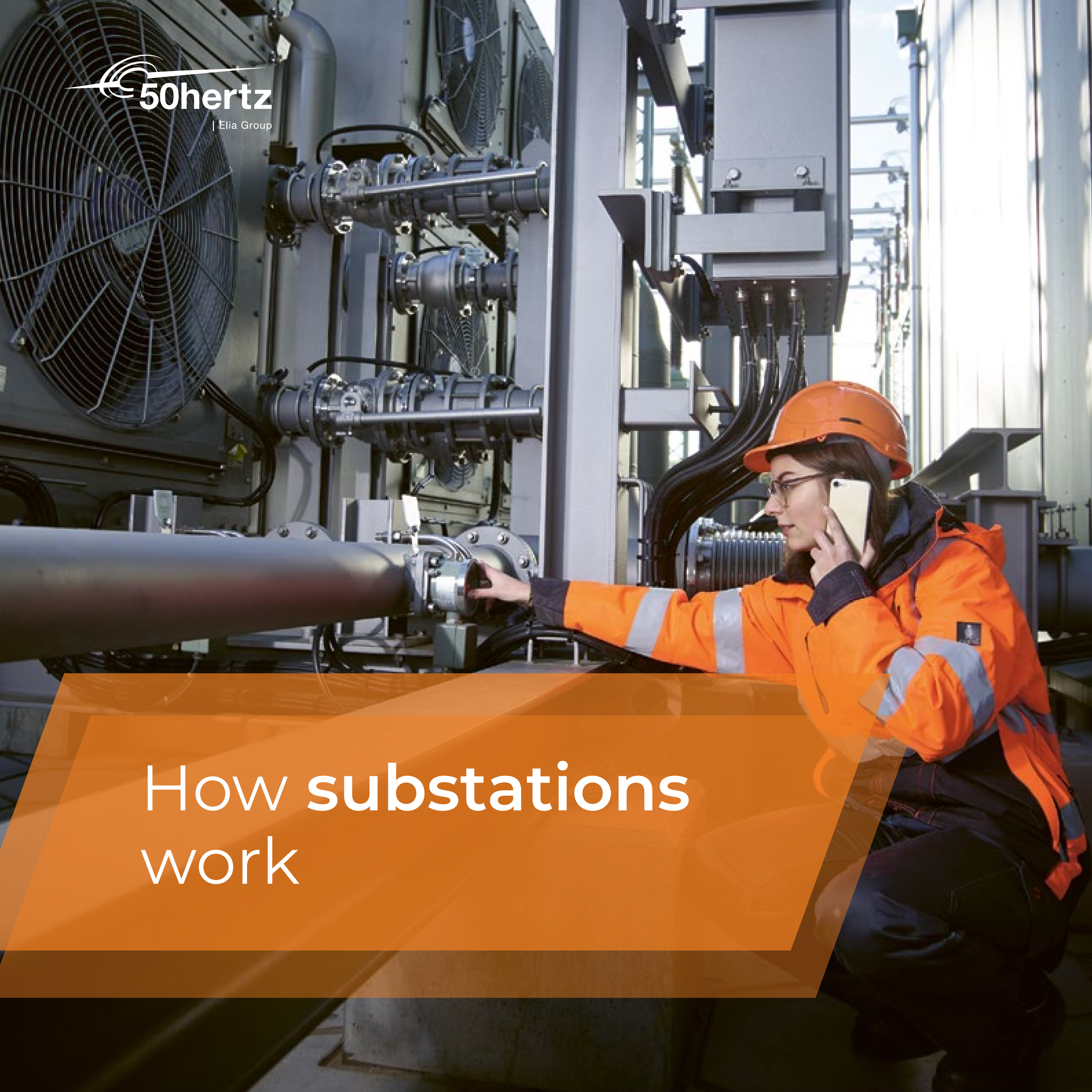
How **substations** work



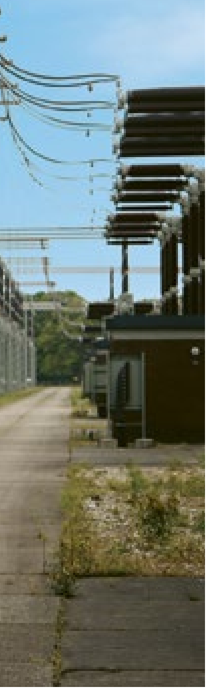

50Hertz employees at the Hamburg-Ost substation.

SUBSTATIONS

Intersections in the electricity grid

In Germany, substations can be found on almost every corner in every village, every town and every metropolis: Usually they are inconspicuous functional buildings dating from various historical periods. They house electrical systems that supply electricity to households and small businesses at 230 volts and 400 volts – specialists call this “transforming”.

These substations are the smallest intersections in the electricity grid, which has a similar structure to the road network: this grid also contains motorways, major roads, regional road links, and city and municipal roads. And just as traffic is guided from one road to another at motorway junctions and intersections, substations are used to transform the voltage levels of electricity: from the extra-high-voltage grid and the high-voltage grid to the medium-voltage grid and the low-voltage grid for private consumers and small businesses – and they do this in both directions. But why is all this necessary?



Why do we need technical systems to reduce or increase the voltage of the electricity? Why don't wind and solar farms and power plants simply generate electricity at the voltage we use at home from our plug sockets? In order to understand this, we need to have a bit of a physics lesson: when electricity flows through power lines, the ohmic resistance of the lines causes some of the electrons' energy to be converted into heat. This effect can be reduced to an acceptable level by transporting electricity at a very high voltage over long distances. The high voltage also makes it possible to deliver a lot of power – enough for entire major cities and industrial enterprises. But this high voltage is unsuitable for household use: it would be impossible to charge a smartphone with extra-high voltage. This is why all consumers must receive the appropriate voltage to meet their needs – and this means that the voltage level needs to be increased in several stages and then reduced again.

