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The 9th International Conference on AC and DC Power Transmission

19 – 21 October 2010, IET:London, Savoy Place, UK

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ACDC 2010

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Papers

Wednesday, 20 October

Session 1: System performance and planning
Chairman: Colin Davidson, *Alstom Grid , UK*

O1.1
Keynote
System Advantages in Conversion of AC Transmission Lines to DC
L O Barthold, *Imod, Inc., USA,* R Adapa, *EPRI, USA,* H Clark, Consultant, USA, D Woodford. Electranix Corporation, Canada

O1.2
Voltage Source Converter (VSC) HVDC for Bulk Power Transmission – Technology and Planning Method
D Westermann, *T.U. Ilmenau , Germany,* D Van Hertem, *Royal Institute of Technology, Sweden and K U Levnen, Belgium* , A Küster, *Swissgrid , Switzerland,* B Klöckl, *Verbund Austria Power Grid , Austria,* R Atmuri, *RBJ Engineering , Canada* **,** T Rauhala, *Fingrid , Finland*

O1.3
Coordination of Multiple Power Flow Controlling Devices in Transmission Systems
D Van Hertem, R Eriksson, L Söder, M Ghandhari, *Royal Institute of Technology Stockholm , Sweden*

O1.4
Analysis of Multi-Infeed HVDC Systems with Inverter and Rectifier Connected to the same AC Network
E Rahimi, A M Gole, *University of Manitoba , Canada ,* J B Davies, *Teshmont Consultants LP , Canada*

O1.5
Detailed Modelling of Large Interconnected AC/DC Systems using a Real-Time Digital Simulator
R P Wierckx, *RTDS Technologies Inc. , Canada , N Dhaliwal , Manitoba Hydro , Canada*

O1.6
The Role of FACTS and HVDC in the future Pan-European Transmission System Development
A L'Abbate, G Migliavacca, *ERSE (ENEA- Ricerca sul Sistema Elettrico) , Italy* , U Haeger, C Rehtanz, S Rueberg, *Technische Universität Dortmund , Germany ,* H Ferreira, G Fulli, A Purvins, *European Commission, Netherlands*

O1.7
Steady-state and Transient Performance of DC Transmission Systems based on HVDC Technology
G P Adam, O Anaya-Lara, G Burt, *University of Strathclyde, UK*

Session 2: FACTS and series compensation
Chairman: Peter Jones, *ABB, UK*

O2.1
Keynote
Series Compensation for Extended Utilization of Power Transmission Systems
R Grübaum, P Halvarsson, *ABB AB, Sweden , P Jones, ABB Ltd, UK*

O2.2
Introducing Series Compensation in the UK Transmission Network
C Hor, J Finn, *Siemens Transmission and Distribution Ltd, UK,* G Thumm, *Siemens AG , Germany,* S Mortimer, *Siemens PTI , UK*

O2.3
Enhancing the Transmission Capability using FACTS: The Finnish Experience
T Rauhala, J Jyrinsalo, H Kuisti, *Fingrid Oyj, Finland*

O2.4
Description and Evaluation of 3-level VSC Topology based STATCOM for Fast Compensation Applications
J Aho, *Alstom Grid, Finland,* A Syomushkin, R Jessler, *Alstom Grid, Finland*

THE ROLE OF FACTS AND HVDC IN THE FUTURE PAN-EUROPEAN TRANSMISSION SYSTEM DEVELOPMENT

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Abstract

The present paper focuses on FACTS (Flexible Alternating Current Transmission System) and HVDC (High Voltage Direct Current) transmission technologies. Particular attention is paid to different specific technical, economic and environmental features of these power electronics-based devices. Final aim of the paper is the investigation of the role that FACTS and HVDC may play towards the development of the future pan-European transmission system.

