VDE-Position Paper

Transmission of Electrical Energy

ETG

VDE

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List of abbreviations

AWE	Automatic reclosing (Automatische Wiedereinschaltung *or* Kurzunterbrechung - KU)
EnLAG	Law on the extension of overhead power line connections (Energieleitungsausbaugesetz - EnLAG) of 21 August 2009 (Federal Law Gazette I p. 2870).
FACTS	Flexible alternating current transmission systems
GIL	Gas-insulated transmission line
HVDC	High voltage direct current transmission
UCTE	Union for the Coordination of Transmission of Electricity, today part of ENTSO-E - European Network of Transmission System Operators
XLPE	Cross-linked polyethylene

Preface

The high quality level of electricity service in Germany plays a key role for energy supply of the present and the future. It is an important prerequisite to the contemporary industrial society's capability to perform on the European single market.

The expanding trading relationships fundamental to a smoothly functioning electricity market presuppose free physical electricity transport. Additional requirements on the transmission system are posed by the integration of renewable energies into the system, especially from large wind farms, and also from the remaining power plant pool that is due to be remodelled in the future.

Moreover, changes in legal and regulatory frameworks lead to changed grid operating regimes that have to be supported by corresponding engineering work that takes the increasingly complex business environment into account.

All demands and requirements presuppose a stable and smoothly functioning transmission system. The synchronous network allows for an optimal interplay between generation and consumption. In the past, the general assumption was for a directional load flow from the power plant via the transmission and distribution system to the customer. The changes in the generation structure occurring as small generating units are added on an increasing scale, and the related more frequent use of power electronics, have modified the traditional structure of load flows. "Frequency" and "synchronicity", two elements of information globally characterising a three-phase electric power system, are influenced by two major effects:

- The increased use of decentralised energy conversion units connected via power converters reduces the rotating mass and thereby the intensity of the "heartbeat of the system" unless a substitute is created through technical means of control.
- The relative coupling capacity available through AC lines for synchronous coupling of the rotating mass reduces as the system load increases.

In future, existing concepts for smart grid use, planning and operation will have to be advanced in order to implement high-performance power transmission at minimum cost and in compliance with all requirements. Besides the classical AC systems, high-voltage direct current (HVDC) systems are increasingly used internationally in both overhead and underground systems. Innovative technologies like gas insulated transmission lines (GIL) or power electronic FACTS devices allow new forms of system extension and optimised system operation.

With the present information paper, the Power Engineering Society (Energietechnische Gesellschaft - ETG) of VDE, the German Association for Electrical, Electronic & Information Technologies, is taking stock of the current status quo and the technological options of energy transmission from the perspective of system operators, manufacturers, industrial associations and science, and provides a structured overview. Besides presenting the current state of the art in AC and DC transmission, the focus is on comparing potential executions as buried or overhead lines. Innovative technologies will be discussed, and assessed with regard to their short- and mid-term applicability. In addition, new planning and engineering approaches to economically efficient system extension, and future options for system management will be highlighted.

Abstract and recommendations

The demands made on power transmission systems in Germany and Europe are increasingly characterised by the European nature of energy markets and geographical shifts of the generation sources, especially as renewable energy use is expanding. Irrespective of the forms of organisation, the ownership situation and the political setting for the system operators, the overriding objective remains to design and operate a transmission system with the highest possible efficiency which meets the criteria of environmental compatibility, acceptance, efficiency, economics and safety in service in an environment of changing requirements. Safe and secure energy supply at adequate prices, and with a low impact on the environment, is a key success factor for Germany as a business location.

The experts of the Power Engineering Society (ETG) of VDE will below describe the current state of the art and technological options for electrical energy transmission from the perspective of system operators, manufacturers, industrial associations and science. Besides related assessments, recommendations will be derived for technological advancement of the transmission system.

- The basic power transmission technology of today and tomorrow is to use **overhead line networks at high and extra-high-voltage level**. This technology allows finding a good compromise between all above-mentioned criteria. Transmission capacities of twice 1800 to 2500 MVA per tower at 400 kV are the standard in Germany. Higher voltages and capacities can be found worldwide. Long-standing experience gathered in installation and operation has led to high safety levels going hand in hand with low costs. Overhead lines with their visual impact have become a firm element of inhabited landscapes. This visual impact may be mitigated with the help of optimised, more compact tower shapes, potentially incorporating new materials, although this may lead to limitations in availability and operations.
- **Buried cable systems** are an alternative that can reduce visibility. At extra-high-voltage level, however, only short stretches of just a few kilometres have been built for special applications, frequently with special laying techniques. No experience has so far been gathered with long-distance buried extra-high-voltage cable systems in meshed systems subject to high fluctuations. Only through pilot installations can initial experience be gathered, so that high safety and availability of the system remain ensured. Because of the high laying expenditure and comparably low transmission capacity up to 1000 MVA, the cost level will at any rate be distinctly higher than for comparable overhead line systems. The visibility of such connections is inevitable, especially in forests because of the requisite protection strips that must be kept largely free of plant growth. The effects caused by electromagnetic fields are, although of the same magnitude like for overhead lines, spatially more concentrated.
- Similar limitations apply to **mixed systems incorporating a share of buried cables**, with additional complexity in installation and operation at the crossover points. To avoid any resulting limitations on system safety, it will again be indispensable to erect pilot installations and gather experience with the components and their operation before full-scale use.

- The application of further innovative technologies must be reviewed in the light of the special requirements made on use in meshed systems and applications over long distances at extra-high-voltage level. **Conductor strand monitoring** is a method that is increasingly used in practice in order to enhance the utilisation of the thermal operating range of overhead lines. The opportunities for enhancing the operating range must be evaluated very carefully in order to rule out any potential danger from locally overheated conductor sections. The potential drawbacks coming with this technique, namely rising losses, lower operating reserves and operational problems caused by high voltage angles and resulting weaker synchronisation, must be carefully weighed against the benefits, and taken into account in engineering and operations.
- The use of **heat-resistant conductors** of different types will initially require gathering more detailed experience with installation and operation. Higher operating temperatures at identical sag allow for higher current-carrying capacity and transmission capacity. This must be compared with losses increasing superproportionately with rising current, and, as above, an increase in voltage angles. Small bending radii, partly brittle material behaviour and changed behaviour at the clamping devices must be taken into account in installation, and reviewed for long-term performance in operations, in order to rule out any risk to human beings and operations. As only little experience has to date been gathered with installation and operations, pilot installations are needed to rule out any risks emanating from the use of this technology.
- An alternative to buried cable systems consists in **gas insulated transmission lines (GIL)**. This technology that was derived from gas insulated switchgear is relatively well-known. The transmission capacity and electrical behaviour are similar to those of overhead lines, so that system integration is relatively simple. The line runs are narrower than for comparable buried cable systems because the capacity is higher. Depending on the respective situation and level of development, this technology requires capital costs similar to those of buried high-voltage lines of comparable capacity. Installation experience is currently being gathered in Germany with a first buried system of slightly under 1 km length.
- A technology that has been tried and tested over many years is **high-voltage direct current transmission (HVDC)** with thyristors. Power transmission over large distances is practiced with this technology in multiple applications around the world. HVDC overhead lines of a capacity of up to 6,400 MW are under construction. Submarine cable runs of up to 1,000 MW capacity are on the point of being started up. Conventional HVDC overhead lines are used to connect asynchronous networks, and are operated in parallel with meshed extra-high-voltage systems.

  Besides the conventional HVDC technology using thyristors, HVDC transmission technology with insulated gate bipolar transistors (IGBT) and much more compact voltage source converters (VSC) is used on the lower capacity range. Such HVDC technology in combination with XLPE cable is especially well-suited for offshore applications. At a transmission capacity of 400 MW, however, the largest ever connection of an offshore wind farm is relatively small-scale in view of a capacity of 1,200 MW being technically feasible at a voltage of ±320 kV. HVDC cable links have advantages over three-phase AC cable connections in long-distance electricity transport, especially over long stretches. The use of HVDC transmission links in a highly meshed three-phase AC network – parallel operation of AC line / HVDC line – has yet to be investigated in practice.

HVDC lines (with thyristors or IGBTs) are generally economically viable over long transmission distances because of the relatively low cost for the HVDC overhead line and lower transmission losses, which more than compensates the high cost of converters and conversion losses. In offshore applications, HVDC lines are usually the only solution on grounds of purely technical reasons.

- The load flows in three-phase AC networks can be influenced by **switched or power electronic-based devices called FACTS**. The need for flexibly usable compensators and power flow controllers is likely to rise steeply. While many executions of these devices are in use worldwide, others have so far only been designed in theory. These devices could frequently allow for more balanced operational use of network sections, an added benefit being higher utilisation rates. Attention must, however, be paid to the fact that this will always mean operation closer towards the stability limits, so that, from the perspective of system engineering, a general increase in transmission capacity will often only be possible to a limited extent, and has to be weighed against the security of service. The cost and benefit of these devices must strictly be judged for each specific application.
- It is conceivable that the existing transmission system will progressively reach the limits of its performance capacity especially as the generation structure is changing. Future transport missions may therefore require **an overlay network** to be created. Its technological implementation will depend on the technical requirements made on the system, and the development potential of the above-described technologies.

Looking beyond the above-mentioned technologies, no revolutionary technology leaps should be expected. Even though today's innovative technologies do in some cases offer benefits in application versus today's overhead lines, experience must be gathered with pilot installations to be able to guarantee the safety and security of the system and operations. Long-term costs of operation, routine attention and maintenance must be determined. Any risk to human beings must be ruled out.

Pilot installations and the expenditure they require for capital investments, planning and engineering, operations, research and development will initially lead to elevated total costs. These, however, must be seen in the light of the benefits achieved, like e.g. lower space consumption by line runs, or reduced visual impact.

In the process of formulating this position paper, it has become evident that the chain of research and development via pilot installations to industrial-scale use has been interrupted in today's world. An idea or technical development will become an innovation only through commercial-scale utilisation. However, the level of support needed to take the step towards innovation with the help of pilot installations is lacking in the current regulatory environment, so that many of the above-stated technologies are awaiting the findings from pilot installations testing applications in meshed systems and systems with volatile operation like in Germany and Western Europe, before full-scale industrial use is possible.

> The authors therefore urgently recommend that the above-mentioned costs of innovative technologies and pilot installations must be recognised by the regulator as an element of the use-of-system charge. This is the only way to create a climate of innovation and new technology, which is the basis for future-proof development of the transmission system in Germany.
>
> Stepping up research and development spending in this area will additionally lead to a considerable advantage for manufacturers and universities in Germany. The participation of system operators in public research projects in Germany and the EU will allow for the results of research and development to be translated into pilot applications. This will accelerate innovation towards commercial use and operation of new technologies.

Looking beyond system technologies, uncertainties regarding future developments and the increasing volatility of operations have come to require new kinds of planning and risk assessment. To prevent a decline in system security, adequate and clearly defined corrective measures must be defined for each and every identified risk. Decisions whether to take operational measures or go for capital spending must be made with the help of probabilistic methods, with economic aspects being taken into due account. Network- and market-related measures as defined in section 13 of the German Energy Industry Act (EnWG) should remain reserved for exceptional cases, and must only be taken if safe and secure functioning of the system is at risk. New planning and assessment methods are available to promote this process.

System extension planning on the basis of just a few deterministic cases of system use will in future be of limited use. Besides the possibility of bottlenecks occurring, the frequency and duration of their occurrence are also of importance. Load flow computations based on the time series of energy-sector market models or probabilistic models offer opportunities to better map the stochastic properties of consumers and generators, and thereby paint a more comprehensive picture of the overall situation in the transmission system. Energy management market models have already become available for use, while probabilistic methods for system computation are still in the process of development.

Considering climatic dependencies between the system load and the system load carrying capacity in the process of system planning allows to use existing degrees of freedom in the loadability of operating resources. However, it must be taken into account that e.g. the above-mentioned technology of conductor strand monitoring allows increases of the transmission capacity on a capacity range of several 100 MW at a certain probability only. Alternative measures must therefore be in store if and when high transmission capacities are required in situations of high ambient temperatures.

Operations are faced with new challenges as the systems will in future be operated ever more frequently and ever more closely to the limits of their load carrying capacity. More complex system monitoring and the automated activation of responses in the event of faults (Defence Plan, special protection schemes) will consequently become an integral element of future system management. To support system management, additional information about the current condition of the system (climate data, voltage angle, neighbouring systems) must be available online in appropriate form, and integrated with an analytical tool. To achieve this, an exchange of information about the current condition of the system, both at the regional and supra-regional levels, must be developed further. Advancing such methods incorporating the use of state-of-the-art measurement, metering and communication technologies is one of the subjects of research.

> Besides pilot testing of the transmission technologies, it is urgently recommended to provide adequate support to the above-mentioned topics for planning and operation by promoting and funding research and development projects of manufacturers, system operators and universities.
>
> On a general note, it is important to recognise that the increased need for transport at a capacity range of several thousand megawatts can first and foremost only be met by extending the network, i.e. by building new extra-high-voltage overhead lines in three-phase AC or DC technology, in order to create the basis for integrating large volumes of renewable energies and flexible market activities.

1 General background and requirements made on the transmission system

This chapter describes the historical development of the transmission system and the modifications the general legal framework has undergone in recent years. The resulting changes will be highlighted.

