Federal Ministry for the Environment, Nature Conservation and Nuclear Safety

MARKET INTRODUCTION PERSPECTIVES OF INNOVATIVE TECHNOLOGIES SUPPORTING INTEGRATION OF RES-E

FINAL REPORT

Imprint

Published by: Federal Ministry for the Environment, Nature Conservation and Nuclear Safety Public Relations/Service -11055 Berlin - Germany Email: service@bmu.bund.de

Internet: www.bmu.de/english
www.erneuerbare-energien.de

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Date: 21 January 2008

Scope of work

In support of the Gleneagles G8 Plan of Action, IEA's Renewable Energy Unit is publishing the study “Grid Integration of Electricity from Renewable Energy”.

Ecofys has been contracted by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety to support this study and assess the capabilities and barriers of new and emerging technologies for improved integration of RES-E in power systems.

The scope of work of this study is

- to classify non-standard and innovative technologies, which are not yet commonly applied in power systems planning and operation,
- to identify their most promising areas of application,
- to reveal potential barriers in the context of regulation, permission and electricity market design for the introduction of these technologies.

The selection of technologies assessed in this study focuses on those technologies and operation concepts that are widely discussed as most promising with respect to their benefits in supporting the targeted future of power systems: highly flexible markets, high shares of renewable energies, high efficiency and cost-effectiveness.

The result of this assessment is presented in technology-specific fact sheets and summary tables.

Table of contents

1 Summary

Electricity markets and networks must continue to provide all consumers with a highly reliable, flexible, accessible and cost-effective power supply while increasingly integrating small distributed power sources and high shares of renewable energies (RES-E) with fluctuating, variable power output (RES-E_v).

Power industry offers a variety of innovative devices, network assets and operation strategies to assist the evolution of power system towards increased flexibility and improved acceptance for higher shares of RES-E_v.

Several of these innovative technologies are widely discussed but far from being commonly applied in power system planning and operation. A closer look at the current status of implementation reveals specific benefits and stepping stones. The technologies assessed in this study belong to three groups: (1) technologies for improvements within the existing infrastructure, (2) technologies for new transmission infrastructure development, and (3) technologies to implement new strategies for network operation.

(1) Technologies for improvements within the existing infrastructure

As power generation from renewables is in many cases located at far distances from load centres, enlarging the power transport capacities is an obvious measure for improving the integration of RES-Ev.

By means of *rewiring of existing lines with low sag, high-temperature wires*, the overhead line capacity can be increased by up to 50 %, as electrical current carrying capacity directly depends on the power line sag and the line temperature. Depending on the specific situation, rewiring may be possible without interaction with permission procedures.

Another measure to increase transport capacities within the existing network infrastructure is based on a change in the operating procedure. By moving away from fixed security rating to *dynamic line rating*, which benefits from the effect of conductor cooling by winds, higher transport capacities are possible. Apart from cost issues, delays in the wide-spread introduction of dynamic line rating arise from regulatory barriers. In several OECD member states, the process of introduction of standards allowing the dynamic rating is still pending.

(2) Technologies for new transmission infrastructure

The continuous renewal of electricity networks requires significant investments. This is not solely due to increasing share of RES-E_v in the power system. Instead, network upgrade, restructuring and modernisation are as well required by aging infrastructure and market liberalisation. The most efficient way forward will be to incorporate new technologies and solutions when planning and executing asset renewal.

The use of *underground transmission cabling* can speed-up the permission construction of new transport lines, especially when the permission of new overhead lines is difficult. The main barriers of transmission cabling are that the investment costs for underground cables are still higher than for overhead lines. But the cable/line costs ratios differ significantly over the voltage levels and have also changed dramatically in the last years. Moreover, economic feasibility has also to take into account line losses.

High voltage direct current (HVDC) transmission is a promising solution especially for bulk power transport of wind power. Not only for connection of offshore wind farms to land, but also for long-distance transmission to load centres over large distances, thus reducing losses and also avoiding undesired load flows. As a barrier, the technical planning has to take into account that realizing meshed, multi-terminal systems is complex, in contrast to alternating current (AC) systems. Controlling power flow in a meshed, converter-based DC system requires good communication between all the terminals and power flow must be actively regulated by the control system.

Power electronic devices for load flow control can play a major role when there is a need to respond to dynamic, fast-changing, network conditions. So-called FACTS (Flexible AC Transmission Systems) based controllers enhance the static performance, i.e. towards increased loading and improved congestion management, and also the dynamic performance of power systems. These are valuable services to increase power system acceptance for RES-E_v. Nevertheless, a major challenge for the introduction of FACTS devices still consists in the competition with standard solutions, such as series capacitors or phase shifting transformers.

(3) Technologies to implement new strategies for network operation

On-line dynamic security assessment provided by *Wide-area monitoring and protection systems* may substantially reduce traditional conservative assumptions about operational conditions. Hence, powerful and monitoring-based system state estimators can increase the actual transfer capability of a power system. This will enable network operators to react in close-to-real-time for trading, fault prevention and asset management. In that way, the required reliability and system performance can be maintained also with increasing contribution from RES-E_v sources. Challenges for the wide-spread introduction are found on organisational and regulatory level, due to the need for standardised monitoring technologies, synchronised data acquisition and online data exchange.

Many strategies for future power system evolution, e.g. published by the European SmartGrids initiatives and the US GridWise initiative, highlight the need for increased end-user involvement. In the context of managing increasing shares of RES-E_v, *demand-side management* offers promising options to improve the match between momentary generation and demand and hence to facilitate integration of $RES\text{-}E_v$ in power systems. The still existing barriers to link $RES\text{-}E_v$ generation to the demand side in such a way are usually due to market design. Load shaping related by RES-Ev generation would work best, when renewable generation capacities are part of the same balance area as aggregators of end-users participating in demand response programs. Such a change in regulation has been implemented in Australia with the establishment of open access to aggregators of demand response for all participants in the Australian electricity market.

