to coordinate the insulation in a proper way, it is recommended to apply and use the same SIL and BIL as is used for the equivalent AC insulation (determined by the arcing distance).

**Selection and design of supports**

Together with the line voltage, the number of circuits (AC) or poles (DC) and type of conductors, the configuration of the circuits poles determines the design of overhead power lines. Additionally, lightning protection by earth wires, the terrain and the available space at the tower sites have to be considered. In densely populated areas like Central Europe, the width of right-of-way and the space for the tower sites are limited. In the case of extra-high-voltages, the conductor configuration affects the electrical characteristics, the electrical and magnetic field and the transmission capacity of the line. Very often there are contradicting requirements, such as a tower height as low as pos-
2.4 Power Transmission Lines

**Table 2.4-3:** Guideline for specific creepage distances for different insulator materials

<table>
<thead>
<tr>
<th>IEC 60815 level</th>
<th>Porcelain and glass insulators (AC system)</th>
<th>Porcelain and glass insulators (DC system)</th>
<th>Composite insulators (AC system)</th>
<th>Composite insulators (DC system)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I Light</td>
<td>16</td>
<td>39</td>
<td>12</td>
<td>29</td>
</tr>
<tr>
<td>II Medium</td>
<td>20</td>
<td>47</td>
<td>15</td>
<td>35</td>
</tr>
<tr>
<td>III Heavy</td>
<td>25</td>
<td>59</td>
<td>19</td>
<td>44</td>
</tr>
<tr>
<td>IV Very Heavy</td>
<td>31</td>
<td>72</td>
<td>24</td>
<td>54</td>
</tr>
</tbody>
</table>

![Fig. 2.4-31a: I-shaped suspension insulator set for 245 kV](image1)

![Fig. 2.4-31b: Double tension insulator set for 245 kV (elevation, top)](image2)

![Fig. 2.4-31c: Double tension insulator set for 245 kV (plan, bottom)](image3)
2.4 Power Transmission Lines

Power Transmission and Distribution Solutions

For low-voltage and medium-voltage lines, horizontal conductor configurations prevail; these configurations feature line post insulators as well as suspension insulators. Poles made of wood, concrete or steel are preferred. Fig. 2.4-32 shows some typical line configurations. Earth wires are omitted at this voltage level.

For high-voltage and extra-high-voltage power lines, a large variety of configurations are available that depend on the number of circuits (AC) or poles (DC) and on local conditions. Due to the very limited right-of-way, more or less all high-voltage AC lines in Central Europe comprise at least two circuits. Fig. 2.4-33 shows a series of typical tower configurations. Arrangement “e” is called the “Danube” configuration and is often adopted. It represents a fair compromise with respect to width of right-of-way, tower height and line costs.

For AC lines comprising more than two circuits, there are many possibilities for configuring the supports. In the case of circuits with differing voltages, those circuits with the lower voltage should be arranged in the lowermost position (fig. 2.4-33g).

DC lines are mechanically designed according to the normal practice for typical AC lines. The differences from AC Line layout are the:

- Conductor configuration
- Electric field requirements
- Insulation design.

For DC lines, two basic outlines (monopole and bipole), with variations should be considered. Fig. 2.4-33i–l show examples for HVDC line configurations that are valid for all voltage levels.

The arrangements of insulators depend on the application of a support within the line. Suspension towers support the conductors in straight-line sections and at small angles. This tower type offers the lowest costs; special attention should therefore be paid to using this tower type as often as possible. Angle towers have to carry the conductor tensile forces at angle points of the line. The tension insulator sets permanently transfer high forces from the conductors to the supports. Finally, dead-end towers are used at the terminations of a transmission line. They carry the total conductor tensile forces on the line side (even under unbalanced load condition, e.g., when conductors of one tower side are broken) and a reduced tension into the substations (slack span).

Various loading conditions specified in the respective national and international standards have to be met when designing towers. The climatic conditions, the earthquake requirements and other local environmental factors are the next determining factors for the tower design.

When designing the support, a number of conditions have to be considered. High wind and ice loads cause the maximum forces to act on suspension towers. In ice-prone areas, unbalanced

![Fig. 2.4-32: Configurations of medium-voltage supports](image-url)
Fig. 2.4-33: (a–h): tower configurations for high-voltage lines (AC); (i–l): tower configurations for high-voltage lines (DC)
conductor tensile forces can result in torsional loading. Additionally, special loading conditions are adopted for the purpose of failure containment, that is, to limit the extent of damage. Finally, provisions have to be made for construction and maintenance.

Depending on voltage level and the acting forces of the overhead line, differing designs and materials are adopted. Poles made of wood, concrete or steel are very often used for low-voltage and medium-voltage lines. Towers with lattice steel design, however, prevail at voltage levels of 110 kV and above (fig. 2.4-34). Guyed lattice steel structures are used in some parts of the world for high-voltage AC and DC lines. Such design requires a relatively flat topography and a secure environment where there is no threat from vandalism and theft. Guyed lattice steel structures offer a substantial amount of cost savings with respect to tower weight and foundation quantities. However, a wider right-of-way has to be considered.

**Foundations for the supports**

Overhead power line supports are mounted on concrete foundations. The foundations have to be designed according to the national or international standard applicable for the particular project.

The selection of foundation types and the design is determined by the:
- Loads resulting from the tower design
- Soil conditions on the site
- Accessibility to the line route
- Availability of machinery
- Constraints of the particular country and the site.

Concrete blocks or concrete piers are in use for poles that exert bending moments on the foundation. For towers with four legs, a foundation is provided for each individual leg (fig. 2.4-35). Pad and chimney and concrete block foundations require good bearing soil conditions without groundwater.

Driven or augured piles and piers are adopted for low-bearing soil, for sites with bearing soil at a greater depth and for high groundwater level. In case of groundwater, the soil conditions must permit pile driving. Concrete slabs can be used for good bearing soil, when subsoil and groundwater level prohibit pad and chimney foundations as well as piles.

