Roadmap to the Supergrid Technologies

Update Report

June 2014

Document prepared by FOSG WG 2 Technological.
Members of the Working Group during 2013-2014 are:

Magnus Callavik	ABB (Convenor)
Alexandre Parisot	RTE
Björn Sonerud	Nexans
Frank Schettler	Siemens
Joe Corbett	Mainstream Renewable Power
Marie-Sophie Debry	RTE
Mike Boden	Alstom Grid
Nikola Kuljaca	Prysmian
Norman MacLeod	Parsons Brinckerhoff

Additional contributors to this roadmap report since 2011 are:

Björn Jacobson	ABB
Christian Lemaitre	RTE
Didier Wiot	Elia
Heather Laurie	Mainstream Renewable Power
Lars Jacobson	Vattenfall
Robert Whitehouse	Alstom Grid
Samer El Oukaili	Siemens
Vegar Syrtveit Larsen	Nexans

Table of Contents

List of Appendices

Abbreviations

°C:	Degrees Celsius
+ve:	Positive
-ve:	Negative
AC:	Alternating Current
ATC:	Available Transfer Capacity
ATP:	Advanced Transients Program
BAS:	Basic Grid with Standard Transmission Capacity
CACM:	Capacity Allocation and Congestion Management
CAES:	Compressed Air Energy Storage
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
CWE:	Central Western Europe
DC:	Direct Current
DCWL:	DC Withstand Level
DENA:	Deutsche Energie Agentur
DEWI:	German Wind Energy Institute
DKE:	German commission for electrical, electronic and information systems
EC:	European Commission
EHV:	Extra High Voltage
EMS:	Energy management system
EMT:	Electro-magnetic Transients Program
EMTDC:	Electro-magnetic Transients Program for DC
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
ICT:	Information and communication technologies
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
JWG:	Joint Working Group (of CIGRE)
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
LIWL:	Lightning Impulse Withstand Level
m:	Metre
MCOV:	Maximum Continuous Operating Voltage
MI:	Mass Impregnated Paper Insulation
MMC:	Modular Multi-level Converter
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
NPV:	Net Present Value
NSCOGI:	North Seas Offshore Grid Initiative
NYPA:	New York Power Authority
OHL:	Over Head Line
PHES:	Pumped Hydro Energy Storage
PPLP:	Polypropylene Paper Laminate Paper

PR:	Primary Reserve
PV:	Photovoltaic
R&D:	Research and Development
RE:	Renewable Energy
RES:	Renewable Energy Source
RMS:	Root Mean Squared
SC:	Study Committee (of CIGRE)
SCADA:	Supervisory, control, and data acquisition
SCFF:	Self-Contained Fluid Filled
SCPP:	Single Cycle Power Plant
SCR:	Short Circuit Ratio
SF_6:	Sulphur Hexafluoride
SIWL:	Switching Impulse Withstand Level
SR:	Secondary Reserve
SSC:	Series and Shunt Compensation
SSC:	Security Service Centre
SSSC:	Static Synchronous Series Compensator
STATCOM:	Static Synchronous Compensator
SVC:	Static Var Compensator
TAL:	High Temperature Conductors
TB:	Technical Brochure (of CIGRE)
TCR:	Thyristor Controlled Reactor
TCSC:	Thyristor Controlled Series Compensator
TF:	Task Force (of CIGRE)
TPSC:	Thyristor Protected Series Compensator
TSC:	Thyristor Switched Capacitor
TSC:	Transmission System Operator Security Cooperation
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
WG:	Working Group (of CIGRE)
WTG:	Wind Turbine Generator
XLPE:	Cross Linked Polyethylene

Preface

We live in an age of unprecedented concern about the security and sustainability of energy production. The threats presented by a changing climate have compounded the existing challenges presented by diminishing carbon resources – often located in unstable regions. Set against this reality, Europe must refashion its relationship with energy, replacing the polluting technologies of the last century with a clean and sustainable platform for meeting the energy needs of the future.

Realizing that goal will see the establishment of a new European energy framework; from clean technologies that harness the continent's wind, solar, tidal and geothermal potential delivered through a transmission network that connects to where people and businesses need it. Just as the challenges we face transcend national boundaries, they require a shared solution based on mutual self-interest and an appreciation of our common future.

The ambitious targets that the people of Europe, through their governments, have set for carbon reduction and energy security can be met. The technology is available, the urgency is recognized, the generation capacity exists; this report sets out how such a future can be accomplished. Doing so will require the ingenuity of engineers and scientists but also needs the leadership and clarity of purpose of governments and regulators.

As the harm caused by the fossil fuel use of the past becomes increasingly apparent, policymakers and the public are turning to energy professionals for solutions that meet the needs of today while respecting the interests of tomorrow. From here on in we must find ways to harness new types of energy, found in new locations and transmitted through new technologies to where it is used to power both industry and comfort. In some ways we have been fortunate in that this pressing need for change coincides with improvements in technology that allow us to do far more than repair or compensate for previous decisions.

A transcontinental Supergrid will allow Europe to confront the threats posed by climate change, secure an independent energy future for the continent and provide ongoing access to affordable and stable supplies of energy that meet all our needs. However, it can do more than that; by simultaneously taking advantage of 'Smart Grid' technologies we can develop a transmission system that acts as an 'electricity internet'. Replacing the constrained, hierarchical one-to-many model of the past, such a grid would become a many-to-many intelligent network that is largely automated and able to operate, monitor and, to some extent, heal itself. As well as providing a safer and cleaner supply of electricity, such a grid will also deliver considerable savings in terms of transmission costs and reductions in lost supply; in short, it will be more flexible, more reliable and better able to meet our needs.

To meet these goals, Europe needs a Supergrid based on smart technology. To meet these goals in time, it needs to begin that transition today.

Summary

This report is compiled on behalf of the Friends of the Supergrid (FOSG), to identify the technologies required to deliver an electrical transmission system that will meet Europe's future needs. FOSG comprises four working groups:

1) Ownership, Regulatory, Grid Codes, Commercial and Financial
2) Technological
3) Logistical (Supply Chain)
4) Commitments, Timetable (Policy) and Communication

This report is written by the second of those groups.

Summary and key findings of chapter one

The first chapter reviews the motivations for making a change to the Supergrid in terms of meeting Europe's greenhouse gas (GHG) reduction and energy security targets. It sets out a future for Europe based on a clean energy mix, much of it based on offshore wind but also including solar from the south of the continent, tidal, wave, biomass, geothermal, existing onshore wind and hydro generation and storage. This chapter also summarises the key requirements and expectations of Transmission System Operators (TSOs).

- The Supergrid will allow future generation to be built where the required natural resources are optimal rather than where they are convenient for transmission
- The Supergrid will allow the transmission of decarbonised electricity across countries, enhancing existing AC networks
- The Supergrid will incorporate Smartgrid technologies that offer considerable savings in maintenance cost and loss of supply during transmission
- The Supergrid will prove integral to meeting carbon reduction targets for 2020 and 2050 including those necessitated by moving an increasing share of transport and heating to the electricity grid
- The Supergrid will expand transmission capacity while, at the same time maintaining (at least) today's security of supply

Summary and key findings of chapter two

The second chapter goes on to examine the current state of play in terms of available – or soon to be available – technology. The chapter tackles head on some of the problems facing the development of clean energy generation within Europe, such as transmission requirements and storage capacity. It identifies enabling technologies such as High Voltage DC (HVDC) and Flexible AC Transmission Systems (FACTS), which serve to allow for efficient transmissions over long distances, using both submarine and onshore cabling, and effective flow regulation and system stability. Towards the end of this chapter (2.10) the ways in which Supergrid, in and of itself, resolves the difficulties of reliability of supply and storage are investigated in detail. The chapter concludes with a look to the future through emerging technologies that hold out the prospect of revolutionising the transmission of electrical energy, such as electric pipelines.

- The development of the Supergrid could begin today
- The required technologies are mostly available in an operational form while the remainder are largely at the point of operational testing or patent application
- Supergrid will resolve the problems of regularity of supply and difficulties of storage by moving away from a reliance on local generation
- Using existing technology it is possible to construct a grid that takes advantage of variable conditions across the continent to ensure reliability of supply
- Large-scale renewable generation can be directed to areas with high demand when there is excess production locally, removing the need to be stored locally
- The scale of the Supergrid compensates for the fundamental limitation of electricity: Use it or lose it

Summary and key findings of chapter three

The third chapter continues looking forward and sets out possible paths from now to the creation of the Supergrid. In doing so, it demonstrates that no insurmountable hurdles to the creation of a pan-European transmission network have been identified. Existing large-scale HVDC technology – already in place in Europe – can be complemented by alternating Current in so-called ‘Supernodes’ that can contribute to achieving the required security of supply in larger HVDC networks. The remaining difficulties relate principally to interoperability between regulatory regimes and manufacturers’ equipment. The chapter sets out the market scenarios that will drive forward the resolution of these issues.

- The working group has identified no technical barriers that would prevent the creation of the Supergrid

- The decarbonisation of Europe’s energy sector requires a strong, integrated Supergrid. The development of such a grid can start today alongside the installation of new renewable power plants

- Most of the new transmission links will require HVDC technology because of long subsea or land cable sections. The individual links can be interconnected via Supernodes

- As a starting point for the standardisation of HVDC grids some fundamental planning criteria still need to be defined

- With increasing AC transmission distances more and more equipment for series and shunt reactive power compensation (SSC) will be needed. Higher costs such as these make HVDC the more economic option over the course of its lifecycle

Appendices

The appendices summarise a questionnaire on Supergrid and multi-terminal HVDC technologies sent to TSOs, an overview of cable installations and their environmental impact, and an overview of the recently completed and ongoing work in CIGRE and CENELEC on HVDC Grids and Supergrid related topics.

Chapter One: Applications for Supergrid

1.1 Introduction

'Supergrid' is the term for the future electricity system that will enable Europe to undertake a one-off transition to sustainability. This transmission network will make possible the delivery of decarbonised electricity across the continent, enhancing the existing AC networks. It will become the backbone of Europe's future power system.

Europe's challenging renewable energy targets will necessitate the development of renewable generation remote from existing population centres, with much of it based offshore. Mixed with solar from the south, tidal, wave, biomass, geothermal, existing onshore wind and hydro resources and storage - and connected to many small-scale inputs - this will form the sustainable energy supply system for the continent. Supergrid will allow future generation to be built where resources are optimal and transported to existing grids for delivery to existing and future load centres.

1.2 Motivations for Change

1.2.1. Greenhouse Gas & Carbon Dioxide Reduction

European Union policy is a legally binding twenty percent reduction of greenhouse gases (GHGs) from 1990 levels by 2020. The EU roadmap for moving to a low-carbon economy by 2050, adopted by the European Commission (EC) in March 2011, emphasised the importance of the energy sector to achieve the Union's objective of reducing GHG emissions by 80-95% by 2050 compared to 1990 levels. Several Member States have already set out their part in this vision beyond 2020. More recently (21 January 2014) the Commission has announced a new EU-wide framework on climate and energy for 2030 based on five strategic pillars:

- A reduction in GHG emissions by 40% below the 1990 level,
- An EU-wide binding target for renewable energy of at least 27%,
- Renewed ambitions for energy efficiency policies,
- A new governance system
- A set of new indicators to ensure a competitive and secure energy system.

There are a number of possible scenarios for the 2050 vision but selected stakeholders (Figure 1-1) suggest that a 75-80% reduction in GHG will be required.

Considering Europe's current fuel mix (Figure 1-2), delivering these levels of GHG reduction will require a significant change to Europe's generation portfolio, most significantly a reduction in coal, oil and gas.

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 (Florence School of Regulation [1])

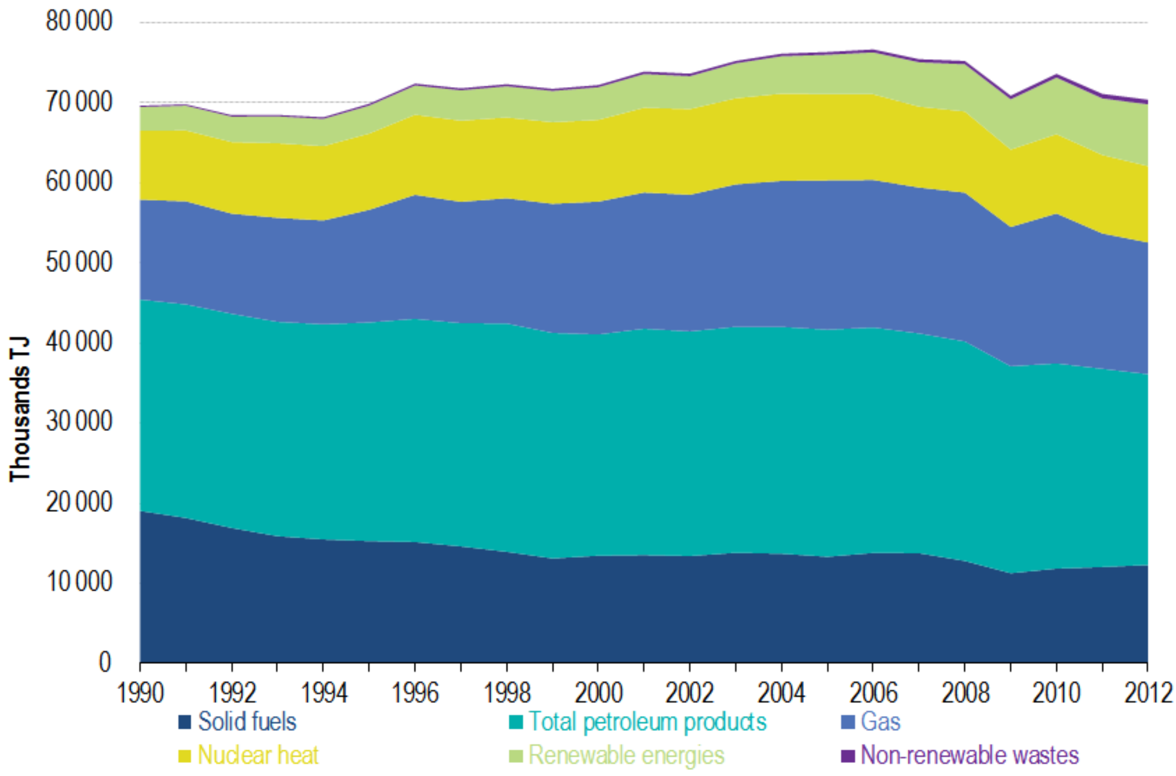


Figure 1-2: Gross Inland Energy Consumption, EU-28, 1990-2012, thousands TJ
Source: **Eurostat Energy (nrg) http://epp.eurostat.ec.europa.eu/portal/page/portal/energy/data/database**

1.2.2. Security of Supply

According to the International Energy Agency (IEA), 'energy security' is described as "the uninterrupted physical availability at a price which is affordable, while respecting environmental concerns". The need to increase energy security was the main objective underpinning the foundation of the IEA, with particular emphasis on oil security.

Figure 1-3 shows Europe's energy dependency trend from 1990 to 2012. 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.

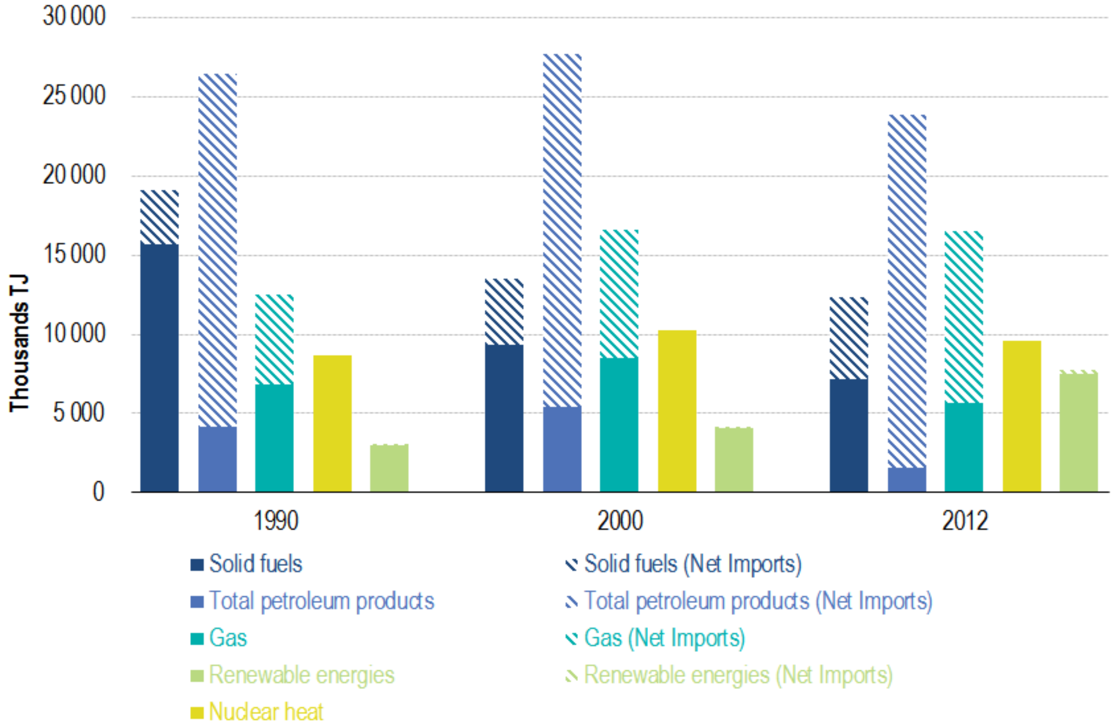


Figure 1-3: Energy dependency by fuel, EU-28, 1990-2000-2012 thousands TJ
Source: **Eurostat [Energy (nrg)](http://epp.eurostat.ec.europa.eu/portal/page/portal/energy/data/database) http://epp.eurostat.ec.europa.eu/portal/page/portal/energy/data/database**

According to Eurostat[1], although consumption fell by eight percent between 2006 and 2012 - from more than 1,800 Million Tonnes of Oil Equivalent (Mtoe) to less than 1,700 Mtoe (Figure 1-4) - in 2012 the EU28 imported more 53% of its primary energy resources.

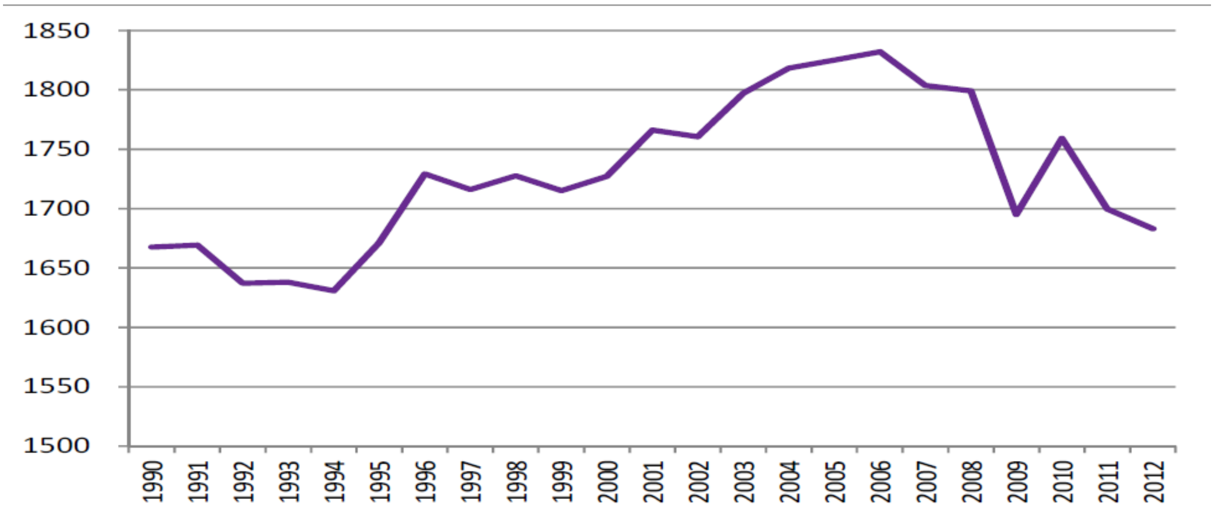


Figure 1-4: Eurostat - gross inland energy consumption EU28, in Mtoe

Today energy security has a broader context. In the short term security relates to reacting promptly to sudden changes in supply and demand. However, in the longer term this is linked to timely investments to supply energy in line with economic developments and environmental needs.

Both long- and short-term considerations have led policymakers and others to debate the over-reliance on certain sources for primary fuels, which has raised concerns about the supply chain. In response to this, diversity, efficiency and flexibility within the EU's energy sector of the EU, and expanding cross-border co-operation in the energy market have been identified as strategic imperatives in terms of energy and more general security. These considerations coalesce with concerns relating to the age of existing fossil plant, much of which is facing decommissioning, and increased popular opposition to nuclear power.

These challenges provide the backdrop for the current debate about Europe's energy future. They place in stark relief the need for a future which meets both the challenges of sustainable growth and those of securing the energy supply.

[1] EU 2050 Low-carbon Energy Future: Vision and Strategies; Robert Schuman Centre for Advance Studies, Florence School of Regulation, European University Institute.
(http://epp.eurostat.ec.europa.eu/cache/ITY_PUBLIC/8-17022014-AP/EN/8-17022014-AP-EN.PDF)

According to the 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"[2].

1.2.3. Other Factors

Shorter term areas of concern which concern both strategic authorities and consumers would include:

- Fossil fuel price volatility
- Consenting difficulties associated with large infrastructure projects

1.2.4. Building the Future

Europe's current energy mix is based upon historical needs and resources that reflect availability and the geo-security of the last century. The existing energy portfolio is based upon carbon reserves that are insecure by the IEA's standards and which produce highly-polluting GHGs. The discussions outlined above point towards the need for a future fuel portfolio that is built on the renewable energy reserves of the future, which plays to Europe's strengths as much as the current mix plays to its weaknesses.

Such a portfolio will include onshore and offshore wind, solar - mainly photo voltaic (PV), biomass, tidal, geothermal and other resources of which the continent has rich reserves. Changing to a mind-set which appreciates these resources for the key strategic reserve that they are will allow policymakers to plan future scenarios in which these resources can be exploited through appropriate demand response, smart grid and storage technologies.

[2] http://www.decc.gov.uk/en/content/cms/news/pn11_061/pn11_061.aspx

1.3 Scenarios

1.3.1. Policy Background and Academic Foundations

The European Commission (EC), in its Green Paper 'A European Strategy for Sustainable, Competitive and Secure Energy'[3], has identified three key pillars, fundamental to the future direction of the EU energy system:

- Improvement of security of supply
- Enhanced sustainability
- Market integration

These foundational principles speak to numerous studies that have been carried out to determine the future shape of Europe's energy system.

The studies, considered in the FOSG report, 'Supergrid Preparatory Phase: Review of Existing Studies and Recommendations to Move Forwards', coordinated by CESI[4], included:

- ENTSO-E studies:
  - Ten Year Network Development Plan (TYNDP)
  - System Adequacy Forecast 2012-2030*
  - Vision 4 "Green revolution"
- Booz & Co, "Benefits of an Integrated European Energy Market", EC DG-Energy, Brussels, July 2013
- European Climate Foundation, "Roadmap 2050: a practical guide to a prosperous low-carbon Europe", McK, KEMA et Al, April 2010, available on www.roadmap2050.eu
- Dii, "Desert Power: Getting Started. The manual for renewable electricity in MENA", 2013
- Greenpeace, "Battle of the Grids – How Europe can go 100% renewable and phase out dirty energy", 2011
- Sintef, 3E, Senergy, "Offshore grid", D8.1 – Draft Final Report, July 2010
- World Business Council for Sustainable Development "Vision 2050 - the new agenda for business", February 2010, available on www.wbcsd.org,
- EURELECTRIC, "Power choices - Pathways to Carbon-Neutral Electricity in Europe by 2050", available on www.eurelectric.org
- The North Seas Countries' Offshore Grid Initiative, "NSCOGI 2012 report", Brussels, 2012, available on http://www.benelux.int/NSCOGI/

[3] [http://europa.eu/documents/comm/green_papers/pdf/com2006_105_en.pdf]

[4] http://www.friendsofthesupergrid.eu/wp-content/uploads/2014/03/REPORT-rev212.pdf

While the conclusions of these studies may differ in specifics, a definite consensus emerges among them. For example, most conclude that the electricity system will have large penetrations of renewable energy and that delivering this will require significant investment in the infrastructure of the transmission grid. 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.

1.3.2. The German Situation

In Germany, the political decision to step away from nuclear power and increase the utilisation of renewable energy is referred to as *Energiewende*. As part of this approach the shift towards renewables is accompanied by the need for transmission grid expansion and development: *“The grid expansion is a fundamental part of the success of the Energiewende, as the speed at which the grid is expanded determines the speed of the Energiewende”* [1].

Based on a requirement of the Federal Network Agency (BNetzA), the four German TSOs (50Hertz, Amprion, TenneT TSO and TransnetBW) have published a Grid Development Plan 2012 showing four generation and consumption scenarios. The scenarios are approved by the BNetzA and describe the measures for grid development with a perspective of 10 years assuring “*safe and reliable operation of the grid”.* [2]

The conclusion of the Network Development Plan states: “*There appears to be a significant and nationwide need for development. In this case, the emphasis is on the high-capacity North-South connections. In the case of lead scenario B, it will be necessary to implement network enhancements and optimisations along a length of 4,400 km in the existing routes by 2022. The construction of new routes spans a length of 1,700 km. The DC transmission corridors are approximately 2,100 km long. They have a transmission capacity of 10 GW along the North-South direction. The expansion of the transmission network will require a total investment of ca. € 20 billion over the next ten years.”* [2].

LEITSZENARIO B 2023

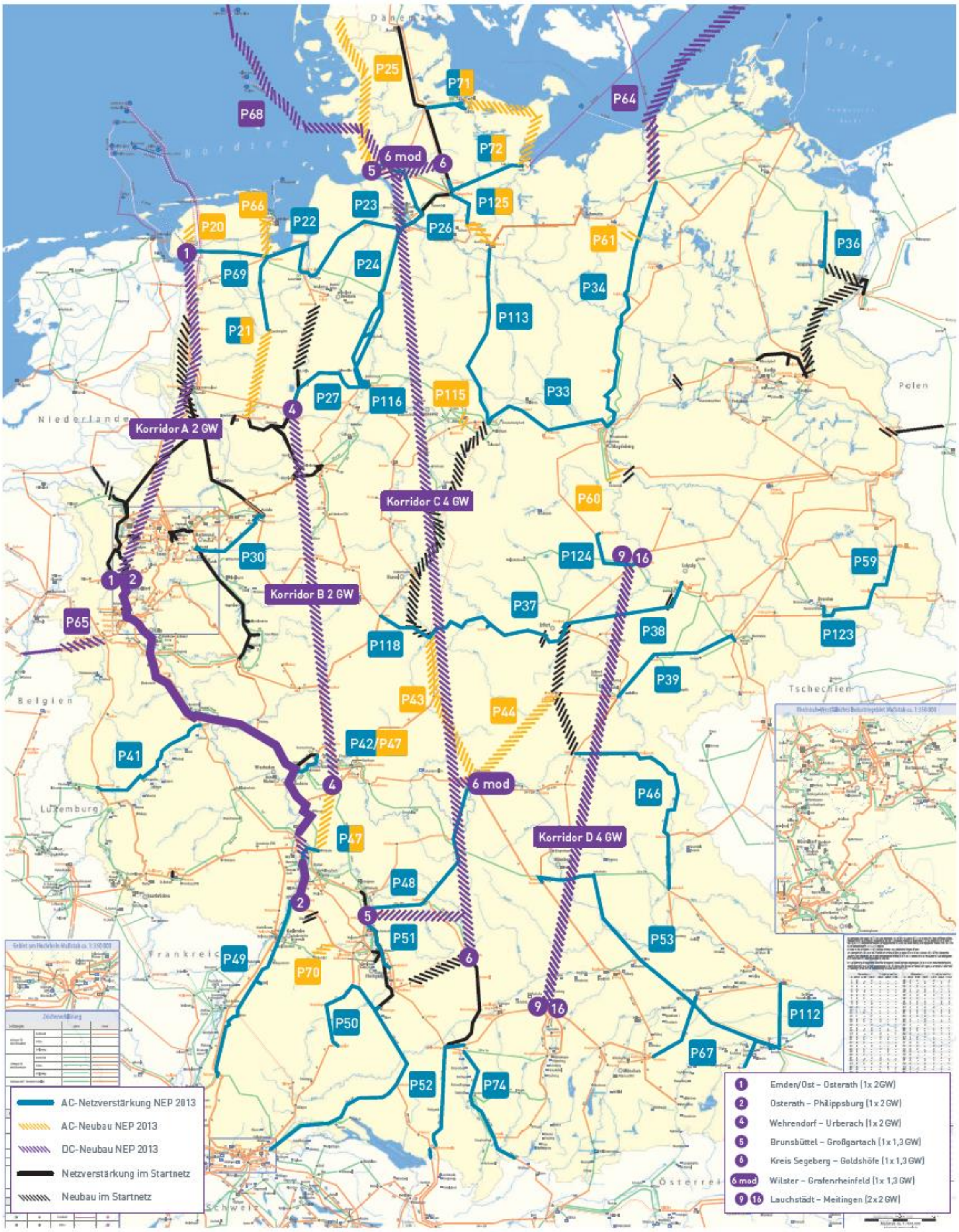


Figure 1-5: German Electric Network Development Plan, lead scenario B 2023 [3]

The Network Development Plan considers HVDC as a key technology for the grid development in combination with strengthening the 380 kV AC transmission system. "*Along with the expansion of the 380-kV three-phase network, high voltage direct current (HVDC) connections are envisaged for the high transmission requirements along the North-South direction. They facilitate a low-loss transfer across large distances. They also stabilise the three-phase network if they are used in conjunction with modern technology. (…) However, the direct current technology does not make the expansion of the three-phase network obsolete. The two have complementary functions. Direct current connections cannot replace the intermeshed three-phase network, but they can complement it. In order to minimise the requirements placed on new routes, the 380-kV three-phase network will, as far as possible, be expanded within the routes of the existing 220-kV network."* [2]

1.3.3. The Swedish Situation

Svenska Kraftnät, the Swedish TSO, has published a visionary plan for the Swedish transmission grid by 2025 [4]. The plan outlines several new VSC-HVDC lines under construction or in planning reaching to the Baltics, Norway and Gotland, and possible expansion of the planned three-terminal system down to Germany [2].

1.3.4. ENTSO-E

The European Network of Transmission System Operators for Electricity (ENTSO-E) Ten Year Network Development Plan [5] (TYNDP, 2012) is an update of the first ten year plan (TYNDP 2010). It summarises the ten year plans for 41 TSOs from 34 interconnected countries. The new version is based on feedback from the 2010 TYNDP and aims to give a regional and pan-European perspective on significant projects. It concludes that the major shift in generation mix (Fig 1-4) will induce a massive relocation of generation including large wind and solar capacities and volatile flows that will require significant grid adaptations. It is predicted that 80% of the bottlenecks are related to renewable energy source (RES) integration. In addition to the grid transfer capability increase, as shown in Figure 1-7, there are also important issues for the grid development beyond the TYNDP 2012. Examples of these ongoing concerns include an offshore wind grid (Figure 1-8), a plan for solar from the south and evolution of interconnections to eastern countries.