The following two concepts can considerably improve dynamic network security with very high shares of $RES\text{-}E_{v,}$ but partially imply far-reaching changes in power system regulation.

As the majority of RES-E will also in future be connected to distribution networks, increased system responsibility on sub-systems level below transmission level is becoming essential in case of high RES-E penetration. *'Intentional islanding'* describes the purposeful fragmentation of the power system during widespread disturbances to create power "islands". According to the concept, these islands maintain continued power supply during disturbances of higher system levels. The challenge of technology market introduction is obvious, as the purposeful fragmentation of the power system cannot be field-tested. Up to now, experience is limited to case studies, laboratory test of equipment. Protection and safety concepts will need a thorough review.

So-called high-temperature superconducting (HTS) devices would allow substantial improvements in network operation, together with a significant reduction of losses. Especially the f*ault containment by superconducting fault-current limiters* is of high interest for improving transient system stability when more and more distributed generation with limited short circuit capacity are installed. It capitalises on the superconductors' ability to transition rapidly between very low resistance and high resistance – precisely when the (fault) current density exceeds a level specific to the superconductor. Yet, presently the use of cryogenic cooling fluids as a dielectric material in high voltage environments is still limited to 30 kV. Higher voltage levels have to be reached to allow the envisaged application of fault-current limiters in transmission networks.

The way forward

Decision-making on the introduction of technologies has to take into account a wide range of aspects. There are many interdependencies between the technologies described above. In distinct situations they can be alternatives, e.g. introduction of FACTS versus upgrading of lines. In other situations they provide options for combinations.

Manufacturers seeking more cost-efficient devices, together with regulators and standardisation bodies working on more flexible power system operation, as well as network operators with a pro-active attitude towards the combination of renewables and innovation in power systems are key actors in this context. They will ensure a reliable, flexible, accessible and cost-effective power supply with increasing shares of renewable energies.

2 Innovative technologies in a demand pull / technology push analysis

2.1 Introduction

Renewable energy sources for electricity generation (RES-E) are on the way to their full scale exploitation. All around OECD countries their share has risen continuously during the past ten years. Renewables provide sustainable electricity while at the same time they affect also significantly the design and operation of the electricity system.

In parallel to the deployment of renewables, the liberalisation of electricity markets has been developing. In this context, grid operators try to operate the electricity grid in a more efficient and cost-effective way. But also investments in new grid infrastructure have been low in many countries in the past to keep costs down.

However, the expected and intended further increase of variable output renewables ($RES\text{-}E_v$) cannot be realised without extension, re-structuring and optimised operation of the current electrical system. In the perspective of the ongoing changes, the reliability and adequacy of generation portfolios, of transmission and distribution grids have to be addressed. Among others, substantial additional transmission capacities will be required to transport large-scale offshore wind power to the load centres.

These and many other challenges that fall in line the deployment of renewables require new technologies, as well as planning and operation methods to be applied. A variety of these technologies is already under development, yet their wide application is still pending. This study reviews the status of a selection of new technologies and elaborates on the barriers for their application.

2.2 Demand pull related to power systems evolution

A demand pull / technology push approach analysing the evolution of power systems and electricity markets leads directly to demand pull arising from power system visions formulated in strategic documents such as the European "SmartGrids Vision" and the US GridWise vision.

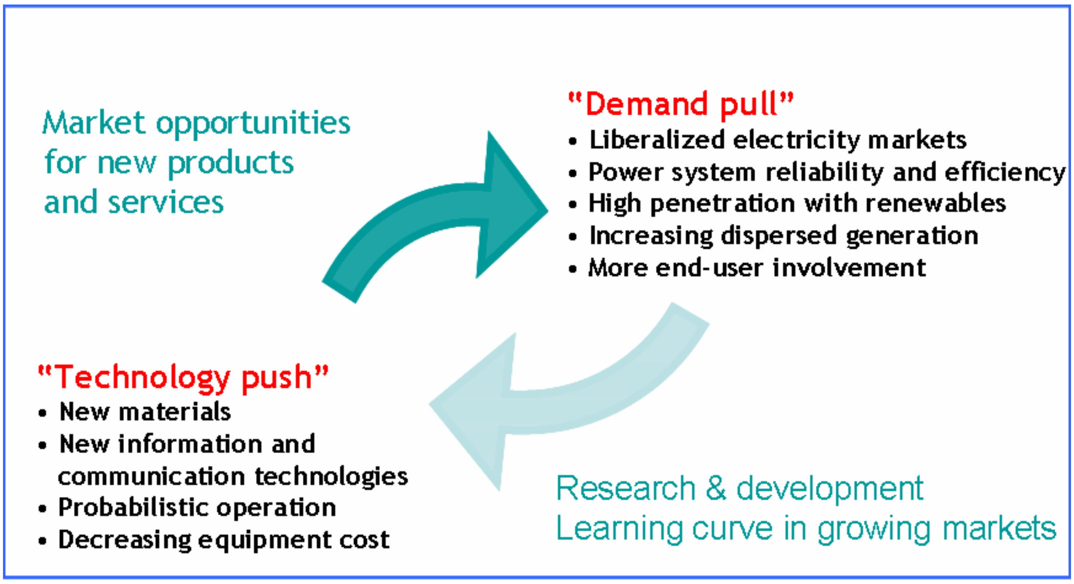


Fig. 1: Driving factors in a demand pull/ technology push analysis of power systems evolution

The establishment of a common strategy for the development of Europe's electricity networks was set in April 2006 when the paper 'Vision and Strategy for Europe's Electricity Networks of the Future' was published. According this vision paper [EC2006]:

> "… future electricity markets and networks must provide all consumers with a highly reliable, flexible, accessible and cost-effective power supply, fully exploiting the use of both large centralised generators and smaller distributed power sources across Europe. End users will become significantly more interactive with both markets and grids; electricity will be generated by centralised and dispersed sources; and grid systems will become more inter-operable at a European level to enhance security and cost-effectiveness."