**Route selection and tower spotting**

Route selection and planning represent increasingly difficult tasks, because the right-of-way for transmission lines is limited and many aspects and interests have to be considered.

Route selection and approval depend on the statutory conditions and procedures prevailing in the country of the project. Route selection nowadays involves preliminary desktop studies with a variety of route alternatives, environmental impact studies, community communication hearings and acceptance approval from the local authorities.
After the route design stage and approval procedure, the final line route is confirmed. Following this confirmation and approval, the longitudinal profile has to be surveyed, and all crossings over roads, rivers, railways, buildings and other overhead power lines have to be identified. The results are evaluated with a specialized computer program developed by Siemens that calculates and plots the line profile. The towers are spotted by means of the same program, which takes into account the conductor sags under different conditions, the ground clearances, objects crossed by the line, technical data of the available tower family, specific cost for towers and foundations and cost for compensation of landowners.

The result is an economical design of a line that accounts for all the technical, financial and environmental conditions. Line planning forms the basis for material acquisition and line erection. Fig. 2.4-36 shows a line profile established by computer.

**Siemens’ activities and experience**

Siemens has been active in the overhead power line field for more than 100 years. The activities comprise design and construction of rural electrification schemes, low-voltage and medium-voltage distribution lines, high-voltage lines and extra-high-voltage installations.

To give an indication of what has been carried out by Siemens, approximately 20,000 km of high-voltage lines up to 245 kV and 10,000 km of extra-high-voltage lines above 245 kV have been set up so far. Overhead power lines have been erected by Siemens in Germany and Central Europe as well as in the Middle East, Africa, the Far East and South America.

Outstanding AC projects have been:
- The 420 kV transmission lines across the Elbe River in Germany comprising four circuits and requiring 235 m tall towers
- The 420 kV line across the Bosphorus (Crossing II) in Turkey (1983) with a crossing span of approximately 1,800 m (fig. 2.4-37).
- The 500 kV Suez Crossing (1998); height of suspension tower 220 m
- The 420/800 kV Bosporus Crossing III in Turkey (1999).

Furthermore, Siemens has constructed two HVDC interconnectors as turnkey projects that include HVDC overhead transmission lines. The two projects are the 300 kV HVDC interconnector from Thailand to Malaysia (bipole transmission line, fig. 2.4-38) and the 400 kV HVDC Basslink project in Australia (monopole transmission line, fig. 2.4-39a–c).
Fig. 2.4-36: Line profile established by computer
Earth wire: ACSR 265/35 * 80.00 N/mm²
Conductor: ACSR 265/35 * 80.00 N/mm²
Equivalent sag: 11.21 m at 40 °C
Equivalent span: 340.44 m
2.4 Power Transmission Lines

Conductor: 4x3x1 AACSR/AW 1802/226 mm² on 420 kV
Upgradeable to 2x3x2 AACSR/AW 1802/226 mm² on 800 kV
Shieldwire: 2x (ASLH-DBBB 1x22E8/125 - A W 33)

Fig. 2.4-37: 420/800 kV line across the Bosphorus, longitudinal profile

Fig. 2.4-38: 300 kV HVDC interconnector from Thailand to Malaysia (bipole transmission line)

Fig. 2.4-39a: 400 kV HVDC Basslink project in Australia (monopole transmission line)
Fig. 2.4-39b, c: 400 kV HVDC Basslink project in Australia (monopole transmission line)
Grid access solutions are custom-engineered solutions for decentralized generating units and remote loads. They are an essential part of Smart Grid and Super Grid developments (refer to chapter 1). Grid access solutions involve reconciling contrasting parameters, such as high reliability, low investment costs and efficient transmission, in the best possible solution. For example, in the design of high-voltage offshore platforms for offshore wind farm connections to the grid (fig. 2.5-1), special attention is paid to intelligent collection systems at the medium-voltage level, followed by the design of the high-voltage transmission system and the onshore receiving substation and its reactive compensation to meet local grid code requirements.

**Turnkey proposition and project execution**

By offering a turnkey solution (fig. 2.5-2), Siemens provides a holistic setup of a complex project involving project administration, design and engineering services, subcontracting, procurement and expediting of equipment, inspection of equipment prior to delivery, shipment, transportation, control of schedule and quality, pre-commissioning and completion, performance-guarantee testing, and training of owner’s operating and/or maintenance personnel.

For both AC and DC transmission technologies, Siemens offers a broad range of solutions. The technical constraints of a decentralized generating unit or remote loads in connection with AC or DC transmission systems are well known and addressed accordingly. The engineering expertise of Siemens is all inclusive from the conceptual and basic design to digital and real-time simulations, therefore assuming responsibility for presenting the solution to the grid owner which is essential in executing such projects.

**System and design studies, engineering**

The final design and specification of all equipment to be installed are verified by system and design studies. Important steps to achieve final design criteria include determining an optimized economical network within a system of generating units, integrating this system within the grid, defining and configuring grid components, carrying out load flow studies and short-circuit calculations for the entire system.

Moreover, an earthing concept and coordination of the insulation for the entire grid connection must also be defined. The static and dynamic characteristics must be checked and the reactive power compensation defined (static and dynamic). The resonance phenomenon for all elements should be investigated, from the transmission system itself to cables, transformers, reactors, wind turbines and capacitor banks. Compatibility and conformity with grid code requirements must be established, as well as a control and protection system.

**High-voltage offshore platform**

Siemens Wind Power Offshore Substation (WIPOS™) is the optimal solution that ensures long-term offshore operation. With WIPOS, Siemens marks an innovative role in the design, engineering and installation of offshore platforms (see section 2.5.1 References).

In the offshore wind industry, the word ‘platform’ reflects two construction entities, namely the ‘topside’ where all the high-voltage, medium-voltage and operational equipment are installed, and the ‘foundation’ entity which serves as the base for the topside. Siemens offers optimized designs for both entities by joining workforces with offshore, maritime and shipyard experts.