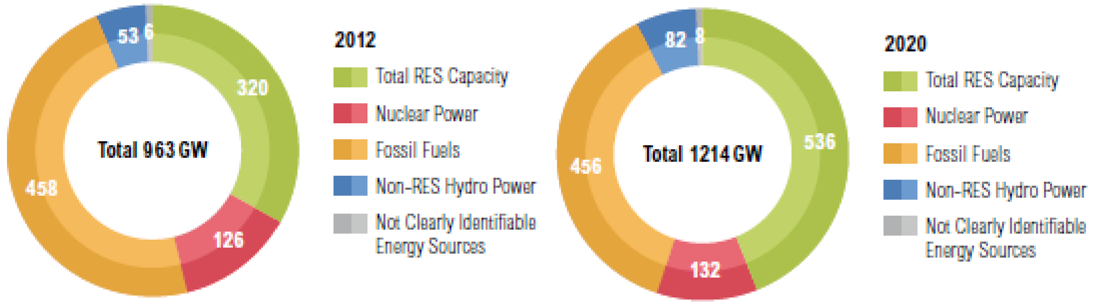


Figure 1-6: Generation mix for 2012 and 2020 in Scenario EU 2020

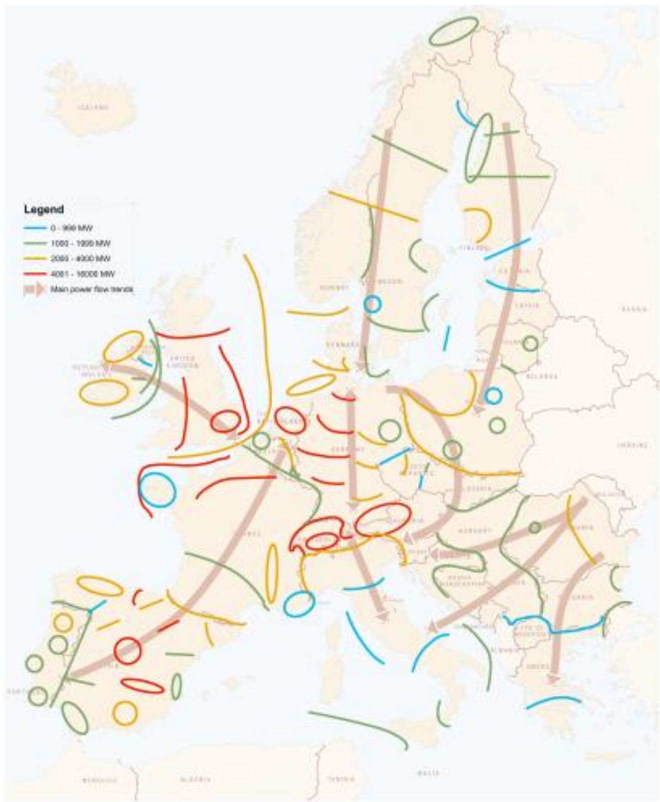


FIGURE 5: GRID TRANSFER CAPABILITY INCREASES

Figure 1-7: Grid transfer capability increases (Source: ENTSO-E TYNDPD 2012 [5])

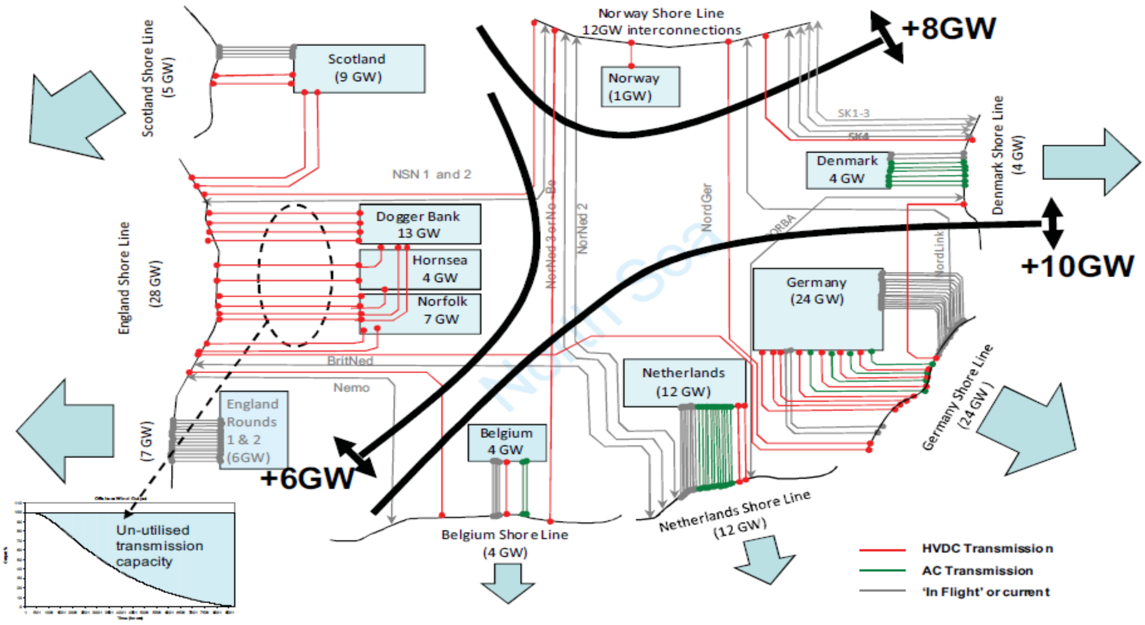


Figure 1-8: ENTSO-E North Sea Vision for 2030

1.3.5. The Scottish, Northern Irish and Irish Situation (ISLES)

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 off the west coast of Scotland and the north and east coasts of the island of Ireland. The Executive Summary Report [6] recognises that although *"…the regulatory considerations highlighted by an integrated cross-jurisdictional concept such as ISLES are complex and continually changing",*

- *"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 multi-developer dimensions which will require anticipatory investment and political commitment to cope with market, regulatory and generation/transmission owner concerns.

1.3.6. The North Sea Situation

A recent ENTSO-E report 'Offshore Transmission Technology' (commissioned by the North Seas Offshore Grid Initiative (NSCOGI) [7]) 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

This report is one of five published by the North Seas Countries' Offshore Grid Initiative (NSCOGI). In the press release for the NSCOGI 'Initial Findings' (3rd December 2012) it was stated:

"Offshore grid developments are taking shape already, with the first cables and platforms already in place in the North Seas. But instead of purely radial connections from the wind farm to the coast and interconnections between countries, new possibilities of combining interconnections between countries with the connection of wind farms are being considered, where it might be cost-effective to do so."

The Initiative's remaining reports [8] reflect the division of work into three WGs within the project and reflecting the scope of issues around electric power system development in Europe:

- WG1: Grid Configuration
- WG2: Market and Regulatory issues
- WG3: Procedural Guidelines

In the grid configuration report, comparisons were made between radial and meshed grid designs for a reference generation portfolio in 2030. In this scenario meshed designs were shown to have a small economic advantage over a radial (or current practice) approach. However, when increased renewable penetration into the European Power System was considered, the report stated:

"Therefore, if future targets are likely to involve significantly increased volumes of offshore RES over those assumed in the Reference scenario, there may be substantial benefits in adopting a more integrated, meshed approach to grid design. This hypothesis should be further examined with the in-depth analysis of an additional scenario covering this outcome."

1.3.7. Varying Levels of Renewable Energy

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.

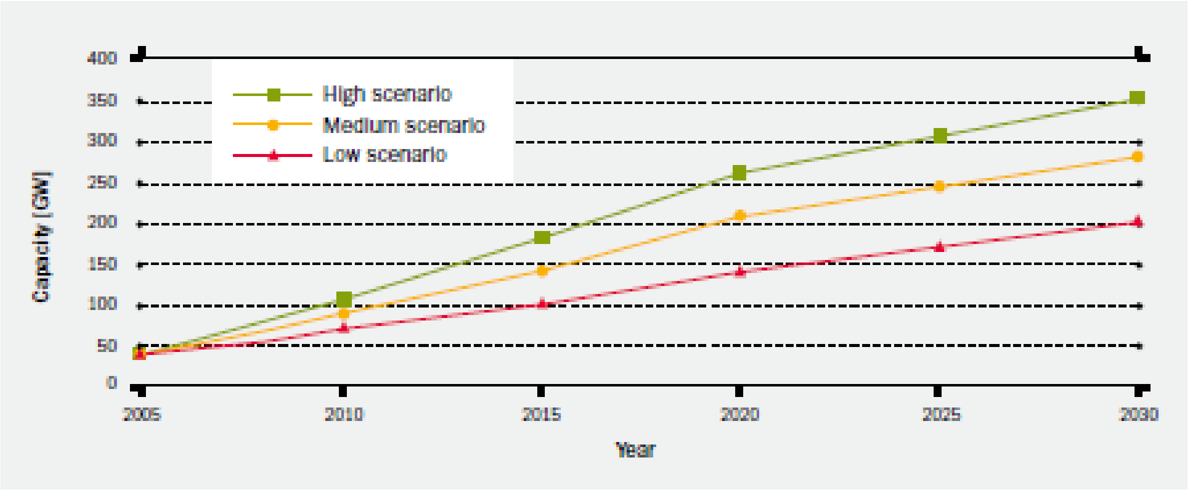


Figure 1-9: Renewable Energy Generation Scenarios (Source: TradeWinds Report [9])

In addition to the increased level of RE, 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 European Climate Foundation roadmap 2050, for instance, suggests that a 30% reduction in electricity consumption by energy efficiency initiatives will be offset by the increased use for transport and industrial/commercial heating (Figure 1-9: Renewable Energy Generation Scenarios (Source: TradeWinds Report [9]).

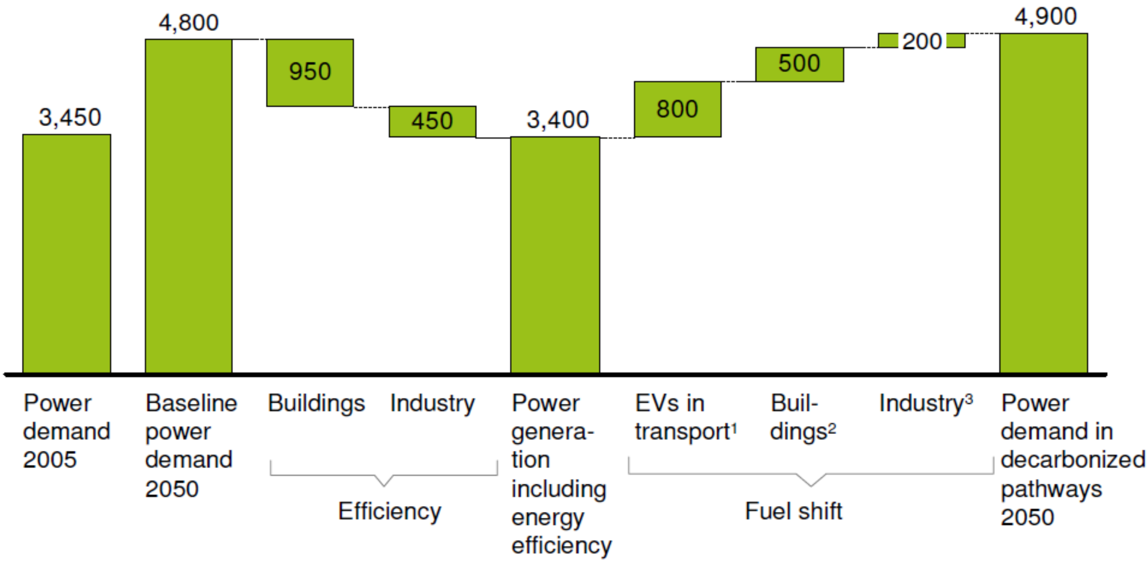


Figure 1-10: Effect of Shift from Primary Fuels to Electric Power in Europe's Transport, Heating and Cooling Load climate and energy framework" (Source: European Climate Foundation Roadmap 2050 [10])

The combination of increased electrical energy consumption coupled with increased levels of RE 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.

1.3.8. Common Themes

Common to all scenarios and reports is the need for increased transmission interconnection across Europe. According to the E3G working paper 'Infrastructure networks and the 2030 climate and energy framework'[5]:

"2050 Roadmaps and scenario studies point to the critical role of network infrastructure for cost-effective decarbonisation pathways, in both integrating variable generation and in enabling more efficient market operation. While investment in transmission and distribution infrastructure will need to increase in nearly all scenarios, the cost is more than offset by the savings made in capital and operational expenditure for power generation.

[5] http://www.e3g.org/docs/E3G_2030_infrastructure_briefing_September_2013.pdf

"Delivering this network infrastructure at sufficient scale and speed to meet with Europe's climate and energy objectives will be a significant challenge. European Commission Roadmaps suggest that rates of overall grid investment would need to double by 2025, and triple by 2040[5]. Electricity TSOs are currently planning to increase their rate of investment by 70% out to 2020.

"Achieving this will require mobilisation of large amounts of capital investment. For power transmission this is in the range of €114-184 billion by 2030 and €273-420 billion out to 2050. Investments requirements for distribution grids are several times larger than transmission grids and could exceed €700 billion by 2030 and €1400 billion by 2050."

The UK Department of Energy and Climate Change (DECC) in its December 2013 report "More interconnection: improving energy security and lowering bills"[6] confirmed the UK Government's support for "appropriate further interconnection". The report concludes that, under some scenarios, increased interconnection can deliver benefits to the UK consumer of up to £9 billion (Net Present Value to 2040) and states:

"Interconnection has the potential to contribute to Government's energy security, affordability and decarbonisation objectives, including through facilitating the single European electricity market. Government supports an appropriate increase in interconnection capacity through projects that efficiently deliver on these objectives."

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 European Climate Foundation's 2050 Roadmap:

"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 realised 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".

[6] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/266460/More_interconnection_-_improving_energy_security_and_lowering_bills.pdf

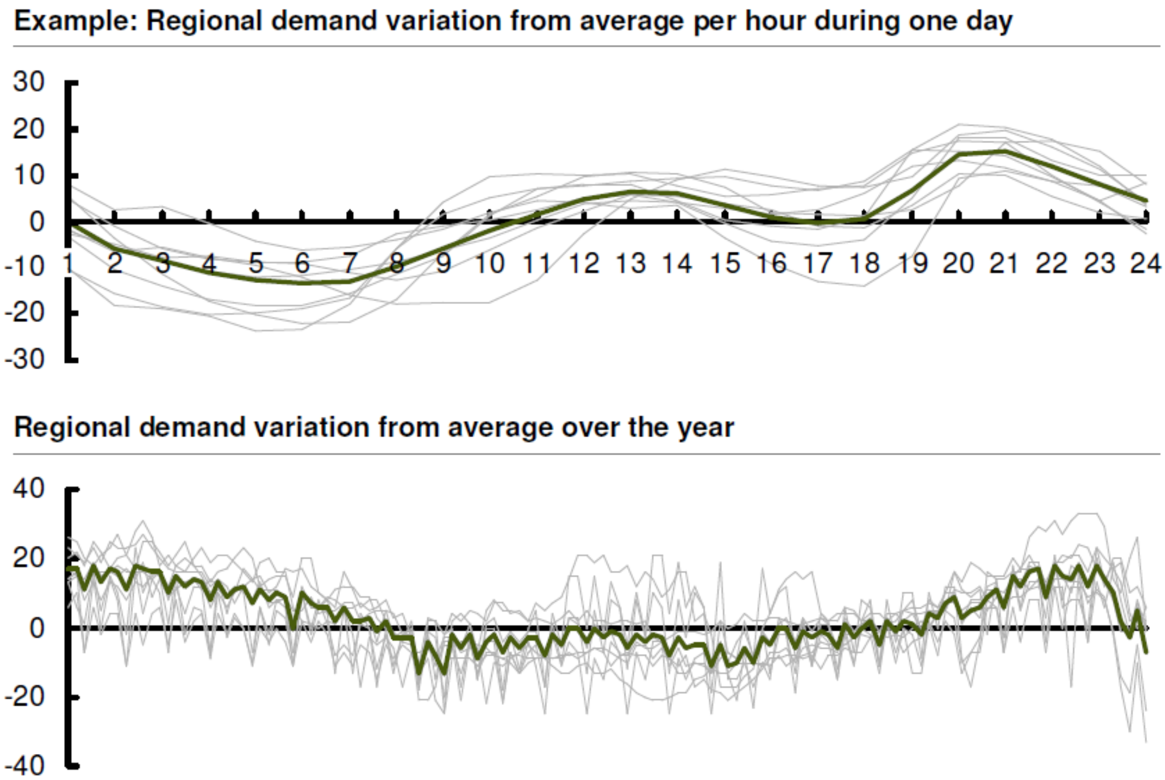


Figure 1-11: Regional Demand Variations from Average (Source: European Climate Foundation Roadmap2050 [10])

1.3 Technological Requirements

1.4.1. Enabling Technologies

An enabling technology for the new grid is HVDC driven by modern power electronics. AC power links become uneconomic over long distances 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 onshore 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 enable 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 and underground 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
- innovative transport and installation methods both on and offshore

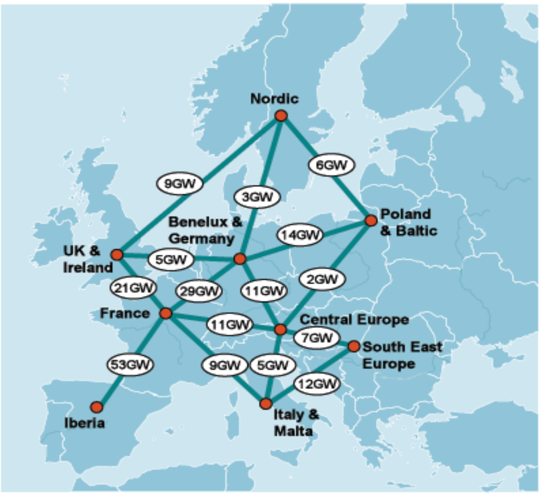
1.4.2. Design Concepts

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 European 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.

Total net transfer capacity requirements
GW (existing + additional)



Interconnection	Capacity addi-tional (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: European Climate Foundation Roadmap for 2050 for 80% RES without Demand Response

Total net transfer capacity requirements
GW (existing + additional)

Interconnection	Capacity addi-tional (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: European Climate Foundation Roadmap 2050 for 80% RES with Demand Response

The following quote from the roadmap report demonstrates the intention behind it:

"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".

1.4 Integration of Supergrid

The challenge of matching an increasingly variable and geographically diverse energy mix will require a power system designed specifically with the new generation portfolio and power market in mind.

According to ABB [11]:

"There is a convergence occurring between the business realities of the utility industry, the energy demands of modern society, and the sustainability requirements of the environment in which we live. The combination of these factors is driving the development and implementation of a new power delivery system. This network will utilise the same basic infrastructure we know today, but will also draw on advanced monitoring, control and communications technology that is presently only beginning to be applied.

"The result will be a grid that is largely automated, applying greater intelligence to operate, monitor and even heal itself. This 'smart grid' will be more flexible, more reliable and better able to serve the needs of a digital economy."

This future grid will see trading of large scale renewable resources (wind and solar) connected to the Supergrid, medium scale storage and backup connected to the existing high voltage AC grids and distributed generation connected to medium voltage distribution networks. With variable resources, storage and Demand Side Management (Smart Grid) and with price as proxy, new data management and real-time communication systems will be required to operate this "intelligent" market: the result will be sustainable, reliable and fair – an "electricity internet".

1.5.1. What Does this New 'Intelligent System' Look Like?

Smart Grid is a general term that is used to describe many of the technical aspects of this future grid. What can we expect from this Smart Grid?

The Global Smart Grid Federation in its 2012 report [12] states:

"At its simplest, the "smart grid" refers to a more efficient, modernised electrical grid. It allows users to manage their electrical demand or output in a way that is most cost-effective for them and beneficial for the power system."

However, we need a broader view of integration and 'intelligence'.

The Siemens paper, 'Highly Efficient Solutions for Smart and Bulk Power Transmission of Green Energy [13], 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).

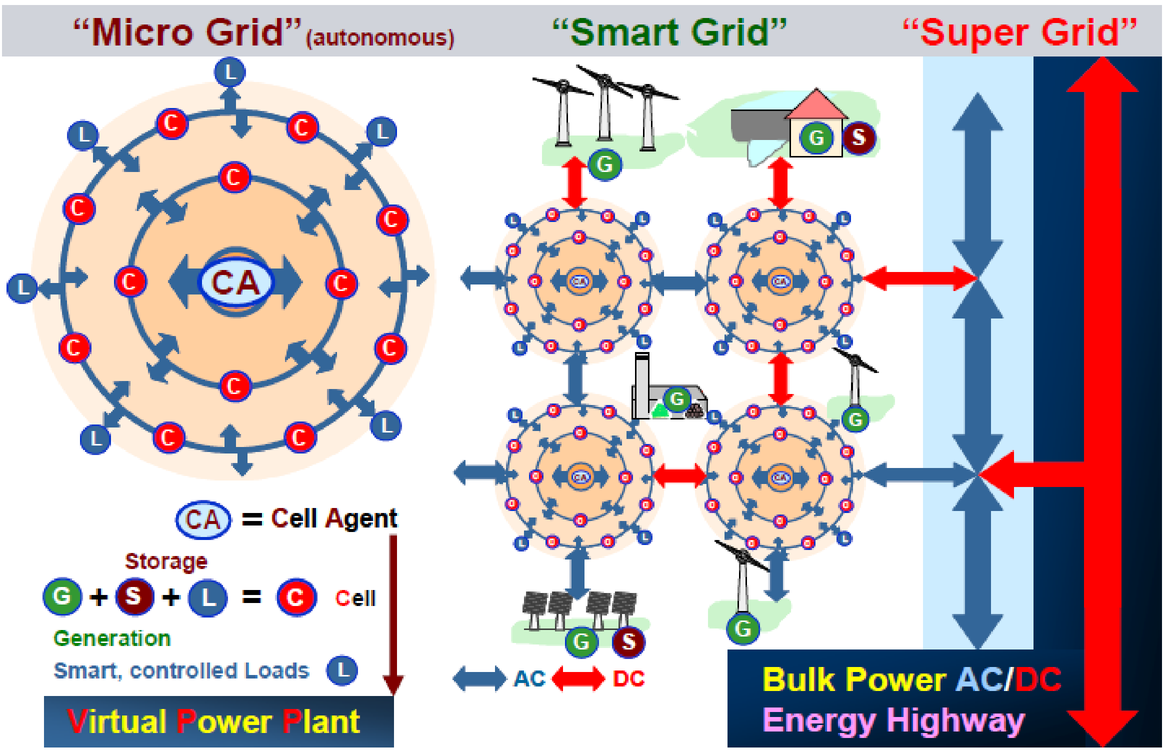


Figure 1-14: Grid Development Prospects according to Siemens

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)

“Just as the internet has driven media from a one-to-many paradigm to a many-to-many arrangement, so too will the smart grid enable a similar shift in the flow of electricity.”

Figure 1-15, below, illustrates this integrated view and compares it with the traditional, ’hierarchical‘ design.

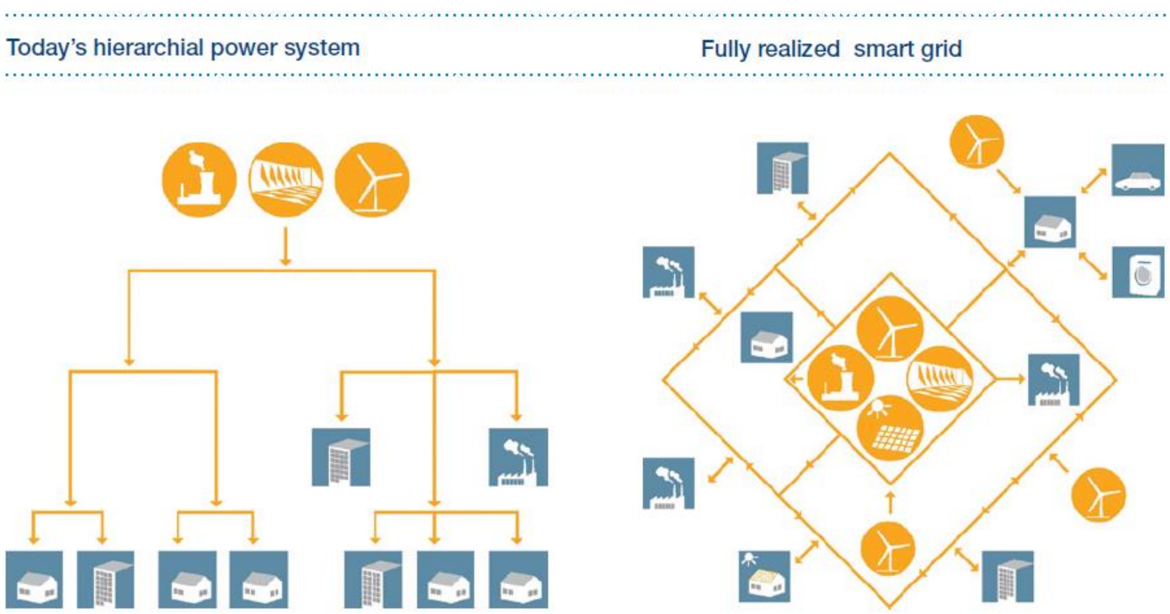


Figure 1-15: Schematic of Old and New Grids according to ABB

1.5.2. ICT

Information and Communications Technology (ICT) has been a 'game changer' in today's world. It is ubiquitous and although power systems have had some level of 'smartness' built in for many years, for example stepped impedance protection with reclosing, modern ICT innovations will allow new models and efficiencies.

According to Alstom [14]:

> *"These intelligent networks evolve regularly with the technological innovation, both at transmission and distribution level, with embedded controls, IT and telecommunications capabilities. Smart grids provide a real-time, bi-directional flow of energy and information, connecting all the stakeholders in the electricity chain – allowing better communication between the power plant and the transmission grid operator, better coordination between the distribution electrical utility and the end-consumer."*

It is not just technology companies that see the need for a new integrated approach. The report 'Foresight Study into Future Market Opportunities in Sustainable Energy Technologies', prepared by the MATRIX Sustainable Energy Horizon Panel for the Northern Ireland Government states [15]:

> *"Going forward, the instantaneous matching of energy supply and demand will become much more complex and will require networks that are flexible and reactive, with new tools that enable the participation of new actors (primarily end users)."*

This report describes how the new power system will use "*technology that can measure, analyse and communicate the status of power transfer at and between all levels of the system* (Figure 1-16) *to optimise performance.*"

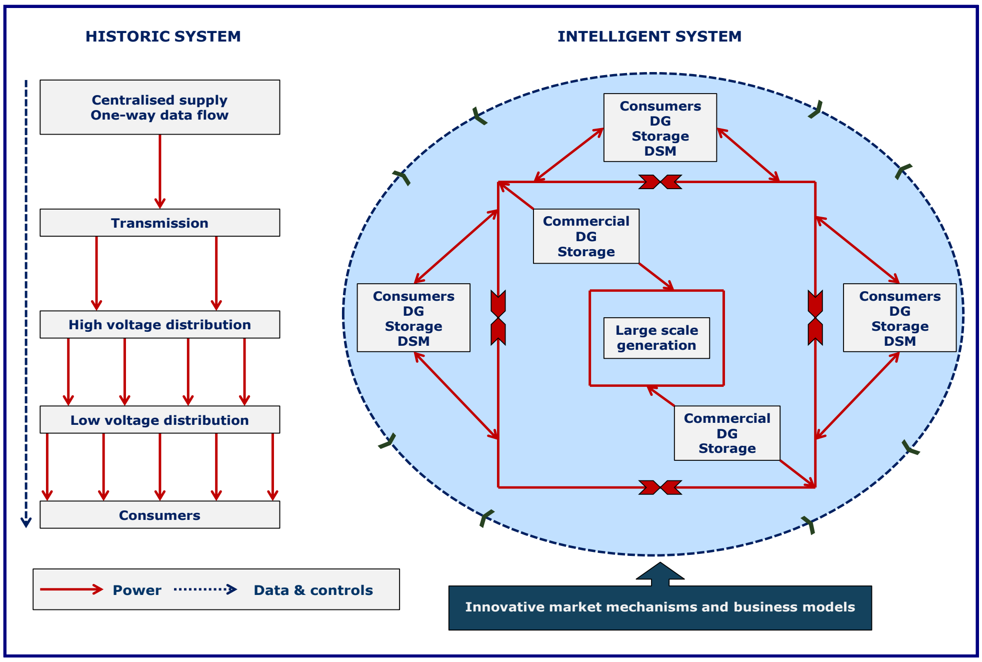


Figure 1-16: Future Power System v Historic Design

Source: Northern Ireland Science Industry Panel

1.5.3. Next Steps

However, technology companies and governments are not enough to realise this future. The Global Smart Grid Federation in its 2012 report [12] states that the "*most difficult challenge to a successful smart grid lies in winning consumer support…* and that this will *require a radical change in thinking by utilities about their customers and by consumers about electricity…"*

It continues:

"… Utilities risk taking their customers for granted, being overly technocratic in their relationship with them, and possibly alienating them. They would be well-advised to engage with consumers on a new level, perhaps borrowing from the best practices of more competitive, consumer-centric industries. Likewise, in many developed countries, consumers risk taking electricity for granted as a low-cost commodity, which is always available, rather than a commodity subject to market swings in a manner similar to gasoline. Active consumer engagement in the power system will depend on a change in this perspective…"

In addition to the transition to sustainability and energy security, there are other economic benefits. The Fraunhofer Institute Report [16] on the potential benefits of an 'intelligent' power system - "Gesamtwirtschaftliche Potenziale intelligenter Netze in Deutschland", estimates that Smart Grids in Germany will result in a societal net benefit of €55.7 billion per year. This benefit is composed of expected efficiency gains (€39.0 billion) and additional growth stimuli (€16.7 billion).

The Supergrid cannot operate in isolation. The power system of the future will require integration of Supergrid and Smart Grid principles with ICT combining the two. Technological innovation in power electronics and telecommunications have allowed us to imagine the immediate future of the world's energy system. However, this is not the end of the story. The new vision will require technological leadership not just in the areas defined by CIGRE WG B4-52 (DC grid feasibility study) [17] such as interoperability between manufacturers, fast acting protection and DC-DC converters, but also in ICT, SCADA, modelling and simulation, and data management.

1.5 Standards

HVAC equipment and operation has been developed over more than 100 years and highly standardised 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 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. This is further elaborated in Chapter Three (3.5) '3.6 The Way to Develop the Supergrid'. FOSG has summarized the ongoing work in CIGRE and CENELEC in IV Appendix [18].

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 basis 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.

