Roadmap to the Supergrid Technologies

Final Report

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Document prepared by FOSG WG 2 Technological.
Members of the Working Group are:

Frank Schettler	Siemens (Convenor)
Maria-Sophie Balavoine	RTE
Magnus Callavik	ABB
Joe Corbett	Mainstream Renewable Power
Nikola Kuljaca	Prysmian
Vegar Syrtveit Larsen	Nexans
Norman MacLeod	ALSTOM Grid
Björn Sonerud	Nexans

Contributors

Björn Jacobson	ABB
Heather Laurie	Mainstream Renewable Power
Christian Lemaitre	RTE
Samer El Oukaili	Siemens

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Abbreviations

°C:	Degrees Celsius
+ve:	Positive
–ve:	Negative
AC:	Alternating Current
BAS:	Basic Grid with Standard Transmission Capacity
CCPP:	Combine Cycle Power Plant
CENELEC:	European Committee for Electrotechnical Standardisation
CIGRE:	International Council on Large Electric Systems
CO_2 :	Carbon Dioxide
CSC:	Convertible Static Compensator
DC:	Direct Current
DENA:	Deutsche Energie Agentur
DEWI:	German Wind Energy Institute
EC:	European Commission
EHV:	Extra High Voltage
ENTSO-E:	European Network of Transmission System Operators for Electricity
EU:	European Union
FACTS:	Flexible AC Transmission Systems
FB:	Full Bridge
FLM:	Flexible Line Management
FOSG:	Friends of the Supergrid
FSC:	Fixed Series Capacitor
GHG:	Green House Gas
GIL:	Gas Insulated Line
GIS:	Gas Insulated Switchgear
GW:	Gigawatt = 1,000 megawatts
GWh:	Gigawatt Hour
HB:	Half Bridge
HR:	Hours Reserve
HTS:	High Temperature Superconductor
HV:	High Voltage
HVAC:	High Voltage Alternating Current
HVDC:	High Voltage Direct Current
Hz:	Hertz
IEA:	International Energy Agency
IEC:	International Electrotechnical Commission
IGBT:	Insulate Gate Bipolar Transistor
IPFC:	Interline Power Flow Controllers
IPS/UPS:	Wide Area Synchronous Transmission Grid
IRC:	Integrated Return Conductor
ISLES:	Irish-Scottish Links on Energy Study
IWES:	Institute for Wind Energy and Energy System Technology
km:	Kilometre = 1,000 metres
kV:	Kilovolt = 1,000 Volts
kW:	Kilowatt = 1,000 Watts

LCC: Line Commutated Converters
LDPE: Low Density Polyethylene
LIPA: Long Island Power Authority
m: metre
MCOV: Maximum Continuous Operating Voltage
MI: Mass Impregnated Paper Insulation
MMC: Modular Multi-level Convertor
MR: Minutes Reserve
ms: Millisecond
MSC: Mechanically Switched Capacitors
MSCDN: Mechanically Switched Capacitive Damping Networks
MSR: Mechanically Switched Reactors
MTDC: Multi-Terminal High Voltage Direct Current
MV: Megavolts = 1,000 kilovolts
MVA: Mega Volt Ampere
MW: Megawatt = 1,000 kilowatts
MWh: Megawatt Hour
N_2: Nitrogen
NSCOGI: North Seas Offshore Grid Initiative
NYPA: New York Power Authority
OHL: Over Head Line
PPL: Polypropylene Paper Laminate
PR: Primary Reserve
PV: Photovoltaic
R&D: Research and Development
RE: Renewable Energy
RES: Renewable Energy Source
SCFF: Self-Contained Fluid Filled
SCPP: Single Cycle Power Plant
SCR: Short Circuit Ratio
SF_6: Sulphur Hexafluoride
SR: Secondary Reserve
SSC: Series and Shunt Compensation
SSSC: Static Synchronous Series Compensator
STATCOM: Static Synchronous Compensator
SVC: Static Var Compensator
TAL: High Temperature Conductors
TCR: Thyristor Controlled Reactor
TCSC: Thyristor Controlled Series Compensator
TPSC: Thyristor Protected Series Compensator
TSC: Thyristor Switched Capacitor
TSO: Transmission System Operator
TUOS: Transmission Use of System Charge
TW: Terawatt = 1,000 Megawatts
TWh: Terawatt Hour
TYNDP: ENTSO-E Ten Year Network Development Plan
UHV: Ultra High Voltage
UPFC: Unified Power Flow Controllers

VDE:	Association for Electrical, Electronic and Information Technology Germany
VFT:	Variable Frequency Transformers
VSC:	Voltage Source Converter
WTG:	Wind Turbine Generator
XLPE:	Cross Linked Polyethylene

Introduction and Summary

To make Europe sustainably energy independent will require a renewable generation portfolio built where resources are optimal and not constrained. Much of this portfolio will be fuelled by wind and will be developed offshore. To deliver this energy to European consumers will require the development of a high capacity transmission system – the Supergrid, capable of delivering this energy to Europe's load centres.

To meet Europe's ambitious carbon and energy security targets requires a new level of Pan-European power transmission system planning, realization and operation. The development of such a European Supergrid must start today.

The FOSG board has decided to launch four Working Groups addressing various aspects of building the Supergrid:

- Working Group 1: Ownership, Regulatory, Grid Codes, Commercial and Financial
- Working Group 2: Technological
- Working Group 3: Logistical (supply chain)
- Working Group 4: Commitments, time table (Policy) and Communication

Working Group 2, "Technological" was founded in April 2011 to investigate the technological challenges for Supergrid, what technology is currently available, what is on the horizon and what common standards are needed. During the following nearly 11 Month, the intensive work of leading companies in their field in Europe: ABB (joining End of 2011), ALSTOM Grid, Mainstream, Nexans, Prysmian, RTE, Siemens has resulted in the present report.

Chapter 1 describes the drivers for European System Expansion. The change in the generation structure and future portfolio selection leads to the need for a Pan-European transmission grid, with appropriate transmission capacity while, at the same time maintaining (at least) today's security of supply. Key requirements and expectations from a Transmission System Operator's point of view are summarized.

Chapter 2 describes the technologies available for the European system expansion and strengthening. High Voltage Direct Current (HVDC) is certainly the enabler for long distance efficient power transmission including submarine and onshore cables while Flexible AC Transmission Systems (FACTS) can provide effective solutions for controlling load flows in the parallel AC system and maintaining system stability.

Chapter 3 presents a possible roadmap and various scenarios for developing the Supergrid. The first multi-terminal HVDC Projects in Europe are seen as the beginning of the development of larger HVDC Grids. HVDC technology can be complemented by AC in so-called Supernodes that can contribute to achieve the required security of supply in larger networks of HVDC.

1. Applications for Supergrid

1.1 Introduction

Supergrid is the future electricity system that will enable Europe to undertake a once-off transition to sustainability. This 21st century transmission network will make possible the delivery of decarbonised electricity across countries, enhancing the existing AC networks. It will be the transmission backbone of Europe's future power system.

Europe's challenging renewable energy targets will necessitate the development of renewable generation remote from existing load centres and much of it based on off-shore wind. Mixed with solar from the south, tidal, wave, biomass, geothermal existing onshore wind and hydro resources and storage; and connected to distributed generation, this will form the sustainable energy supply system for the continent. Supergrid will allow future generation to be built where resources are optimal and not constrained and transported to existing grids for delivery to existing and future load centres.

1.2 Drivers

1.2.1 GHG / CO_2 Reduction

EU Policy is a legally binding 20% reduction of GHG from 1990 levels by 2020. And while the EC has committed to deliver a 2050 roadmap by the end of 2011, a number of member states have already defined a vision beyond 2020. There are a number of possible scenarios for the 2050 vision but a consensus among selected stakeholders [1] suggests 75-80% GHG reduction Figure 1.1

Stakeholder	Vision	GHG Target*	Fuel Prices	Technologies Development	
				CCTS **	RES ***
Eurelectric	Power Choices	75%	Medium-High	2025	Low
European Gas Advocacy Forum (EGAF)	Low gas price	80%	Medium-Low*****	2030	Medium
	High gas price	80%			
	Low gas price and constrained nuclear****	80%			
International Energy Agency (IEA)	BLUE Map	75%	Low	2015-2025	High
European Climate Forum (ECF)	Roadmap 40% RES	80%	Medium-Low	2020	Medium
	Roadmap 60% RES	80%			
	Roadmap 80% RES	80%			
EREC/ Greenpeace	Energy [R]evolution	80%	High	Not needed	Medium-High

* GHG emission reductions relative to 1990 levels
** Year when it is assumed to be commercially available
*** Learning rates (in qualitative terms)
**** Nuclear capacity constrained at 30GW by 2030
***** The fuel prices considered are the same as in the ECF report, except for gas, for which two different price scenarios (low and high) are considered. The high gas price scenario is the one corresponding to ECF values.

Figure 1.1: GHG reduction targets for various Scenarios (Source: Florence School of Regulation[1])

Figure 1.2 shows Europe's fuel mix in 2008. To deliver this level of Green House Gas reduction will require a significant change to Europe's generation fuel mix, especially a reduction in coal and gas fuelled generation.

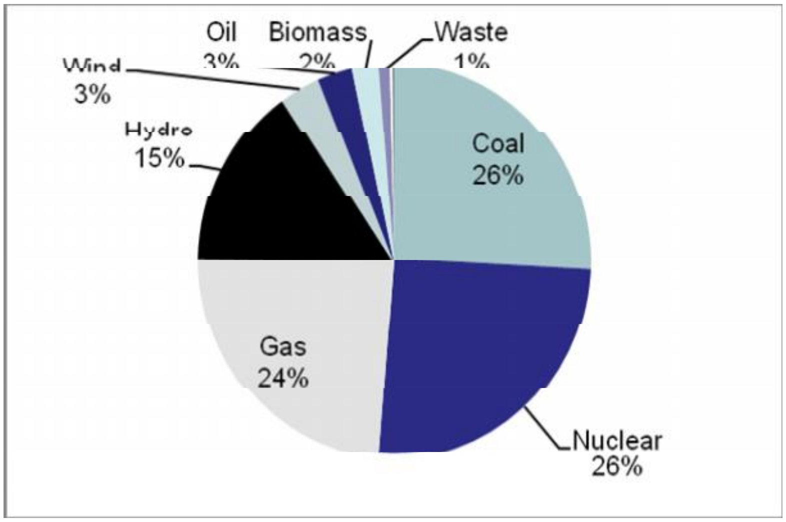


Figure 1.2: Europe's Fuel Mix in 2008 (Source: IEA)

1.2.2 Security of Supply

According to IEA, Energy Security can be described as "the uninterrupted physical availability at a price which is affordable, while respecting environment concerns". In fact the need to increase "energy security" was the main objective underpinning the establishment of the IEA, with particular emphasis on oil security.

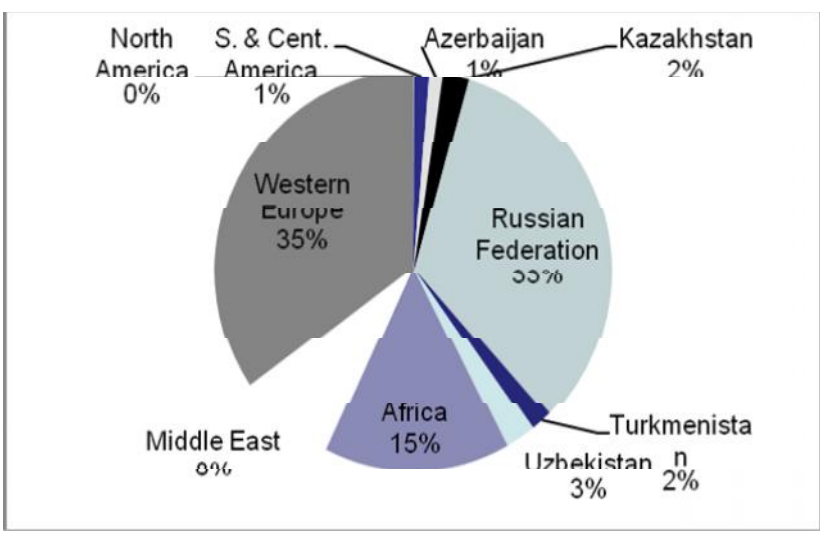


Figure 1.3: Europe's Sources for Natural Gas 2010 (Source: BP)

Figure 1.3 shows Europe's gas sources in 2010. Replacing coal with significant increase in gas generation, to reduce GHG from the electricity system, will negatively impact on security of supply by increasing dependence on outside sources.

Today energy security has a broader context which, in the long term, is linked to timely investments to supply energy in line with economic developments and environmental needs, while in the short term reacting promptly to sudden changes in supply and demand. As part of the new debate a concern regarding over-reliance on certain sources / supply chain has arisen with the effect of promoting diversity, efficiency and flexibility within the energy sectors of the EU and expanding cross-border co-operation in the energy market.

These issues, in addition to the age of existing fossil plant (and hence imminent decommissioning of same) and the increased opposition to nuclear power have forced policy makers to consider the strategic fuel mix required within the continent to deliver both the security and green agendas and the delivery mechanisms to get the energy to market.
According to he UK's Department of Energy and Climate Change:

"With a quarter of the UK's generating capacity shutting down over the next ten years as old coal and nuclear power stations close, more than £110 billion in investment is needed to build the equivalent of 20 large power stations and upgrade the grid. In the longer term, by 2050, electricity demand is set to double, as we shift more transport and heating onto the electricity grid. Business as usual is not therefore an option".
(Source: http://www.decc.gov.uk/en/content/cms/news/pn11_061/pn11_061.aspx)

Other factors affecting these decisions include:

- fossil fuel price volatility and,
- consenting difficulties associated with large infrastructure projects

Resulting from these discussions are proposed future fuel portfolios that include increasingly large renewable energy generation sources – onshore and off shore wind, solar (mainly photo voltaic (PV)), biomass etc., in combination with demand response / smart grid and storage.

1.3 Scenarios

Numerous studies have been carried out to determine the future shape of Europe's Energy System and, while the conclusions may differ in specifics there is a definite consensus emerging around some. For example most conclude that the electricity system will have large penetrations of renewable energy and that to deliver this will require large investments in transmission grid infrastructure. Many of the studies considered various scenarios to be examined in the analysis of future grid design in the context of large scale renewable penetration in Europe by 2050.

The DENA II study [2] which was prepared by a consortium led by the Institute of Energy Economics at the University of Cologne, in cooperation with DEWI GmbH – German Wind Energy Institute, Fraunhofer Institute for wind energy and energy system technology (IWES), 50Hertz Transmission GmbH, Amprion GmbH, EnBW Transportnetze AG and TenneT TSO GmbH, considered:

- Flexible mechanisms for the generation of electricity
- Forecast as to the quality of wind energy fed into the grid and of electricity consumption
- Demand-side management
- Provision of balancing and reserve power by wind turbines
- The use of storage technologies
- Comparison of suitable means of transmitting wind-powered electricity to load centres inland
- Reliability of electricity supply, even in difficult situations
- The current capacity of overhead lines depending on the ambient temperature and wind speeds (temperature monitoring)

Figure 1.4 shows the study results from DENA II showing the additional high voltage transmission needed to connect the additional renewable energy predicted for 2020 for a base case (BAS000) and when flexible loading (FLM000) and high temperature conductors (TAL000) are used.

Variant	Additional transmission grid needed (km)	Route length to be modified (km)	Costs (€ million / annum)
BAS 000	3,600	0	946
FLM 000	3,500	3,100	985
TAL 000	1,700	5,700	1,617

Figure 1.4: DENA II Findings

Various other technologies were also considered in DENA II – including, fully meshed underground VSC, point-to-point VSC (also underground), Gas Insulated Line and hybrid HVDC/HVAC with bulk supply north-south by VSC HVDC underground. Annualised costs comparisons are shown for each (including the base, FLM and TAL options) are shown in Figure 1.5.

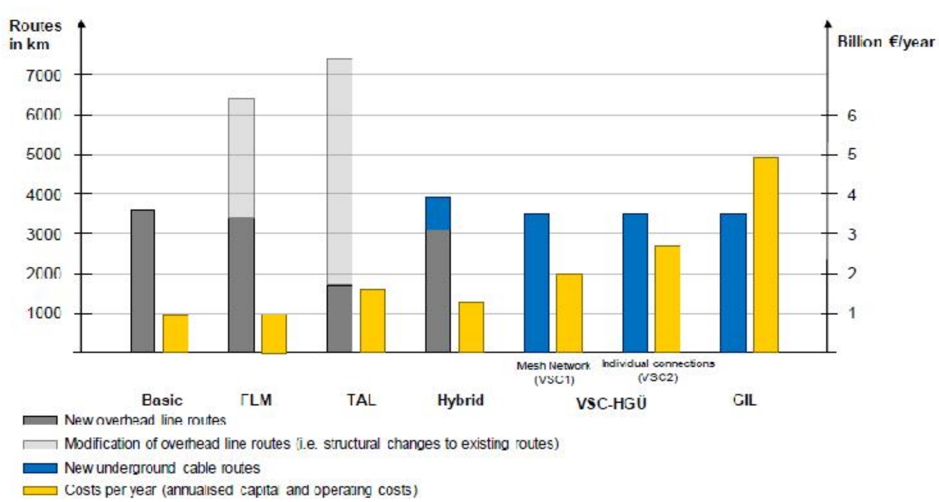


Figure 1.5: Cost Comparison of technology Choice from DENA II

More recently the German government's decision not to extend its nuclear program has led to scenarios with increased renewable energy installed. Various scenarios up to 2032 are shown in Figure 1.6 from the National Network Development Plan [3]:

	Reference	Scenario A	Scenario B		Scenario C
	2010	2022	2022	2032	2022
Total Conventional Plant	106.1	92.3	98.8	92.4	82.4
Onshore Wind	27.0	33.4	44.0	61.0	69.9
Offshore Wind	0.2	11.3	13.0	28.0	18.0
PV	16.9	34.1	54.0	65.0	46.8
Other RE	10.9	14.7	15.6	17.7	15.3
Total RE	55.0	93.5	126.6	171.7	150.0

Figure 1.6: GW Installed for Various Scenarios in National Network Development Plan

The ENTSO-E Ten Year Network Development Plan [4] (TYNDP, 2010) is based on the installed capacities shown in Figure 1.7 and, due to the level of off-shore wind in the North Sea, results in the interconnections shown in Figure 1.8.

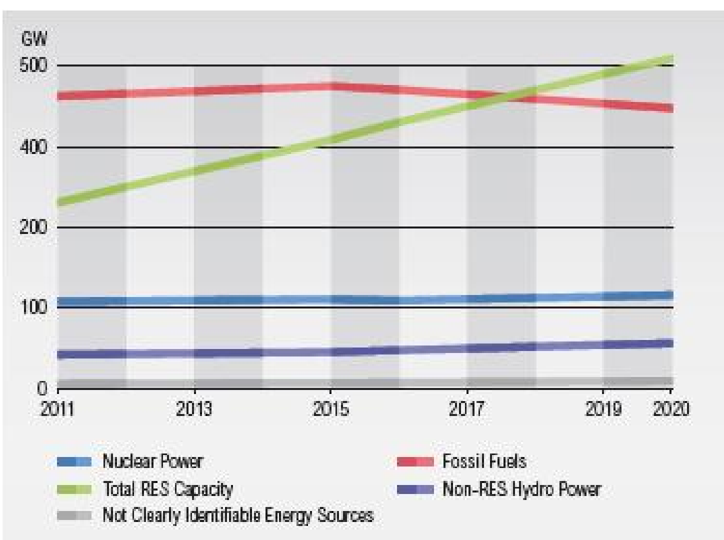


Figure 1.7: Generation Forecast to 2020 (Source: ENTSO-E: Scenario Outlook and Adequacy Forecast (SO & AF) 2011 – 2025 report [4])

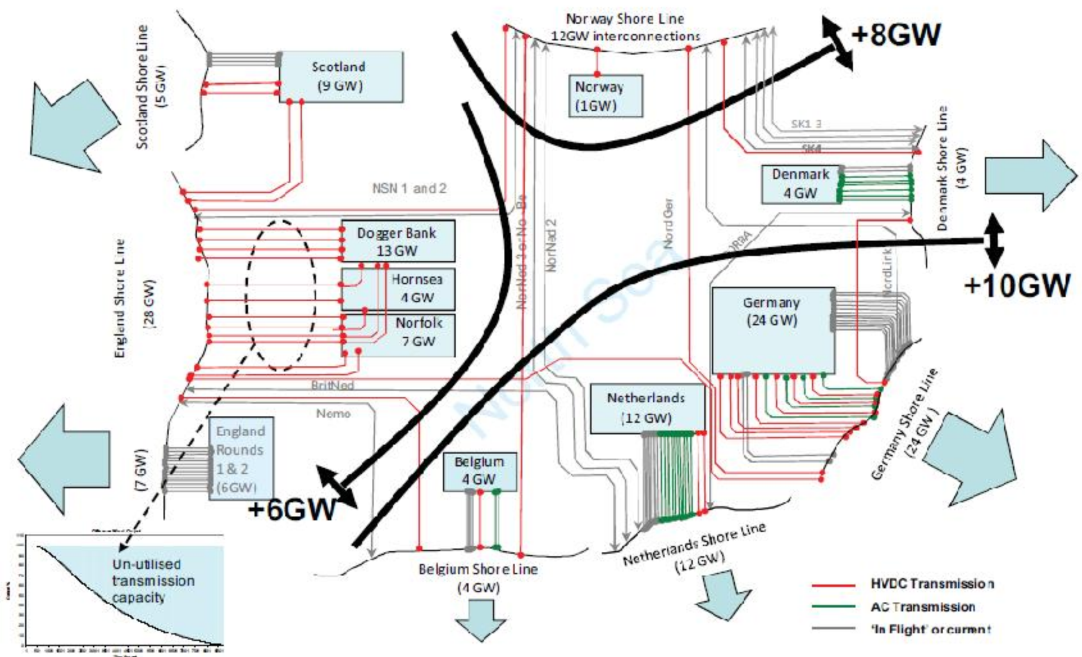


Figure 1.8: ENTSO-E North Sea Vision for 2030

The ten year plan was produced in 2010 and includes the German nuclear programme that as then in place. The next ten year plan will be TYNDP 2012 and will have to reflect the revised European energy mix.

In January 2010 the governments of Scotland, Northern Ireland and Ireland commissioned The Irish Scottish Links on Energy Study (ISLES) to advise on the feasibility of creating an offshore interconnected electricity grid based on renewable resources (wind, wave and tidal) in the seas of the west coast of Scotland and the north and east coasts of the island of Ireland. Executive Summary Report. Although the full report is not available at the time of writing the Executive Summary (Draft) [5],concludes that *"an ISLES cross-jurisdictional offshore integrated network is economically viable and competitive under certain regulatory frameworks and can potentially deliver a range of wider economic, environmental and market related benefits".* Other conclusions from the report are:

- *"There are no technological barriers to the development or deployment of an ISLES network. High Voltage Direct Current (HVDC) using Voltage Source Conversion (VSC) technology is a suitable transmission system for the ISLES offshore network …"*
- *"The ISLES concept does not require the development of new equipment, such as HVDC circuit breakers, but rather builds on the capabilities of current devices".*
- *"The ISLES offshore network design allows a phased construction and deployment strategy with potentially wider benefits to the power transfer capacity of onshore grids".*

The ISLES Report identifies as the main hurdles to be overcome multi-jurisdictional and multideveloper dimensions which will require anticipatory investment and political commitment to overcome market, regulatory and generation/transmission owner concerns.

A recent ENTSO-E report – Offshore Transmission Technology (commissioned by NSCOGI) [6] describes the available technology, cost data and references to relevant HVDC projects recently completed or in planning. The focus of the report is on VSC Transmission and the requirements for multi-terminal HVDC. The report concluded that technology-wise it should be possible to start planning based on availability of the following by 2017:

- 500 kV, 2,000 MW Multi-terminal VSC Transmission
- 500 kV XLPE cables
- 1 - 2 GW platforms

The report also highlights that the technology will not be available if the market signals are scattered. A few risk items with this scenario are listed, such as:

- There is no VSC Multi-Terminal DC installed onshore yet
- Multi-vendor solutions and work on guidelines and standards is needed
- At the time of this report, no DC Breaker concepts had been presented

The TradeWinds Project – funded by EU, which showed high, medium and low RE scenarios (Figure 1.9) and recommended high levels of interconnection to capture this level of RE.