1 Introduction

In the European Union (EU), issues concerning security of energy supply, electricity market restructuring and increasing environmental constraints represent key drivers for new trends which may have significant impact on the design and the operation of the electric power system. This is particularly true for the European electricity grids, which are on the critical path to meet the EU's climate change and energy policy objectives for 2020 and beyond.
Concerning the European transmission network, the challenge will be the integration of very large amounts of variable renewable energy sources (RES), especially wind and also solar, into the power system, while keeping its reliability levels, in a liberalised background. To this scope, a more flexible transmission grid would be then needed. Furthermore, the ongoing energy market liberalisation process in Europe is leading to the steady rise of inter-area power exchanges, generally increasing the transmission network congestion. To address such issues, the solution of enhancing the power transmission capacity, traditionally realized by adding new High Voltage Alternating Current (HVAC) infrastructures, is nowadays seriously hampered by economic, social and environmental constraints. Thus, the need for evolution in the design and operation of transmission networks emerges in Europe: this will require a re-engineering process. Among the different measures to support such a process, a crucial role may be played by advanced power transmission devices like FACTS (Flexible Alternating Current Transmission System) and HVDC (High Voltage Direct Current) technologies.
The present paper focuses on these power electronics-based devices offering the possibility to increase transmission network capacity and flexibility and generally enhance system reliability and controllability with a limited environmental impact. These properties are especially important in a deregulated environment, where, in presence of more frequent and severe corridor congestions, fast-reacting FACTS and HVDC elements can efficiently avoid or relieve network constraints. This can then lead to a reduced need for building new HVAC lines with consequent environmental and economic benefits. Moreover, the deployment of FACTS and HVDC can allow a further, smoother integration of variable RES power plants into the European power system.
Within this background, the present paper aims also at investigating the role that FACTS and HVDC may play towards the development of the future pan-European transmission system. In fact, FACTS and HVDC elements may provide European Transmission System Operators (TSOs) with effective solutions to the several criticities they encounter nowadays in their grid planning processes.
This paper, which results from the ongoing activities within the European research project named REALISEGRID [1], is structured as in the following. Section 2 provides a short overview of transmission expansion planning processes. Section 3 and Section 4 respectively deal with the main technical, economic and environmental features of FACTS and HVDC, which can serve as a support for transmission planners in their decision-making process to select the most sound expansion alternative. The cost-benefit analysis represents a crucial stage of the transmission expansion planning process. Section 5 focuses on the development of the future pan-European transmission system, where these technologies may be effectively deployed. Particular attention is paid to the northern, eastern and southern edges of the ENTSO-E (European Network of Transmission System Operators for Electricity) system as well as the continental network up to 2030.

2 Overview of the transmission planning process

Transmission network planning is a very complex process and recent trends and challenges make it even more complicated.
In the past, before the electricity market liberalisation, in a centrally managed power system the system operator could in general control the whole power system: the transmission

network was then expanded with the aim to minimise both generation and transmission costs, while meeting static and dynamic technical constraints to ensure a secure and economically efficient operation.
Nowadays, in a liberalised environment, the TSO, responsible for the sole transmission, shall plan the expansion of its network by minimising transmission costs (investment and operation), overcome bottlenecks and pursuing maximum social welfare, when requested by specific regulation, while meeting static and dynamic technical constraints to ensure a secure and economically efficient operation. Moreover, the penetration of variable Renewable Energy Sources (RES) brings additional uncertainties posing further challenges to transmission planners: they have in fact to reliably integrate variable RES power plants into the grids and cope with rapid and less predictable flows changes so as to preserve an adequate level of security for the system. Socio-environmental constraints must also more and more be duly taken into account in the planning process [2],[3],[6].
The basic tasks of transmission grid planners can be summarised as in the following: to forecast the power and energy flows on the transmission network, drawing upon a set of scenarios of generation/demand evolution for the targeted period, within the market and regulatory framework; to check whether or not acceptable technical limits might be exceeded within the unchanged network, in standard conditions as well as in case of loss of system components (security analysis); to devise, in presence of criticalities, a set of possible transmission reinforcements/strategies that overcome the constraints and to select the one(s) having the best cost-benefit performance [2].
Central element of the transmission planning process is the cost-benefit analysis of the different transmission reinforcement options. It is then crucial to quantitatively assess the possible benefits provided by transmission expansion: this task, especially in a liberalised power system, generally represents a rather complex stage as the evaluation strongly depends on the viewpoint taken for each considered benefit [3]. In this respect, planning the transmission expansion by taking into consideration the options of applying advanced technologies, like FACTS and HVDC, needs to undergo a detailed screening of the benefits and costs related to the utilisation of these technologies.

3 Main FACTS features

3.1 Technical aspects

An abundant technical and scientific literature is available on FACTS (Flexible Alternating Current Transmission System) devices (see [11],[12] among others). These power electronics-based transmission technologies give the possibility to fast control one or more of the interdependent parameters that influence the operation of transmission networks. These parameters include e.g. the line series impedance, the nodal voltage amplitude, the nodal voltage angular difference, the shunt impedance, and the line current. The design of the different schemes and configurations of FACTS devices is based on the combination of traditional power system components (such as transformers, reactors, switches, and capacitors) with power electronics elements (such as various types of transistors and thyristors). The development of FACTS controllers is strictly related to the progress made by the power electronics. Over the last years, the current rating of thyristors has evolved into higher nominal values making power electronics capable of high power applications (up to thousands of MW). FACTS devices, thanks to their speed and flexibility, are able to provide the transmission system with several advantages such as: transmission capacity enhancement, power flow control, transient stability improvement, power oscillation damping, voltage stability and control. Depending on the type and rating of the selected device and on the specific voltage level and local network conditions, a transmission capacity enhancement of up to 40-50% may be achieved by installing a FACTS element [4].
In comparison to traditional mechanically-driven devices, FACTS controllers are also not subject to wear and require a lower maintenance. In general, FACTS devices can be traditionally classified according to their connection, as:

- Shunt controllers. Among the shunt controllers the main devices are the Static VAR Compensator (SVC) and the Static Synchronous Compensator (STATCOM);
- Series controllers. This category includes devices like the Thyristor Controlled Series Capacitor (TCSC) and the Static Synchronous Series Compensator (SSSC);
- Combined controllers. Elements such as the Thyristor Controlled Phase Shifting Transformer (TCPST), the Interline Power Flow Controller (IPFC), the Dynamic Flow Controller (DFC) and the Unified Power Flow Controller (UPFC) belong to this third category of FACTS.