1.6 Questionnaire

A questionnaire was circulated in the end of 2013 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:

- Examples of driving factors to develop an HVDC Grid are:
    - The connection of large scale offshore wind as well as other renewable energy sources and interconnections supplementing single point-to-point connections.
    - HVDC Grids are expected to provide economically viable solutions for high security, reliability and better utilisation of transmission system assets.
    - Precise control on active power as well as system ancillary services like frequency control or power oscillation damping are important advantages of DC vs. AC.

- Examples of limiting factors to develop an HVDC Grids are:
    - DC Grids will most likely be built up from several manufacturers requiring interoperability of their equipment. Standardization at an international level is needed. At the same time coordination of the TSOs involved will be required.
    - DC Breakers would be beneficial in the development of extended meshed DC Grids in order to avoid DC faults leading to a collapse of the entire DC Grid. New protection systems (algorithms and devices) need to be coordinated with the capabilities of DC Breakers.
    - The planning of HVDC Grid Systems and the upgrade of existing planning tools should be considered strategic for success.
- Multi-terminal HVDC systems have to contribute to the security of supply according to the TSOs requirements. The maximum active power loss criterion is an important parameter for system planning.
- Both VSC and LCC are seen as technological options with factors like cost, controllability, system performance requirements, system configuration (point-to-point or multiple-terminal), application (wind connection or others), maximum DC system ratings, maturity and supply capability being decisive in selection.
- Multi-terminal HVDC Systems will play an important role for power system stability and therefore should be highly reliable. The maximum active power loss criterion is an important parameter for system planning influencing the configuration of HVDC systems with respect to system redundancy. Any possible single fault in the HVDC system must not violate the maximum active power loss criterion.
- The power losses are an important design criterion for HVDC systems and will be evaluated by the TSOs for projects individually. If more TSOs are commonly involved with a HVDC system, the demarcation points for separating losses between the TSOs are proposed to be the points where the MW ratings are defined.
- For long distance high power transmission, the power losses on the transmission lines, e.g. the cables, become more important compared to the converter losses. Higher transmission voltages are considered an important step in reducing the overall transmission losses.
- Increasing the rating of HVDC system components today allowing for a possible future system expansion has to be handled with great caution. Expansion is considered to be relatively easy as long as the DC voltage level will not be changed. Tapping into existing HVDC links could be one possible scenario. However, even this step requires interoperability of the HVDC components (e.g. converters) and systems (e.g. control and protection) which requires further steps on international Network Code development and standardisation.

- HVDC systems will be specified on a functional basis. DC fault clearing capability is considered an important function. Besides existing technologies also new solutions may be developed in the future. Therefore, Network Code or international standards should not create barriers with respect to one or another technology or for possible new developments. Large HVDC Grids (e.g. rated 3 GW or above) are expected to require solutions preventing the entire DC power transmission to collapse in case of DC fault.
- In principle all transmission system performance criteria, such as black-start, energisation of a DC network, reactive power support, AC frequency control, and AC short-circuit power, will be needed for future multi-terminal systems. The ENTSO-E Network Code HVDC will define the system requirements. Besides that, interoperability of equipment and solutions of different manufacturers will be needed.
- There is presently little experience with fault handling in multi-terminal systems. In general, fast fault clearing and active power recovery in case for DC faults is important to maintain power system integrity and stability. The ENTSO-E Network Code HVDC or corresponding agreements with the TSOs involved will define the requirements with respect to the fault behaviour.

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

Chapter Two: 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 storage for levelling out peak generation and peak load conditions. Various types of storage 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 storage 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 the course of more than 150 years of development, expanded integrated AC systems have been formed. With only 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 the 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 Section 0 has been used most widely. Another technology is Variable Frequency Transformers (VFT) which has been used in a few projects in North America.

State of the art AC transmission systems make use of various transmission voltage levels [19]:

- High Voltage (HV) nominal voltages typically ≥52 to 400 kV
- Extra High Voltage (EHV) nominal voltages typically 500 to 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, these 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 over-voltages jeopardising system stability.

Reactive power cannot be avoided. The European transmission networks currently benefit from many generating units located in the vicinity of load centres providing reactive power support. Considering that more and more conventional power plants are being replaced by renewable energy sources, new methods for reactive power compensation will be needed. Effective solutions can be found by making use of the complementary nature of reactive power caused by electrical fields on 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.

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 by 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 2-17):

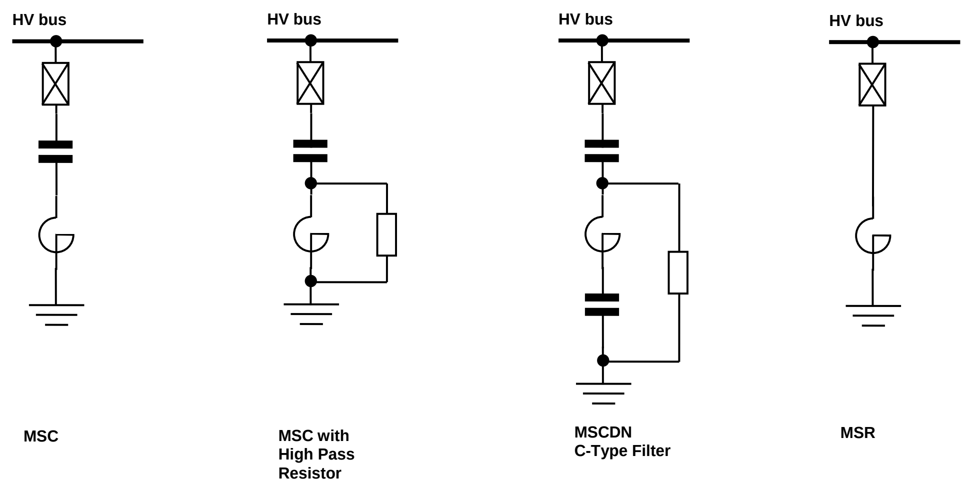


Figure 2-17: Mechanically Switched Branches for Reactive Power Compensation

The speed of response is subject to the following constraints:

- Response time of the mechanical breakers is typically in the range of 100ms or more for closing and typically 60ms 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 of, typically, 15 seconds or more are needed [20].
- Capacitors in the switched branch often need to be discharged before reclosing; possible discharge devices have to be rated for the number of successive times they reclose.
- 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 [21].

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 2-17) are used. The damping is effective at the tuning frequency of the branch and at higher frequencies.

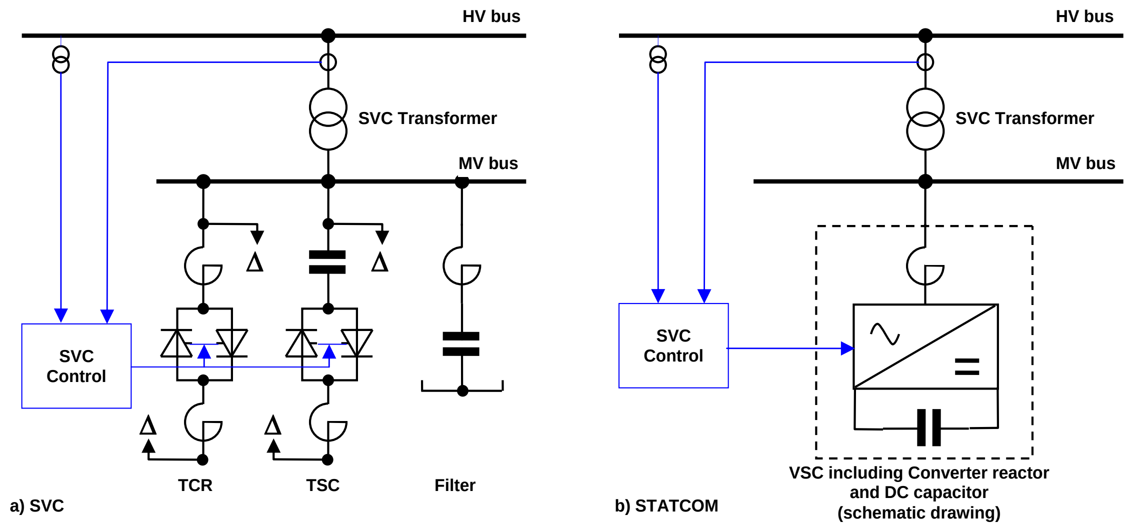


Figure 2-18: Dynamic Shunt Compensation Devices
a) Static VAR Compensator - typical arrangement comprising:
- one Thyristor Controlled Reactor (TCR)
- one Thyristor Switched Capacitor (TSC)
- one fixed capacitor (Filter)
b) Static Synchronous Compensator (STATCOM) with schematic drawing of converter

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 2-18a
- Static Synchronous Compensators (STATCOM), Figure 2-18b

The principle single line diagrams in Figure 2-18 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 [22] and [23].

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 Section 0.

2.2.2.2 Series Compensation

The inductive line impedance of long transmission lines of, typically, 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 quickly reducing the energy to be absorbed by the capacitor overvoltage protection in the 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 2-19a)
- Static Synchronous Series Compensation (SSSC) (Figure 2-19b)

More details of the various technologies are described in 'Flexible AC Transmission Systems (FACTS)' [22].

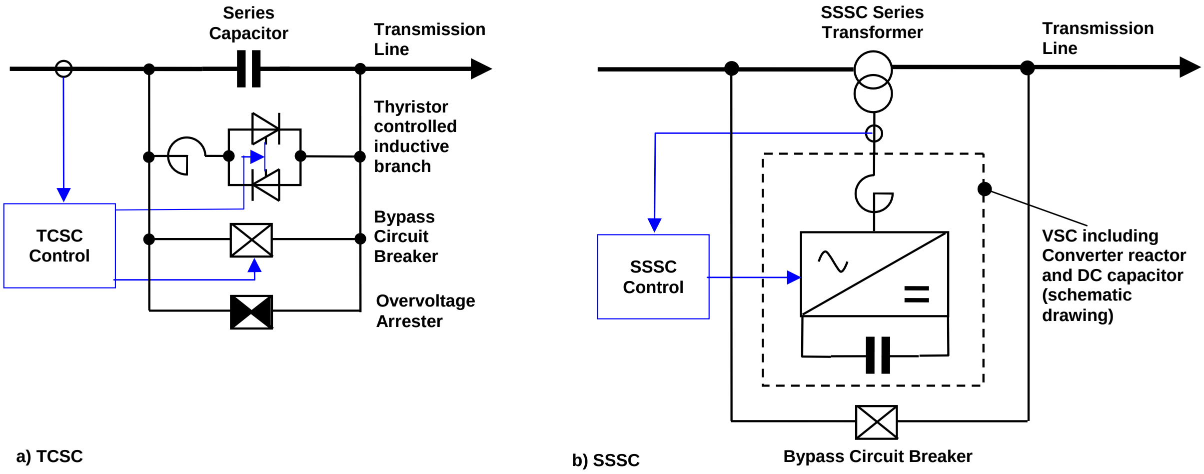


Figure 2-19: Dynamic Series Compensation Devices
a) Thyristor Controlled Series Compensator (TCSC)
b) Static Synchronous Series Compensator (SSSC) with schematic drawing of converter

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 for the insertion of 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 influences 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 2-20
- Interline Power Flow Controller (IPFC), Figure 2-21
- High Voltage Direct Current Systems (HVDC) in Back-to-Back Configuration, Figure 2-22

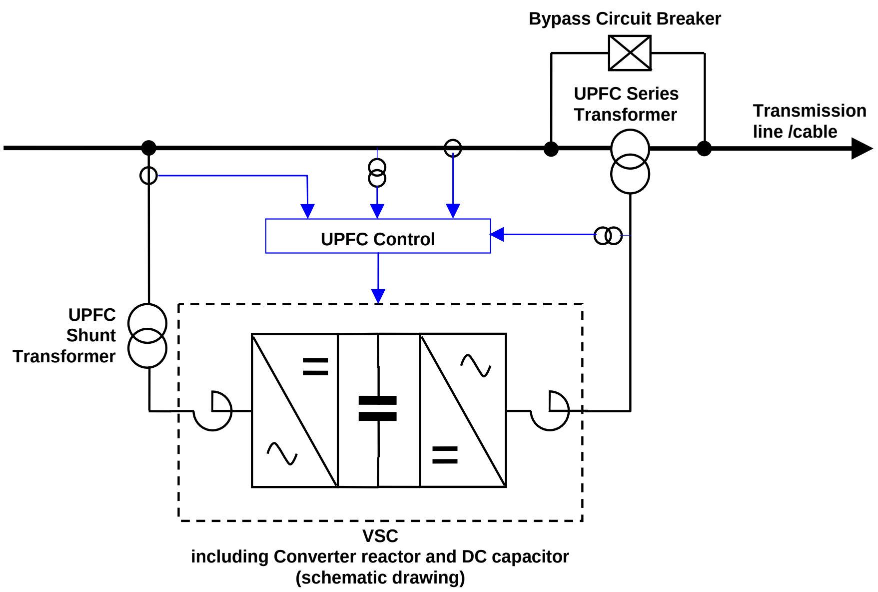


Figure 2-20:.Unified Power Flow Controller (UPFC); typical arrangement

There is a competitive market for HVDC. However, UPFC and IPFC have been used so-far in demonstration projects ([24], [25]) and may be an option for future applications.

A principle single line diagram of a Unified Power Flow Controller (UPFC) is shown in Figure 2-20. 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 for control of 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 [24].

An example for an IPFC is shown in Figure 2-21. Two VSCs 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 for 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 an NYPA 345 kV substation [25].

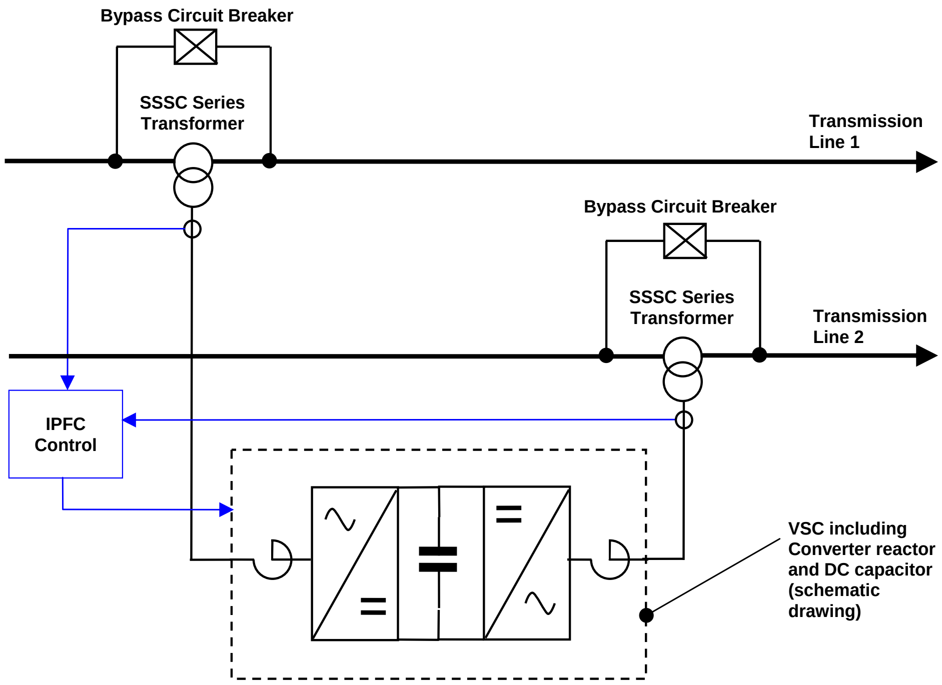


Figure 2-21:.Interline Power Flow Controller (IPFC) with schematic drawing of converter

HVDC Back-to-Back systems have been widely used for its decoupling characteristic to connect asynchronous AC systems. Figure 2-22 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, LCCs 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 on 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.

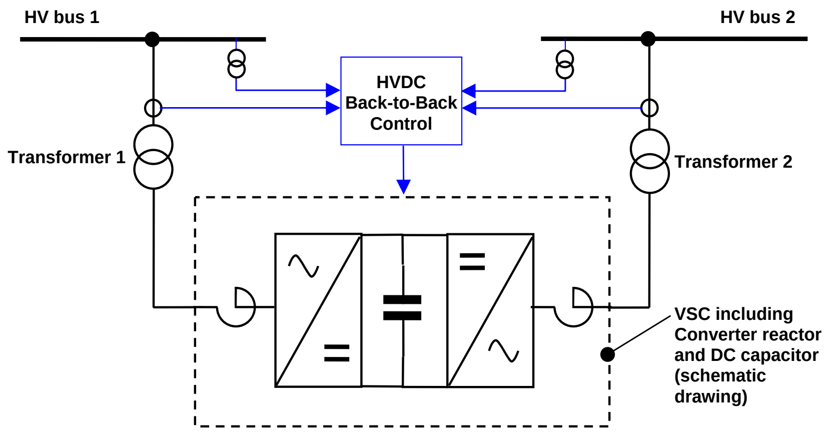


Figure 2-22: High Voltage Direct Current Back-to-Back Converter with schematic drawing of converter (example based on VSC technology)

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 of pure AC transmission. Any change in the AC system, e.g. a fault due to lightning or a load rejection, causes 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) condition without developing sustained oscillations.

To explain the aspects of system stability the principle system diagram shown in Figure 2-23 should 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 cases 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 where the power flow is higher.

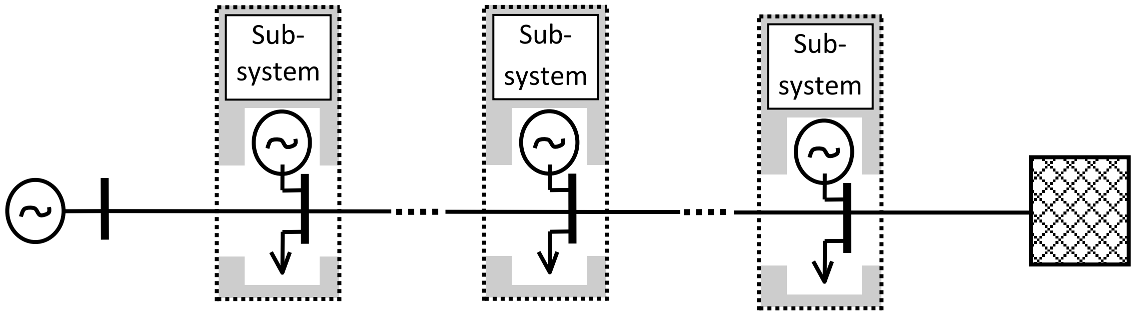


Figure 2-23: AC Transmission through Interconnected Power Systems

Power System Stabilisers are currently used 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 aspect 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 of the remaining system components and without jeopardising 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 blackouts as already experienced in North America or, more partially, 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 Condensers

The phasing out of conventional power plants with large rotating generators leads to a reduction in 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 condensers are a well-proven solution compensating both effects.

Synchronous condensers 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 2-24 shows the main components of 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.

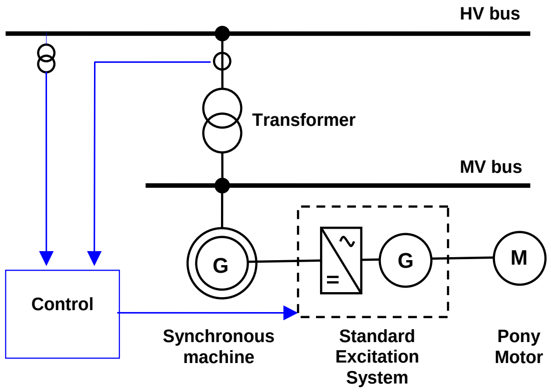


Figure 2-24: Synchronous Condenser

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 1940s to the first commercial scheme in Sweden in the early 1950s, 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 [26]. 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 wind park in Germany), and the highest voltage used today is 350 kV in a 300 MW scheme (Caprivi in Namibia with OHL).

Table 2.2 gives a comparison of the main features of LCC and VSC technology;

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[7] ≥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%)

Table 2.1:Comparison of LCC and VSC technologies

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

Today’s state of the art technology 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 wind park connectors up to 900 MW at 320 kV DC voltage (BorWin 2, HelWin, SylWin, DolWin 1-3) as well as the interconnection between Sweden and Lithuania and the embedded VSC-HVDC link in Sweden. With the notable exception of Caprivi, which is based on overhead line, to date most VSC schemes still have used submarine or underground cables.

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

2.3.1.1. Introduction

The following sections do not treat VSC technology at the detailed power electronic level, but consider 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 their 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 are described further in the following paragraphs.

2.3.1.2. Asymmetrical monopoles

This is the simplest scheme topology, as shown in Figure 2-25, 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 incorporates 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.

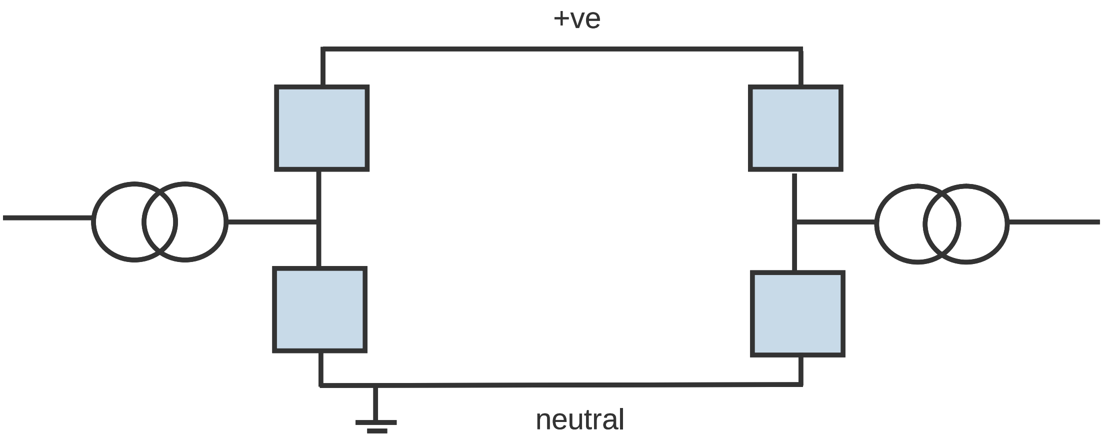


Figure 2-25: Schematic of an asymmetric monopole configuration

2.3.1.3. *Symmetrical monopoles*

This topology uses two HV cables (positive and negative) and operates in an isolated mode on the DC side, as shown in Figure 2-26.

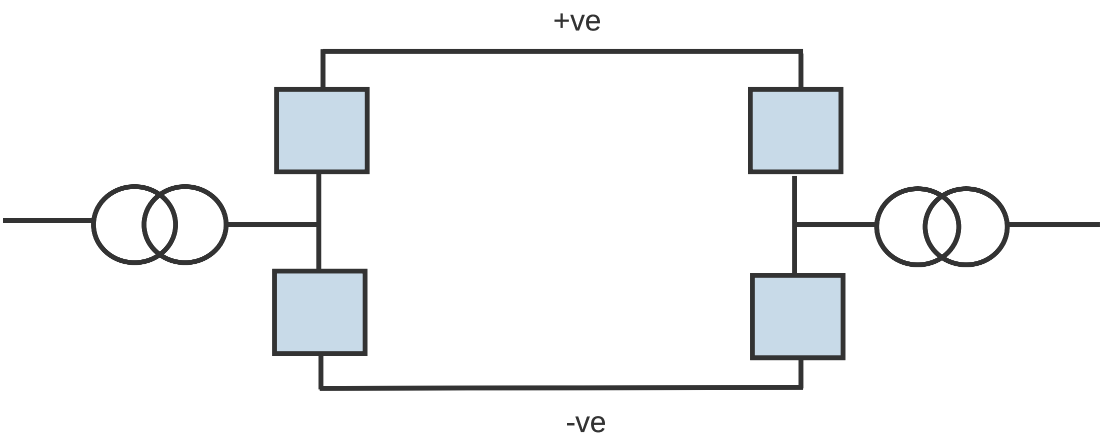


Figure 2-26: Schematic of a symmetric monopole configuration

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.

2.3.1.4. Bi-pole with ground/sea return

This topology consists of two asymmetrical monopoles, as shown in Figure 2-25, connected in a bi-polar arrangement, as shown in Figure 2-27. 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 secondary transformer 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 positive and negative 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.

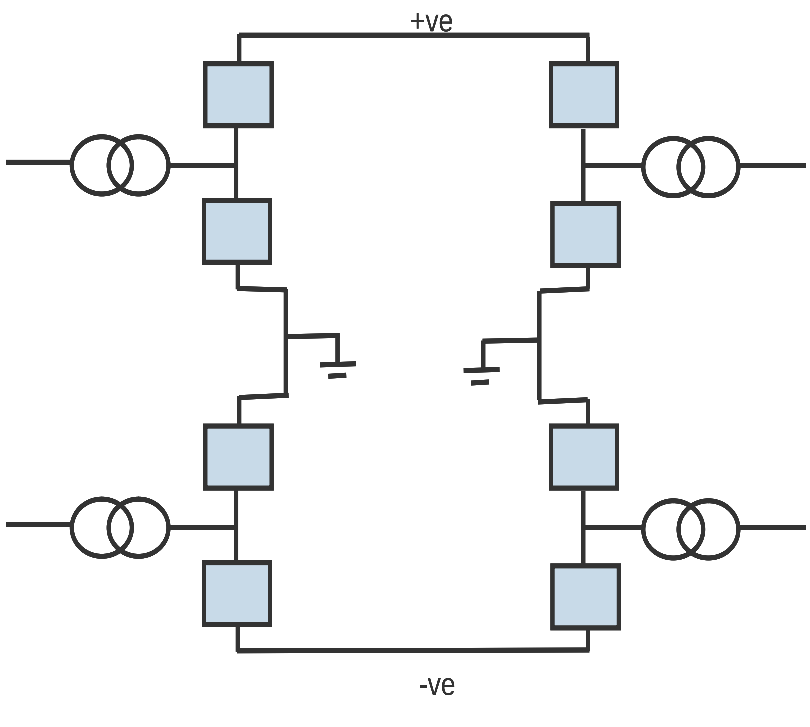


Figure 2-27: Schematic of a bi-pole with ground/sea return

2.3.1.5. *Bi-pole with metallic return*

As shown in Figure 2-28, this has the same topology as Figure 2-27, but the neutral return path is a third conductor, lightly insulated and connected to ground.

This scheme has the same functionality as Figure 2-27, but without the environmental impact 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 2-27. 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.

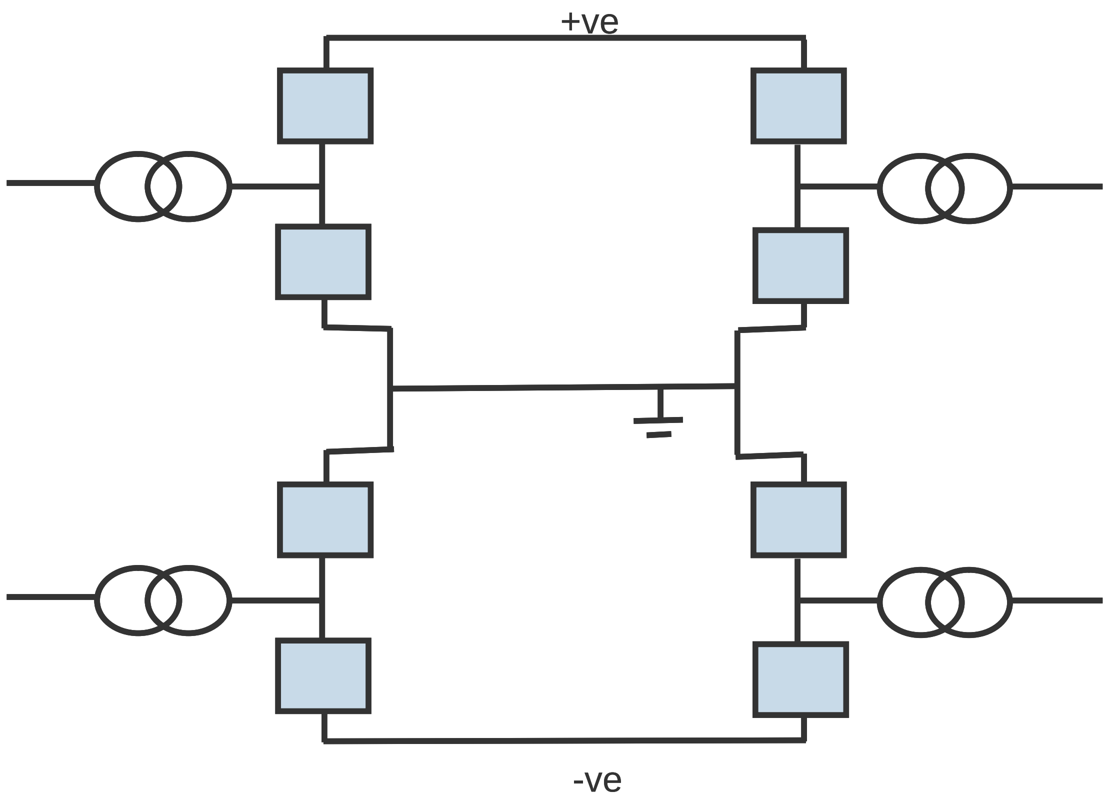


Figure 2-28: Bi-pole with metallic return

2.3.2. Modular Multi-level 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 in 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 2-29.

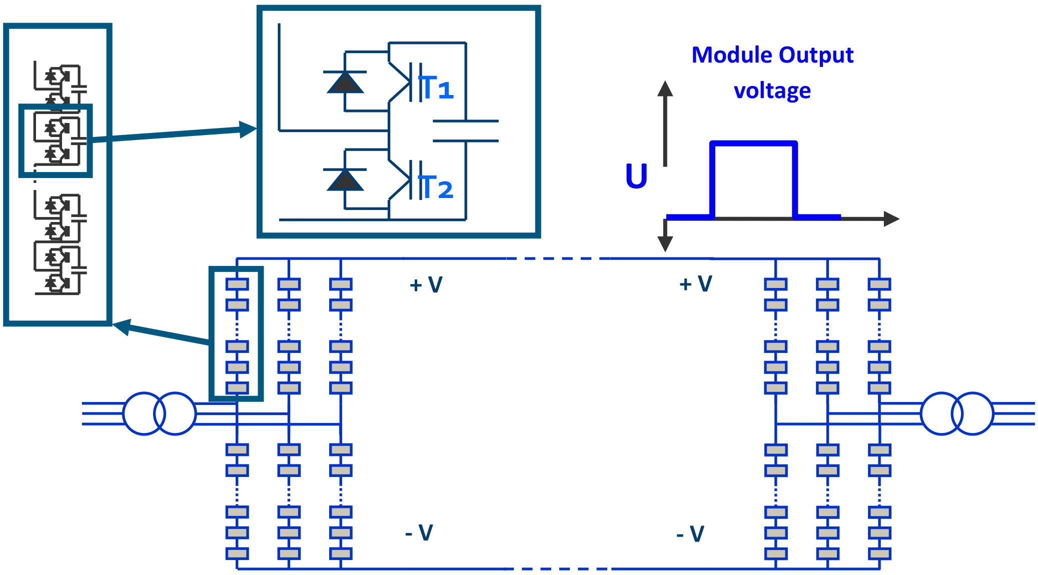


Figure 2-29: "Half Bridge" Modular Multi-Level Converter

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 cannot 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 2-30.