1.1 Historical development of the grids

In the year 1913, there were approximately 4000 electricity companies in Germany. Nearly all of them worked on a self-sufficient basis, that is without any interconnections among each other. Following plans for 100 kV lines, the first 220 kV line was built in North-South direction in 1922 to connect conventional generation capacity in the Rhineland and in Westphalia with hydro and storage power plants in the Alps. The next objective was to build an interconnected system between the lignite-fired power plants in the Rhineland and Lusatia on the one hand and the hard coal-fired power plants in Westphalia and the Saarland and the hydro power plants in Austria on the other. Especially the available hydropower reserves in Austria were to be harnessed for use in northern Germany. The transmission of the related electrical capacity was to be performed with a 220 kV double-circuit line system including a downstream 110 kV distribution network. It was not until after the Second World War that the 380 kV transmission system in Germany and Europe was further extended and interconnected across borders.

These developments towards system integration were driven by the following four major benefits:

- stochastic balancing of load and generation,
- compensation of faults through immediate aid among the generators,
- achieving a mix of primary energies in generation,
- less power plant reserve capacity required.

On the technical basis of a new, high-performance transmission system, and in the light of the growth prospects of the 1960s, the electric industry had already directed its research and development efforts at voltage levels above 380 kV, and developed and tested corresponding equipment (see Figure 1-1). As the increase in electricity consumption slowed down, it did not become necessary to increase the voltage.

With the construction of nuclear power plants, including in regions without any natural primary energy resources, the focus of the system was now on ensuring the compensation of faults and preserving synchronicity. This guiding principle was also applied in the approval procedure for connection of the five new, former East German states to the European interconnected system in 1990. Transporting large electricity volumes across long distances was not in the focus of planning of the transmission system.

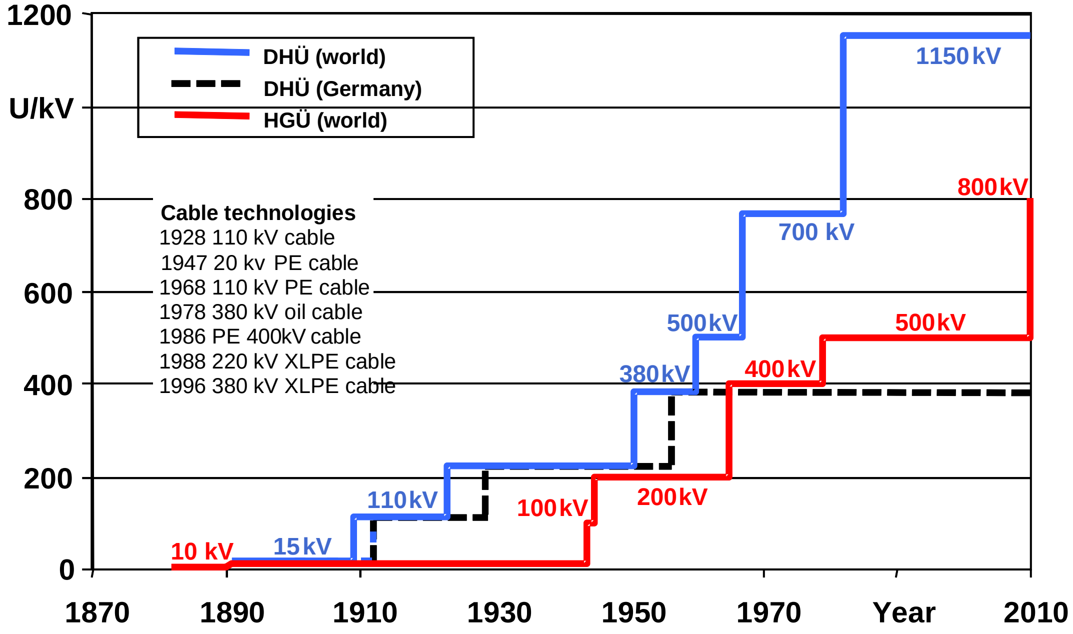


Figure 1-1: Development of voltage levels (DHÜ = three-phase high-voltage transmission =, HGÜ = high voltage direct current transmission); Source: ETG of VDE

1.2 Political and regulatory framework

In view of the high importance of service security for the population, the economy and the industry with regard to the delivery of electrical energy, and to enforce compliance with political and ecological objectives, framework conditions have been set for the extension and operation of electric systems and energy trading. Annex A provides a list of the most important laws pertinent to this, and the operational guidelines derived from them. In a nutshell, the effects on the transmission system of these objectives being enshrined in the law (Annex A. Laws and Directives [1] through [13]) can be summarised as follows:

- Establishment of an electricity market → increasing and volatile power flows; changed structure of the generation pool with regard to primary energy use and spatial distribution
- Subsidising of renewable energies → volatile load flows and feedback from downstream system levels; changed power plant scheduling and control energy needs
- Environmental protection aspects → limitations on the way overhead lines and line runs are designed; changed approach to expanding the power plant pool

These framework conditions have a crucial impact on the extensions and operation of the transmission system:

With electricity market liberalisation being implemented at EU and German level in the 1990s, and the establishment of electricity markets, the scope of long-distance electricity transport within Europe expanded. European energy policies aim at an entirely free, single electricity market. To achieve this, the transmission system - that had to date been dimensioned with a focus on fault clearing – must be developed such that, ideally, no bottlenecks occur within Europe. At the same time, the customers presuppose that the levels of quality and reliability of supply are maintained, and that the electricity system as a whole is managed at high stability, with voltage and frequency bands being complied with.

In Brussels, the “3rd package of energy directives“ has been adopted, dealing, among other things, with strengthening the independence of transmission system operators. Besides ownership unbundling, the alternative of a “third way“ has been allowed. This requires setting up a so-called Independent Transmission Operator, i.e. independent of generation and sales. This means that ownership unbundling of integrated energy supply companies is not absolutely necessary.

Subsidising of the expansion of renewable-based electricity generation is regulated by the Renewable Energies Act (EEG, [7]) in Germany. It has led to changes in the structure of the generation portfolio and power plant pool. In addition to the constantly increasing output of onshore energy generators using renewable energy resources at numerous decentralised locations with small-size plant, large offshore wind farms in the Baltic and North Seas are being erected. The resulting high generation output must be transported to the consumption hotspots in central and southern Germany. An additional challenge is posed by the decision to phase out nuclear energy. It will lead to decommissioning of power plant capacity mostly concentrated in the south. Moreover, the Ordinance on system connection of power plants grants power plant operators the right to choose their new power plant locations, rather than on the basis of the optimal point for grid connection, on grounds of criteria focused on the capital and operating costs of the power plant. This leads to geographical shifts of power plant sites.

In order to speed up the necessary development of the transmission systems, the legislator has adopted the Act on extension of overhead power line connections (EnLAG, [12]). This law incorporates a plan stating the demand for network extension projects. These result mainly from the “dena network study I“ [16] and have been classified as urgent. The law has given binding force to the necessity to build these connections.

1.3 Future requirements made on transmission systems

The changes in energy policies, regulatory frameworks, the general environment in the society and the generation structure require the adaptation of existing transmission systems. The historically developed structure of the transmission systems is not up to the requirements made on future networks. Large-scale works to enlarge and upgrade the systems are necessary.

An essential responsibility of the system operators is to contribute to ensuring that electricity service remains guaranteed to consumers. The high reliability of energy transmission and distribution we have become used to will also be the yardstick for the future and the overarching responsibility of the transmission and distribution system operators. Besides the local focus on service security, each transmission system operator must ensure compliance with the global criterion of system stability of the networks. It must be met at high reliability and quality. Besides managing the energy flows with the help of central operational management systems, particular attention must be paid to the operating resources used. New technologies must be tested in the scope of pilot projects. Particularly high importance must be attached to safe and secure operation, high availability and a stable condition of the system as a whole. Faults in the transmission systems may impact energy supply all over Europe, involving potentially massive adverse economic consequences.

The politically motivated changes in the general business setting, e.g. the unbundling of generation and distribution, the integration of renewable energies into the system and stepped-up international electricity trading, imply that the transportation of electric energy will in future increase in importance. Additionally, the preconditions for network extensions in terms of efficiency, economic viability and ecological aspects must be respected.

The integration of offshore wind energy as well as the shifts in generator locations have it that the transmission systems will in future have to cope with ever-increasing transport tasks coming hand in hand with higher temporal volatility. To meet these requirements, the networks must be adequately extended. In the light of the European legislation on nature conservation (FFH Directives, Natura 2000 areas, protection of species) and its transposition into the German Nature Conservation Act, the responsibility to extend the network as needed represents a formidable challenge. The lack of acceptance of such infrastructure projects among the population represents an additional limiting factor.

The transmission system operators are obliged by the law to extend their systems as needed while preserving the level of system safety and security, furthermore to give priority to taking off and fully integrating the output of renewables-based generators and cogeneration plants, to guarantee non-discriminatory system access and free use of the system for all market players like power plant investors, and to promote the European single electricity market through improved cross-border interoperability.

Some 850 kilometres of new line runs have initially been identified for additional north-south connections [16] necessary for the transmission to consumers especially of wind energy generated in the North and Baltic Seas. The networks have to be extended in compliance with section 43 EnWG (plan approval procedure including public participation). The key extension projects are listed in the EnLAG [12]. System extension represents an essential contribution towards achieving the climate protection goals of the German government and the European Union: the mitigation of carbon emissions by expanding wind electricity generation at the North German coasts and integrating the output into the system. The German government has therefore included the above-mentioned network extension projects in its requirement plan for accelerated extension of extra-high-voltage systems. The envisaged 380 kV three-phase AC projects have to be implemented now in order to not endanger the envisioned (on- and offshore) wind power projects.

In future, the changes in the generation structure and the load situation in Germany will require strong north-south and northeast-southwest transport routes. Additionally, the “dena network study II“ [17], a study that is currently under way and deals especially with the further integration of offshore wind power projects, has scrutinised several innovative technologies with regard to their suitability for increasing transmission capacities. Pilot projects are intended to be run at appropriate locations without endangering the usual level of service security.

In this context, the question is arising what technologies are to be used. The following factors must be considered:

- The technologies must have matured to the point of being applicable to highly loaded power transmission lines; they must be tried and tested, and in accordance with good engineering practice;
- The increase in total costs that may come with the use of new technologies (capital and operating costs, research and development) must be accepted by the regulator and incorporated in the use-of-system charge.

The following key challenges will be faced by policy-makers, system operators and technology developers in the economic, political and social process of structural change of the energy sector:

Political setting:

- The objectives of climate protection and the activities derived, including the harnessing of renewable energy sources and system extensions, must be explained to, and understood by, regional stakeholders.
- A broad basis of acceptance of transmission technologies and the extension of the transmission corridors must be created. This will include that new technologies, operating resources and techniques remain environmentally compatible and in keeping with the strict German legislation in the field of nature conservation.

System analysis:

- Preserving the synchronicity and stability of the network in an environment of increasing electricity transmission volumes and structural changes in the power plant pool;
- Increased, economically efficient use of control energy to smooth out the generation profiles of volatile generators;
- Coordination and control of a permanently increasing number of market players and influence factors on the transmission system;
- Dynamic and static stability, including after potential outages of operating resources essential for transport, and keeping up the ability to act.

Primary/secondary areas:

- The use of new-technology hardware in the energy sector must be justified from a national economy perspective, i.e. besides the capital investment, it must not be allowed to cause overly high routine attention, maintenance and operating costs that would be out of balance with its benefits.

- Today's infrastructure, especially the space taken up by existing line corridors, must be used in the best possible way.
- It must be possible to repair deficient operating resources easily and quickly, even after years. This includes effective stocking of spare parts, the compatibility of connections etc.
- The efficiency of operating resources and system operation must be enhanced through the reduction of capacity losses.

2 Technologies of the transmission system

In three-phase AC transmission in Europe, electric energy is transmitted at a system frequency of 50 Hz. The load flow is split up to the various links on the basis of the impedance ratios between the respective links. In the event of a blackout on a line, these impedance ratios are altered, and the power flows over the respective lines will change. This may lead to overloading of lines. The principles of system planning, engineering and management are designed such as to prevent any impermissible line loading rate (overloading) in the case of a blackout of one operating resource (first contingency or n-1 case) in the operating system. The steady-state frequency is identical in the entire interconnected system. All structures, electric plant and equipment are erected according to the applicable legislation and technical principles and conditions.

The European electricity infrastructure is currently characterised by a high measure of reliability. Both industrial processes and private applications are built on this. And this is an aspiration all customers, power generators and users connected to the electricity system will continue to have into the future. All modifications of the networks must therefore be carefully reviewed and assessed as to what impact they have on reliability. As far as the transmission systems are concerned, this relates in particular to matters of system stability as these may have European-scale rather than regional or national repercussions on the reliability of electricity service.

The technologies described below are situated across a spectrum ranging from basic technologies to innovative concepts. The described overhead lines up to 400 kV and beyond are the most important and cheapest basic technology for power transmission in Germany and Europe. New materials like heat-resistant conductors are still fraught with many question marks regarding their installation and operation, i.e. while they do promise potential for the future, they will have to be carefully tested before full-scale use. Conductor strand monitoring, in contrast, is gaining more and more weight as a practical option in operations, with its limits being sounded out to make sure no safety risks are run.