The TCPST type includes the two subtypes of the Thyristor Controlled Quadrature Boosting Transformer (TCQBT) and the Thyristor Controlled Phase Angle Regulator (TCPAR).
FACTS devices can be also classified according to the power electronics technology used for the converters as:

- Thyristor-based controllers. This category includes the FACTS devices based on thyristors, namely the SVC, the TCSC, the TCPST and the DFC;
- Voltage source-based controllers. These devices are based on more advanced technology like Gate Turn-Off (GTO) thyristors, Insulated Gate Commutated Thyristors (IGCT) and Insulated Gate Bipolar Transistors (IGBT). This group includes the STATCOM, the SSSC, the IPFC and the UPFC.

The voltage source-based devices are the most advanced ones of the FACTS family, offering the possibility for a smoother, faster control of active and/or reactive power flow and/or nodal voltage amplitude independently of the current. The most complete and versatile (and costly) FACTS device is the UPFC, able to independently and simultaneously control active power flow, reactive power flow and nodal voltage magnitude. The UPFC has been so far applied only in three installations worldwide (all outside Europe: two in the United States, one in South Korea), while the most widespread FACTS is the SVC, mostly suitable for voltage control, reactive compensation and oscillation damping.
In Europe there are several SVC installations, some of them also having the relocatability feature (such as in England):

this aspect may play a role in the future as an additional benefit provided by these technologies. The most recent SVC device in Europe has been installed in Finland [4], while other SVC installations are planned or under study in other European countries [8]. Another promising FACTS element is the TCSC, which can provide different benefits including dynamic stability and power flow control by regulating the series impedance. TCSC devices are also more frequently used worldwide (recent applications are in Brazil, China, and India), whereas in Europe only one installation has been recorded, namely in Sweden. An already increasingly deployed FACTS device is the STATCOM, which can provide a fast control of voltage and reactive power and can therefore be very useful for wind power plants integration.
The drawbacks of the FACTS technology so far are represented by its complexity and, mostly, by its costs, which are higher than those ones of mechanical devices. This factor has slowed a more widespread insertion of FACTS devices in transmission systems. However, since all FACTS controllers are applications of similar technology, their deployment can benefit from economies of scale linked with volume production. The cost of these devices is decreasing as development of high-power electronics improves, also bringing increased savings due to economy of scale [4]. Moreover, the increasing awareness of system operators with respect to potential benefits of FACTS may also contribute to the future further deployment of these technologies.
Table 1 provides an outlook of the main features of the most promising FACTS devices.

Device description	SVC	STATCOM	TCSC	SSSC	TCPST	DFC[1]	IPFC	UPFC
Device ratings (MVA/MVAR)	100-850	100-400	25-600	100-400	50/150 [(2)]	-	200	100-325
Future device trend	Higher ratings	Further deployment	Further deployment					
Operational experience	>30 years	>20 years	>15 years	Pilot	Pilot	No	Pilot	Pilot >10 years
Lifetime [(1)]	40 years	30 years	30 years	30 years	30 years	-	30 years	30 years
Converter losses (full load, per converter)	1-1.5%	1-2.5%	0.5-1%	-	-	-	2-3%	
Availability	> 98%	> 98%	> 98%	-	-	-	-	-
Device capabilities								
Transmission capacity	■	■	■■■	■■■	■■	■■	■■■	■■■
Power flow control	■	■	■■	■■■	■■	■■	■■■	■■■
Transient stability	■	■■	■■■	■■■	■■	■■	■■■	■■■
Voltage stability	■■■	■■■	■	■	■	■■	■■	■■■
Power oscillation damping	■■	■■	■■	■■	■■	■■	■■	■■■
Control of wind farms reactive power output	yes	yes	no	no	no	no	no	yes
Investment costs	■	■■	■	■■	■/■■ [(2)]	-	■■■	■■■
■ — Small; ■■ — Medium; ■■■ — Strong; [(1)] estimated values, not enough experience yet; [(2)] TCQBT and TCPAR respectively								

Table 1: Key features of selected FACTS technologies

3.2 Economic aspects

In order to plan the expansion of transmission system, and particularly to assess the feasibility of installing advanced technologies, it is a key issue to have a clear picture not only of the benefits provided by each specific device, but most crucially of the related costs. Capital expenditures for transmission systems are highly dependent on different parameters, such as technological parameters (power rating, operating voltage, etc.), local environmental constraints and geographical characteristics as well as material and manpower costs. In general, environmental constraints increase costs and implementation time - e.g. for overhead lines (OHL) - while technological advances in manufacturing usually reduce costs (e.g. for power electronics components).
As of today, there are only few FACTS projects implemented worldwide that deploy turn-off based power electronics (like STATCOM, SSSC, UPFC). This makes it difficult to perform a comparable and reliable cost detail analysis since there are not enough cost figures to form a representative average value. Furthermore, manufacturers are reluctant to provide or publish cost figures. Taking all these factors into account, typical cost ranges of selected FACTS devices are reported in Table 2. It is assumed that the proposed investment costs ranges presented in the following sections include costs for equipment, project engineering and installation. In addition, operation and maintenance costs have to be considered [4].