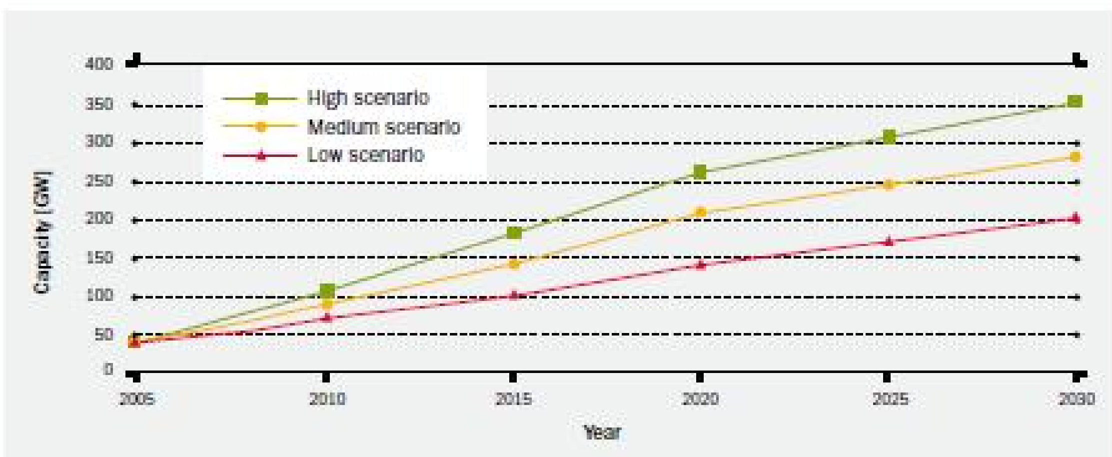


Figure 1.9: Renewable Energy Generation Scenarios (**Source: TradeWind Report** [7]**)**

In addition to the increased level of renewable energy, which will be installed where resources are optimum, by 2050 it is expected that electricity will replace fossil fuels currently used in the transport, buildings services and industrial sectors. The climate foundation roadmap 2050, for instance, suggests that 30% reduction in electricity consumption by energy efficiency initiatives will be offset by the increased use for transport and industrial/commercial heating (Figure 1.10).

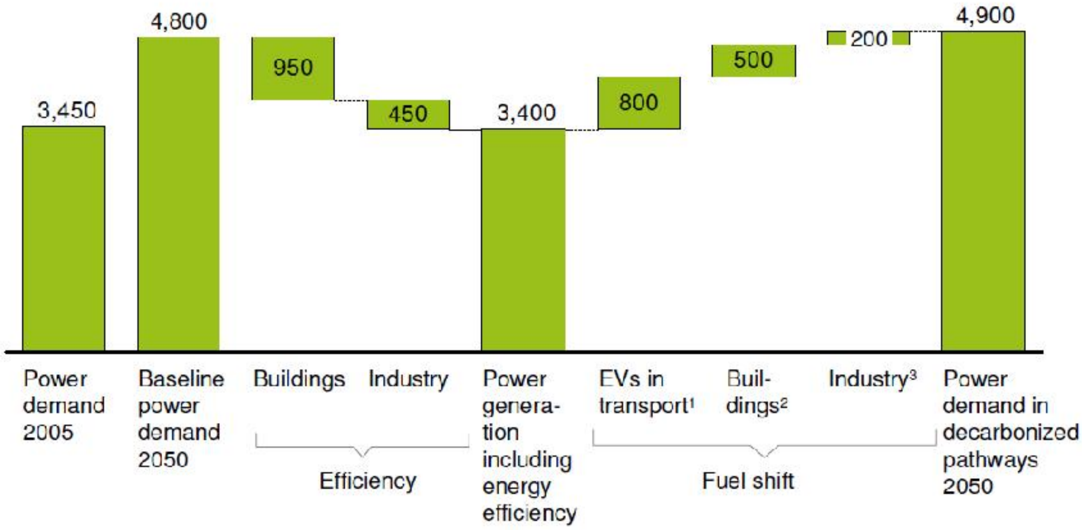


Figure 1.10: Effect of Shift from Primary Fuels to Electric Power in Europe's Transport, Heating and Cooling Load **(Source: Climate Foundation Road Map 2050 [8])**

The combination of increased electrical energy consumption coupled with increased levels of Renewable Energy installed means that the existing AC grid will not be suitable or conditioned for delivery of the new generation mix to this energy profile. Today's generation was built based on our fossil fuel history, located close to large coal deposits, or with access to cooling water or port facilities or on the ability to install gas pipelines underground, relatively inexpensively. The transmission grid followed this generation. Tomorrow's generation will be more dispersed and built where renewable resources are abundant. The new grid must follow the new mix.

Common to all scenarios and reports is the need for increased transmission interconnection across Europe. The nature of the renewable generation requires a new thinking in interconnection. In addition to demand response initiatives / smart grid technology and storage (hydro, battery and/or flywheels etc.), wider interconnected grids can enhance delivery by taking advantage of various time zones and different peak / seasonal demand profiles.

Figure 1.11 for example, shows the benefits of Regional Interconnection in reducing the variation in demand.

According to the Climate Foundation's 2050 Road Map:

"By 2050, Europe could achieve an economy wide reduction of GHG emissions of at least 80% compared to 1990 levels. Realizing this radical transformation requires fundamental changes to the energy system. This level of reduction is only possible with a nearly zero-carbon power supply. Such a power supply could be realized by further developing and deploying technologies that today are already commercially available or in late stage development, and by expanding the trans-European transmission grid".

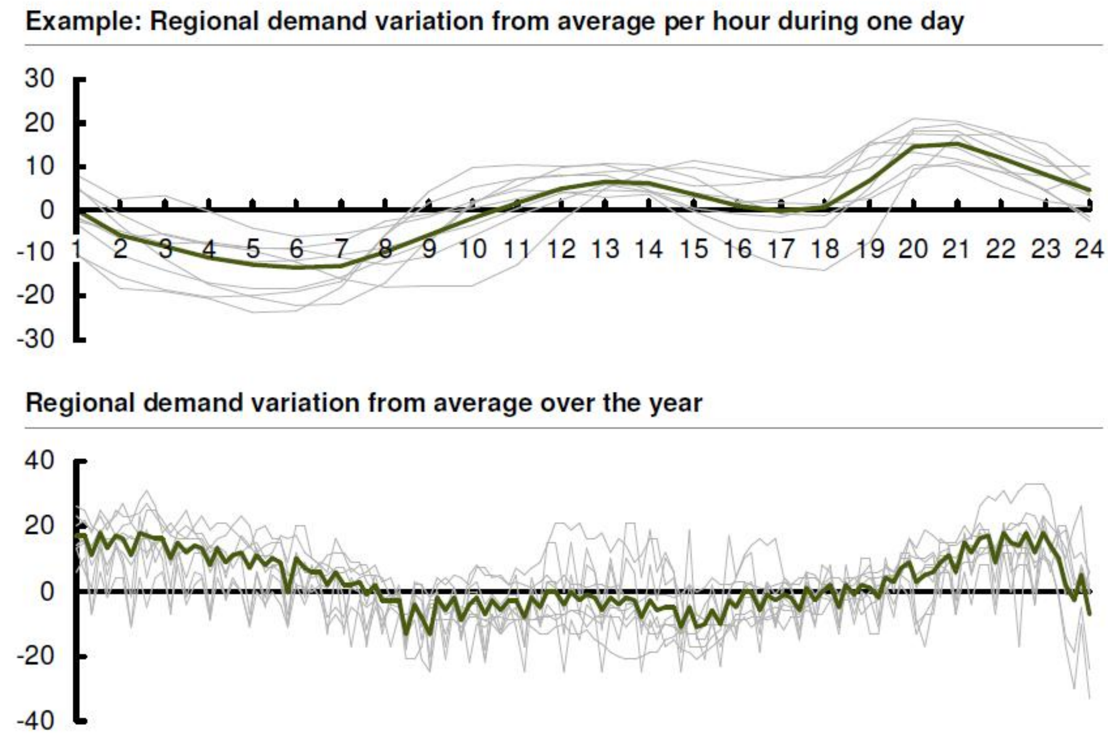


Figure 1.11: Regional Demand Variations from Average (Source: Climate Foundation Road Map2050 [8])

1.4 Technological Requirements

An enabling technology for the new grid is HVDC driven by modern power electronics. AC power links become uneconomic of long distance due to the reactive power requirements, especially in underground (or undersea) cable networks where the cable capacitance dominates the power flow equations. DC, conversely, while requiring expensive terminal equipment, becomes economic for large power over long distance. What is now known as "classic HVDC", based on Line Commutated Converters (LCC) using thyristors has become the norm for bulk power long distance transmission and international interconnection. LCC has the advantage of high power delivery – more than 6,000 MW at 800 kV on one link delivered in China recently, and low losses. LCC does require strong networks at each end, thus limiting its use for offshore wind connections, for example.
However, the advent of modern HVDC links based on Voltage Source Converter (VSC) – using Insulated Gate Bipolar Transistors (IGBT) rather than thyristors, technology will facilitate the interconnection of offshore wind clusters with existing on shore grids and with each other. These new links can form a European Supergrid and will be developed and built using the next generation of HVDC technology, installation vessels, and of marine generating plant. It will capture clean energy generation and deliver firm renewable power across the EU. The technology enabling Supergrid will be both evolutionary and revolutionary and will include:

- optimised, low loss, high power HVDC and hybrid systems;
- extra high voltage undersea cables;
- new concepts in wide area network control and protection for HVAC and HVDC;
- Flexible AC Transmission Systems (FACTS)
- high power HVDC switchgear
- new large power onshore connections and
- innovative transport and installation methods both on and offshore

There are a number of design concepts for the new European Supergrid developed by various organisations and consortia, both public and private. These concepts share the characteristics of a master plan based on selection of:

- Fuel Portfolio Mix
- Generation / Load Location
- Technology Choices

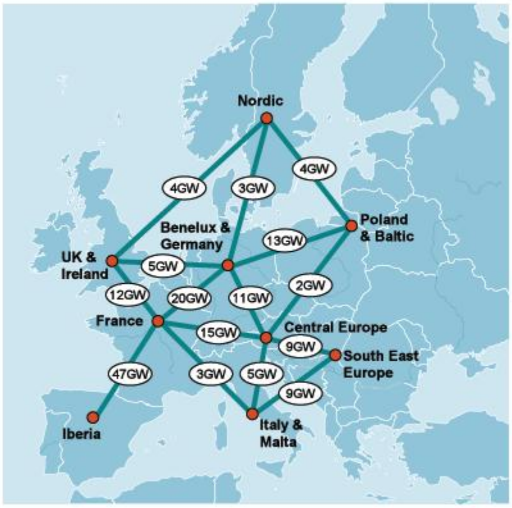
An example is The Climate Foundation Roadmap for 2050 which identifies net interregional transfer capacities to deliver renewable energy from abundant sources to centres of load for various renewable energy levels of penetration (see Figure 1.12 and Figure 1.13 for 80% case, with and without demand response) and is an example of the output of these design concept studies.

Interconnection	Capacity additional (existing) [GW]	Annual utilization [%]
UK&Ireland-France	19 (2)	57
UK&Ireland-Nordic	9 (0)	74
UK&Ireland-Benelux&Germany	5 (0)	61
France-Iberia	52 (1)	61
France-Benelux&Germany	23 (6)	54
France-Central-Europe	11 (3)	70
France-Italy&Malta	6 (3)	77
Nordic-Benelux&Germany	0 (3)	67
Nordic-Poland&Baltic	5 (1)	62
Benelux&Germany-Central-EU	7 (4)	56
Benelux&Germany-Poland&Baltic	13 (1)	72
Central-Europe-Poland&Baltic	0 (2)	52
Central-South East EU	5 (2)	62
Central-Europe-Italy	0 (5)	47
South East EU-Italy	11 (1)	57
Total	166 (34)	

SOURCE: Imperial College: KEMA

Figure 1.12: Climate Foundation Roadmap for 2050 for 80% RES without Demand Response

Total net transfer capacity requirements
GW (existing + additional)



Interconnection	Capacity additional (existing) [GW]	Annual utilization [%]
UK&Ireland-France	10 (2)	78
UK&Ireland-Nordic	4 (0)	90
UK&Ireland-Benelux&Germany	5 (0)	81
France-Iberia	46 (1)	74
France-Benelux&Germany	14 (6)	77
France-Central-Europe	12 (3)	89
France-Italy&Malta	0 (3)	92
Nordic-Benelux&Germany	0 (3)	85
Nordic-Poland&Baltic	3 (1)	72
Benelux&Germany-Central-EU	7 (4)	68
Benelux&Germany-Poland&Baltic	12 (1)	82
Central-Europe-Poland&Baltic	0 (2)	72
Central-South East EU	7 (2)	76
Central-Europe-Italy&Malta	0 (5)	69
South East EU-Italy&Malta	8 (1)	74
Total	127 (34)	

SOURCE: Imperial College; KEMA

Figure 1.13: Climate Foundation Roadmap 2050 for 80% RES with Demand Response

The following quote from the road map report demonstrates the intent:

"The most noticeable case for this is Iberia, where favourable onshore wind and solar conditions could result in significant export potential for RES capacity. The resulting need for transmission capacity to France (32GW in the 60% pathway) is therefore also large. However, the composite cost for the grid assumes a significant amount of underground/submarine HVDC for the grid expansion, which could be used to minimize the challenge by, for instance, running cable undersea through the Bay of Biscay. It is also clear that more wind and solar could be built outside Iberia lessening the need for transmission capacity from Spain to France. Finally, while adding capacity in this region has historically been limited, it should be seen in the light of the overall context of this work: a European energy system that will be fundamentally different from that of today in which overcoming this challenge will be only one of the large obstacles for decarbonisation".

1.5 Integration of Supergrid

The challenge of matching an increasingly variable energy mix with the changing and variable load requires the integration of:

- Large scale interconnection (Supergrid)
- Forecasting and Demand Side Response (Smart Grid)
- Storage

The Siemens paper - Highly Efficient Solutions for Smart and Bulk Power Transmission of "Green Energy" [9], describes the integrated solution as a hybrid using HVDC, and Flexible AC Transmission Systems (FACTS) technologies interconnecting Microgrid, Smart Grid and Supergrid (Figure 1.14).

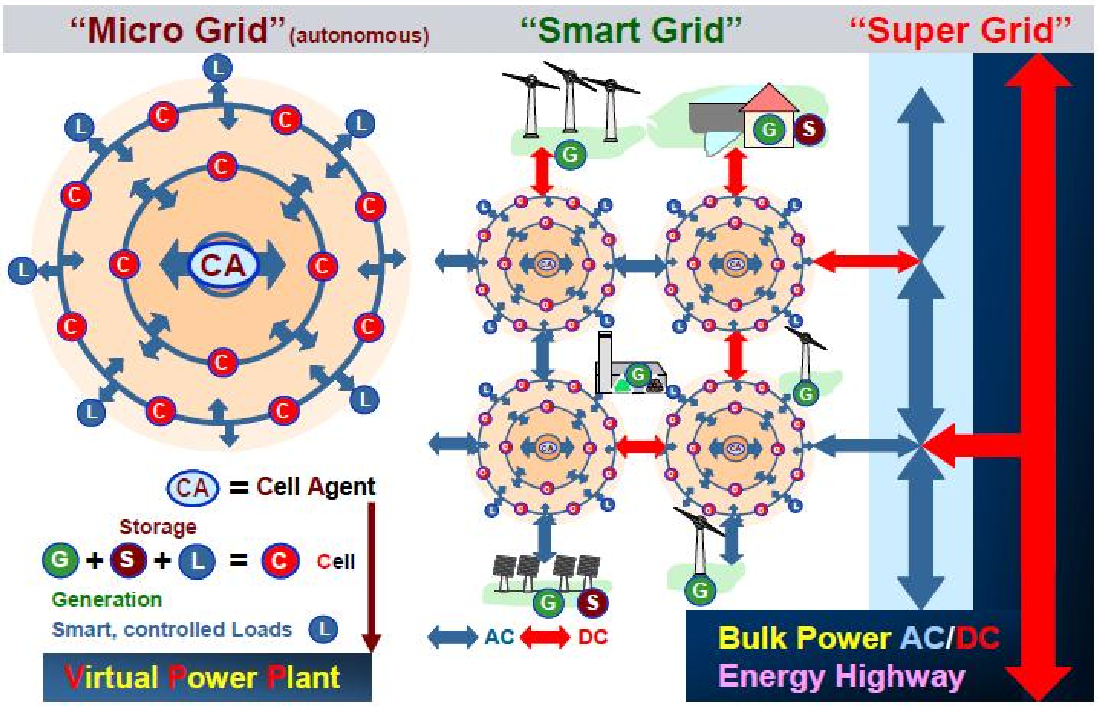


Figure 1.14: Grid Development Prospects according to Siemens

According to the Siemens paper:

"These integrated hybrid AC/DC systems provide significant advantages in terms of technology, economics as well as system security. They reduce transmission costs and help bypass heavily loaded AC systems. With these DC and AC Ultra High Power transmission technologies, the "Smart Grid", consisting of a number of highly flexible "Micro Grids" will turn into a "Super Grid" with Bulk Power Energy Highways, fully suitable for a secure and sustainable access to huge renewable energy resources such as hydro, solar and wind …

This approach is an important step in the direction of environmental sustainability of power supply: transmission technologies with HVDC and FACTS can effectively help reduce transmission losses and CO_2 emissions". (see Figure 1.14)

These hybrid designs expect some use of classic HVDC links, where appropriate, where the current state of the art includes voltages up to 800 kV and power transfer capabilities greater than 6 GW.

1.6 Standards

HVAC equipment and operation has been developed over more than 100 years and highly standardized solutions are available today. This allows competitive supply chains for all network components, such as transformers, switchgear, protection relays etc.

For HVDC technology, however, this is not the case. With very few exceptions, HVDC links are point-to-point connections, each built by one manufacturer. Each manufacturer's technology differs significantly in detail and cannot be easily combined with that of others. This applies both to the relatively mature Line Commutated Converters (LCC) and even more to the new technology based on Voltage Sourced Converters (VSC).

When Multi-terminal HVDC networks or HVDC Grids are to be developed, interoperability of the equipment provided by different manufacturers becomes important. In a first step, agreement on some fundamental operating principles of HVDC networks is needed, such as:

- Fault behaviour including:
    - short circuit currents of converter stations
    - location of fault clearing devices (at each converter station or at each DC feeder)
- Power System Protection including:
    - separation of normal transients from faults
    - relays and communication to selectively detect faults
    - fault clearing mechanisms including (fault current and overvoltage limitation)
- Converter Control and Protection including:
    - sequences for start-up and shut-down
    - converter station control
- HVDC grid controls

To ensure optimised development of the future integrated grid it is critical to agree such basic principles for the technologies.
Work is under way within organisations such as CIGRE and Cenelec to develop the necessary standards and to suggest standard transmission voltage levels for the Supergrid links. (Chapter 3.7 "The Way to Develop Supergrid")

Developing standards takes time and experience. HVDC Grids are new and consequently standardisation should be focused on functionality rather than on detailed parameters and technical solutions. This approach will provide the ground for an open market for HVDC Grid technology while at the same time allowing for innovative solutions.

Other standard definitions are required for the performance requirements for the Supergrid including reliability, availability, Loss of Load Expected, Infeed Loss etc. Transmission systems are typically designed based on N-1 criteria and the Supergrid design must address these reliability issues.

The design concepts will include investigation of the interactions of the new HVDC grid with the existing AC network, ensuring the stability of the integrated power system during DC faults and loss of large generation resources.

Regulators must provide leadership and appropriate rules for multi-jurisdiction links including allocation of use-of-system charges and ownership of system losses.

1.7 Questionnaire

To assist the working group in preparing this report a questionnaire was circulated to elicit the views of the System Operator stakeholders on the development of HVDC grids. The questions related to the following:

- Drivers for a HVDC grid
- Technical Requirements
- Reliability Requirements
- Future Proofing of Current Plans
- Black Start, System Services, Short Circuit Performance
- Fault Performance

The questionnaire results are summarised is Appendix I but common responses included:

- Drivers for HVDC include the need for higher transmission capacity over long distances, low transmission losses, long offshore connections, integration of large scale variable renewable generation, precise power flow control, connection of oil and gas platforms and the integration of electricity markets

- HVDC grids will be expected to meet the same reliability criteria as today's AC grids including N-1, loss of infeed and selective fault clearing

- HVDC will deliver other functionality such as interconnection of asynchronous systems, power flow control and power oscillation damping when embedded in the AC system

- While TSO's expect to minimize additional ratings for future system expansion to avoid stranded investments there is a view that early projects should allow for future expansion

- Early agreement is required on the fundamental operating principles of DC Grids and the Standardization of DC voltage levels to ensure interoperability between different manufacturers

- The technology selected will depend on the functional requirements

Chapters 2 & 3 of this document will address these issues, the technology available and possible future scenarios for the development of the Supergrid.

2. Network Technologies for Supergrid

2.1 Introduction

A broad variety of technical solutions is available today for connecting renewable energy sources (RES) as well as strengthening or expanding existing transmission networks. The two basic principles of electric power transmission are Alternating Current (AC) and Direct Current (DC).

Both principles are used today. High power converters provide the necessary conversion of voltages and currents to exchange power between AC and DC networks. This chapter deals with the main features, capabilities and limitations as well as the availability and practical experience of AC and DC technologies including converters and cables. All considerations in this chapter take the perspective of technologies for power transmission. Aspects of distribution networks are focused less.

The variable nature of RES requires energy storages levelling out peak generation and peak load conditions. Various types of storages for increasing the transient system stability and providing primary and secondary control reserve are expected to become part of future transmission systems. The different types of energy storages for power transmission networks and their applications are also described.

2.2 AC Transmission

2.2.1 AC Transmission Systems

By far the most common electric power transmission technology used today is AC transmission. Over a time of more than 150 years of development, expanded integrated AC systems have been formed. Besides a few exceptions AC systems in the world are operated at either 50 Hz or 60 Hz nominal power frequency. The railway supply system operated at $16^2/_3$ Hz in Germany is one example for an AC system having another power frequency.

An integrated AC system is defined by its common AC system frequency, which is kept the same within the system all time. Neighbouring AC systems may be operated at the same nominal power frequency but still are not operated as one integrated system. This is because the individual systems are not kept synchronous, meaning that the system frequency may vary slightly between the systems. The two integrated power systems in northern and central Europe are one example of asynchronous AC systems having the same nominal power frequency. To transmit power between asynchronous AC systems, HVDC technology as explained in Chapter 2.3 has most widely been used. Another technology is Variable Frequency Transformers (VFT) which has been used in few projects in North America.

State of the art AC transmission systems make use of various transmission voltage levels [10]:

- High Voltage (HV) nominal voltages typically ≥52 … 400 kV
- Extra High Voltage (EHV) nominal voltages typically 500 … 800 kV
- Ultra High Voltage (UHV) nominal voltages typically 1000 kV and above

The voltage level appropriate for a specific transmission task is determined by different factors, as there are:

- Historical factors (e.g. connection voltage levels, standard voltage levels used elsewhere in the system, etc.)
- the amount of power to be transmitted
- the transmission distance
- the use of cables, overhead lines or a combination thereof.

The main features of AC systems are:

- Simple principle of electro-mechanical energy conversion (electrical power generation and load)
- Voltage levels can be changed quite easily using transformers; high voltages are beneficial for long distance power transmission, because the transmission power losses decrease with increasing voltage level
- Switches and circuit breakers use natural current zero crossings to interrupt currents.