About this publication

In this brochure, you will find out how our substations are structured, why we are expanding our substations and building new ones, what we are doing to protect residents and the environment. You will also find out why newly developed technology is making its way into our substations as a result of the energy transition.

50Hertz operates the motorway junctions in this electrical system:
In our substations, transformers convert electricity from the highest voltage levels used in the German alternating current grid – 380,000 and 220,000 volts – to the next lowest voltage level of 110,000 volts and vice versa. And our substations have another important function, too: they're also motorway intersections. This is where power lines come together from various different directions and can either be merged or separated.

Why 50Hertz is expanding its sub-stations and building new ones, and what we bear in mind in this process

The requirements for our electricity grid are changing due to the energy transition in Germany and the expansion of renewable energy sources.

Gone are the days when electricity used to be generated in just a few large power plants before flowing to consumers. Nowadays, there are also wind farms, photovoltaic installations and biogas facilities distributed across the entire country. They all feed electrical energy into the distribution grid or the transmission grid (see page 8). And what's more, demand is changing, too, thanks to new industrial facilities and residential areas. Transmission system operators such as 50Hertz and distribution system operators are therefore not only upgrading their lines, but also their electricity intersections.

Criteria for selecting sites

Before the construction of a new substation can begin, a suitable site needs to be found. Here a wide range of criteria need to be met. Substations are always located at sites that lines already pass through or where lines are planned. The site needs to have good transport links and should ideally have a railway connection for the delivery of the transformers, which can weigh up to 300 metric tonnes. Environmental aspects also play a key role: conservation areas are never used as construction sites. The sites should be as far as possible from inhabited areas.

50Hertz employees checking a circuit breaker.

The construction of a substation is a complex process that can take several years. A detailed planning and approval process needs to be completed before construction can begin. The future operator needs to provide the authorities not only with all the documents for the construction, but also with reports on noise and on magnetic and electric fields. Before construction begins, compensation measures are planned and initiated together with local partners. These measures aim to offset any interference with nature and the environment. They may include planting, renaturation of bodies of water, conservation measures for endangered species or dismantling and maintenance measures for buildings.

50Hertz for animals

Before construction of the 50Hertz substation in Altdöbern could begin, amphibians such as these lizards were collected and taken to a new location.

A 50Hertz employee works on a transformer in the Wolmirstedt substation near Magdeburg.

Noise in residential areas

Noise in residential areas is governed by the legally defined limits set out in the German Federal Immission Control Act. 50Hertz makes sure that the noise levels in the areas surrounding the substations are significantly below these limits.

Type of area	Day	Night
Purely residential areas	50 dB(A)	35 dB(A)
General residential areas	55 dB(A)	40 dB(A)
Village areas and mixed-use areas	60 dB(A)	45 dB(A)

How loud is 35 db(A), and how loud is 60 db(A)?

A decibel (db) is a unit of measurement used to describe the sound level. Inserting (A) after db indicates that the different sound frequencies are perceived differently by the human ear. Medium frequencies are given a greater weighting. People with healthy ears have a hearing threshold as low as 0 dB(A). Values above 120 dB(A) are perceived as unbearably loud. A noise level of 35 dB(A) is the volume of a whisper, for example, and 50 db(A) corresponds to a normal conversation or a quiet radio.

How we protect the environment, nature and residents

Electric and magnetic fields are all around us all the time – both in the home and outside in nature. The earth's mantle has its own magnetic field. Household appliances need electricity to run and therefore generate both electric and magnetic fields.

Overhead lines and substations also generate electric and magnetic fields. The limits for these fields are set out in the German Federal Immission Control Act:

- 5 kilovolts per metre (kV/m) for electric fields
- 100 microteslas (μT) for magnetic fields