The US GridWise initiative highlights the role of innovative technologies in this context:

> "The 'technology readiness' of critical electric systems needs to be accelerated, particularly for high-temperature superconducting cables and transformers, lower cost electricity storage devices, standardised architectures and techniques for distributed intelligence and 'smart power' systems".

2.3 Technology push

Power industry offers a variety of new, emerging technologies for the evolution of power systems. Key features of these electrical power technologies and innovative information systems and methods include:

New information and communication technologies, including advanced sensors and measurement for the acquisition and transfer of critical measures, as well as new data management concepts.

Probabilistic operation, including flexible, optimised reaction to network fault conditions, unusual transient behaviour and post-event recovery

New materials and devices, among others in the area of high-temperature superconducting devices.

Decreasing equipment cost through material and equipment R&D as well as by economy of scale.

2.4 Classification of technologies analysed

The following technologies and operation concepts are widely discussed as most promising with respect to their benefits in supporting the targeted future of power systems: highly flexible markets, high shares of renewable energies, high efficiency and cost-effectiveness.

Improvement within existing infrastructure

1. Rewiring of existing lines with high-temperature conductors
2. Dynamic line rating

New transmission infrastructure development

3. Transmission cabling
4. HVDC transmission
5. Power electronic devices for load flow control (FACTS)

New operation strategies

6. Wide-area monitoring and protection systems
7. Demand-side management
8. Intentional islanding and black-start capable sub-systems
9. Fault containment by superconducting fault-current limiters

Decision-making on the introduction of technologies has to take into account a wide range of aspects. There are many interdependencies between technologies listed. In distinct situations they can be alternatives: e.g. Introduction of FACTS vs. upgrading of lines. In other situations they provide options for combinations.

3 Technology Profiles

The assessment of capabilities and barriers of new and emerging technologies in this chapter focuses on

1. Application and expected benefits:
    - **Static system performance** (increased line capacity, congestion management, reduced system losses),
    - **Load / generation balance** (mitigate increase in reserve demand induced by RES-E_v),
    - **Transient performance** (i.e. return to standard conditions after faults; increased stability limits),
    - **Acceleration** of infrastructure development.

2. Technology status and experience:
    - **Experience level** between laboratory tests via field-test to market implementation.

3. Challenges and efforts needed:

One or several out of

- **Research and development on equipment** (e.g. materials, manufacturing),
- **Information Technology and operation strategy** (e.g. communication devices, data acquisition and processing),
- **Cost reduction potential** (especially in comparison to existing or competing technologies),
- **Regulation, market design** (e.g. when market incentives fostering the introduction of specific technologies still have to be developed),
- **Standards and permission** (e.g. when the introduction of specific technologies is not yet covered by applicable standards).

3.1 Improvements within existing infrastructure

3.1.1 Rewiring with high-temperature conductors

1. Application and expected benefits

Increasing infeed by RES-E_v can lead to momentary overloading of power lines.

Increase in transmission line capacity up to 50 %

The power transmission capacity directly depends on the power line sag and the line temperature. As standard conductors for transmission lines can be operated up to a temperature of approx. 80° C only, one way of increasing the transmission capacity is refund with high temperature low sag conductors that can be operated up to 150° C.

Using these conductors, increase of the electrical current carrying capacity of the transmission line is possible for the same conductor diameter without increasing the line sag. Depending on the specific situation, rewiring may be possible without interaction with permission procedures. Hence, the option potentially allows dramatic acceleration of capacity extension.

Due to the potential increase to 150 % overhead line capacity, reconductoring is technically and economically advantageous in cases where existing overhead lines have to be dimensioned for momentary peak loading by high amounts of installed RES-E_v capacities (especially wind power).

2. Technology status and experience

Promising application of thermal resistant aluminium (TAL)

The following four different types of thermal resistant aluminium (TAL) conductors are based on an alloy of aluminium and in application in different stages [FIERS2007]:

- Gap conductors were one of the first solutions. They are composed by a steel core that serves as the mechanical carrier and a loose TAL conductor that surrounds the steel core. Gap conductors have good sag characteristics but their installation is relatively complex and expensive. They are only rarely applied in Europe.
- ACSS (Aluminum Conductor Steel Supported) are composed by soft glown aluminium conductors that are bound over a very solid steel core. ACCS conductors are relatively cost-effective but their aluminium wires tend to slackening under load. They are applied in Canada.
- ACCR (Aluminum Conductor Composite Reinforced) are composed by a ceramic composite that replaces the steel core. ACCR conductors have good sag characteristics but their sensitivity to shear forces are still unknown and their costs are very high. They are not applied the United States but not in Europe.
- Invariant conductors such as STACIR/AS, STACIR and TAL/HACIN conductors. They are based on an alloy of aluminium and nickel that reduces the thermal expansion coefficient to a third of a comparable steel core. As most promising appear TAL/HACIN conductors that were successfully performed in 2004 by the Suisse TSO EGL Grid on their

380 kV transmission line Sils – Soazza – Forcola as an example. Invariant conductors have good sag characteristics, can use conventional cable structures and standard fittings. But their costs equal 2.5 to 3 times the costs of conventional Al/St cables.

3. Challenges

Technical restrictions and cost reduction potential

Depending on the conductor type, increased resistance of high-temperature conductors can lead to an increase of line losses. In some situations the higher specific weight can also affect the mechanical design of the masts.

Depending on network specifications, also neighbouring components (switches, transformers) have to be upgraded to cope with the higher transmission capacity.