WIPOS (fig. 2.5-3) serves as an interface between the wind turbines and the mainland, whereby power harvested from wind is bundled and then passes through the export cables to reach the point of connection onshore.

*Fig. 2.5-1: A comprehensive overview for both AC and DC offshore wind grid connections*
A typical topside comprises a multi-deck construction with the main deck, where all electro-technical equipment is installed, as well as a helideck for helicopter landing designed to meet aviation regulations.

From a complete platform approach, Siemens also offers the self-lifting platform concept due to its versatility in function, and the possibility for transportations and installation without exorbitant efforts by avoiding heavy crane vessels.

Siemens offers a family of WIPOS designs with the flexibility to meet various offshore weather, tide and seabed conditions with three main configurations:

- WIPOS self-lifting solution
- WIPOS topside solution (topside/jacket)
- WIPOS floating solution.

Further potential for the size reduction of offshore grid access platforms is provided by the application of DC compact switchgear (DC CS) in the DC switchyard, see chapter 2.2.

Fig. 2.5-2: Siemens executes projects as an EPC contractor

Fig. 2.5-3: A model of Siemens’ Windpower Offshore Substation (WIPOS): Siemens supplies comprehensive offshore grid connection solutions with flexible substation configurations for both AC and DC applications
2.5.1 References

Fig. 2.5-4: The offshore wind farm Lillgrund, consisting of 48 wind turbines, each 2.3 MW, from Siemens Wind Power, is installed in Oresund. Its location is on Swedish national waters, roughly 7 km away from the Swedish coast line near to the City of Malmö. The owner is Vattenfall AB, Sweden. The 33/138 kV transformer substation with its 120 MVA transformer is mounted on an offshore platform located within the wind farm area. Power transmission is realized via one three-phase 138 kV XLPE submarine cable towards the existing substation in Bunkello (Sweden).

Besides the transformer substation on the platform, Siemens Energy Transmission performed the grid studies as well as the design and performance studies for the entire wind farm and its grid connection.

In service since late 2007, the Lillgrund Offshore Wind Farm provides enough energy for approximately 80,000 homes and reduces the CO₂ emissions by 300,000 tons a year.

Fig. 2.5-5: The offshore wind farms Lynn and Inner Dowsing, consisting of 54 wind turbines, each 3.6 MW, from Siemens Wind Power, are located in the Greater Wash area, on Great Britain national waters. This is roughly 5 km away from the coast line of Skegness, Lincolnshire. The owner is Centrica Renewable Energy Ltd., U.K.

The 33/132 kV onshore transformer substation with its two 100 MVA transformers is located at Middle Marsh, approximately 5 km away from the sea wall. Power transmission from the offshore wind farms is realized via six submarine three-phase 33 kV XLPE cables. Further on to the grid, two 132 kV cables are used. Besides the transformer substation and the cable system, Siemens Energy Transmission also performed the grid studies as well as the design and performance studies for the entire wind farm and its grid connection.

The grid connection was energized in January 2008. Both wind farms were in full service in autumn 2008. They provide enough energy for approximately 130,000 homes, and reduce the CO₂ emissions by 500,000 tons.

Fig. 2.5-6: The Thanet Offshore Wind Farm, consisting of 100 wind turbines, each 3 MW, from Vestas (Denmark), is located in the North Sea. It is roughly 11 km away from the coast line of Kent, Foreness Point. The owner is Thanet Offshore Wind Ltd., U.K.

The 33/132 kV transformer substation with its two 180 MVA transformers is mounted on an offshore platform located within the wind farm area. Power transmission is realized via two three-phase 132 kV XLPE submarine cables. The point of coupling to the grid is a specific switchgear in Richborough, Kent.

In service since 2009, the Thanet Offshore Wind Farm provides enough energy for approximately 300,000 homes and reduces the CO₂ emissions by 500,000 tons.
Apart from the offshore transformer substation, the onshore substation with its compensation systems (two SVC PLUS) and harmonic filters, as well as the cable system, Siemens Energy Transmission also performed the grid studies as well as the design and performance studies for the entire wind farm and its grid connection.

The grid connection was energized in autumn 2009, with all 100 wind turbines running by autumn 2010. Now the offshore wind farm provides enough energy for approximately 215,000 homes, and reduces the CO₂ emissions by 830,000 tons a year.

Fig. 2.5-7: The Greater Gabbard offshore wind farm, planned with 140 wind turbines, each 3.6 MW, from Siemens Wind Power (Denmark), is located in the North Sea close to the Thames Estuary. It is roughly 26 km (respective 46 km) away from the coast line of Suffolk.

The owner is Greater Gabbard Offshore Winds Ltd., U.K. The 33/132 kV transformer substation with its three 180 MVA transformers is mounted on two offshore platforms (Inner Gabbard and Galloper) located within the wind farm area. Power transmission is realized via three three-phase 132 kV XLPE submarine cables.

The point of coupling to the grid is realized in Sizewell Village, Suffolk, where Siemens built a reactive power compensation substation to allow the wind farm to meet the requirements of the GB grid code. SVC PLUS multilevel technology is used for all of the three export circuits.

Here again, Siemens Energy Transmission performed the grid studies as well as the design and performance studies for the entire wind farm.

Now the offshore wind farm provides enough energy for approximately 350,000 homes and reduces the CO₂ emissions by 1,350,000 tons a year.

Fig. 2.5-8: In September 2009, Siemens was awarded a contract for the first phase of the offshore grid access solution to the prestigious London Array wind farm.

The grid access project was completed in two phases. In phase one, two offshore substations (each with two 150 MVA transformers) will be delivered to collect the 630 MW of power generated from 175 wind turbines – also supplied by Siemens – before transferring it to shore via the main 150 kV export cables.