The use of buried cable is also widespread. However, using underground cable at 400 kV level must be regarded as innovative. The same applies to partly buried stretches of lines combining overhead with buried cable, as many questions have as yet remained unanswered and require testing in pilot installations. Other technologies like high-voltage direct current transmission (HVDC) or gas-insulated transmission lines (GIL), although known for many years, require additional knowledge to be acquired especially as to their application in meshed interconnected systems. Power electronic FACTS devices in different designs are, in some respects, regarded as a standard technology. Some technical concepts, however, have been used just a few times or not at all worldwide, so that a new learning curve is necessary for application in each individual case.

The following sections therefore describe a range of innovative technologies and their individual drawbacks and benefits in planning and engineering, construction and operation.

2.1 Three-phase AC transmission with overhead lines

Basic technology

The basic elements of overhead lines include the towers with their foundations and the overhead line circuits including their insulators. The towers of an overhead line serve as anchor points for the suspension of conductors. They consist of the tower body, the shield wire support, the crossarms (cross beams) and the foundation. The insulator sets are fastened to the crossarms, and the conductors are fastened to the insulator sets. The shield wire support (usually the peak of the tower above the highest crossarm) serves the purpose of fastening the ground conductor required to protect the overhead line from lightning stroke.

Especially the number of electric circuits, their voltage level, the possible distances between towers and the limitations that have to be respected with regard to the width of the right of way or height of the towers are the determinants for the structural shape, type and sizing of the towers. The towers must be dimensioned such as to safely absorb the tensile forces of the conductors used and the additional forces resulting from external loads, especially wind and icing.

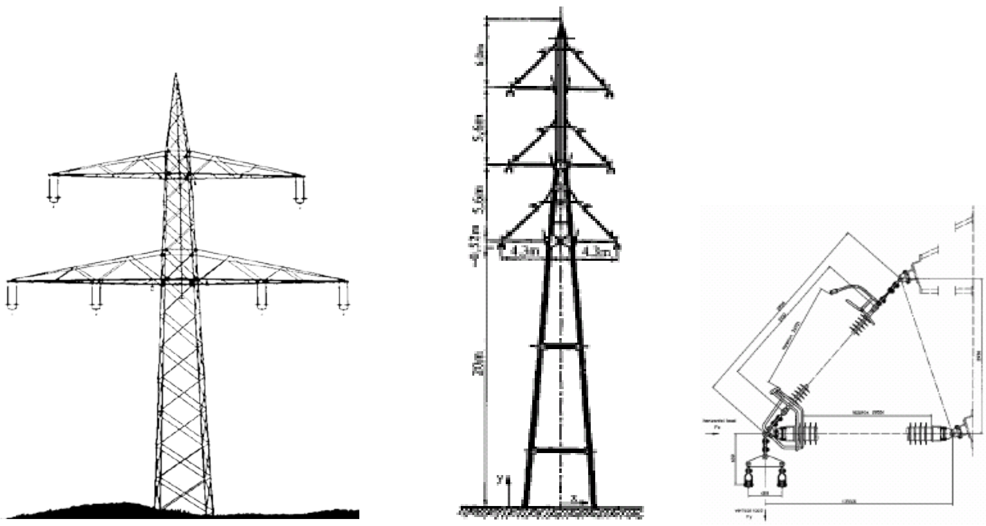
In Germany and Western Europe, the transmission system is operated at a voltage of 380 kV. Each electric circuit consists of three bundled conductors, with each bundled conductor being composed of up to four individual conductors connected by spacers. The most common variant used is bundles of four conductors. The four connected conductors of a four-conductor bundle of 380 kV circuits are composite conductors the core of which today consists of steel wires sheathed with several layers of aluminium wire. The transmission capacity of the system amounts to between 1800 MVA and 2500 MVA.

Besides the current-carrying conductors, a ground conductor (shield wire) providing protection against lightning stroke is suspended at the peaks of the towers. The purpose of the shield wire is to prevent lightning from striking the current-carrying conductors, causing a fault of the affected electric circuit. The shield wire is an aluminium-steel conductor similar to the current-carrying conductors. The lightning stroke current is discharged through the shield wire to the neighbouring towers and from there into the ground.

Generally speaking, a large variety of different shapes of towers is used worldwide. In Germany, the so-called “Danube tower“ is used predominantly (see Figure 3.1). It usually represents the optimum for the conditions prevailing in Germany on technical, economic and aesthetic grounds. These 380 kV overhead line towers are 40 to 60 m high, depending on the type, with a crossbeam projection of approx. 2 x 10 – 15 m. To ensure safe operation, a right of way sized approx. 2 x 40 m is necessary, requiring clearing of plant growth and limits to the height of buildings. In cases where a reduced overall height of the overhead line towers is necessary (e.g. to mitigate the visibility from large distances), single-level towers or short towers may be used.

Because of the limited availability of space for transmission corridors and the debate about the lack of environmental compatibility of overhead lines, efforts have in the past been made time and again to give high-voltage overhead lines a more compact shape. In striving for a more compact design of the lines, a number of aspects want to be taken into account, like magnetic and electric field strengths, changed mechanical stress patterns due to wind loads, limitations on the length of span due to the conductors' characteristics in terms of subsidence of "swing", resulting in a higher number of towers and higher costs, furthermore ageing of composite materials, and distinct limitations on accessibility for maintenance works.

The first measure that can be taken for a more compact design of high-voltage overhead lines is to reduce the phase spacing when using the usual steel lattice design by employing so-called "V-chains" to more or less fasten the phase conductors. Towers in solid web design are an option to further reduce the phase spacing to the lattice structure. As an alternative, portal lattice structures with vertical or horizontal arrangement of the circuits can be used.



(a) (b.1) (b.2)

Figure 2-1: Typical "Danube tower" (a) and compact lines (b.1) with crossarms consisting of composite insulators in triangular design (b.2)

A further opportunity for more compact design is offered by the use of crossarms consisting of composite insulators instead of steel crossarms. Figure 2-1 shows a design with two vertically arranged electric circuits. The conductors are attached to a triangle of composite insulators. With this option, a 380 kV line will be approx. 9 m wide, also reducing the width of the route corridor.

In addition, a more compact structure of the lines can also be achieved by using insulators with short flashover distances. As shortened flashover distances will also reduce the overvoltage withstand capacity of the line, surge voltage protectors have to be installed in parallel with the insulators. The surge arresters that are usually equipped with composite insulators can limit the lightning overvoltage occurring on a line, and reduce the fault frequency. For economic reasons, only line sections particularly exposed to lightning strokes can be equipped with surge arresters.

Although compact line design is standard engineering practice, it has in Germany only been used for special applications because of the above-mentioned drawbacks.

When electrical energy is transmitted, electric and magnetic fields occur in the immediate vicinity of live current-carrying operating resources (buried cable, overhead headlines, transformation equipment etc.). In the current transmission technology environment, these are low-frequency alternating fields with a frequency of 50 Hz. Both existing and future technologies must respect the applicable emission consent limits for electric and magnetic fields. The requirements laid down in the German environmental pollution prevention legislation (26th BImSchV [13]) are applicable to 50 Hz fields.

An environmental impact of a different kind comes from noises that can be sensed as a humming noise in the surroundings of transformation equipment, or as high-frequency corona noise occurring around overhead lines audible in rare weather situations. Noise emissions, too, are subject to consent limits in the surroundings of residential developments, as laid down in the "Technical Guideline on Noise" *(Technische Anleitung Lärm - TA Lärm)*. Existing and future transmission technologies must meet these requirements.

Projects implemented and experience gathered to date

Overhead lines have to date been the most well-proven transmission technology in extra-high-voltage engineering, with extensive operating experience having been gathered with them. 380 kV overhead lines have been planned and built since the 1930s. On aggregate, Europe has some 220,000 circuit kilometres of extra high-voltage overhead lines (220 kV and 380 kV lines). They permit synchronous interconnected operation and ensure the level of service quality in the interconnected grid to which we have become used today. Faults are quickly recognised and can usually be remedied at very short notice.

This technology is characterised by a relatively simple structure and the use of air as an insulating medium, with self-healing properties in many kinds of faults. It has therefore become the standard choice worldwide. Overhead lines boast long service lives of approx. 80 to 100 years, with conductors having to be replaced after approx. 40 years.

Costs

An overhead line of the classic type (designed for two 380 kV electric circuits with a transmission capacity of 2000 - 3000 MW each) will incur capital costs of approx € 1 million per km.

Medium-term development steps (<5 years)

Extra-high-voltage overhead lines have been developed to nearly full technical maturity, and no major development steps are to be expected on a medium-term basis. Current efforts focus on the extent to which conductor strand monitoring (see chapter 2.6) and heat-resistant conductors (see chapter 2.5) can be employed on a medium-term basis. Long-term development potential resides in improvements of the conductor systems, accessories, of the visibility for avifauna through special ground conductor marking etc. Expanding transmission to multi-conductor solutions with more than three outer conductors could also be contemplated.

Benefits

A high availability of overhead lines can be achieved by safely and quickly recognising the vast majority of faults occurring in a system (one-line-to-ground faults) and remedying them with the help of automatic reclosing, i.e. single-pole disconnection that is of very short duration so that it goes unnoticed by the customer and does not cause any interruption in service.

Because of aboveground installation, all components are easily accessible, leading to short repair periods in the event of outages. Overhead lines lend themselves well to airborne inspection and allow easy locating of faults.

As the air cooling effect is usually very good, overhead lines can be operated across a relatively wide temperature range, and will quickly cool after heating up for a limited period of time. This means temporary overloading of up to several tens of minutes are acceptable in operations.

Limitations

The visibility of overhead lines leads to limited acceptance, depending on the nature of the surrounding landscape.

Compact lines feature increased material stress, limited accessibility for live maintenance works, and a higher probability of outages.

2.2 Three-phase AC transmission with buried cable

Basic technology

Generally speaking, cable types suitable for undergrounding extra-high-voltage lines are available. They consist of an inner copper conductor separated from the cable shield by an insulating layer made of cross-linked polyethylene (XLPE). Another option used is mass-impregnated cable with oil-impregnated paper being employed as an insulating medium. This type of cable, however, is no longer used in new installations except for HVDC lines. Purely oil-insulated cable or external pressure gas cable systems are no longer built today. Still, a few buried cable systems of this type are still in operation.

As only a limited cable length will fit onto a drum, the cable sections must be connected with so-called splices. In order to create balanced electrical conditions along the cable with regard to the three phases, cross-bonding of the cable shields is required at the places where the splices are located. Such splices are quite complex structures and therefore require walk-in junction boxes. Buried cable systems usually include reactive power compensation equipment in order to keep the voltage level up at varying working points. Such compensation equipment consists of special units that have to be installed in intervals of approx. 30 - 50 km along the cable route.

The condition of the soil in which the cable is laid largely determines how the thermal losses of the cable can be discharged into the ground. This forms the basis for deriving the ampacity of the cable system such that damage to the cable by overheating is prevented.

A cable system with three single-conductor cables 2500 mm² can usually transmit a capacity of 1000 MVA without any additional cooling. In order to replace a 380 kV overhead line system, at least two 380 kV buried cable systems will be needed for the same capacity to be transmitted. In order to bury one 380 kV overhead line with two three-phase AC systems, one would therefore need four 380 kV buried cable systems with three phases each (4 x 3 x 2500 mm²). Because of the thermal load at a design current of 2700 amps, this would, according to current assessments, require a cable trench of approx. 15 m width (approx. 2 m depth). After adding in a working strip, the total width will be up to 40 m. Variations may well occur at crossing points with other utility lines.

In certain geographic situations, like buried cable systems being installed in mountainous regions, variations over these figures may become necessary. If, additionally, a 380 kV buried cable connection is sized for a current of 3600 A, wider cable corridors will be needed because of the necessary thermal decoupling in rocky soils. Here, a 20m width of the cable bed must be expected. Furthermore, it must be lastingly ensured that no roots grow into the cable bed in woodlands. This requires an additional 5 m wide lateral strip on each side in forests.

In the medium voltage (MV) distribution system, the heavy intraday fluctuations in the load profile are taken into account in sizing buried cable systems for the respective transmission capacity, so that MV buried cables are dimensioned for a load factor of 0.7. A similar approach is not permissible for buried cable systems in the extra-high-voltage system. Today's structure of the tasks of a transmission system requires sizing for extended periods of maximum loading. This must be taken into account especially in dimensioning. As opposed to overhead lines, buried cable requires a much longer time to cool because of its thermal properties in overload situations.

A buried cable system can be monitored with the help of diagnostic checks and suitable monitoring systems (see chapter 2.6) to detect potential fault situations at an early point in time. This includes partial discharge measurements at the splice boxes and cable sealing boxes, and temperature monitoring with the help of fibre-optic cable inside the power cable, or discrete temperature sensors to assess the maximum loadability.

Projects implemented and experience gathered to date

Buried cable systems up to 110 kV, sometimes 220 kV, are quite common today. XLPE cable is preferred for these uses. In some isolated cases, oil pressure cable and external pressure gas cable is still in use. No extensive operating experience has to date been gathered with 380 kV buried cable in interconnected systems either in Germany or internationally. Current installations are limited to a few kilometres dedicated to special applications. As a result of provisions contained in the EnLAG law [12], some buried cable sections can in future be built in Germany on pilot stretches. This is where corresponding operating experience is to be gathered.

Table 3.1 provides an overview of the 380 kV XLPE cable systems used in Europe to date. It should be borne in mind that many of these buried cables have been installed in special tunnels, feature partly small cross-sections, and are usually not operated close to the limits of their loadability. This is why the operating experience is only to a limited extent applicable to the use of buried cable in a meshed extra-high-voltage system.

