High Voltage Engineering
for
Modern Transmission Networks

O.Univ.-Prof. Dipl.-Ing. Dr.techn. Dr.h.c. Michael MUHR
Dipl.-Ing. Thomas JUDENDORFER

Institute for High-Voltage Engineering and Systems Management
Graz University of Technology
Austria

Abstract

Electricity transmission systems are the backbones of modern energy networks. Several different approaches and systems for the transmission of electricity over long distances have been developed in the past. At present, the framework of the electricity market changed dramatically, so that such systems are assessed differentially nowadays.
This work gives an overview about the different technologies for transmission (direct current and alternating current) and also about the three systems that are currently in operation: overhead lines, cable lines and gas insulated transmission lines. Finally, new technical developments and trends are presented.

1. Introduction

Nowadays, the rising need for electricity worldwide and the liberalisation of the energy marked with the involved changes are demanding a great deal of electrical energy transmission systems and the related grid structures. Several diverse aspects have to be studied to find reasonable and sustainable solutions in the transmission network sector.
Different systems for the transmission networks exist nowadays where each solution has its own characteristics and advantages. But one has to examine its technical features as well as the issues in network operation and the co-operation with other operating resources, networks and systems critically. Furthermore, besides the reliability of such a transmission system, the impact on the environment and the acceptance of the society are at least equally important as technical features and questions of quality and security of supply.
Therefore, several disagreements developed lately, few have even evolved into some sort of “religious wars”. Finally, the total costs of each system has to be questioned in detail. The systems described above, which are in operation nowadays are

- overhead lines
- cable lines
- gas insulated transmission lines (GIL)

The application of superconductivity is now in the focus again, as the development of the High-Temperature-Superconductivity (HTSC) allows to operate equipment at temperatures of above 90 K (-183 °C). But for sure, it is still a long way to go until such technologies can be applied to the electricity transmission sector on a broad basis.

2. High Voltage Alternating Current Transmission (HVAC)

A economical, efficient and environmental friendly transmission of electrical energy with alternating current is only possible trough the usage of high voltage. The voltage levels of the transmission grids in Austria and for major parts of Europe are 110 kV, 220 kV and 380 kV. In other parts of the world (Asia, South America, Africa), even higher voltage levels are in discussion (up to 1000 kV....1200 kV). For example, there are projects planned in China and Japan to transmit electrical energy at ultra-high voltage levels (UHV) over long distances within 10 years.
The easy transformation of the electrical energy between the voltage levels is one of the biggest advantage of such systems. One big disadvantage of HVAC is the issue with reactive power. Its transmission limits the capability of active power transport. Therefore additional measure have to be taken for the compensation of reactive currents. Frequency effects and efficiency considerations are limiting the maximum length of lines.
For the control of power flow, basically two systems can be utilized: Phase Shift Transformers (PST) or FACTS-Elements. Flexible AC Transmission Systems (FACTS) are, in general, systems which can control the flow of electrical energy with power electronic devices. Such elements are very flexible and they are able to react fast to changes in the grids. Besides the control of (active) power flow, FACTS can also compensate reactive power.
Phase shift transformers (PST) can basically achieve the same, but their design is different. The operating principle bases on the insertion of a voltage source into the grid to control the active power flow, which depends in general only on the different network line impedances. For that reason, the PST inserts an additional voltage with 90 degrees phase shift compared to normal phase voltage. Therefore a well defined phase shift between primary and secondary side occurs.

3. High Voltage Direct Current Transmission (HVDC)

For the transmission of large amounts of electrical energy over long distances (which can be even more than 1000 kilometres), the high voltage direct current transmission (HVDC) is a good solution. No reactive power needs to be transmitted and a compensation of suchlike can therefore be omitted. Furthermore, there are no (capacitive) charging currents. These are very important factors, especially for sub-sea connections.
With the help of HVDC it is possible to connect grids with different frequencies or to run them in an asynchronous mode. It is also possible to interconnect grids with different frequencies without a raise of short-circuit currents. Because of the nature of direct current, no frequency effects or stability issues can occur at HVDC. Moreover, there is no skin effect at DC, so the efficiency of conductor wires is improved. With HVDC it is possible to transmit more energy than with comparable HVAC systems.