Siemens is responsible for the turnkey construction of the onshore substation. As for the two offshore substations, Siemens is responsible for the overall layout design to ensure that the facility functions as a substation, including all primary and secondary equipment as well as testing and commissioning.

Situated 24 km from Clacton-on-Sea, Essex, the system will generate 1,000 MW of green power, enough to supply the electricity needs for nearly 600,000 homes across the South East of England, and will be the largest offshore wind farm in the world in 2012.

For further information:
www.siemens.com/energy/grid-access-solutions
www.siemens.com/energy/wipos
BorWin2

800 MW offshore HVDC PLUS link BorWin2, Germany
For the BorWin2 project, Siemens will supply the voltage-sourced converter (VSC) system – using Siemens HVDC PLUS technology – with a rating of 800 MW. The wind farms Veja Mate and Global Tech 1 are designed to generate 800 MW and is connected through Siemens’ HVDC PLUS link to shore. The converter is installed on an offshore platform, where the voltage level is stepped up and then converted to ±300 kV DC. The platform will accommodate all electrical equipment required for the HVDC converter station, two transformers, four AC cable compensation reactors and high-voltage gas-insulated switchgear (GIS). The Siemens wind power offshore substation (WIPOS) is designed as a floating, self-lifting platform. Power is transmitted via subsea and land cable to Diele close to Papenburg, where an onshore converter station will reconvert the DC back to AC and feed it into the 380 kV AC network.

Fig. 2.5-9: BorWin 2, 800 MW HVDC PLUS, North Sea

HelWin1

576 MW offshore HVDC PLUS link HelWin1, Germany
For the project HelWin1, Siemens is supplying a voltage-sourced converter (VSC) system with a rating of 576 MW using Siemens HVDC PLUS technology. The wind farms Nordsee Ost and Meerwind are designed to generate 576 MW and is connected through a Siemens’ HVDC PLUS link to shore. The converter is installed on an offshore platform, where the voltage level is stepped up and then converted to ±250 kV DC. The platform will accommodate all the electrical high-voltage AC and DC equipment required for the converter station. Similar to the BorWin2 project, the Siemens wind power offshore substation (WIPOS) will also be designed as a floating, self-lifting platform. Energy is transmitted via subsea and land cable to Büttel, northwest of Hamburg, Germany, where an onshore converter station will reconvert the DC back to AC and transmit it into the high-voltage grid.

Fig. 2.5-10: HelWin 1, 576 MW HVDC PLUS, North Sea
SylWin1

864 MW offshore HVDC PLUS link SylWin1, Germany
Siemens will supply the world’s largest voltage-sourced converter (VSC) offshore system with a rating of 864 MW for the SylWin1 project. Siemens’ HVDC PLUS link will connect the Dan Tysk wind farm to the German shore. The converter is installed on an offshore platform, where the voltage level is stepped up and converted to ±320 kV DC. The platform will accommodate all electrical equipment required for the HVDC converter station: two transformers, four AC cable compensation reactors, and high-voltage gas-insulated switchgear (GIS). Similar to the BorWin2 and HelWin1 projects, the Siemens wind power offshore substation (WIPOS®) is designed as a floating, self-lifting platform. The energy is transmitted via subsea and land cable to Büttel, where an onshore converter station will reconvert the DC to AC and feed it into the 380 kV AC grid.

HelWin2

690 MW offshore HVDC PLUS link HelWin2, Germany
Siemens Energy in consortium with the Italian cable manufacturer Prysmian is erecting HelWin 2, the link between the North Sea offshore windfarm Amrumbank West and the onshore grid. The customer is TenneT TSO GmbH of Bayreuth, Germany. The grid connection, designed as a high-voltage direct-current transmission link, has a rating of 690 megawatts (MW). Amrumbank West is built in the North Sea, about 55 kilometers from the mainland, 35 kilometers north of Helgoland, and 37 kilometers west of the North Frisian island of Amrum. The wind farm will have a power capacity between 300 and 400 MW. Together with the Meerwind and North Sea East offshore windfarms, Amrumbank West is part of the North Sea cluster HelWin.
2.6 SIESTORAGE

2.6.1 The Modular Energy Storage System for a Reliable Power Supply

As part of Totally Integrated Power, SIESTORAGE – Siemens Energy Storage – exemplifies the motto “We bring power to the point”. Renewable energy sources have already become key power sources in the current energy mix. Their heavy penetration and the growth of distributed generation have changed the structure of power grids (fig. 2.6-1 and 2.6-2). However, the unpredictable nature of renewable energy generation capacity can lead to fluctuations and imbalances between generation and load, affecting grid stability and power quality.

To ensure a stable and reliable power supply, Siemens has developed SIESTORAGE, a sustainable and modular stationary energy storage and power flow management system that combines fast-acting power regulation function and lithium-ion batteries. The batteries are supplied by world leading manufacturers. In case of an imbalance between production and consumption, the system can either release power into the grid, or store it in milliseconds, thus controlling the frequency of the grid.

The challenge: Reliable power supply

The use of renewables on a large scale leads to new challenges for grid stability: Short-circuit power is a measure for grid stability which producers using wind and solar energy can usually not provide. The infeed of energy from distributed sources can cause a reversed load flow. In distribution grids not designed for this event, damages and power outages can be the result. Even the shortest interruption of energy supply can lead to a complete failure of production plants and result in an enormous loss of quality and time, along with noticeable financial damage. A sufficient amount of balancing energy needs to be provided to secure a constant high quality of power supply.

The answer: SIESTORAGE

SIESTORAGE is able to deliver available power with next to no delay by providing balancing power for primary reserve power. Indeed it improves the voltage and supply quality by providing active and reactive power on demand, thus compensating for low voltage fluctuations in generation within milliseconds. In this way, SIESTORAGE can be readily adapted to specific power demands and storage capacities, and therefore used for a wide range of applications (fig. 2.6-3).