Components	**Voltage Level (kV)**	**Available Power Rating (MVAR/MVA)**	**Cost Range**		**Unit**
			Min	**Max**	
SVC	400	100-850	30	50	kEUR/MVAR
STATCOM	400	100-400	50	75	kEUR/MVAR
TCSC	400	25-600	35	50	kEUR/MVAR
SSSC	400	100-400	50	80	kEUR/MVAR
UPFC	400	100-325	90	130	kEUR/MVA

Table 2: Investment cost ranges for FACTS

The values presented in Table 2 refer to the base case, wherein the installation of these equipments over flat land and in sparsely populated areas is considered. The lower limit (min value) refers to countries with low labour costs and the upper limit (max value) concerns countries with higher labour costs (for example, France, Germany or The Netherlands). Due to additional infrastructure costs the presented values should be increased by 50% when addressing installation costs in mountains and densely populated areas. For hilly conditions this increase should be of 20%.
The infrastructure costs are due mainly to the local configuration of the substation where the FACTS device shall be installed, and in particular to:

- Need to purchase additional land, if the space available is not sufficient;
- Possible changes in the layout of the existing substation, if necessary for variations on connections, on the auxiliary, or interventions on protective devices and manoeuvre;
- Civil works (building construction, foundations, drains, fences, etc.).

In terms of operational costs, one can consider two issues: maintenance and losses.
Concerning maintenance, FACTS controllers, in comparison to mechanical devices (such as transformer tap changers, shunt capacitor switches, which have controlled the AC power system so far) are not subject to mechanical wear, having subsequently a very reduced need for maintenance: the figures in the available literature range between 2-3 man days up to hundreds man hour per year.

In terms of device losses, FACTS controllers present values that range from 1-3%, depending on the type and manufacturer of the device.

Concerning durability, the FACTS devices manufactured nowadays have a life expectancy between 30 and 40 years, depending on the device and its respective manufacturer [4].

3.3 Environmental aspects

FACTS devices have an environmental impact in terms of increased surface occupation in the substations.

The usual range of surface occupation (or land use) due to the installation of FACTS devices lies between 3 and 20 m^2 per MVAR (see Table 3), depending on the type of device, the power rating and whether the device is relocatable (prepared to be moved to a different location) [4].

Device	Surface occupation
SVC	5-20 m^2/MVAR
STATCOM	3-5 m^2/MVAR
TCSC	3-10 m^2/MVAR
UPFC	3-20 m^2/MVA

Table 3: Surface occupation of selected FACTS devices

If the device is relocatable, it usually takes 3 to 6 months to move it from one location to another. Some other aspects need or can also be evaluated, such as the potential increased noise, or the electromagnetic interference (EMI) emissions. Furthermore, as stated before, FACTS controllers are not subject to mechanical wear, having here also an impact in environmental terms, for instance, concerning a lower need of manufacturing spare parts and lower need of traveling to perform the maintenance required [4].

4 Main HVDC features

4.1 Technical aspects

Based on the same basic power electronics components as FACTS devices, the HVDC technology however differs from FACTS controllers, which are installed in substations within the AC (Alternating Current) system. In fact, HVDC can be basically represented by the combination of a DC (Direct Current) circuit with two power electronics converters, each one at a link terminal, for AC/DC and DC/AC conversion. The DC circuit can consist of a cable or a line (in a full HVDC scheme) or simply a capacitor (in a back-to-back HVDC scheme). The first HVDC installations date back to 50ies; nowadays, HVDC technologies are worldwide widespread and used counting on a long operational experience. In fact, this technology exhibits characteristics that have already made it widely attractive over HVAC transmission for specific applications, such as very long distance power transmission (several hundreds to few thousands kilometres), long submarine cable links and interconnection of asynchronous systems, as well as bulky energy transport. The most recent (and world record) example has concerned the installation of 800 kV, 6400 MW HVDC links in China. Thanks to its speed and flexibility, the HVDC technology is able to provide the transmission system with several advantages such as: transfer capacity enhancement, power flow control, transient stability improvement, power oscillation damping, voltage stability and control, rejection of cascading disturbances, absence of reactive power. Currently, recent advances in power electronics, coupled with HVDC traditional features, may lead to a further deployment of this technology to improve system operation and support the development of onshore and, possibly, offshore European transmission grids. This is the case of the very promising self-commutated (or commutating) Voltage Source Converter (VSC)-based HVDC, which represents the state-of-the-art technology for connection of offshore wind farms and for multi-terminal applications. The key advantages of VSC-HVDC with respect to the line-commutated Current Source Converter (CSC)-based HVDC (the classic HVDC) are that it gives the possibility to feed reactive power into a network node and provide a smoother voltage support [4],[5],[13].