The magnetic field that surrounds high temperature conductors increases proportionally with higher conductor currents. Therefore, legally defined acceptable immission levels for magnetic fields in the vicinity of the overhead line may need assessment. In case of violated standards in these specific cases modifications in ratings or conductor geometry may be required.

Investment costs for high-temperature low sag conductors are generally about 50 % higher than for standard conductors.

3.1.2 Dynamic line rating with temperature monitoring

1. Application and expected benefits

Increase in transmission line capacity up to 50 %

The momentary electrical current carrying capability of overhead lines is determined by the line's sag which in turn depends on the conductor temperature and, hence, also on the ambient weather conditions such as wind speed, air temperature and irradiation. These weather conditions are usually regarded by TSOs as fixed values that represent the worst case. Based on the worst case, the allowed maximum power capacity is determined by the network operators according to international (IEC / CENELEC) standards.

However, generation by wind power increases obviously with rising wind speeds. Since the wind tends to cool the overhead line's conductors the line's sag is reduced and the transmission line in respective areas can carry more power. It was shown that increase of transmission capacity correlates significantly with an increase of wind generation.

This correlation can be used through different online capacity rating methods: measuring of conductor temperature, metering of weather conditions or monitoring of the mechanical tension along the transmission line route. Also the installation of temperature or line sag sensors at certain sections of the transmission line is possible. The application of these methods can increase in the transmission line capacity by up to 50 percent.

As a simplified approach, a standard with seasonally variant weather conditions could already slightly increase transmission capacity during the colder season. Both, seasonal and dynamic rating, are technologies available in short term and therefore can meet momentary demand for increased transmission capacities whereas new overhead lines are built in the medium and long term.

2. Technology status and experience

Successfully completed field-tests

The technology is unevenly applied among OECD member states. A first Transmission Line Monitoring System was installed by Virginia Power, United States in 1991 and then developed to series maturity. Since then, over 300 Transmission Line Monitoring Systems have been installed at 95 utilities in over a dozen countries on five continents including the United States, Canada, Finland, Sweden, Denmark, Belgium, Germany, Spain, Argentina, Norway, Poland, the Netherlands, Brazil, Australia, New Zealand, and the Middle East. Over two thirds of the 30 largest utilities in North America apply these monitoring systems (e.g. CAT-1), and over half of those utilities operate these systems in real-time to provide accurate real-time ratings to utilities' EMS/SCADA. [VALLEYGROUP2001]

Also grid operators in OECD member states having expressed reluctance with respect to the application of this technology in the past, currently, are actively investigating the potential benefits. E.ON Netz, for example, conducted a one year field test, with dedicated focus on increased wind power penetration. In the respective area in the North of Germany substantial curtailment of wind power was required during the last years because of the mismatch between installed wind capacity and nominal transmission capacity of the existing overhead lines. Measured with speeds and other weather data from specific sites were send to the TSOs master display where the momentary capacity was computed and shown to the operation engineer. In line with earlier findings, it turned out that transport capacity of a 110 kV line could temporarily be increased to up to 150 % of its nominal power and, hence, this approach led to a reduction of wind generation curtailment of over 80 % in the region considered. Thanks to these promising results, dynamic line rating with temperature monitoring is to be applied also in further 110 kV-circuits in Schleswig-Holstein from now.

The application of the technology in the 380 kV network is still premature. Throughout Europe, only four pilot projects exist [JARASS2007]. As an example, a dynamic rating system for overhead lines is presently installed in a 400 kV line of the Italy- Switzerland cross-border network. It consists of a system monitoring conductor temperature and predicting the maximum transmission capacity of the overhead line on the basis of the actual and foreseen meteorological conditions. [TEN-E2005]. One has to mention that the expected results from a 380 kV field test can differ significantly from the results for lower voltage levels. This is mainly due to higher stability requirements but also weaker correlation between wind speeds and load flows on the transmission level. A final evaluation for the application of dynamic line rating at the transmission level is still pending.

In order to maximise transmission capacity gains, the above mentioned seasonally dependent grid operation is being practised in the United Kingdom since the 1980’s, and in the Netherlands since the late 1990’s [ECOFYS2006].

3. Challenges

Regulatory barrier: Necessary revision of standards

Introduction barriers arise mainly from (national) regulatory barriers. In several OECD member states, the process of introduction of standards allowing the dynamic rating is still pending.

The wide application of dynamic line rating at the extra high voltage level must be further analysed and developed regarding the transmission system security.

IEEE and CIGRE offer standard methods for the calculation of the transmission line ampacity in the steady state and dynamic states.

3.1.3 Summary tables - Improvements within existing infrastructure

Main applications and benefits

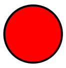
	Static system performance	Load / generation b...	Transient System perform	Acceleration of infrastr.
Rewiring with high-temperature conductors				
Dynamic line rating				

Primary benefits **Secondary benefits**

Introduction efforts focussing on ...

	RTD on equipment	ICT operation strategy	Cost reduction potential	Regulation / market design	Standards / Permission
Rewiring with high-temperature conductors		-		-	-
Dynamic line rating					

Not an issue **Strong efforts for progress**

	**Minor barrier**	**Focus of efforts for progress**

3.2 New infrastructure development

In many cases, the need for network upgrade is not solely due to increasing share of renewables in the power system. Network upgrade, restructuring and modernisation is as well required by aging infrastructure, market liberilasation, etc. itself. Much of the equipment of the present electricity networks was installed with a nominal design life of about 40 years. Increasingly this equipment is reaching the end of its life cycle.

As very significant investments will be required to renew this infrastructure, it is likely that the most efficient way forward will be to incorporate new technologies and solutions when planning and executing asset renewal.