China and India, for example are currently evaluating and planning HVDC systems with 800 kV.
HVDC systems are also more flexible and are better to control than HVAC systems. The disadvantage here is the need for converter stations, which require large spaces and are expensive to erect. Additionally, the occurrence of harmonics and the need of reactive power in these substations need to be named here, HVDC systems generally have only a restricted overload capability as the converters is limiting this.

4. Transmission Systems

Because of the changes in the framework of the electricity market, the facility for the transmission of electricity have been completely reassessed. A so called energy-economical necessity is now one of the most important factors for driving decisions. With the liberalisation of the energy market, the flow of electrical power changed and increased dramatically during the last years.
New transmission lines in the high voltage and very high voltage levels are urgently needed in several countries to secure the supply with energy. Also the (n-1) criteria is still important although it is violated in several parts of the European grid.
Transmission systems therefore have to cope with several requirements:

- Reliability of supply
- Operational conditions
- Environmental requirements
- (Civil) engineering feasibility
- Economics

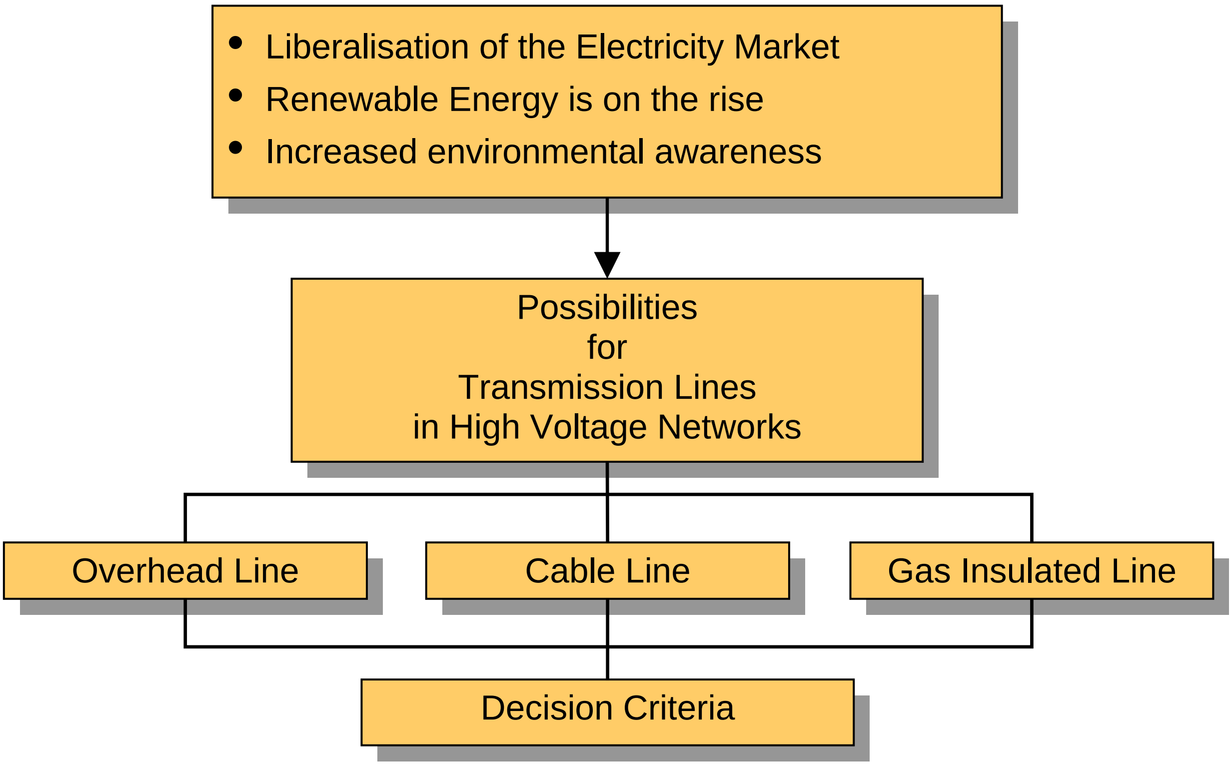

Figure 1 Framework for different Transmission Line Technologies

There are also several scenarios which are dealing with the usage of renewables (offshore wind, solar, hydro) on big scale. Such concepts can only be realised with high voltage transmission systems that are able to transfer notable quantities of electrical energy over large distances.