The main limitations for extended AC systems arise from:

- The reactive power component associated with the periodic reversal of electrical and magnetic fields, which occur with the network power frequency in all network components.
- The need to keep the frequency exactly the same and close to its nominal value throughout an integrated system under all conditions

2.2.2 Reactive Power

Reactive power flow in the network is an unwanted side-effect of AC transmission because:

- Reactive power cannot be transformed into other forms of energy but causes loading of the transmission lines, transformers and other system components
- It causes extra power losses
- It contributes most to fluctuations of the AC voltage magnitude

Under unfavourable conditions unbalanced reactive power in the system can lead to voltage collapse or excessive overvoltages jeopardizing system stability.

Reactive power cannot be avoided. The European transmission networks today benefit from many generating units located in the vicinity of load centres providing reactive power support.

With replacing more and more conventional power plants by renewable energy sources, new means for reactive power compensation will be needed. Effective solutions can be found making use of the complementary nature of reactive power caused by electrical fields on the one side and magnetic fields on the other side. Any surplus of reactive power due to electrical fields (capacitive reactive power) can be compensated by magnetic fields (inductive reactive power) and vice versa. Examples of network components providing capacitive reactive power are capacitors, examples of network components providing capacitive reactive power are reactors.

The reactive power condition of a network varies with the network configuration (connection or disconnection of transmission lines, transformers, power plants or reactive power compensation equipment) or the loading of the network. Means for compensating reactive power are distinguished regarding the way they are connected to the power system:

- Shunt compensators (connected line to ground or line to neutral)
- Series compensators (connected in series with a transmission line)

2.2.2.1 Shunt Compensation

For permanent or long term reactive power compensation, switched reactive power components like Mechanically Switched Reactors (MSR) or Mechanically Switched Capacitors (MSC) are used (Figure 2.15)

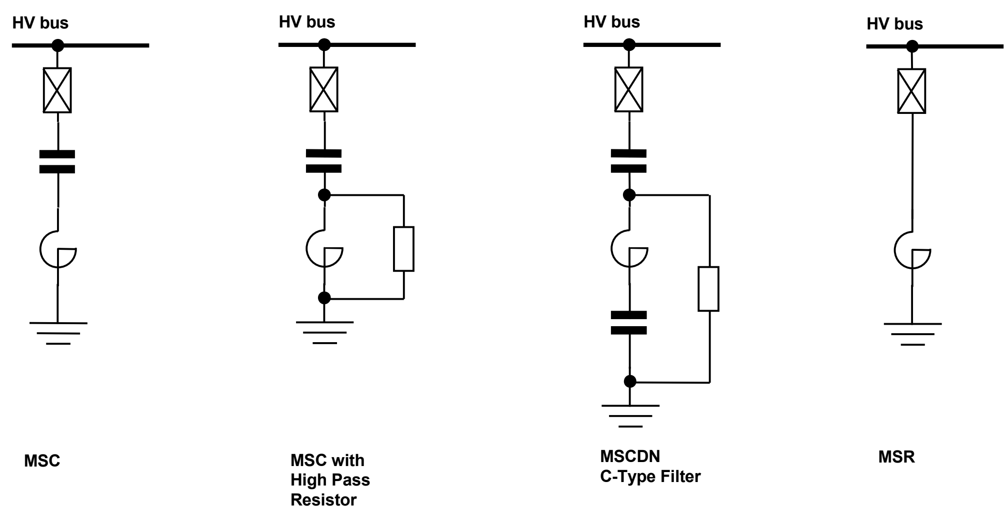


Figure 2.15: Mechanically Switched Branches for Reactive Power Compensation
- MSC
- MSC with High Pass Resistor
- MSCDN
- MSR

The speed of response is subject to the following constraints:

- Response time of the mechanical breakers is typically in the range of 100 ms or more for closing and typically 60 ms or more for opening, depending on the controls.

- Repetitive switching is constrained by charging times of the breaker mechanics. After one open-close-open cycle, recharging times typically 15 seconds or more are needed [11].
- Capacitors in the switched branch often need to be discharged before reclosing; possible discharge devices have to be rated for the number of successive reclosing.
- Switching causes transient voltage fluctuations which may impose further constraints on the tolerable number of successive switching events within a certain time (voltage flicker issues).
- Capacitors have limited permissible switching frequencies per year (1000 times) under certain conditions [12].

Connecting capacitor banks to an AC system may cause harmonic voltage levels existing in the network to be increased. If voltage levels exceed tolerable limits, capacitor branches can be designed to provide harmonic damping. Depending on harmonic requirements and tolerable power losses, MSC with High Pass Resistors or so-called Mechanically Switched Capacitive Damping Networks (MSCDN) also referred to as C-type Filters (Figure 2.15) are used. The damping is effective at the tuning frequency of the branch and at higher frequencies.

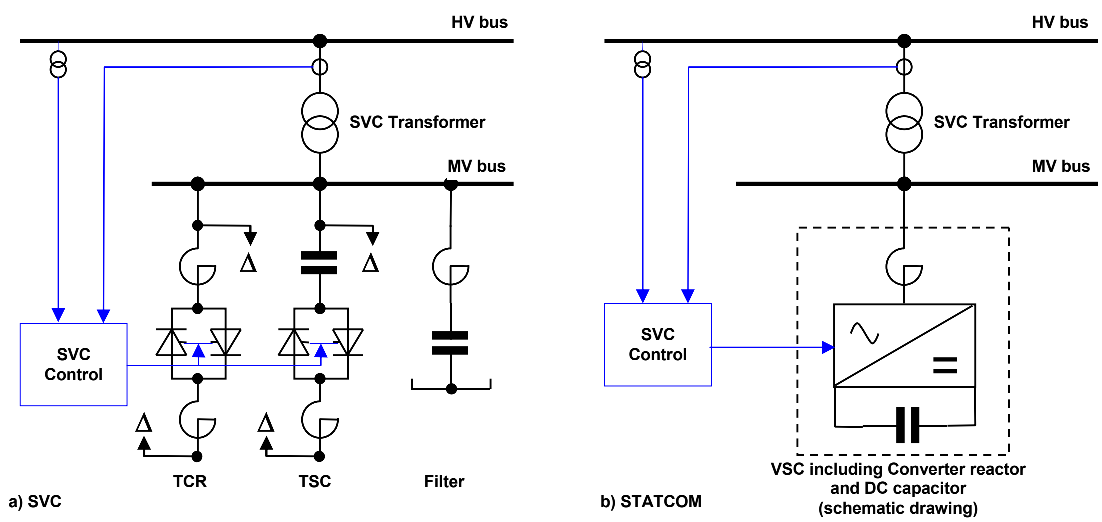


Figure 2.16: Dynamic Shunt Compensation Devices
a) Static VAR Compensator (typical arrangement comprising:
- one Thyristor Controlled Reactor (TCR)
- one Thyristor Switched Capacitor (TSC)
- one fixed capacitor (Filter)
b) Static Synchronous Compensator (STATCOM) with schematic drawing of converter

For dynamic or transient reactive power compensation dedicated equipment known as Flexible AC Transmission Systems (FACTS) are used. In FACTS devices, the rapid and often continuous control of reactive power is achieved by power electronic valves based on Thyristors or Voltage Sourced Converters (VSC). The following devices belong to the group of shunt connected FACTS:

- Static VAR Compensators (SVC), Figure 2.16a
- Static Synchronous Compensators (STATCOM), Figure 2.16b

The principle single line diagrams in Figure 2.16 show typical configurations of SVC and STATCOM devices. The number and type of the individual branches depends on the requirements of the application. More details of the various technologies are described in [13] and [14].

State of the Art HVDC converter stations based on VSC can be designed to provide dynamic reactive power support to the AC system, thus combining DC transmission with STATCOM functionality. The HVDC technology is described in more detail in Chapter 2.3.

2.2.2.2 Series Compensation

The inductive line impedance of long transmission lines of typically some 100 km or more can be compensated by Fixed Series Capacitors (FSC). For protection purposes the capacitors are in many cases bypassed in case of system faults by fast bypass circuit breakers. The Thyristor Protected Series Compensation (TPSC) is an alternative for bypassing the capacitors very fast reducing the energy to be absorbed by the capacitor overvoltage protection in case of faults and allowing repetitive fault scenarios. The Thyristor Controlled Series Compensator (TCSC) uses a Thyristor controlled reactor branch modulating the impedance of the series compensator.

Series Compensation can also be based on FACTS achieving continuously controlled output:

- Thyristor Controlled Series Compensation (TCSC), Figure 2.17a
- Static Synchronous Series Compensation (SSSC), Figure 2.17b

More details of the various technologies are described in. [13]

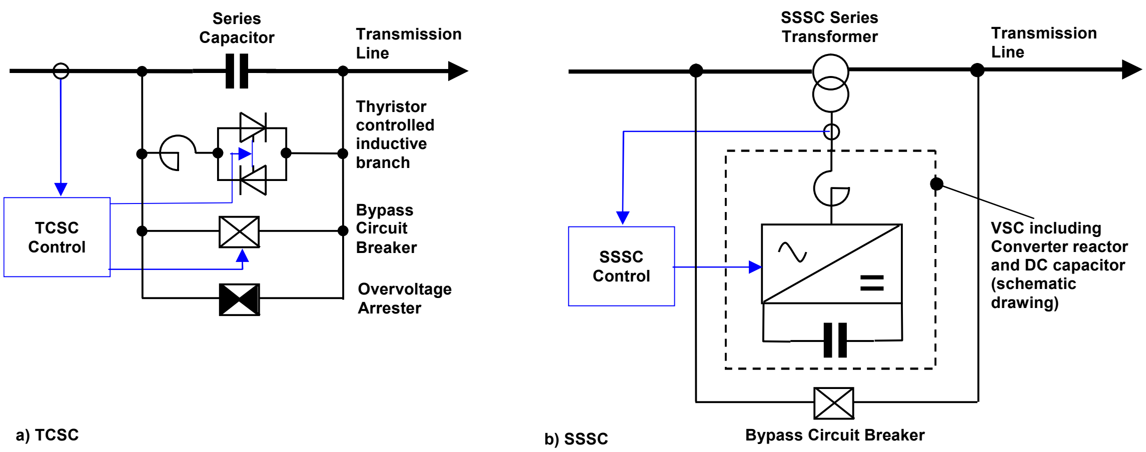


Figure 2.17: Dynamic Series Compensation Devices
a) Thyristor Controlled Series Compensator (TCSC)
b) Static Synchronous Series Compensator (SSSC) with schematic drawing of converter

2.2.3 Load Flow Control

In a passive meshed AC system, the split of load flow between parallel transmission paths depends on their impedances, e.g. the line impedances. Under certain conditions this may result in unequal loading of transmission lines limiting the power transmission capability of the network. One way to influence the impedance of long transmission lines is series compensation using FSC or series reactors for fixed compensation or TCSC for dynamic compensation.

For permanent or long term load flow control, tap changing transformers are also used. Such transformers contain on-load tap-changers allowing to insert an extra voltage in series with the normal transformer ratio. Depending on the transformer winding configuration the extra voltage can have various phase angles. Voltage applied longitudinally mainly influence reactive power flow through the transformer, voltages applied in quadrature to phase mainly influence the active power flow. Transformers introducing extra voltages with 60° phase shift are widely used. For a given transformer, only the magnitude of the extra voltage inserted can be changed, not its phase angle.

For dynamic load flow control, dedicated FACTS devices have been used:

- Unified Power Flow Controllers (UPFC), Figure 2.18
- Interline Power Flow Controller (IPFC), Figure 2.19
- High Voltage Direct Current Systems (HVDC) in Back-to-Back Configuration, Figure 2.20

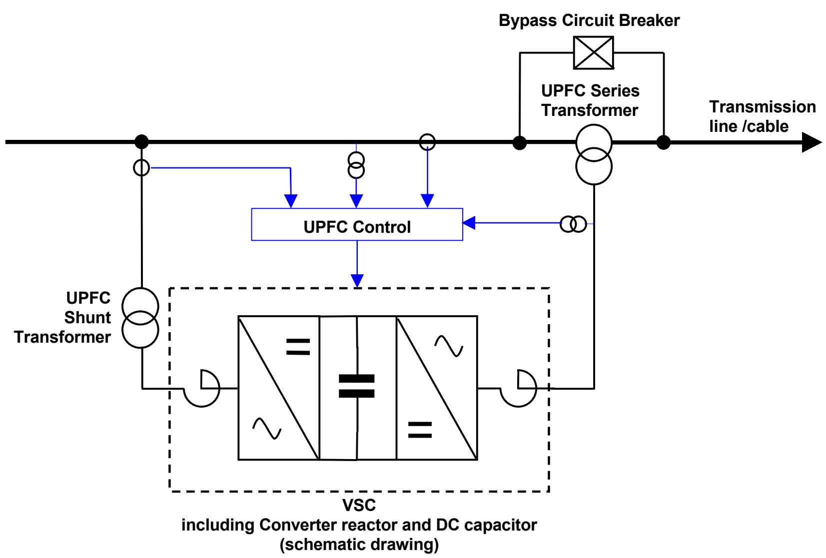


Figure 2.18: Unified Power Flow Controller (UPFC); typical arrangement

There is a competitive market for HVDC. However, UPFC and IPFC have been used so-far in demonstration projects ([15], [16]) and may be an option for future applications.

A principle single line diagram of a Unified Power Flow Controller (UPFC) is shown in Figure 2.18. The device combines a shunt connected VSC and a series connected VSC having a common DC circuit. The exchange of active power between both converters through the DC link allows controlling the voltage of the series connected converter to have an arbitrary phase angle with respect to the line current and variable magnitude. The device can thus be used to control active and reactive power flow through the respective transmission line independently within the power rating of the device. Additionally, the shunt connected VSC can be operated like a STATCOM controlling the bus voltage. The first UPFC installation was commissioned in the USA 1998 [15].

An example for an IPFC is shown in Figure 2.19. Two VSC having a common DC circuit are series connected into two transmission lines. Each converter can exchange reactive power independently with its transmission line. The connection through the DC circuit allows exchanging active power between the two transmission lines to control the power flow through the lines. An IPFC configuration can be selected as one operating mode of the "Convertible Static Compensator (CSC), at a NYPA 345 kV substation [16].

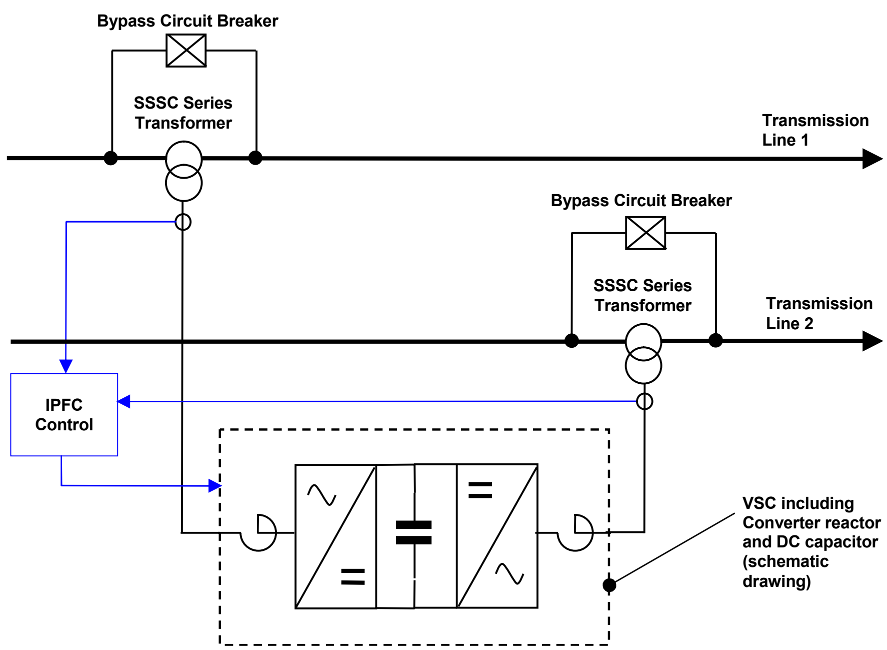


Figure 2.19: Interline Power Flow Controller (IPFC) with schematic drawing of converter

HVDC Back-to-Back systems have been widely used for its decoupling characteristic to connect asynchronous AC systems. Figure 2.20 shows a principle single line diagram based on VSC technology. Such a system can control active power and reactive power independently from one another within the power rating of the Back-to-Back station. However, most of the HVDC Back-to-Back systems used so far are based on Line Commutated Converters (LCC) equipped with Thyristors. Compared to VSC technology, LCC converters still have somewhat lower transmission losses. However, LCC have restricted reactive power control capabilities compared to VSC solutions. In particular, the reactive power exchange of one side of the DC link is not independent from the reactive power exchange on the other side. The LCC converters at both sides can only vary their reactive power absorption, i.e. they can only operate inductively. Capacitive operation of the station can be achieved installing appropriate filter and MSC branches.

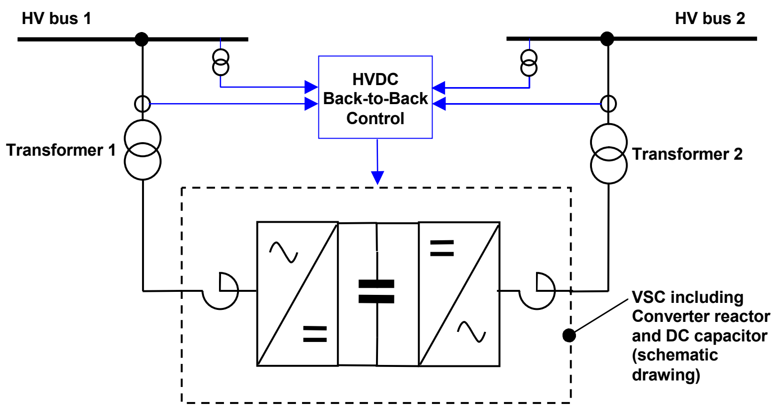


Figure 2.20: High Voltage Direct Current Back-to-Back Converter with schematic drawing of converter (Example based on VSC technology)

2.2.4 Frequency Control; Steady State and Dynamic System Stability

Besides reactive power balancing and load flow control, maintaining the stability of extended integrated AC systems is a further aspect for pure AC transmission. Any change in the AC system, e.g. a fault due to lightning or a load rejection cause a transient system response leading to a new steady state condition in terms of voltages, currents and frequency. A system is considered stable, if following a system disturbance it returns to a steady state (undisturbed) conditions without developing sustained oscillations.

To explain the aspects of system stability the principle system diagram shown in Figure 2.21 shall be considered. It shows an extended integrated AC system comprising a number of subsystems. While each subsystem is highly meshed, the coupling between the subsystems is given by a relatively small number of connections. Each of the subsystems contains generation and other big rotating machines. All rotating machines have to be synchronised to the common AC system power frequency. This synchronism has to be maintained even in case of sudden changes in the system topology or disturbances, where the machines in a single subsystem temporarily accelerate or decelerate. In such events oscillations between several subsystems may occur which are also known as Inter-Area Oscillations.

Any oscillations caused by the different speed of the machines have to be damped rapidly. The oscillations tend to be more critical the weaker the connection between the subsystems or the higher the power flow.

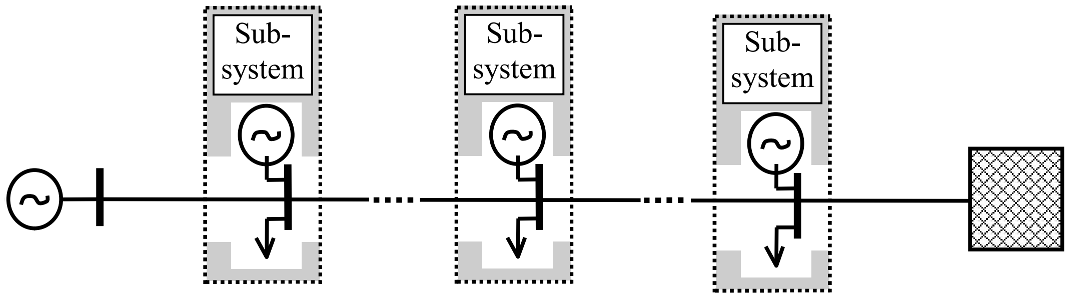


Figure 2.21: AC Transmission through Interconnected Power Systems

Power System Stabilizers are used today to damp Inter-Area oscillations. HVDC links that are connecting individual subsystems in parallel to the existing AC connections also provide effective solutions for damping such oscillations.

Another important point of system stability is load flow control within an integrated AC system. Without any control measures, the load flow in a meshed system is determined by the location of load and generation as well as the impedances of the individual transmission routes comprising lines, cables and transformers. The system design and operation normally follows the (N-1) principle, meaning that any single component of the system can be lost without causing overload at the remaining system components and without jeopardizing system stability. If the (N-1) principle fails, the outage of a single component can cause another component to run into overload, resulting in a trip of this component as well. Further on, this could lead to a cascading effect which in the worst case can lead to a Black-Out as already experienced in North America or partly in Europe. Maintaining the (N-1) principle requires careful system planning and congestion management.

Effective measures for load flow control include FACTS devices that are able to react quickly to control voltage (e.g. SVC) or transmission line impedance (e.g. TCSC). For long term load flow control phase shifting transformers are used.

2.2.5 Synchronous Condensors

The phasing out of conventional power plants having large rotating generators leads to a reduction of the system inertia and thus affects the dynamic system stability. The loss of the generator's contribution to the short circuit power of the network is another side effect of the change in power generation. Synchronous condensors are a well proven solution compensating both effects.

Synchronous condensors are rotating machines that are equipped for applications without active power utilization. These machines are powered by standard excitation systems either through static excitation with slip rings or through brushless excitation. In addition, step-up transformers and bus-ducts similar to those used in SVCs are used to connect to the grid. Figure 2.22 reflects the main components for such a solution.

Similar to normal generators, synchronous condensers can control reactive power by varying the excitation voltage. Typically, the reactive power that can be provided in overexcited operation (capacitive power) is higher than what can be provided in case of underexcited operation (inductive power). The response time is typically in the range of seconds.

Installation and maintenance costs are often high compared to static solutions like SVC/Statcom.

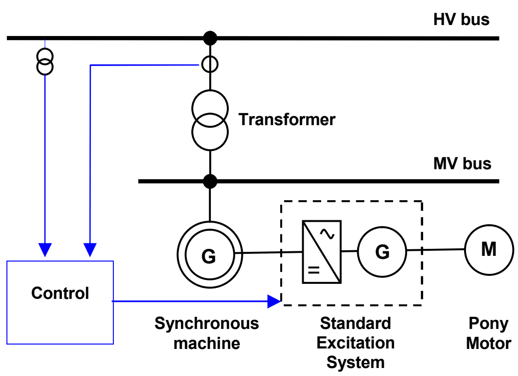


Figure 2.22: Synchronous Condensor

2.3 DC Transmission

The use of High Voltage Direct Current (HVDC) for power transmission is now a mature technology. From the first experimental schemes in Germany in the 1940's to the first commercial scheme in Sweden in the early 1950's, HVDC has found wide acceptance for many projects throughout the world. These have included:

- point to point connections using overhead wire
- point to point connections using submarine cable
- point to point connections using underground cable
- back to back connections between systems of the same nominal frequency (50/50 Hz or 60/60 Hz)
- back to back connections between systems of different frequency (50/60 Hz)
- multi-terminal connections with multiple rectifier and/or inverter station using the same transmission system
- multi-terminal connections with a tapping connection on the DC system

Most of these schemes have used Line Commutated Converter (LCC) technology. LCC schemes are now in service at DC voltages up to ±800 kV and power levels up to 7,200 MW. Studies are now in progress to take LCC technology to ±1,100 kV DC voltage and scheme powers of 10,000 MW.

In the last 15 years Voltage Sourced Converter (VSC) technology has arisen to provide an additional functionality for HVDC Power transmission. First VSC-HVDC schemes were based on so-called 2-level and 3-level converter technology. With 3-level converters DC transmission voltages of up to ±150 kV and power ratings of up to 330 MW were reached with one symmetric monopole transmission system [17]. Five VSC-schemes are in commercial operation in Europe today: Gotland, Estlink, Troll 1 & 2, and Valhall, where the last two schemes connect to offshore oil & gas platforms. The largest scheme in operation is at 400 MW at a DC voltage of ±150 kV (BorWin 1, connecting a windpark in Germany), and the highest voltage used today is 350 kV in a 300 MW scheme (Caprivi in Namibia with OHL).