3.2.1 Transmission cabling

1. Application and benefits

Accelerated realisation of grid extensions

Alternating current underground cables are discussed as an alternative to standard overhead electricity lines if new transmission capacity in the existing grid is needed. The construction of new overhead lines commonly faces strong public opposition from the locally affected people and their communities. Reasons for that are mainly concerns about environmental and visual impact and a widely spread public anxiety against exposure to magnetic and electric fields. Thus, the period to get the permits for the construction of new overhead lines can easily reach up to ten years [ICF2003].

Due to these very long approval times a number of important priority crossborder interconnections between some European OECD member states, as an example, were significantly retarded or are still not constructed. Underground cabling can accelerate grid extension, thereby, significantly due to lower public opposition against them. Underground cables are regarded as having only very little environmental impacts. For example, cables generally irradiate no or only very little electrical fields.

The use of underground cables in environmentally critical sections of cross-border interconnections may, therefore, solve the problems and also facilitate and speed-up the construction of missing links in the near future [EC2003]. The accelerated grid extension through underground cables will steadily gain more importance when it comes to the duly integration of large amounts of renewable energies into the electricity grids (e.g. offshore wind power). A very advanced regulation has been adopted by the German Federal State of Lower Saxony through its 'Law on the Planning Permission of Underground High- and Extra-High Voltage Lines' (Press releases see [LOWSAXONY2007a], [LOWSAXONY2007b]).

2. Technology status and experience

Successfully completed field-tests

Promising conductor technology for high voltage applications are XLPE cables [BRAKELMANN2004] and gas insulated lines (GIL) [FORWIND2005]:

XLPE Underground cables: Extruded polyethylene is used extensively worldwide at voltages up to 132kV. But only few industry projects with higher voltages were implemented yet. However, slightly over 100 km of 400 kV XLPE cable systems are installed in Europe. [ICF2003]

Gas insulated lines/cables (GIL): Gas insulated transmission lines are composed of pipes that house conductors in highly isolative sulfur hexafluoride (SF6) gas, which have high load-transfer capacity. The conductor lies in the middle of the tube separated from the tube by regular spacers. There is finally an outer protection of anticorrosion coating.

GILs may be promising for underground transport of high loads of power (above 2.000 MVA) in metropolitan areas and can be laid into tunnels or directly in the ground. Since experience with GILs is still very little compared to the application of XLPE underground cables, they are not regarded in the further analysis.

3. Challenges

Major challenge: reduction of investment cost

The investment costs for underground cables are still higher than for overhead lines. But the cable/line costs ratios differ significantly over the voltage levels and have also changed dramatically in the last years.

Costs for underground cables are continuously falling with their further application due to economies of scale from mass production. At the same time, their economic feasibility in comparison to overhead lines improves, if in addition to the investment costs for procurement and laying of underground cables, also the operating costs over the cable’s entire service life time are considered: Since electrical losses are at 2-4 times lower for underground cables than for overhead power lines, underground cables can become an economical viable alternative in specific situations.

Technical issues

Beside the economical feasibility also technical issues have to be taken into account when using underground AC cables instead of overhead lines:

a) Integration into meshed systems: Due to their lower impedance, underground cables tend to “pull” the electrical current from neighboring transmission lines on the cable. That can significantly influence the load flows especially in meshed grids. Through the application of a series impedance, this effect can be mitigated but only at the price of increased electrical losses.

b) Reactive power compensation: Underground AC cables are usually operated in a capacitive manner, especially when load flows are much smaller than their rated transmission capacity. Under this condition, underground cables consume reactive power that is needed by the alternating current to load and unload the cable’s capacitance. These capacitive load currents increase proportionally with the cable’s length and boost the electrical losses. Therefore, electrical power can only be transported over a limited distance through an underground AC cable. If transmission over longer distances is required, underground AC cables need cost expensive reactive power compensation in several stations.

c) Magnetic fields: Basically, the magnetic field around an underground cable or an overhead line is proportional to the current in the conductors. The field decreases with the distance to the conductor. Because of the close arrangement of the conductors in case of 3 core AC cables, external magnetic fields are nearly negligible: the magnetic fields of the three conductors just compensate each other. However, because of capacity limitations of 3 core cables, underground transmission circuits are likely to use three single core cables. As a consequence of the distance between these cables forming one system, the external fields do not diminish and may amount substantial values. Whereas overhead line's conductors hang usually more than 15 m above the ground, underground cables are buried only 1-2 m in the ground. Thus, the magnetic field on the ground straight above the cable can be very high compared to overhead lines. However, the spatial expansion of a single three-phase cable system is usually less than of an overhead line and the magnetic field of a cable, therefore, decreases faster and reaches negligible values already some 5-10 m to the side of the cable. If underground cables were constructed in the very proximity of people, constructive measures like the laying in a steel tube could reduce the magnetic field straight above the cable significantly.

d) Required space: Depending on the voltage level and needed transmission capacity, underground cables occupy about five times less space than overhead lines. However, since the transmission capacity of a single cable is limited and multiple cables must be laid with a certain distance to each other in order to cope with the thermal losses, underground transmission for huge amounts of electricity still may result in some ten meters wide corridors. These corridors have to be cleared from plant with deep routs that would possibly damage the underground cable.

3.2.2 HVDC transmission

Application and expected benefits

High voltage direct current (HVDC) circuits have advantages over alternating current (AC) circuits for transferring large amounts of power over long distances. HVDC circuits have resistance but do not have reactance associated with AC, resulting in a lower voltage drop than in case of AC circuits. Also, inherently in the technology concept, HVDC circuits can be easily controlled to carry a specific amount of power, thus improving controllability of power flows, helping to avoid overload, especially after components outages, and to mitigate loop flows problems.

HVDC attractive for bulk RES-E power transport

For the special case of RES-E_v it is the bulk power transport of wind power that is interesting. HVDC is therefore a promising solution not only for connection of offshore wind farms to land (projects now underway) but also for long-distance transmission to load centers over several hundred kilometers, thus reducing losses and also avoiding undesired load flows.