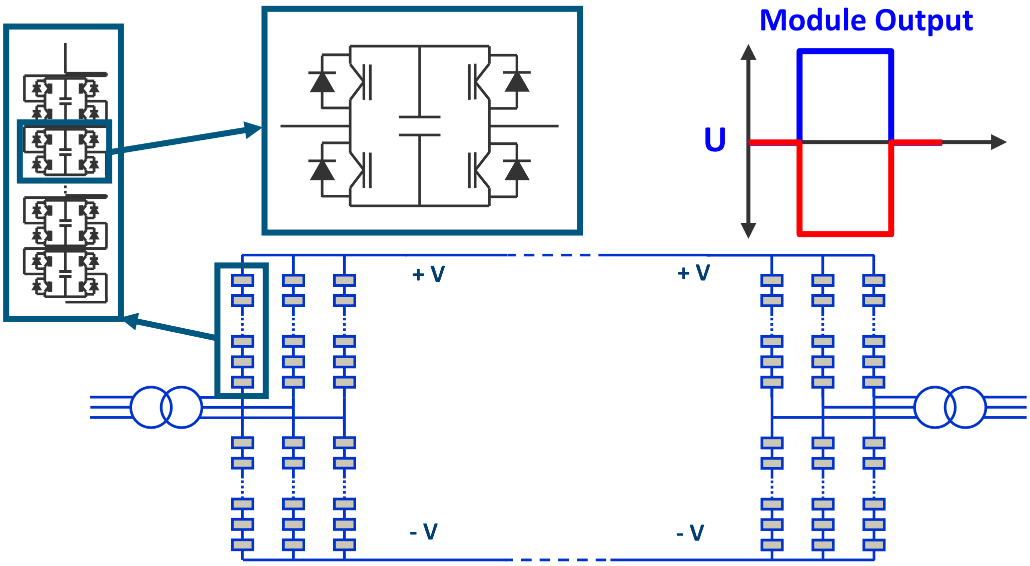


Figure 2-30 "Full Bridge" Modular Multi-Level Converter

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 optimised 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. Modern DC circuit breakers normally consist of an AC circuit breaker plus an auxiliary circuit which creating 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 paragraph 0, 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 eliminate the in-service losses while maintaining the required speed [27].

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 cost 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
- Hybrid
  - using a combination of the methods above, such as the Hybrid HVDC breaker announced by ABB. This is a breaker combining an IGBT semiconductor breaker with a low resistive current path with a mechanical ultra-fast disconnector and commutation switch. In normal operation the current pass the low resistive path. The low loss path brings down losses to <0.01% while the semiconductor functionality still maintain a very fast (<5 ms) short circuit current breaking capability [27]

2.3.4. Multi-terminal HVDC Systems

In conventional LCC technology reversing power flows requires the reversal of the polarity of the converters. The complexity that this introduces into multi-terminal operations 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.

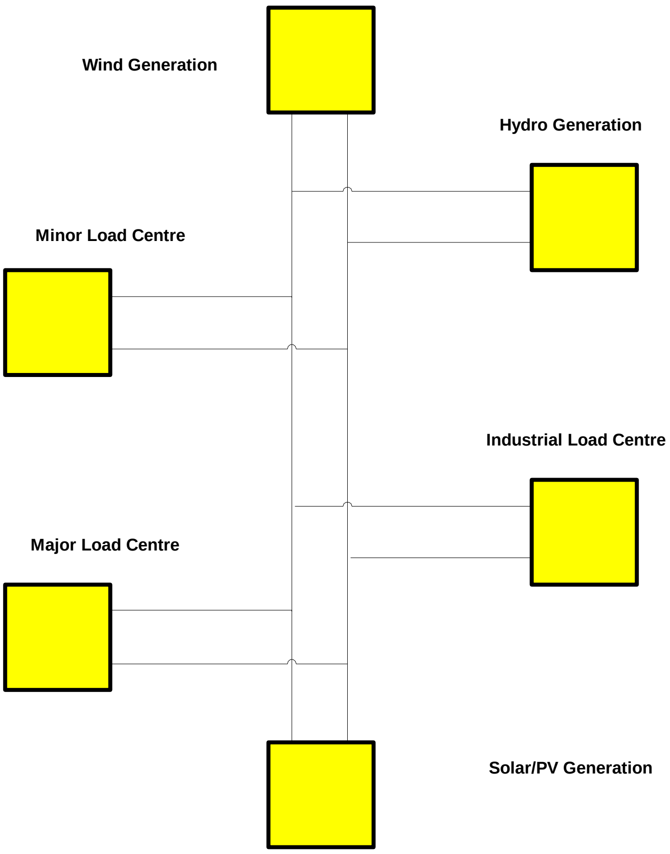


Figure 2-31: Multi-terminal DC system in radial topology

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 2-31 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 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 2-32. 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

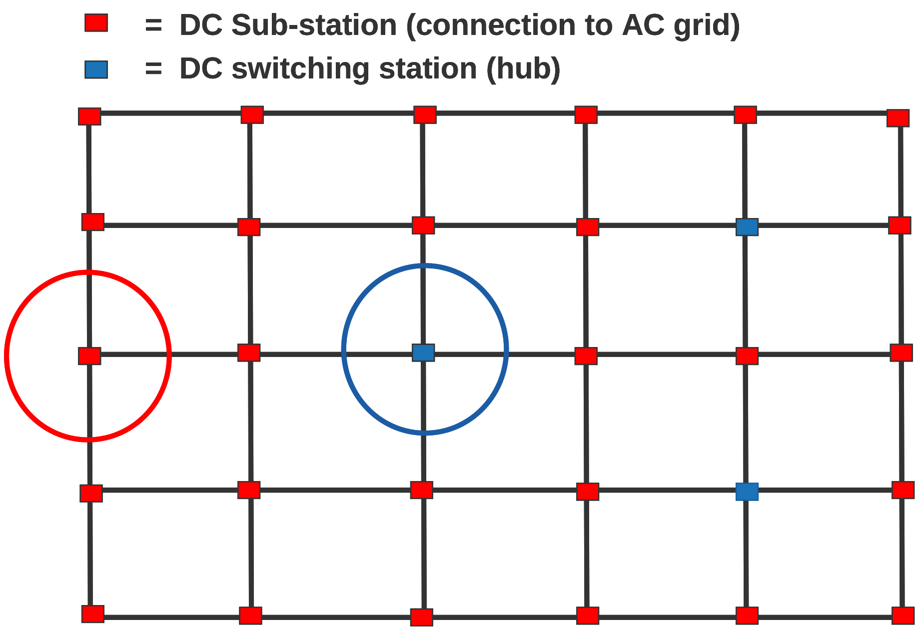


Figure 2-32: DC grid system (meshed topology)

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 2-33.

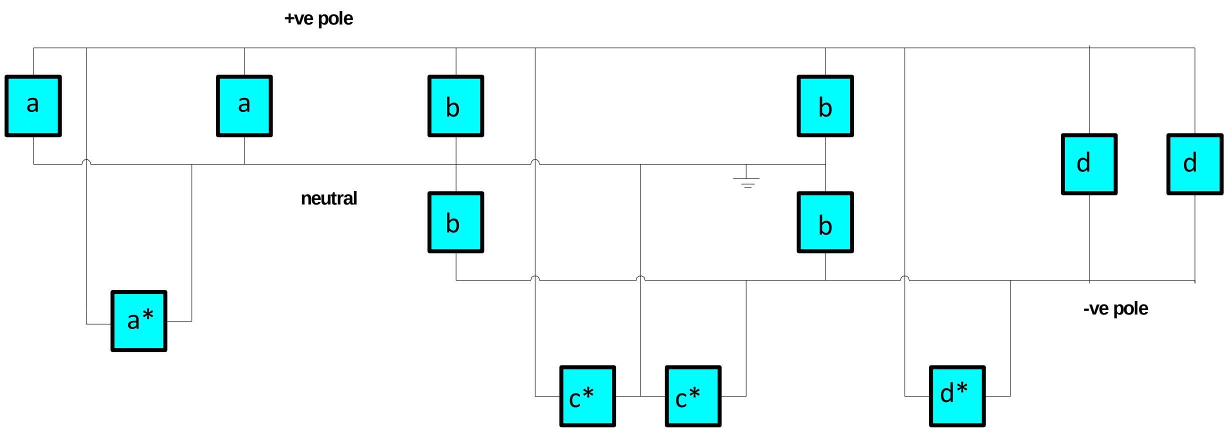


Figure 2-33: Multi-terminal HVDC system

This example shows:

- Three asymmetrical monopole terminals, connected between the neutral and the +ve pole (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 2-33 consists of a transformer connection to the AC grid and the upper and lower bridge power electronic converters, as shown in Figure 2-34.

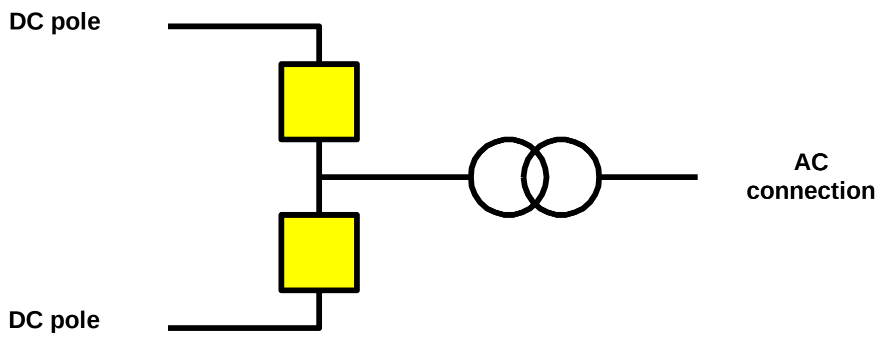


Figure 2-34: VSC HVDC converter pole

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 2-33 show T-connections from the main ’backbone‘ system to remote converter stations marked with an asterisk, 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 Control in AC and DC Transmission Grids

2.4.1. Control in AC Grids

In a meshed AC network, any major disturbance, regardless of where it occurs, may spread to the whole system. The time constants in play cover extremely diverse time scales. For example, disturbances resulting from a short-circuit spread at speeds close to the speed of light, programmable logic controllers or protections operate in fields ranging from tens of milliseconds to a few seconds. Some controls govern processes with time constants of several minutes or even several hours. The security of the system relies on the perfect coordination of all control and protection systems.

In the following paragraphs, the control of a meshed AC network is described. Depending on the time constant of the phenomena, it includes automatic and manual controls. Both are necessary to ensure the security of the system.

2.4.1.1 Protection plans

Transmission facilities sustain tens of thousands of short-circuits per year, the largest number of them brought about by meteorological conditions. Short-circuit currents cause voltage drops, result in mechanical and thermal stresses of the equipment or may affect the stability of generating units. The adverse effects of short-circuit currents largely depend on the fault duration. Therefore, the protection functions are most critical when it comes to system security. Fault protection systems are expected to operate reliably (no failure or unwanted operation), selectively (opening of circuit-breakers necessary to clear the fault only) and fast (minimising equipment stresses and preserving the stability of generating units).

2.4.1.2 Frequency control

Within an integrated AC system and under normal operating conditions, the frequency can be considered to be the same throughout the network at any given time. The frequency stays constant if generation and load are in equilibrium. As electricity cannot be stored on a sufficiently large scale, the level of generation has to be constantly adapted to demand. This is done by maintaining the frequency to a fixed value.

Three action levels with different time constants co-exist:

- **Primary control** is a real-time automatic control carried out by the speed controllers of the generating units. Rapid (in a matter of seconds) and decentralized, it restores the balance between generation and load by adapting the power produced by the generating units. If the demand is higher than the supply (for example following the trip of a generating unit), each generating unit produces a little more power. If the demand is lower than the supply, each generating unit produces a little less

- **Secondary load-frequency control**: the quick adaptation of generation to load carried out by primary control however leaves a frequency deviation at the end of the action and brings about flow variations between the control zones. All the generating units of the various control zones react to the variation of the frequency, which is common to the overall grid, regardless of the control zone in which the disturbance has occurred. The aim of the secondary load-frequency control is to bring the frequency back to its reference value and the exchanges between partners back to their scheduled values. It is a centralised control, slower than the primary one (time constant of a few minutes). It modifies the set points of the generating units subject to secondary power frequency control by means of a signal calculated from the exchanges between the control zones

- **Tertiary control**: reserves of power must be available for the primary and secondary controls to be effective. The aim of tertiary control is to build these up again when they are used by the primary frequency control and the secondary load-frequency control on a permanent basis to provide protection against any new contingency. The corresponding actions are under the control of system operators

2.4.1.3 Voltage control

Voltage control has three main objectives:

- Keeping the voltage of customers in its contractual variation range and respecting the equipment's operating constraints

- Reducing network losses

- Improving the security of the system

To achieve these aims, generating units are equipped with an automatic device called a primary voltage controller. By acting on the excitation voltage, it maintains the voltage at the connection node of the generating unit at a fixed value. Its time constant is a few seconds. It allows the system to manage random load fluctuations, topology changes and incidents - at least as long as the generating units have not reached their reactive power limits.

Generating units are the major means used to control the voltage on AC grids. In some locations, FACTS devices like SVC or VSC HVDC provide effective solutions for voltage control. Depending on the location of renewable generation, the need for such local voltage control is expected to increase in some countries.

For lower voltage levels, transformers can be equipped with automatic on-load tap-changers.

2.4.1.4 *Power flow control*

Means used to control power flows

In an interconnected, meshed AC network, power flow depends on the location of loads and of operational generating units, cross-border exchanges, the location of reactive power compensation and the impedances of transmission facilities. The higher the power, the greater the current loading will be and system operators must ensure that the current flow in the transmission facilities stays within a set threshold: maximum admissible loading under steady-state operating conditions for lines, cables and transformers. If the limits are exceeded, for instance when a facility has tripped following a fault, flows are controlled by changing two parameters:

- Network topology: by adapting the operating schemes, the operator modifies the impedances of the different network meshes (creating long lines to increase the network impedance or, on the contrary, placing facilities in parallel to lower it) and acts on the distribution of loads depending on the generation sources
- Generation dispatch: by adapting generation unit production schedules, the operator acts on the output of the generation sources to match load and system requirements

If changing the topology and/or generator re-dispatch does not resolve a system imbalance or overload then the operator may implement load-shedding as a last resort.

Using simulation tools, the flows in transmission facilities can be calculated according to the load location and to the set-points of generating units that are selected by producers. The impact of the loss of a line or of a generating unit can also be evaluated. These calculations are used on a permanent basis by TSOs to check the operating schemes, particularly to ensure compliance with the N-1 rule[8], and, when needed, to modify set-points of transmission system facilities (FACTS or transformer tap changers). This is done both at the planning stage, using forecasts of load and generation, and in real-time, using measurements.

Need for coordination

In a meshed AC network, events happening in the zone operated by one TSO can impact neighbouring zones. The physical electricity flows, which depend on the characteristics of the network, are also different from the commercial ones. Some of them can go through zones, without the electricity being produced or consumed in it. To control the physical flows, active devices such as phase shifters can be installed, but their action must be coordinated to be efficient. This also applies for the active power set points of point-to-point HVDC embedded in AC networks or linking two asynchronous networks. For instance, the set points of the HVDC links IFA2000 between Great Britain

[8] N-1 rule: network elements remaining in operation after a fault of one of them must be capable of accommodating the new operational situation without exceeding operational security limits

and France and BritNed between Great Britain and the Netherlands have to be coordinated. The interaction between these two links impact not only Great Britain, France and the Netherlands, but also Belgium.

TSOs thus need to have a view of the electricity flow beyond the national picture. That is why some coordination initiatives – such as CORESO (COoRdination of Electricity System Operators), TSC (Transmission System Operator Security Cooperation) or SSC (Security Service Centre) in Europe – have been created, which contribute to improve the security of the system. The topic of coordinating the tap position of phase shifters and the active power set point of point-to-point HVDC links is also addressed, for example by the working group 'Coordinated System Operation' of ENTSO-E.

CORESO provides the national control centres of the participating TSOs (50Hertz, Elia, National Grid, RTE, Terna) with forecasts concerning the security within the interconnected transmission grid for the following day. To achieve this, the day-ahead activity includes several steps:

- Each TSO from the Regional Group Continental Europe of ENTSO-E creates everyday files giving a vision of its own grid for the following day. These files are merged by CORESO to create a Continental Europe wide merged file.
- The loss of any 400 kV line and generator connected to the grid in interest and observability areas is then simulated. Also, in accordance with Elia and RTE's internal Grid Procedure, the tripping of 400 kV busbars is simulated in Belgium and in France. This complete analysis is processed for a minimum of six timestamps, with additional timestamps often required for special cases, e.g. exchange programs, outage, level of wind generation etc. The aim is to guarantee a full 24 hour vision of the security risks for the next day.
- The constraints detected are then analysed and remedial actions to solve them are found. If necessary, some variants (such as an alternate hypothesis for wind power generation) can also be studied. The remedial actions are then discussed by phone with the concerned TSOs.

CORESO delivers advice, proposes solutions to participating TSOs and coordinates the agreement on the remedial actions needed to master the constraints. The decision to implement these remedial actions remains the responsibility of the TSOs.

CORESO also reviews during the day the forecasts made the day before. Thanks to a dedicated tool, the differences between real-time flows and forecasts flows are continuously checked. In cases where significant differences are detected, studies are updated to check whether the recommendations made the day before are still valid.

CORESO performs further security analyses every 15 minutes. Using real-time snapshot files provided by some TSOs every quarter of an hour and merged by a dedicated tool, which simulates the loss of lines, generating units and busbars on the 400 kV grid. Should any data be missing, it is replaced with the forecasted data sent the day before. In case new constraints appear, CORESO's engineers may call national control centres and propose solutions. The final decision of which remedial action to take remains the responsibility of the national control centres.

CORESO also actively participates in the Central Western Europe (CWE) regional market coupling process by performing and publishing, each day, merged files representing two-day-ahead forecasts for the CWE area (Belgium, France, Germany, Luxembourg and the Netherlands). This process, jointly developed by the power exchanges and the TSOs, allows more efficient usage of available cross-border capacity and is expected to bring further price harmonisation in the region. These aspects are important prerequisites for realisation of a single European electricity market. Since 2010, CWE market coupling has started as coordinated ATC-based (Available Transfer Capacity) market coupling. Flow-based market coupling is expected to start soon in the CWE region.

The ENTSO-E Network code on Capacity Allocation and Congestion Management (CACM) also defines common rules for capacity allocation in the short-term electricity markets (day-ahead and intra-day) and sets a framework to achieve a common market using implicit auctions for these time frames. This code also tackles governance issues and determines the roles of responsibilities of actors involved in this process. The code is being validated by ACER in its final draft form.

Capacity Allocation

The capacity offered to the market is calculated by TSOs. The CACM code states that capacity calculation must be coordinated but does not refer to a single operator. When the capacity is calculated, it is allocated to the different market participants by power exchanges that organise the auctions. The capacity allocation may be centralized, but the creation of a single market coupling operator is not made compulsory by the CACM code.

2.4.2 Control in DC Grids

2.4.2.1 Protection System

HVDC Grid Systems should contribute to the security of supply requirements of the entire transmission system, i.e. the HV AC system and the HVDC Grid System together. For the HVDC Grid System, this could mean selecting a certain topology in terms of monopolar or bipolar DC circuits, defining the protection zones as needed and specifying requirements for the fault isolation and system recovery times.

A possible short circuit fault will propagate through the DC circuit and appear at the individual converter stations as a sudden DC voltage drop. The protection systems of the converter stations will react accordingly interrupting the fault current and isolating the faulty section. Fast communication between the converter stations will be needed to provide selective fault isolation. After the faulty section of the HVDC Grid System is isolated, a fast recovery of the remaining system can take place. Selective protection systems for HVDC Grids are currently under development.

2.4.2.2 *Maintaining the DC voltage*

In consideration of modern HVDC Grid Systems, loads and generators are connected to the DC circuit via AC/DC converters.

Similar to AC systems, an HVDC Grid System needs to maintain equilibrium between power import and export. Any deviation between import and export will result in a change of the DC voltage. Thus, maintaining the DC voltage within a defined bandwidth in a DC circuit corresponds to maintaining the frequency in an AC system.

Energy storage systems could be used to balance a temporary mismatch between power export and import but there are no practical applications for such devices yet. However, to provide the so-called Fault Ride=Through capability required from generating units, HVDC wind park connections may be equipped with so called 'DC braking devices' capable of absorbing power from the DC circuit in the case that the AC system is temporarily unable to absorb the energy generated by the wind park.

The European Study Group 'Technical Guidelines for HVDC Grids' has identified three control concepts for a AC/DC converter station which are referred to as 'Voltage-power Droop together with Dead band', 'Voltage-Current Droop' and 'Voltage-Power Droop [28]. As described by the names of the control concepts, a converter station will contribute to the DC voltage control following defined characteristics. Carrying out a benchmark study, the Study Group found that interoperability between the control concepts within one DC circuit appears possible. A common way of specifying the functional requirements of the control concepts would be needed to achieve the expected power flow as well as stable operation of the HVDC Grid System.

The operating concept of a converter station always affects the connected AC system. If, for example, a certain converter station is dedicated to control the DC voltage to a fixed value (within certain power limits), this station will control its power exchange with the AC system accordingly, meaning that the AC system will have to provide or absorb power as needed to balance the complete DC system. In general, the droop characteristic will determine to what extent the DC voltage will be allowed to vary with the power exchanged.

To take another example, converter stations connected to a wind park will often be set to maintain the frequency of the respective wind park network by varying the power through the converter. Such a station will not be able to control the DC voltage at the same time.

These two examples show that the control concept of a converter station must be coordinated with the operating concept of the AC system.

2.4.2.3 Controlling the power flows

In a manner similar to the conditions in AC systems, the power flow through a HVDC line needs to be controlled to avoid exceeding the power rating of its components. In radial HVDC Grid Systems, where there is just a single line connecting two converter stations, the flow through each line can be controlled by the DC voltages of the individual converter stations.

Systems that have more than one line connecting two converter stations (at least partly) are referred to as ’meshed systems‘. In meshed systems, the flow through parallel paths depends - in addition to the DC voltage at the converter stations - on the line impedances. Such systems may need additional DC Line Power Flow Controllers to achieve a required power flow. DC Line Power Flow Controllers will insert a certain DC voltage in series with the line in order to control the current through it. DC Line Power Flow Controllers are currently under development.

In all cases the power exchange between the HV AC system and the HVDC Grid System can be exactly controlled by the converter stations. This provides an additional degree of freedom for the operators of the combined HV AC and HVDC Grid System which can be used to influence the load flow conditions in the surrounding HV AC systems.

2.4.2.4 Coordination of HVDC Grid Controls

Maintaining the DC voltage as well as controlling the DC Load Flow can be done without communication between the converter stations. However, communication is needed to provide the necessary coordination between the individual converter stations. This coordination includes transmitting the necessary signals to run sequences to a converter station, like start-up or shut-down, or transmitting the corresponding control characteristics and set-points. Information on the status of the individual converter station or their associated AC system needs to be known in the reverse direction. To provide this coordinating function, HVDC Grid System control concepts currently being discussed by the HVDC Grid Study Group include central controllers, called ’HVDC Grid Controllers‘.

The HVDC Grid Controllers would provide the control interface to the Transmission System Operators and exchange information with the individual ’Converter Station Controllers‘ allowing them to adjust the status of the HVDC Grid System or to optimize its operating point, to, for example, achieve least loss operation. However, the optimization of the combined AC-DC network is not limited to the minimization of loss operation of the HVDC Grid. The combined power flow and capacity for AC voltage support by individual VSC-HVDC converter stations merits the interaction between the state estimation and power flow control of the two systems. In a similar way as the AC grid optimises the flows in the whole system, the HVDC state estimation would require a combined system perspective, including the transmission capacity between the individual HVDC stations, the AC voltage support requirement and AC transmission capacities. Here the time constant or speed of control in the HVDC system is significantly faster due to the nature of the high controllability of the HVDC stations. Although there is currently limited experience of how to use the full benefit of an embedded HVDC link, as more embedded HVC comes into operation and the HVDC density increases in the AC grid, the experience of coordinated AC-DC grids will grow.

With a given set of control characteristics and set-points, the HVDC Grid System should be able to continue in operation even were the communication to the HVDC Grid Controllers to be lost.

Yet, depending on the topology of the HVDC grid, HVDC Grid Controllers may not be needed. Studies by part of the FP7 European project TWENTIES show, for instance, that dedicated Power-Voltage droop controls may take advantage of the grid topology to implement specific power flow policies (such as mitigating variable generation) relying only on local measurements [29].

Whether or not an ’HVDC Grid Controller‘ proves necessary, HVDC grids will require coordination between the Transmission System Operators, as today's meshed AC networks demonstrate. The coordination initiatives presented above could thus play an important role in the operation of the Supergrid.

2.5 ICT and SCADA for the Supergrid

Swift and efficient Information and Communication Technologies (ICT) are needed to facilitate the operation of a pan-continental Supergrid. Contemporary supervision and control of the present electric transmission grid is provided by SCADA systems (Supervisory, Control and Data Acquisition). Similar systems are to be implemented for pan-European grids, with a higher level of coordination or enhanced specialised versions to enable market integration, control and protection over several independent regions and, potentially, very large sets of data in real time. Without SCADA systems it would not be possible to maintain a secure and optimal operation of the grid or restore the grid in a fast and secure way after power failures.

2.5.1 Present SCADA systems

Present SCADA systems for the electrical grid have several bespoke features that distinguish them from standard Industrial Control Systems. The electrical grid is vast and spread over huge geographical areas, the European continent for example. A large variety of communication media and specialised protocols of differing ages are used for the data acquisition. Real-time process state is mirrored to a real-time database in a central server to manage the vast variation in speed of communication across the grid. All presentations and calculations in the control centre are done in this real-time database since it would take too long time to acquire the process data from the process itself. Electrical SCADA systems are operated continuously and around the clock, i.e. are always available and staffed. The requirement is to achieve better than 99.98% availability, which is met and exceeded in almost all installations. To accomplish this availability, dual computer configurations are required where a standby computer is always prepared to automatically take over operation within a few seconds. No data can be lost during a failover.

A normal sized SCADA dataset consists of 50,000 real-time measurements. The measurements consist of both status signals, e.g. breaker status, and analogue values, e.g. active and reactive power flows. However, many SCADA systems with more than 200,000 real-time measurements exist already today. These sizes put very high demands on data acquisition systems and throughput capacity.

A central requirement in electrical SCADA is performance. Normally the electrical process is such that only analogue values change at a relatively slow speed. However, during disturbances considerable amounts of data can change in a very short time. The SCADA systems must have an event throughput capacity of up to thousand events per second to able to handle disturbances in a short period of time without losing data.

Display call-up times are critical. When an operator requests a process image, e.g. a single line representation of a big substation, for display on his screen, that display - including the real-time process information - must be presented in less than one second. This means that up to 10,000 attributes must be accessed from the real-time database in fractions of that time. Another requirement is to be able to update a display already on the screen when a single process variable changes. It is not possible to refresh the whole display in this situation so an update of the individual display object is required.

The perhaps most characteristic feature of electric SCADA systems is the large variety of dedicated power applications. The electrical process is relatively easy to model and established mathematical algorithms can be applied to calculate a precise process state and to do simulations. SCADA systems including these types of power applications are normally called Energy Management Systems (EMS).

The first step of these calculations is to create a real-time bus-branch model mirroring the dynamic topology of the grid. This is done by analysing the static topology and using incoming real-time status signals to define the current breaker and isolator position. The dynamic topology must continuously and accurately reflect the current process state, including during disturbances. If the dynamic topology model is combined with real-time measurements of voltages, active and reactive power flows and power line impedances, including HVDC lines, a complete and consistent flow model of the grid can be calculated provided that enough, but not all, measurements are available. This is called State Estimation. Using the State Estimator results, the part of the network that is not measured can still be supervised.

The State Estimator base case, i.e. the current real-time flow situation, can now be used for studies of alternative network states in parallel study databases (Operator’s Load Flows) or automatically run through all possible network faults and arrange them according to severity (Contingency Analysis). This is used to verify that the grid fulfils the N-1 operating criteria. The EMS can make recommendations on how to reach a more secure state of the grid for potential faults above a certain severity level. Using the Optimal Power Flow application, the EMS can calculate the optimal way of running the grid based on different optimisation criteria, for example, minimal active losses.

The Automatic Generation Controls use frequency measurements to automatically send new set-points to the generators in order to keep the frequency of the network constant and to compensate for frequency error introduced in the primary regulation. If cost curves for the different generators are introduced the Economic Dispatch function will use the most economic generators when ordering changes in the generator production.

In addition to these basic power applications, more specialised applications are used for Dynamic Stability Analysis, Available Transfer Capacity Calculations, Short Circuit Calculations, Security Constrained Dispatch, Load Forecasting, Scheduling, and similar activities.

2.5.2 Future ICT and SCADA requirements for the Supergrid

The present SCADA systems for AC networks, combined with the state-of-the-art existing HVDC control and protection systems, will manage the first steps of a Supergrid. SCADA systems suitable for multi-terminal operation of HVDC links covering continents and interconnecting grids are available already. Certain parts of HVDC control systems, such as valve control and protection, operate in the nanosecond regime.

The complexity of the future Supergrid does not necessarily lie in the number of measurements, the vast geographies covered or speed requirements, but in considerations such as

- Interoperability between systems
- Reliability and availability
- Decision support
- Differences in requirements on decision time in a combined AC and DC grid
- Backward/forward compatibility during the decades needed to construct the Supergrid
- Cyber-security measures
- Integration with market system

Although challenging, none of these items are foreseen as ’deal-breakers’. Given the present capacity, along with the rate of developments in ICT, it is not anticipated that ICT requirements will prove limiting but, instead, should enable the development of the Supergrid.

2.6 Overhead Line Technologies

Overhead lines have been widely used for both 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 fewer transmission voltage constrictions compared to cables and thus can transmit considerably more power per system.

In many countries suitable rights-of-way for long distance DC overhead line transmission remain a big hurdle that cannot be easily overcome. One way to avoid such a hurdle is to convert already existing AC overhead lines to DC ones. Such a conversion requires taking account of various electrical and mechanical aspects, such as:

- 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 is the case with AC

- Conductor Ratings
  DC lines do not experience current displacement due to the skin effect, which may allow higher current ratings in the case of DC

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

In the case of multiple three phase AC systems at one tower, one or more AC system may be replaced with 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 of both systems due to induction phenomena in steady state and during faults in the AC or DC systems

- Mutual coupling 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 cases where the conversion takes place in stages.

For AC and DC overhead lines, considerations have to be made for ground clearance 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 and taking into consideration their interaction with the environment, transmission operators can develop and apply line ratings in real time.

2.7 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 will only be possible using HVDC cables, because of the long distances.

For onshore transmission, limited rights of way, the preservation of the natural environment, short permitting times and the fact that cable routes have virtually no 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, such as densely populated areas.