Table 3.1: 380 kV XLPE buried cable systems in Europe

Country	Route	Number of systems	Length of section (km)	Type of laying	Cable cross section (mm²)	Capacity per system (MVA)	Commissioned
D	Berlin	2	6.3 5.2	Ventilated tunnel	1600	1100	1998 2000
E	Madrid Airport	2	12.8	Ventilated tunnel	2500	1390 (winter) 1720 (summer)	2005
DK	Copenh. (city cable)	1 1	22 14	Buried	1600	975 800	1997 1999
UK	London Connection (city cable)	1	20	Ventilated tunnel	2500	1600	2004
DK	Aarhus-Aalborg	2	14.5	Buried (three sections)	1200 (Alu)	500	2004
I	Turbigo-Rho	2	8.4	Buried	2000	1050	2006
A	Northern feeder, Vienna	2	5.2	Buried, cooling possible	1200	620 cooled 1040 no cooling	2006
NL	Rhine crossing near Rotterdam	2	2.2	Duct	1600	1000	Under construction

Costs

The costs of buried cable systems vary a lot as a result of the differences in local conditions, especially in the soil texture and related civil engineering costs. It can be reasonably assumed that the capital cost for 380 kV buried cable systems including the required compensation equipment is four to 10 times higher than for overhead lines of a comparable transmission capacity.

The total losses of a transmission line depend on the dimensioning and utilisation rate of the cable system in question, and have to be assessed on a case-by-case basis.

Medium-term development steps (<5 years)

Development works to advance the XLPE cable technology and accessory components like splice or cable sealing boxes are under way, so that the assumption appears justified that the service life will increase, and the susceptibility to faults will reduce. If demand is adequate, the production workflows are expected to improve, leading to higher quality and lower costs of production.

Benefits

Once laid, buried cable is practically maintenance-free. Maintenance works, however, are required for the compensating devices etc.

With burying of the cable, limited visibility of the power line is achieved, except for the necessarily visible right of way.

While the magnetic fields are of the same magnitude like those of overhead lines, they are more concentrated in space.

Burying cables offers much better protection against impacts from the environment (icing, lightning stroke etc.) in comparison with overhead lines. This leads to a reduced frequency of faults.

Limitations

The construction of buried cable systems is comparably costly. The interventions in natural habitats and landscapes necessary to construct the cable tray are of a major scope. The right of way must be kept free of any buildings and deep-growing plants. Because of the phase-to-earth capacitance being higher in three-phase AC buried cable sections, a compensating device is required every 30 to 50 km. Every 600 to 1000 m, junction boxes with complex field control systems are needed, which are technically intricate and must be installed on site with an extremely high degree of care.

Any fault occurring during operation will lead to much longer repair periods as new cable joints will have to be made. Extended non-availability in the event of a fault will be the consequence. Many cable faults are caused by third parties (e.g. excavators).

In operations, it is important to safely prevent any overheating of cables as a result of overloading. Accordingly, a sufficient operating reserve must be taken into account for buried cable used in meshed systems, or additional elements controlling the power flows must be provided to contain the transmission capacity (see chapter 2.8).

2.3 Use of buried cable for individual sections of transmission lines

An overhead transmission line with one or more buried cable sections could be called a hybrid line. In the light of the increasing relevance of this mode of execution, its most important aspects will be discussed below.

Basic technology

The basic technology is analogous to the technology of overhead lines and buried cable, respectively. However, special requirements must be posed on power system protection and overvoltage protection when engineering a hybrid line.

On an overhead-only transmission line, faults caused e.g. by lightning, bird droppings or short contact with branches etc. are remedied by automatic disconnection and reclosure of the affected phase without any interruption in supply occurring. This method cannot be copied to a hybrid line with buried cable sections, as phase-to-earth faults in cable always include an insulation breakdown that will not be self-healing. For cable sections of an overhead transmission line run, three methods for protection can be considered:

- Separate zone of protection for each section: Upon response of a protective device, the zone will be localised where the response was caused. In response, either a phase-to-earth automatic reclosure is performed if the fault is located on an overhead section, or a disconnection in three poles is performed.
- A single zone of protection for the entire line run; upon response of a protective device, a disconnection in three poles is performed.
- A single zone of protection for the entire line run; upon a phase-to-earth response, a phase-to-earth autoreclosure is performed, with major damage to the cable being possible.

Furthermore, overvoltage protection must be carefully analysed. If, for example, travelling surges occur on the transmission line e.g. as a result of a lightning stroke, this will cause overvoltage at the points of transition from the cable to the overhead line (transition from solid dielectric to air insulation) as a result of refraction and partial reflection. As the surge impedance levels of buried cable and overhead lines differ at a ratio of 1:10 (cable: approx. 35 ohms, overhead line: approx. 350 ohms), these reflections and refractions can be substantial and lead to very high overvoltage. This is why it makes sense to analyse the planned overvoltage protection measures for each single application. This must be done in the context of material testing and testing of the cable sealing boxes. Furthermore, additional measures for protection of the cable sealing boxes must be considered, potentially in the form of enclosures for the transition points.

Benefits

The benefit of this type of construction is that it allows for line runs to meet with a higher level of acceptance on the side of the local residents at a reasonable cost/benefit ratio, i.e. cost reductions due to the shorter total length of underground stretches.

Limitations

Besides special attention having to be paid to power system and overvoltage protection, the same limitations like in non-hybrid buried cable systems or overhead line systems are applicable.

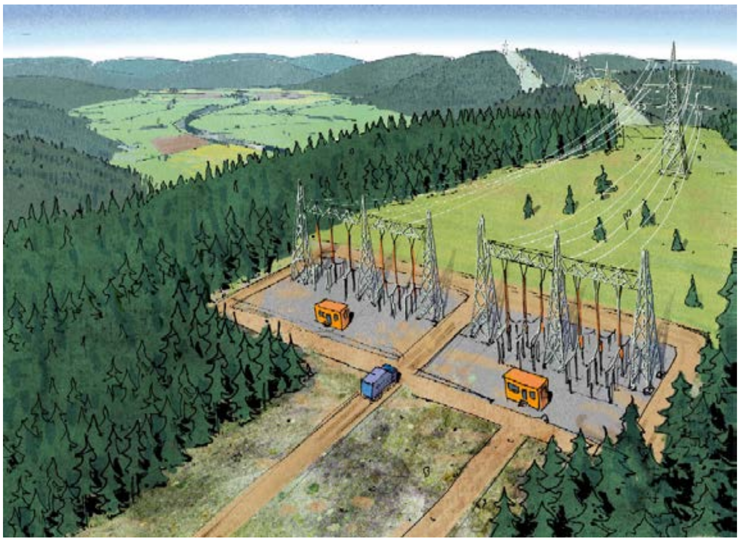


Figure 2-2: Example of a structure for transition of an overhead line to a four-circuit transmission line

2.4 Gas-insulated transmission lines

Basic technology

Gas insulated transmission lines (GIL) use an insulating gas mixture made up of nitrogen and SF_6. Gas-insulated lines in the extra-high-voltage system consist of an aluminium conductor tube and a seamlessly welded, gas-tight aluminium enclosing tube. The insulating medium used is a gas mixture consisting of 20% SF_6 gas and 80% nitrogen. The tube system itself has sealed-off partial sections (every 20 to 1200 m) so that only part of the gas mixture is lost in the event of damage, and to enable partial evacuation and refilling for maintenance works. This helps minimise the environmental impact of a spill of SF_6, an insulating and greenhouse gas that is harmless for humans. The GIL technology is suitable for burying or laying in a tunnel. In the case of burying, the right of way will roughly have to be 7 m wide.

Because of the very low impedance of GIL, long GIL lines in an interconnected system may require use of a series compensation device or load flow controls to prevent overloading of the GIL. As a rule, however, the GIL technology will only be used for relatively short line sections, so that the impedance of the transmission route as a whole will not change substantially.

Figure 2-3: Cross-section of a GIL conductor tube

Examples of previous executions, and operating experience

Systems built in the 1970s are still working smoothly today. The world's first GIL working with a gas mixture filling was built in 2001 for Palexpo in Geneva, Switzerland. At the Frankfurt airport, approx. 1 km of an existing extra-high-voltage overhead line is being converted to a buried GIL (to be commissioned in 2010) in the scope of a pilot project. In China, GIL are under construction at several storage dams. The service life of GIL has been calculated to be at least 50 years.

Table 2-1: GIL projects in German-speaking countries

Country	Location	Number of systems	Length of the route (km)	Type of laying	Capacity per system (MVA)	Commis-sioned
Germany	Frankfurt airport	2	0.9	Buried	1800	2010
Germany	Wehr pumped-storage power plant	2	0.7	In tunnel	1400	1976
Switzerland	Geneva fair-grounds	2	0.45	In tunnel	760	2001

Costs

Although the costs of a GIL installation are way above the cost of an overhead line of identical capacity (roughly the six- to twelvefold amount), they are competitive in comparison with buried cable for high-capacity transmission applications.

Planned medium-term development steps (<5 years)

GIL have technically been largely perfected. Mid-term leaps forward in development can be expected in laying technology. While laying has so far been restricted to tunnels, direct burial is another development step that has the potential to lead up to applications in connecting offshore wind farm clusters to electricity systems ashore.

Benefits

In comparison with XLPE cable, GIL have a distinctly higher transmission capacity, reaching, at 3000 MVA, the range of overhead transmission lines. This implies narrower transmission corridors than for XLPE cable. The technology is also suitable for relatively long sections of line, and may make sense in applications where high transmission capacities are required while overhead lines are not feasible. In addition, GIL lines can be routed over any terrain, including steep inclines or vertical sections. As opposed to buried cable, relatively long stretches are possible without any reactive power compensation.

GIL have operating characteristics similar to those of overhead lines. Even automatic reclosing following failure events is possible, i.e. in the case of a flashover on a GIL, extinction of the arc will usually come automatically in the event of short interruptions, and the GIL will go back to its original dielectric strength.

Limitations

Because of the costly construction design, GIL is usually only used over few kilometres, e.g. to connect up load centres and conurbations.

No operating experience has yet been gathered with very long GIL stretches in parallel with, or interconnected with, existing overhead line connections in a closely meshed 380 kV system.

In the case of failure events on a GIL, maintenance works will become necessary.

The SF_6 gas requires very careful handling to prevent it from being released into the environment, because it is a non-toxic greenhouse gas. Its handling is state-of-the-art as gas insulated switchgear is widely used.

2.5 Heat-resistant conductors

Basic technology

The use of heat-resistant (hot) conductor strands is a way to increase the transmission capacity of existing overhead lines. They are stranded conductors for overhead lines that can cope with elevated conductor temperatures without damage. The safety of persons and systems, however, must be ensured at any time. Generally speaking, there are two kinds of hot conductors.

The first type (conventional temperature-resistant conductors, so-called TAL) are no different from standard stranded conductors in terms of their cable design. However, the materials used are treated such that they can resist distinctly higher conductor temperatures. The sag of these conductors is higher than in standard conductors at high conductor temperatures, which means existing towers may have to be increased in height, or the structural design of the towers has to be adapted because of increased conductor tension.

The design of the second type is different from standard conductors. The conductor strand has a gap between the core of the conducting strand and the actual conductor material surrounding the conductor core. The strands are anchored at the conductor core only, so that the material of the core is the sole determinant for the expansion properties at elevated temperatures. The materials are selected such that no increased sag will occur at high temperatures. High temperature conductors like ACCC (hybrid carbon and glass fibre core) and ACCR (core made of ceramic fibre aluminium composite material) are not used as a standard technology in Germany and Europe today.

The second type requires special accessories which are currently available from US American suppliers based on US American standards. Development joint ventures with German suppliers are under way, so that no bottleneck is to be expected in this field in future. However, it should be taken into account that there is no consistent German or European standardisation in place for all components of this conductor system, especially with regard to the required tests.

Examples of previous executions, and operating experience

Hot conductors of the ACCC and ACCR types are not yet in use in Germany. At the moment, tests using GAP conductors, ACCR and ACCC conductors and TAL conductors are under way. The installation and operating characteristics are to be investigated in the scope of the above-mentioned pilot trials. Following successful completion of the pilot projects, hot conductors will, in principle, be available for further use in transmission systems.

Applications outside Europe

The conductor types in use in Japan are, rather than being utilised to full capacity, only envisaged for use in special situations (earthquakes). This means there is no experience with high utilisation rates during normal operation.

Costs

Stranded conductor costs exceed the costs of standard conductors by 1.1 to 6 times. Additional costs have to be expected due to more complicated accessories and higher costs of installation.

Planned medium-term development steps

Potential applications will have to be identified on the basis of the results of the pilot trials. The technical, economic and regulatory setting will be key factors determining what applications are meaningful. An overview of currently available hot conductors including their benefits and drawbacks will be included in the “dena network study II“ [17] that is currently being drafted.

Benefits

Heat-resistant stranded conductors permit increased transmission capacities without increasing the conductor cross-section. This, however, also represents a disadvantage: Because of the quadratic dependence on current, losses will see a distinct increase. This effect wants to be assessed, not just in terms of cost.

Limitations

Conductor systems consisting of conductor strands, accessories and insulators are not consistently standardised for operating temperatures above 80°C. Ceramics conductors may be fractured due to cable oscillation. Softening might occur at high conductor temperatures (150°C) in glass-fibre cores impregnated with epoxy resin. Whether equipping existing overhead lines with new conductors is preferable over a newbuild line featuring high-current conductors must be checked from regulatory, technical and economic angles. In particular, an answer must be found to the question whether full-scale use of high-ampacity conductors might not have a detrimental impact on system stability.