Technology status and experience

Since decades, extensive experience has been gathered with HVDC technology for interconnectors between synchronous zones.

High power HVDC transmission technology also offered new dimensions for long distance transmission. This development started with the transmission of power in a range of a few hundred MW and was continuously increased. Transmission ratings of 3 GW over large distances with only one bipolar DC line are state-of-the-art in many grids today. World's first 800 kV DC project in China has a transmission rating of 5 GW and further projects with 6 GW or even higher are at the planning stage. In general, for transmission distances above 700 km, DC transmission is more economical than AC transmission (≥ 1000 MW). Power transmission of up to 600 - 800 MW over distances of about 300 km has already been achieved with submarine cables, and cable transmission lengths of up to about 1,000 km are at the planning stage. Due to these developments, HVDC became a mature and reliable technology. [SIEMENS2007]

Advantageous combination with voltage source converters

Voltage source converters (VSC) present a number of advantages over the conventional line commutated converters (LCC). After fast switching power semiconductors became available for high voltage application, VSC transmission systems were developed (e.g. HVDC PLUS [Siemens], HVDC Light [ABB]). The ability to stabilise voltage at AC terminals and reduced space requirements is are specific advantages of this technology potentially in particular in case of grid connection of offshore windfarms.

Challenges

In the technology evaluation the (specific) losses of the electronic power converters have to be included. In particular, in cases where the loading of the DC transmission is low for an substantial share in time (e.g. related to wind generation) this aspect may substantially influence the techno-economic performance of this option.

When the converters are integrated to the AC substations with very low short circuit strength, special attention has to be paid to the transient behaviour due to frequent operations like converter energisation and converter deblocking.

Multi-terminal systems are complex

In contrast to AC systems, realizing meshed, multi-terminal systems is complex, as is expanding existing schemes to multi-terminal systems. Controlling power flow in a meshed, converter based DC system requires good communication between all the terminals; power flow must be actively regulated by the control system instead of by the inherent properties of the transmission line. The configuration of multiple terminals can be series, parallel, or hybrid (a mixture of series and parallel). Parallel configuration tends to be used for large capacity stations, and series for lower capacity stations. An example is the 2000 MW Quebec - New England Transmission system opened in 1992, which is currently the largest multi-terminal HVDC system in the world [ABB-FACTS*]*.

3.2.3 Power electronic devices for load flow control (FACTS)

1. Application and expected benefits

Advantageous where rapid response needed

Flexible Alternating Current Transmission Systems (FACTS) are power electronic based systems that provide control of AC transmission system parameters to enhance controllability and increase power transfer capability. FACTS controllers have been readily accepted as feasible means for power control for enhancing steady and dynamic performance of power systems during normal and abnormal operation conditions.

The use of FACTS devices can be an effective approach to remove or at least alleviate the transmission constraints that limit transfer capacity. Given the nature of power electronics equipment, FACTS solutions will be justified wherever the application requires one or more of the following attributes: rapid response, frequent variation in output and/or smoothly adjustable output.

FACTS controllers enhance the static performance (e.g. increased loading, congestion management, reduced system loss, etc) and dynamic performance (e.g. increased stability limits, damping of power system oscillation, etc.).

- Meshed Systems & Bulk Power Transmission: Power Flow Control
- Radial Systems & Parallel Lines: Impedance Control
- Weak Systems: Voltage Control

Increase in usable transfer capacity

Particularly, the installation of FACTS devices controlling the active power (Power Flow Controllers: PFC) can provide an alternative to increase transfer capacity in the short term. Moreover power flow controllers can be a temporary alternative to improve the network until reinforcement measures can be carried out.

2. Technology status and experience

Power electronic controllers form the basis of Flexible AC Transmission System (FACTS) device concepts, which have been under development for nearly twenty years and are now entering the third generation. The first generation of FACTS devices used power electronics to control large transmission circuit elements, such as capacitor banks, to make them more responsive to changing system conditions. Second generation FACTS devices were able to perform their functions, such as providing voltage support to a long transmission line, without the need for large, expensive external circuit elements. Both first and second generation FACTS devices are currently in operation in utility transmission networks.

The first installations were put into service over 20 years ago. In the year 2000, the total worldwide installed capacity of FACTS devices was more than 40,000 MVAr in several hundred installations [HABUR2002].

3. Challenges

Major challenge: competition with standard solutions

FACTS devices are required when there is a need to respond to dynamic (fast-changing) network conditions.

The introduction of FACTS solutions is usually compared to the conventional alternatives

- conventional series capacitors
- controllable series capacitors
- phase shifting transformers

The conventional solutions are normally less expensive than FACTS devices – but limited in their dynamic behavior.

The research challenges in this area lie in new devices and materials for high-current, high-voltage switching, new device configurations/systems and the control of these switching devices to optimise network support.

Co-ordinated control schemes to be developed

In highly meshed transmission networks a real increment in the transfer capacity between areas by means of fast controller (corrective control actions) can be accomplished in an appropriate manner only if a coordinated control scheme is implemented. A coordinated control implies that a device located somewhere in the interconnected network must actuate in a coordinated fashion with other controls to relieve overload or voltage limit constraint at some specific point after a contingency occurs. Coordinating the operation of multiple FACTS devices on such a time scale will require several other technological advances, including development of a wide-area, real-time information gathering system, on-line system analysis, and a sophisticated hierarchical control system [TEN-E2005]. See also section 2.3 New operation strategies.

3.2.4 Summary tables - New infrastructure development

Main applications and benefits

	Static system performance	Load / generation balance	Transient System performance	Acceleration of infrastructure
Transmission cabling				
HVDC transmission				
Power electronic devices (FACTS)				

Primary benefits **Secondary benefits**

Introduction efforts to focus on ...