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

2.7.1 Cables for HVAC Applications

HVAC cables can be divided into a few large families, based on design and insulation material. With respect to design, three-core and single-core cables are to be distinguished. In terms of the insulation material, it is worth noting the difference between Paper Insulated Self-Contained Fluid-Filled (SCFF) cables and Cross-Linked Polyethylene (XLPE) cables. These are the two most commonly used technologies today.

Table 2.2: HVAC cables: Maximum Data summarizes typical maximum values of SCFF and XLPE cables based on existing installations and projects in execution.

	SCFF	XLPE
Maximum nominal operating voltage [30]	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

Table 2.2: HVAC cables: Maximum Data

(*) depending on voltage and power rating

2.7.1.1 *Paper insulated self-contained fluid filled cable (SCFF)*

To keep the dielectric losses of paper-filled cables low and the permeability for the fluid high the paper used is usually low density. The fluid is of a low viscosity and pressurised during operation. For single-phase cables hollow conductors are used which allows 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 of up to 500 kV [30].

The core construction is similar to that described for underground cables, where electrical and thermal properties of the insulation could be enhanced by 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 the event of case cable damage.

2.7.1.2 Cross-Linked Polyethylene (XLPE)

Cross-linked polyethylene is formed by introducing cross-links between polyethylene chains in low density polyethylene (LDPE), resulting in the formation of a network. One significant characteristic of cross-linking 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 cross-linking 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 used currently for HV application up to 500 kV for land cable AC applications and 420 kV for submarine AC applications.

2.7.1.3 Single and Three Core Cables

A typical application for three-core HVAC cables is as 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 are available at 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 the case of the high transmission capacity required, single-core cables offer a preferable solution because of their better heat dissipation. The better thermal behaviour, 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.

2.7.2 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. DC-XLPE is most commonly used nowadays as insulation material for extruded HVDC cables. There are different types of cables with laminated insulation, of which the Mass-Impregnated Cables (MI) are most commonly used today.

Table 2.3 summarises typical maximum values of MI and XLPE cables based on existing installations and projects in execution.

	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

Table 2.3: HVDC cables: Maximum Data

2.7.2.1 HVDC cables with laminated insulation

Three types of cables have been used for HVDC transmission. These are the Mass Impregnated Paper 'solid type' Cable (MI), the Gas Filled pre-impregnated Paper Insulated Cable (MI-PPL) 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 as early as 1906 (Moutiers-Lyon) [31]. An MI cable at ±100 kV was used first in 1954 for a Sweden – Gotland connection. A number of later HVDC projects used the same type of cable, e.g. the Sardinia-Corsica-

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 a long time, thus limiting the production capacity for this kind of cable.

The insulation is then coated with an extruded lead alloy sheath, protected with a polyethylene jacket and reinforced with metallic tapes. An armour layer may consist of one or two layers of round or flat galvanised steel.

This design is surely the most long-serving for DC applications; its developments during previous years have mainly been related to the optimization of materials (paper and insulating compounds) allowing an 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 at up to one mile below water).

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 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 the electrical and thermal performances of the Mass Impregnated Cables a new insulation technology consisting of Paper Polypropylene Laminate (PPL) has recently 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 at approximately 600 kV is reached 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 Cables

The Gas-Filled Cable was used in 1965 for the Cook Strait interconnection. Notwithstanding its intrinsic suitability for medium-span submarine links, this type of cable is no longer used, due to the fact that it requires gas pressurisation 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 with the intention of conversion 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 portions of the submarine connection between Italy and Greece.

2.7.2.2 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 offered by polymeric insulation in comparison to traditional laminated ones. These advantages include the relative simplicity of the technology required to produce extruded cables compared to that needed to produce mass impregnated or oil filled cables; as a result, the production costs are lower as well. In addition, extruded insulation can operate at higher temperatures than mass impregnated cables, which 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 to reduce the accumulation of space charge. Uncontrolled space charges could otherwise increase the electric field within the cable to a level where the insulation would break down. In recent years, considerable progress for semi-conductive and insulation polymeric materials has been achieved and insulation technology has improved significantly alongside it. 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.

Extensive development from the second half of the 1990s onwards allowed for increased application of new technologies and a rapid transition towards industrial use with confidence. Currently there are ongoing HVDC projects with extruded-insulation submarine cables that have reached voltages of ±320 kV, but higher voltage cables are being developed and are their implementation is anticipated in the future.

Additionally, the broad application of VSC technology (which allows a reversal in the power flow without changing the polarity of the DC voltage) is encouraging the use of solid synthetic insulated cables. Significant advantages and disadvantages include:

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

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

2.7.2.3 HVDC transition joints

It is also possible to use a transition joint to connect an extruded HVDC cable with a laminated type cable. This can be useful in the case of repairs or replacements of old laminated cables as well as when it is desirable to have laminated cables for the subsea part of an installation and extruded

HVDC cables for the land part. A transition joint makes it possible to utilise both and to bury the installation.

2.7.3 Special types of HV cables

2.7.3.1 Integrated return conductor cable

To comply with regulations on magnetic fields and to avoid electrolytic corrosion due to return currents in earth/sea 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 comprises a concentric, integrated return conductor, which forms 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.

2.7.3.2 Superconducting cable

Superconducting cables offer very high transmission capacity in compact conductors with low losses. As a result, superconducting cables are very well suited to 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 consists 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 included:

- ✓ 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

2.8 Gas Insulated Switchgear and Gas Insulated Lines

Both GIS and GIL technologies can find their corresponding fields of use in HVDC applications in addition to their well-established AC-system counterparts. Just as in AC power systems, the DC-GIS technology spans a number of switchgear components (e.g. bus-ducts, disconnect and earthing switches, current and voltage measurement sensors etc.) that can be applied in various HVDC applications. A DC-GIS installation can be built with a much higher degree of compactness and significantly lower sensitivity to ambient factors than with air-insulated switchgear (AIS). Possible applications are in the field of cable as well as overhead line systems.

The most obvious cost-saving potential can be found on off-shore converter platforms where the required air-clearance for AIS leads to much larger and heavier off-shore structures. By using DC-GIS, the volumetric space of the switchgear installation can be drastically reduced e.g. by 70%-90%. Furthermore, the obtained space-savings can either reduce the costs or accommodate new functionality such as off-shore hubs i.e. marshalling points for multiple cable connections on offshore platforms. By such multiple cable connections, an offshore wind park with a converter platform can be connected to different grids in different countries combining both the wind-park grid connection with cross-border trading. This increases the potential utilisation of the connected cables, increases the security of supply and can provide redundancy of the transfer capacity of the wind park in case of capacity reduction at one of the receiving ends.

On-shore HVDC installations may also be reduced in land-size and building height by applying DC-GIS although these savings must be considered in the light of more costly switchgear components. Just as in AC-systems, the technology decision has to be done on a case-by-case basis taking the total life-cycle costs into account. The first major DC-GIS installation took place in 1999 at the Kii-channel HVDC link between Honshu and Shikoku in Japan. The installed DC-GIS equipment has a rated voltage of 500kV DC and has been in continuous operation at 250kV DC since June 2000.

2.8.1 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 to connect the Schluchtsee power plant, Germany, to the transmission grid [32]. This so called first generation GIL used 100% sulphur hexafluoride (SF_6) for the main insulation. Aiming at cost optimisation, 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 improvements in the system’s reliability. Today the GIL is used for voltages up to 550 kV AC [33].

The GIL consists of two concentric aluminium 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 aluminium 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 a tunnel, can be directly buried or be laid above ground using special constructions (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 [34]
- ✓ Environmentally friendly: No visual impact, no audible noise, no risk of fire, very low external electromagnetic fields [35]
- ✓ 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; SF_6 substitute would be desirable

Current research and development of DC gas-insulated system insulators has focused on fully understanding the factors that contribute the surface charge accumulation and decay. Experiments are being undertaken on various types of conditions and insulator designs regarding geometry, the usage of materials etc. Some of basic ideas revolve around applying coating to insulators with materials that have lower surface resistivity than the rest of the insulator, for example in a range of 10^{11} to 10^{12} Ω in comparison to the usual range of resistivity of insulators of closer to 10^{16} to 10^{17} Ω. Progress is also being made in making the geometry of the spacer more suitable for DC GIL conditions. The basic mechanisms are explained - and possible solutions are elaborated - in CIGRE technical brochure 506 “Gas Insulated System for HVDC: DC Stress at DC and AC Systems” [36]. From that perspective, DC GIL technology seems to be feasible and should be available in the next few years, resulting in the efficient transmission of large power over long distances.

Earlier long-term test installations have also confirmed that AC-GIS insulators can be adapted to the stress conditions witnessed in DC application [37]. A newly-defined working group at CIGRE (JWG D1/B3.57) aims to outline both the fundamental phenomena in electrical gas-insulated systems under DC stress as well as developing and proposing testing strategies covering type tests, routine tests and on-site tests. Based on the well-established AC GIS technology with voltage ratings up to 1100 kV, it is anticipated that DC-GIS components up to 500 kV DC will be developed by manufacturers and offered to the market in the next years. Once dimensioning guidelines have been established, development of higher voltage ratings should then follow.

2.9 Energy Storage Technologies and Applications

2.9.1 Introduction

In transmission networks, large-scale energy storage has provided the capacity to level out generation and load mismatches in power systems, to maintain grid frequency and ensure network stability – providing reserve capacity. However, energy storage currently plays a major role in the management of renewable energy sources; load capacity firming, transforming intermittent energy sources into predictable sources and peak shifting and solving congestion issues. Historically the rate of electric generation from stored capacity, i.e. pumped hydro, has been around 2-3% of the total global electric supply. In recent years, however, that rate has slowly decreased as new generation capacity has been added faster than new storage capacity has come into operation. Finding and gaining consent for new sites for pumped hydro is very challenging, while new technologies - such as compressed air, battery and flywheel energy storage systems - have so far not met the competitive price range for large scale deployment.

Energy storage is expected to play an increasingly significant 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 variable 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.
- Power systems with a large renewable energy penetration will, in addition to large scale interconnection, need to have access to stored bulk energy for longer time periods.
- New types of generators connected to the grid by power electronic converters replace conventional rotating generators, e.g. in wind turbines, resulting in a reduction of inherent inertia of the power system. The inertia of rotating machines plays an important role in today's AC systems.

Voltage source converters equipped with energy storage can be controlled to provide synthetic inertia, which means that they can provide temporary stabilization to the system frequency.

The purpose of this report is to describe how energy storage can be used in the future power system. Comprehensive overviews of electric energy storages technologies and applications, however, are readily available in work that is regularly updated, for example reports from Sandia National Laboratories or IEC [38] [39] [40]. It is not intended to replicate this work here.

2.9.2 Energy storage classification

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 a percentage (2% - 10%) of their actual power output for balancing. PR must be fully supplied within 30 seconds and the secondary load frequency control should have restored the PR within 15 minutes

- Secondary Reserve (SR). SR has the same dynamics as PR but is activated by a level. This level will start to change no later than 30 seconds after the AC frequency variation. The dynamic of this signal is slow; it is made to level out the frequency deviation in less than 15 minutes

- Minutes Reserve (MR). MR has to start manually no later than 15 minutes after the frequency deviation. MR is activated to restore SR. MR is supplied by thermal plants, Combined Cycle Power Plants (CCPP) and (pumped) hydro power plants

- Hours Reserve (HR). Reserves that starts after more than 15 min

In terms of power rating and energy storage capacity, three sizes may be distinguished, namely small-scale to middle-scale energy storage (some MW for a few seconds up to minutes) and large scale energy storage (GW for hours).

Small-scale energy storage 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 can even be integrated directly into the converters. If the converter couples a rotating machine to the AC system, as in case of a Wind Turbine Generator (WTG), some of this inertia can be provided by the wind turbine. To serve the purpose of emulating inertia, the stored energy has to be accessible within a few tens of milliseconds.

Middle-scale energy storage can be used as a primary and secondary control reserve to maintain system frequency in case of contingency conditions, such as the sudden loss of generation. This is also referred to as spinning reserve. When replacing conventional power plants with renewable energy, the spinning reserve could be provided by energy storage devices that are added to the new power plant. Additionally, energy storage devices can be used to replace expensive and less efficient forms of spinning reserve – thermal power plants and CCPP for example. A further advantage can be gained by placing the energy storage devices locally, close to the load centre, thus reducing losses. Flywheels or Battery storage devices can be considered for that purpose [41]. Pumped hydro plants are now used for providing primary control reserves for bigger networks [42].

Large-scale energy storage can be used to balance renewable energy sources that fluctuate according to the weather conditions or time-of-day. Peak generation is normally not co-related to peak demand. This requires storing energy under high generation and low load conditions to be provided when it is needed at a later time.

2.9.3 Why and how is energy storage used in the transmission grid?

Electric energy storage is a way to handle the fundamental limitation of electricity. That limitation is that electricity is consumed at the same instant that it is generated in the electric transmission and distribution system. The frequency, e.g. 50 or 60 Hz, is used to control the prompt output from generators in alternating current (AC) grids. In transmission by high voltage direct current (HVDC) a similar control signal is the voltage or current. In contrast, a grid such as the internet does not balance input and output instantaneously. Instead information flow can be cached - or stored - for short periods to find a fast and efficient way to connect sender and receiver. It would naturally be beneficial if electricity could be stored, at a competitive cost, in the short time period of seconds and minutes to optimise the transmission path of electricity from generation to load and for scheduling of generation and demand. In the longer time period of hour and days it would be beneficial to store energy generated at low cost when demand is low and dispatch it when demand is high.

Furthermore the introduction of large scale variable renewable energy such as wind and solar changes the parameters of supply/demand balance. On the one hand, all renewable electricity generated would ideally be used and not spilled at low demands. On the other hand, there will be time periods when there is a lack of renewable energy during low wind or dark periods. The solution to having variable sources (large scale renewable generation) connected to variable loads will require a combination of interconnection (Supergrid), Demand Side Management (Smart Grid) and Storage.

Electric energy storage is already widely used in the transmission system. Historically about 2.5% of the generated electricity world-wide is from stored energy; predominantly through the use of pumped hydro energy storage (PHES). As previously noted, the percentage has decreased in recent years as the rate of new generation resources exceeds the rate of new pumped hydro installed. The most obvious sites are already in use and the process to approve and build new ones can take decades – where it is possible at all - at least in Europe.

A pumped hydro storage is similar to conventional hydro power with the additional availability to pump up water to the dam. The dam may be fed by water upstream in addition to the pumped capacity or it may be a stand-alone dam. Both generators and pumps work at high levels of efficiency; approximately 80% of the energy input is regenerated. Another benefit of PHES is that large amount of energy, i.e. water at elevated level, can be stored at relatively low cost. So far no other energy storage technology has been able to match the cost of PHES. Therefore ca. 99% of all energy storage installed today is PHES.

Battery energy storage systems (BESS) are deployed commercially in Japan where the electricity price difference between day and night justifies the additional costs of the energy. These are sodium sulphur battery systems (NaS) optimised for charging during night, e.g. six to eight hours. There are similar grid-connected small scale installations in North America and demonstration units in Europe deploying new battery technologies such as Lithium Ion (Li-Ion). One of the largest BESS installations based on Nickel Cadmium batteries (45 MW during 7 minutes) is in Alaska where it is used to manage transmission power outages which would have life-threatening impacts at cold conditions.

There are also other technologies deployed such as compressed air energy storage (CAES) and flywheels. So far only two CAES units have been built. That is the 290 MW Huntorf plant in Germany (1978) using a salt dome as gas storage and the 110 MW McIntosh plant in Alabama (1991). Similar to hydro power, a CAES requires a suitable storage facility, which is partly why development has been restricted. In addition the CAES design needs to be developed further to make it cost effective. Several projects are currently in the planning stages, for example, in both the United States of America and Germany, which will serve to develop and demonstrate new CAES technology. Several flywheel technologies exist and are used for small-scale energy storage and, in rare cases, for large scale - such as at CERN.

2.9.4 What is new?

New technologies for electric energy storage are being developed but progress during the last decade has been slow. No technology has, so far, been able to compete on a cost per MWh with pumped hydro energy storage. However, the supply of primary and secondary reserves in the form of active (MW) and reactive power (Mvar) allows for other costs of the primary technology to be based on the power rather than the energy supplied. This is particularly the case in deregulated markets such as North America, where the utilities are paid back in exchange for the service.

The search for low cost, long-life batteries is on-going. Much of the work from battery suppliers is directed towards transport applications, e.g. for hybrid and electric vehicles. If the production volume takes off, it would be possible to produce larger volumes of low cost batteries. Then these batteries may also be attractive to use in grid connected applications.

The recent introduction of large amounts of solar power through photovoltaic (PV) generation in the southern part of Germany has had a negative impact on the pumped storage profitability in, for instance, Switzerland. Peak costs of day-time electricity have decreased as PV-generated electricity has increased, naturally producing most of the electricity at noon. The overall need for storage has probably not decreased, but the business model may need to be revised when the net difference between a high and a low price of electricity is more difficult to predict.

2.9.5 The Supergrid as an enabler for energy storage

The Friends of the Supergrid has defined the Supergrid as "*a pan-European transmission network facilitating the integration of large-scale renewable energy and the balancing and transportation of electricity, with the aim of improving the European market*". However, the Supergrid is only part of the solution. In the future power system large scale variable resources with large scale interconnection will be complimented by large scale hydro and pumped storage, Smart Grid solutions and local storage systems.

The Supergrid in itself both fulfils and enhances some of the functions of energy storage. The total need of energy storage would decrease if remote generation and load can be balanced. As markets are interconnected with low loss transmission the usage of available electric energy can be optimized over a larger market area. Moreover long distance transmission enables connecting different time zones and load patterns with each other. Thereby large-scale renewable generation can be directed to areas with demand when there is excess production locally, instead of being stored locally.

2.10 Technologies under Development

2.10.1 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. They do not have fault current interrupting capability and have relatively slow operating times, typically 2 – 3 cycles.

Fast 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, which occurs in AC applications. This has been demonstrated with full electronic breakers which operate very fast but have relatively high on-state losses. Recently, a hybrid DC breaker concept has been presented with a mechanical bypass path to reduce the losses to near zero (60 kW at 320 kV DC) while maintaining a clearance time within milliseconds [27]. Several manufacturers are now testing prototype DC circuit breakers under the operational conditions that will be experienced in a DC grid. Independent witnessing of these tests provides confidence in the capabilities of the devices to achieve the necessary fast current interruption times required for DC grid applications. For fully mechanical breaker concepts, losses most likely will be even lower, but it still needs to be shown that the short clearing times needed can be achieved.

Overall, recent years have seen significant progress towards the development of commercially available HVDC breakers. For instance, as part of the TWENTIES project[9], the technical feasibility of an innovative DC breaker was proven through successful medium-voltage power tests witnessed by an independent observer: including current conduction in closed state, fast current interruption, and voltage withstand in open state. The assembly of the high-voltage DC breaker demonstrator and new power tests have been carried out as of the end of 2013. The current that was interrupted during the tests had reached over 5,200 amps, with switching voltage peaking at more than 160 kilovolts. The interruption and total extinction of current across the grid were achieved in less than 5.5 milliseconds, thereby succeeding in the most challenging part of the circuit-breaker’s mission.

[9] http://www.ewea.org/fileadmin/files/library/publications/reports/Twenties_report_short.pdf

2.10.2 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:

- DC – AC – DC converters

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

- 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 minimising the size of the device

Whether either of these technologies is used, or others not yet developed, 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

2.11 Possible Future Technologies

2.11.1 Electric Pipelines

Electric Pipelines also referred to as 'Elpipes' have been proposed for high capacity electric power transmission by the US entrepreneur Roger Faulkner [43], [44]. The main idea is based on using underground passively cooled non-superconducting transmission lines.

The proposed lines are modular type consisting of 10 - 15m segment modules linked together with splice modules. The whole system is installed in protective conduit, which can be either ’pipe‘ or modular ’cable trench’.

For the transmission of such power the patent owner proposes high operating current. However, in order to keep the transmission losses to an acceptable level, the conductor has to have quasi-superconducting properties. To keep the resistance of conductor at a low level and to increase thermal conductivity, the patent author proposes that the conductor comprises one or more aluminium elements where at least one of them contains sodium. The sodium could melt at the upper rated temperature limit. The melting point of sodium is 97°C at atmospheric pressure. However, if the volume remains the same (as it is the case for the HV conductor) the pressure of sodium will increase significantly. In order to compensate the pressure increase (or volume change) a so-called volume compensation device is proposed, which would be located in the middle of the conductor.

A pipe-shaped insulator features primary HV insulation. The patent author proposes that the best method to apply the insulation to the conductor is to have no mechanical attachment between the conductor and the pipe-shaped insulator (cable-like).

The proposed concept raises a number of still unresolved issues, such as:

- No specific insulation material for primary HV DC insulation has been proposed. Suppressing space the accumulation of surface and space charges is a key technical challenge for DC insulation systems.
- Handling the different thermal expansion coefficients the materials being used, considering possible formation of voids, generation of partial discharges, etc.
- Low Loss Flexible Joints that ensure insulation integrity are also a challenge

Solving these issues is seen a pre-requisite for the technology of Electric Pipelines becoming an alternative to the technologies used today.

Chapter Three: Scenarios for the Development of Supergrid from a Technical Perspective

3.1 Introduction

The availability of appropriate technology is an important pre-requisite for the development of the Supergrid and the 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, while some others even need research work to understand their basic principles and develop concepts for design and operation of equipment.

This chapter describes a roadmap and various scenarios in the development of the Supergrid from a technical perspective; it places the relevant technologies in their context of demand, solutions and time.

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

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 the 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 One: Applications for Supergrid describes important drivers for strengthening and expanding the power transmission system in Europe.

Chapter Two: Network Technologies for Supergrid outlines the current state of the technologies required for the project. Both, the demand to transmit power as well as the technology available determine system planning and project execution. Taking the project forward will require the synchronicity of these two factors, which will, inevitably, drive progress on the project. The working group has identified three phases for developing the Supergrid from a technical perspective:

- Today – 2015
- 2015 – 2020
- Beyond 2020

The three phases are differentiated by the degree of European and outer European system integration. These are discussed below and in the demands, solutions and product requirements of that transition are set out in Table 3.4: The development of Supergrid in three phases. The development of new products and systems is further described in Section 3.6 The Way to Develop the Supergrid

3.2.1 Phases for Developing the Supergrid

3.2.1.1 Today – 2015: Foundations

The period from today through 2015 is characterised 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 1000 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 [45] and the Climate Foundation 2050 Road Map [10] alongside initiatives such as North Seas Countries Offshore Grid Initiative (NSCOGI) [8]] 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: Development

In the second half of this decade, the utilization of wind power is further developed, building far shore (>100 km) bulk power wind park clusters that 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 will call for stronger system integration at 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: Integration

This phase is characterised 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 storage systems 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 deserts or to Eastern Europe and even Asia.

3.2.2 Challenges and Solutions for developing the Supergrid

Fossil and nuclear power are the dominating sources of electricity today as shown in Section 1.2.1 Greenhouse Gas & Carbon Dioxide Reduction, Figure 1-2. The corresponding fossil and nuclear power plants were built at locations providing the best conditions for fuel supply and operation. The existing transmission system was built to accommodate the power flows supplying the loads from these power plants.

The increased use of renewable energy, as described in Section 1.3 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 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. Section 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 the inherent inertia of the system which plays an important role in today's grid and consequently the reduction of 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. 2.9 Energy Storage Technologies and Applications).

Furthermore, there are also non-technical drivers and challenges for a Supergrid such as

- Reducing the time and effort required for the application processes for right of way
- Further integration of the European electricity market by direct connections between key markets, generation and load centres

3.2.2.1 Connecting Renewable Energy Sources and Increased Transmission System Capacity

Europe is currently witnessing the emergence of a new era of electrical generation. The first large scale offshore wind parks in the power range up to about 500 MW have been connected in Denmark and the UK with transmission distances that allow connection by HVAC cables. Wind parks of up to 900 MW with transmission distances to shore of more than 100 km are now the focus of attention. 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 in Point-to-Point HVDC systems 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 off-shore wind park projects include considerable transmission distances on-shore in addition to those off-shore. 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 it requires less time to complete a joint (approximately one day instead of several), it delivers significant advantages for onshore installation cost and reliability.

The utilisation 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 1.3 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, with a power rating of 2 x 1,000 MW is one example of VSC transmission with XLPE land cables in action.

3.2.2.2 Compensating Reactive Power

Long distance power transmission, which becomes necessary due to the 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 Systems

(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 dynamic reactive power requirements at their point of connection.

State-of-the-art HVDC transmission based on VSC technology 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, including the controls of generators and large loads, can be precisely studied using appropriate computer modelling. 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 around the world [46], [47], [48].

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 storage, such as pumped hydro power plants. In order to achieve this, various high power links should be integrated into one Supergrid (ref. Section 1.3 Scenarios).

Overleaf: Table 3.4 sets out the state of existing technologies, as well as those currently being developed, in meeting the challenges of a sustainable and secure energy future for Europe.

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 • Increase power flow in existing corridors by use of overlay VSC HVDC e.g. German Grid Plan (NEP) • Development of grid code for cross-border HVDC by ENTSOE and approval by ACER	• First HVDC radial (point-to-point) systems connecting offshore wind parks • Increased use of FACTS • Delivery and Construction of embedded point-to-point HVDC transmission e.g. SydVästlänken (South West Link), Western Link etc. • 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 at different onshore and offshore projects (500 MW per cable) • DC cables with extruded insulation >320 kV developed • 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 CIGRE, CENELEC started
2015 – 2020	• Integration of far offshore bulk power generation (typical 1,000-2,000 MW)	• High power long distance multi-terminal with few stations (3 to 5) up to 3 GW	• DC cables with extruded insulation >320 kV in operation[a] • MI-PPL 600kV cable in operation[a]

Table 3.4: The development of Supergrid in three phases. The development of new products and systems is further described in Section 3.6 The Way to Develop the Supergrid

Time	Demand	Solutions	New Products and Systems
2015 – 2020 cont'd	• European power system integration to balance generation and load in face of increased content of renewable generation • Replacement of nuclear power plants in Germany	• Connection of multi-terminal and point-to-point systems by Supernodes • Increased use of FACTS • Small and Middle-scale Energy Storage systems adopted	• MI >500kV in operation[a] • Development of new extruded insulation compounds for HVDC cables • System for fast selective fault detection in HVDC networks • VSC FB and HVDC circuit breakers (selective fault clearing and system reconfiguration) • DC GIL for 500 kV • Hierarchical control architecture for integrated AC and DC Grid in Europe • Demonstrators for DC/DC Converter
Beyond 2020	• Integration of large scale solar power (e.g. Desertec, Medgrid, etc.)	• European HVDC Grid, no power limit (much greater than 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/DC converter

Table 3.6 (cntd): The development of Supergrid in three phases. The development of new products and systems is further described in 3.6 The Way to Develop the Supergrid

[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 [43] the total cost of connecting 126 GW of offshore wind in an integrated grid design is compared to the cost of connection using the current practice of individual radial connections and a more efficient hub design, which interconnects wind farms offshore first before bringing 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 off-shore wind generating stations are made later while in the Split Design, the interconnectors are routed via the off-shore wind stations, similar to the FOSG Phase 1 proposal [49].

The cost comparison is summarised in the following chart (Figure 3-35) from the Off-shore Grid report's executive summary:

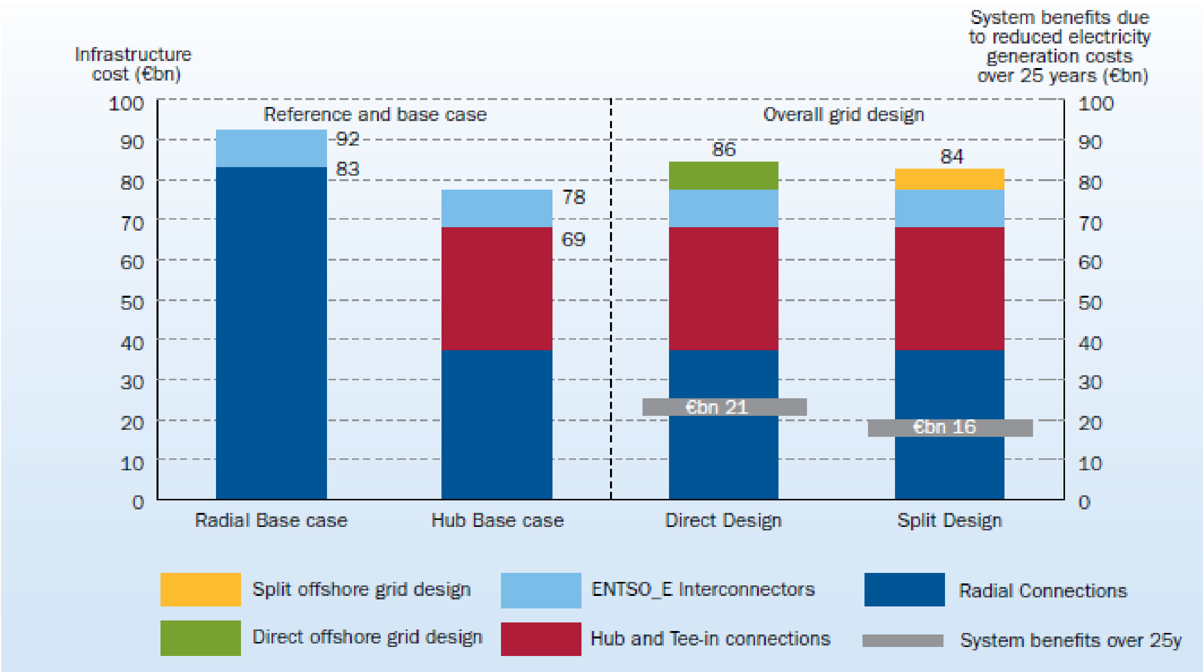


Figure 3-35: Investment Cost Comparison – Offshore Grid report [Error! Reference source not found.]

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) [5] 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 [50], 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 [49] 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 3-36, below, shows how the TUOS (€/MWh) varies with capacity or utilisation factor.