Table 2.1: Comparison of LCC and VSC technologies

Item	LCC technology	VSC technology
1	Mature technology with 50 years experience	Emerging technology, in particular the multi-level converters
2	Good overload capability provided by robust power thyristor devices	Limited overload capability, limited by available IGBT devices
3	Requires strong AC systems at both end of the system (SCR[1] ≥2)	Can operate into weak AC systems, SCR is not critical
4	“Black start” capability requires additional equipment to generate voltage source	“Black start” capability is inherent
5	Generates harmonic distortion on the AC and DC systems. Harmonic filters are required	No significant harmonic generation. No AC or DC filters are required in most cases
6	Converters always absorb reactive power, extra shunt reactive power compensation is needed	Converters can control reactive power independently from active power within the station power rating (STATCOM functionality)
7	Large site area required, dominated by AC side harmonic filters	More compact site area, typically 50 - 60% of LCC site area.
8	Typically requires converter transformers, built to withstand DC stresses by specialised design and test facilities	Can use conventional grid transformers in some topologies
9	Power reversal is achieved by changing polarity of DC voltage	Power reversal is achieved by changing current direction
10	Polarity reversal requires the use of Mass Impregnated (MI) cable	Lack of polarity reversal means that both XLPE and MI cables can be used
11	Multi-terminal schemes are difficult to engineer due to the polarity reversal issue	Multi-terminal systems are simpler to engineer
12	DC grids are not considered feasible	DC grids become possible
13	Low station losses (typically 0.75%)	Higher station losses (typically 1%)

[1] SCR = Short Circuit ratio = Minimum Short circuit level of the system (MVA)/power transmission (MW)

The state of the art today is the Modular Multi-level Converter (MMC), and this technology is considered in the remainder of this document. There are schemes under construction at 2 x 1,000 MW, at a DC voltage of ±320 kV (65 km underground cable interconnector France-Spain) as well as a number of windpark connectors up to 900 MW at 320 kV DC voltage (BorWin 2, HelWin, SylWin, DolWin). Besides Caprivi, which is based on overhead line, to date most VSC schemes still have used submarine or underground cables.

Table 2.1 gives a comparison of the main features of LCC and VSC technology.
Although VSC is an emerging technology, particularly the multi-level topology, its advantages over LCC technology make it preferable as the solution for developing HVDC grids. This does not preclude the incorporation of existing LCC schemes into HVDC grids or of building LCC “backbones” for large power transfer within AC grids.

The following section considers the topologies of VSC schemes which may be used in the evolution of HVDC grids. Although the present level of VSC HVDC technology can be considered to be at 500 kV, 800 MW per cable for cables with laminated insulation (Mass Impregnated Paper – MI) and 320 kV, 500 MW per cable for cables with extruded insulation (XLPE), this situation will change in the next few years. Advances in semi-conductor technology and cable technology will provide higher levels of power transmission than are presently available.

2.3.1 DC Circuit Earthing and Converter Topologies

The following sections do not treat VSC technology at the detailed power electronic level, but considers only three phase converters between the AC (transformer) connection and the positive, negative, or zero DC voltage connection. There are two different types of systems which distinguish by there connection to earth:

- earthed DC circuits
- isolated DC circuits

Earthed DC circuits are used in asymmetrical monopoles or bipoles. Isolated DC circuits are also called symmetrical monopoles. The topologies of these systems is described further in the following paragraphs.

2.3.1.1 Asymmetrical monopole

This is the simplest scheme topology, as shown in Figure 2.23, using a single HVDC conductor between the stations and a neutral voltage (grounded) return conductor.

This scheme minimises the cost of the cable (or overhead wire) transmission system, as the return cable has full current rating but is only lightly insulated. Any outage, either due to a fault or maintenance, means complete loss of power transmission. The transformer is connected to the mid point of the converter, hence it experiences ½ of the DC voltage of the scheme. This requires a special converter transformer, as used on LCC schemes, although unlike LCC the transformer will experience no high harmonic content or fast transient voltages under normal conditions. The number of facilities which can build and test converter transformers is limited compared to those which can build and test conventional AC transformers.

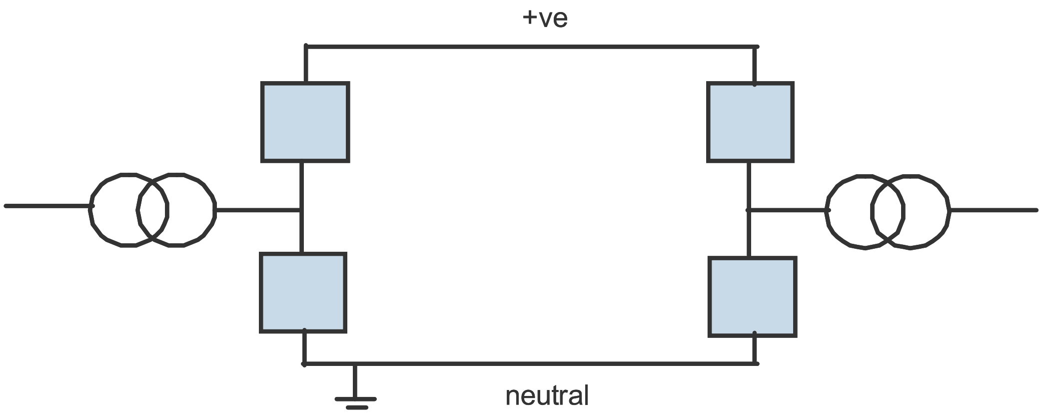


Figure 2.23: Schematic of an asymmetric monopole configuration

2.3.1.2 Symmetrical monopole

This topology uses two HV cables (+ve and –ve) and operates in an isolated mode on the DC side, as shown in Figure 2.24.

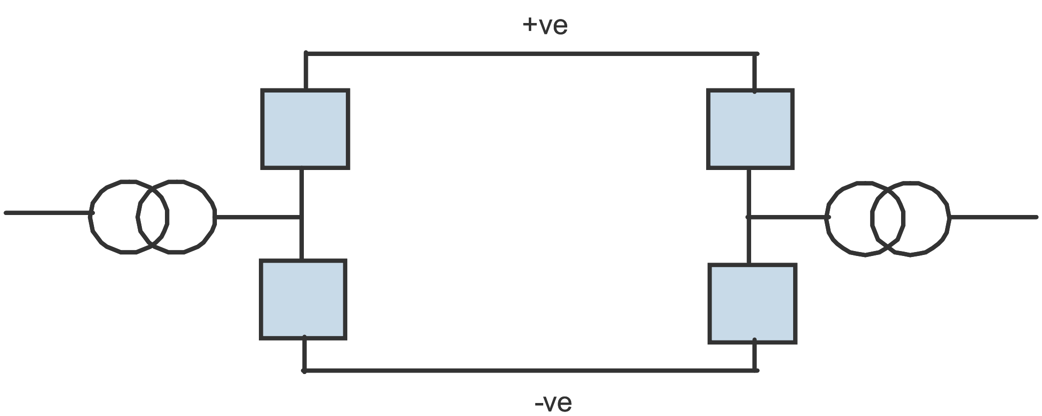


Figure 2.24: Schematic of a symmetric monopole configuration

Any outage, either due to a fault or maintenance, means complete loss of power transmission. The transformer is connected to the zero voltage point between the two converters and experiences no prolonged DC stress. This means that a conventional design of an AC transformer can be used. This increases the number of manufacturing facilities available to build such units.

2.3.1.3 Bi-pole with ground/sea return

This topology is two asymmetrical monopoles, as Figure 2.23, connected in a bi-polar arrangement, as shown in Figure 2.25. Like an asymmetrical monopole, a bi-pole requires the use of converter transformers as there is a continuous DC stress (50% of the DC transmission voltage) on the transformer secondary winding.

This topology uses two HV conductors, with the neutral conductor being provided by the ground or by the sea. In normal operation the DC current is balanced between the +ve and –ve conductors and there is no current through the neutral connection. If one pole trips or is taken out for maintenance, the current automatically passes through the ground/sea return path, giving an N – 1 capability of 50% power. This requires ground electrodes, which are normally located some distance (30 – 50 km) from the HVDC station, connected via a medium voltage insulated distribution line. For a sea crossing an electrode terminal is required at the coast, or some distance from the coast via a short submarine cable connection. It is an advantage of the ground/sea return path, that it has very low resistivity and therefore causes minimum power losses. However, the location of ground or sea electrodes must be studied to avoid any environmental effect or interaction with metallic structures in the ground or sea.

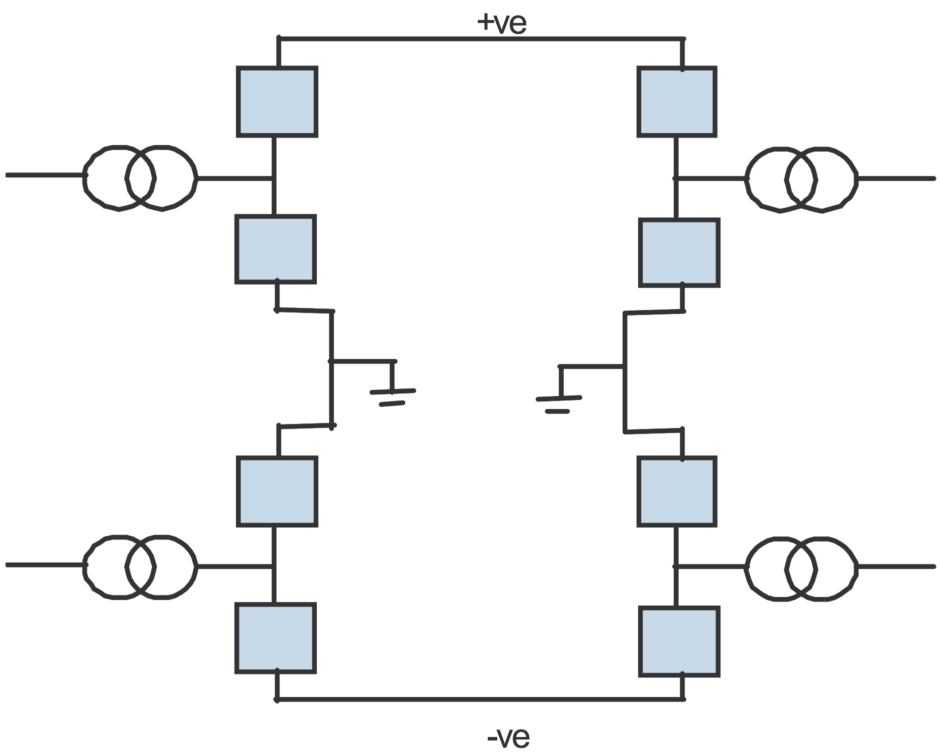


Figure 2.25: Schematic of a bi-pole with ground/sea return

2.3.1.4 Bi-pole with metallic return

As shown in Figure 2.26, this has the same topology as Figure 2.25, but the neutral return path is a third conductor, lightly insulated and connected to ground.

This scheme has the same functionality as Figure 2.25, but without the environmental impacts of using the ground or sea as a return current path during pole outages. The additional cost of laying a third conductor needs to be balanced against the costs of the ground or sea electrodes required by Figure 2.25. In normal operation the current in the neutral conductor would be zero. During maintenance outage or a fault on one pole, the scheme power would be 50% of total power. Depending on the design the remaining pole may operate in overload for a short period of time.

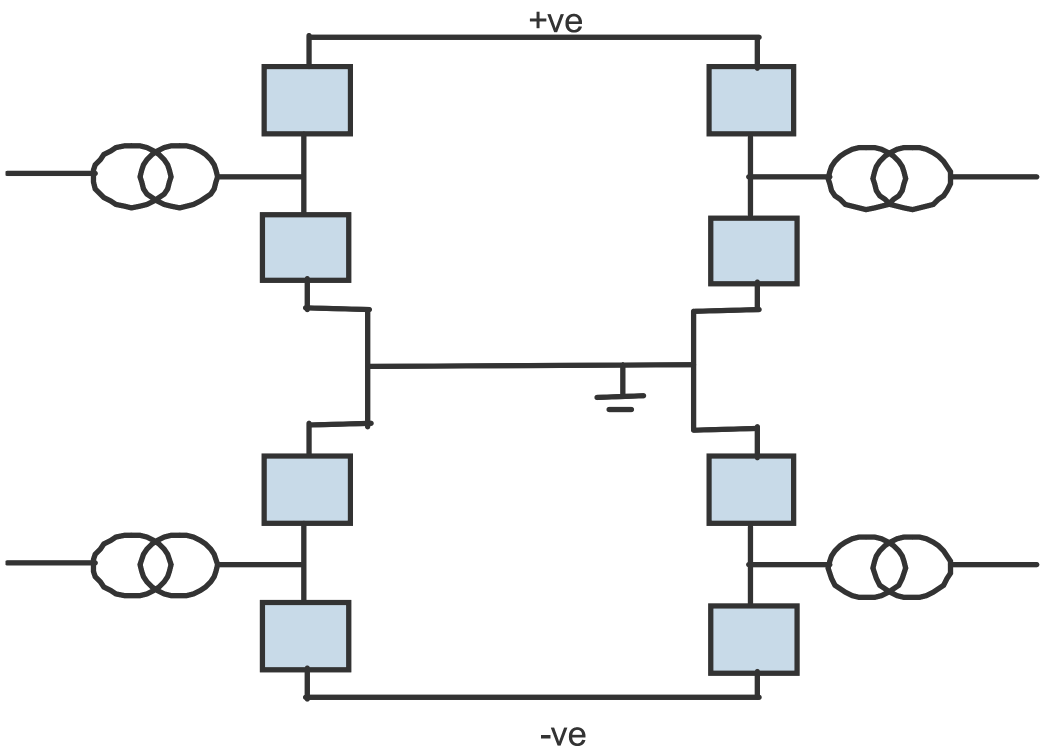


Figure 2.26: Bi-pole with metallic return

2.3.2 Modular Multilevel Converter

2.3.2.1 Introduction

The use of Voltage Sourced Converters for HVDC power transmission was first pioneered (by ABB) over 15 years ago and since then there have been a number of evolutions of the converter technology used. The main driver for this evolution has been the need to reduce the operating losses of the converter stations to the levels achieved by LCC technology. The development (by Siemens) of the Modular Multi-level Converter (MMC) technology radically improved the operating losses of the converter stations, by avoiding the need for high frequency switching of the semi-conductor devices. Following this change of technology, there has been a convergence of VSC solutions from the three major European HVDC manufacturers (Siemens, ABB and Alstom). Although there may be differences in the design of the power electronic converters, the technical solutions being offered are all based on the same concepts, thus replicating the situation which has existed in LCC technology for many years. In the following sections the basic principle of the VSC technology is described. This may have different names from different manufacturers, but is here described as a "half-bridge" converter. A variant of this topology is the "full-bridge" converter, which has additional functionality, but at the "expense" of higher cost and operating losses. The full-bridge solution is well adapted for applications with overhead line sections or for limited regional multi-terminal systems.

2.3.2.2 "Half Bridge" Modular Multi-Level Converter (MMC)

A VSC HVDC Multi-level converter based on "half bridge" modules is illustrated in Figure 2.27.

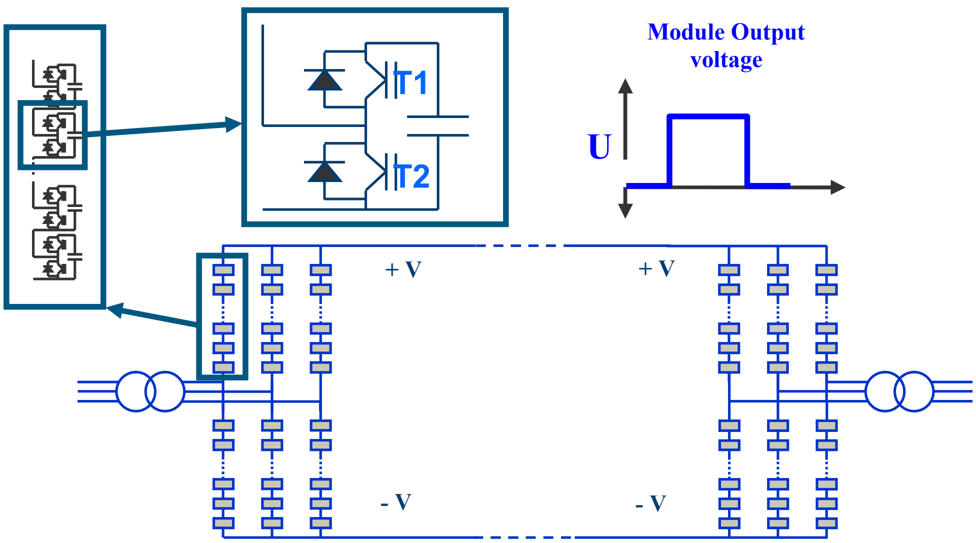


Figure 2.27: "Half Bridge" Modular Multi-Level Converter

The basic module design is relatively simple with a minimum of components although other power components are required in a practical design. Each module is only capable of generating two voltage levels; zero voltage or positive module voltage, consequently under fault conditions the presence of the anti-parallel diodes in each IGBT means that the converter can not prevent, or block, conduction between the AC terminals of the converter into a fault in the DC system. The fault current path can only be blocked by disconnecting the AC feed and then isolating the fault using off-load isolators. This arrangement has been widely used for two – terminal schemes and may be suitable for schemes up to a few terminals. However, for large multi-terminal systems or HVDC grids, DC breakers are needed to isolate faulty parts of the grid during faults.

2.3.2.3 "Full Bridge" Modular Multi-Level Converter (MMC)

A VSC HVDC Multi-level converter based on "full bridge" modules is illustrated in Figure 2.28.

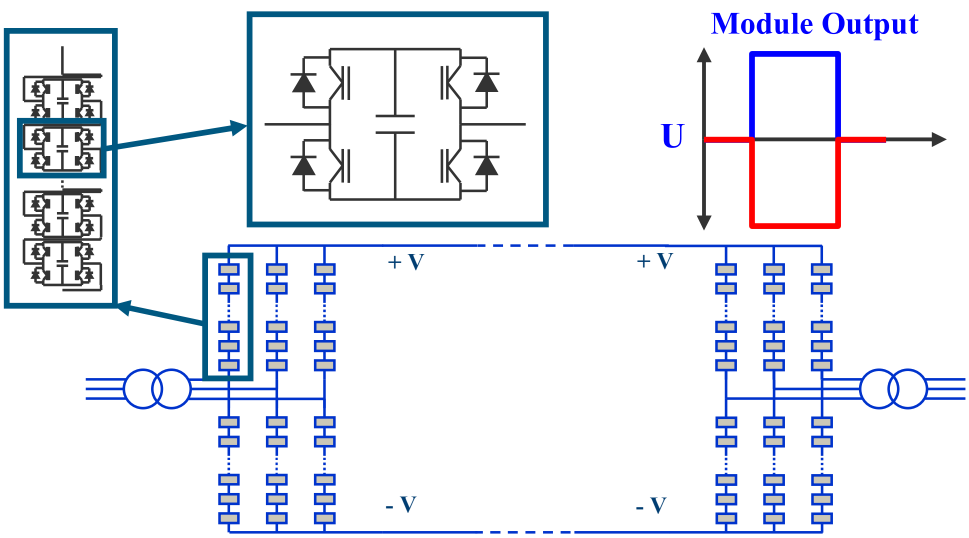


Figure 2.28: "Full Bridge" Modular Multi-Level Converter

At first glance the full bridge module requires more switching devices than the basic half bridge module and, at any point in time, two switching devices will be in conduction in each module. It would appear that the conduction losses for this topology are twice that of the half bridge topology. In practice this is not necessarily the case as the module can produce three different voltages at its terminals; zero voltage, positive module voltage and negative module voltage. This allows the converter designer considerably greater freedom over choice of AC terminal voltage and hence AC current flow through the semiconductors. Consequently, in an optimized converter design, the losses of the full bridge converter are probably 30 to 50% higher than those of a converter based on a half bridge module.

The availability of the module to generate a negative gives the full bridge converter the ability to "oppose" the AC terminal voltage driving a fault current into a short circuit in the DC system and therefore stop the fault current. The full bridge converter integrates the converter and DC breaker functionality so that off load isolators can be used to provide for isolating the faulted feeder. These isolators can be fast acting (30 – 40ms) devices allowing rapid re-configuration of the grid and re-start of power flow. For HVDC grids to be developed in the future, additional DC breakers are most likely needed.

2.3.3 DC Breakers

The breaking of DC current is technically demanding and consequently true DC breakers are considerably larger and more expensive than their AC counterparts. DC circuit breakers which exist today normally consist of an AC circuit breaker plus an auxiliary circuit which creates a high frequency oscillatory current, allowing the arc to be interrupted when the current passes through zero. Alternatively DC breakers can be made out of semiconductor devices such as IGBT's, for example one half phase of the full-bridge circuit shown in Figure 2.28, is the equivalent of a single pole breaker. Whilst much faster than their mechanical counterparts, they would be considerably larger and more expensive, which will add to the costs of operating the DC breaker. Concepts have recently been proposed that eliminates the in-service losses while maintaing the required speed [18].

A robust DC breaker would need to fulfil the following basic functions:

- rapid opening in response to a signal from the DC protection system
- ability to interrupt the DC fault current, which could be 5 – 10 times the load current
- ability to withstand the recovery voltage across the open "contacts" (which may not necessarily be mechanical contacts)
- ability to withstand the rate of rise of recovery voltage, without "re-striking"
- rapid re-closure in response to a signal from the HVDC controller
- frequent operation without the need for major maintenance
- compact footprint suitable for off-shore platforms and stations in urban environments, where space is critical
- costs commensurate with its function as a protective device, which only operates on rare occasions. DC breakers will on the other hand lead to system designs with significant overall investment costs benefits if the number of converters can be reduced as discussed above for Multi-terminal solutions
- low operating losses
- low maintenance requirements

In common with AC transmission systems, a breaker failure scenario would need to be considered. This could be another series connected DC breaker, the converter itself, if it were of the full-bridge design, or the AC circuit breaker.

DC circuit breakers are currently in development by a number of manufacturers. Possible technologies may consider some of the following techniques:

Mechanical
- some variant of an AC breaker designed to quench and interrupt the arc
- magnetic assisted arc blow out techniques
- gas pressure assisted blow-out techniques
- some variant on the techniques used for medium voltage DC traction circuit breakers

Semi-conductor
- high voltage, high current thyristor based converters
- IGBT based converters

Superconducting

- using the rapid resistance change between superconducting and normal temperature states

Vacuum/plasma

- using high voltage vacuum systems
- using plasma tubes

2.3.4 Multi-terminal HVDC Systems

In conventional LCC technology reversing power flows requires reversal of the polarity of the converters. The complexity that this introduces into multi-terminal operation has limited the widespread use of multi-terminal systems. Only two such schemes, i.e. with a tapping connection on the DC system, are in operation, although a third is now under construction and others are planned. With VSC technology, power reversal is achieved by reversing the direction of current flow, but requires no change to the polarity of the converter terminals. This opens up the possibility of designing multi-terminal systems and hence full meshed DC grids.

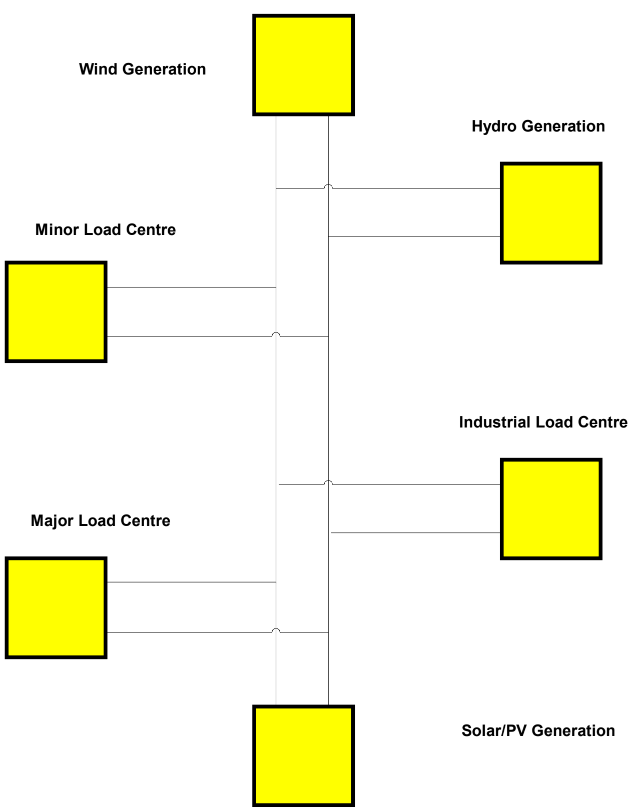


Figure 2.29: Multi-terminal DC system in radial topology

A multi-terminal system would consist of a number of AC – DC converter stations as well as a number of DC – AC converter stations. Figure 2.29 illustrates this concept, with 6 terminals supplying a “linear” (radial) DC network.