	RTD on equipment	ICT operation strategy	Cost Reduction potential	Regulation / market design	Standards / Permission
Transmission cabling					
HVDC transmission					
Power electronic devices (FACTS)					

-	**Not an issue**	**Strong efforts for progress**
	Minor barrier	**Focus of efforts for progress**

3.3 New operation strategies

In general, the introduction of information and communication technologies delivers major advancement and opportunities to improve processes and operational control.

The integration of large amounts of RES-E_v requires increased data exchange. If these data are delivered to the different players in the electricity system in a transparent manner and via suitable 'platforms', this will enable these players to react in close-to-real-time for trading, fault prevention and asset management. In that way, the required and specified reliability and system performance can be maintained also with increasing contribution from RES-E_v sources.

3.3.1 Wide-area monitoring and protection systems

1. Application and expected benefits

Making use of information and communication technologies

If system limitations can be calculated for actual conditions rather than off line, the system can be operated closer to actually applicable limitations. These calculations require on-line measurements of actual loading, generation, and transmission system status. On-line dynamic security assessment may substantially reduce conservative assumptions about operational conditions. Hence, powerful and monitoring-based system state estimators can increase the actual transfer capability of a power system.

Wide area monitoring systems generate recommendations within minutes, based on steady state and dynamic contingency calculations using online measurements and the actual grid topology.

Wide area protection systems, create actions in >200 ms – 10 s, based on accurate measurement of voltages, phase angles, frequency in node units, co-ordinated by central computers. [BUCHHOLZ2006]

2. Technology status and experience

A monitoring system based on the phasor measurement (phasor measurement units - PMU) was originally introduced by Bonneville Power Authority (USA) in the early 1980'ies. It monitors voltage and current phase angles, which can be used to predict developing instability.

The TSO China State Grid started deploying wide-area monitoring systems in 2002. Today, China has installed 10 central computers with 200 to 300 PMUs in five regional and five provincial power systems. [REHTANZ2005].

In Europe, collaboratively exploited state estimators covering the control areas of several neighbouring TSO's may improve system performance, flexibility and robustness, in particular in relation to fluctuating load flows as a consequence of RES-E_v generation.

3. Challenges

Large investment in ICT infrastructure

The current generation of state estimators assumes steady state behaviour within their calculation intervals of some tens of seconds and applies probabilistic concepts only to a limited extent. Response times may be insufficient and / or reliability as well as quality of results may be compromised when dealing with alert or emergency situations. Progress may be achieved by further elaborating concepts for distributed computing, probabilistic and non-linear modelling and applying them to this application.

Computational concepts to be improved

Though not forming a fundamental challenge, also organisational issues as synchronised data acquisition, online data exchange between TSO areas and the use of standardised wide-area-monitoring technologies and conventions for system analysis and evaluation will require attention (see also [EC2006]).

Organisational and regulatory issues have to be tackled

Additionally, responsibilities may require re-allocation if the full range of benefits is to be deployed. The operation of the interconnected UCTE system is based on the principle that each TSO is responsible for its own control area. Implementing this principle the UCTE introduced a set of rules and procedures (i.e.: UCTE Operation Handbook). These procedures cover also operational situations when contingencies outside the control area of a TSO affect the operational conditions as well as the functioning of interconnections. All kinds of corrective measures remain under the sole responsibility of respective TSOs to the extent of their national commitments. When implementing concepts for collaborative state estimation and system operation, situations may occur where mitigation of constraints in one TSO control area is best achieved by an action in a neighbouring area. The regulative and organisational framework for such an optimisation still has to be developed. [TEN-E2005]

3.3.2 Demand-side management

1. Application and expected benefits

Demand-side activities offer promising options to improve the match between instantaneous generation and demand and hence to facilitate integration of RES-E_v in power systems.

Relevant aspects are:

- Dynamic pricing and time-of-use implementations that are based on variable pricing to customers..
- Demand bidding structures that allow direct participation of customers offering load reduction.
- Aggregation of many smaller demand-side resources (e.g., less than 1MW) for market participation

2. Technology status and experience

Routes of introducing demand-side measures are

(1) expansion of the already existing controllability of load (e.g. large industrial consumers) gradually towards populations of small scale applications (e.g. private consumers) and

(2) via further development of utility – consumer data exchange from automatic meter reading to two-way communication.

In order to incentivise these changes, appropriate market rules are prerequisite.

Changing market structure in Australia

A significant regulatory change has been implemented in Australia with the establishment of open access to aggregators of demand response for all participants in the Australian electricity markets. The most significant practical implementation has been the establishment of the commercial company Energy Response as an open access aggregator of demand response for all participants in the Australian electricity market. Energy Response provides its demand-side management services to retailers, transmission network service providers, distribution network service providers and the system operator. [SCHWAEG2007]

3. Challenges

Major challenge: market design

A major challenge to link RES-E_v generation to demand side is market design. Load shaping related to balancing needs motivated by RES-E_v generation will work best, when these generation capacities are part of the same balance area as aggregators of end-users participating in demand response programs. Wholesale market structures predominantly lack components stimulating demand-side measures.

In general, aggregation of many smaller demand-side resources (e.g., less than 1MW) for market participation requires updating operating procedures, computer systems, and business processes of regional operators and various demand-side market participants.

Automation of demand response is needed to affect widespread integration of end-use resources that could be made available to support grid and market operations.

Infrastructure investment

The typical program implementation requires the presence of interval metering and two-way communication systems. Of course, investments in the required hardware infrastructure have to be justified by profitable business concepts.

3.3.3 Intentional islanding and black-start capable sub-systems

1. Application and expected benefits

Purposeful power system sectionalization

As the majority of RES-E will also in future be connected to distribution networks, increased system responsibility on sub-systems level below transmission level is becoming essential in case of high RES-E penetration.