2.6 Conductor strand monitoring

Technology description

The relevant standard DIN EN 50182 “Conductors for overhead lines“, Annex F, states maximum continuous current-carrying capacities for standard executions of stranded conductors. The indicated values relate to the following ambient conditions:

- ambient temperature of 35°C
- insolation of 900 W/m²
- wind speed of 0.6 m/s
- vertical angle of wind attack
- final conductor temperature of 80°C.

The current-carrying capacity of the conductor strand is limited by its maximum permissible operating temperature. The current operating temperature depends, besides on the current carried, also on the prevailing weather conditions.

With conductor strand monitoring, transmission capacities of overhead lines can be reached that deviate from the above-stated ambient conditions and are oriented to the maximum permissible conductor strand temperature. This requires, on the one hand, an adequate set of measuring instruments to record the conductor strand temperature, and on the other, mapping of the current-carrying capacity - that, instead of being constant, now depends on the weather – in the control system.

There are basically two methods available to record the conductor strand temperature:

- Direct measurement at the operating resource by way of
  - Load cells for measurement of tensile stress
  - Optical fibres integrated in the conductor strand
  - SAW sensors on conductor strands
  - Active temperature sensors on conductor strands
  - Determining the temperature based on PMU measurements
- Indirect determination of the strand temperature using weather data (e.g. ambient temperature, wind velocity, wind direction)

Previous experience / development steps

Screening of the investigations conducted to date suggests that utilising the weather-related current-carrying capacity in system operations is technically feasible, in particular to manage network situations of temporarily high load flows. The focus is on operational use of the temperature-dependent current-carrying capacities.

To be able to use the weather conditions for planning purposes, a supra-regional map indicating the potential for current-carrying capacities of overhead lines in a high-wind scenario has been derived [17]:

- North and east German coastal area 150%
- North and Central Germany up to the line of the low mountain ranges 130%
- Remaining areas 115%

At the transition lines between the regions with the indicated potential, detailed analyses must be carried out for dimensioning overhead lines.

Costs

The costs will crucially depend on the kind of monitoring used. If the overload capability is, rather than by direct measurements on the conductor strand, determined by way of suitable modelling, i.e. by capturing regional weather data and transmitting them to a control system that has to be adapted for this purpose, the costs for the required infrastructure and adaptation of the control system must be considered. If, however, the conductor strand temperature is to be recorded directly, the critical sections of the line in question (e.g. wind shading in forest aisles, different angles of the line sections to the main wind direction etc.) must be determined, and the measuring instruments plus the accessory hardware for data transmission to the control system have to be installed. The number of measurement locations and the installation work can be quite costly depending on the line in question, so that the cost/benefit ratio can only be assessed for each specific project.

Benefits

The weather-dependent utilisation of the existing conductor strand cross sections permits higher transmission capacities, although only temporarily as a function of the weather. This, however, also represents a disadvantage: Because of the quadratic dependence on current, losses will see a distinct increase. This effect wants to be assessed, not just in terms of cost.

Limitations

Additions to, or deductions from, the above-mentioned current-carrying capacities must be determined by assessing each specific overhead line based on its routing and its local and technical specifics. As the transmission capacity of connections equipped with temperature monitoring facility depends on the weather, it is safely available only to a certain limit. This limitation must be taken into account in planning and operation.

Any application of conductor strand monitoring will, however, require a comprehensive set of tests in view of reinforcement of the transmission lines and use of this method in operations. It will have to be reviewed whether the increased need for transmission capacity can indeed be met with an additional, temporary increase in critical loading.

2.7 High-voltage direct current transmission (HVDC)

Technology description

In high-voltage direct current transmission, three-phase current is first rectified, then transmitted and finally converted into three-phase current again. Rectification and inversion at the ends of the transmission length are performed in so-called converter stations. For electricity transmission, underground cables and - particularly where transmission capacities are high - overhead lines are used.

No reactive power is needed to operate direct current lines (whether underground or overhead lines); only the active power is transmitted. The electric and magnetic fields in the vicinity of direct current lines are way below the field strengths recommended by e.g. the International Commission on Non-Ionising Radiation Protection (ICNIRP 2009).

The controllability of power converters allows for prompt changes of the transmission capacity independently of what is going on in the surrounding three-phase current networks. Two different power converter technologies are today available for conversion.

Classic HVDC

The classic HVDC set-up consists of line-commutated converters with a DC link. Power thyristors (thyristor valves) are used which can be switched on but not off. This disadvantage is accepted as it comes with the benefit that power converter circuits can be set up in a three-phase current network which are particularly simple and economical for high capacities. Converters of classic design usually require reactive power during operation (approx. 50 – 60% of the transmitted active power) which must be made available by the surrounding three-phase current system. This means a constant-voltage three-phase system is required for HVDC operation. As an alternative, capacitors can be installed in addition to the harmonics filters which are needed anyway. This will of course lead to more space being taken up by the converter stations. The losses of line-commutated converters presently amount to 0.7% per converter.

VSC HVDC

VSC HVDC is based on self-commutated converters with a DC link (VSC - Voltage Source Converter). Insulated gate bipolar transistors (IGBT) are used here. These valves can be switched on and off in response to corresponding control signals. Various methods can be used for triggering.

In contrast to classic HVDC, reactive power input and output can be controlled independently of the active power flow in VSC HVDC. As VSC HVDC requires a distinctly reduced effort for harmonics filtering vs. classic HVDC, the converter stations take up much less space. Reversal of the power flow is performed by reversal of the current direction, which means XLPE cable can be used for transmission.

Projects implemented and experience gathered to date

Classic HVDC

The power range of classic HVDC today extends from 300 to 6,400 MW at voltages of up to ±800 kV (so-called ultra-HVDC).

Onshore transmission is usually performed with DC overhead lines. Where underground cables are used for transmission, mass-impregnated cable (MI cable) is today manufactured up to voltages of ±500 kV. XLPE cable is not used in classic HVDC because of the voltage reversal upon power direction reversal. Table 1 shows some project examples for classic HVDC. Worldwide, over 90 projects have been implemented, with an aggregate installed capacity of nearly 80,000 MW. In Europe, HVDC has (except for the use of back-to-back links) so far only been used for submarine cable connections because of the usually relatively short transmission distances.

Table 2-2 Project examples of classic HVDC

	Line length [km]	Voltage [kV]	Overhead line / buried cable	Capacity [MW]	Commissioned
China	2,000	±800	Overhead line	6,400	2010
Brazil	2,500	±600	Overhead line	3,150	2012
Germany – Sweden	250	±450	Submarine cable	600	1994
Norway – Nether-lands	580	±450	Submarine cable	700	2008

VSC HVDC

The power range of VSC HVDC today extends from 50 to 1,200 MW at voltages up to ±320 kV.

Electricity is usually transmitted with XLPE underground cable. Transmission via overhead links is also possible. XLPE DC cable up to a voltage of ±320 kV and conductor cross-sections for aluminium up to 3,000 mm^2 is available today. Mass-impregnated cable can also be used.

The first VSC HVDC was commissioned in Sweden in 1997. Worldwide, nine systems are in operation, and another five systems are under construction. Table 2 shows a few project examples for VSC HVDC.

Table 2-3 VSC HVDC project examples

	Line length [km]	Voltage [kV]	Overhead line / buried cable	Capacity [MW]	Commissioned
Australia	180	±150	Onshore buried cable	220	2002
Estonia – Finland	105	±150	Submarine cable	350	2006
Namibia	970	±350	Overhead line	300	2009
Germany (off-shore wind farm)	200	±150	Submarine/onshore cable	400	2009
San Francis-co Bay	85	200	Submarine cable	400	2009

Costs

As the costs of an HVDC link depend very much on the respective transmission task, it is very difficult to give a general indication of the costs.

The costs of a direct current line (whether overhead or underground) are, at identical transmitted capacity, below those of an AC line because of lower losses, material savings and the compact construction design. Additionally, however, the costs of the converter stations must be taken into account, so that three-phase AC transmission is more economical for short transmission distances.

However, the longer the transmission distance is, the more will the savings for the direct current line outweigh the additional cost of the converter stations. The break-even point for a classic HVDC overhead line is usually at a transmission length of 800 to 1,200 km [CIGRE Report 388, August 2009]. Above this transmission length, an HVDC solution will be more economical. Below this transmission length, the factor by which the cost has to be multiplied will, depending on the transmission task, vary between two and seven in comparison with an equivalent 380 kV three-phase AC overhead line solution. In comparison with 380 kV three-phase underground cabling, the costs of an HVDC buried cable solution are of the same magnitude for shorter stretches, or lower if the distances are longer. Especially in the case of VSC HVDC, the stabilising and loss-reducing effect on the surrounding three-phase system must be included in the assessment.

HVDC multi-terminal systems

Branches in a DC system are only possible with additional converters, leading to so-called HVDC multi-terminal systems. In classic HVDC, however, multi-terminal operation is highly complex. This is why the projects implemented to date have no more than three terminals. With the VSC HVDC technology, it is easier to set up a multi-terminal system. In this case, the number of terminals is unlimited. The respective converter stations may both feed power into the DC voltage link or draw power from the latter.

Medium-term development steps (<5 years)

Classic HVDC

A major development step towards higher transmission capacities at lower losses has only just been taken with the implementation of an operating voltage of ±800 kV. The five years to come will especially see basic research into 1000 kV systems in focus.

VSC HVDC

In VSC HVDC, higher transmission voltages, and hence higher transmission capacities, have been enabled by the use of new IGBT modules, which will additionally reduce the conversion losses in VSC HVDC from the current 1.6% to a maximum 1% per converter station. XLPE cable will also be available for voltages of ±500 kV, so that a transmission capacity of approx. 1,700 MW per cable system can be expected.

The probably most exciting prospects for VSC HVDC reside in the possibility to form systems with several terminals. At the moment, the CIGRÉ working party B4.52 is working on an HVDC grid feasibility study than is due to be published in April 2012. It is meant to create the basis for the construction of direct current power systems.

Benefits

HVDC is particularly suitable for high-capacity transmission across long distances (over 600 – 800 km). HVDC also offers the opportunity to influence the surrounding three-phase system by way of the controllability of load flows. A further major advantage of this method is that an HVDC link cannot be overloaded.

VSC HVDC is additionally distinguished by the fact that active and reactive power can be regulated very quickly and separately from each other. It can make the full reactive power available within an extremely short period of time (approx. 100 ms) after occurrence of a fault, thereby making an important contribution to stability of the transmission system. In addition, operation connected to low-power three-phase systems with low fault power, and the connection to separate networks are possible. This converter technology also affords black start capability.

Where direct current is used, no dielectric losses will occur in the cable insulation, and no eddy currents occur in the cable shield and armouring, which means there will be no additional heating-up of the cable. DC transmission therefore incurs fewer losses than three-phase AC transmission if just the transmission length is considered. However, the losses at the converters must also be taken into account.

The length of the transmission link is only limited by the ohmic resistance of the conductor, which means there is practically no limitation on the length for practical applications. Direct current transmission requires only two conductors per circuit. At identical expenses for conductor materials and installation, a DC link can transmit a capacity distinctly higher than a comparable AC line. No cross-bonding of cable shields is required.

Limitations

A key drawback of an HVDC consists in the basic costs of the rectifier/converter stations at the ends of the transmission link. In addition, multi-terminal systems are only feasible if additional power converters are used, which leads to higher investment costs and larger footprints than for three-phase technology. To build up a DC network, DC breakers are needed, which are still in the process of being developed for the voltages under consideration.

2.8 FACTS

Technology description

The load flow in a three-phase system is determined by the impedances of the branches to each other. Switched compensators or control elements, and power electronic FACT systems (Flexible AC Transmission Systems) afford the opportunity to influence impedances in a targeted manner. A distinction is made between phase-shifting devices and series components. An overview of usable devices and their mode of action is provided in Figure 2-3.