Overhead Lines

Energy transmission with overhead lines is by far the system with the longest time in service and operational experience. With air as insulating material and long distances and spaces it is possible to handle even very high voltages comparatively easy.
Overhead lines are normally also easy to construct and to repair. Their good operational behaviour and long life time of 40 years or more is outstanding. Due to its construction principle, overhead lines have the smallest capacitive charging current. The natural power P_{nat} is the design criteria here, but the thermal power is a multiple of P_{nat} .
Although overhead lines have the highest failure rate, this is not really an issue as most failures are arc failures (caused by atmospheric discharges for example). Depending on the network operation strategy, most of such failures do not have serious consequences.
On the other hand, the visual impairment of landscape trough the lines is a negative factor.
Low electromagnetic fields can be achieved by distances and system arrangement. Overhead lines have furthermore high losses and high operational costs, caused by losses dependent on the electrical current.
But then, overhead lines have a very short time of unavailability, in fact the lowest of all transmission systems. The investment costs are also the lowest, when compared to cable lines and GILs.


Figure 2 Overhead Line

Cable Lines

With the advent of suitable synthetic materials for high voltage application, cables are nowadays manufactured from such synthetics like polyethylene for example (PE, XLPE). Besides that, there are still long lengths of cables with Oil-paper and Polypropylene Laminated Paper (PPLP) in service.
Such PPLP-cables have very little losses and a higher electrical strength when compared to cables with oil-paper-insulation. In terms of an environmental friendly system, cable made of synthetic are suited best. Unfortunately, the synthetic materials are facing aging processes in service. Nevertheless, nowadays they can be applied to voltage levels of up to 500 kV.
A high voltage cable can be basically represented as a capacitance. This is the reason for the limited line lengths, because the reactive charging current needs to be compensated.
The thermal limit of the dielectric marks the restrictions in transfer capacity and also overload capability. For continuous operation, the thermal power is S_{therm} decisive.

For high voltage cables, P_{nat} is considerable larger than S_{therm} (factor of about 2...6)

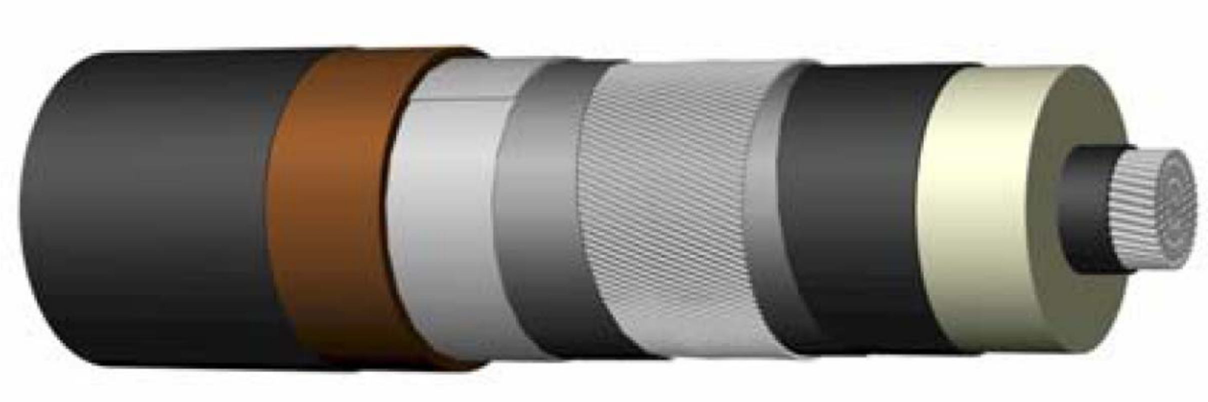

Figure 3 Cross-linked polyethylene (XLPE) cable for high voltage application

With the usage of thermal bedding and cross-bonding it is possible to achieve a notable loading capacity nevertheless. There is basically no electrical field on the surface above a cable line. The failure rate of cable lines is, when compared to overhead lines, reduced. But the time of unavailability is significantly higher, as failures normally need long repair periods. Investment costs for a cable line are about factor 3 to 6 higher than for overhead lines but the operational costs are only the half of overhead lines.