AC – DC converters supply power to the DC system from an AC power source, e.g. an interconnected AC system, wind parks or pumped hydro storages DC –AC converters will supply load centres or form an interconnection to another AC system node. While converter stations being connected to pure load or generation respectively have a unique power flow direction, converter stations connected to AC systems may be operated in both power flow directions.

Various converter stations can also be connected together forming a meshed DC system, also referred to as a HVDC grid. A meshed grid will achieve higher reliability of power transmission, i.e. there will be parallel paths for power flows in the event of outages of equipment or overloading of transmission corridors. A simple concept of a meshed HVDC grid is shown in Figure 2.30. This contains two distinct types of sub-station:

- a converter station where there is a DC – AC converter which connects to the existing AC transmission network
- a DC switching station (or Hub station), where there is no conversion equipment i.e. connection to the AC network, only DC switchgear, either isolators or circuit breakers.

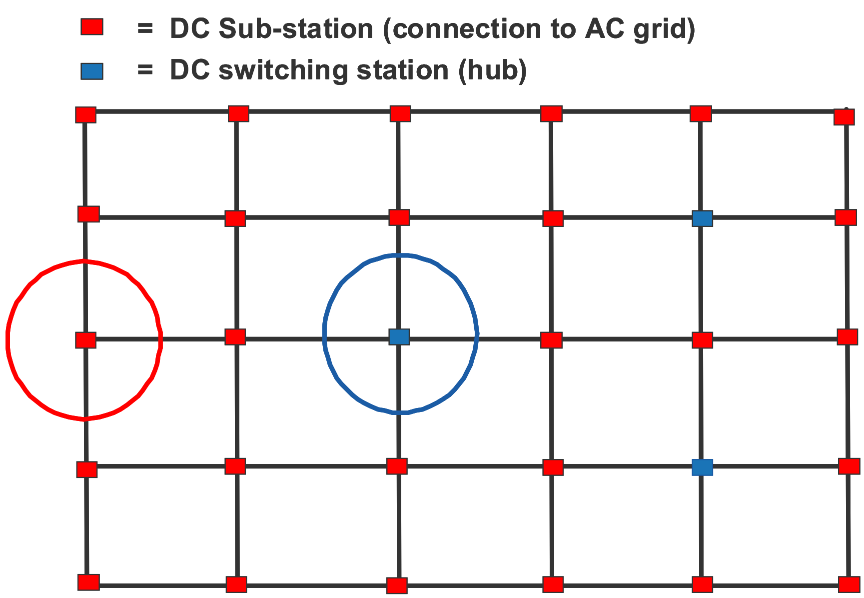


Figure 2.30: DC grid system (meshed topology)

2.3.4.1 DC grid topologies

Besides various ways of connecting converter stations in radial and meshed DC circuit, different earthing systems can be accommodated in a DC circuit as shown in Figure 2.31.

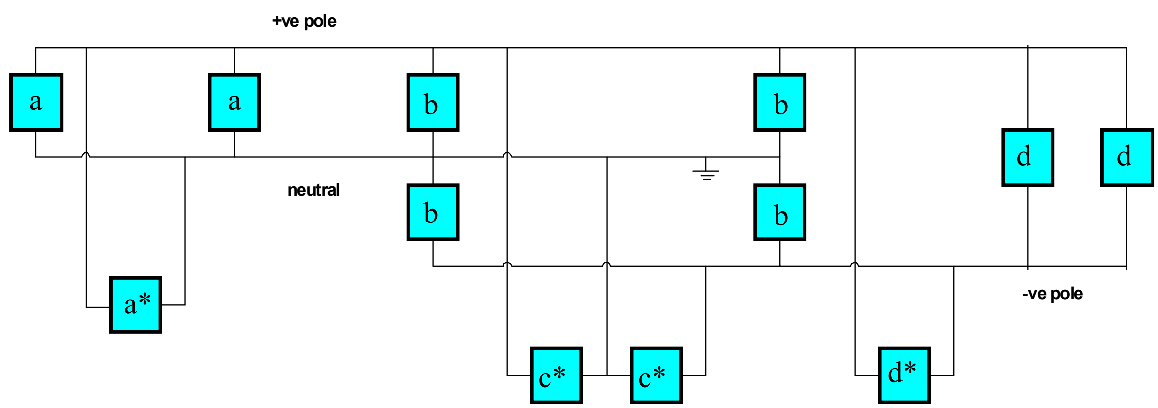


Figure 2.31: Multi-terminal HVDC system

This example shows:

- three asymmetrical monopole terminals, connected between the neutral and the +ve pole (a)
- a two terminal bi-pole system with a metallic neutral conductor (b), with a mid-point bi-pole tap connection (c)
- three symmetrical monopole terminals (d), connected between the +ve pole and the –ve pole, one of which is a mid-point tap connection

In detail each of the converter stations in the diagram in Figure 2.31 consists of a transformer connection to the AC grid and the upper and lower bridge power electronic converters, as shown in Figure 2.32.

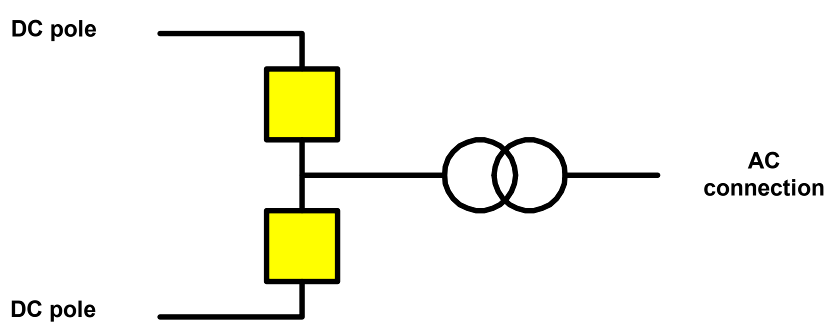


Figure 2.32: VSC HVDC converter pole

One pole of each converter station may be connected to the neutral connection (at ground potential), either for a monopole or as part of a bi-pole, but the transformer secondary winding will experience half of the scheme DC voltage.

Some of the connections in Figure 2.31 show "T" connections from the main "backbone" system to remote converter stations marked by "*", one each from the asymmetrical monopole section, the bi-pole section and the symmetrical monopole section. In each case a switching (hub) station would be required at the "T" point to allow connection and disconnection of the various incoming feeders.

2.4 Overhead Line Technology

Overhead lines have been widely used for AC and DC transmission. The absence of reactive power leads to DC transmission having an advantage over AC transmission when long distance bulk power links are considered.

Assuming constant current, an increase in transmission voltage results in an increase in transmission capacity. In this context, due to their high voltage transmission capabilities, overhead lines have significantly less transmission voltage constrictions and thus can transmit considerably more power per system when compared to cables.

Still, suitable right of ways for long distance DC overhead line transmission remains a big hurdle that cannot be easily overcome in many countries. One way to overcome such a hurdle is converting already existing AC overhead lines to DC overhead lines. Such a conversion requires taking into consideration various electrical and mechanical aspects, as there are:

- Number of conductors;
  AC lines typically consist of triple conductor arrangements (three phase system) while DC typically needs two conductors (bipolar system).
- Insulation requirements;
  While for a given Maximum Continuous Operating Voltage (MCOV) the protective levels for both lightning and switching type overvoltages are the same for DC and AC, DC requires longer creepage distances and DC corona effects may lead to different conductor cross-sections or bundling configurations than in case of AC.
- Conductoring;
  DC lines do not experience current displacement due to the skin effect, which may allow higher current ratings in case of DC.

The electrical requirements lead to corresponding mechanical and structural aspects that may impose limits on the HVDC system that is intended to replace an AC system on existing towers.

In case of multiple three phase AC systems at one tower, one or more AC systems may be replaced by DC leading to a hybrid AC/DC transmission line. The design of such hybrid AC/DC transmission lines requires additional effects to be taken into account, as there are:

- Mutual coupling for both systems due to induction phenomena in steady state and during faults in the AC or DC systems.
- Mutual cupling of both systems due to corona.
- Cross-faults between AC and DC and the necessary fault clearing measures, e.g. with respect to possible DC fault current components.

These requirements also apply in case the conversion takes place in stages.

For AC and DC overhead lines, considerations have to be made for ground clearances as well as line sags making sure that the lines are not being operated beyond their maximum design temperatures. Otherwise, the line sags may violate the permissible design clearances. Installing online monitoring devices on overhead lines helps circumvent any violation of design clearances. By evaluating line conductors taking into consideration their interaction with the environment, transmission operators can develop and apply line ratings in real time.

2.5 Cable Technologies

Adequate cable technologies are a pre-requisite for building the Supergrid. This is because the energy generated in offshore wind parks requires cable connections to the onshore main grid. For shorter transmission distances HVAC submarine cables have been used. Transmission distances longer than typically 50-100 km require HVDC links. However, the Supergrid will not only connect wind farms but will also interconnect countries across the sea, which because of the long distances in most cases will only be possible using HVDC cables.

For onshore transmission, limited rights of way, preservation of nature, short permitting times and the fact, that cable routes virtually do not have any visual impact on the landscape, are important drivers for cable connections. Overhead lines that may be acceptable for some parts of the grid may also be complemented by cable sections in sensitive parts, like for example in densely populated areas.

This chapter briefely describes the HVAC and HVDC cable technologies available today for onshore and offshore installation and shows typical applications and limitations of a technology. More detailed descriptions of offshore cable installation are given in Appendix II.

2.5.1 Cables for HVAC Applications

HVAC cables can be divided into a few large families, based on design and insulation material. With respect to the design three-core and single-core cables are to be distinguished. Concerning the insulation material Paper Insulated Self Contained Fluid-Filled (SCFF) cables and Cross-linked Polyethylene (XLPE) cables are described. These are the two most commonly used technologies today. Table 2.2 summarizes typical maximum values of SCFF and XLPE cables based on existing installations and projects in execution.

Table 2.2: HVAC cables: Maximum Data

	SCFF	XLPE
Maximum nominal operating voltage [19]	500 kV	500 kV
Maximum continuous conductor temperature	85-90 °C	90 °C
Conductor material	Copper/Aluminium	Copper/Aluminium
Maximum power installed	1200 MW/three phase	1000 MW/three phase
Maximum water depth	830 m	400 m
Maximum length	50 km	50-125(*) km

(*) depending on voltage and power rating

2.5.1.1 Paper insulated self contained fluid filled cable (SCFF)

The paper used for fluid-filled cables is usually low density in order to keep the dielectric losses low and the permeability for the fluid high. The fluid is of low viscosity and pressurized during operation. For single-phase cables hollow conductors are used which allow for an axial fluid flow to storage systems in order to mitigate thermal expansion of the fluid whereas for three-phase cables the space between the phases is used for axial fluid transport. In subsea cables the pressure of the fluid is maintained from shore stations and must allow for thermal expansion and contraction. The SCFF cable has long service experience and terminations and joints are well tested in operation. The operating temperature is in the range of 85-90°C. Significant advantages and disadvantages include:

- ✓ Long service experience
- ✗ Pumping stations limit length
- ✗ Risk for fluid leakage

SCFF cables have been used for nominal operating voltages up to 500 kV [19].
The core construction is similar to that described for underground cables, where electrical and thermal properties of the insulation could be enhanced replacing the traditional Kraft paper with Polypropylene Paper Laminate (PPL).

One limiting factor is the use of fluid mineral oil as the main insulation due to possible oil spilling in case cable damage.

2.5.1.2 Cross-Linked Polyethylene (XLPE)

Crosslinked polyethylene is formed by introducing crosslinks between polyethylene chains in low density polyethylene (LDPE), resulting in the formation of a network. One main characteristic of crosslinking is that the heat deformation properties are improved. LDPE is a thermoplastic material with a softening temperature of around 70°C and a melt temperature of around 110-115°C, whereas XLPE is a thermoset that does not melt but only softens above about 90°C. The continuous operating temperature is increased from 70°C to 90°C by crosslinking the material. Significant advantages and disadvantages include:

- ✓ Low dielectric loss
- ✓ No risk for oil leakage
- ✗ Risk of water treeing in case of moisture ingress

Dry design with XLPE insulation material can be currently used for HV application up to 500 kV for land cable applications and 420 kV for submarine applications.

2.5.1.3 Single and Three Core Cables

A typical application for three-core HVAC cables is the export cable for offshore wind farms. Critical aspects of this type of cable are the resulting global dimensions (when large conductor cross-sections have to be used) and the availability of flexible joints which today are available up to 420 kV for submarine applications. However, land cables make use of well-proven prefabricated joints.

For HV application also three single-core cables are used instead of three-core cables. In case of high transmission capacity required the solution with single-core cables is preferred because of better heat dissipation. The better thermal behavior as received by a large cable spacing has the drawback of a higher installation cost, because there would be three laying campaigns for each circuit. Single core AC cables are available with SCFF and XLPE insulation.

2.5.2 Cables for HVDC Applications

HVDC cables can be divided into two large families, based on insulation technology. HVDC cables with laminated insulation and HVDC cables with extruded insulation are to be distinguished. DC-XLPE is most commonly used nowadays as insulation material for extruded HVDC cables. There are different types of cables with laminated insulation, upon which the Mass-Impregnated Cables (MI) are most commonly used today. Table 2.3 summarizes typical maximum values of MI and XLPE cables based on existing installations and projects in execution.

Table 2.3: HVDC cables: Maximum Data

	MI	XLPE
Maximum nominal operating voltage	600 kV MI-PPL (awarded) 500 kV MI (installed)	320 kV (awarded) 200 kV (installed)
Maximum continuous conductor temperature	70-80 °C (MI-PPL) 55-60 °C (MI)	70 °C
Conductor material	Copper/Aluminium	Copper/Aluminium
Maximum power (cable pair)	2200 MW (awarded) 1600 MW (installed)	900 MW (awarded) 400 MW (installed)
Maximum water depth	Approx 1600 m	Approx 400 m

2.5.2.1 HVDC cables with laminated insulation

Three type of cables have been used for HVDC transmission i.e. the Mass Impregnated Paper "solid type" Cable, the Gas Filled pre-impregnated Paper Insulated Cable and the Self Contained Fluid (Oil) Filled Paper Insulated Cable.

The Mass Impregnated Paper Cable (MI)

MI has been used for HVDC for more than 100 years, reaching a voltage of ±75 kV already in 1906 (Moutiers-Lyon) [20]. An MI cable at ±100 kV was used first in 1954 for Sweden – Gotland connection. A number of later HVDC projects used the same type of cable, e.g. the Sardinia-Corse-Italy link at ±200 kV in the early 1960. From then, this type of cable has represented the major share of the HVDC cable installations, up to system voltages of 500 kV (Neptune RTS, USA and SAPEI, Italy).

Cables basically consist of a conductor lapped with semiconducting and insulating tapes which are then impregnated with a suitable viscous compound. The lapping of the paper is performed in a controlled environment to ensure high levels of cleanliness. The impregnation is made in large vessels and takes long time, thus limiting the production capacity for this kind of cable.

Insulation is then covered with an extruded lead alloy sheath, protected with a Polyethylene jacket and reinforced with metallic tapes. Armour layer may consist in one or two layers of round or flat galvanised steel.

This design is surely the most experienced for DC applications; its developments during past years have mainly been related to the optimization of materials (paper and insulating compound) allowing to increase the dielectrical stress level. This made it possible to realize long links at 500 kV operating voltage, even in very severe environmental conditions (like the SAPEI installation up to 'one mile' water depth).
The maximum conductor temperature for this type of cable is still limited to 55-60 °C and the power rating to about 800 MW per cable by using the largest conductor sizes. Significant advantages and disadvantages include:

- ✓ Long service experience
- ✓ Not limited by converter technology
- ✓ Long production lengths
- ✗ Not well suited for land cable installation due to higher weight/length

The Mass Impregnated Paper Polypropylene Laminate (MI-PPL)

In order to improve electrical and thermal performances of the Mass Impregneted Cables recently a new insulation technology consisting of Paper Polypropylene Laminate (PPL) has been developed and tested. The maximum conductor temperature for this type of cable can reach 70-80 °C and the power rating of 1200 MW per cable approximatly at 600 kV by using the largest conductor sizes. Significant advantages and disadvantages include:

- ✓ Not limited by converter technology
- ✓ Long production lengths
- ✗ Limited service experience
- ✗ Not well suited for land cable installation due to higher weight/length

The Gas Filled cable
The Gas Filled Cable was used in 1965 for Cook Strait interconnection. Not withstanding its intrinsic suitability for medium-span submarine links, this type of cable is no longer used, due to the fact that it requires gas pressurization at the extremities and may experience uncontrolled water propagation in case of cable severance.

Self Contained Fluid Filled Paper Insulated Cables
SCFF cables have the peculiarity that they can operate in AC and DC systems, with practically no change in cable design and manufacturing technology. This characteristic has been adopted in some links that were planned to start operation in AC and to be converted to DC at a later stage, in order to increase the power transmitted by the link. SCFF cables can operate up to 90 °C and can therefore be competitive for short-medium length (there is a technical limitation for longer links, due to the need for adequate oil feeding systems) and very high power links. Because of their enhanced thermal capability, Self Contained Fluid Filled cables have sometimes been used associated to Mass Impregnated cables to overcome thermal hot spots, for instance for land portion of submarine connection between Italy and Greece.

2.5.2.2 HVDC cables with extruded insulation

HVDC cables with extruded insulation have been in operation since 1998 at ±80 kV (Visby-Näs). During recent years, the use of extruded insulation in the HVDC cable links showed a large increase due to some advantages that polymeric insulation can offer in comparison to traditional laminated one. The advantages include that the technology to produce extruded cables is normally less complicated than technology needed to produce mass impregnated or oil filled cables and production costs are lower as well. In addition to that, extruded insulation can operate at higher temperatures than mass impregnated cables that allows a higher transmissible power per cable pair using the same conductor cross section of the cables.

The polymeric insulation compound used for HVDC cables is different from the one used for HVAC but otherwise the manufacturing of the insulating system is identical. For DC the insulating material needs special composition reducing the accumulation of space charge. Uncontrolled space charges could otherwise increase the electric field within the cable up to the breakdown level of the insulation. During last years considerable progress for semi-conductive and insulation polymeric materials has been achieved and insulation technology was significantly improved as well. All current project experience of extruded HVDC cables is based on VSC converter technology, meaning that the cable system is never set out for polarity reversals.

The extensive development starting from the second half of the 1990's allowed to get acquainted with new technologies and to move towards industrial application with reasonable confidence. Currently there are ongoing HVDC projects with extruded-insulation submarine cables that have reached voltages of ±320 kV, but higher voltage cables are under development and are expected to be implemented in the future.

In addition to that, the broad application of VSC technology (that allows reversing the power flow without changing polarity of the DC voltage) is encouraging the choice of solid synthetic insulated cables. Significant advantages and disadvantages include:

- ✓ Faster jointing due to pre-molded joints (land)
- ✓ Reduced production cost
- ✓ Higher possible operating temperature
- × Limited service experience

It is expected in the next few years a further development of polymeric insulating materials that will improve electrical and thermal performances of this HVDC cable technology leading consequently to higher transmissible power per cable pair.

2.5.3 Special types of HV cables

2.5.3.1 Integrated return conductor cable

To comply with regulations on magnetic fields and to avoid electrolytic corrosion due to return currents in earth/sea in mono-polar HVDC cable transmission systems, either a separate insulated metallic return conductor (IMRC) or an integrated return conductor, (IRC) is required. The IRC solution comprise of a concentric integrated return conductor, i.e. forming a coaxial cable. This has the advantage that the magnetic field outside the cable is zero.

For the system to function, the IRC must be earthed at one end, and the insulation system must be designed to sustain the DC voltage at full load. Transients and capacitively induced voltages over the IRC solution must also be taken into consideration during construction of the cable.

2.5.3.2 Superconducting cable

Superconducting cables offer very high transmission capacity in compact conductors with low losses. As a result, superconducting cables are very well suited in densely populated areas with limited underground space.

The superconducting material used as conductors in these cables must be cooled to cryogenic temperatures in order to act as superconductors. High temperature superconductors (HTS) are superconductive at temperatures corresponding to liquid nitrogen. A superconducting cable system therefore consist of conductors, dielectrics, cryostat (maintaining cryogenic temperatures) and a cooling system that ensures constant flow of liquid nitrogen.

In April 2008 the Long Island Power Authority (LIPA) energized a 138 kV, 574 MVA AC superconducting cable system. Significant advantages and disadvantages include:

- ✓ Large power ratings
- ✓ Existing rights of way
- ✓ Thermally independent from the environment
- × Requires cooling system which needs maintenance
- × Not yet applicable for submarine applications
- × Limited service experience

2.6 Gas Insulated Lines

Gas insulated lines (GIL) are based on gas insulated switchgear (GIS) technology and use a similar high voltage insulation system consisting of insulating gas and solid insulators. The first GIL was put into operation in 1974 at a voltage level of 420 kV AC and is used to connect the Schluchtsee power plant, Germany, to the transmission grid [21]. This so called first generation GIL used 100% sulfur hexafluoride (SF_6) for the main insulation. Aiming at cost optimization, the second generation GIL was developed in the early 1990's, applying an insulating gas mixture of SF_6 and nitrogen (N_2) . At the same time, a new welding technology allowed improving the system reliability. Today the GIL is used for voltages up to 550 kV AC [22].

Basically the GIL consists of two concentric aluminum pipes with insulators fixing the conductor in the middle of the enclosure. Two different types of insulator are in use, post and conical type, where the latter can also be gas-tight in order to build separate gas compartments. The conductor consists of pure electrical aluminum with low resistivity, so that electrical transmission losses and weight of conductor are at a minimum. The mechanical design of a GIL has to take into account the laying technology as well. A GIL can be laid in tunnel, can be directly buried or be laid above ground using special constructions (e.g. for bridges, viaducts, etc.). The laying technology influences the thermal design of GIL.

Significant advantages and disadvantages include:

- ✓ Low transmission losses due to the large cross section of conductor
- ✓ Long time electrical and thermal stability [23]
- ✓ Environmentally friendly: No visual impact, no audible noise, no risk of fire, very low external electromagnetic fields [24]
- ✓ AC GIL has low capacitive load. Reactive power compensation is needed typically every 100 km or longer distances
- ✗ High cost especially when laid in dedicated tunnels, e.g. for submarine applications
- ✗ Large gas volumes; SF6 substitute would be desirable

Application for DC requires basic investigations to understand DC charging phenomena.

2.7 Energy Storages

Energy storages provide capacity to level out generation/load mismatches in power systems. They are expected to play an increasing role in the future. The main driver can be seen in the replacement of conventional power plants by renewable energy sources. The following aspects are important from a power transmission perspective:

- Continuously available power is replaced by renewable energy sources that are fluctuating in nature. Peak generation and peak load have to be leveled out; power will have to be transmitted according to the local load/generation conditions.
- New types of generators connected to the grid by power electronic converters replace conventional rotating generators resulting in a loss of inertia in the power system. The inertia of rotating machines is an important factor of system stability in AC systems.