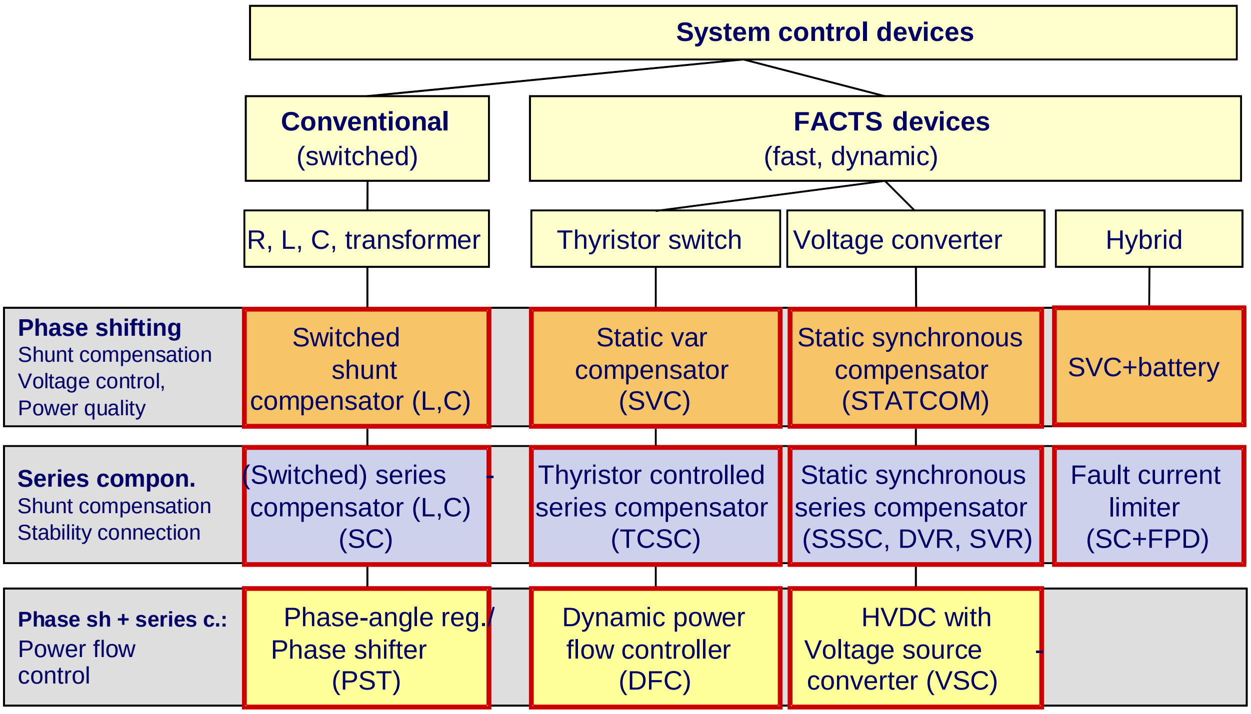


Figure 2-3: Overview of FACTS systems

The conventionally switched components are either phase-shifting devices or series compensators. Capacitors or inductors are connected or disconnected with the help of load breakers. Combined use of parallel and series devices is possible by way of a phase-angle regulating transformer. Where more frequent, faster or better controlled switching is desired, power electronics will be used. Special thyristor circuits are used in SVC or TCSC. DFC is a combination of a phase-angle regulating transformer and thyristor-controlled series inductors and/or series capacitors. Where voltage controlled converters are used, an extremely fast and continuous response to the network is possible. VSC is again employed here, as it can control both the power flow and voltage at both ends independently of each other, and therefore has a stabilising effect on all system variables. Special variants result from combination with batteries, or as a fault current limiter.

Applications to date

Conventional phase-shifting devices, or systems designed as SVC and STATCOM, have been in operation worldwide in hundreds of cases for years, and are regarded as a state-of-the-art technology. However, STATCOMs are mostly used for voltage support at major industrial sites.

Series compensators designed as SC or TCSC in international applications mostly serve the purpose of improving the stability of very long transmission links. While TCSC are well established in the market, they have only been installed in the scope of altogether about 10 applications. The remaining series compensators can only be found in research or pilot applications. Phase-angle regulators are state-of-the-art. The same applies to HVDC with voltage link up to a capacity class of 400 MW (for further details, see section on HVDC). While DFCs are in supply, they have not yet been installed. They are composed of established phase-angle regulators and SVC components.

Medium-term development steps (< 5 years)

The further development of HVDC technology with voltage link will also be a driver for the development of STATCOMs. Particularly the higher capacity classes are more economical to build, so that STATCOMs will be used more frequently as opposed to SVCs.

The demand for power flow controllers today reflected in the increased usage of phase-angle regulators will lead to sophistication of alternatives like DFCs.

Entirely new concepts should not be expected in the near future.

Costs

Reasonable estimates of the magnitude of cost for these devices can be derived from various sources and information about real-life projects. It should, however, be noted that the actual project costs vary considerably because a whole range of boundary conditions means each project is specific.

Table 2-4: Estimated costs of selected FACTS at 380 kV level

FACTS device	Capacity class (MVAR)	Cost range in EUR k/MVAR	
		Min	Max
SVC	100-700	30	60
STATCOM	100-400	50	85
SC	100-1000	10	20
TCSC	25-600	25	50
SSSC	100-400	70	120
PST	100-1600	10	40
DFC	100-1600	20	70

Benefits

With the help of phase-shifting devices, the voltage modulus can be influenced through the targeted provision of reactive power. In order to avoid additional limitations to the transmission capacity of three-phase AC lines resulting from the transmission of reactive power, the latter should be provided locally. Especially FACTS lend themselves well to responding quickly and flexibly to system faults and failures.

The use of series FACTS devices which can influence impedances and apply additional voltages in a very targeted manner allows to specifically influence the power flow and shift it to neighbouring lines carrying lower loads. Attention must, however, be paid to influencing the voltage, so that, in most cases, an additional phase-shifting component is required.

Power flow control helps to smooth out the utilisation patterns of existing operating resources. Spare transmission capacity on parallel transmission corridors can be utilised when applying power flow control, especially in emergency situations. Power flows on overloaded lines can be limited.

On the whole, the flexibility of system operation can be increased with FACTS, enabling system operators to manage the surge of volatile influence factors caused by the market and renewable energies.

Limitations

While compensators generate a permanent improvement of the system stability, the shifting of load flows can only be regarded as a stabilising emergency measure that cannot serve the purpose of increasing the current-carrying capacity in day-to-day operations.

Especially where several FACTS with overlapping reach are used, or where FACTS are combined with HVDC, it is necessary to coordinate these components in order to avoid reciprocal negative impacts and ensure efficient use of these techniques. This requires thorough knowledge of the current system condition. To determine the latter, a monitoring system for the network with an adequate communication infrastructure is needed. Such processes, with automated coordination at the high end of the spectrum, are, however, still at the stage of research and development.

3 Advancing the “transmission grid as a total system“

Success in guaranteeing the supply with electrical energy is not only determined by the transmission system and the technologies used. The properties and operating characteristics of the existing power plant pool, the market model and the usage patterns of consumers also play a major role. This means a big-picture view of the entire system and its technological aspects is needed, taking the entire process chain from generation via transport and distribution up to the connected load into account. Only an analysis of the overall system will allow safe and secure, economically viable and efficient operation and development of the transmission system. This is because of the central role it plays in the system as a whole. The legislation and regulatory principles for the electricity industry in Europe and Germany should be framed such that an efficient and optimised total system is promoted.

A factor that wants to be taken into consideration in this context is a process initiated some years ago and due to continue with ever increasing thrust: the transformation of the transmission system into a wholesale market platform for the European single electricity market. The liberty of all generators to freely choose locations for their plants practically irrespective of the network situation is leading to an increasing number of generation plants situated in places remote from the transmission system (especially on- and offshore wind farms). The consequences of these developments include higher utilisation rates of the transmission system, and high-capacity, long-distance power transit operations. The transmission systems are thereby increasingly operated closely to the limits of their safety and stability. The mandatory targets set by the legislator with regard to ensuring service security can only be achieved in the above-mentioned challenging environment if, besides the application of preventative and curative congestion management procedures, both the further extension of the transmission systems is investigated, considering the use of innovative transmission technologies and operating resources, and planning principles and processes for sizing the transmission networks are matched with these developments and advanced where appropriate.

3.1 System planning

In order to meet the future transmission tasks while maintaining service security, the networks must be planned such that the system operators have a sufficiently dimensioned grid with adequate degrees of freedom and flexibility for operational purposes available. In system planning, selected cases of grid use are used as an orientation (combinations of feed-in/load and transit situations that represent the system loads relevant for system dimensioning). Respect of the first contingency (n-1) criterion as the classic principle for planning ensures that safe system operations continue to be possible in the event of an outage or disconnection of an operating resource, without any infringement of operating limits or overloading of the remaining operating resources (n-1 security). This standard international practice in system planning uses a deterministic process to calculate the dimensions of the system for one or several technically disadvantageous situations. Computer-aided steady-state and dynamic network calculation is today's standard tool for computing an electrical energy system based on the determined nodal power combination. Specific statements about the expected duration and frequency - and hence probability – of the maximum loads forecasted this way are generally not possible with this method. Quantifying risks, or accepting a certain risk, are approaches that are at odds with these planning principles. Rather, the focus is on consistent risk minimisation. This approach that has proven its worth over decades ensures a high measure of service security. In expanded analyses, it must also be considered that an outage of an operating resource during the simultaneous disconnection of selected operating resource combinations for routine attention and maintenance works must not be allowed to jeopardise functioning of the system, bearing in mind the large scale of the transport mission and the reliability of regional electricity supply. This means operational measures weakening the network have to be considered in planning in order to ensure reliable fulfilment of the respective supply task.

In future,

- the volatile behavior of international market players,
- the massively increasing supply-dependent generation of electricity, and
- the high level of uncertainty regarding future conventional power plant capacity

will make it more difficult to develop representative network usage cases relevant for dimensioning of the system. It will generally be no longer possible to make valid statements about the level of system extensions required if just a few cases of network usage are analysed. As prescribed by the legislation requiring efficient and economically viable system operation, unnecessary redundancy must be avoided, while enough reserve has to be maintained to ensure reliable operation.

3.2 Forecasting grid use

Two methods are available to forecast the probability of occurrence of cases of full operating resource utilisation. Probabilistic load flow computation is based on the combination of probability density distributions of feed-ins and loads with determined network scenarios. Energy-sector market models permit forecasting of the installed capacity of power plants on the basis of economic boundary conditions, and deliver non-determined variables on the basis of time series histories, e.g. dispatch profiles of power plants in the analysed market.

In essence, we distinguish between two different approaches to carrying out a probabilistic load flow computation. The first approach uses the classic load flow computation to calculate the network variables by using selected feed-in profiles. The probability of the computed system state is determined on the basis of the probability of the corresponding feed-in profile. Due to the high computational complexity, this approach uses Monte Carlo simulations. The second method is based on system models that allow the use of folding algorithms to calculate the system state. As opposed to methods based on Monte Carlo simulations, these consider all possible combinations and are distinguished by a low computational complexity. These methods will in future have to be advanced in order to enhance the accuracy of computation and take stochastic line outages and the necessary system regulation into account.

Where probabilistic load flow computations are used in system planning, the input variables (probability density distributions of nodal powers) map the features over a long period of time. Forecast system extension scenarios can be weighted with the relevant probabilities of occurrence. Based on these data, the necessity of power system extensions can be assessed, even if the input variables are not reliable. The previous methods used for probabilistic load flow computations have so far not offered any opportunity to map the features of the energy market. This is the reason why the use of probabilistic load flow computations for the transmission system has so far not been feasible for practical applications. These techniques must therefore be developed further.

Energy-sector market models have been in use for many years, e.g. to support decisions on the construction or decommissioning of power plants. Considerable progress has been made in recent years as far as the utilisation of the results of these market models for dimensioning transmission systems is concerned. This approach is, for example, used in Part 2 of the European Wind Integration Study (EWIS II) [18] and the dena network study II [17]. In a first step, the development of the power plant pool economically optimal for a certain market area is determined subject to the economic boundary conditions defined for the scenario under review. Ideally, the market area will, as things stand now, comprise all of Europe. In a second step, the power plants are assigned to submarkets with interconnection capacity being taken into account. In a third step, power plant dispatching is determined in each submarket for defined time horizons (5, 10 or 15 years) and periods (e.g. 8760 hours). The characteristic curves of feed-ins and loads are then transferred to a network model. In the last step, load flow computations are, for the determined system usage situations, carried out for the base case and with outage simulations, and are statistically evaluated. The results include e.g. statements about prospective situations of system congestion, and the demand for energy needed to cover network losses.

3.3 Expanded planning and dimensioning criteria

Besides the classic planning criteria like conformity to equipment ratings or operational voltage bands, new aspects are increasingly coming to the fore as a result of changed tasks and higher demands made on the transmission systems. These aspects had before been of merely subordinate importance. On the one hand, this concerns the utilisation of transmission capacity potential inherent in the thermal ratings of operating resources, on the other, however, additional technical limit values and stability criteria have to be heeded.

The weather-dependent loadability of overhead lines may, for example, be taken into account in system planning. To date, the general basis used in system planning has been a maximum thermal rating of the conductor strands subject to standard conditions of environmental influences (especially ambient temperature, wind speed and wind direction, insolation). However, particularly when wind speeds are higher and ambient temperatures lower than under standard conditions, the conductor strands can carry distinctly higher currents before reaching their thermal ratings. When certain system usage cases correlate with favourable ambient conditions, the corresponding weather-dependent rating of the operating resource can be assumed for these situations. A system usage case with high wind energy feeding therefore allows thermal line ratings to be assumed which are based on higher wind speeds corresponding to the wind energy feeding, in deviation from than the standard conditions.

Another factor that will in future be of greater importance is a more profound analysis of the voltage modulus and voltage angle limits across opened breaker contacts. When lines are connected subject to large voltage angles, sudden transient active-power variations will occur at generators, which may e.g. lead to impermissibly high torsional strain on drive shafts in power plants. Future system planning must therefore analyse whether the increase utilisation of operating resources still permits switching without any adverse impacts on network customers.

Another aspect gaining importance in highly loaded networks consists in the preservation of voltage stability. The operation of lines above a certain capacity limit (natural load) requires considerable extra reactive power. This additional need can be managed with leading reactive power compensation. In this case, however, the operating point of the system will shift, so that the critical limit of voltage collapse may be on the range of nodal voltages common in operation. Paying attention to voltage stability therefore becomes more important. The limitations to operating a large-scale transmission system considerably above the natural load, and thereby to a generally higher utilisation rate of operating resources, have yet to be analysed.