Saving potentials

This is dependent on the specific application. Everything begins with the analysis of the grid to determine the adequate business model. Siemens offers a complete consultation package that includes power flow calculation and reactive power analysis, contingency analysis, short-circuit current calculation, probabilistic reliability analysis, dynamic stability calculation, and protection coordination. The optimized efficiency of an application also depends on the local regulation and on potential financial incentives. SIESTORAGE can therefore play a key role in the achievement of ambitious climate goals.
Siestorage offers more
• Consistency
  Comprehensive range from LV, MV and energy storage components to power supply solution expertise
• One-stop-shop
  From planning via installation to commissioning and services
• Safety
  Overall safety equipment, proven components and battery systems
• Reliability
  Power supply in milliseconds and high redundancy of the system for more availability
• Efficiency
  Optimization and saving potential for a wide range of applications
• Flexibility
  Modular concept for all needs of storage power and capacity up to 20 MW/20 MWh
• Advanced technology
  State-of-the-art components combining cutting-edge power electronics and Li-ion batteries.

Fig. 2.6-3: Spot-on for a wide range of applications
2.6.2 Spot-on for a Wide Range of Applications

Thanks to SIESTORAGE, energy can be taken from the grid during low load periods, and stored for peak load periods. This way, SIESTORAGE provides a cost-efficient and sustainable solution for industrial processes, infrastructure businesses, and energy-efficient building. SIESTORAGE ensures furthermore the reliability of electrical grids for isolated sites and areas where access to power is limited, and the system is able to guarantee energy reliability even in the case of an outage. The black-start capability of SIESTORAGE makes the start-up of a grid possible when the main supply is not available. The energy stored is sufficient, e.g., to start a gas turbine and bridge the grid’s power requirements.

Integration of renewables
SIESTORAGE makes it possible to integrate an increasing amount of solar and wind power into distribution grids without having to extend them immediately. Thus, the system not only contributes to grid relief, but also can buffer additional capacity for e.g., electromobility (fig. 2.6-4) and public transport. In case a PV or wind system is connected as a power source, weather and seasonal dependencies as well as the forecastability of these dependencies must be looked into.

Offset diesel
Microgrids with renewable generation or industrial businesses with large amounts of power require a self-sufficient reliable supply of energy. SIESTORAGE stores energy in case of high generation, and releases it on demand. This makes the system an eco-friendly alternative to diesel generators. With SIESTORAGE, the size of generators can be optimized, since it functions as “range extender” to smaller gensets. SIESTORAGE is able to reduce the runtime of diesel generators (switching off at lower loads), thus providing lower fuel consumption and gas emissions for a better environmental footprint.

T & D deferral
The growing demand for energy and the rising share of renewables can make power supply systems reach the limits of their transmission capacity. This makes the costly extension of power supply systems necessary. In case of imminent overloads, SIESTORAGE stores energy that cannot be transmitted over the power supply system. It is fed back into the system during low load levels to avoid a system overload. A costly extension of the power supply system can be avoided, and consequently grid operators are better able to meet the high energy demands of industrial and infrastructure businesses.

Spinning reserve
The variation between power generation and actual load is compensated with the help of spinning reserve. SIESTORAGE reliably provides balancing power within milliseconds, guaranteeing a constant energy supply and cost savings for power generation, and the provision of additional reserve power. In addition to that, the stored renewable energy can be traded at electricity exchanges in a more targeted manner.

Peak load management
Industrial businesses and grid operators agree on fixed prices for power and maximum load. However, production factors can cause peak loads. Even a single case of exceeding the agreed maximum load causes high costs. SIESTORAGE stores energy in times of low energy consumption, providing reliable energy for peak loads with next to no delay. (fig. 2.6-5). This means that industrial businesses need not use their own generators for short-time peak loads, and thus support eco-friendly operation with SIESTORAGE.
2.6.3 High Power Availability and Reliability

The modularity of SIESTORAGE enables the highest design flexibility. The system can be combined and adapted to suit any system operator’s needs. It comprises an inverter cabinet, a control cabinet, a grid connection cabinet, and up to five battery cabinets per inverter (depending on the supplier).

The system can reach a performance of up to 20 MW and can be integrated into a standard container.

Thanks to the parallel connection of the inverters on the AC side, the very high redundancy of SIESTORAGE is an advantage in case of a single point of failure, which has no influence on the availability of the storage system. This leads to the highest availability of power, and a high reliability. Through individual balancing of the battery cabinets, the installed battery capacity is optimized at the maximum, providing more reliability by minimum maintenance (fig. 2.6-10).

Inverter cabinet (fig. 2.6-6) – fig. 2.6-10
- Width: 600 mm, depth: 600 mm, height: 2,200 mm
- 2 inverter modules and related control equipment
- Each module:
  - V nominal: 400 V
  - I nominal: 170 A
  - S nominal: 118 kVA
- P nominal: depending on the battery type

Grid connection cabinet* (fig. 2.6-7) – fig. 2.6-10
- Width: 400 mm, depth: 600 mm, height: 2,200 mm
- Cable tap for grid connection
- Busbar systems.

Control cabinet (fig. 2.6-8) – fig. 2.6-10
- Width: 800 mm, depth: 600 mm, height: 2,200 mm
- Human Machine Interface (HMI)
- System Control Unit (SCU)
- Ethernet switch
- 24 V DC power distribution
- Auxiliary power transformer*

Battery cabinet (fig. 2.6-9) – fig. 2.6-10
- Width: 600 mm, depth: 650 mm, height: 2,200 mm
- Content example (depending on supplier):
  - 14 modules
  - 1 BMS (Battery Management System)
  - Power: 90 kW
  - Capacity: 45 kWh

* optional
A modular concept to address all needs of storing power and capacity
The SIESTORAGE system is scalable according to your power needs (from 500 kW up to 20 megawatts at a capacity of 500 kWh/20 MWh) and can be installed in standard containers.