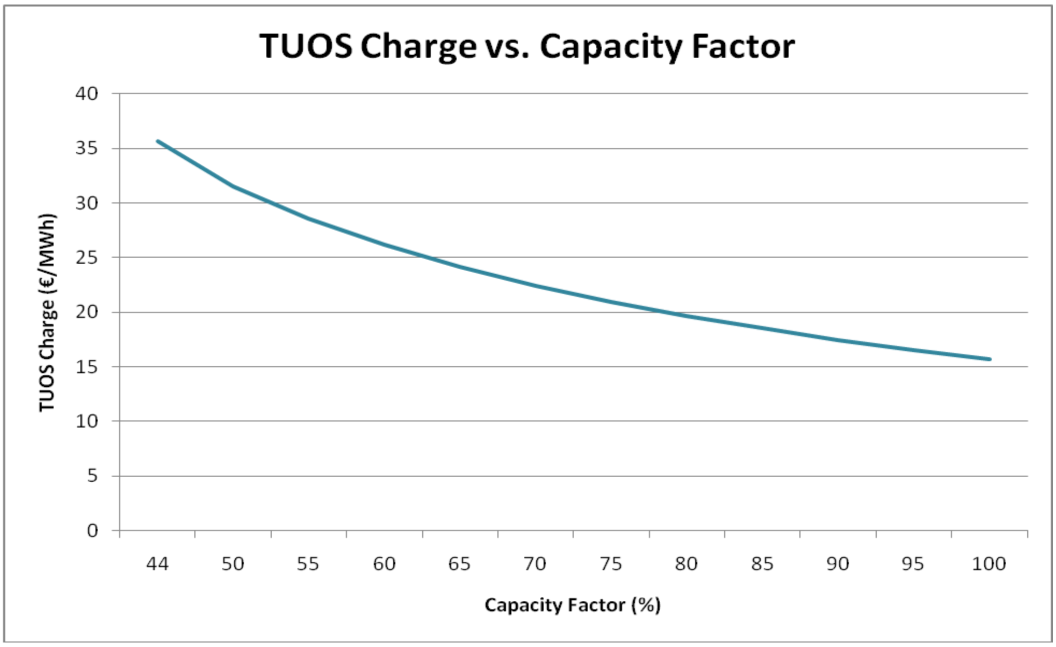


Figure 3-36: FOSG Phase 1 TUOS v Grid Capacity Factor

3.3 AC and DC Transmission for Supergrid

3.3.1 Criteria for Selecting the Transmission Technology

The European transmission network comprises several integrated AC systems including Continental Europe, Nordic, Ireland, Iceland, and the United Kingdom. Some countries such as Estonia and 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.

New AC connections can be built within an integrated AC system, while interconnections between asynchronous systems require HVDC links. However, 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 AC 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, where a mid-span platform would be required to house compensation reactors
- **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 section.

3.3.2 Comparison of AC and DC for Long Distance Transmission

The topic of AC transmission and reactive power has been discussed in Section 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 lines and reactive power equipment will make HVDC the more economical alternative beyond a certain break even distance as shown in Figure 3-37. The methods of SSC are not applicable to all cable systems, especially submarine cables.

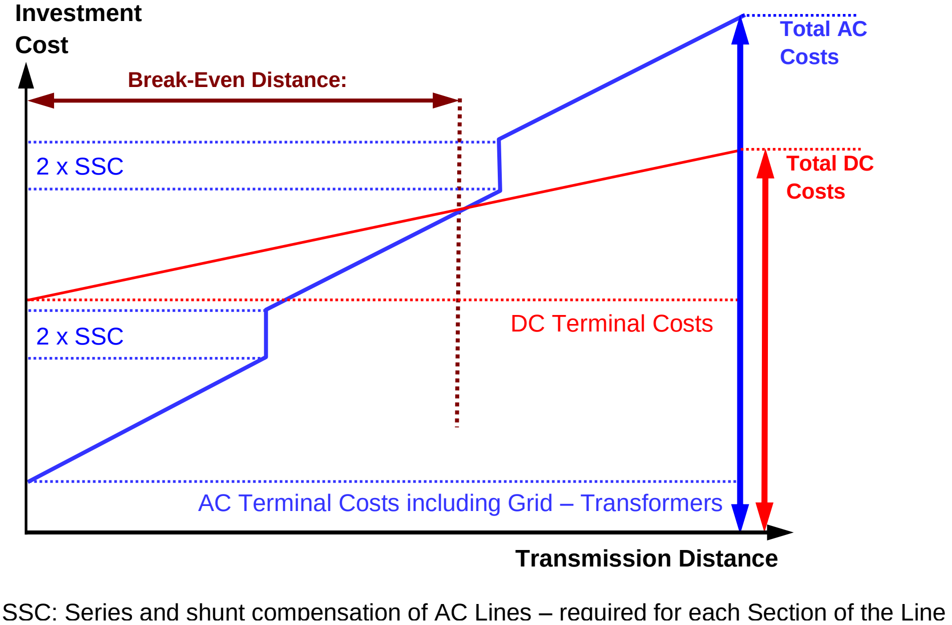


Figure 3-37: Cost Comparison of DC versus AC transmission
A typical break even distance would be about 600 km for a 1000 MW transmission system. Higher power ratings tend to shorten the break even distance

For long overhead transmission distances HVDC has significant advantages compared to AC in terms of transmission capacity and losses as is illustrated in Figure 3-38.

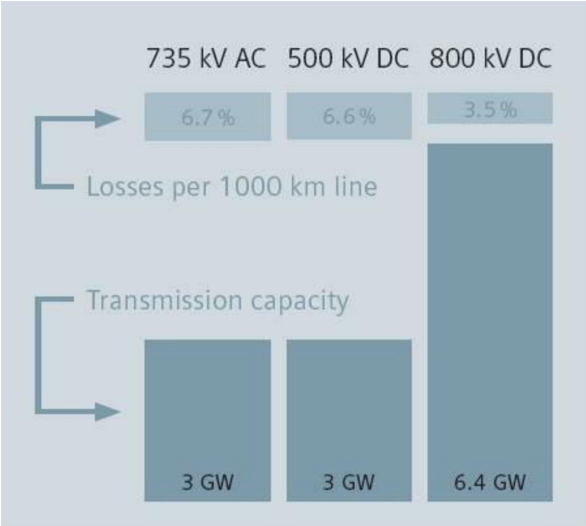


Figure 3-38: At similar voltage level, a DC line can transmit more than double the power at about half the losses compared to an AC line.

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 at ground level, determines the height of the overhead line towers and the width of the transmission corridor (ref. Section 2.6 ’ Overhead Line ‘). HVDC overhead lines, have a considerably reduced footprint with consequent reduced consenting risk. Figure 3-39 shows the visual impact of an AC transmission corridor compared with the equivalent HVDC system.

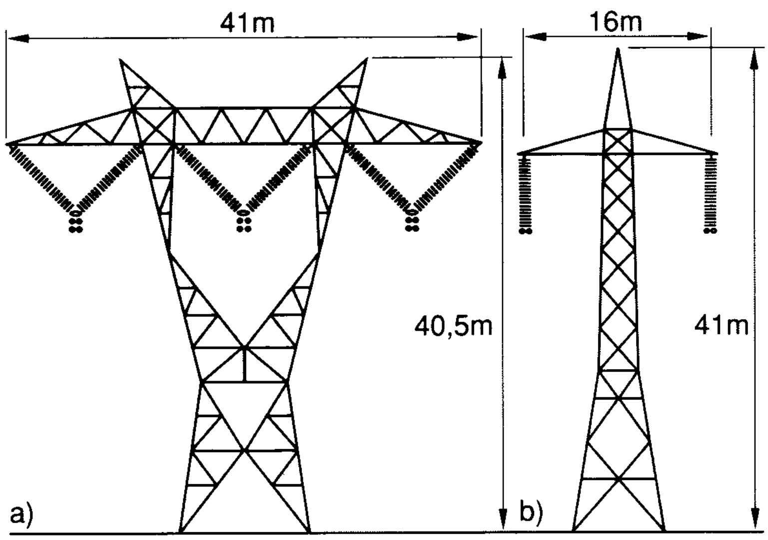


Figure 3-39: Comparison of Towers at the same transmission capacity of 3000 MW for
a) 800 kV AC Line
b) 500 kV DC Line
(To achieve the same level of redundancy as in case of the bipolar DC transmission, two parallel AC lines would be needed doubling the transmission corridor)

If the connection is made using underground cable systems then the visual impact is (following installation) potentially zero. However, for direct burial 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 [46]. 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 3-41 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.

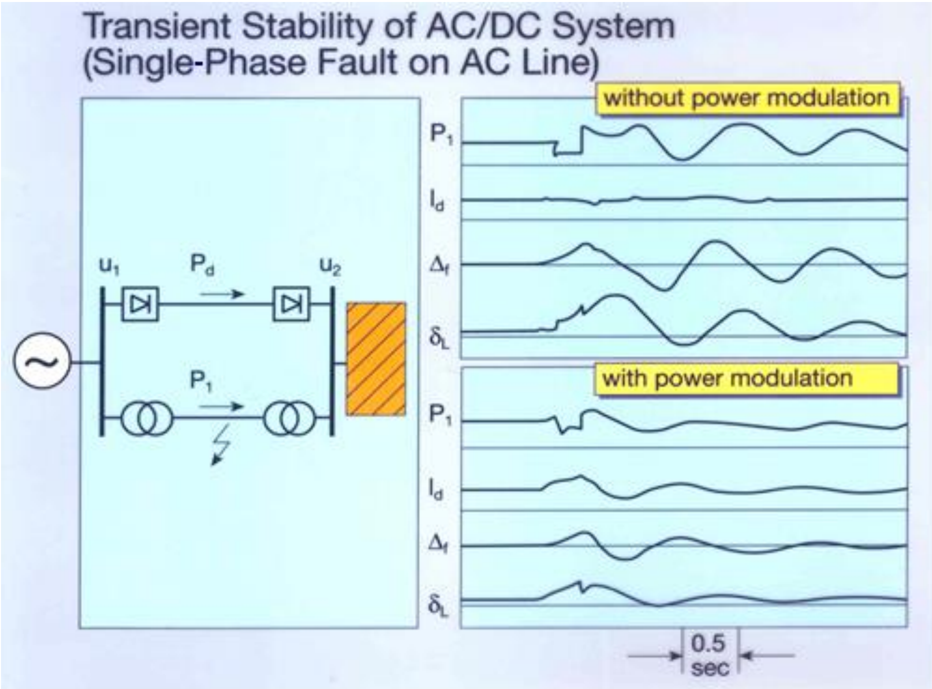


Figure 3-40: Hybrid System comprising an HVDC link in parallel to an AC connection demonstrating the stabilizing function of the HVDC

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 3-40 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 (f) or the transmission angle L. 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 below in Figure 3-41 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.

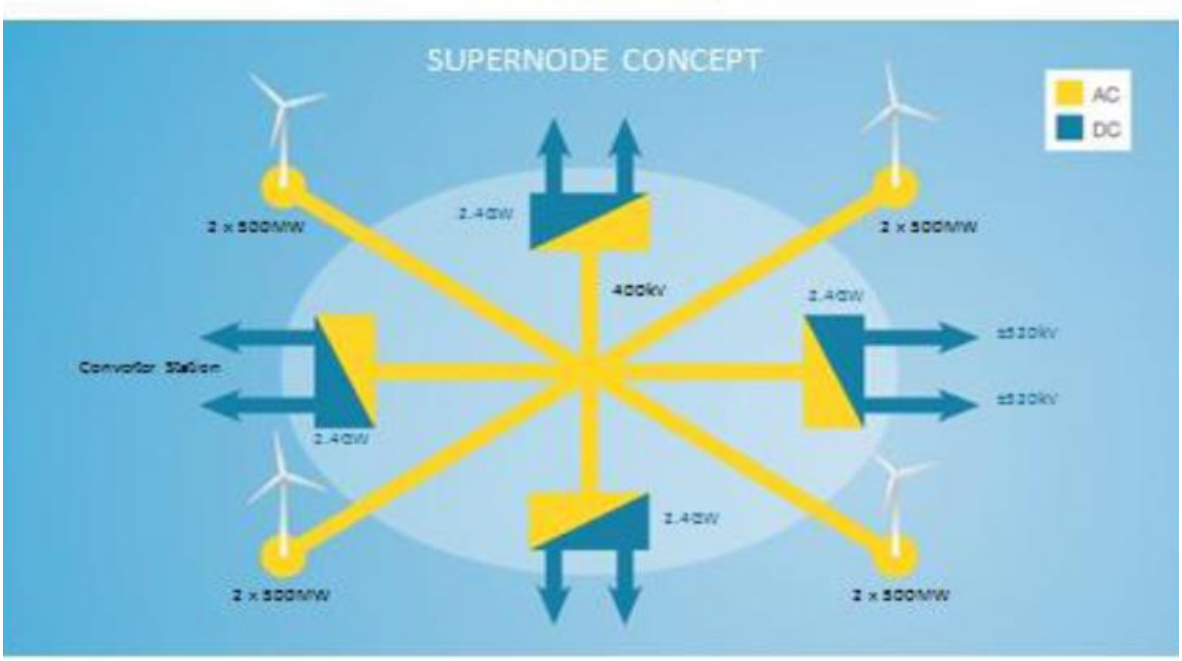


Figure 3-41: Supernodes can provide an effective way to interconnect various HVDC links together with wind parks via an islanded AC system

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. A 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: Impact of Different Power Frequencies on the Transmission System gives an overview of the 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	They become smaller	They become larger
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

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

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

- The maximum length of an uncompensated cable section should be as long as possible, which would allow building long AC cables.
- 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.

Both aspects result in contradictory requirements for an optimised AC system power frequency. Figure 3-42 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 optimised 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 optimised 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, larger and heavier.

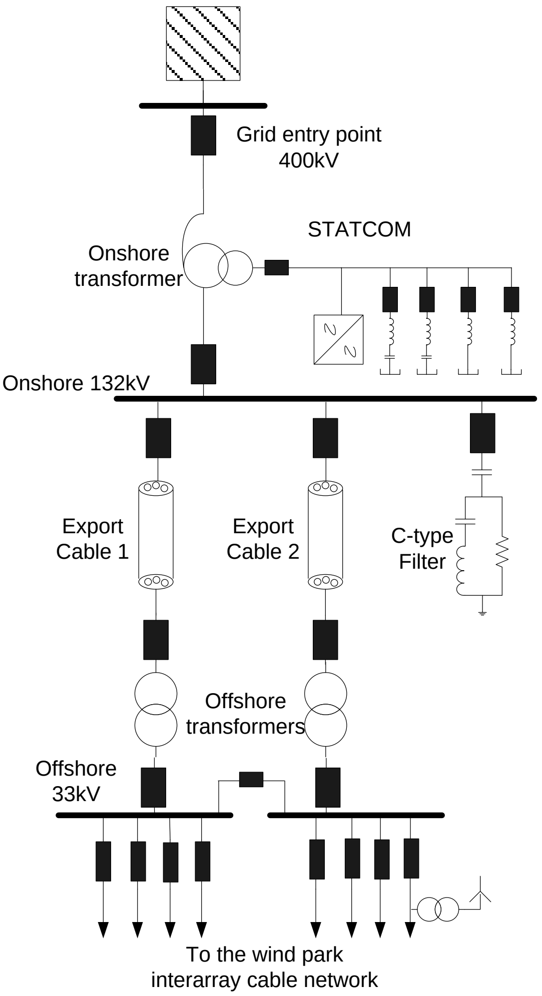


Figure 3-42: Typical network topology connecting a wind park via an AC transmission system to the main grid

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 the 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 Section 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 for railway electrical supplies 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 the course of replacing conventional power generation with 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.

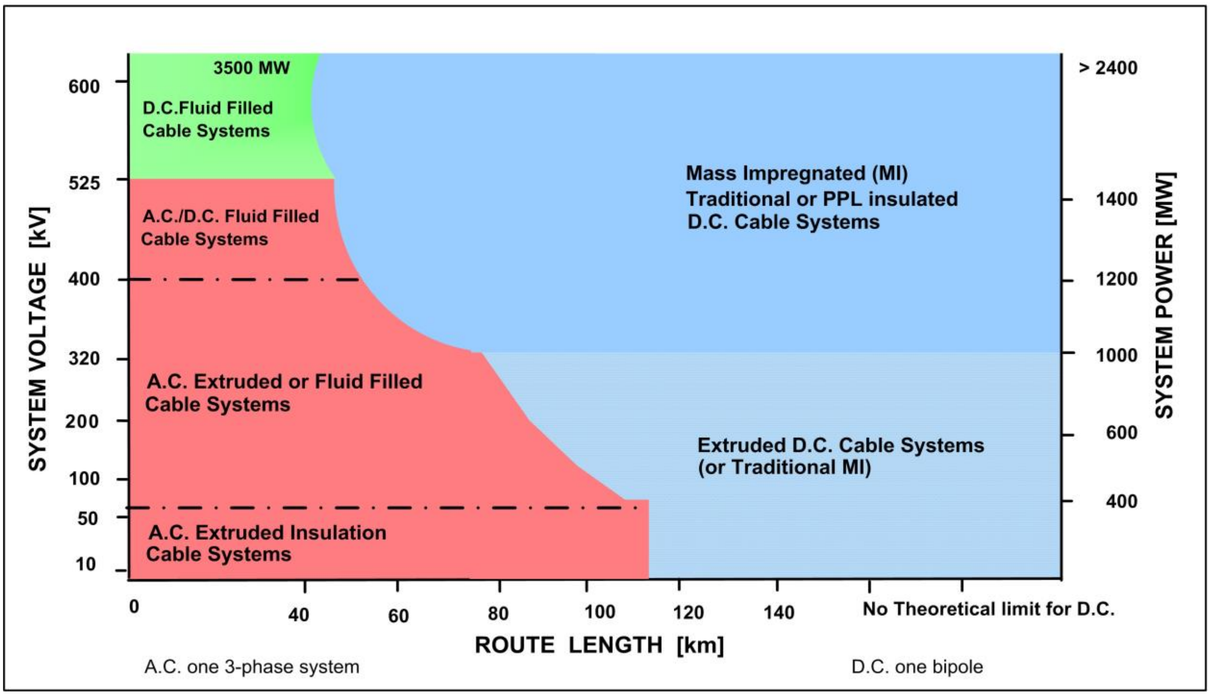


Figure 3-43: Typical applications of AC and DC submarine cable technology indicating the technology chosen vs. transmission voltage level and power transmitted. The development of cable technology is expected to shift the limits towards higher voltages or power respectively in the future

In some cases, however, reactive power compensation measures alone may not be economical or even technically feasible. Examples of this would be long distance submarine cable links (typically 80 km or above as shown in Figure 3-43, 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 for 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 a straightforward option for submarine cables, which is a limiting factor of the maximum length of AC submarine cables. Any mid-point compensation would require an additional platform to accommodate the necessary shunt reactors, plus associated cable sealing ends and switchgear, adding considerable cost to a long distance HVAC solution.

3.4 HVDC Transmission systems

3.4.1 The first 15 years of VSC Transmission Development

The first 3 MW VSC Transmission pilot field installation (conducted by ABB) was in Hellsjön, Sweden in 1997 and was shortly followed by the first commercial VSC transmission scheme in Gotland. This was the start of 15 years of unforeseen market growth and technical progress. By the end of 2011 around 10 GW and 500 km of VSC transmission schemes had been awarded/contracted 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 the 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 schemes, driven by the entrance of other European and now Chinese manufacturers and the expansion of offshore wind generation in Germany. Examples of the latter are the 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 the integration of remote large-scale wind and solar power generation with 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 dependent on the near-term targets and development of market scenarios.

The evolution of the HVDC Grid will be taken in steps. In late 2013 the first multi-terminal VSC transmission scheme was successfully tested in China, using HVDC converter equipment supplied by multiple manufacturers. This scheme connects two terminals (rated at 100 MW and 50 MW) on the island of Nan'ao, with the mainland station (rated at 200 MW), as shown in Figure 3-10. The scheme, which is designed to export wind power from the island, operates at a voltage of ±160 kV. A fourth terminal (rated at 50 MW) is due to be added in 2014. The first main development step foreseen to take place, in parallel to such a regional multi-terminal project, 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.

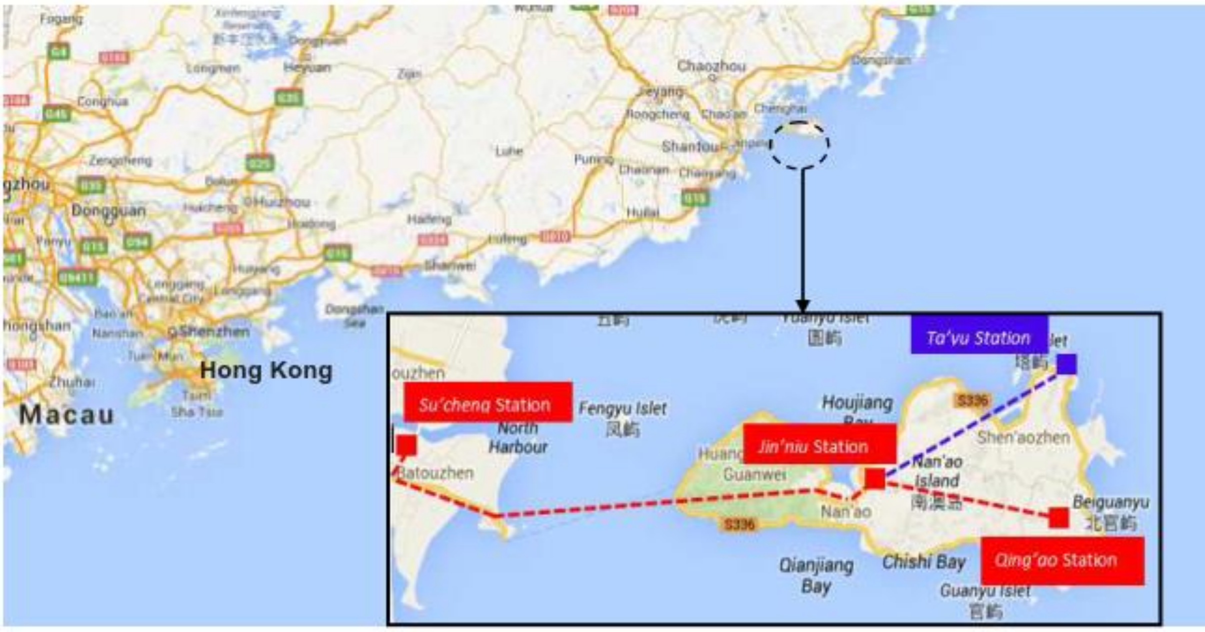


Figure 3-10: Nan'ao Multi-terminal scheme, China

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 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 CIGRE, 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. (Section 1.5 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 gradually be introduced.

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.

3.4.3 From point to point (radial) systems to MTDC grids

Future offshore DCGs are likely to be built stepwise. The TWENTIES project's R&D activities distinguished three stages beyond radial connection of wind farms:

- A first stage with small backbone-shaped DC grids (see figure 3-11 below)

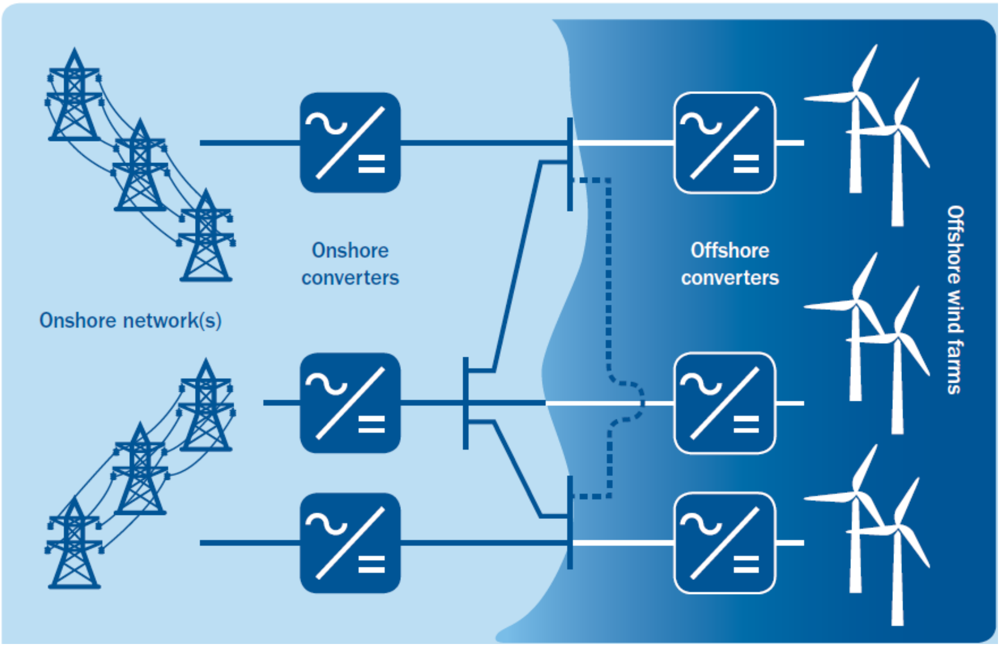


Figure 3-11: Tree-like backbone network, with possible extension to a meshed DC grid (meshed line)

- An intermediate stage with simple meshed networks, such as the five terminal configuration in figure 3-12 for which a low power mock-up with 15 km cables and protection devices has been implemented as part of the project. The mock-up used hardware-in-the-loop facility on actual and simulated equipment to study and validate the viability and robustness of various DCG converter controls, including coordinated control.

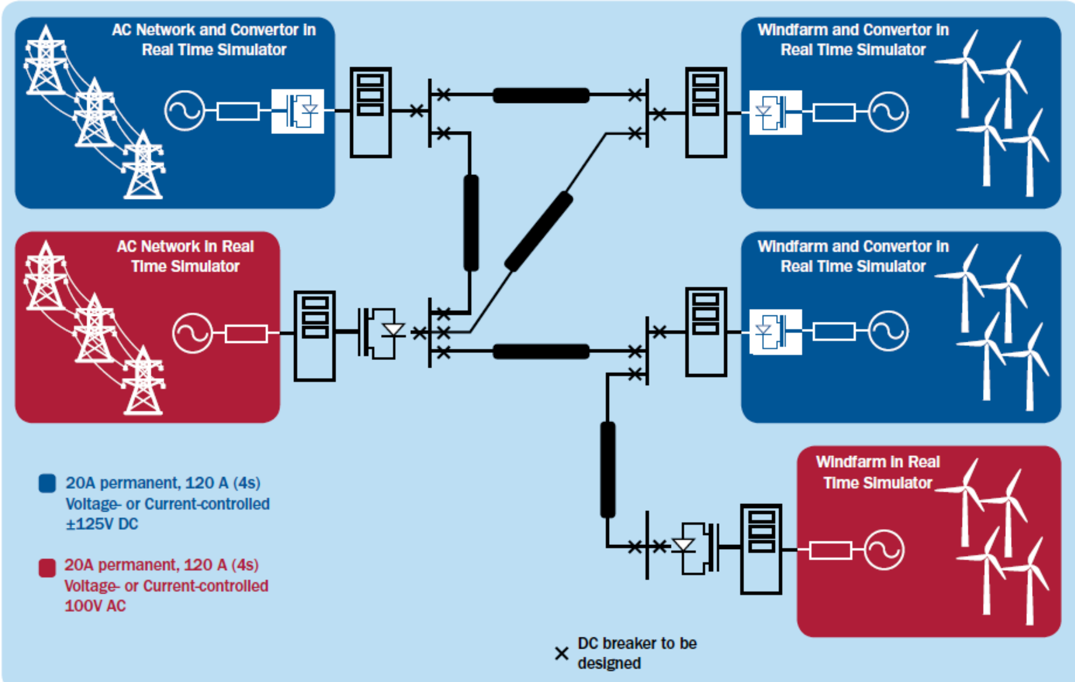


Figure 3-12: Five terminal DC grid mockup assembled for the TWENTIES project

- A final stage with complex meshed DC grids

3.5 Possible limitations for Supergrid as of today

The working group has not identified any insurmountable technological "hurdles" to the development of a European Supergrid.

3.6 The Way to Develop the Supergrid

The decarbonisation of Europe's energy sector requires a strong, integrated Supergrid. The development of such a grid can start today alongside the installation of new renewable power plants. While there are currently, individual links planned and constructed, Supergrid planning in the phase 2015 to 2020 can now 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 sections. 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 issue of the interoperability of different individual projects and the respective technologies of different manufacturers. Interoperability requires standardisation of the basic principles of design and operation of HVDC grids. Testing will be required In order to prove the interoperability of manufacturers' control and protection schemes, either using fully digital simulators or by incorporating hardware controllers into digital simulations of the AC and DC grid systems. A number of manufacturers, consultants and Transmission System Operators are actively working on such testing facilities.

As a starting point for the standardisation 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 standardisation include:

- Standardisation 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, examples of where these are needed would be:

- AC/DC Converters
- Cables
- DC Overhead Lines
- Dynamic Braking Systems ("DC Choppers")
- Charging Resistors
- DC Circuit Breakers
- Communication for network control and protection

The technical aspects of future HVDC grids are subject of various CIGRE working groups, which are due to report in 2014. The new working group 06 of technical committee 8X at CENELEC aims at elaborating the fundamentals of Standardization in Europe. A comprehensive overview is given in Appendix IV to this report.

The list below show most of groups presently active internationally on HVDC Grids issues, with estimated time-frames for the reports of their respective working groups:

CIGRE (International Council on Large Electric Systems)

- B4-52 HVDC Grids Feasibility Study (2009-2012). The final report was published in Electra (2013 April). Technical Brochure No. 533
- B4-56 Guidelines for Preparation of Connection Agreements or Grid Codes for HVDC Grids (2011-2014)
- B4-57 Guide for the Development of Models for HVDC Converters in a HVDC Grid (2011-2014)
- B4-58 Devices for Load flow Control and Methodologies for Direct Voltage Control in a Meshed HVDC Grid (2011-2014)
- B4/B5-59 Control and Protection of HVDC Grids (2011-2014)
- B4-60 Designing HVDC Grids for Optimal Reliability and Availability Performance (2011-2014)
- B4/C1.65 Recommended voltage for HVDC Grids (2013 – 2015)

CENELEC (European Committee for Electrotechnical Standardisation)

- European Study Group on Technical Guidelines for DC Grids (2010-2012)
- New TC8X WG06 started 2013. A continuation of the 2010-2012 study group

IEC (International Electrotechnical Commission)

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

The step by step development of the 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 converter 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.

3.6.1 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 remain in focus, the main technology items to start building a DC Grid are available today. Therefore the development of non-technical key issues outlined below will trigger or hold back the market evolution:

1. International harmonisation of grid codes and transmission investments
2. International harmonisation of regulatory procedures
3. Methods to share cross-border renewable subsidiary schemes
4. Multi-vendor and multi-stakeholder revenue models

It is possible to construct three scenarios for progress on these issues; pessimistic, intermediate and optimistic:

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

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

In the **optimistic** market scenario, 2012-2027 sees the EU changes rules and regulations to promote the formation of the 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.

3.6.2 Conclusions

The working group has not identified any insurmountable technological ’hurdles‘ to the development of a European Supergrid. The VSC Transmission technology has already matured significantly during the last 15 years to the point where multi-terminal schemes are a reality and DC grids can be foreseen. 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, off-shore 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-terminal schemes; the building blocks for a larger overlaid grid. The critical time-line for introduction of new technology lies primarily in the 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.

Since the first version of the report was released in March 2012, the development towards a Supergrid has shown significant progress, as shown in Table 3.6, which shows some of the development that has taken place during 2012 and 2013. Hence the first steps to enable a future Supergrid are being taken.

Table 3.6 Outlines progress to date (√) and identifies areas for future development.