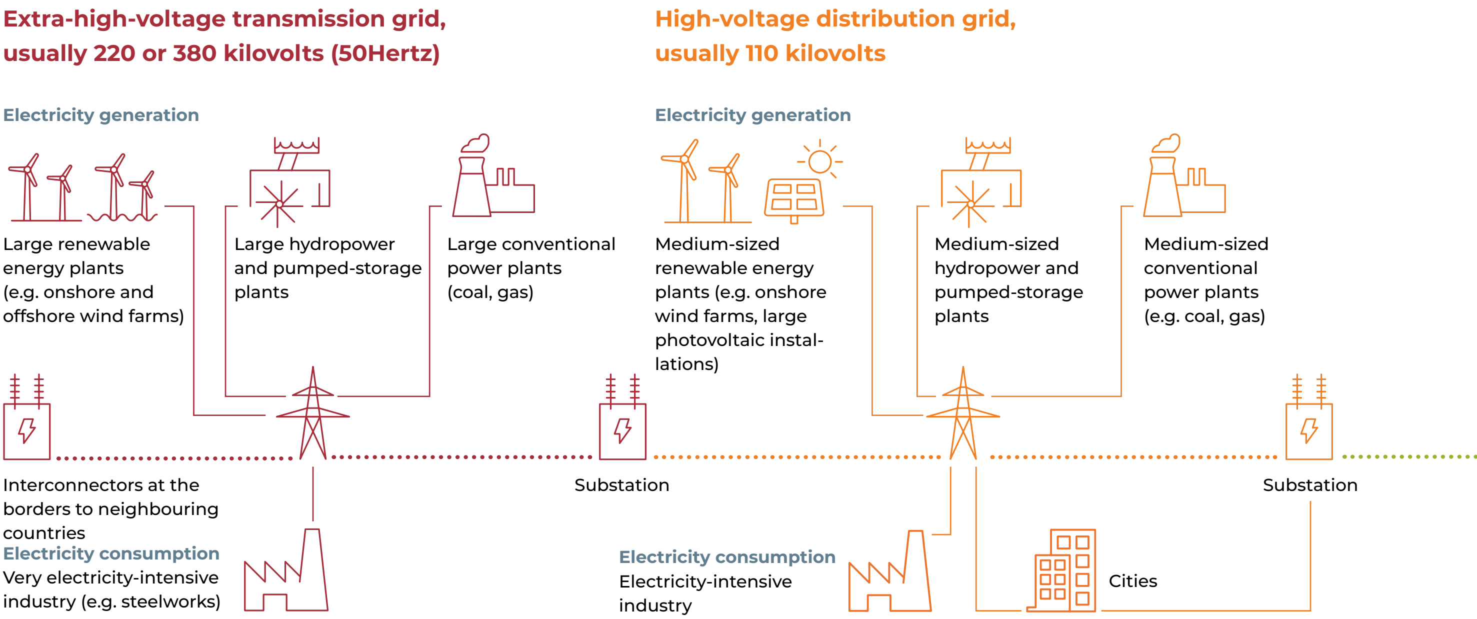
A comparison
An electric drill can generate a magnetic flux density of up to 800 microteslas when used at a distance of around three centimetres from the body.

Quiet neighbours

Substations generate noise, but they're quiet neighbours. One source of noise is the overhead lines that connect the substation to the electricity grid. These overground lines crackle due to small discharges – especially in damp weather. The most distinctive noise in a substation comes from the transformers. Their humming sound is produced inside the plant, where there is an iron core with a coil wrapped around it. The two components are firmly joined together. During operation, a magnetic field is generated with forces so large that they make the parts vibrate. These vibrations are perceived as a humming sound.

THE PATH TO ELECTRICITY

The four levels of the German electricity grid

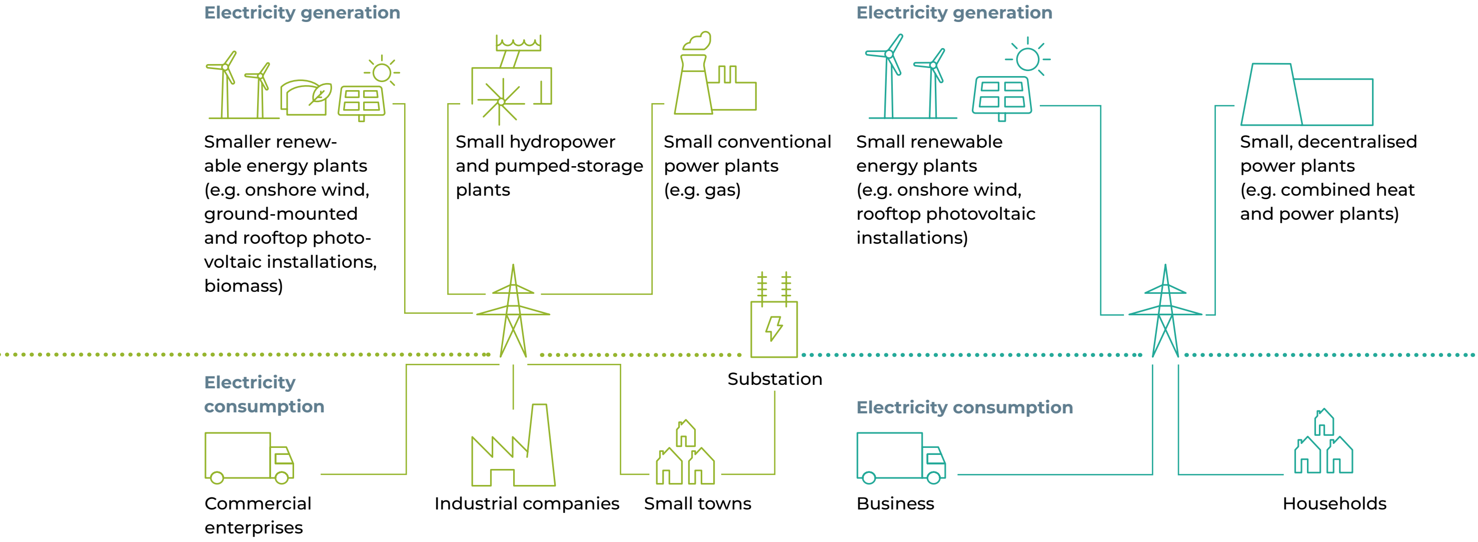


The **extra-high-voltage transmission grid** transports large quantities of electricity from large renewable and conventional generators at the extra-high-voltage level of 220 or 380 kilovolts (kV). This grid carries electricity over long distances to the regions, with minimal losses. It also connects the German electricity grid with those of neighbouring countries and allows for the cross-border exchange of energy across Europe.

The **high-voltage distribution grid** is operated by the regional grid operator. It transports electricity to metropolitan areas at 110 kilovolts (high voltage) and supplies electricity for most industry.