In the process of dimensioning systems, increasing attention must in future be paid to the ability to carry out works indispensable to maintain operations at minimal interference with system customers and market operations. Such interference will usually come at the expense of the system operator, e.g. in the form of costs for re-dispatching power plants. This requirement implies the necessity of higher equipment redundancies, like e.g. for reserve bus bars or bypass switchbays.

3.4 System operation/system operation planning

For safe and secure system operation, it must be possible to promptly identify both the current system condition and potential fault situations and, if necessary, to propose, and implement in a coordinated way, remedial action to maintain or restore system security. This is today performed by centrally organised monitoring centres (control centres). The basic criterion used here is the first contingency (n-1) principle, i.e. one outage of a system component must not be allowed to lead to any malfunction of the system or violation of technical limit values. For the purpose of operational monitoring, all required information about the system condition needed today to assess the system security is available to all transmission system operators. It is state-of-the-art to carry out cyclical automated system reliability computations on the basis of the current system condition and system load situations.

In addition, information systems are today available in the control rooms which provide an overview of the current system condition, including for neighbouring transmission systems. As soon as a vulnerable system condition is signalled by one of the neighbouring networks, effective remedial action is coordinated and implemented, with the immediately adjacent systems being involved.

The future requirements made on online operational monitoring have to be analysed, taking account of higher utilisation rates of the transmission systems and the potential of up-to-date measuring and communication systems. The wide-area measuring systems common today can, in particular, be used to recognise dynamic events and record the course of fault events in detail. For this purpose, measurement points have been set up at selected places in the transmission system to perform measurements of current, voltage and frequency at high time resolution and time-synchronised through signals of the Global Positioning Systems (GPS - global navigation satellite system providing location and time information). Besides the steady-state system condition, dynamic events and their spreading within the transmission system can be captured by way of comparisons between the various measurements taken at different places. This information is today, above all, used to validate dynamic models of the interconnected grid, to improve them and to analyse faults that have occurred. In some cases, these systems have already been connected up to information systems of the system control centres, allowing for remedial action to be initiated automatically in the event of certain faults and critical operating conditions, with such remedial action having been defined with the help of system analyses.

Further development is needed to ensure support to the personnel in control centres with such systems in critical situations, especially in view of suitable processing of the captured data on the system condition and their visualisation. As the data can be captured throughout the whole system, large-scale events, too, can be registered. While an exchange of selected information across the responsibility limits of individual system operators is being practiced today, it can be expanded if this turns out to be advantageous or necessary to initiate and coordinate suitable remedial action in response to critical or impaired operating conditions. The operational use of additional system information in control centres requires more development efforts in this respect.

Because of the volatile power flows and the strong reciprocal influencing between neighbouring transmission systems, the system operation planning tools and computations have for years been systematically expanded at international level. For a few years, so-called DACF data records (DACF: Day Ahead Congestion Forecast) have been exchanged between the control centres of the west European transmission systems on day (d-1). This data exchange permits, as a function of the expected generation and system situation on the ensuing day, carrying out system analysis computations and recognising critical situations and system bottlenecks in good time in advance, so that remedial action can be prepared in a coordinated manner. The international exchange of wind generation data is playing an increasingly important role in this context. These tools are being continuously improved and adapted to match the new requirements.

3.5 Communication technology

The measuring points in the system need communication links for flexible connection with evaluation facilities. For the latter, both decentralised and centralised concepts are feasible. Decentralised concepts are highly likely to involve much less sophisticated communication. Besides high reliability and short latency, the communication system must, in such concepts, accommodate the data transmission rates required for the respective application. It must be possible to reliably recognise failures, including of parts of the communication system. High-speed networks for data integration between switchplants have been employed around the world, and are marketed by several manufacturers.

It can be assumed that this technology will be integrated with the next generations of control system technologies (SCADA/EMS - supervisory control and data acquisition / energy management systems - comprehensive installations for monitoring, visualisation, control and instrumentation of a process), so that applications based on time-synchronised data and non-time-synchronised data run in parallel within the same network control system, and provide information support to system operation teams.

3.6 System protection (Defence Plan)

The use of state-of-the-art technology to preserve the safety and security of the system (Defence Plan, special protection schemes) should be investigated to sophisticate the action taken to prevent the propagation of faults, cascading effects and stability loss. For this purpose, generating units and power-using units are today included in the process of capturing measuring data, and they are automatically controlled to avert danger. These systems must be advanced, and must be used and dimensioned on a case-by-case basis, working from stability analyses. They have already come to be employed for the protection of sections of the systems which are exposed to substantial dangers as a result of high transit volumes or special network topologies, or are in a state of critical stability. The foreseeable increase in the demand for high transit volumes over long distances, and the integration especially of offshore wind energy, require the further development and use of special systems for protection of the networks. There is a need for research and development work in this field.

3.7 An overarching voltage level – the “overlay” network

To meet the even more comprehensive task of transporting simultaneously required power over very long distances, a higher-tier network would be imaginable. Implementing such a system in three-phase AC technology is only feasible at a higher nominal voltage permitting the transmission of more power at comparable current levels. Transformers would be needed to connect such a network to the existing system. The impedance ratios of lines and transformers must be engineered such as to ensure that the power flows on the new voltage level are neither too high nor too low. Because of the very high voltage, they can currently only be executed as overhead lines, implying that the towers would have to be distinctly higher, and the right of way considerably wider. This makes actual execution more difficult.

In the Western European interconnected system (formerly UCTE), no transmission has so far been performed at 750 kV level. Eastern Europe has already seen several connections over long distances built at this voltage level. The cost of construction of such overhead lines is of course much higher than usually.

In its initial execution, the overlay system may consist of a few connections hooked up to the existing 380 kV system via transformers. At these points, the short-circuit power towards the existing 380 kV system which must be technically controlled will be distinctly higher. Benefits may result from advancing such a system into a meshed pan-European overlay system.

Executing this system with HVDC technology might be another option to meet the requirements of such high-capacity transmission, although this is currently only feasible with overhead line technology, involving implementation problems similar to those mentioned above for three-phase AC systems. In the long run, however, even an HVDC overlay system will only make sense if this system can be structured such that it has sufficient redundancy by itself. This would presuppose meshing of the individual HVDC connections (multi-terminal systems).

A. Laws and Directives

Essential legislation and legal instruments relevant for the electricity market, the construction and operation of the transmission system:

[1] EU Internal Electricity Market Directive 2009/72/EC of the European Parliament and of the Council of 13 July 2009 concerning common rules for the internal market in electricity and repealing Directive 2003/54/EC (Official Journal of the European Union, L 211 p. 55),

[2] Regulation (EC) No. 714/2009 of the European Parliament and of the Council of 13 July 2009 on conditions for access to the network for cross-border exchanges in electricity and repealing Regulation (EC) No 1228/2003 (Official Journal of the European Union, L 211 p. 15),

[3] Directive 2005/89/EC of the European Parliament and of the Council of 18 January 2006 concerning measures to safeguard security of electricity supply and infrastructure investment (Official Journal of the European Union, L 33 p. 22),

[4] TEN-E Guidelines - Decision No 1364/2006/EC of the European Parliament and of the Council of 6 September 2006 laying down guidelines for trans-European energy networks and repealing Decision 96/391/EC and Decision No 1229/2003/EC (Official Journal of the European Union, L 262 p. 1),

[5] Act on Electricity and Gas Supply (German Energy Industry Act - EnWG) of 7 July 2005 (Federal Law Gazette I p. 1970 (3621), last amended by Article 2 of the Act of 21 August 2009 (Federal Law Gazette I p. 2870),

[6] Ordinance on Power System Access (StromNZV) of 25 July 2005 (Federal Law Gazette I p. 2243), last amended by Article 2 Paragraph 1 of the Ordinance of 17 October 2008 (Federal Law Gazette I p. 2006),

[7] Act on the Priority of Renewable Energies (German Renewable Energies Act - EEG) of 25 October 2008 (Federal Law Gazette. I p. 2074), last amended by Article 3 of the Act of 29 July 2009 (Federal Law Gazette. I p. 2542),

[8] Act on Maintaining, Modernising and Expanding Combined Heat and Power Generation (CHP Act) of 19 March 2002 (Federal Law Gazette. I p. 1092), last amended by Article 5 of the Act of 21 August 2009 (Federal Law Gazette. I p. 2870),

[9] Ordinance Regulating the Network Connection of Plants for the Generation of Electrical Energy (Ordinance on system connection of power plants - KraftNAV) of 26 June 2007 (Federal Law Gazette. I p. 1187),

[10] Ordinance on the Charges for access to electricity supply systems (German Ordinance on power system charges - StromNEV) of 25 July 2005 (Federal Law Gazette. I p.

2225), last amended by Article 6 of the Act of 21 August 2009 (Federal Law Gazette. I p. 2870),

[11] Ordinance on Incentive Regulation of Electricity Supply Systems (Incentive Regulation Ordinance - ARegV) of 29 October 2007 (Federal Law Gazette. I p. 2529), last amended by Article 4 of the Act of 21 August 2009 (Federal Law Gazette. I p. 2870),

[12] Act on the Extension of Overhead Power Line Connections (Power Line Extension Act - EnLAG) of 21 August 2009 (Federal Law Gazette I p. 2870).

[13] 26th Ordinance Implementing the Federal Ambient Pollution Prevention Act (Ordinance on Electromagnetic Fields – 26th BImSchV), 16 December 1996

The resulting obligations and responsibilities are executed in the day-to-day work of the transmission system operators, and are currently reflected e.g. in the following documents:

[14] European Network of Transmission System Operators for Electricity (ENTSO-E, formerly UCTE), “Operation Handbook“ as amended; its application has been agreed between the European transmission system operators (UCTE Multilateral Agreement)

[15] Verband der Netzbetreiber VDN e.V., (German Association of System Operators) under the umbrella of BDEW: “Transmission Code 2007“, August 2007

B. Studies and reports:

[16] Deutsche Energie-Agentur GmbH (dena): “Energiewirtschaftliche Planung für die Netzintegration von Windenergie in Deutschland an Land und Offshore bis zum Jahr 2020“ *(Energy management planning for the integration of wind energy into the grid in Germany, onshore and offshore by 2020)*, 24/02/2005.

[17] Deutsche Energie-Agentur GmbH (dena): “Netzstudie II“ *(Network study II)*, not yet published

[18] European wind integration study (ewis): Towards a Successful Integration of Wind Power into European Electricity Grids, European Transmission System Operators 15/01/2007

Studies briefly described below (Annex C):

[19] Prof. B.R. Oswald; “Vergleichende Studie zu Stromübertragungstechniken im Höchstspannungsnetz“ *(Comparative study of electricity transmission techniques on the extra-high-voltage system)*; 20/09/2005, http://www.forwind.de/forwind/files/forwind-oswald-studie-langfassung_05-09-23_1.pdf

[20] Prof. H.-J. Haubrich; “Abtransport der in den Kraftwerken Kopswerk I & II und Rodundwerk II der Vorarlberger Illwerke AG erzeugten elektrischen Energie“ *(Transport of electrical energy produced by the Kopswerk I & II and Rodundwerk II power plants owned by Vorarlberger Illwerke AG)*; July 2007; http://www.pronofatnom.at/informationen/downloads/files/03_studie_illwerke1.pdf

[21] Prof. Heinrich Brakelmann; “Netzverstärkungs-Trassen zur Übertragung von Windenergie: Freileitung oder Kabel?“ *(Line runs for network reinforcement supporting the transmission of wind power: overhead or underground?)*; October 2004; http://www.ets.uni-duisburg-essen.de/~bra/Freileitung_Kabel.pdf

[22] KEMA; “Machbarkeitsuntersuchung zur Gesamt- oder Teilverkabelung der 380- kV-Leitung „St. Peter – Tauern“ im Bundesland Salzburg“ *(Feasibility study into total or partial undergrounding of the St. Peter – Tauern 380 kV line in the Austrian Federal state of Salzburg)*; 27/01/2008; http://www.salzburg.gv.at/kema_abschluss.pdf

[23] S. Cole, C. De Jonghe , R. Belmans (KU Lueven); “Die elektrotechnischen Grundlagen für die Planung der 380 kV Höchstspannungsleitung“ *(Electrotechnical basis for planning the 380 kV extra-high-voltage line)*; http://www.thueringen.de/imperia/md/content/tmwta/energie/gutachten_380-kv-trasse_technischer_teil.pdf

[24] ATW-Forschung GmbH, Wiesbaden (Prof. Dr. L. Jarass , Prof. G. M. Obermair); “Notwendigkeit der geplanten 380kV-Verbindung Raum Halle - Raum Schweinfurt“ *(Necessi-*

ty of the planned 380kV link between the Halle and Schweinfurt regions); 21/08/2008; http://www.jarass.com/Energie/A/Gutachten%20380kV,%20Kurzfassung.pdf

[25] Transpower, New Zealand; “Comparison of the Reliability of a 400 kV Underground Cable with an Overhead Line for a 200 km Circuit“; 2005; http://www.gridnewzealand.co.nz/f394,13204/13204_comparison-reliability-400kV-ug-cable-mar-2005.pdf

C. Briefs of current studies

This chapter presents some recent studies that have also assessed potential transmission techniques. No assessment of the respective studies is given.

Title:	Comparative study of electricity transmission techniques on the extra-high-voltage system (technical, business and environmental assessment of overhead lines, XLPE cable and GIL, using the Ganderkesee – St. Hülfe 380 kV line as an example)
Author:	ForWind (Prof B.R. Oswald, Hanover University)
Client:	Lower Saxon state government
Date:	20/09/2005

Objective:

The study investigated and compared overhead lines, underground XLPE cable and GIL.