ENTSO-E has distinguished different types of energy reserve capacity:

- Primary Reserve (PR)
  PR is to balance rapid load/generation changes. Conventional power plants supplying PR have to keep 2% of their actual power output for balancing.
  PR must be supplied within 30 sec and has to be stopped after 15 min to be available for the next PR demand.
- Secondary Reserve (SR)
  SR has to start 30 sec after the drop or increase of AC system frequency. It is usually supplied by Single Cycle Power Plants (SCPP) and pumped hydro power plants due to their quick start ability.
- Minutes Reserve (MR)
  MR has to start manually no later than 15 min after the frequency deviation. MR is supplied by thermal plants, Combined Cycle Power Plants (CCPP) and pumped hydro power plants.
- Hours Reserve (HR)
  For durations longer than one hour HR or cold stand-by is used.

In terms of power rating and energy storage capacity, the following applications may be distinguished:

Small- and Middle-scale energy storages (some MW for a few seconds)
Small-scale energy storages can be used for power electronic converters to emulate the inertia of rotating machines. The amount of energy needed for that purpose is quite small and may even be integrated into the converters directly. If the converter couples a rotating machine to the AC system, as in case of a Wind Turbine Generator (WTG), the energy needed to emulate the inertia on the network side could also be exchanged by accelerating or decelerating the rotating machine temporarily. To serve the purpose of emulating inertia, the stored energy has to be accessible within a few milliseconds.

Middle-scale energy storages can be used as a primary and secondary control reserve to maintain system frequency in case of contingency conditions, like the sudden loss of generation. This is also referred to as spinning reserve. When replacing conventional power plants by renewable energy, the spinning reserve could be provided by energy storage devices that are added to the new power plant. Flywheels or Battery storage devices are considered for that purpose [25]. Providing primary control reserve for a bigger network, pumped hydro plants are used today [26]

Large-scale energy storages (GWh)
Renewable energy sources fluctuate according to the weather conditions or daytime. Peak generation is normally not co-related to peak demand. This requires storing energy under high generation / low load conditions to be provided when it is needed at a later time. Energy storages considered so far include pumped hydro plants, hydrogen or compressed air.

In principle, energy storages can be connected to AC or DC parts of the Supergrid. Besides hydro pump storages no big energy storages have been used so far on a commercial basis. The technology to connect the energy storage to the grid will largely be driven by the energy storage technology itself.

3. Scenarios for the Development of Supergrid from a Technical Perspective

3.1 Introduction

The availability of appropriate technology is an important pre-requisite for developing Supergrid. Technologies to be considered are in different stages of maturity: While some solutions are ready to use today, others may have well defined targets of development or some even need research work to understand basic principles and develop concepts for design and operation of equipment.

This chapter describes a roadmap and various scenarios for developing Supergrid from a technical perspective putting the relevant technologies in context of demand, solutions and time.

The development of Supergrid can start today. Some of the technologies described in Chapter 2 provide excellent solutions for connection of large scale renewable power and transmission system strengthening. For mid and long term planning, the roadmap described in this chapter gives a realistic outlook as to what technologies can be expected and when.

As the development of technology will be largely driven by the market requirements, scenarios for optimistic, normal and moderate development of demand are described.

To support the roadmap and scenarios described, the chapter gives guidance to answer some fundamental questions concerning the selection of AC and DC transmission.

3.2 Technical Roadmap for Developing Supergrid

Chapter 1 "Applications for Supergrid" describes important drivers for strengthening and expanding the power transmission system in Europe. Both, the demand to transmit power as well as the technology available determine system planning and project execution. The working group has identified three phases for developing the Supergrid from a technical perspective as shown in Table 3.4, page 59:

- today – 2015
- 2015 – 2020
- after 2020

The three phases differentiated by the degree of European and outer European system integration.

3.2.1 Phases for Developing Supergrid

3.2.1.1 Today – 2015

The period from today to 2015 is determined by renewable energy starting to replace older coal fired power plants as well as nuclear power, the latter especially in Germany. Europe's first large scale near shore and far shore wind parks are commissioned, typically in the power range of 500 to 1,000 MW. AC transmission is used as far as possible to connect the wind parks to the onshore grid. Projects that are more than 100 km away from their onshore connection point are connected by radial VSC based HVDC point-to-point links. To transmit the energy generated offshore to the load centres, the existing transmission system reaches its capacity limits and planning is underway for system strengthening and expansion. Studies such as the Offshore Grid Study [27] and the Climate Foundation 2050 Road Map [8] alongside initiatives such as North Seas Countries Offshore Grid (NSCOGI) [6] and ENTSO-E's 2050 Electricity Highways Working Group all point to the need for higher levels of network integration.

3.2.1.2 2015 - 2020

In the second half of the decade, the utilization of wind power is further developed building far shore (>100 km) bulk power wind park clusters, which have power ratings in the range of some Gigawatts. At the same time the phasing out of coal fired and nuclear power plants continues. Balancing generation and load calls for stronger system integration on a European level. To achieve the required flexibility of power flows and facilitate power trading, offshore wind parks are connected to one another and tapped into cross country links. A common European Grid Code is developed providing a basis for pan-continental system planning.

3.2.1.3 After 2020

This Phase is determined by continuing the system integration process leading to a European wide overlay grid. The overlay grid, mainly based on DC, is built to interconnect wind parks and pumped hydro storages in the North as well as large scale solar power plants in the South with the European load centres. Trans-continental power transmission is planned to connect to the solar power plants in the African desserts or to Eastern Europe and even Asia.

3.2.2 Challenges and Solutions for developing Supergrid

Fossil and nuclear power are the dominating sources of electricity today as shown in Chapter 1.2.1 "GHG / CO2 Reduction", Figure 1.2. The corresponding fossil and nuclear power plants were built at locations providing best conditions for fuel supply and operation. The existing transmission system was built to accommodate for the power flows supplying the loads from these power plants.

The increased use of renewable energy, as described in Chapter 1.4 "Technological Requirements", creates significant challenges for the electric power transmission system, due mainly to the location of the planned large scale renewable energy sources, whether offshore wind in the north or large scale solar power in the south of the continent. As a consequence:

- The load centres in central Europe need to be supplied more and more from the renewable energy sources over long distances, resulting in a demand for increased transmission capacity. Long distances require efficient power transmission solutions keeping transmission losses low.
- The shut-down of existing power plants means that at the same time their voltage and reactive power control capability ”is lost” to the power system (ref. Chapter 2.2.2 "Reactive Power"). This is even more significant as the demand for voltage control increases with longer transmission distances.
- The disconnection of large generators reduces inertia of the system and consequently the , reducing dynamic system stability (ref. Chapter 2.2.4 "Frequency Control; Steady State and Dynamic System Stability").
- The fluctuating nature of renewable energy sources requires new methods for providing adequate frequency control reserve (ref. Chapter 2.7 "Energy Storages").

3.2.2.1 Connecting Renewable Energy Sources and Increased Transmission System Capacity

The first large scale offshore wind parks in the power range up to about 500 MW have been connected in Denmark and UK with transmission distances that allow connection by HV AC cables. Today, wind parks up to 900 MW with transmission distances to shore of more than 100 km are built. HVDC systems based on VSC technology are used to connect the wind parks by separate point-to-point connections. Modular Multilevel Converters (MMC) in so-called Half-Bridge design (HB) are applied today providing the conversion from AC to DC and vice versa. Using today's XLPE cable technology, about 500 MW can be transmitted per cable at transmission voltages of up to 320 kV; and for MI these figures are 1,000 MW and 500 kV. Cables for higher voltages and power greater than 1,000 MW per cable are under development.

Some offshore wind park projects include considerable transmission distances on-shore in addition to offshore. Compared to offshore conditions, where long cable sections can be laid by ship, physical limitations (e.g. drum capacity) reduce the maximum section length on land making more joints necessary. As XLPE is lighter and requires less time to complete a joint (approximately one day instead of several), it delivers significant advantages for onshore installation cost and reliability.

The utilization of renewable energy leads to an increased power flow North – South in Europe. New links will be required to strengthen the connection between central Europe with northern and southern Europe (ref. Chapter 1.4 "Technological Requirements", Figure 1.12). In northern Europe sub-sea cable connections are needed while in the central and southern part overhead lines or land cables can be used. VSC DC transmission via XLPE land cables provides an attractive alternative where environmental or other constraints prevent overhead lines from being used. The Spain-France interconnector Inelfe (France – Spain Interconnector) having a power rating of 2 x 1,000 MW is one example of using VSC transmission with XLPE land cables.

3.2.2.2 Compensating Reactive Power

Long distance power transmission, which becomes necessary due to replacement of existing power plants, changes the reactive power flow within the HVAC system and can have unwanted side effects as explained in Chapter 2.2.2 "Reactive Power". Reactive power compensation can therefore be an effective measure to increase the utilization of existing systems. Flexible AC Transmission System (FACTS) or Mechanically Switched branches can be used to compensate reactive power where needed.

Wind parks connected by HVAC cables are often equipped with FACTS devices to meet the reactive power requirements at their point of connection.

State-of-the-art HVDC transmission based on VSC combines both the transmission of power with control of reactive power at the converter station. Moreover, VSC stations, designed appropriately, can be used to energize AC networks i.e. they have black-start capability.

3.2.2.3 Maintaining System Stability

The stability of an AC system can be precisely studied today using appropriate computer modelling including the controls of generators and large loads. Thus possible weaknesses and effective countermeasures can be identified at an early stage of system planning.

With its precise power flow control capability, HVDC systems can provide damping to power oscillations. This feature has been successfully implemented in various HVDC projects in the world [28], [29], [30].

Another important aspect of AC system stability is frequency control. The fluctuating nature of generation from renewable energy sources requires new methods of balancing load and generation. A strong European overlay network will help to level out differences in the local generation and provide connection to large scale energy storages like pumped hydro power plants. In order to achieve that, various high power links should be integrated into one Supergrid (refer Chapter 1.3 "Scenarios").

Table 3.4: The development of Supergrid in three phases

Time	Demand	Solutions	New Products and Systems
Today – 2015	• Connecting large scale near shore and far shore offshore wind parks (typical power rating 500 … 1,000 MW) to on-shore main grid • Development / strengthening of national and cross country transmission systems • Partial replacement of nuclear power plants in Germany, replacement of older coal fired power plants	• First HVDC radial (point-to-point) systems connecting offshore wind parks • Increased use of FACTS • Planning of embedded point-to-point HVDC transmission • Planning of Multi-terminal Projects, e.g. Kriegers Flak, ISLES, Round Three, Firth of Forth HVDC Hub etc. • Development of demonstrator of Supernode	• Increased power ratings for VSC HB (1,000 MW at 320 kV DC) • Demonstrators for VSC FB applications and HVDC circuit breakers • DC 320 kV cables with extruded insulation in operation[a] at different onshore and offshore projects (500 MW per cable) • DC cables with extruded insulation >320 kV developed[b] • MI-PPL 600kV (1.1GW per cable) developed[b] and higher voltages in development[c] • MI >500 kV cable developed[b] • AC GIL in operation[a] • Standardization work for HVDC grids in CIGRÈ, CENELEC started
2015 – 2020 contd'	• Integration of far shore bulk power generation (typical 1,000 … 2,000 MW) • European power system integration to balance generation and load in face of increased content of renewable generation • Replacement of nuclear power plants in Germany • Definition of grid	• High power long distance multi-terminal with few stations (3 to 5) up to 3 GW • Connection of multi-terminal and point-to-point systems by Supernodes • Increased use of FACTS • Small and Middle-scale Energy	• DC cables with extruded insulation >320 kV in operation[a] • MI-PPL 600kV cable in operation[a] • MI >500kV in operation[a] • Development of new extruded insulation compounds for HVDC cables • System for fast selective fault detection in HVDC

Time	Demand	Solutions	New Products and Systems
2015 – 2020	code for European Overlay Grid	Storages	networks • VSC FB and HVDC circuit breakers (selective fault clearing and system reconfiguration) • Hierarchical control architecture for integrated AC and DC Grid in Europe • Demonstrators for DC/DC Converter
after 2020	• Integration of large scale solar power (e.g. Desertec, Medgrid, etc.)	• European HVDC Grid, no power limit (>> 3 GW) • Interconnecting European Overlay grid	• Further Development of MI and MI-PPL Cables • HVDC cables with new extruded insulation compounds in operation • Superconducting cables • DC GIL • DC/DC converter

[a] in operation=existing project
[b]developed=available to Market
[c] in development=R&D

3.2.3 Cost

A number of studies have considered the cost of developing the Supergrid in a European context. In the Offshore Grid study [27] the total cost of connecting 126 GW of offshore wind in an integrated grid design is compared to the cost of connecting using the current practice of individual radial connections and a more efficient hub design, which interconnects wind farms offshore first before bring bulk power onshore to the existing networks. Two integrated designs are considered – a Direct Design and a Split Design.

In the Direct Design transnational interconnections are first built and tee-in connections to offshore wind generating stations are made later while, in the Split Design, the interconnectors are routed via the offshore wind stations – similar to the FOSG Phase 1 proposal [31].

The cost comparison is summarised in the following chart (Figure 3.33) from the Offshroe Grid report's executive summary:

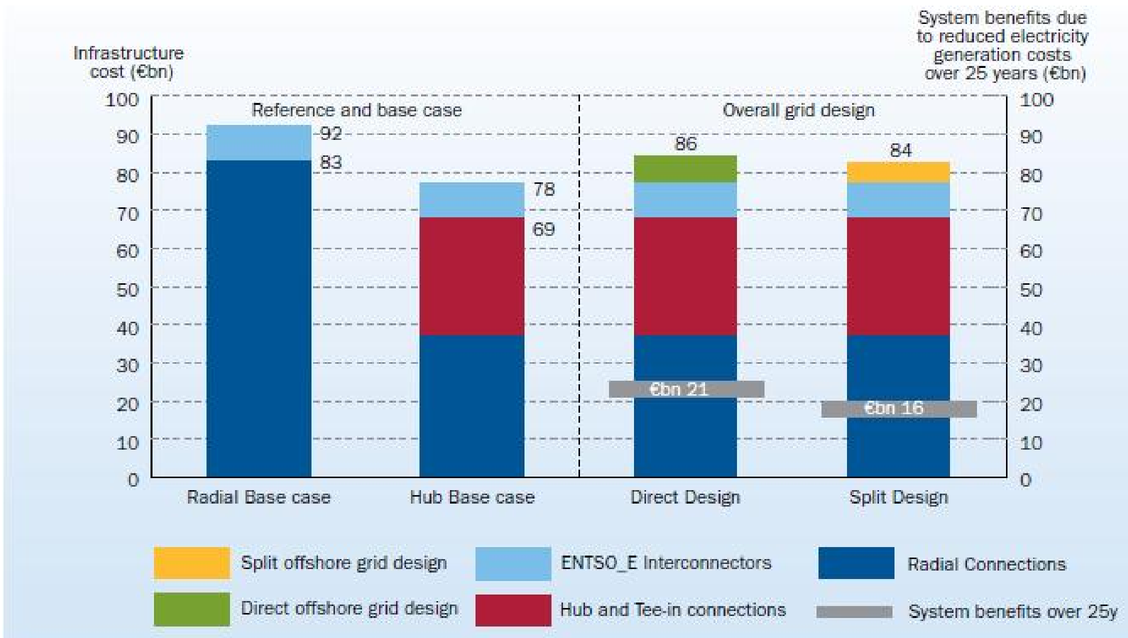


Figure 3.33: Investment Cost Comparison – Offshore Grid report [27]

Added to the radial base case and the offshore Hub design is the cost of the planned interconnectors included in the ENTSO-E Ten Year Network Development Plan (TYNDP) [4] of €9,000 million. The differences between the integrated designs considered and the more efficient hub design are:

- €86,000 – 78,000 = €8,000 million
- €84,000 – 78,000 = €6,000 million

However, the study concludes that this additional investment generates system benefits of €21,000 million for the Direct Design and €16,000 for the Split Design over 25 years lifetime of the assets.

In addition the Offshore Grid report concludes that the meshed grid investment represents about one fifth (1/5) of the value of the wind energy over 25 years (13,300TWh @ €50/MWh) and the *"additional cost for creating the meshed offshore grid would amount to only about €¢ 0.1 per kWh consumed in the EU27 over the project lifetime."*

In the UK study "Offshore Transmission Network Feasibility Study" by National Grid and the Crown Estate [32], a comparison is made between the radial connection of offshore wind and an integrated approach. The conclusions are summarised as follows:
"Total potential cost savings associated with the coordinated strategy of £6.9 billion by 2030 have been identified, when compared with the development of the offshore transmission network on a radial basis"
For comparison, the FOSG Phase 1 Proposal [31] has been costed on the basis that the direct user pays a Transmission Use of System (TUOS) charge for each MWh transmitted. Here the level of TUOS is dependent on the capacity factor for the grid which can vary from 44%,

offshore wind only on the network, to 100% where the grid becomes the mechanism for trading in a wider market context. The Figure 3.34 below shows how the TUOS (€/MWh) varies with capacity or utilisation factor.

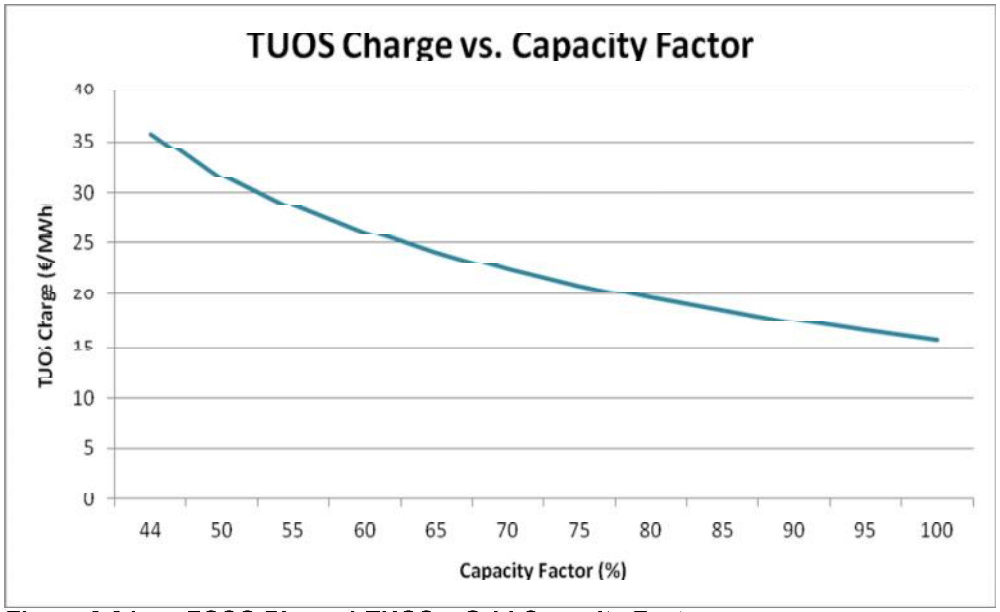


Figure 3.34: FOSG Phase 1 TUOS v Grid Capacity Factor

3.3 AC and DC Transmission for Supergrid

3.3.1 Criteria for Selecting the Transmission Technology

The European transmission comprises several integrated AC systems including Continental Europe, Nordic, Ireland, Iceland, and United Kingdom. Some countries like Estonia or Latvia are connected to the IPS/UPS system of Eastern Europe. All these systems are operated at 50 Hz nominal AC system frequency but in an asynchronous way, i.e. the actual frequencies are allowed to deviate from one another.

Within an integrated AC system new AC connections can be built, while interconnections between asynchronous systems require HVDC links. Besides that, the choice of AC or DC transmission may be influenced by one or more of the following criteria:

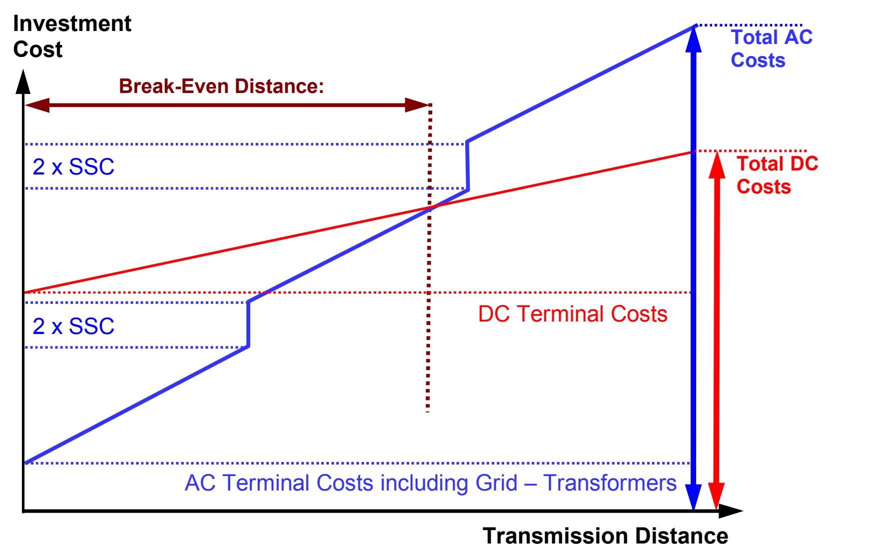
- Transmission distance;
  Long distance transmission of bulk power is often more economic in HVDC, both in terms of investment and operational cost.
- Long cable links, in particular subsea cables, require shunt reactive power compensation;
  In case of long AC cables (typically 100 km and more), the charging current requires compensation by shunt reactors, which is often not an economic solution, especially for AC subsea cables

- Reduced right-of-way requirements of HVDC systems - the transmission corridor needed for a HVDC line is considerably less than what is needed to transmit similar power with AC.
- Increasing AC system stability - in extended AC systems, HVDC links may be considered to improve the steady state and dynamic system stability.

Some important aspects of selecting the transmission technology are explained in the following paragraphs.

3.3.2 Comparison of AC and DC for Long Distance Transmission

The aspect AC transmission and reactive power has been discussed in chapter 2.2.2 "Reactive Power". With increasing AC transmission distances more and more equipment for series and shunt reactive power compensation (SSC) will be needed. Compared to HVDC transmission the higher cost for transmission line and reactive power equipment will make HVDC the more economic alternative beyond a certain break even distance as shown in Figure 3.35. The methods of SSC are not applicable to all cable systems, especially submarine cables.



SSC: Series and shunt compensation of AC Lines – required for each Section of the Line

Figure 3.35: Cost Comparison of DC versus AC transmission
A typical break even distance would be about 600 km for a 1000 MW transmission system

For long overhead transmission distances HVDC has significant advantages compared to AC in terms of transmission capacity and losses as is illustrated in Figure 3.36.

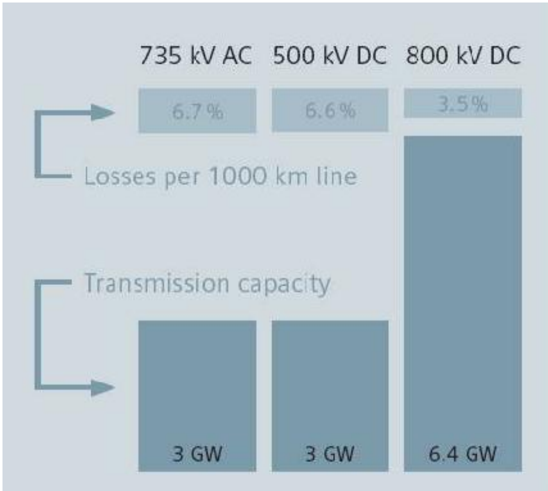


Figure 3.36: At similar voltage level, a DC line can transmit more than double the power at about half the losses compared to an AC line.

Today, the consenting process for power transmission projects can be long and poses an increasing risk to project delivery.

In case of overhead lines the number of three phase systems, the insulation distance between the individual conductors and the tolerable electrical and magnetic field strength determine the height of the overhead line towers and the width of the transmission corridor (ref Chapter 2.4 "Overhead Line Technology"). HVDC lines, even overhead, have a considerably reduced footprint with consequent reduced consenting risk. Figure 3.37 shows the visual impact of an AC transmission corridor compared with the equivalent HVDC system.