4 Power Stacks – Content (fig. 2.6-12)
• 2 inverter cabinets (with max. 2 inverter modules)
• 1 control cabinet
• 1 grid connection cabinet (optional)
• X battery cabinets*
• Power: max. 472 kVA
• Rated capacity: up 180 to 900 kWh

12 Power Stacks – Content (fig. 2.6-13)
• 6 inverter cabinets with max. 2 inverter modules
• 1 control cabinet
• 1 grid connection cabinet (optional)
• X battery cabinets*
• Rated power: 1,080 kW (scalable)
• Rated capacity: up 540 to 2,700 kWh (scalable)

Example of a containerized integrated solution (2x12 Power Stacks – fig. 2.6-14)
incl. HVAC (Heating, Ventilation and Air Conditioning) control, fire detection and extinguishing system
• Rated power: 2,160 kW (scalable)
• Rated capacity: 1,080 kWh (scalable)

* max. 5 connected to one inverter module

Fig. 2.6-11: SIESTORAGE has been installed with a performance of 1 MVA and a capacity of 500 kWh in the MV distribution grid of ENEL in Italy

Fig. 2.6-12: 4 Power Stacks

Fig. 2.6-13: 12 Power Stacks

Fig. 2.6-14: Example of an integrated containerized solution
2.6.4 Benefits of Comprehensive Competence

Comprehensive and consistent portfolio
With its comprehensive competence, Siemens contributes to maximizing returns and optimizing energy consumption. Decades of experience and continuous innovation are the basis for this know-how. The results are integrated solutions with state-of-the-art components ranging from storage components, including power electronics, to LV and MV switchgear, transformers and energy automation, all of which ensure grid integration. In addition, Siemens provides the HVAC system (heating/ventilation/air conditioning) for smooth operation at high ambient temperatures, as well as a fire detection and extinguishing system (fig. 2.6-11). As an E-house manufacturer, Siemens has expertise in power packaging, and can deliver a ready-to-install solution that has been thoroughly developed, manufactured, assembled and pre-tested. This reduces both construction risks and installation time.

Single source through all phases of the project (fig. 2.6-16)
Siemens is with its customers every step of the way through all phases of the project, from engineering to installation and commissioning. Reliable and competent local support is provided right from planning to after-sales service. Components and auxiliary equipment are globally sourced, and integrated in an E-House or the customer’s building. Siemens experts bring their experience in project management, financial services, and life cycle management to every project around the globe.

After-sales service
Our after-sales service concept is based on a Customer Support Center (hotline) available 24/7. It offers professional maintenance services, scheduled or on call. Life time of the batteries can be extended by tracking crucial parameters and optimizing operation.

For further information:
www.siemens.com/siestorage
Hotline:
Phone: +49 180 524 84 37
Fax: +49 180 524 24 71
E-mail: support.ic@siemens.com

Fig. 2.6-15: With SIESTORAGE, customers benefit from the consistency of Siemens’ portfolio and advanced technology

Fig. 2.6-16: Project life cycle management
2.7 E-Houses for Power Distribution

2.7.1 Plug-and-Play Power Supply Solution

E-Houses are pre-fabricated electrical buildings (power equipment centers) that are fully equipped and pre-tested for a fast and reliable power supply. They accommodate our comprehensive portfolio of medium-voltage switchgear, low-voltage switchboards, busbar trunking systems, and auxiliary equipment (fig 2.7-1).

The E-Houses are completely developed, manufactured, assembled and pre-tested at the factory, connected, and put into operation on site. They are therefore fast and easy to install and can be used as an interim solution. They are easy to upgrade, using available space optimally. This makes them a time-efficient and cost-effective alternative to conventional site-built substations for a broad range of applications.

Benefits of an E-House at a glance

- Cost-effective
- Fast to install
- Flexible
- One-stop solution.

A true alternative to conventional site-built power substations

A conventional solid building is often too expensive or time-consuming for many projects. In other cases, the project schedule or the attributed restricted space do not allow for site-built construction, and sometimes building permits for conventional buildings are not available. E-houses are the ideal solution in all these cases. They can be installed in very little time, and they can be adapted to virtually any situation and application. E-Houses have been a standard solution for power supply in the oil and gas (fig. 2.7-3), as well as in the mining industry (fig. 2.7-4) for many years. They are used even more frequently for the installation of equipment in other industries (e.g., metals and chemicals) and in infrastructure facilities (e.g., data centers, ports), or by grid operators for the extension of distribution grids, critical and temporary power supply, grid connection, and balance of plant for fossil and renewable power generation.
2.7.2 Cost-Effective Solution

The standardization and the modular design of E-Houses lead to more flexibility and cost-efficiency. The expected saving potential for typical projects with E-Houses is up to 20% (Fig. 2.7-5a) of the total costs of ownership, regarding:
- Reduced cost in planning
- Reduced manpower on-site (pre-fabricated)
- Reduced civil works on-site
- Reduced construction risks
- Flexible and space saving design
- Possible interim solution and relocation.

2.7.3 Time-Efficient Solution

E-Houses are fast and easy to install. Compared to a conventional site-built construction, the overall lead time using an E-House is reduced up to 50% (Fig. 2.7-5b), thanks to:
- Reduced civil works due to pre-fabrication and pre-test
- Reduced installation time through “Plug, commission and play”
- Reduced construction delays (e.g., due to weather)
- Minimum interference with other on-site activities
- Reduced time in planning thanks to modular design
- Reduced time in planning (in case a construction permit is not required).

2.7.4 Flexible and Optimized Design

Thanks to their modular design, various E-House types allow for tailor-made space saving solutions that can easily be expanded or moved to another location. The project and application requirements determine the type of an E-House:
- One module, e.g. on pre-cast concrete foundation

- Multi-modular E-Houses with several modules that are placed on top of or next to each other on a foundation, for the transport of large E-Houses and the optimal use of available space
- Mobile modules on wheels or for relocation with own foundation.