Table 4 summarizes the main features of CSC-HVDC and VSC-HVDC.

System description	CSC-HVDC	VSC-HVDC
System ratings in operation	±800 kV, 3000 MW	±150 kV, 350 MW
System ratings available	±800 kV, 6400 MW	±300 kV, 1100 MW
Future trend of system ratings	towards higher ratings	
Operational experience	> 50 years	~ 10 years
Lifetime	30-40 years	30-40 years(1)
Converter losses (at full load, per converter)	0.5-1%	1-2%
Availability (per system)	> 98%	> 98%
System capabilities		
Transmission capacity	■■■	■■
Power flow control	■■■	■■■
Transient stability	■■	■■■
Voltage stability	■	■■
Power oscillation damping	■■	■■■
Reactive power demand	■■■	■
System perturbation	■■■	■
Reactive power injection possible	no	yes
Easy meshing	no	yes
Limitation in cable line length	no	no
Ability to connect offshore wind farms	no	yes
Investment costs per MW	■■	■■■
Legenda: ■ — Small; ■■ — Medium; ■■■ — Strong; (1) estimated value, not enough experience yet		

Table 4: Key features of HVDC technologies

Modern HVDC transmission systems do not only allow for electrical power transmission from one area to another but also offer several technical advantages over conventional HVAC transmission. These essential advantages are briefly described as follows [4],[13]:

1. Practical absence of transmission line length limitation: HVDC transmission systems offer the special capability needed to carry out long submarine or underground cable transmission lines with a low level of losses - differently from AC cable transmission - without the need of reactive compensation. As there is no charging current in the DC cable, the transmission distance is almost unlimited and losses are lower for long-distance transmission compared to those ones of AC cables in equal conditions.
2. Transmission capacity increase: For a given conductor cross section, HVDC transmission can transfer more current through a conductor compared to conventional HVAC transmission. Accordingly, the conversion of transmission lines, formerly operated with HVAC, into HVDC operated ones increases the transmission capacity of the considered line. Such an increase in transmission capacity could be very

worthwhile in liberalized power systems, e.g. for cross-border trade.

3. Ability of quick and bi-directional control of power flow: Active power can be transmitted in both directions and quickly reversed if needed. Also, the amount of transmitted active power can be set to a fixed value that is maintained during all operating conditions, especially during the occurrence of faults in neighbouring network sections. This avoids the overloading and the consecutive loss of the transmission line. These features of HVDC can improve the stability of the surrounding AC power system or even of the total network.

4. No increase of short-circuit power at the connection points: HVDC lines can be integrated into a power grid without the need to upgrade downstream equipment, e.g. circuit breakers, transformers etc. In case of short-circuit at one of the terminals of the HVDC transmission line, the converters can be switched off within milliseconds preventing them from contributing to the short-circuit current.

5. Interconnection of asynchronously operated power systems: HVDC transmission lines can be used to connect two asynchronously operated power grids in order to provide not only for active power exchange in emergency situations but also for active power cross-border trade. This can either be carried out by a DC link between two distantly located AC substations of two different power grids or by a back-to-back (B2B) coupling inside one single AC substation.

6. Environmental advantages: For the same transmitted power, the required right-of-way of HVDC transmission is much smaller than the one of HVAC transmission. Since there is no need for reactive compensation, the use of HVDC makes it easier to go underground using cables as the transmission medium. In addition, electromagnetic field emission is not pulsating and can be reduced to a minimum. Hence, the environmental impact is smaller with HVDC transmission systems.

4.2 Economic aspects

Costs ranges for HVDC devices (for a throughput power ranging between 350 and 3000 MW for HVDC OHLs and 1100 MW for HVDC cables) are reported in Table 5 [4].

The lower limit (min value) refers to installation costs in European countries with low labour costs, while the upper limit (max value) refers to installation costs in European countries with high labour costs, e.g. Germany, The Netherlands or France.

System component	Voltage level	Power rating	Cost range		Unit
			min	max	
HVDC OHL, bipolar[1]	±150÷±500 kV	350÷3000 MW	300	700	kEUR/km
HVDC underground cable pair	±350 kV	1100 MW	1000	2500	kEUR/km
HVDC undersea cable pair	±350 kV	1100 MW	1000	2000	kEUR/km
HVDC VSC terminal, bipolar	±150÷±350 kV	350÷1000 MW	60	125	kEUR/MW
HVDC CSC terminal, bipolar	±350÷±500 kV	1000÷3000 MW	75	110	kEUR/MW

(1) cost ranges correspond to the base case, i.e. installation over flat land. For installations over hilly landscape +20% and +50% for installations over mountains or urban areas have to be factored in.