Cable lines also need much space and they can dry out the soil locally. The (agricultural) usage of line routes is very restricted. Furthermore, the threshold value for the magnetic field (100 µT) can be exceeded. The overload capability of cable lines is very limited and overload conditions have a direct influence onto the total lifetime. It is also necessary to install PD-monitoring systems on bushings and to have a temperature monitoring systems on critical sections.

Gas Insulated Transmission Lines (GIL)

Currently, the gas insulated transmission lines (GIL) are in their second generation. Such lines are using a mixture of Sulphur hexafluoride (SF_6) and nitrogen (N_2) at pressure levels between 3 and 6 bars.

With GILs it is possible to transmit high quantities of electrical energy, also over large distances. At present, there are only few short sections of with lengths of several 100 metres installed world wide.

Different methods exist for the laying of GIL: in tunnels or ducts. The direct laying into the soil might be possible but this has not be conducted in practice yet. Because of the co-axial conductor arrangement, which is housed in pipelines, it necessary to compensate the axial thermal expansion of the tubes. The interconnections between the single tube sections have been problematically within the first GIL generation but with the introduction of

Figure 4 Gas Insulated Transmission Line (GIL)

the second generation this has been solved.
As SF_6 has environmental impact, it is necessary to install gas monitoring devices along the route.
The advantages of GILs are justified in the high transmission capacity, high overload capability, low dielectric losses, low mutual capacitance and a very good ability for heat dissipation to the surrounding environment. It is also expected that a GIL has a very long lifespan, as there are nearly no aging processes taking place.
Compared to other technologies, gas insulated transmission lines have the lowest electromagnetic fields of all transmission systems and also very little losses during operation (even lower losses than cable lines)..
GILs make heavy demands during production and operation in terms of purity and gas-tightness. Additional systems, for example, gas-monitoring, failure location and partial discharge measurements need to be installed. As failures in GILs often result in long repair periods, the unavailability is higher than for cable lines. At present, there are only short distances in operation, so no experience with long(er) transmission lines exist. And although the costs of a GIL could be reduced notable with the introduction of the second-generation GILs, they are still 7 to 12 times higher than the costs for an overhead line.

5. Outlook

Nanotechnology

Nanotechnology is applied in cables for direct and alternating current. At present, cable technology enables the usage of voltages up to about 500 kV. With the help of nanotechnology and for example, nanofillers, it is possible to reduce the effects of space charges within the cable. They can lead to an improved partial-discharge behaviour and moreover, the field strength can also be raised.

Figure 5 High-Voltage Transmission Cables with Nanofillers

High Temperature Superconductivity (HTS)

Superconductivity in cable lines is currently a matter for the medium voltage level networks, where new developments are applied at present. Superconductivity can lead to reduced losses and a lowered weight of a cable section. Furthermore, the alignment of a cable system can be more compact here, which is important in areas with little space available, for example connections in urban areas.
Currently, the temperature which is necessary for the superconductivity to work is in the region of 138 K (-135° C).