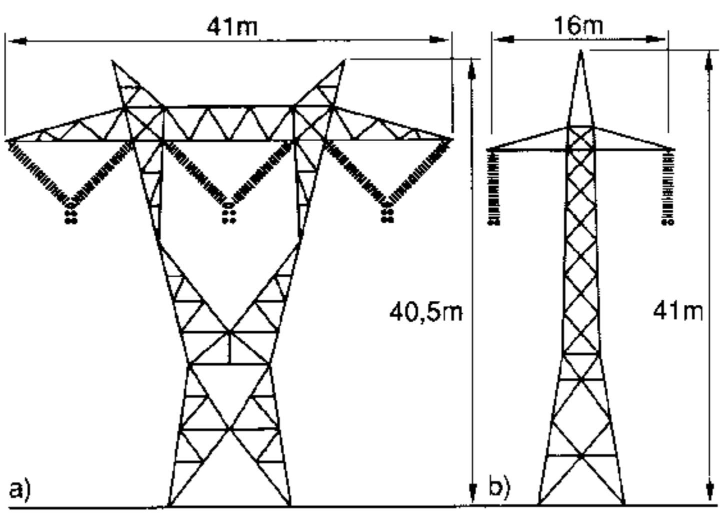


Figure 3.37: Comparison of Towers at the same transmission capacity of 3000 MW for
a) 800 kV AC Line
b) 500 kV DC Line

(To achieve the same level of redundancy as in case of the bipolar DC transmission, two parallel AC lines would be needed doubling the transmission corridor)

If the connection is made using underground cable systems then the visual impact is (following installation) potentially zero. However, for direct bury installation, the cable corridor width, which has an impact during construction, is determined by the thermal resistivity of the soil i.e. the ability of the surrounding ground to dissipate the heat generated by the cable losses. More details are given in Appendix III.

3.3.3 Hybrid AC and DC Systems

HVDC transmission can be operated in parallel with an integrated HV AC system forming a hybrid transmission system. Besides the increase of transmission capacity the HVDC can provide additional benefits to the AC system, such as load flow control and increase of system stability [28]. Here, a new type of combination of HV AC and HVDC systems is described, called the "Supernode". The Supernode is a hybrid system, which uses an islanded AC network to provide collection and routing of power on the Supergrid. Figure 3.39 shows the Supernode concept. Connecting the HVDC systems via AC combines the advantages of AC systems with those of long distance HVDC transmission while providing effective solutions for connecting offshore wind parks or oil and gas platforms.

3.3.3.1 Strengthening Integrated AC Systems using HVDC

An HVDC system in parallel to an AC system increases power transmission capacity and at the same time contributes to system stability.

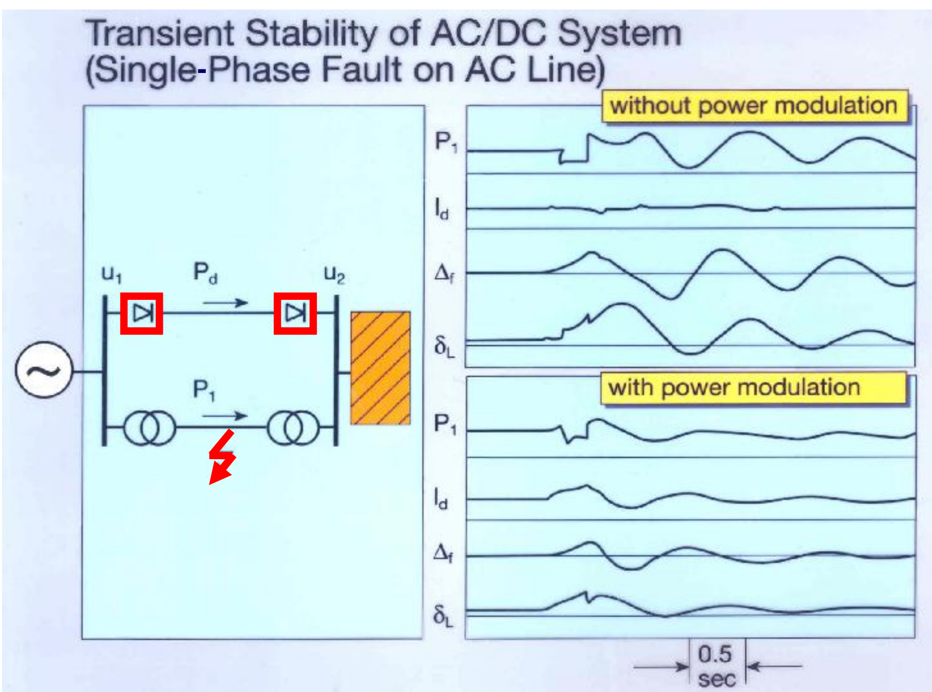


Figure 3.38: Hybrid System comprising an HVDC link in parallel to an AC connection demonstrating the stabilizing function of the HVDC

Extended AC systems or AC systems with dominating subsystems may suffer from power oscillations between the individual subsystems. An HVDC link running in parallel to an AC connection can effectively support AC system stability. This is illustrated in Figure 3.38, where a single phase fault was simulated on an AC line running in parallel to an HVDC link. Without the HVDC link providing any damping function, the system develops sustained oscillations as can be seen from the traces for power (P1), frequency deviation (Δf) or the transmission angle δL. With the HVDC modulating the DC current (Id) the oscillations decay rapidly and the system remains stable.

3.3.3.2 Supernodes

The Supernode concept as shown in Figure 3.39 is largely based on technology existing today. The development needed to build Supernodes is mainly in the field of control and protection for the islanded AC network, which includes frequency control, fault detection and fault clearing strategies.

The preferred DC transmission technology for building Supernodes is VSC. This is because a VSC transmission system can generate and maintain the AC voltage at the node with respect to amplitude and frequency, a feature also referred to as black start capability. As long as there are VSC systems providing sufficient short circuit power available at the AC node, LCC based DC transmission can also be connected. The concept of VSC transmission controlling islanded AC networks has been demonstrated by the first HVDC connected wind parks in the North Sea which are currently in operation or under construction.

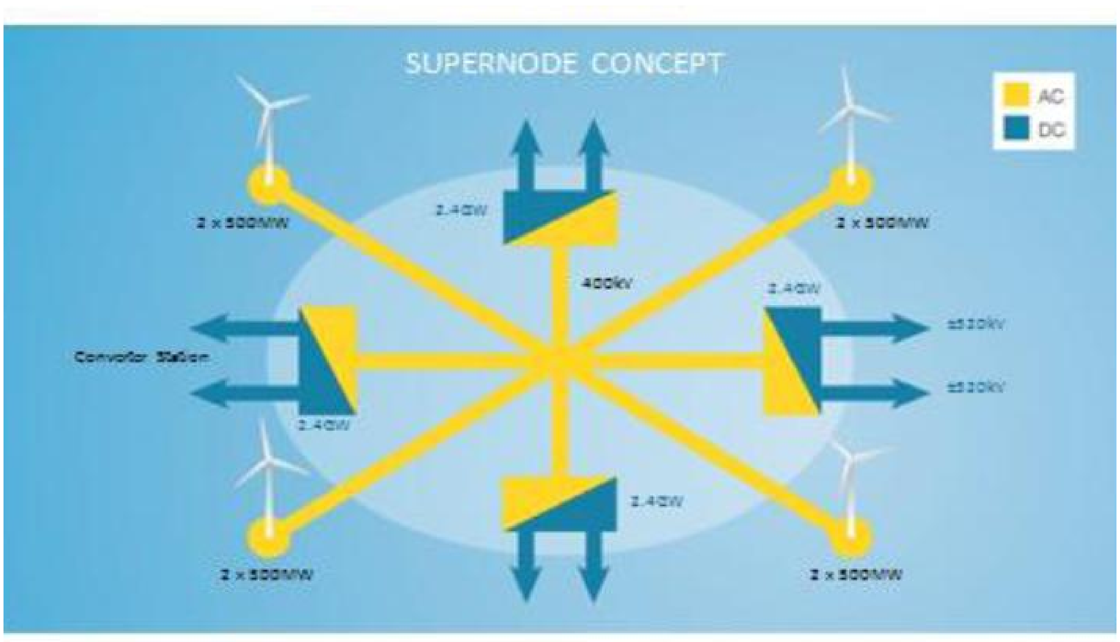


Figure 3.39: Supernodes can provide an effective way to interconnect various HVDC links together with wind parks via an islanded AC system

The additional power converters needed compared to a Multi-terminal system are costly; require relatively expensive space on offshore platforms and cause extra power losses. Eliminating some of the power converters requires HVDC links to be interconnected on the

DC side forming multi-terminal systems or HVDC grids. However, Supernodes may be required as part of the Supergrid to decouple HVDC networks during faults.
Supernode is therefore seen as a solution for the Supergrid today, it can be complemented by multi-terminal HVDC systems or HVDC grids in the future.

3.3.4 Connecting Wind Parks

Besides the two dominating power transmission frequencies of 50 Hz and 60 Hz, higher or lower frequencies are considered for specific tasks. Table 3.5 gives an overview about the impact of different power frequencies on the transmission system.

Table 3.5: Impact of Different Power Frequencies on the Transmission System

Influence on Power System	Higher Power Frequency than 60 Hz	Lower Power Frequency than 50 Hz
Size and weight of iron core components like transformers or rotating machines	become smaller	become bigger
Reactive power compensation requirements and maximum length of uncompensated cable sections	capacitive reactive power of transmission lines and cables increases in direct proportion with frequency, requiring more compensation or shortening the maximum length of uncompensated cable sections	capacitive reactive power of transmission lines and cables decreases in direct proportion with frequency, increasing the maximum length of cable sections
Power transmission losses	become higher	become lower

To build a Supergrid, two aspects are important, especially with respect to connecting offshore wind energy:

1. The maximum length of an uncompensated cable section should be as long as possible, which would allow building long AC cables.
2. The size and weight of iron core components should be as small as possible in order to allow for a compact design of offshore platforms.

Table 3.5 shows that both aspects result in contradictory requirements for an optimized AC system power frequency. Figure 3.40 shows a typical AC network connecting a wind park to the main grid.

A low frequency would allow building cables that are longer according to the factor f_{base}/f_{opt} with f_{opt} being the selected optimized frequency and f_{base} being the normal power frequency, i.e. 50 Hz or 60 Hz respectively. However, assuming that the frequency throughout the connected offshore network would be the selected optimized transmission power frequency, all the network components, especially the wind park step-down transformers and the transformers at the Wind Turbine Generators (WTG) would have to be designed for that lower frequency. This would make them more expensive, bigger and heavier.

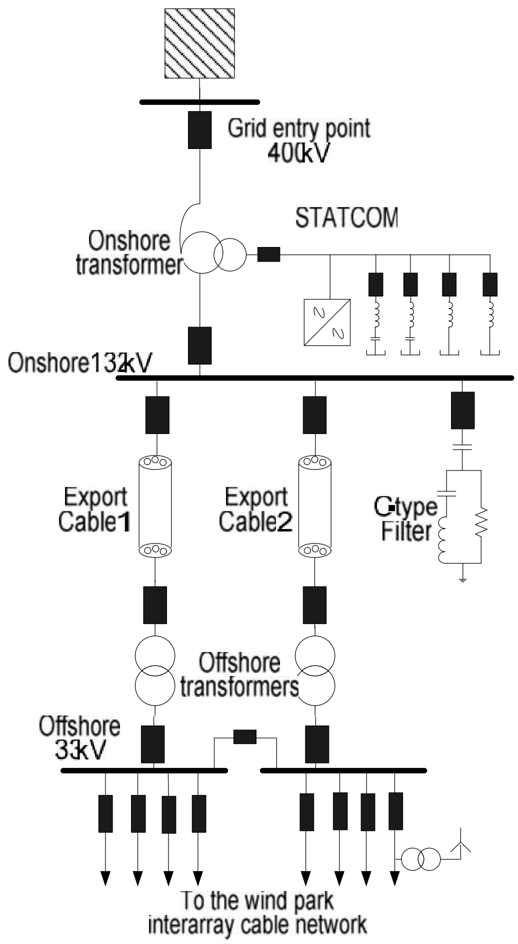


Figure 3.40: Typical network topology connecting a wind park via an AC transmission system to the main grid

In the extreme case of using DC for the wind park network, DC/DC converters would be needed to transform the voltages of generators and wind park network. Moreover, efficient DC circuit breakers for fault clearing would be needed to achieve reliable operation of the wind park. These are two important challenges of DC networks, which have prevented this concept from being used so far.

Eliminating the disadvantage of the lower frequency inside the wind park would require building a frequency converter at the offshore connection point. Such a frequency converter would be similar to an HVDC system containing one AC/DC and one DC/AC converter at the same location as described in chapter 2.2.3 "Load Flow Control". In that case, however, using DC transmission would be the better alternative to connect the wind park to the onshore grid. In case of an HVDC system, just one AC/DC converter onshore and another one offshore would be needed. The maximum cable transmission distance would be virtually unlimited. Moreover, the equipment needed would even be less compared to the low frequency solution, where there are two conversions necessary to convert one AC system frequency into another one.

Selecting a high transmission frequency instead would reduce the size and weight of all offshore components but would shorten the uncompensated AC cable length accordingly.

It is worth mentioning, that for all frequencies deviating from today's most common frequencies of 50 Hz or 60 Hz respectively, competitive markets for all important network components, such as transformers, circuit breakers or protection relays would have to be developed which might not be economically justified. To some extent this also applies to $16^2/_3$ Hz which is used in a few countries only and with a limited voltage range.

Evaluating the concepts of higher and lower transmission system power frequencies, both alternatives appear to be applicable under specific conditions only. Therefore, the normal transmission system frequencies as well as DC appear attractive for the Supergrid, other frequencies should be avoided.

3.3.5 The Role of FACTS in the Supergrid

The demand for FACTS is expected to grow in course of replacing conventional power generation by RES. This is because RES are often located remotely from the load centres. The long transmission distances are associated with significant changes in the reactive power conditions of the networks leading to unacceptable voltage variations, extra transmission losses due to the reactive power flow or system stability issues. In many cases, fixed or dynamic reactive power compensation can be an effective solution to overcome these limitations.

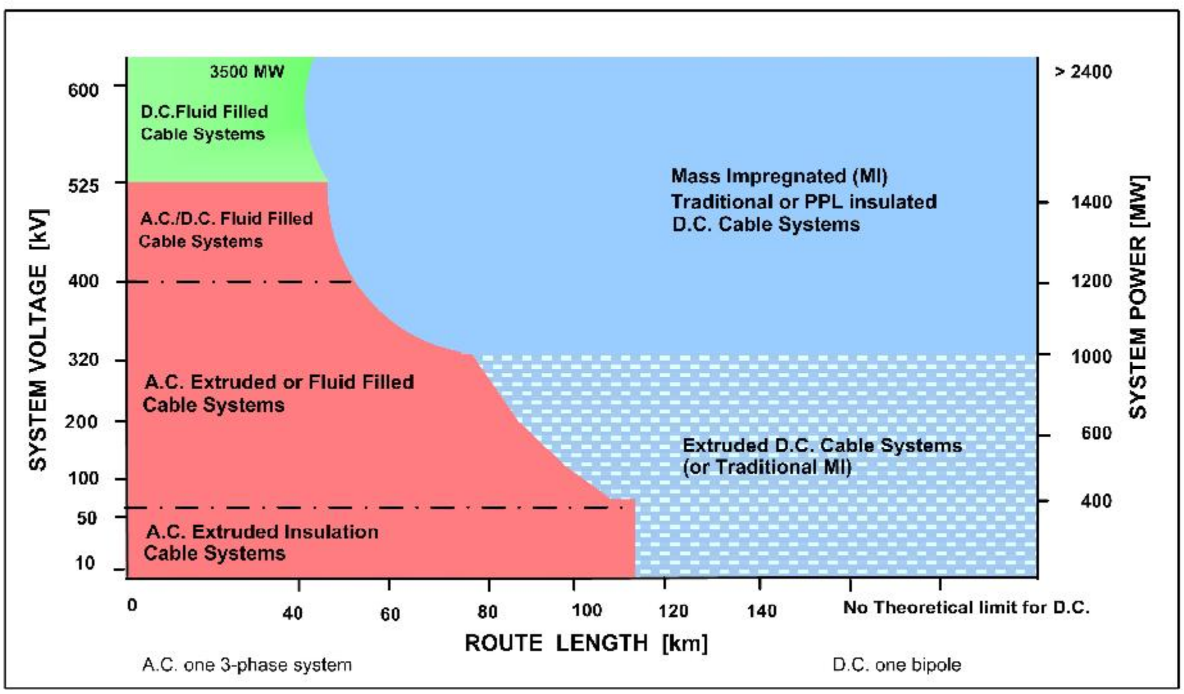


Figure 3.41: Typical applications of AC and DC submarine cable technology indicating the technology chosen vs. transmission voltage level and power transmitted. The development of cable technology is expected to shift the limits towards higher voltages or power respectively in the future

In some cases, however, reactive power compensation measures alone may not be economical or even technically feasible. Examples are long distance submarine cable links (typically 80 km or above as shown in Figure 3.41, depending on system voltage or extended AC transmission lines (500 km or above).

Due to their cable capacitance, the electric fields of AC cables provide a capacitive reactive power surplus. With increasing cable distance the charging current of the cable becomes bigger and bigger compared to the cable load current making the cable increasingly expensive. To compensate the capacitive charging current, reactors would have to be connected at the cable ends and also along the cable route. Connecting along the cable route, however, is obviously not an option for submarine cables which is a limiting factor of the maximum length of AC submarine cables.

3.4 HVDC Transmission systems

3.4.1 The first 15 years of VSC Transmission Development

The first three MW VSC Transmission pilot field installation by ABB in Hellsjön, Sweden 1997 was shortly followed by the first commercial VSC Transmission Gotland. This was the start of 15 years of unforeseen market growth and technical progress. By the end of 2011 ca. 10 GW and 500 km of VSC Transmission has been awarded/contracted for globally. Furthermore utilities and transmission system operators have a total accumulated operational experience of VSC Transmission of about 63 device years.

The market has been driven by applications where fundamental benefits of VSC Transmission systems with extruded plastic cables have been needed. Advantages such as easy on-shore undergrounding, black-start capability and support of weak grids have been propitious. In recent years there has been large growth in the market for VSC Transmission driven by the expansion of offshore wind generation in Germany; examples are Borwin, Dolwin, Helwin and Sylwin projects.

3.4.2 Expected Evolution of HVDC Transmission Technology

On several continents an evolution of the electrical grid is needed to enable integration of remote large-scale wind and solar power generation and growing mega-cities. HVDC Grids can leverage the fundamental benefits of VSC Transmission with the additional value of integrating the point-to-point connections into an electric network, e.g. sharing of transmission capacity between generation, balancing and load resources as well as the creation of a larger market exchange of electric power. Furthermore a grid design will reduce the total amount of equipment and capital cost compared to building multiple single links.

The gradual introduction of HVDC Grids during the next 15 years is foreseen to be the key enabling technology to match renewable targets on the global markets. The speed of introduction of more advanced VSC-schemes is heavily depending on the near term targets and development of market scenarios.

The evolution of the HVDC Grid will be taken in steps. The first main development step foreseen to take place, in parallel to a few first regional multi-terminal projects, is that the customers planning a grid will require grid-enabled point-to-point systems that should be prepared for a future extension to a three- or multi-terminal system.

Some recent VSC point-to-point projects, e.g. Nordbalt (SE-LT) and South-West Link (SE) have a "grid-enabled" feature as a specified requirement. In addition plans for regional Multi-Terminal HVDC (MTDC) Grids have emerged on the market during 2011. Examples are projects such as Shetland (UK), Atlantic Wind Connection (US), and South-West Link (SE). Once one or a more of these breakthrough projects have been commissioned it is likely that the market for Grid will expand, both as new multi-terminal projects and expansion of existing point-to-point systems to three or more terminals in one network.

Organisations such as CIGRÈ, CENELEC and IEC are studying various aspects of HVDC Grids to prepare guidelines and technical reports/standards on common operational procedures to facilitate an open market for future system expansions. (Chapter 1.6 "Standards")

The first small regional systems can be operated as one protection zone without interruption equipment such as DC breakers, but as the size and complexity of DC networks increase, DC breakers may be introduced gradually.

It is realistic to expect that the existing rated voltage and power will increase while losses will reduce during the next ten years. Significant incremental improvements are foreseen from the levels today of 320 kV (XLPE-cable) and 600 kV (MI-PPL cable) with transmission capacity of more than 1 GW per cable. With incremental shifts in technologies, voltages greater than 600 kV, with higher power ratings may be achievable by 2020.

3.5 Technologies under development

3.5.1 DC circuit breakers

Today DC breakers or switches are commercially available even up to ultra-high voltage levels. However, they are working as transfer switches commutating the current from one circuit to another one. They do not have fault current interrupting capability.

DC fault current breaking functionality will be needed for larger HVDC grids to separate faulty parts of the grid during earth faults. It should be noted that most other faults can be handled by the converter itself or slower DC switches depending on the fault.

DC breakers for HVDC grids need to handle fault currents with very fast rising times and operate without a natural current zero crossing as in AC applications. This has been shown earlier with full electronic breakers which operate very fast but have relatively high on-state losses. Recently, a hybrid DC breaker concept has been presented having a mechanical bypass path to reduce the losses to near zero (60 kW at 320 kV DC) while maintaining clearance time within milliseconds [18]. For mechanical concepts, losses most likely will be even lower, but it still needs to be shown that the short clearing times needed can be achieved.

3.5.2 Transformation of DC voltages

Unless the Supergrid is specifically designed to operate at a common DC voltage and any schemes not at the common voltage are excluded, there will be a need to develop a DC – DC converter. This would be a device to convert one DC voltage to another, i.e. the equivalent of a transformer on an AC grid. The AC transformer has greatly facilitated the optimisation of AC transmission systems at different voltage levels (110kV, 220kV, 380kV etc) and their inter-connection to form AC grids. The DC equivalent would fulfil the same function.

In Europe there are many HVDC schemes inter-connecting different national grids and they have used a wide variety of DC voltages. Even for off-shore wind farm connection using HVDC, the first four schemes to be designed have all used a different voltage (±150kV, ±250kV, ±300kV and ±320kV). In the absence of a DC – DC converter, these schemes could only be integrated into a Supergrid by their AC connections.

DC – DC converters are a common device in industrial and commercial applications, i.e. they operate at low voltage and low power. However, the development of high voltage DC – DC converters is still at the academic stage of investigation or at the patent stage from some manufacturers. Technologies considered to date can be classified in two broad groups:

a) DC – AC – DC converters
The DC voltage is inverted to an AC voltage, typically at high (400 – 1000Hz), before being rectified to a DC voltage. This adds a power equipment stage between the converters. High frequency operation minimizes the physical size of the AC equipment, but impacts on losses. This scheme does introduce galvanic isolation between the two DC schemes.

b) Direct DC – DC converters
Here there is no intermediate AC stage, the conversion only being achieved by power electronic converters, with some form of amplification circuitry. This adds to the complexity of the converter, but avoids the intermediate AC equipment, this potentially minimizing the size of the device.

Whichever technology, or others not yet developed, is used a number of key functions will need to be achieved:

- DC voltage control (tap-changer function)
- Power flow control
- minimum operating losses
- compact footprint for off-shore and urban applications
- high reliability (as a series device in the power flow)
- minimum maintenance requirement
- acceptable capital cost in comparison with converter station scheme costs

Such a device should also deliver some ancillary benefits, which should be available from its design as a semi-conductor based converter.

- fault current limiting capability
- DC circuit breaker capability

3.6 Possible limitations for Supergrid as of today

The working group has not identified any “show-stoppers” to the development of a European Supergrid.

3.7 The Way to Develop Supergrid

The decarbonisation of Europe’s energy sector requires a strong integrated Supergrid. The development of such a grid can start today according to the installation of new renewable power plants. While today, individual links are planned and constructed, Supergrid planning in the phase 2015 to 2020 can already be based on a European level of system planning.

Most of the new links will require HVDC technology because of long subsea or land cable parts. The individual links can be interconnected via Supernodes. The concept of VSC transmission controlling frequency in islanded AC networks will be demonstrated by the first HVDC connected wind parks in the North Sea which are currently under construction. In principle, the entire Supergrid can be built by individual HVDC links that are interconnected via Supernodes.