'Intentional islanding' describes the purposeful fragmentation of the power system during widespread disturbances to create power "islands". According to the concept, these islands maintain continued power supply during disturbances of higher system levels. The potential benefit is not in first instance uncompromised security of supply for the customers connected to the islanding network section. Most likely, it will be impossible to maintain a perfect balance between generation and load and, hence, load shedding will be a essential part of the scheme. Nevertheless, the concept promises to overcome the difficulties related to system recovery in case of highly decentralised generation at lower voltage levels. Synchronisation and reconnection of fragmented network sections is much easier and faster than restarting a system from a blackout without large synchronous generators at transmission levels [FUANG2003].

Of course, implementation of these concepts implies a paradigm change regarding the operation of distribution systems. As a consequence, design and operation of the networks and in particular of protection and control systems requires fundamental review and adaptation.

2. Technology status and experience

Case studies and component laboratory tests underway

The purposeful fragmentation of the power system cannot be field-tested. Up to now, experience is limited to case studies, laboratory test of equipment and transfer of experience from 'neighbouring fields'. In this context, research on 'Microgrids' at distribution level is of importance.

In the USA, several utilities (Vermont, Washington) are participating in Microgrids field tests under the supervision of NREL. Microgrids R&D projects have been carried out with support of the European Commission. (DG Research projects Microgrids, More Microgrids) [HATZ2007]

3. Challenges

major challenge: revision of standards

Introduction of islanding capabilities at distribution level implies a fundamental change of the design principles of nowadays power systems. Protection and safety concepts need a thorough review. As compromises related to these aspects cannot be tolerated, a roll-out of islanding capabilities has to be supported by positive experience and backed by established standards and guidelines. Additionally, existing assets will need adaptation or replacement. As a consequence, introduction of islanding capabilities will take time.

In the current revisions of standards, intentional islanding of DERs is not allowed due to worker and equipment safety issues. In the current revision of the standard IEEE 1547 “Interconnecting Distributed Resources with Electric Power Systems” [IEEE2003], these topics were stated as to be addressed by future revisions. An IEEE1547 intentional islanding subgroup has been formed.

3.3.4 Fault containment by superconducting fault-current limiters

1. Application and expected benefits

High-temperature superconductors (HTS) promise to substantially improve power distribution because of a significant reduction of losses.

Benefits for transient power system stability

Commercial experience with HTS technologies has up to now mainly been gathered in medical engineering. In the power sector, R&D efforts focus on superconducting cables (first installation in high-populated city centers), as well as generators, transformers and last not least HTS fault-current limiters (FCL).

HTS fault-current limiters can be of high interest for improving transient system stability with rising amount of generation with limited short circuit capacity installations. It capitalises on the superconductors' ability to transition rapidly between very low resistance and high resistance – precisely when the (fault) current density exceeds a level specific to the superconductor [KALSI2004]. Fault-current limiters may help to selectively reduce network meshing and thus limiting the effects of network faults.

High fault currents are a major source of outages on transmission and distribution systems. Controlling fault currents to 3-5 times rated current would greatly reduce these outages. In addition, line reactors, which are sometimes used to help control fault currents, can cause voltage instability by adding reactance to the system. This forces the utility to add other equipment to counter-balance the reactive element further increasing costs. HTS FCLs avoid this problem.

An HTS FCL can reduce potential fault currents from 10-20 times rated current to 3-5 times rated current. This can significantly reduce capital expenditures on the support infrastructure in the transmission or distribution system by dramatically reducing the costs of upgrading current breakers or even reducing the ratings and size of circuit breakers, eliminating the need for line reactors, and minimizing clearance requirements in substations [KALSI2004].

2. Technology status and experience

Laboratory tests underway

Development of HTS Fault Current Limiters to date has involved test installations at a number of electrical substations in USA.

The HTS industry currently consumes approximately 1000 km of 1G ("first generation") wire per year. The use of cryogenic cooling fluids as a dielectric material for 2G ("second generation") wires, especially in high voltage environments and under all operating conditions (transient, fault, etc.) is being investigated in laboratory test.

Commercial prototypes are expected around the year 2012 [NAVIGANT2006].

3. Challenges

major challenge: reaching higher voltage levels

Presently, the use of cryogenic cooling fluids as a dielectric material in high voltage environments is still limited to 30 kV. Much higher voltage levels have to be reached to allow the envisaged application of fault-current limiters in transmission networks.

3.3.5 Summary tables - New operation strategies

Main applications and benefits

	Static system performance	Load / generation balance	Transient System performance	Acceleration of infrastr.
Wide-area monit./ protection system				
Demand-side management				
Intentional islanding				
HTS Fault-current limiters				

Primary benefits **Secondary benefits**

Introduction efforts to focus on ...

	RTD on equipment	ICT operation strategy	Cost reduction potential	Regulation / market design	Standards / Permission
Wide-area monit./ protection system					
Demand-side management					
Intentional islanding					

HTS Fault-current limiters	-	-

-	Not an issue	Strong efforts for progress
	Minor barrier	Focus of efforts for progress

Abbreviations

B2B	Back-to-back (high voltage direct current connection)
CENELEC	Comité Européen de Normalisation Electrotechnique
FACTS	Flexible alternating current transmission system
FCL	Fault-current limiter
GIL	Gas insulated line
HVDC	High voltage direct current
HTS	High-temperature superconductor
IEC	International Electrotechnical Commission
LCC	Line commutated converters
PMU	Phasor measurement unit
PFC	Power flow controller
RES-E_v	Renewable energy sources for electricity production, with variable output
TAL	Thermal resistant Aluminium
TSO	Transmission system operator
VSC	voltage sourced converter
XLPE	Extruded polyethylene (underground cable)

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