Example:	Ganderkesee – St. Hülfe 380 kV line
Length:	approx. 60 km
Capacity:	1500 and 2200 MW (due to increased offshore wind power generation)

Summary:

All three solutions are feasible in principle.

In all cases under review, the overhead line definitely proved to be the best solution from technical and energy business angles.

Capital expenditure (net present value): Overhead line € 40-42m, buried cable € 162-183m, and GIL € 396-478m.

Total costs (NPV of CapEx and OpEx including losses): Overhead line € 88-92m, buried cable € 190-215m, GIL € 411-493m.

Please note:

According to information from manufacturers, the costs shown for GIL in this study are no longer valid. As at today, the costs of buried cable and GIL are much closer to one another.

Web:

http://www.forwind.de/forwind/files/forwind-oswald-studie-langfassung_05-09-23_1.pdf

Title: Transport of electrical energy produced by the Kopswerk I & II and Rodundwerk II power plants owned by Vorarlberger Illwerke AG

Author: Prof H.-J. Haubrich (RWTH Aachen)

Client: Vorarlberger Illwerke AG, Bregenz

Date: July 2007

Objectives:

To investigate alternatives to the existing 220 kV overhead line. The options investigated included buried three-phase AC cable (220 kV), gas insulated transmission lines (GIL, 220 kV) and VSC HVDC using buried cable (±150 kV). Because of the importance of this transmission line (it connects power plants to the system), the "n-1" principle has been taken into account.

Length: approx. 30 km (sections of 2, 10 and 28 km for different capacities).

Summary:

The technologies were compared from technical and economic angles.

The analysis considered the transmission capacity, availabilities (frequency of outages, duration of repairs, non-availability), service lives and environmental influences. All three alternative solutions are technically feasible.

As far as the business case is concerned, the costs of investment, maintenance and losses have been considered in the calculations. In comparison with construction of a new 220 kV overhead line, the following factors must be applied in order to weight the costs of underground line options:

Factor 8 for three-phase AC cable (220 kV, two/three circuits, XLPE cable 2,000 mm2)

Factor 12 for GIL (220 kV, two circuits, additionally: three-phase AC cable)

Factor 20 - 30 for VSC HVDC (±150 kV, two circuits, additionally: three-phase AC cable).

Web:

http://www.pronofatnom.at/informationen/downloads/files/03_studie_illwerke1.pdf

Title: Line runs for network reinforcement to support the transmission of wind power: overhead or underground?

Author: Prof Heinrich Brakelmann (Duisburg-Essen University)

Client: Bundesverband WindEnergie e.V. (2004)

Date: October 2004

Objective:

The reinforcement of the network envisaged to respond to the increase in wind power generation has been analysed for a 30 km line length. Three-phase AC buried cable and three-phase AC overhead lines have been investigated and compared for the voltage levels of 110, 220 and 380 kV.

Summary:

The study takes account of properties like current-carrying capacity, overload capability, dielectric strength, service life, reactive power compensation, maintenance works, fault rates and non-availability, impacts from and on the environment, electromagnetic compatibility, noise, safety/security, visual impairments, restrictions on use, losses and economic efficiency.

The investigations were based on the following assumptions for boundary conditions which - in this comparison - speak in favour of a buried cable solution:

a) Additional operating safety can be achieved with generation management (disconnecting the wind farm);

b) the load on the reinforcement line is not constant over time; rather, it is substantially influenced by the wind situation.

110 kV: For all options under review, a 110 kV buried cable system was more favourable than a double-circuit overhead line system. The double-circuit 110 kV buried cable system comes at roughly the same price like a double-circuit overhead line.

220 kV: The net present value of the double-circuit overhead line is 8-23% above the net present value of a buried cable system. The double-circuit buried cable system is distinctly more costly than a double-circuit overhead line system (5% to 31%).

380 kV: The buried cable system is distinctly more expensive than the overhead line – i.e. by factors of 3 to 6. The cost of construction of a buried double-circuit system is higher by the factor of 9.

Observations concerning the cost comparison: When a regulating transformer is used on the buried cable system, the cost of this technology will increase. The cost of overhead lines can be reduced if larger conductor cross sections are used.

Comment:

The outcomes of the study (110 kV voltage level) have been assessed by EON Netz as incorrect because of deficiencies in methodology. The buried cable solution is, according to EON Netz, distinctly more expensive than calculated in the study. (http://freenet-homepage.de/natur2000/Bewertung-BWE.pdf)

Web:

http://www.ets.uni-duisburg-essen.de/~bra/Freileitung_Kabel.pdf

Title: Energy management planning for the integration of wind energy into the grid in Germany, onshore and offshore by 2020

Authors: Consortium headed by Prof Dr Walter Schulz of the Institute of Energy Economics at the University of Cologne. Additionally, the interim and final results were checked by external experts Prof Dr Jürgen Schmid of Institut für Solare Energieversorgungstechnik in Kassel and Dr Martin Schmieg of DIgSILENT GmbH in Gomaringen.

Client: Deutsche Energie Agentur, Berlin

Date: February 2005

Objective: Basis for fundamental long-term energy planning

The central purpose was to develop strategies for the integration of renewable energies into the energy supply system. The dena Network Study I presents programmes that allow reaching a 20% proportion of renewable energies in electricity production in Germany between 2015 and 2020.

Summary: The continuing expansion of renewable energy use in northern Germany is leading to the necessity of nationwide transport, which implies nationwide network extensions at the 380 kV extra-high-voltage level. On aggregate, 850 km new 380 kV overhead lines must be built, and a number of reinforcements performed.

Web : http://www.dena.de/de/themen/thema-esd/projekte/projekt/netzstudie-i/

dena opinion: The Jarass/Obermair expertise on the southwest interconnector is untenable.

Climate protection and system security require development of the extra-high-voltage system.

11/12/2007

http://www.dena.de/de/infos/presse/pm-archiv/pressemeldung/dena-stellungnahme/

Title: Expert opinion on the 380 kV Salzburg line

Impact of potential (partial) undergrounding of the Tauern-Salzach section

Author: University Prof Dr Ing habil B.R. Oswald

Client: Energie-Control GmbH, Vienna (regulator)

Date: 27/12/2007

Objective:

To assess the transmission technology suitable for the 380 kV Salzburg line.

Summary:

This expert opinion has assessed three different transmission technologies with regard to their technical maturity, capital and maintenance expenditure.

1) Building the line as an **overhead line** is definitely the **best solution** according to technical, operational and economic assessments.

2) A **buried cable system** is much less loadable than an overhead line system because of the inferior discharge of heat losses if natural cooling is used, regardless of much larger conductor cross sections. In the event of a **fault,** the time for repair of a buried cable system (weeks) is many times longer than for an overhead line (hours to days).

3) A buried cable system equivalent to an overhead line should have an identical **maximum capacity** (thermal limit rating) and an identical **availability,** failing which the buried cable system would either represent a bottleneck or a risk to service.

4) One-to-one (partial) undergrounding of a double-circuit overhead line **at equivalent capacity** (one buried-cable system for one overhead line system) is not feasible with the XLPE cable commercially available today (without additional cooling), and would also have to be dismissed on grounds of **service reliability** in comparison with an overhead line because of the much longer time for repair of the buried cable.

Web:

http://www.e-control.at/portal/page/portal/medienbibliothek/presse/dokumente/pdfs/PK%20SalzburgLeitung_Endfassung_4KS_20080118_0_0.pdf

Comment: See: Feasibility study into full or partial undergrounding of the KEMA St. Peter – Tauern 380 kV line in the Austrian state of Salzburg, p. 55

Title: Feasibility study into full or partial undergrounding of the St. Peter – Tauern 380 kV line in the Austrian state of Salzburg

Author: KEMA

Client: Salzburg state government

Date: 27/01/2008

Objective:

For the 380 kV St. Peter – Tauern line, the following solutions have been investigated and compared: Overhead line, partial burying (several options) and full burying.

Length: approx. 125 km – not yet finally decided

Summary:

All three solutions (overhead line, partial burying and full burying) are suitable in principle.

From the viewpoint of town and country planning, the planned overhead line solution has been found to involve conflicts with regard to existing settlements and settlement development. These conflicts can only be reduced to a limited extent by optimising the line route.

From a business perspective, the overhead line is superior to the buried cable solution. Underground extra-high-voltage cable systems require higher capital expenditure. In addition, buried extra-high-voltage cable of large lengths incurs higher costs of losses than overhead lines during operation (based on the same number of three-phase AC current systems).

A full-fledged financial comparison from a national economy angle between the different technologies was not possible because of the identified uncertainties.

Cost comparison between overhead line, full and partial burying:

Capital expenditure:

Full burying is 5.8 times more expensive than an overhead line

Partial burying is 2.3 times more expensive than an overhead line

Total costs, annuity (80 years, 5% interest):

Full burying is 4.0 times more expensive than an overhead line

Partial burying is 1.8 times more expensive than an overhead line

Web:

http://www.salzburg.gv.at/kema_abschluss.pdf

Comment: See expert opinion of Prof Oswald re the 380 kV Salzburg line, p. 54

Title: Electrotechnical basis for planning the 380 kV extra-high-voltage line and legal assessment of the 380 kV extra-high-voltage line from Lauchstädt to Redwitz

Authors: S. Cole, C. De Jonghe, Prof R. Belmans (Lueven University) and Prof Dr jur, Dr rer pol, Dr hc Franz Jürgen Säcker, Berlin Free University

Objective:

The development of new transmission lines is technically (system security) inevitable in view of the envisaged offshore wind farms in the Baltic Sea. Against this background, 380 kV overhead lines, 380 kV buried cable and HVDC (buried cable ± 500 kV) have been investigated and compared for several line routes in the service area of VE-T**:** The aim was to review the necessity in terms of energy system management and the legal obligation to construct and operate the planned 380 kV extra-high-voltage line (southwest interconnector), and to assess the way of execution (buried cable sections) on the basis of legal aspects.

Summary:

Potential solutions include an overhead line, a buried cable or - for certain sections – a DC link. The last two options are considerably more costly (3 and 5 times more expensive). In addition, the benefit of an overhead line is that it is relatively easy to reinforce, if necessary, by adding an additional circuit. Electromagnetic fields are unlikely to represent an issue in this context, as a range of technologies is available today to manage electromagnetic fields. The climate protection goals of the European Union, and hence of the Federal Republic of Germany, can only be achieved by continuing, speedy expansion of renewable energy use.

Web:

http://www.thueringen.de/imperia/md/content/tmwta/energie/gutachten_380-kv-trasse_juristischer_teil.pdf

http://www.thueringen.de/imperia/md/content/tmwta/energie/gutachten_380-kv-trasse_technischer_teil.pdf

Comment: See: Necessity of the planned 380 kV link between the Halle and Schweinfurt regions, by ATW Forschung GmbH, p. 57

Title: Necessity of the planned 380kV link between the Halle and Schweinfurt regions

Authors: ATW-Forschung GmbH, Wiesbaden (Prof Dr L. Jarass, Prof G. M. Obermair)

Clients: 33 district councils, lord mayors and mayors and local action groups in Southern Thuringia and Upper Franconia

Date: 21/08/2008

Objective:

The power link between the Halle and Schweinfurt regions, a project that has already been applied for, was to be investigated from technical, economic and environmental perspectives.

Part A: Stocktaking of the existing transmission system and the planned project. Investigation into the transmission capacities and the necessity to extend the 380 kV system.

Part B: Investigates potential responses like system optimisation, system reinforcement and construction of new parts of the system as well as potential undergrounding.

Parts C and D: Investigates and reviews wind-related system extensions taking account of the costs for the national economy. Future wind power scenarios have also been considered in this context.

Length: approx. 60 km

Capacity: 1,800 – 2,400 MW, and 5,400 MW during peak-load periods

Summary:

The planned Vieselbach - Altenfeld - Redwitz 380 kV overhead line (approx. 60 km) is not necessary. Its construction is unreasonable in consideration of the financial reasonableness of system extensions, a principle laid down in the law, because its benefit is far lower than its costs.

The necessary reinforcement of the system can be achieved at low costs with heat-resistant conductors and overhead line monitoring.

Comment:

The outcome of the study (system extension is not necessary) has been questioned by the relevant transmission system operators E.ON Netz and VET, and by DENA.

Web:

http://www.jarass.com/Energie/A/Gutachten%20380kV,%20Kurzfassung.pdf

Comment: See: Electrotechnical basis for planning the 380 kV extra-high-voltage line, Prof Belmans, p. 56

Title: Comparison of the reliability of a 400 kV underground cable with an overhead line for a 200 km circuit

Author: Transpower, Neuseeland

Date: 2005

Objective:

The study looked into the expected behaviour of a 400 kV underground XLPE cable and a 400 kV overhead line with regard to failure rates, repair times and availability.

Length: 200 km

Summary:

The figures for the 400 kV overhead lines could easily be determined.

Because of the low number of sections and their relatively short lengths, it is very difficult to determine the reliability figures for the 400 kV XLPE cable.

The outage times are much longer for underground cable than for overhead lines. They are at best between 10 and 19 days.

The availability of a 200 km 400 kV underground cable section is far worse than the one of a 400 kV overhead line section.

Web:

http://www.gridnewzealand.co.nz/f394,13204/13204_comparison-reliability-400kV-ug-cable-mar-2005.pdf

VDE

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