The most important step needed to develop HVDC grids further is the aspect of interoperability of different individual projects and technologies of different manufacturers. Interoperability requires standardization of the basic principles of design and operation of HVDC grids.

As a starting point for the standardization of HVDC grids some fundamental planning criteria need to be defined, leading to different types of HVDC grids (e.g. transmission and distribution HVDC networks, sometimes also referred to as "local" and "inter area" grids). A Grid Code for the pan European Overlay Grid needs to be defined.

Based on the fundamental planning criteria, important questions to be answered with respect to HVDC grid standardization include:

- Standardization of DC voltage levels
- Concepts for interconnecting local and inter area DC grids, probably with different DC voltage levels
- DC grid topologies
- Control and protection principles
- Fault behaviour
- Typical block sizes for converter stations

A number of key network components need to be developed and competitive supply chains need to be established. Investors should be provided with clear guidelines on how to specify the equipment for a multi vendor HVDC grid. Such guidelines are normally summarized in functional specifications which are needed for, e.g.:

- AC/DC Converters
- Cables
- DC Overhead Lines
- DC Chopper
- Charging Resistors
- DC Circuit Breakers
- Communication for network control and protection

The technical aspects of future HVDC grids are subject of various CIGRÉ working groups. The European Study Group "Technical Guidelines for HVDC Grids" hosted by the German Electrical Commission VDE/DKE aims at elaborating the fundamentals of Standardization in Europe.

The groups listed below show most of the present active international working groups on HVDC Grids aspects (with estimated time-frames):

CIGRÉ

- B4-52 HVDC Grids Feasibility Study (2009-2012)
- B4-56 Guidelines for Preparation of Connection Agreements or Grid Codes for HVDC Grids (2011-2013)
- B4-57 Guide for the Development of Models for HVDC Converters in a HVDC Grid (2011-2013)
- B4-58 Devices for Load flow Control and Methodologies for Direct Voltage Control in a Meshed HVDC Grid (2011-2013)
- B4/B5-59 Control and Protection of HVDC Grids (2011-2013)
- B4-60 Designing HVDC Grids for Optimal Reliability and Availability Performance (2011-2013)

CENELEC

- European Study Group on Technical Guidelines for DC Grids (2010-2012)

IEC

- TC-57 (WG13 CIM) Power systems management and associated information exchange

The step by step development of Supergrid will be accompanied by gaining operational experience with equipment. For example, different technologies for selective fault detection and fault clearing will be developed and implemented, such as VSC Half Bridge and VSC Full Bridge stations and various technologies of HVDC breakers. Developing the most economic and most reliable solutions requires an open market supported by the EU. Without the market, the development of technology will be slow.

3.7.1 Market Scenarios for DC Grids

Given the existing operational experience and rapid development of VSC Transmission, the bottleneck is not the development and introduction of new technology. Even though operational experience and continued R&D should be in focus, the main technology items to start building a DC Grid is available today. Therefore the development of non-technical key issues outlined below will trigger or hold back the market evolution:

1. international harmonization of grid codes and transmission investments
2. international harmonized regulatory procedures
3. methods to share cross-border renewable subsidiary schemes
4. multivendor and multi-stakeholder revenue models

In a pessimistic market scenario the development of these four issues will be slow during the next five years, implying that only regional DC can be planned, tendered, constructed and commissioned. New harmonization, support schemes and a Supergrid business model will be delayed until at least 2018. Consequently technology development will be slow.

In the intermediate realistic scenario, new technical improvements will come continuously. Tendering under new grid codes and harmonized support schemes can be done already by 2014. Several interregional onshore and offshore multi-terminal schemes may be in operation by 2017. Commitments to reach 2020 targets are driven by pushing aggressively for building new renewable generation capacity.

In the optimistic market scenario during 2012-2027 the EU changes rules and regulations to promote formation of Supergrid. The first multi-terminal schemes taken into operation are already prepared to be connected to each other in a larger pan-continental scheme to open up integrated energy markets. To be pre qualified for Supergrid operation, suppliers have taken a major step forward in voltage and power levels of VSC Transmission by 2020.

3.7.2 Conclusions

The working group has not identified any “show-stoppers” to the development of a European Supergrid. The VSC Transmission technology has already matured significantly during the last 15 years. For visionary long term planning of Transmission or Independent System Operators, the availability of key VSC-Grid technologies such as control and protection methods, main circuit design, grid master control, offshore operation experience and selective fault clearance techniques such as, dc breakers, can be assumed. This should give confidence to specify grid-enabled point-to-point connections that could be expanded to multi-terminals building blocks for a larger overlaid grid. The critical time-line for introduction of new technology lies primarily in solution of non-technical issues that will create a strong market growth and technology push. An early solution of these hurdles will influence the future roadmap to a greater extent than may be foreseen, due to the extended time constants in planning and construction of new transmission capacity.

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Appendix I

Summary of Questionnaire

Question 1	*HVDC technology has been used for power transmission worldwide for more than 60 years. With a few exceptions only, all HVDC transmission systems today are point-to-point. What are the driving factors from a TSO's perspective to develop the technology for HVDC grids?*
TSO 1	There are several drivers for the development of HVDC grids including: • the need to integrate large scale renewable generation such as offshore wind, • the electrification of oil and gas platforms and • the integration of different electricity markets. Of particular importance is the development of offshore HVDC grids in order to obtain economical and reliable access to low carbon energy sources, both directly and via access to European markets.
TSO 2	The main driving factors for HVDC are: • Higher transmission capacity • Control of power transmitted • Capability to transmit very high power and longer distances • Lower transmission losses
TSO 3	Among possible new perspectives: • To provide an interconnection capability compared to radial point-to-point connections • To use the expected capability of DC grids to adjust power injections for each terminal (control of active power) • In the case of offshore wind farms connections, to use the DC grid to mitigate the fluctuations of each individual wind farm.

Question 2	*The technical requirements for multi-terminal HVDC systems or HVDC grids may vary with their application. For example, in some cases it may be tolerable to temporarily shut down a HVDC system for system reconfiguration (connecting or disconnecting converter stations/DC lines). Do TSO's consider different types of HVDC systems and how would they differentiate between them?*
TSO 1	The TSO specifies the functionality of a DC system rather than the technology itself. It is the role of the supplier to choose a technology that meets the required functionality Different technical considerations apply to the different uses such as: • Links with other TSOs and radial links to generation where the main issue is the loss of generation infeed to the system that will result from a fault on the link, and the resultant frequency fall or rise. Such links can be used to provide frequency response to the system • DC lines embedded within the existing AC network where the infeed loss risk is not an issue. Often the relatively low capacity of a DC link compared to an ac double circuit, the disturbance is likely to be less severe. The controllability of the link means that it will be useful in responding to events on the AC system e.g. adjusting the power flow may remove overloads in parts of the network and power oscillation damping may help maintain generator stability • Multi-terminal DC links to connect future offshore generation where all of the above factors need to be considered
TSO 2	TSOs expect HVDC grids to be used as closely as possible to present AC systems. This will require HVDC multi terminal links and HVDC circuit breakers
TSO 3	This question has a clear answer for point-to-point HVDC: different types of HVDC are considered, since the call for tender gives a *functional need* to be provided a DC transmission system; hence, according to the requirements (which vary from one project to another), the proposals from manufacturers may cover different kinds of systems. Then, the final "multi-criteria" choice depends on the priority given to each features and the corresponding capabilities provided by the manufacturers (project-dependant). As there is no MTDC or DC grid project so far, we have not experienced this issue; yet it is most likely that the same principle should apply.

Question 3	*Multi-terminal HVDC systems or HVDC grids will be integrated into existing AC transmission networks. What reliability requirements will TSO's apply to the power transmission capability of an HVDC network? Is this dependent on the power transfer capability?*
TSO 1	For radial connected circuits providing an infeed to the system it is expected that the frequency of faults will be no worse than that for generation. For embedded links, the performance should be similar to that of AC circuits. Reliability and availability should be either 1. Similar to AC grid or 2. Energy availability should not be less than 97% and 3. The Forced Energy Unavailability (FEU) shall not be greater than 1.5% It is worth noting that the reliability for a DC station is based on the failure rate of the components in the station, the configuration and the components' need for maintenance. Some of the components are "newly developed" and the failure rate and maintenance needs are unknown. For the newly developed components some relaxation in availability might be acceptable.
TSO 2	TSOs expect HVDC to have no lower reliability levels than present AC systems. Moreover, higher the power means higher expected reliability.
TSO 3	Multi-terminal HVDC reliability requirements are expected to be similar to that for more "traditional" AC equipment. The reliability requirement applies to the complete DC grid unless outages can be limited by appropriate fault detection/location and isolation. The DC grid must comply with the relevant single infeed loss criterion.
Question 4	*Power transmission is associated with power losses. Within certain limits the power losses can be influenced by the design of the network components, e.g. cables, converter station or transformers. What would be the requirements of a TSO for losses per converter station/terminal and per line or cable section?* *For international interconnection how do the TSOs expect to divide the total link losses?*
TSO 1	Normally, the design of components is determined by the required rating and the permissible temperature rise. Losses are not normally specified as a limit, but the lifetime cost of losses may be taken into account when evaluating offers.
TSO 2	TSOs expect the full system (HVDC+AC) losses to be in the same level of present AC systems. If the average transmission distance increases, losses could be expected to increase also but not dramatically. For a single element, a converter or a cable section there is no particular limit that TSOs consider up to now.

TSO 3	• The issue is important as the cost of losses must be covered by the TSO • The choice of DC results from various other considerations, not including losses; however total losses (transformers, converters, cables) is an important parameter for the final contract award. • Now that VSC losses have decreased towards LCC levels, the next target should be cable voltage which now becomes the major factor for losses for medium to long distance VSC transmission.
Question 5	*An HVDC multi-terminal system or HVDC grid may not be built in a single step. It can be expected instead, that it starts with a relatively small number of HVDC converter stations (e.g. 3 to 5) to be extended later on. Making precautions for future system expansions may require increasing the rating of HVDC network components above what is necessary right from the beginning. How does a TSO intend to achieve system expandability? How can this be coordinated at a European level?*
TSO 1	Installing components of the network with a higher rating than initially required poses a risk of stranded investments. This stranding risk must be set against the sub-optimal development that may take place if the network is only developed to meet immediate needs. The relative benefits of any anticipatory development need to be assessed on the basis of the costs of the different options and the likelihood of future expansion being needed. Where it is considered that initial over-investment is merited, it will be necessary to minimise the extent of this. For example, if a 2GW link is to be built where only 1GW is immediately needed, it is likely that a 2 GW cable will be installed but converters rated at only 1GW will be used. Future expansion will be allowed for by ensuring that sufficient land is available or platforms are sufficiently large to allow for the addition of further converters. A key factor will be to ensure that the control and protection philosophies of the early converters allow for future expansion. There are a number of initiatives currently underway within Europe to define control and protection system requirements to ensure compatibility between suppliers. In addition to this the standardization of DC voltage levels will be a minimum requirement if systems are to be expandable. At a European level this can be coordinated through industry and standard bodies such as ENTSOE, CIGRE and CENELEC.
TSO 2	TSOs have not answers yet for these questions. Work is to be done probably in cooperation with suppliers.
TSO 3	We agree that HVDC grids will be built step by step, starting from existing schemes. However, in the absence of a precise plan to build up such DC grids, over sizing the planned HVDC links would be hard to justify. In fact, the most likely DC grid scheme to emerge first would probably consist in tapping into existing DC links (for example, intermittent wind power generation tapped to a high power HVDC link, in order for this extra generation to have the minimum impact on the DC power).

Question 6	*There are basically two types of converters available to HVDC transmission today: Line Commutated Converters (LCC) based on Thyristors, Voltage Sourced Converters (VSC) based on IGBTs. VSCs can be built as so-called half bridge VSC (fixed voltage polarity of the lines/cables) or full bridge VSC (allows for dynamic voltage polarity reversal and can used for fault clearance on the DC side). Does the TSO have a preference for one of these solutions over the other and what are the reasons behind the choice?*
TSO 1	We normally procure equipment against functional specifications and the choice of technology will not normally be specified explicitly. The functional requirements will, however, often determine that one technology has an over-riding advantage. For example, space considerations would normally preclude the use of LCC for offshore platforms, as would a requirement for black start. The use of a full bridge VSC would potentially allow more rapid clearing of DC faults than a half bridge VSC but the greater number of semiconductors would represent an increased cost. Where a full bridge VSC is used, it will still be necessary to interrupt operation for the whole of a multi-terminal link until the link is re-configured and the healthy parts returned to service. The advantages of combining LCC and VSC technology in a common HVDC system are not clear, given the potentially greater cost and complexity of the solution.
TSO 2	TSOs will prefer VSC if the technology is reliable enough for high voltages and powers. However, LCC could be also used in particular point to point links.
TSO 3	With regards to Half-Bridge (HB) or Full-Bridge (FB) VSC topologies, here are some rough considerations (to be refined for each individual project): • FB-VSC is very promising (if not the only solution) to tap a VSC converter to a LCC scheme. This solution is therefore very interesting for connecting a few offshore wind farms (hence VSC-based converters) to an existing LCC link. • However, FB-VSC has greater losses than the equivalent HB-VSC converters; therefore, we see no need to use this technology for point-to-point connections. • In the case of DC grids, FB-VSC can provide significant benefits to interrupt a fault current caused by a DC fault; yet this comes at the expense of higher losses (during steady state operations) and the blocking of whole converter. Therefore, this would be a stopgap in the absence of a decent DC breaker (unless its cost and/or conducting losses are crippling).

Question 7	*It can be expected, that future multi-terminal HVDC systems or HVDC grids will play an important role for transmission system operation. What performance does the TSO expect from future HVDC systems concerning:* *1. the capability of a station to start-up a de-energized AC network (black start)* *2. the capability of a station to energize the DC network or parts thereof* *3. the capability to provide reactive power* *4. the capability to control AC system frequency* *5. the capability to provide short-circuit power to the AC systems* *6. the capability to ride through AC system faults* *7. Are there any other special capabilities expected?*
TSO 1	It is expected that the performance of HVDC systems be at a minimum that of existing generators (for generation connections) or similar to the AC system for embedded solutions. While some of the following is still under discussion it is felt that: • HVDC systems are expected to be able to start-up a de-energized AC network (black start) • HVDC systems are expected to be able to energize the DC network • HVDC systems are expected to be able to provide reactive power • HVDC systems are expected to be able to control AC system frequency and to also provide synthetic inertia • The ability of HVDC systems to provide short circuit power to the AC system is currently being assessed • HVDC systems/grids are expected to have the capability to ride through AC system faults In addition to this other capabilities such as Power Oscillation Damping and rapid re-direction of power flow may also be specified for HVDC systems.
TSO 2	All the characteristics listed are necessary, Any other that could be needed so that the HVDC grid can be operated in a similar way to the present AC grids will be valuable. Any limitation regarding flexibility in the operation, any characteristic that could lead to faults or to service interruption will be undesirable.
TSO 3	1. Interesting feature, yet probably only mandatory in certain cases 2. No clear opinion on this feature, yet 3. Voltage support is an important feature for our planned point-to-point HVDC connections; therefore, this is also most likely the case when it comes to the DC grid terminals (hence VSC technology) 4. Not mandatory, but using the converter stations for POD (Power Oscillation Damping); it would be a smart solution for inter-area oscillations 5. No clear opinion on this feature, yet 6. This is mandatory: the DC grid must be resilient in order to meet requirements such as the maximum infeed rule 7. So far, there has been not actual assessment of inter-operability between different manufacturers. Standardization is a major concern from now on.

Question 8	*As any other power system, multi-terminal HVDC systems or HVDC grids will be subject to temporary or permanent faults. However, considering the nature of DC current, voltage suppression due to faults must be expected to spread over longer distances compared to what is known from AC systems. What requirements will the TSO impose on the fault behaviour of HVDC systems?* *- during faults* *- during fault clearing* *- for system recovery from faults (e.g. over- / undervoltages, fault clearing times)?*
TSO 1	We are still at a very early stage of assessing this issue. These requirements will be heavily influenced by the extent to which DC circuit breakers can be used, as their use will affect the size of any DC grid and the impact of any faults on it. However, without such technology the following will be specified: • fault current and over voltages within HVDC grid • time required to detect and isolation of faulty element and consequences of delayed clearing • Converter control and sequence strategies required to ensure timely restoration and recovery. The recovery time is critical to make sure satisfactory operation of the overall AC and DC system.
TSO 2	Voltage suppression in HVDC systems should be limited in duration as much as possible with HVDC circuit breakers. Faults in HVDC systems should not go though the converter and should never cause trips in the AC system. The AC system will be always prepared to lose the HVDC connection (n-1 criterion). During faults and fault clearing in the HVDC system any perturbation transmitted to the AC system must be minimised. Fault duration and Fault clearing should be as fast as possible. Existing protection systems in AC systems allow for fault duration times of about 100 milliseconds (faults correctly cleared)
TSO 3	This is a very complex issue, to which a simple and synthetic answer is hard to give. We suggest to refer to ongoing work on this issue done in the TWENTIES project (especially refer to the Work Package 5 on DC grids design and protection).

<u>Other Remarks related to DC and System performance</u>

- For DC Overhead Line faults, an LCC HVDC typically performs up to 3 restarts for fault clearing. If the third attempt is unsuccessful, a permanent line fault is expected and the line remains de-energized, until the cause of the fault is eliminated. Cable faults allow no restart. Mixed line and cable sections can be handled individually by means of special fault locators, similar to the AC distance protection
- The maximum infeed loss criterion varies across Europe from 3GW as specified by ENTSOE, 1,300 MW in Spain and 1,800 MW in Great Britain

Appendix II

Installation of Submarine Cables

The installation of submarine cable systems is a very critical activity and a high level of reliability can be gained only through a large experience, and the availability of suitable installation equipment. For long submarine cable links a cable-ship with very large storage capacity is a mandatory requirement (for big cables a large rotating platform has to be used).
The main advantage of a large storage capability is that power cables for long connections can be installed with less transportation and laying campaigns and therefore reduced costs and risks.
Installation services for submarine systems include some activities similar to the underground power cable systems installation (e.g. accessories installation on shore, site testing, project management), but there are specific activities strictly related to submarine cables, which are described herewith.

Marine survey and engineering activities

All installation activities are planned and designed to fulfill specific requirements coming from a deep analysis of the site conditions. This is particularly applicable to submarine systems, where the "site" is - for the majority of the route - the sea bed. To do that, a detailed marine survey is required prior to any installation activity.

Cable loading and transport

During cable loading, the cable-ship will be typically moored at the pier of the cable factory. On board the vessel, the submarine cables are stored in suitable tanks and areas.
Once loading is completed, the vessel is prepared for transit to the installation area.
Depending on practical conditions (availability, cost, etc.) different ships/freighters may be used.

Figure II.1: Cable-ship transporting long lengths of submarine HV cables accommodated in platforms

Cable Laying

Typically, the laying vessel approaches the landing point with the stern facing shore, then the cable head connected to a wire is passed to a motor boat. The cable is paid out from the vessel and kept floating with floats attached at intervals. When the cable head approaches the shore, it is connected to the winch wire and it is pulled on land until the cable is in its final position. The vessel sails along the cable route while the cable is paid out and laid on the sea bottom. The cable is paid out under tension control, while the speed is adjusted considering various parameters. The vessel approaches the final landing point while laying the submarine cable. Close to the landing point, the vessel slowly turns around and stops as close as possible to the landing point. Particular attention is given so to avoid dangerous bends. Once the cable reaches the shore, the cable is pulled ashore.

Figure II.2: Cable floated from the cable-ship to shore

Cable protection

There are different methods to protect a submarine cable along its route. The chose among them depends on various factors such as water depth, sea bed typology, fishing activity, anchoring activity, environmental restrictions, etc.
Most frequently used cable protection methods are:

Burial by jetting tool - The jetting machine, typically positioned on the cable, fluidizes the sea bed soil under the cable and allows the cable to be buried in the soil.

Burial by trenching tool - In case of too hard sea bed soil a specific "trenching machine" is required to trench the soil.

Installation of cast iron shells, ***protection mattresses***, ***cement bags*** or ***rock dumping*** in order to assure protection when burial is not possible or in other particular situations (e.g. cable crossings with other cables or ducts)

Typical jetting machine

Typical trenching machine

Application of cement bags

Figure II.3: Submarine cable protection methods

Appendix III

Environmental Impact of Cable Connection

In different reports from ENTSO-E and Europacable [III.1] [III.2] different aspects related to the environmental impact and limitations of underground HV cable systems are described in detail. This appendix summarizes some important aspects.

HV underground cables are typically installed within an authorized corridor in trenches that could be 1 to 1.5 m deep and 1 to 2 m wide. Buildings or trees with deep roots have to be kept outside that corridor, but apart from that there are no major limitations to farming, cultivation or other land use.

Main parameters that influence directly the corridor width are the number and size of the cables to be installed, the transmitted power and various parameters related to the conditions of the soil such as geological composition, maximum temperature, humidity, thermal resistivity etc.

Multiple parallel HV cable systems are usually installed in separate trenches, spaced 3-5 meters in order to reduce the mutual thermal influence between them. As an order of magnitude a corridor width of less than 10 m would be necessary for two separate cable trenches, while for three trenches the required space will be approximately 15 m.

In general it can be said that for the same power to be transmitted HVDC underground cable systems would require less corridor width than HVAC cable systems (considering similar cable designs and sizes). In figure III.1, a comparison between a HVAC and a HVDC cable systems installed in a same trench is shown, with the same number of cables, equally spaced and buried at the same depth, having a similar design (i.e. same conductor cross section, and similar extruded insulation thickness). As it can be seen from the data presented in the figure with the HVDC solution it would be possible to transmit significantly more power (approximately 3 times more) than with the HVAC solution. This also means that for the same power to be transmitted the HVDC underground cable solution would require in principle fewer cables and consequently a significantly smaller corridor width.

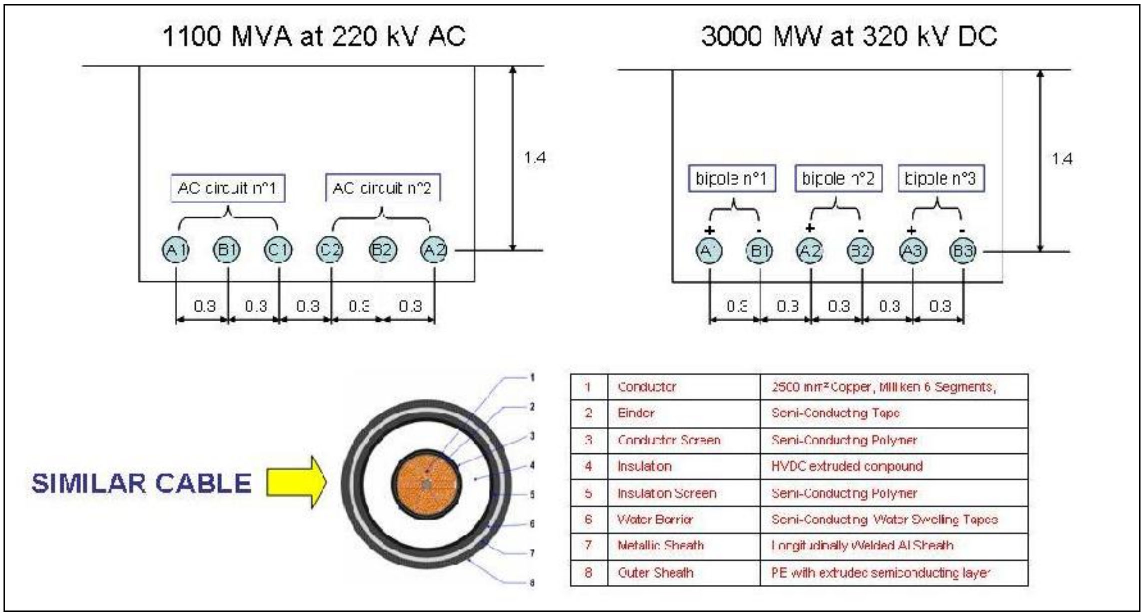

Fig. III.1 - HVDC vs. HVAC underground cable systems with similar cables

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