Medium-voltage distribution grid, 3 to 30 kilovolts

Low-voltage distribution grid, usually 230 or 400 volts



The **medium-voltage distribution grid** (usually 3, 6, 10, 15, 20 or 30 kilovolts) supplies electricity to industry and business. Electricity is distributed to regional transformer stations or directly to large facilities such as hospitals or factories.

The **low-voltage distribution grid** (less than 1 kilovolt, usually 230 or 400 volts) is used for distribution at the local level. Private households, smaller industrial operations, businesses and public administration buildings are connected to the low-voltage grid.

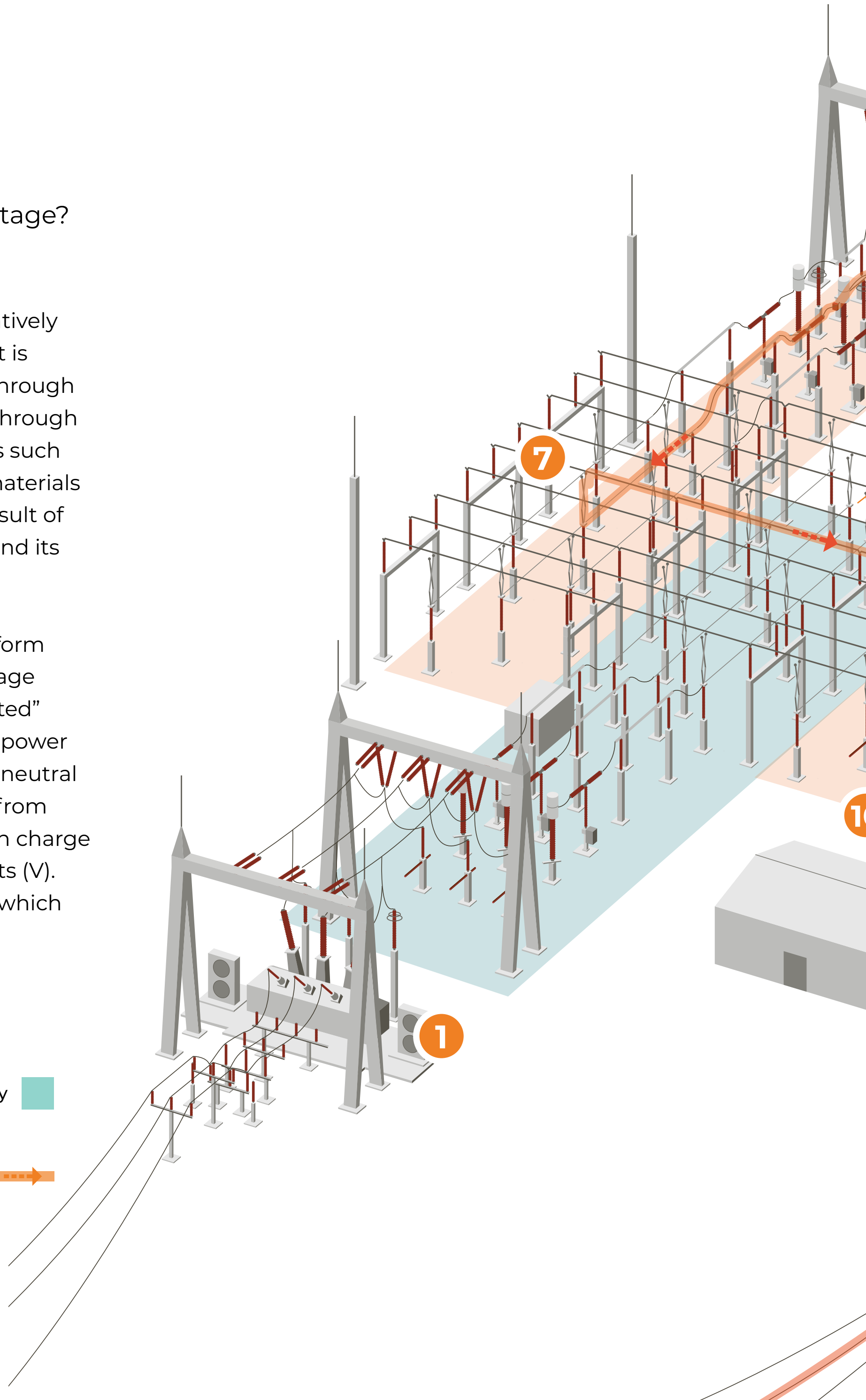
The different voltage levels are connected by sub-stations. This is where the voltage is increased or reduced.

A bit of physics

What is current, and why does it need voltage?

Electrical current refers to the flow of small, negatively charged elementary particles (electrons). Current is invisible – like the wind, it can be detected only through its effect. Like a river in a riverbed, current flows through a conductor made of conductive material. Metals such as aluminium or copper are especially suitable materials for conductors. The water in a river moves as a result of the difference between the height at its source and its mouth.

Inside the conductor, these two “sides” take the form of an excess of electrons on one side and a shortage of electrons on the other. The electrons are “created” when electricity is generated in a wind farm or a power plant. Since electrons will always try to achieve a neutral state, they will move “to the other side” – that is, from the negative to the positive side. The difference in charge is referred to as voltage, and it is measured in volts (V). The higher the voltage, the larger the force with which the electrons flow through the conductor.