Table 5: Investment cost ranges for HVDC devices

It shall be clearly pointed out that the displayed cost ranges represent typical average values and shall not be taken as absolute data. The actual overall project costs may differ from the provided average values if exceptional technological, geographical, and/or environmental circumstances apply.

Costs for HVDC overhead lines refer to the base case, wherein the installation of overhead lines over flat landscape and in sparsely populated areas is considered. In this base case, high towers with a large span length can be used which directly results in lower overall installation costs. Costs for installations over hilly and averagely populated land as well as over mountains or densely populated areas are taken into account by a surcharge of +20% and +50%, respectively.

The proposed investment cost ranges for HVDC overhead lines include all costs related to the transmission medium (i.e. equipment costs, engineering costs, installation costs). The cost ranges provided for HVDC converter equipment are presented "per terminal", wherein a terminal includes all equipment at one side of the bipolar transmission line: both converters, reactive compensation (if needed), active filtering, AC/DC switchgear, engineering, project planning, taxes etc. except any costs related to the transmission medium. This accommodates the facts that on the one hand a voltage source converter is by nature bipolar and on the other hand that bipolar HVDC installations are preferred within a synchronized power grid for system security reasons. In case of a bipolar transmission line, the provided converter cost ranges need to be multiplied by the factor of 2, i.e. one bipolar converter terminal at each the feeding and the receiving end of the transmission line, in order to yield the overall installation costs (excluding the costs for the transmission line). Moreover, as an essential part of HVDC-based transmission systems, the transmission medium itself plays an important role in costs saving and environmental fitting.

In a comparison of DC vs. AC, for the restriction of charging currents, the transmission distance of AC-operated cables without reactive compensation is limited while DC-operated cables are not subject to such a restriction. In addition, the absence of charging currents in DC-operated cables leads to lower operational losses and a longer lifetime. Although the initial investment for an HVDC converter station is higher than the one for an AC substation, the investment costs of the overall DC transmission system can be lower than those ones of the AC transmission system: the cost savings in the transmission line and the absent need for reactive compensation can make up for the higher HVDC station costs if a certain transmission distance is reached. Concerning maintenance of HVDC systems, it is comparable to the one of HVAC systems. The high voltage equipment in converter stations is comparable to the corresponding equipment in AC substations, and maintenance can be executed in the same way. Maintenance will focus on: AC and DC filters, smoothing reactors, wall bushings, valve-cooling equipment, valves. Normal routine maintenance is recommended by manufacturers to be about one week per year. The newer systems can even go for two years before requiring maintenance. In fact, in a bipolar system, one pole at a time is stopped during the time required for the maintenance, and the other pole can normally continue to operate and depending on the in-built overload capacity it can take a part of the load of the pole under maintenance. In addition, preventive maintenance shall be pursued so that the plants and equipment will achieve optimally balanced availability with regard to the costs of maintenance, operating disturbances and planned outages [4].

4.3 Environmental aspects

The environmental fitting of an electrical power transmission system is of increasing importance. Due to political restrictions and public environmental awareness, environmental considerations have become an important part of approval procedures and project planning. In order to accommodate this circumstance, Table 6 reflects the land use for selected transmission system components. In case of overhead lines the term land use refers to the surface area occupied by the tower footing and the span, while in case of cables this term quantifies the surface area over the underground cable run. For both the span and the surface area of the cable run, the usability is constricted after construction of the line. For HVDC terminals and reactive compensation the term land use refers to the area occupied by the facility buildings [4].

System component	Voltage level	Power rating	Land use		Unit
			min	max	
HVDC OHL, bipolar	±150..±500 kV	350..3000 MW	20000	40000	m^2/km
HVDC underground cable	±350 kV	1100 MW	5000	10000	m^2/km
HVDC undersea cable	±350 kV	1100 MW	0		m^2/km
HVDC VSC terminal, bipolar	±150..±350 kV	350..1000 MW	5000	10000	m^2
HVDC CSC terminal, bipolar	±350..±500 kV	1000..3000 MW	30000	60000	m^2

Table 6: Surface occupation for HVDC devices (average)

HVDC transmission provides a clear environmental advantage over HVAC OHL due to its ability to go underground by the use of HVDC cables. The use of cables minimizes the visual impact of the transmission line since the surface area over the cable run can be re-naturalized with e.g. bushes or shallow root trees, as long as the cable can be made accessible for maintenance or repair purposes at short notice. In case of overhead lines, the width of right-of-way can be significantly reduced by approximately 30 to 50% when choosing HVDC instead of HVAC transmission [4].
Furthermore, the electromagnetic field emission of HVDC lines is not pulsating and can be forced to a minimum value in case a dedicated return conductor is used and the conductor arrangement is selected accordingly. The result is a significantly lower electromagnetic pollution compared to the electromagnetic emissions by conventional HVAC transmission, especially when overhead lines are used. However, it shall be stated clearly that today all HVAC overhead and cable lines comply with all legal requirements in terms of electromagnetic compatibility. The acoustic emission of HVDC stations has to be considered but can be reduced to comply with the legal requirements by an indoor station design.