The design requirements of an E-House are also dependent on the environmental conditions:
- Weather (temperature, humidity, rain fall, snow and hail, ice and frost)
- Environment (altitude, radiation, wind loads, atmospheric pollution)
- Hazardous environment/substances (chemicals dangerous gases and vapors, dusts)
- Seismic conditions
- Corrosion classification.

E-Houses can be installed on raised platforms to protect them from flooding and enabling the installation of cable tray and bus duct systems under the E-House without excavation.

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**Fig. 2.7-4:** E-house provides energy to all the processes of mineral foundry in the mining industry (Cerro Matoso in Columbia)

**Fig. 2.7-5a:** Cost saving potential up to 20%

**Fig. 2.7-5b:** Reduced lead time up to 50%
Optimized design fitted to our MV and LV portfolio (fig. 2.7-8)
The design of an E-House starts with the overall electrical layout. The equipment list has to be defined as a first step. Every variable is taken into account, from the dimensions and heat dissipation to the weight of the electrical equipment for load calculation (fig. 2.7.7) and all the way to the project requirements such as cable layout, external interfaces, etc. The structural and mechanical design is then performed on the basis of structural and seismic calculations and simulations in 3D (fig. 2.7.6). The most widely used designs use self-framing, interlocking wall and roof panels that are installed on a structural steel base. The manufacturing or procurement of wall, roof and floor panels also depends on the project requirements (environment), standards, and the weight of the equipment to be installed. Further steps during the design process include planning of HVAC (heat ventilation air conditioning) access doors and explosion-proofed battery rooms with separate ventilation, for example, all essential parts of the design process focusing on maximum personnel and equipment safety.

Auxiliary equipment for equipment utilization and ambient conditions
Last but not least, there is a wide range of auxiliary equipment that can be selected according to the local, individual environment, health and safety requirements, standards, and regulations. It includes lighting and earthing systems, sockets, distribution boards, cable trays, electrical metallic tubing, and plug accessories.

To ensure safe operation, E-Houses are equipped with fire and smoke detection systems, fire fighting systems, emergency exits, and access control. A heating, ventilation and air conditioning system (HVAC) for smooth operation at high ambient temperatures, can be installed on the roof, inside or outside of any E-House. Air filtration systems, gas-detection and pressurization systems can be added (e.g. for hazardous areas).

With our E-Houses, you benefit from a single interface competence for the overall electrical design, the structural mechanical design, HVAC design, and the procurement of the auxiliary equipment.

Benefits
• High flexibility due to modular design
• Space saving design
• Optimized design, fitted to our comprehensive and consistent MV and LV portfolio.

Fig. 2.7-6: Structural and mechanical analysis are performed on calculations as well as on simulations in 3D

Fig. 2.7-7: Load calculation in order to ensure the structural integrity of the E-House

Fig. 2.7-8: Optimized design fitted to our MV and LV portfolio
2.7.5 One-Stop Solution

Comprehensive and consistent portfolio
With its comprehensive and consistent portfolio, Siemens contributes to maximizing returns, and optimizing energy consumption. Decades of experience and continuous innovation are the basis for this know-how. The results are integrated solutions with state-of-the-art components ranging from:

- Low-voltage and medium-voltage switchgear (GIS and AIS) up to 52 kV
- Low-voltage and medium-voltage motor control centers (MCC) and main distribution centers (MDB)
- Variable frequency drives (VFD)
- Dry-type transformers
- Control and protection panel boards
- SCADA and energy automation systems
- Relay panels
- Busbar trunking systems.

In addition, E-Houses are equipped with batteries, instrumentation, uninterruptible power supply (UPS) and a wide range of auxiliary equipment. With our E-Houses, system operators benefit from the consistency of Siemens’ advanced technology and expertise in power supply solutions. Everything from a single source!

One interface through all phases of the project (fig. 2.7-9)
Siemens is with its customers every step of the way through all phases of the project, from engineering to installation and commissioning. Reliable and competent local support is provided right from planning to after-sales service. Components and auxiliary equipment are globally sourced, and integrated in the E-House. Siemens’ production facilities and centers of competence are found around the globe. Siemens supports the local creation of value, and guarantees a competent contact person in close reach of every project. Siemens experts bring their experience in project management, financial services, and life cycle management to every project. This enables them to consider any aspect of safety, logistics, and environmental protection.

Benefits
- All equipment from a single source
- Reliability and safety thanks to proven Siemens products and systems
- Application expertise
- Global experience
- One contact for the entire project
- Financing support.

For further information:
www.siemens.com/e-house
2.8 Microgrids – The Next Step towards an Efficient Use of Distributed Resources

A microgrid is electricity generation and loads, and in some cases storage, managed collectively in a network. Besides electricity, microgrids may include other vectors such as heat, gas, water. Microgrids manage energy resources according to a given set of criteria. They may be operated in off-grid, on-grid as well as in dual mode to optimize technical (e.g., power quality, frequency) and economic aspects (e.g., optimal use of renewable energy). In an optional emergency mode, the microgrid provides blackstart capabilities.

Siemens microgrid management systems (fig. 2.8-1)
- Optimize use of intermittent generation, and increased efficiency by combining heat and electricity generation
- Increase stability of supply and grid resilience through on- and off-grid functionality
- Optimize energy management for reduced or better controlled energy costs and CO$_2$ footprint
- Optimize economic performance of energy system through peak load management and limitation of grid extensions.

2.8.1 Operation, Monitoring, Administration, Planning – All Under One Roof

The Siemens microgrid management system monitors and controls grids with large and small distributed energy generators, renewable assets, storage and loads. The scalable system helps to automate, display, alarm and control all elements in the grid, thus assuring the needed quality of supply at all times. It generates schedules, automatically monitors their observance, and readjusts them in real time. This is enabled by automatic switching sequences based on rules or forecasts that draw on a large number of constantly updated parameters—such as weather forecasts, type of plant or power price. Siemens solutions also help to efficiently incorporate such as cogeneration plants. Intelligent networking of energy infrastructure using Siemens microgrid management systems not only increases the added value of the power supply, but also protects its operation from outages, regardless of whether the microgrid is connected to the supply network or not. Siemens’ solutions are flexible and expandable – today and in the future (fig. 2.8-2).