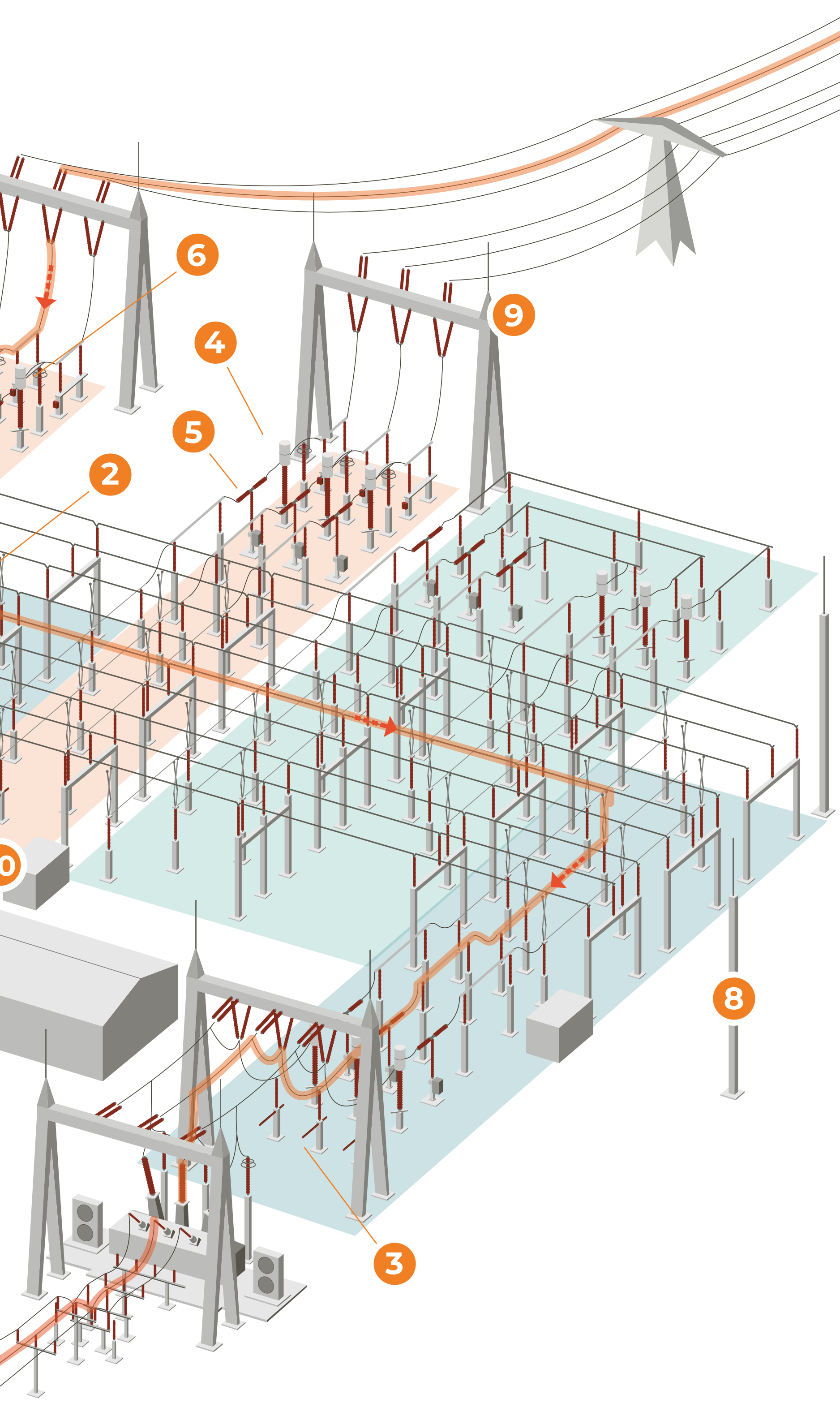
Key

Line switchgear bay

Coupling switchgear bay

Transformer switchgear bay

Example current flow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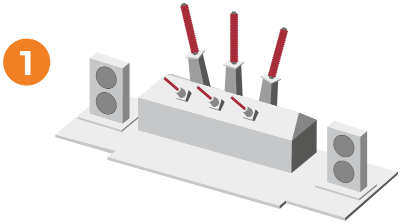
The heart of a substation
The transformer



In the European transmission grid, electrical current is transported at up to 380,000 volts – 380 kilovolts. This minimises the losses that occur while the energy is being transported.

How is 380,000 volts turned into the standard voltage for a household? The voltage is changed in transformers. But the large jump from extra-high voltage (380,000 volts) to household voltage (220 volts) doesn't happen all at once. Instead, it takes place in several steps at different voltage levels. The grids for the different voltage levels are connected by substations.

The nearer these substations are to the end consumer, the lower the voltages and the smaller the installations are. Voltage is not converted to the standard supply voltage for household use until it reaches the direct vicinity of these homes.

A transformer that transforms voltages from 380 kilovolts to 110 kilovolts – that is, from the voltage level of the transmission grid to that of the distribution grid – is roughly the size of a garage. They are mainly made of metal, both outside and inside. A distinction is made between the primary side of a transformer and the secondary side. The current on the extra-high-voltage side flows through a large coil on the primary side. This coil is wrapped around a large iron core. The magnetic field that is created inside the transformer generates a current flow in the coil on the secondary side. Due to the relationship between the coils, the resulting voltage on the secondary side is lower – around 110 kilovolts. Inside the transformer, oil is used for insulation and heat removal. To ensure that the transformer is sufficiently cool in any operating status, the temperature of the oil is lowered in large heat exchangers next to the transformer.

The heavyweights in the energy supply

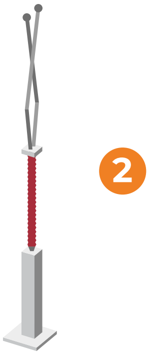
Apprentices being trained in carrying out inspection work on a transformer. The large devices weigh several hundred metric tonnes.