5 FACTS and HVDC in the European system

5.1 Potential FACTS applications in Europe

One of the key benefits provided by FACTS is the possibility to relieve congestion constraints.
In case there is enough free transmission capacity available, the shifting of active power to other lines inside the system by a FACTS device should be considered before the construction of new lines: the scope is then to efficiently utilize the given network topology as well as to reduce the economic expenditure and the environmental impact that come along with a physical network expansion. A FACTS device suitable for efficient power flow shifting could be installed in one of the substations of the overloaded transmission line.
In cases where the congestion is discontinuous, the application of dynamic devices may be advantageous since these devices are able to monitor the power flow on a transmission line and to limit this power flow to a permitted value when needed. For a congestion that is associated with a relatively low degree of volatility, slow-switching devices (such as mechanical devices) can be feasible while in case of a relatively high degree of volatility fast-adjusting devices (such as TCSC, SSSC, UPFC) present possible solutions [4].
In addition to transmission applications and the benefits offered by FACTS for gridlock resolution and improved system controllability (see also Table 1), these technologies can be also beneficial when implemented for the connection of certain RES to the grid. In this case, FACTS are especially advantageous when applied for wind generator connections. Due to the nature of the source of wind power, a continuous and steady supply from a wind generation unit or wind farm is difficult to achieve. As such, the inherently unsteady nature of this type of generation source requires measures of stability and control on the power transmission system. In addition, due to issues associated with voltage control, as well as real and reactive power dispatching, measures must be established for power system operators in order to adjust to wind generation output as base load, peak load, or other dispatching criteria.
As wind farms become a larger part of the total generation base and as the penetration levels increase, issues related to integration, such as transients, stability, and voltage control, are becoming more and more important. Moreover, due to the stochastic nature of wind, the integration of such renewable sources of generation into the transmission system significantly differs from the one related to conventional types of generation. For wind generation applications, FACTS can be implemented for voltage control in the form of SVC or STATCOM configurations. In addition to voltage support and control, there are also benefits that can be realized by allowing generating units to increase real power output by relieving the reactive power requirements through the application of these dynamic compensation technologies. By implementing FACTS technologies in coordination with wind (and other RES) generation applications, a reliable, steady, and secure connection to the power transmission grid is ensured. In addition, maximum output of wind capacity and efficient operation of wind generating units are realized through interconnection with FACTS controllers [4].

In case of offshore wind connection via HVAC submarine cable transmission and depending on the line length, reactive compensation at both ends of the cable has to be considered. As an approximate value, a cable with a line length of more than 40 km needs reactive compensation (about 1.5-2.5 MVAR/km): this naturally has to be taken into account in the cost-benefit analysis.

An option could also be given by the utilisation of FACTS like SVC or STATCOM in combination with HVAC cables (at the onshore end), aiming at both cable reactive compensation and output voltage support and reactive control. It is worth to outline that FACTS devices have a specific potential for application in different European systems.

In Italy, SVC and STATCON are under consideration for static and dynamic applications, while series and combined controllers might be very useful to relieve congestions in different parts of the system both at internal and cross-border level. In Poland, the different types of FACTS devices might be very effective to manage active and reactive power flow control, voltage regulation and system stability control. In Germany, SVC and series controllers are under consideration, especially for wind integration and power flow control issues [8]. Also in Spain devices like shunt controllers and SSSC are under study [7]. In Central and Northern Europe, series and combined devices may be also very effective for solving several network issues.

In general, the different types of series and combined FACTS devices could provide more effective solutions to the European issues on several cross-border ties than the PSTs (Phase Shifting Transformers) there installed actually do.

5.2 Further potential HVDC applications in Europe

There exist several full HVDC links in the European power system of ENTSO-E, mainly used for long submarine ties and/or asynchronous systems interconnections. There is currently also an installation of B2B HVDC (between Finland and Russia). Further asynchronous interconnections of both HVDC types, CSC and VSC, are expected at pan-European level in a short-mid term horizon (as full or B2B HVDC), namely between Baltic, Scandinavian and Continental European regions [8]. In this sense, the interconnection project linking Poland and Lithuania via HVAC and B2B CSC-HVDC assumes a strategic role being the first link between the still asynchronised Continental European and Baltic systems [8]. In the medium term, further interconnections between the Continental European and the Russian systems via full or B2B HVDC are also expected.