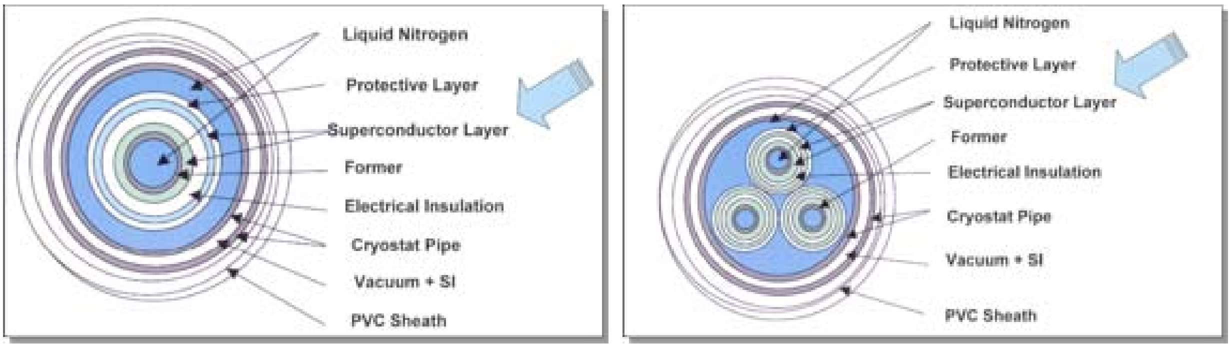

Figure 6 Cables with Superconductivity

6. Resume

Every transmission system has to cope with several different and sometimes even diametric requirements. The issues of energy losses are making heavy demands to energy transmission systems. Basically, three effects are occurring: the joule effect which is responsible for the heating of conductors. Furthermore, the magnetic and dielectric losses for energy stored in the magnetic field and within the insulating material respectively.
Possible remedies for this issue could be the usage of transformers with very little losses, for example. Also the application of superconductivity in transformers and for cable lines can reduce the loss of energy dramatically. With the advent of nanotechnology in electrical engineering, new materials can be used for transmission systems and existing technologies can be improved. The application of (HV)DC for transmission systems is a possibility to reduce losses and to cope with stability issues. Finally, the usage of Ultra-High-Voltage (UHV) in alternating current transmission systems is a practicable solution.

HVAC:

A HVAC transmission can be applied to all 3 transmission systems (overhead lines, cable lines, gas insulated transmission lines). The voltages, which are currently possible in terms of technology and economy are 1500 kV for overhead lines, 500 kV for cable lines and about 550 kV for gas insulated transmission lines. For the GIL it would be possible to also have higher transmission voltages.

HVDC:

Currently, HVDC systems are used for overhead lines and cables. The application of direct current in gas insulated transmission lines is currently under research. About 1000 kV can be achieved with HVDC on overhead lines. Oil-filled cables reach voltage levels of about 500 kV, whereas XLPE are often limited to 200 kV (space charges) in the transmission sector, but with the help of nanofillers, higher voltages are also possible.

7. Summary

To sum up, HVAC energy transmission is possible for each of the three transmission systems. The application of cables and GIL is currently limited to short lengths and to special applications, for example: in urban areas, tunnels, underpasses etc. Therefore there are no experience and no total costs for the application of these systems for long distance energy transmission available. The usage of ultra high voltages (1000 kV) for long distance transmission systems seems to be reasonable from the present point of view within a manageable time scale.
HVDC is a technology with big potentials in the near future. Projects for long distance HVDC with 800 kV are currently in planning. Basically, HVDC can be applied to overhead lines and cables. The applicability onto GILs needs to be researched first.

In an economic view, the overhead line is the favourable system. The costs of a cable line are about 2 to 3 times and the costs of a GIL are about 4 to 6 times higher. From the technical and economical point of view, the overhead line is currently also the best solution.

8. Literature

/1/ Q. Bui-Van et.al, "***Long-Distance AC Power Transmission and Shunt/Series Compensation overview and experiences***", Cigre Session A3-206, 2006

/2/ Cigre Working Group 37.27; "***Ageing of the System – Impact on Planning"***, Brochure 176, December 2000

/3/ V.F. Lescale, "***Power Transmission with HVDC at 800 kV***", Cigre Session B4-106, 2006

/4/ Cigre Working Group 14.20; ***"Economic Assessment of HVDC Links"***, Brochure 186, June 2001

/5/ Cigre Joint Working Group 14/37/38/39.24; ***"FACTS Technology For Open Access"***, Brochure 183, April 2001

/6/ Cigre Working Group 22.14; ***"High Voltage Overhead Lines - Environmental Concerns, Procedures Impacts and Mitigations"***, Brochure 147, October 1999

/7/ G. ORAWSKI; ***"Overhead Lines – The state of the art"***, Power Engineering Journal, October 1993

/8/ Michael MUHR; ***"Machbarkeit und Betriebsmöglichkeiten von langen Kabelstrecken im 380 kV Übertragungsnetz"***, Vortrag VEÖ, Wien, September 2002

/9/ Wolfgang LAURES, "***Untersuchungen zum Einsatz von Höchstspannungskabeln großer Längen in der 400-kV-Ebene***", Dissertation Universität Duisburg-Essen, April 2003