2012 – 2015 Supergrid Preparation Phase	2015 – 2020 Supergrid Phase 1	After 2020 Supergrid Phase 2
√ Increased power rating for VSC (1000 MW at 320 KV DC)	DC cables with extruded insulation >320 kV in operation	Further development of MI and MI-PPL cables
√ Demonstrator for DC side fault clearing (e.g. DC circuit breakers)	MI-PPL 600 kV cable in operation	HVDC cables with new extruded insulation compounds in operation
√ MI-PPL 600 kV (1.1 GW per cable) developed and higher voltages in development	MI >500 kV in operation	Superconducting DC cables
√ Standardisation work for HVDC grids in CIGRE, CENELEC started	Development of new extruded insulation compounds for HVDC cables	DC GIL and DC GIS
√ AC GIL in operation	System for fast selective detection in HVDC networks demonstrated / in construction / in operation	DC/DC converter
√ MI >500 kV cable developed	DC side selective fault clearing and system reconfiguration demonstrated / in construction / in operation	Meshed multi-terminal multivendor VSC-HVDC systems in operation
√ Radial multi-terminal, multi-vendor system in operation (China South Grid)	Hierarchical control architecture for integrated AC and DC grid in Europe demonstrated / in construction / in operation	
DC 320kV cables with extruded insulation in operation at different on-shore and off-shore projects (500 MW per cable)	Demonstrators for DC/DC converter	

Table 3-6: Roadmap of the Supergrid technologies. Progress and updates towards the future Supergrid. Checked items indicate progress since 2012

References

[1] "Conclusion of the GDP", August 15, 2012.

[2] "Grid Development Plan 2012", Facts sheet, August 30, 2012

[3] "Power Grid Development Plan", Slides, Second Draft, 2012-08-15

[4] Perspektivplan 2025, Oct 2012 in Swedish, Svenska Kraftnät (www.svk.se)

[5] Scenario Outlook & Adequacy Forecast 2011-2025; ENTSO-E

[6] Irish Scottish Links on Energy Study (ISLES), Executive Summary April 2012

[7] Offshore Transmission Technology, Jan 2011; ENTSO-E (commissioned by NSCOGI)

[8] The North Seas Countries' Offshore Grid Initiative (http://www.benelux.int/NSCOGI/)

[9] EWEA; TradeWinds Report – Integrating Wind, Developing Europe's power market for the large-scale integration of wind power; Second Edition May 2009

[10] Road Map 2050 - A Practical Guide to a Prosperous, Low-Carbon Europe; European Climate Foundation, Volume 1, April 2010

[11] Toward a Smarter Grid; ABB's Vision for the Power System of the Future

[12] The Global Smart Grid Federation 2012 REPORT

[13] Breuer, W. et.al.; "Highly Efficient Solutions for Smart and Bulk Power Transmission of "Green Energy"", 21th World Energy Congress, Montreal, September 2010

[14] Alstom Smart Grid (http://www.alstom.com/grid/smart-grid/)

[15] "Foresight Study into Future Market Opportunities in Sustainable Energy Technologies"; MATRIX Sustainable Energy Horizon Panel for the Northern Ireland Government

[16] Gesamtwirtschaftliche Potenziale intelligenter Netze in Deutschland ; BITKOM and Fraunhofer-Institut

[17] CIGRE WG B4-52 -DC grid feasibility study

[18] FOSG WG2 2013 Supplementary Report #1, www.friendsofthesupergrid.eu

[19] IEC 62271-104, "High-voltage switchgear and controlgear – Part 104: Alternating current switches for rated voltages of 52 kV and above", 2009-04

[20] IEC 62271-100, "High-voltage switchgear and controlgear – Part 100: Alternating current circuit breakers", Edition 2.0, 2008-04

[21] IEC 60871-1, "Shunt capacitors for a.c. power systems having a rated voltage above 1000 V – Part 1: General", 2005-07

[22] Yong Hua Song, Allan T Johns, "Flexible ac transmission systems (FACTS)", IEE 1999, ISBN 0 85296 771 3

[23] Nari G. Hingorani, Lazlo Gyugyi, "Understanding FACTS", IEEE 2000, ISBN 0780334558

[24] B.A. Renz et.al., "AEP Unified Power Flow Controller Performance", IEEE Transactions on Power Delivery, Vol 14, No 4, October 1999.

[25] Sun, J., et. al., "Operating characteristics of the convertible static compensator on the 345 kV network", Power Systems Conference and Exposition, 2004. IEEE PES, Issue Date: 10-13 Oct. 2004, ISBN 0-7803-8718-X

[26] Ronström L et.al.; "Cross Sound Cable Project, Second Generation VSC Technology for HVDC" CIGRE Paper, Session 2004, Paper Number: B4-102

[27] Häfner J., Jacobson B., "Proactive Hybrid HVDC Breakers - A key innovation for reliable HVDC grids", CIGRE paper 264, Bologna September 2011

[28] "Technical guidelines for first HVDC grids – A European study group based on an initiative of the German commission for electrical, electronic and information technologies", F Schettler, X Guillaud, J Descloux, B Raison, S Nguefeu and J B Curis, CIGRE, Paris, 2012

[29] "Offshore DC Grids: Impact of Topology on Power Flow Control", O. Despouys, ACDC 2012

[30] IEC 60183, "Guide to the selection of high-voltage cables", second edition, 1984

[31] Black, R. M., "The history of electric wires and cables", Peter Peregrinus Ltd, London, UK, pp. 94-95, 1983.

[32] Abilgaard E.; "Installation of SF6 gas insulated high voltage pipe cable"; in German, special edition ENERGIE und TECHNIK; 1972

[33] Peschke E., et.al.; "Kabelanlagen für Hoch- und Höchstspannung" in German; first edition; ISBN: 3-89578-057-X; Publics MCD; 1998

[34] Koch, H.; "GIL Gas-Insulated Transmission Lines"; first edition; ISBN: 978-0-470-66533-6; John Wiley & Sons, Ltd.; 2012

[35] CIGRE Brochure: "Gas Insulated Transmission Lines (GIL)", CIGRE Paper, Paper Number: 218 - by WG 23/21/33-15 – February 2003

[36] CIGRE technical broshure 506 “Gas Insulated System for HVDC: DC Stress at DC and AC Systems”

[37] Mendik M., Lowder S.M., Elliott F.,”Long term performance verification of high voltage DC GIS”, Transmission and Distribution Conference, 1999 IEEE, vol.2, ISBN: 0-7803-5515-6.

[38] “Sandia National Laboratories Energy Storage for the Electricity Grid: Benefits and Market Potential Assessment, Sandia 2010.0815

[39] Sandia National Laboratories Characterization and Assessment of Novel Bulk Storage Technologies, Sandia report 2012-3700

[40] IEC Electric Energy Storage White Paper, December 2011

[41] Steffen, B.; "Prospects for Pumped-Hydro Storage in Germany; EWL Working Paper No. 07/2011

[42] The study “Integration of Renewable Energies into the Electricity Grid in Germany in the Period of 2015 – 2020 with Forecast on 2025” (DENA Grid Study 2, January 2011); Institute of Energy Economics at the University of Cologne (EWI), DEWI GmbH, Fraunhofer Institute (IWES), 50Hertz Transmission GmbH, Amprion GmbH, EnBW Transportnetze AG and TenneT TSO GmbH

[43] Magazine "Electricity Today", issued March 2010

[44] Patent PCT/US2010/048719

[45] Offshore Grid; Offshore Electricity Grid Infrastructure in Europe, A Techno-Economic Assessment; 3E (coordinator); Final Report, October 2011

[46] Arrillaga, J.; "High Voltage Direct Current Transmission", 2nd Edition, IEE 1998, ISBN 0 85296 941 4, p.136f

[47] Breuer, W. et.al.; "Application of HVDC for Large Power System Interconnections", CIGRE Session 2004, paper B4-106

[48] Povh, D. et.al.; "Advantages of Large AC/DC System Interconnections", CIGRE Session 2006, paper B4-304.

[49] Supergrid Phase 1 Proposal - Position paper on the EC Communication for a European Infrastructure Package; FOSG, December 2010

[50] Offshore Transmission Network Feasibility Study, Version 1.0, 26th September, 2011; National Grid, Crown Estate

Bibliography (Other Reading)

(1) "How to meet the EU's 2020 renewables target", Stephen Tindale, Centre for European Reform

(2) "Energy infrastructure investment needs and financing requirements", Commission Staff Working Paper, European Commission

(3) "Power Europe: wind energy and the electricity grid", EWEA

(4) "Climate and Electricity Annual 2011-Data and Analyses", IEA

Appendix I

Summary of Questionnaire

Preamble	
ENTSO-E	*This document represents the views from TSO experts in ENTSO-E's drafting team on Network Code for HVDC Connections (NC HVDC). Most of the questions posed in this questionnaire are valid also in context of the NC HVDC. ENTSO-E welcomes FOSG's active contribution in the development of this network code, e.g. in participating in the NC HVDC User Group, and is open to discuss these questions further if needed.*
TSO 1	-
TSO 2	-
TSO 3	-
TSO 4	-

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 and what could be potential limiting factors from a TSO's perspective to develop HVDC grids?
ENTSO-E	*not related to NC HVDC*
TSO 1	*One of dominant driving factors from the TSO perspective to develop HVDC grids is to connect large scale offshore wind farm plants to the AC grid. The HVDC grid has been seen as an economically viable solution of connecting a number of wind farms located far offshore in the ocean. With a network configuration rather than point-to-point connection, the multiple HVDC system or DC grid offers high security and reliability and better utilisation of the system asset in the case of outages. Precise control of the DC system is also a reason (may not be decisive) for the planner to consider the DC over the AC. Multiple terminal DC systems offer the potential for further system expansion to Europe continent in the future. The potential limiting factors for building a multiple-*

	terminal HVDCDC or DC grid are 1. *No HV DC breaker is commercially available yet as a mean to provide a fast and effective protection* 2. *Lack of international standards for component (like converter) manufacturers and the TSOs.* 3. *We are at an early stage in DC grid development although there is great interest and considerable R&D projects on this topic.* 4. *No effective tools (both hardware and software) to perform the system planning studies covering many complicated studies for steady state, dynamic, transient and fault conditions with very large AC and DC systems.* 5. *Cable manufacturing capability and cable dynamic performance and withstanding capabilities* 6. *There are as yet no developed protection and control devices that are available for post fault scenarios at the ratings required for high capacity offshore DC networks. e.g. 2000MW DC chopper and fast acting flow controls for multiple links to shore in interconnected HVDC networks such that short-term >1800MW loss of a link could be feasible if power were diverted to other in-service links within approximately 1 second.*
TSO 2	*Main driving factors:* ➢ *Strong environmental constraints;* ➢ *Natural energy resources far away from load centres;* ➢ *Changing of generation mix, more RES and less synchronous generators connected in the future;* ➢ *Competitive European markets;* ➢ *Transition to a low carbon economy.* *Limiting factors:* *To create a HVDC grid it would be necessary to develop very fast detection techniques to operate the correct DC circuit breaker at the correct time. Whilst such protection methods exist today for point-to-point HVDC converter schemes, for a complex, meshed, HVDC grid there are likely to be challenges in terms of detection and discrimination.*

TSO 3	*Among the possible driving factors:* - *To provide supplementary interconnection capability compared to single point-to-point connections.* - *To use the expected capability of DC grids to adjust power injections for each terminal (control on active power). This capability could be used for basic power transfer, as well as high-level services such as frequency control, or power oscillation damping.* - *In the case of offshore wind farms connections, to use the DC grid to mitigate the fluctuations of each individual wind farm.* - *At 2020-2030 time horizon, the development of offshore wind generation will drive the interconnection of HVDC links initially planned to connect offshore power park modules, resulting in the emergence of meshed DC network and hybrid AC/DC systems (see NSCOGI study)* *The foreseen limitations are the following:* - *In the absence of DC circuit breaker (DCCB), any fault on a DC circuit would lead to the full collapse of the whole DC grid. Therefore, no significant DC grid can be erected without DC circuit breaker (or else, it must be under-exploited in order to maintain the disturbances in the adjacent AC synchronous areas at a reasonable level). The protection of a DC grid is a very difficult issue for which the principles cannot be straightforward derived for AC (see conclusions of the "DC GRID demo" in the TWENTIES project). As mentioned above, the DCCB is one key element, but its integration in an effective protection plan must also be considered; as an example, the robust and selective detection of DC faults (to trigger the right DCCBs remains challenging for large DC grids, as exposed in TWENTIES).* - *As a DC grid will most likely be built up from several manufacturer's equipment, some preliminary issues have to be handled: interoperability of various converters, standardization (for example: DC voltage, interfaces between the converters controls, etc.).* - *The flexibility provided by the HVDC grids will also require supplementary coordination between the TSOs involved in it, as well as with other devices (PST, other FACTS).*
TSO 4	*Possible driving factors: decreasing prices* *Potential limiting factors: technical issues, e.g. missing compatibility between different vendors/technologies*

Summary	Driving Factors: - The connection of large scale offshore wind as well as other renewable energy sources and interconnections supplementing single point-to-point connections. - HVDC Grids are expected to provide economically viable solutions for high security, reliability and better utilisation of transmission system assets. - Precise control on active power as well as system ancillary services like frequency control or power oscillation damping are important advantages of DC vs. AC. Limiting Factors - DC Grids will most likely be built up from several manufacturers requiring interoperability of their equipment. Standardisation at an international level is needed. At the same time coordination of the TSOs involved will be required. - DC Breakers would be beneficial in the development of extended meshed DC Grids in order to avoid DC faults leading to a collapse of the entire DC Grid. New protection systems (algorithms and devices) need to be coordinated with the capabilities of DC Breakers. - The planning of HVDC Grid Systems and the upgrade of existing planning tools should be considered strategic for success.

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?
ENTSO-E	*In case of multi-terminal systems or HVDC grids it is important that the capability to transmit power is available even if one of the converters is shut down. For this special attention has to be taken to* - *Converter synchronization and disconnection from the AC or DC-network* - *Unexpected changes: Each HVDC converter station (of a multi-terminal system) shall handle in a predefined way, in case of expected or unexpected changes in the HVDC system, without tripping.* - *Temporarily shut-down of the HVDC grid and further reliability requirements need to be consistent with TSO(s) requirement on maximal loss of active power. This requirement avoids economically inefficient sizing of reserves.*
TSO 1	*For each and every project we consider all possible options including AC and DC in order to achieve optimum solution economically and technically. Although the LCC and VSC belong to DC systems, they are fundamentally different technologies and hence possess very different control characteristics and capabilities. Table below shows the major differences between both technologies. In the planning we consider all the characteristic attributes of each technology, and often the factors like cost, controllability, system performance requirements, system configuration (point-to-point or multiple-terminal), application (wind connection or others) and maximum DC system ratings are decisive in selection. Of course, the maturity of technology and possible supply capability are also the important factors to be considered.*

Attributes	CSC-HVDC	VSC-HVDC
Converter technology	Thyristor valve, grid commutation	Transistor valve (IGBT), self commutation
Max converter rating at present	6400 MW, ±800 kV (OH line)	1200 MW, ±320 kV (cable) 2400 MW, ±320 kV (overhead)
Relative size	4	1
Typical delivery time	36 months	24 months
Active power flow control	Continuous ±0.1Pr to ±Pr (Due to the change of polarity)	Continuous 0 to ±Pr
Reactive power demand	Reactive power demand = 50% power transfer	No reactive power demand
Reactive power compensation & control	Discontinuous control (Switched shunt banks)	Continuous control (PWM built-in in converter control)
Independent control of active & reactive power	No	Yes
Scheduled maintenance	Typically < 1%	Typically < 0.5%
Typical system losses	2.5 - 4.5 %	4 - 6 %
Multiterminal configuration	Complex, limited to 3 terminals	Simple, no limitations

TSO 2	*The technical requirements for HVDC grids should be similar to the HVDC link requirements, because in the future an existing HVDC link could be integrated in a meshed DC grid. The main requirements for all HVDC systems should be defined in order to ensure and enhancing security of supply and maintain system security.*
TSO 3	*Some minimal requirements are commons for all HVDC systems or HVDC grids. For example TSOs are setting references for maximum active power loss for a given LFC Block, in order to avoid unreasonable increase in the cost of operational reserve needed to cover the loss of the DC link or the DC grid (see Entso-e draft HVDC connection code). In our country, current rules for HVDC connection require a maximum loss of active power of 1800 MW (to avoid an excessive increase of Frequency Restoration Reserve). Flexibility for shutting down a HVDC system for system reconfiguration (connecting or disconnecting converter stations/DC lines) can be considered as long as the previous requirements are met. These shut-downs should be scheduled and coordinated with the adjacent TSOs.*
TSO 4	*The planned HVDC links in our country are realized as point-to-point connections in a first step. The option for multi-terminal operation shall be taken into account.*
Summary	Multi-terminal HVDC systems have to contribute to the security of supply according to the TSOs requirements. The maximum active power loss criterion is an important parameter for system planning. Both VSC and LCC are seen as technological options with factors like cost, controllability, system performance requirements, system configuration (point-to-point or multiple-terminal), application (wind connection or others), maximum DC system ratings, maturity and supply capability being decisive in selection.

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?
ENTSO-E	- *In a first stage requirements for the AC connection point of each converter must apply. Requirements at each converter AC connection point in many cases include meshed HVDC systems as well, whereas requirements for each converter DC connection point should not pose a barrier to future expansion into multi-terminal or meshed DC grids. Further requirements on the DC connection point of each converter in order to have certain withstand capabilities on the DC circuit could be covered in future amendments of the NC HVDC.* - *As for Q2, also for this question it is important to note that the draft NC HVDC requires that a temporarily shut-down of the HVDC grid and further reliability requirements need to be consistent with TSO(s) requirement on maximal loss of active power. This requirement avoids economically inefficient sizing of reserves.*
TSO 1	*The network planning documents are equally applicable to the AC and DC systems. The reliability requirements to an HVDC link (maybe a network in future) is the same as those to any AC links on the transmission network. The system has to be designed to be able to cope with the loss of the defined maximum generation capability including the generation infeed via HVDC link(s)*
TSO 2	*The sudden loss of a large amount of active power injected into, or delivered out of a synchronous area can result in large generation/load imbalances which need to be covered by operational reserves. For that reason the HVDC network should be designed in order to operate without faults as possible to avoid wide scale system instability, specific consideration may need to be given to the configuration of an HVDC systems in order to get some transmission redundancy. As a general principle, it needs to be ensured that HVDC systems are the most reliable items of the system, i.e. are the ones withstanding the widest deviations in voltage and frequency in abnormal situations.*
TSO 3	*The overall MTDC reliability requirements are expected to be at least the same than for others (more "traditional") AC equipment. Here, it is important to stress that this reliability indicators should correspond to the whole DC grid (which depends on each individual component, the detection / selectivity / protection system, and the underlying topology).* *The reliability and the level of redundancy in the design of the HVDC system are highly dependent on the power transfer capability, due to the previous requirements on the*

	maximal loss of power. They shall ensure that any DC contingency will not trip more than the maximum active power defined by the adjacent TSOs (use of DC circuit breaker and adequate protection plan).
TSO 4	*Due to the high power transfer capability of future HVDC systems/grids and therefore its impact on power system stability and reliability of the whole system, a high reliability is necessary.*
Summary	Multi-terminal HVDC Systems will play an important role for power system stability and therefore should be highly reliable. The maximum active power loss criterion is an important parameter for system planning influencing the configuration of HVDC systems with respect to system redundancy. Any possible single fault in the HVDC system must not violate the maximum active power 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?
ENTSO-E	*not related to NC HVDC*
TSO 1	*The requirement for the losses associated with the DC system is one of major factors in the system specification. TSOs often specify the requirement of the total loss of the system at different levels of power transmission levels (minimum, 50%, 100% etc.). It is down to the tenders to provide the detailed calculations of the losses including the breakdown of the losses in association with each part of the system. The claimed losses (resulting in the operational cost) will be included into the cost benefit analysis during project evaluation according to the relevant international standard.* *On the international interconnection link there always is a point defined along the DC route for the MW rating of the link. For example, the point could be at the AC side of transformer at inverter or at the mid of the DC line. This point is the demarcation point separating the losses to the two connected TSOs in two countries.*
TSO 2	*The losses in the HVDC systems should be taking in account when evaluating different proposals from different manufactures. Nevertheless, a maximum value for HVDC system losses should be defined by the TSO in order to achieve overall system efficiency. Actually we don't have a reference for that value because we do not have any HVDC connection planned for the next years.*
TSO 3	*Some elements on losses:* *TSO 3 is responsible for the losses occurring on his network (which means TSO 3 has to pay for the losses).As a consequence, this issue is very important for TSO 3.* *However, the choice for DC options results from various needs, which have nothing to do with losses; thus, there is no a priori requirement with regard to losses at the call for tender stage, but the overall losses value (transformers, converters, cables) provided by manufacturers is an important parameter for the final contract award.* *Note on losses and VSC trends: manufacturers highlight lower and lower VSC losses for converters; they have significantly decreased from the first VSC stations generation, and are now becoming quite close to LCC converter ones. However, the main stress should be put on cables voltage for VSC, which now becomes the major factor for losses for medium to long distance VSC transmission (compared to LCC): cables losses (for cables below +/-320kV) is indeed the predominant factor (compared to converter losses), and*

	PI cables for LCC schemes do not suffer from comparable limitations (as higher DC voltage is possible).
TSO 4	*At the moment it there is no strict requirement for losses per converter station/terminal and per line or cable section. But there is the intention to build HVDC links with up to 500 kV (overhead line) in the future, which also reduces losses substantially.*
Summary	The power losses are an important design criterion for HVDC systems and will be evaluated by the TSOs for projects individually. If more TSOs are commonly involved with a HVDC system, the demarcation points for separating losses between the TSOs are proposed to be the points where the MW ratings are defined. For long distance high power transmission, the power losses on the transmission lines, e.g. the cables, become more and more important compared to the converter losses. Higher transmission voltages are considered an important step reducing the overall transmission losses.

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?
ENTSO-E	*not related to NC HVDC, but core element in pan-European TYNDP, forward looking e-Highways 2050 project, and various regional initiatives.*
TSO 1	*This is a question at its very early stage in the development of the HVDC grid; nevertheless, it is worthwhile to be considered. Expanding the DC grid in the way of rising the DC network voltage level will profoundly change the entire network design, and is not expected to take place easily. Expansion by the way of adding more converter stations into the DC network or extending the existing DC line (cable) can be achieved relatively easily. In this case, there will be no many requirements for the hardware (converter, transformer, insulation protection devices) change, but sophisticated software for control and protection and for communications.* *As the DC equipment is very expensive, any requirement for addition headroom for future system expansions has to be exercised with great caution.* *TSO 1 is actively participating in the development of ENTSO-E HVDC code which covers the requirements for the HVDC system at European level.*
TSO 2	*It is expected that HVDC Grid Systems will be built in steps, starting with a small number of interconnected stations with the possibility of future system expansion and interconnections. This will involve different TSOs and different HVDC manufacturers. In order to make the future expansion easier is important to define a standardization of the principles of equipment function, system operation, control and communication. Other planning issue could be the development of HVDC system with maximum cable capacity but with the immediately needed converter capacity, ensuring a future expansion of the converter system.* *The coordination at European level can be achieved by European entities such as ENTSOE.*
TSO 3	*We agree that HVDC grids will be built step by step, starting from existing schemes. However, since there is no precise plan to build up such a DC grid, oversizing the planned HVDC links is clearly not an option.* *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 level). *As a consequence, assessing the operational compatibility of VSC converters tapped on LCC links must be considered.*
TSO 4	*See Q2*
Summary	Increasing the rating of HVDC system components today allowing for a possible future system expansion has to be handled with great caution. Expansion is considered to be relatively easy as long as the DC voltage level will not be changed. Tapping into existing HVDC links could be one possible scenario. However, even this step requires interoperability of the HVDC components e.g. converters) and systems (e.g. control and protection) which requires further steps on international NC code development and standardisation.

Question 6	There are basically two types of converters available to HVDC transmission today: Line Commutated Converters (LCC) based on Thyristors and Self Commutated 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 (variable DC voltage including dynamic DC voltage reversal and DC fault clearing capability). VSC of both types can be combined with various DC current limitation and dynamic fault clearing equipment. These variants have different optima with respect to functionality vs CAPEX and OPEX. Does the TSO have a preference for one of these solutions over the other and what are the reasons behind the choice?
ENTSO-E	*With regards to system security all solutions should consider the system needs at the connection points, such as* - *Active power control and frequency support* - *Reactive Power control and voltage support* *without an ex ante preference for either technology.*
TSO 1	*The VSC technology used as an HVDC system for power transmission is at an early stage of development. The pace of the VSC HVDC development has been very fast over the last about 15 years. It is expected that there will be more new circuit configurations and designs coming out in the near future. Up to now we know there are a few VSC HVDC systems in operation which are based on half-bridge converter topology, while it has been heard that some VSC projects with build-in DC fault blocking capability are under way. Under this circumstance, we intend to specify the system requirements and control characteristics rather than any specific technologies. It gives the manufacturers a freedom to propose an overall best solution to the requirements.*
TSO 2	*It is recognised that there are differences between the inherent functionalities of the two technologies described, but from the point of view of the system security, it's important that all HVDC connections (independent of its technology) fulfil the minimum requirements, defined by regulations or by the TSO, in order to ensure the reliable operation of connections and to maintain the systems security. It is important to ensure that the full potential of all technologies can be used while no barriers should be created for future use of any of them.* *However, in order to increase system stability and contribute to higher integration of RES, it would be important that HVDC systems have DC fault clearing capability in order to achieve faster fault clearing times.*
TSO 3	*PRELIMINARY NOTE: contrary to what is written in the question, full-bridge VSC cannot clear DC faults' but may 'block the fault current feeding a DC fault'. The question should*

	be slightly revised. *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 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 block fault currents caused by a DC fault; yet this comes at the expense of higher losses (during steady state operations) and the blocking of whole converter; in addition, this would make sense if all converters were alike, thus providing the same capability. Therefore, a DC grid based on FB-VSC converters would collapse for a while following a DC fault, while DC circuit breakers would make it possible to isolate the faulty portion of the grid with virtually no impact on the rest of the HVDC grid. Therefore, the absence of a DC breaker and related protection plan would certainly be a showstopper when considering a large DC grid (rated at 3 GW or above).*
TSO 4	*There is still no preference for one of these solutions, due to pros and cons for both solutions.*
Summary	HVDC systems will be specified on a functional basis. DC fault clearing capability is considered an important function. Besides the technologies mentioned in the question, other solutions may be developed in the future. Therefore, NC or international standards should not create barriers with respect to one or another technology or for possible new developments. Large HVDC Grids (e.g. rated 3 GW or above) are expected to require solutions preventing the entire DC power transmission to collapse in case of DC fault.

Question 7 7.1	It can be expected, that future multiterminal 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: - the capability of a station to start-up a de-energized AC network (black start)
ENTSO-E	*All the mentioned capabilities are valuable to mention. The draft NC HVDC provides a*

	European frame for all capabilities needed today and in future in order to meet the system needs. This frame prescribes which requirements should be mandatory for all HVDC systems, and how parameters are to be selected.
TSO 1	*We expect the future HVDC systems are able to provide all the above-mentioned capabilities, many of them are essential in the case of wind farm connections.*
TSO 2	*The future HVDC grids will always need to interact with the AC systems, and for that it´s essential that the HVDC grids have the capacity for provide ancillary services such as voltage or reactive power support, frequency control, active power flow control, contribution to short circuit power or power system restoration services. Services like these will reduce the risks of AC system instability or blackouts, maintaining the system stability and secure operation. The expected ancillary services that the future HVDC systems should provide has to be defined in regulation or by the TSO, and should be at least similar to those provided by the generators.*
TSO 3	*In a general way, TSOs require HVDC systems to be compliant with the Entso-e HVDC connection draft code. This capability can be expected by the TSO in some cases (depending on system needs).*
TSO 4	*All points seem to be very important for future system operation with a high amount of HVDC included!*

Question 7.2	- the capability of a station to energize the DC network or parts thereof
ENTSO-E	*See 7.1*
TSO 1	*See 7.1*
TSO 2	*See 7.1*
TSO 3	*No clear opinion on that feature, so far…*
TSO 4	*See 7.1*
Question 7.3	- the capability to provide reactive power
ENTSO-E	*See 7.1*
TSO 1	*See 7.1*
TSO 2	*See 7.1*

TSO 3	*Voltage support is an important feature. TSO 3 require this capability in its current HVDC connection code, at least in the range [-0,35Pmax- 0,32Pmax].*
TSO 4	*See 7.1*

Question 7.4	- the capability to control AC system frequency
ENTSO-E	*See 7.1*
TSO 1	*See 7.1*
TSO 2	*See 7.1*
TSO 3	*This capability is required for various system needs:* 1) *HVDC systems embedded in a synchronous area shall contribute to operate the network topology in a flexible way. They shall have the capability to feed a passive electric island and to do so they shall be capable of controlling the frequency in this island.* 2) *HVDC connections between control areas or synchronous areas shall support the development of cross-border exchange of reserve and control energy and shall be capable of providing Frequency Containment Reserve at each end of the system. To do so capability to control AC system frequency is needed.*
TSO 4	*See 7.1*

Question 7.5	- the capability to provide short-circuit power to the AC systems
ENTSO-E	*See 7.1*
TSO 1	*See 7.1*
TSO 2	*See 7.1*
TSO 3	*This capability can be expected by the TSO, especially when rate of penetration of renewable is high and few synchronous generators are expected to be connected to the grid.*
TSO 4	*See 7.1*

Question 7.6	- the capability to ride through AC system faults
ENTSO-E	*See 7.1*
TSO 1	*See 7.1*
TSO 2	*See 7.1*
TSO 3	*This is mandatory: the DC grid must be resilient in order to meet requirements of Entso-e HVDC connection draft code at the connection points with AC systems. In addition, the TSO can require converters to deliver reactive power to support the voltage during an AC fault (for VSC converters).*
TSO 4	*See 7.1*

Question 7.7	Are there any other special capabilities expected?
ENTSO-E	*See 7.1*
TSO 1	*See 7.1*
TSO 2	*See 7.1*
TSO 3	*So far, there has been not actual assessment of technology inter-operability between different manufacturers. Yet, it is most unlikely that one single manufacturer will be awarded to build a whole DC grid on his own… Hence, standardization and inter-operability is a major concern from now on.*
TSO 4	*See 7.1*
Summary	In principle all performance criteria will be needed for future multi-terminal systems. The ENTSO-E NC HVDC will define the requirements. Besides that, interoperability of equipment and solutions of different manufacturers will be needed.