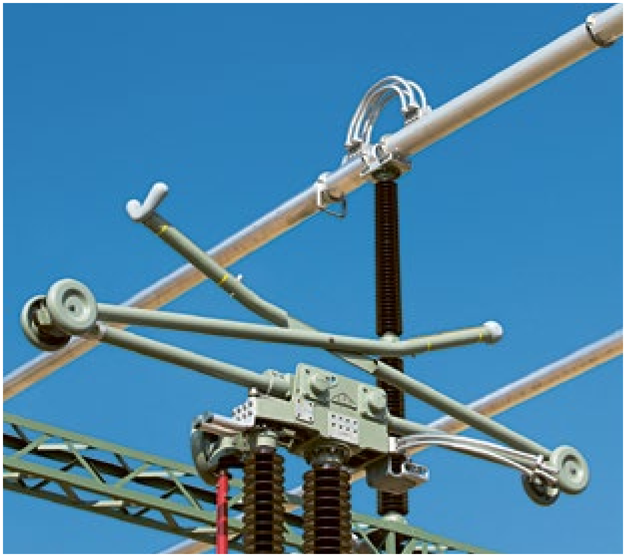
Components of a substation

Every single piece of equipment in a substation has a crucial function. They vary in shape and size depending on their location and task. They make sure that the entire system can be operated safely and reliably.

The collection of devices surrounding a circuit breaker is known as a switchgear bay. The circuit breaker is always located in the centre of a switchgear bay. It is able to interrupt the current flow under normal operating conditions or in the event of a fault. The switchgear bay is connected to the other pieces of equipment via disconnectors with integrated earthing switches. The combined current and voltage converter sends information about the current flow and the voltage to the protection and control system and the metering technology. Depending on the function, a distinction is made between:

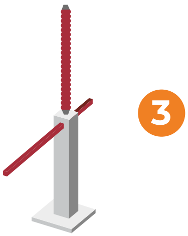
- A line switchgear bay ... this switchgear bay connects the high-voltage line to the busbars.
- A transformer switchgear bay ... this switchgear bay connects the transformer to the busbar. The transformer is a special case and is connected directly rather than via a disconnector.
- A coupling switchgear bay ... this switchgear bay is used for the flexible connection of the busbars.





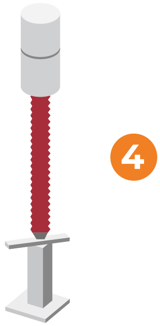
Disconnector

Disconnectors can be found in many places within a substation. Depending on where they are used, they either take the form of line disconnectors or busbar disconnectors. Their task is to open the circuit in order to disconnect certain system parts from the rest of the system. They do not switch current directly and serve as visible disconnection points. Opening a disconnector can be compared to unplugging a switched-off device from the plug socket.



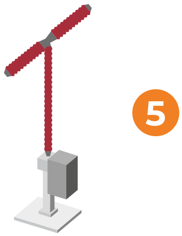
Earthing switch

An earthing switch earths a switched-off (and therefore voltage-free) system component. It prevents the dangers that may arise if the switched-off components are charged. When used in combination with disconnectors, this helps to create a safe working environment in the substation.



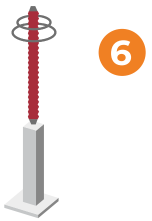
Current and voltage converter

In order to ensure the safe operation of a substation, being aware of its operating status at all times is essential. This information is provided by current and voltage converters. The data is processed by the protection and control system so that it can respond automatically in the event of a fault. These electrical values are also used by the metering technology in order to bill customers based on the energy flow.



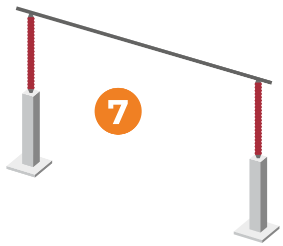
Circuit breaker

The circuit breaker can be pictured as a combination of a light switch and an automatic circuit breaker in high-voltage technology. It switches lines and system components on and off. Alongside the transformer, it is the most important high-voltage device in a substation.



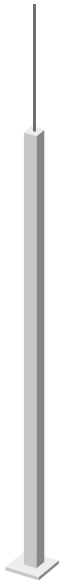
Surge arrester

Surge arresters are often located at the end of an overhead line or cable. They limit overvoltages. These are temporary voltages (for example, due to lightning) that are considerably higher than normal voltage. By limiting this voltage to the normal voltage level, the devices in the substation can be protected without interrupting the supply.



Busbar

The busbar is the backbone of a substation. It connects the various switchgear bays and ensures the transport of current within the substation. There are often multiple busbars in order to make the system more fail-safe and allow for more flexible control of the current transport. The busbars can be interconnected in an extremely wide variety of ways.



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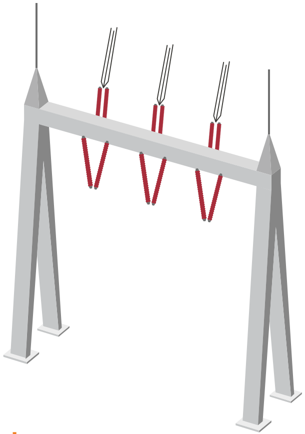
Lightning protection rod

The lightning protection rod is not part of a substation's operating equipment. Nevertheless, it is crucially important. Substations are often situated in an exposed location and have a large number of metal devices. It is therefore not unlikely that a substation might be hit by lightning. In order to protect the devices and guarantee the power supply, substations are fitted with several tall lightning protection rods. Just like a lightning conductor in the home, these devices aim to control the lightning strike and conduct the lightning into the ground without any danger to people or the operating equipment.