Intelligently managing microgrids
Siemens microgrid management systems are the ideal solution to ensure the most optimized control of fluctuating electricity generators within a microgrid. The tailored solutions meet the individual challenges of each power scenario with a modular structure and flexible scalability. This means that our customers receive a software solution exactly tailored to their needs.

Microgrid administration comprises a range of intelligent, versatile and user-friendly tools for a wide range of applications. End-to-end SCADA and numerous functions for forecasting, planning and real-time optimization support in:
- Monitoring and controlling the microgrid components
- Monitoring and controlling generation
- Monitoring and controlling consumption
- Providing ancillary services
- Buying and selling power.

It is flexible, direct and progressive.

Benefits
- All equipment from a single source
- Reliability and safety thanks to proven Siemens products
- Application expertise
- Global experience
- One contact for the entire project
- Financing support.

Fig. 2.8-1: Microgrid with one common point of coupling to the utility grid
2.8 Microgrids – The Next Step towards an Efficient Use of Distributed Resources

Trouble-free engineering
The intuitive design tools are a core element in the microgrid management system. Even the most complicated power infrastructures can be represented digitally with just a few clicks of the mouse. This saves time and minimizes the potential for error, thanks to many automatic support functions.

Benefits of a fully integrated microgrid solution
• Modular construction, flexible and scalable
• Reliable microgrid operation
• Intuitive modeling and parameterization
• Intelligent forecasting and planning
• Simple, real-time optimization
• Incorporation of distributed generators, storage units and loads
• No 24/7 operator required.

2.8.2 Microgrid Market Segments

According to today’s experience and publications, there are four major microgrid market segments:

Institutional microgrids – the challenges of renewable energy
Rising energy prices, as well as reliable and resilient energy are increasingly becoming concerns to large energy consumers. Fundamental business changes such as market deregulation offer new opportunities for corporations, governmental organizations, municipalities and universities to manage their energy supply optimized for their own use. Siemens delivers tailored solutions to meet energy goals, like energy reliability, sustainability, resiliency, or economic aspects. By adding renewable generation sources and storage to the microgrid, the reliability of energy supply increases, and costs are reduced. As multiple generation sources and energy assets are added to a microgrid, advanced control functionality is required to ensure the system is operating as efficiently as possible (fig. 2.8-3).

Critical infrastructures microgrids – renewable energies in critical environments
For operation of critical power grid infrastructures, the increasingly deregulated energy market, and the advances in renewable energy sources offer both opportunities and challenges. The use of renewables to supply critical infrastructure increases the
independence from grid supply and lowers operating costs, especially since surplus electricity can be sold. If storage systems are used, operations can take the form of an electrical island, providing security in case of emergencies such as storms. Fluctuations in electricity generation in a microgrid demand intelligent control mechanisms, reliable forecasts, and – especially in island mode – a balance between available power and power consumed (fig. 2.8-4).

Remote locations microgrids – stable power supply for weak grids
For the operation of power grids in remote locations, the advances in renewable energy sources offer both opportunities and challenges: By incorporating renewable and storage facilities in the supply systems, operators can cut their power costs dramatically – while increasing grid availability even in poorly supplied areas. Wherever the transportation of fossil fuels over long distances is costly and unreliable, the use of wind or solar plants can take a lasting improvement in terms of both independence and economic efficiency. Fluctuations of electricity generation in a microgrid demand intelligent control mechanisms as well as reliable load and generation forecasts. It is essential to maintain a balance between energy generated and energy consumed (fig. 2.8-5).

Industrial microgrids – modern energy challenges and chances
Operators of industrial power grids face two major challenges: They need to optimize their average production costs – which includes ensuring a secure and reliable power supply to assure production – and at the same time reducing CO₂ emissions. The use of renewables to supply industrial facilities reduces both CO₂ emissions and the requirement for imported electricity. This lowers operating costs, especially since surplus electricity can be sold. If storage systems are used, it allows operations to take the form of an electrical island, ensuring smooth production, regardless of a public power supply that in many locations may be insufficient. Fluctuations in electricity generation in a microgrid demand intelligent control mechanisms, reliable forecasts and – especially in island mode – a balance between available power and power consumed (fig. 2.8-6).
2.8.3 Siemens Microgrid Management Systems

To meet decentralized infrastructure development needs and provide advanced functionality to maximize its value, Siemens supplies scalable microgrid management systems and solutions based on automation equipment in the SICAM series and software solutions based on the leading Spectrum Power™ platform. These are providing solutions for microgrids covering energy and optionally heat. Depending on the case of use, the solution can range from field devices for equipment control over decentralized automation to a fully functional microgrid manager. Depending on scale and required functionality, two main solution lines are available:

- SICAM Microgrid Manager
- Spectrum Power Microgrid Management System.

**SICAM Microgrid Manager**

The SICAM Microgrid Manager is the ideal solution for small to medium-sized microgrids covering energy and optionally heat. It is focused on 24/7 autonomous control with minimum operator intervention (fig. 2.8-7).

**Functionality**

- Grid monitoring and control
- Small and large distributed generator control (electrical power, heat)
- Storage control
- Load control
- Generation forecast
- Load forecast
- Schedule optimization.

**Spectrum Power Microgrid Management System**

The Spectrum Power Microgrid Management System is the ideal solution for medium- to large-sized microgrids covering electricity and optionally heat. It offers advanced application functionality, market interface, enhanced consideration of grid constraints, and can be enriched with applications up to a full distribution management system (fig. 2.8-8).

**Functionality**

- Grid monitoring and control
- Small and large distributed generator control (electrical power, heat)
- Storage control
- Load control
- Generation forecast
- Load forecast
- Schedule optimization
- Online control.