The fast development of VSC-HVDC is presently increasingly expanding the potential fields of application of HVDC technology in Europe comprising also urban in-feed, offshore RES connection and integration, multi-terminal applications. Concerning the latter, although there are currently just very few multi-terminal HVDC (MTDC) installations in operation worldwide (in Europe the only one is the Sardinia-Corsica-Italian peninsula link), the demand for a MTDC system frequently arises among TSOs. This is mainly driven by the operational advantages in terms of bulk power transmission which they have gained from conventional point-to-point HVDC installations and which they expect to come along with the implementation of MTDC. In addition, the recent push for increasing the share of RES in the power generation mix leads to an increased number of offshore wind parks in operation, under construction or being planned. The consequence is an increased amount of power generation far away from the load centers. A multi-terminal HVDC system could be then a solution for picking up offshore generated power, for transmitting it to the mainland and for feeding it into the power grid.

In this respect, there is a very strong potential for HVDC offshore grids development in Europe [8], especially in the North Sea and in the Baltic Sea, and also in the Irish Sea. VSC-HVDC can be very useful for the connection of remote offshore wind farms to the main power grid since VSC-HVDC does not depend on a specified ESCR (Effective Short Circuit Ratio) or on reactive power support at the connection points in order to perform a reliable commutation process. VSC-HVDC can be then the key technology for building offshore grids. Furthermore, the independency of reactive power support enables VSC-HVDC to perform a black start which may help TSOs to re-energize network sections that suffered from a system blackout. VSC-HVDC can provide additional capacity for the point-to-point power transmission over short- to medium-long distances within a power grid while also providing reactive power support at its terminals. This contributes to power system stability and frees up transmission capacity on neighbouring lines that was formerly occupied by reactive power transmission. In combination with a wide-area monitoring system, the fast modulation of power injection at the HVDC terminals can be also used to damp power oscillations within the power grid and to assure system stability.

Further potential applications of HVDC in Europe in the short-medium term horizon refer to the possibility of embedding HVDC lines into the meshed AC system, either by replacing existing HVAC with HVDC devices or by building HVDC links ex novo.

In fact, converting an HVAC overhead line to HVDC constitutes an interesting option for the increase of transmission capacity due to the increased power density for a given width of right-of-way that can be obtained from an HVDC transmission circuit compared to a conventional HVAC transmission circuit [9]. For the conversion of the line, the suitability of the tower geometry and the tower configuration have to be determined, especially with respect to tower cross arm geometry, tower statics, insulator assemblies and conductor configuration. Generally, no change in the tower construction, the foundations and in the conductors is accepted since these major modifications would lead to high investments which would make the conversion economically unfavourable compared to the replacement of the complete line. In any case, insulators need to be changed when converting from HVAC to HVDC as well as additional space needs to be allocated within or at least in the vicinity of the existing substations in order to accommodate the HVDC converters. This leads to limit investment costs and a project execution time within the medium-term horizon, bringing also advantages in terms of reduced environmental impact by

HVDC. In the case of bulk power point-to-point transmission (>1500 MW), the choice of which HVDC technology to apply is today limited to CSC-HVDC as the currently available power ratings of VSC-HVDC are still limited. Furthermore, in case of CSC-HVDC, if the ESCR of both considered network nodes assumes a low level (lower than 2.0), the grid needs first to reinforced. However, in the case of power transmission lower than 1100 MW, VSC-HVDC already constitutes a feasible option which provides higher benefits in both environmental impact and network controllability. The future technological developments of VSC-HVDC towards increased power ratings may allow for considering VSC-HVDC as another option for bulk power transport.

The planned France-Spain interconnection line is a clear example where the implementation of a VSC-HVDC interconnection is chosen as a technically and environmentally feasible solution [8]. The aim is to address cross-border congestions (frequently occurring in both directions), enhancing the net transfer capacity and avoiding overloading of the transmission line, with a clear environmental advantage over conventional HVAC transmission. The exploitation of VSC-HVDC features is also expected by the further deployment of this technology for the planned France-Italy interconnection line as well as for the link under construction in southern Sweden (South-West project) [8].

Finally, possible medium-long term (2030 and also beyond) applications of HVDC refer to the ambitious projects of transport of huge energy produced by North-African solar power plants to the European power system, in the frame of DESERTEC Initiative [5]. This would be a challenging move towards the realisation of the vision of a pan-European (mixed HVAC and HVDC) supergrid [8].

6 Conclusions

The present paper investigates the potential role that FACTS and HVDC may play towards the development of the future pan-European transmission system. In fact, FACTS and HVDC elements may provide European TSOs with effective solutions to the several criticalities they encounter nowadays in their grid planning processes. Among these criticalities, one can refer to intra- and inter-zonal congestions, RES integration, power controllability. Particular attention is paid to different specific technical, economic and environmental features of FACTS and HVDC that have to be taken into account in a transmission expansion plan. It has to be said, however, that some other aspects (related e.g. to components protection and reliability) are not in the scope of the present paper. These will have to be considered in the respective application of these power electronics-based technologies, also in dependence on local network conditions, topology etc.

Finally, it has to be noted that in a highly meshed network, as the European one, if HVDC and FACTS become extensively deployed, they will deliver real benefits only when subjected to a coordinated and hierarchical control. These aspects have been investigated in [10].

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