Protection against lightning strikes

The voltage that occurs during a lightning strike can be up to 100 million volts, so the lightning must be safely conducted away in order to avoid damage to the substation.



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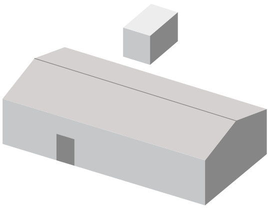
Portal

In addition to the operating equipment and the lightning protection rods, a substation has another striking structure – the portal. Overhead lines, busbars and transformer connections cannot just be suspended in the air; they need to be supported in a way that is mechanically stable. This is where the portals come in. In the case of line portals or transformer portals, they look like large frames in which the insulated lines are suspended. Busbar portals, on the other hand, act as a support structure on which the insulated tubular busbars are mounted.



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Relay and operating building

There are also relay and operating buildings in a substation. Relay buildings mainly contain components for the protection system and the control system. To keep the distances between the building and the devices being monitored short, there may be several relay buildings distributed across the substation. The operating building contains the remaining components for the control system, communications technology and the storage rooms, common rooms and sanitary facilities.

A view inside a 380-kilovolt switchgear in a 50Hertz substation.

PROTECTION AND CONTROL SYSTEM

Monitoring and protecting substations

The protection and control system includes all the equipment that is indirectly involved in the energy transmission process.

In substations, information about the status of the grid is provided by voltage and current converters and switchgears. The control system is used to monitor and control the grid and to display information on the grid’s current state. It records all the necessary data and forwards the information to central points via communication networks. Information about the status of the entire 50Hertz extra-high-voltage grid is collected in the Control Centre (CC) in Neuenhagen bei Berlin 24 hours a day. Experts in the CC analyse the data in real time.

The protection system ensures the safety of people and the operating equipment. Faults such as short circuits can cause very high currents to flow. They pose a risk to lines, transformers and other items of operating equipment. To prevent damage, these currents need to be interrupted as quickly as possible. If a fault is reported by the protection technology, the affected line can be switched off very quickly, for example. This happens automatically, and the end consumer usually does not notice this interruption, as the current will simply flow via a different line.

24/7 grid safety

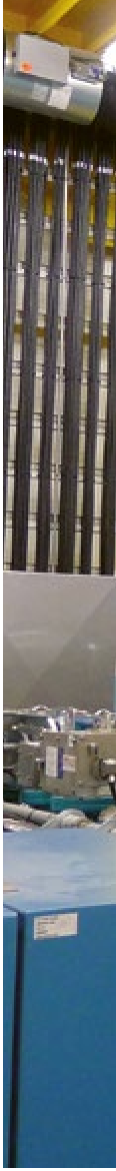
Employees in the Control Centre work around the clock to make sure the grid operates safely. From here, they control systems across the entire grid.

Air-insulated and gas-insulated switchgears

Current needs voltage in order to flow. The live lines come together in the substations. But many components in the substation need to be voltage-free in order to work. These elements therefore need to be insulated from the live parts within the plant. Normal air is the most cost-effective insulation medium. It is the most widely used medium in substations and switchgears.

Switchgears that use air as the insulation medium are known as air-insulated switchgears. They need enough space to guarantee a sufficient distance – and hence insulation – between the large number of elements. This is reflected in the size of air-insulated switchgears. They cover several thousand square metres and are usually located outside towns and cities.

In towns and cities and the surrounding areas, households and industrial facilities need electricity. Extra-high voltage is the optimal voltage level for transporting electricity due to the low losses. Electricity is therefore transported at a higher voltage level until it is as close as possible to the consumers. It then needs to be converted to a low voltage (usually 230 or 400 volts) in several stages before being supplied to the consumers. This means that switchgears and substations are also needed within cities. For substations in cities, gas-insulated switchgears are the preferred choice. In these plants, the gas sulphur hexafluoride (SF_6) is used as an insulation medium. The gas has better insulating properties than air. This means that the distance between the individual elements can be reduced. The plant can therefore be more compact than an air-insulated switchgear. In a gas-insulated switchgear, only the conductor in the housing is live. The insulating gas is located between the conductor and the housing walls. The housing itself is earthed and can therefore be touched without risk. Complete insulation means that the area outside the switchgear is free from electric and magnetic fields. The greenhouse gas SF_6 and the gas-insulated switchgears ensure that the switchgear is operated responsibly and with great care. Special safety regulations govern the use of this gas. Regular maintenance is carried out in order to prevent adverse impact on the environment. 50Hertz joined the Voluntary Commitment by SF_6 Producers and Users in 2005 and monitors its SF_6 consumption in the operation and maintenance of gas-insulated plants on an annual basis.



Carrying out inspection work in the switchgear on the platform of the Baltic 1 offshore wind farm.

What are insulating materials?

Electrical insulating materials have low electrical conductivity. They have high electrical resistance, good durability and exceptionally low water absorbency. Insulating materials include porcelain, glass and various plastics.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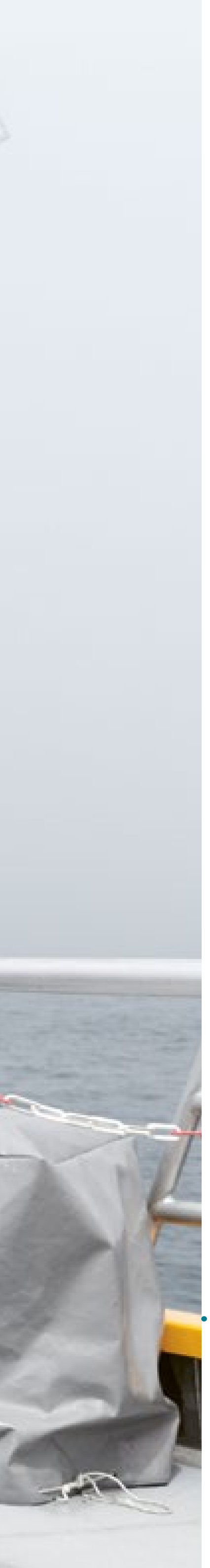

Substations at sea

Large offshore wind farms generate large amounts of electricity, which needs to be transported to land in order to continue its journey to end consumers. Substations are needed out at high sea, too, and they can be found on substation platforms. The cables from all the wind turbines in a wind farm come together on these platforms. The voltage is transformed from 33 kilovolts to 150 or 220 kilovolts in order to ensure efficient onward transport.

Operating a substation platform at sea is a very complex task. Because sea air is very damp, the hall of the substation platform needs excellent air conditioning and has to be dehumidified. This creates almost the same climatic conditions as on land. Offshore substation platforms have a similar structure to gas-insulated switchgears on land. The gas SF_6 is also used as an insulation medium here. The substation platform has additional reinforcement to equip it for the harsh weather conditions at sea.

Substation platform on the Baltic Sea

50Hertz employees on a ship in front of the Arkona offshore platform. The power cables from all the turbines in the wind farm come together on this platform. From here, they are connected all the way to the coast.

Converter stations for direct current connections

Historically, alternating current (AC) has always been able to hold its own against direct current (DC). It's easier to distribute via networked lines, easier to switch and can be easily converted to different voltage levels. But the benefits of DC are now making it a strong contender again.

DC has been experiencing a real recovery in recent years, and this has been seen in Germany, too. High-voltage direct current (HVDC) transmission is becoming more and more widespread, as it can be used to transport even larger quantities of energy over long distances with lower losses. It also allows electricity flows to be influenced in a more targeted manner. Several new DC connections will be needed in Germany in the future. They will connect the areas in northern Germany that produce large amounts of wind energy with the centres of consumption in the south.

Alternating current becomes direct current

This is what the inside of the 50Hertz converter station in Bentwisch looks like. This striking structure is known as the converter tower. It is needed to convert DC into AC and vice versa.

HVDC electricity transmission at 50Hertz

Together with the Danish grid operator, Energinet.dk, 50Hertz has operated a 170-kilometre-long HVDC connection for over ten years. The Kontek cable in the Baltic Sea connects the German and Danish grids. The cable comes ashore in Bentwisch.

Complex converter stations will be required to transport the DC and integrate these connections into the existing AC grids. These converter stations can be described as the "entry and exit points for high-speed connections" in long-distance electricity transport. They convert the current between AC and DC and control the transmission of the electricity through the DC lines. Investing in DC transmission is a particularly good idea if large amounts of electricity are to be transported over long distances (several hundred kilometres). A DC connection also allows for targeted control of the electricity flows. This has a positive impact on the stability of the electrical system.

Systems for reactive power management

In AC grids, energy flows in the form of active power and reactive power. Active power refers to the portion of the energy that carries out the work and that ultimately arrives at the consumer. Active power is what causes bulbs to light up, for example. Reactive power, on the other hand, does not actually perform any useful work but is required in order to build up the voltage.

The reactive power compensation system in the Altenfeld substation in Thuringia.

The energy transition means greater demand for reactive power:

If plants such as renewable energy plants supply huge amounts of electricity to a particular region, the transmission grid in this region will need to work harder to transport the electricity away. This will lower the voltage – and this increases the demand for reactive power.

One efficient way of generating the necessary reactive power is to use mechanically switched capacitors with damping networks (MSCDNs). These systems increase the voltage, thereby ensuring an unimpeded flow of electricity.

STATCOM systems

A second type of system that is used to regulate the reactive power in substations is a STATCOM system. STATCOM stands for STATic synchronous COMpensator. To a certain extent, these systems are responsible for fine adjustment: with a STATCOM system, not only can the voltage needed to maintain the reactive power be increased – it can also be reduced. In simple terms, MSCDN systems ensure sufficient pressure, and STATCOM systems provide the correct amount of voltage. STATCOM systems are also used to safeguard the operation of future 50Hertz DC lines: If a cable in the DC line were to fail, STATCOM systems make sure that the electrical power can still be safely transported via the normal AC grid. In this way, STATCOM systems guarantee the safety of the electrical system at all times.

Components of the STATCOM system in the Lubmin substation.

Phase-shifting transformers

In order to regulate electricity flows more effectively, phase-shifting transformers (PSTs) are installed at various points in the 50Hertz grid, with more under way. These transformers are located at the intersections where lines meet neighbouring countries and other transmission system operators.

The three phases of the current are shifted in relation to one another, making it possible to increase the resistance of a line. As the current always takes the path of least resistance, shifting the phases causes it to take different paths.

Similar to valves in water pipes, phase-shifting transformers allow the load flow within the three-phase supply system to be controlled in a more targeted way. This prevents individual grid elements from being overloaded. It also makes it easier to predict the transport possibilities offered by individual lines in regions subject to heavy loads, which makes these lines more useful for electricity trading. And this is a good thing for safe grid operation and for electricity consumers: more trade means more competition on the European energy market – and this tends to lead to lower prices.

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