Question 8	As any other power system, multiterminal 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- or undervoltages, fault clearing times)?
ENTSO-E	*See NC HVDC, Q6 &Q7* *Capability for transient faults on HVDC system: Fault clearing and active power recovery in case of DC faults enables fast restoration of the integrity of the network and reduce risk of system stability. Article 25(2) prescribes auto-reclose capability of HVDC Systems with overhead DC lines.*
TSO 1	*Fault behaviour of the HVDC systems should comply with the Grid Code; generally the same requirements apply as for AC systems or generators. Fault clearance time on the generator's or DC converter station owner's equipment directly connected to the National Electricity Transmission System has to comply with the requirements set out in the specific Bilateral Agreement Grid Code requirements in our country specify that these requirements included in the Bilateral Agreement shall not be faster than* - *80mS at 400kV* - *100mS at 275kV* - *120mS at 132kV and below.* *This however shall not prevent a generator or a DC converter station owner of having faster fault clearance times.*
TSO 2	*These requirements will be dependent of the capacity of the DC circuit breakers technology. However a very fast detection technique and discrimination of a fault will be an importance issue in the development of a DC meshed grid.*
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 and 11).* *From a functional standpoint, the Dc grid must be able to:* - *Limit the impact and isolate DC faults without shutting down the whole DC grid.*

	This requires DC circuit breaker and adequate DC protection system. Two manufacturers claim that DC Circuit Breakers are feasible; however, there is no evidence of an effective, robust and selective protection system for long distance, for instance. - *Limit the impact of the DC grid (in case of a contingency) on the AC network, and vice-versa; this requires coordination between both AC and DC protection systems.* - *HVDC systems with overhead lines shall be capable of auto reclosing for transient fault within the HVDC system.*
TSO 4	--
Summary	There is presently little experience with multi-terminal systems. In general, fast fault clearing and active power recovery in case for DC faults is important to maintain power system integrity and stability. The ENTSO-E NC HVDC or corresponding agreements with the TSOs involved will define the requirements with respect to the fault behaviour.

Remark: for DC 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.

Question 9	What is the maximum single in-feed loss criterion for the TSO?
ENTSO-E	*Technology does not strongly limit the max capacity of HVDC facilities. Possible new HVDC connections of high capacity (e.g. > 4 GW), and which are already being planned in some regions (though not Europe), need to be covered by the NC HVDC. To avoid unreasonable increase in costs of operational reserves, the NC HVDC requires new connections to design their system as to limit the loss of power in case of outage (e.g. redundancy in design). The limit is defined per LFC Block. Example: in France current transitory rules for HVDC connection require a maximum loss of active power of 1800 MW to avoid an excessive increase of Frequency Restoration Reserve (FRR).*
TSO 1	*Under the national standards in our country, the system is secured against:* ○ *Normal infeed loss of 1000MW (1320MW as of 1st April 2014)* ○ *Infrequent infeed loss of 1320MW (1800MW as of 1st April 2014).*
TSO 2	*HVDC technology allows links with a capacity of several GWs. So, in order to avoid unreasonable increase in costs of operational reserves, it`s important to define the maximum loss active power allowed for HVDC connections. Actually we don't have a reference for that value because we do not have any HVDC connection planned for the next years.*
TSO 3	*In our country, current rules for HVDC connection require a maximum loss of active power of 1800 MW (See Q2)*
TSO 4	--

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 fulfil 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, fluidises 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 authorised 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, in principle, for the same power to be transmitted the HVDC underground cable solution would require fewer cables and consequently a significantly smaller corridor width.

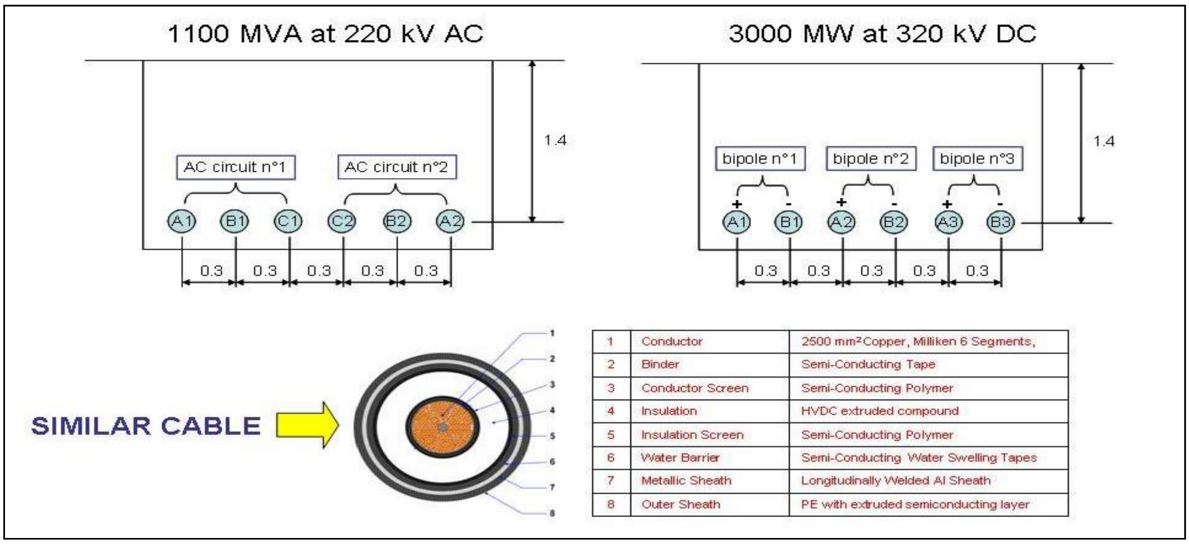


Fig. III.1 - HVDC vs. HVAC underground cable systems with similar cables

References

[III.1] ENTSO-E & Europacable "Joint paper on the Feasibility and technical aspects of partial undergrounding of extra high voltage power transmission lines" Brussels, December 2010

[III.2] Europacable "An Introduction to High Voltage Direct Current (HVDC) Underground Cables" Brussels, October 2011

Appendix IV

Overview of work on HVDC Grids and other aspects of the Supergrid in CIGRE, CENELEC and other organizations

1 Introduction

The report published by the Friends of the Supergrid (FOSG) in March 2012 [Ref 1-1] considered the technological issues which would be involved in the creation of a Supergrid. The concept of the Supergrid is an electricity network, based primarily on High Voltage Direct Current (HVDC) power transmission, which could transport renewable energy from remote generation sites to load centres across Europe. The report considered the drivers for the Supergrid and the core technologies which would be required to create such a transmission capability. Although not precluding overhead line transmission, the report focused on the availability of underground and submarine cable technology, as this was considered to be one of the core technologies on which a future Supergrid would be based. The other core technology was the Voltage Source Converter (VSC) variant of HVDC, which is now available from multiple manufacturers. The report also considered what new control and protection techniques would be required to implement such a widespread HVDC grid. Two key technologies were identified which were still under development, either at the research phase or at the prototype testing phase. These were a fast acting DC circuit breaker and a DC/DC converter, the latter being the equivalent of a transformer in an AC transmission system. The report concluded that there were no “show-stoppers” to the development of a Supergrid. All of the required technologies were available or were at a suitable state of development, such that the Supergrid could become a reality in the near future.

Since the publication of the report there has been considerable interest in the future Super grid and a significant amount of activity has been undertaken by a number of organisations, to create the underpinning framework for a Supergrid. This work has been undertaken by experts in the field working for a number of international organisations, covering both technical and standards organisations. There is a significant overlap between the members of these organisations and the members of the FOSG WG 2 (Technological). This has allowed a significant cross-fertilisation of ideas between the different groups and provides a strong technical basis for the work of each group.

An initial Supplementary Report No.1 prepared by FOSG WG 2 [Ref 1-2] summarised the work of the different groups now active in the area of Supergrid technology and presented an overview of the "state of the art" as of 2013. The report considers the new publication by CIGRE on testing of high voltage cables for DC applications, which provides recommendations for testing of extruded HVDC cables. The availability of high voltage cables from multiple manufacturers is a key technology in the development of the Supergrid. In addition to extruded (XLPE) cables, both mass impregnated (MI) and polypropylene laminated paper (PPLP) cables are suitable options for the development of the Supergrid. Both CIGRE and CENELEC have set up working groups to look in more detail at specific aspects of the Super grid technologies. Within CIGRE, from the work of the original working group B4.52, Now published as a Technical Brochure, five daughter working groups are now active, which are expected to report in early 2014. In parallel the CENELEC working group has concluded its work and the report was published in November 2012. CIGRE had also created a Task Force (TF), which considered the subject of the need for standardisation of DC voltages for the future Supergrid. The preliminary report of this TF was issued, which has instigated a Joint Working Group (JWG B4/C1.65) which will study the issues related to DC voltage standardization in more detail. Up-dated information on all of these active technical groups are provided in this Supplementary report No.2.

The original report by FOSG WG2 and this supplementary report are part of a sequence of reports being issued by the FOSG, which is assessing all aspects of the feasibility of building a wide area Supergrid, including economic, logistics, employment, supply chain and social issues.

A key aspect of the functionality of the Supergrid will be the integration of both small scale and large scale renewable energy sources. The technical issues related to these areas are the subject of a separate report from WG 2.

References

[1-1] FOSG report from WG 2 dated 14.03.2012

[1-1] FOSG WG 2; Supplementary Report No. 1, "Overview of work in CIGRE and CENELEC related to the Supergrid vision"; March 2013

2 Testing of DC cables

Today, DC cable technology for the Supergrid comprises mass impregnated, PPLP cables and extruded cable voltages according to the previous FOSG WG2 report. Relevant recommendations for testing of land and submarine cables have been issued by CIGRE and are briefly presented below.

The technical brochure *TB 496: Recommendations for testing DC extruded cable systems for power transmission at a rated voltage up to 500 kV* was recently released [2-1]. The document replaces TB 219 issued in March 2003. The main focus is the electrical testing of the cable system and DC extruded cables are defined to include insulation systems which consist of thermoplastic or cross-linked polymers, which can be both filled and unfilled, as well as differing in manufacturing process.

The tests in this recommendation follow the same principles as in TB 219. The main changes made to the text of TB 219 can be summarised as follows:

- The voltage range covered is extended up to 500 kV
- The text has been updated to take into account the latest revisions of IEC 60840 (Edition 4) and IEC 62067 (Edition 2)
- The range of approval for both prequalification tests and type tests has been revised
- Recommendations for routine and sample tests on cable accessories have been included
- It is noted that the lack of operational experience above 200 kV represent an uncertainty in the preparation of the recommendations

For paper insulated cables *Electra 189: Recommendations for tests of power transmission DC cables up to 800 kV* can be mentioned [2-2]. The recommendations apply to cables and accessories for both submarine and land applications and are to be used for paper insulated cables of up to 800 kV as well as for cables with lapped insulation of all types.

A CIGRE working group (*B1.42 Recommendations for Testing DC Transition Joints for Power Transmission at a Rated Voltage up to 500 kV*) has been set up to issue recommendations for testing of transition joints between lapped and extruded HVDC cables. The work is expected to be finished in 2014.

For mechanical testing *Electra 171: Recommendations for mechanical tests on sub-marine cables* has been issued and gives recommendations for mechanical testing for single or three-core submarine cables, both for AC and DC voltages. It is primarily intended for cables having a rated voltage higher than 36 kV AC or 100 kV DC [2-3]. This document is currently under revision by the CIGRE B1.43.

References

[2-1] CIGRE Technical Brochure 496, "Recommendations for testing DC extruded cable systems for power transmission at a rated voltage up to 500kV", Paris, 2012

[2-2] Elektra, *Recommendations for tests of power transmission DC cables up to 800 kV,* No. 189CIGRE, Paris, 2000

[2-3] Elektra, *Recommendations for mechanical tests on sub-marine cables,* No. 171, CIGRE, Paris, 1997

3 DC Grid - Design issues

3.1 Introduction

Many organisations throughout the world are considering the use of HVDC power transmission for more than simple point–to–point applications. These range from offshore wind farm systems, to international interconnectors and embedded schemes to relieve congestion issues in the AC networks. At the heart of these concepts is the idea of a DC grid which can provide the same functionality as the existing AC grid, but also bring the additional features which are distinct to HVDC, such as no limitation on distance, lower losses in the transmission circuits, more controllability of real and reactive power flows, and inherent “Firewall” capability. The question raised then becomes, “Is such a DC grid feasible?” CIGRE Working Group B4 – 52 considered this question, specifically whether it was technically and economically feasible to build a DC Grid. The results of the work have been circulated for comment and the final report was published in a Technical Brochure in 2013 [Ref 3-1]. A summary of the work of WG B4 – 52 is provided in Section 3.2.

3.2 WG B4 – 52 “DC grid feasibility study”

This WG undertook a detailed evaluation of the economic case and the technical challenges which would be encountered to build such a grid. The final report of B4 - 52 concluded that the building of a meshed DC grid would be the most economical solution, when compared with building an overlay AC grid, or simply adopting multiple long distance HVDC links. It was accepted in the report that some aspects of the costs of DC switchyards were unknown, but it was anticipated that these would be lower than using multiple HVDC converter stations. A number of technical challenges were identified in the work, which are summarised briefly as follows,

- The need for a wide area control system to schedule and control power flows between installations build by many manufacturers over a long period of time
- The need for a fast acting protection system, which can detect DC system faults in a very short time-scale (<2ms) and discriminate the faulted section of the grid.
- The need for a fast acting (<2ms) DC circuit breaker, which can interrupt the potential DC side fault current and withstand the recovery voltage.

- The need for a DC to DC converter (the equivalent of an AC transformer), which can adjust DC voltages for optimum economic power flow.

- The development of modelling tools and generic models of HVDC controllers

- The development of central control facility to coordinate the operation of the DC grid

- The adoption of preferred DC voltages for DC grids

- The development of Grid Codes for the DC grid systems

- The development of benchmark tests for the addition of new converter stations to the grid.

The work of WG B4.52 was published as a Technical Brochure in 2013 [Ref 3-1]. Following the work of WG B4 – 52, CIGRE instigated a number of daughter Working Groups to address these and other technical challenges in more detail. The activities of these groups, which are expected to report during 2014, are summarised in the following sections.

3.3 WG B4.56 "Guidelines for the preparation of "connection agreements" or "Grid Codes" for HVDC grids"

It is expected that HVDC Grids will be built over many years and will consist of DC submarine and underground cables, overhead transmission lines, Switching Hubs and Converter Stations provided by many different Manufacturers or Contractors. In order that all items of the grid will work together efficiently, safely and reliably it will be necessary to define a number of technical issues, to which all components of the grid must adhere. This WG will provide guidelines for the studies and documents necessary to prepare the following activities:

- The grid development plan of a power system including HVDC Grid solutions
- The technical specifications of a HVDC Grid control and protection system
- The technical performances of a HVDC Grid guaranteed to its users
- The technical requirements for new equipment to be connected to a HVDC Grid, including high voltage and control and protection specifications
- The requirements for the connection, testing and operation of new equipment to be connected to a HVDC Grid
- The specifications of the data to be exchanged between individual equipment and the HVDC Grid central co-ordination control system

The Technical Brochure to be published from the work of the WG will comprise guidelines in the following areas:

HVDC Grid Planning Code: The objective of this is to ensure safe and secure operation of the HVDC Grid as it evolves in the future, ensure that the HVDC Grid will be able to fulfil its intended purposes, and facilitate the connection of cost effective future converter stations and transmission lines as the HVDC Grid evolves. In order to achieve this objective it is necessary to perform studies for all plausible normal and abnormal operating conditions based on a future vision of the HVDC Grid to determine the technical parameters, to which the components of the HVDC Grid may be exposed, and for which they have to be rated. Reliability and security criteria need to be defined, as well as the general control and protection methodology to be used.

Technical performance of new connections; The objective of this is to define the functional requirements for new converter stations and transmission lines, e.g. control and protection characteristics and settings, communication protocols and signals, DC side insulation levels, DC chopper settings and characteristics (if appropriate), and any special requirements concerning responses to events on the DC side (over and under voltages). Definitions will be proposed for the DC voltage range for the converters and transmission lines during operation, including steady state variations and temporary over and under voltages. The Short Circuit Currents that may be experienced by components in the HVDC Grid need to be defined. DC Harmonic that may exist in the HVDC Grid, and DC side harmonic current and voltage injections that may be permitted by the new converter station need to be defined. Digital models and verification studies to be provided for the new connection will be required.

Most of the data above can be established based on studies similar to those described above.

Operation of a HVDC Grid. This code sets out the guidelines for operation of the HVDC Grid. It defines the operating modes of the HVDC Grid, how the converters connected to the HVDC Grid are dispatched and how the control characteristics should be set to ensure reliable operation, the procedures for connecting and disconnecting components to/from the Grid, and the operation under and after fault conditions. The latter includes “Black Start” procedures and operation during emergencies and during maintenance conditions.

Connection Code. This code defines the minimum technical requirements that a new converter station needs to meet to be able to connect to the HVDC Grid, including fault ride through performance, reliability criteria, model provisions, and other technical requirements as defined above for a new connection. The code will also define the connection procedure and the information to be exchanged between converter stations.

Data Exchange code. This code defines the converter stations and DC switching stations data and settings that are received from and sent to the HVDC control centre(s) and the AC Transmission System Operators. During normal operation the converter control is set up so that the station can operate without fast input and the data transmission is used primarily for minor adjustments to set points. Following a major system event, there may be a need for fast signals to ensure that the system returns as quickly as possible to a new optimum operating state.

3.4 WG B4.57 “Guide for the development of models for HVDC converters in a HVDC grid”

Modelling of the DC Grid and its converters and components and studies using these models are an essential part of the planning of a DC Grid. New models will continue to be added and new studies are expected to be performed during the life of the DC grid.

WG B4.57 has concentrated on writing guidelines for the development and usage of simulation models necessary to study DC Grids and their interactions with AC networks. A DC Grid will comprise of many diverse converter station technologies, configurations and topologies, which are sourced from multiple vendors and integrated in the DC grid and connected to neighbouring AC network(s).

The current knowledge on AC networks and HVDC point-to-point systems provides a starting reference for the simulation of DC Grids. The simulation of the complete network system has historically used a frequency based representation of the AC and DC network systems, together with a high-level representation of the control and protection systems. With increasing utilisation of power electronic converters, more detailed models (i.e. multi-frequency, electro-magnetic transient) need to be envisioned to provide the same level of confidence for DC system models, as exists today for AC components.

B4.57 has looked at the requirements of simulation models for modular multi-level voltage-sourced converters (MMC-VSC) and will provide a framework for model development that is consistent with known MMC-VSC technologies presently used, but which can also be adapted to changing power electronic topologies and control algorithms. The simulation requirements of MMC-VSC topologies have resulted in the development of new simulation approaches and technologies.

Descriptions of different types of computational models for the simulation of voltage source converters will be presented in the published Technical Brochure. Depending on the type of phenomena being analysed various types of EMT and phasor models are available. A brief description of the nature of these models will be presented, along with their applicability to various simulation studies.

A simulation methodology to accommodate the large number of simulation variants that can arise in the modelling of multi-terminal VSC-HVDC will be presented. The objective is to describe simulation methods that can accommodate different types of models and allows models to be easily interchanged throughout the life-cycle of a project, without having to develop new simulation files, or cases, for each study from the beginning. The basic guidelines for the construction of re-usable generic models will be outlined in the Technical Brochure.

One important conclusion from the work to date is the separation of the control system into upper and lower level controls. These upper level controls are independent of the power electronic implemented topology. The lower level controls system is very dependent on the power electronic topology. This finding means that only the lower level control system need to be modified or replaced when a different converter power electronic topology is studied and evaluated.

The Technical Brochure will present overhead transmission line and cable modelling approaches for VSC MMC systems. Models for the large variety of protective elements that can be expected in a DC Grid will also be described and illustrated.

B4.57 and B4.58 have jointly developed a HVDC Grid test system, as shown in Appendix 1. This HVDC Grid test system is used by all B4 DC Grid working groups and provides a common test system for DC grid investigations. The complete 9 station DC grid system can be quite complex for EMT simulation and thus two smaller test systems that are subset(s) of the main test system are also used in the study.

The WG is also addressing simulation model and intellectual property (IP) security issues and several methods to address the IP issues will be described in the Technical Brochure.

When published in 2014, the Technical Brochure is expected to lay the foundations for the models required to study VSC based HVDC grids.

3.5 WG B4.58 "Devices for load flow control and methodologies for direct voltage control in a meshed HVDC Grid"

The control of load flow and AC voltage control in HVAC systems is well understood. Similar technologies will be needed in DC grids and this WG is looking at different control solutions.

The DC voltage is the single most important variable within a meshed HVDC grid, which determines the integrity and stability of the whole HVDC grid, the power flow and the capability of VSC converters to operate normally. In a DC grid, contingencies such as AC network faults, converter trips and uncoordinated load changes give rise to a current imbalance that is reflected in the DC node voltages in the grid. This imbalance has to be corrected for by changing the currents flowing in and out of the DC system. The correction needs to be done rapidly, since an DC system has a low inherent inertia (i.e. capacitance).

After the correction, new DC node voltages will settle and since the power flow on individual transmission lines within the DC Grid simply depends on the voltage difference between its nodes and the resistance of the line, new power flows will be established in the meshed DC system. The new DC node voltages and converter powers might deviate from the set point values and the power flow in lines may not be as desired. Therefore, there is also a need for a second means of control for analysis of the new operating conditions and for change of the set-points for the converter stations (DC voltage and AC power), to re-establish the optimal and the most secure operating conditions for the DC Grid.

In addition, a DC grid cannot be controlled and operated independently of the AC system. The stakeholders of a DC grid, mainly the TSOs (Transmission System Operators), but also other stakeholders such as regulators, are likely to require that the DC grid should facilitate efficient and secure operation of the combined AC and DC systems. This gives requirements on the DC grid control, such as to follow set-points during normal operation as close as possible, to fulfil the electricity market perspective, and to divide the current imbalance correction between several AC/DC connections for different contingencies.

Based on the above system requirements, the Technical brochure being prepared by the WG describes and tests different DC node voltage control strategies for the imbalance correction. The test is done in a DC Grid test system, which was jointly developed by the WG B4-57 and B4-58, as shown in appendix 1. The second means of control is described by the WG as a coordinated system controller, using optimal power flow. This optimal power flow takes into account the desired set-points for power exchange at all AC/DC connections, together with the constraints on DC node voltages, and flows on the different lines. This determines the DC node voltages and the acceptable power exchange with the DC Grid at each converter node to be sent out as new set-points to the AD/DC converters.

Since the DC grid can be spread over hundreds or thousands of square kilometres, the incoming data of the central control is characterised by a communication delay. In case of normal operation (e.g. schedule changes) this delay is not important, but in emergency cases a local back-up control inside the converter station is required to ensure system security. The Technical Brochure will give an overview of the communication system requirements and the data it needs from the HVDC grid.

The power flow on individual transmission lines within the DC Grid depends on the voltage difference between its nodes and the resistance of the line. In a meshed DC Grid with different resistances of the lines, some lines may be highly utilised or risk to be overloaded whilst others will be much less loaded. For a better utilisation of the overhead lines and cables, load flow controlling devices are envisaged. The Technical Brochure will describe a range of such devices, ranging from switchable resistors to DC to DC converters that would be equivalent to a FACTS device, e.g. a Thyristor Controlled Series Capacitor in an AC network.

3.6 JWG B4/B9.59 “Control and Protection of HVDC Grids”

Control and protection of possible future DC grids will be fundamentally different from that of an AC network, because DC systems behave differently. The protection of the converter station equipment will be relatively unchanged from that provided in a point to point scheme, but the protection of the transmission lines and any DC switching stations will have to be completely reconsidered. On the DC side it is important to be able to quickly determine the faulty parts of the DC transmission system and to immediately disconnect this part. Furthermore, it is essential that only the faulty equipment or section of the grid is removed from service. Preliminary assessments show that the fault clearing action needs to be achieved within less than 5ms of the fault occurring.

In a DC Grid the fault currents which flow during faults to ground are limited initially by the surge impedance of the lines and the reactance of the smoothing reactors and other reactors involved in the circuit. However, this is quickly followed by a period where the DC resistances in the circuit will play the dominant part.

A DC Grid is most likely to be based on VSC HVDC technology, which in its basic implementation does not have fault current blocking capability. During a fault on the DC side, VSC converters operate as diode rectifiers and in a point to point scheme with DC cables they are typically tripped immediately, by the AC circuit breakers. On the Caprivi VSC HVDC scheme, which uses an OHL, the converter is also tripped, but can be re-started within one second, but it is unlikely to be acceptable to use the same methodology and trip all converters in a HVDC Grid, because the restart would probably take longer because of the need for co-ordination and the impact on the AC networks is unlikely to be acceptable.

The use of converters with fault current blocking capability may be beneficial in some cases, as this will reduce the fault current amplitude from the converter and make fault clearance easier. However, travelling waves from cables could be associated with high amplitude currents and converters may be connected to more than one transmission lines.

The WG is examining means for slowing down the progression of the DC voltage collapse. The use of large inductive reactors will provide some assistance and reactors are likely to be required in the DC transmission network, to facilitate correct determination of the faulty transmission elements. However, reactors are expensive and will contribute to system losses.

In a DC Grid it is important, in the event of a DC side fault, to identify very quickly the lines that have to be tripped and the tripping action must be achieved before the fault has spread too far.

With VSC HVDC the fault currents within the HVDC Grid can become very large, unless rapid action is taken to disconnect the faulty elements. Since the design of the elements in the DC Grid will depend on the prospective fault currents, it is necessary to identify the current levels at an early stage. It is also important to establish the consequences of failing to trip or remove a faulted section of the grid on the integrity of the overall system (equivalent to breaker fail philosophy in AC).

The WG is considering the entire HVDC Grid protection system e.g. the measurement, fault detection and interruption devices. It will develop the requirements for the system in relation to:

- Availability and reliability including redundancy requirements
- Speed
- Selectivity
- Maintainability

All plausible faults within the DC grid or affecting the AC grid, including DC line faults, “DC breaker” failures, and converter faults will be considered. The WG is looking at the pro’s and con’s of including passive elements in the DC grid to slow the rate of rise of fault current and/or to slow and reduce the voltage sag in the healthy parts of the DC Grid..

The WG is looking at the methods available to identify reliably the faulty elements within a DC Grid. The WG is considering different methods and approaches to limiting fault stresses and for the removal of faulty elements of the DC Grid.

The WG is drafting functional specifications for detection devices and for devices within and external to the converter stations, to achieve the disconnection of the faulty elements within the required time.

The WG is looking at the converter control and sequence strategies required to ensure timely restoration and recovery of the remaining DC Grid. The restoration and recovery time is likely to be critical to ensure satisfactory and robust operation of the overall AC and DC system.

The Telecommunication needs resulting from these strategies are also being identified.

3.7 WG B4.60 “Designing HVDC Grids for Optimal Reliability and Availability performance”

A key feature of any future DC grid will be its ability to deliver at least the same levels of reliability and availability presently achieved by AC grids. WG B4.60 has reviewed the existing AC network definition of reliability and availability to consider suitable criteria for use on DC grids. As many AC assessments of reliability and availability relate to energy not supplied to consumers, this was not considered appropriate for a DC grid, where there will be very few direct supplies to consumers. Instead the TB will propose the single figure of “energy not supplied by the grid” as the measure of the availability of the system. This considers the level of energy not supplied during station or circuit outages, e.g. under N – 1, N – 2, etc. conditions, as compared with inherent energy capability of the stations and transmission lines of the DC grid. This metric can be evaluated as energy (GWhr) and as a percentage loss of energy.

The Technical Brochure to be published by the WG will review the technologies and topologies of the DC grid, recognising that grids will potentially evolve from more limited multi-terminal systems. The impact that the topology of the DC Grid, whether based on radial or meshed systems, has on the overall reliability and availability will be discussed in the brochure. The choice of HVDC technology will also impact on the reliability and availability of the grid and the brochure will present typical Mean Time to Failure (MTTF) rates and Mean Time to Repair (MTTR) times associated with the main items of equipment. This work also includes the transmission systems, i.e. the overhead lines, submarine cables and underground cables, which will interlink the nodes of the DC grid.

The converter station operating strategies, the recommendations for spares holding, and the maintenance regimes adopted will all have an impact on the reliability and availability of a DC grid and these will be discussed in the brochure. The principles and practices of DC grid protection will be a key issue in determining the reliability achieved and the availability of energy served by the grid. An overview of this key area will be presented in the brochure, although this is covered in more detail by Working Group, B4.59, see Section 3.7.

A study will be presented in the Technical Brochure based on a Test Circuit developed by WGs B4.57 and B4.58, as shown in Appendix 1. This study is based on a deterministic approach, where each element of the test circuit is assigned a specific failure rate per annum. Appendices to the brochure will discuss other evaluation methods, such as a probabilistic approach using Monte Carlo techniques. This study will show the impact of different scenarios, such as line outage or converter outage, on the energy not served by the grid. The study will illustrate where some outages in well meshed parts of the circuit may have little impact on energy availability, whereas in other more radial regions, some outage scenarios may have a major impact on the energy availability of the grid. The results are presented in terms of the overall energy not served by the grid (in GWhr) and as a percentage reduction from the inherent energy transport capability of the grid.

3.8 Test Circuit for DC grid evaluation

A test circuit proposed by WG B4.58 has been adopted by many of the WGs as a common basis for DC grid evaluation. Each WG will make use of the test circuit and adapt it to its own needs as required. A copy of this test circuit and its parameters is given in Annex 1.

References

[3-1] CIGRE Technical Brochure 533, Paris, 2013

4 DC grids – needs for DC voltage standardisation

4.1 Introduction

A small CIGRE Task Force organised by SC B4, was set to elaborate proposals on recommended voltage levels aiming at prospective standardization of DC voltages for future DC grids. This initiative arose from the report prepared by CIGRE Working Group B4.52 on "HVDC grid feasibility study" and the on-going work from five daughter working groups, discussed in Section 3. The Objective of the TF was to give to developers, proposals on recommended DC voltage levels to be considered, in case it might be beneficial to build a scheme that could be integrated in a HVDC Grid. Although just choosing the right voltage level would not be the single parameter to be considered, at least that is one step in the right direction towards future integration to a DC Grid. Other parameters, such as the operating range, the dynamic range and insulation levels would also need to be part of the standardisation work. An interim report from the TF was issued during the CIGRE Study Committee meeting in Paris in August 2012 and was summarised in the Supplementary Report, issued in 2013. This recommended the establishment of a joint working group between B4 and C1 to study the issues related to DC voltage standardization in more detail.

4.2 CIGRE JWG B4/C1.65 – "Recommended voltages for DC grids"

This joint working group (JWG) was established in 2013. Earlier activities within SC B4 recognized that agreeing on a set of recommended DC voltage levels to be used in HVDC Grids could be beneficial for anyone planning HVDC projects that might potentially become part of a future DC Grid. However, whilst adopting the recommended DC voltages would facilitate future extensions towards DC grids, they would preclude the optimization of DC voltage levels in individual projects, thereby leading to potentially higher investment costs. Therefore, it was recognised that the views and recommendations from system development and economic experts within CIGRE should be included before recommended voltages could be published.

The scope is limited to the steady state Pole to Ground and the Pole to Pole DC voltages. The emphasis will be on VSC HVDC schemes, but LCC HVDC schemes will also be considered. Insulation coordination aspects of DC grids are not being covered in detail in the work.

The JWG is undertaking the following activities:

- Conducting a survey of existing and future HVDC projects with respect to chosen voltage levels
- Presenting a short historical review of harmonisation and subsequently standardisation of voltages in AC networks, as background for similar initiatives in DC grids
- Reviewing available literature and knowledge on insulation coordination of HVDC links and proposing working definitions for voltage levels (nominal/operational, highest, lowest, temporary, transient, etc.) as the basis for the recommendations to be provided.
- Assessing current relevant technical limits and making projections for the future, including:
    - Insulation levels and over-voltage ratings of DC equipment and cables
    - Design aspects of multi-level VSC converters with respect to DC voltages
    - Power levels and limits including the requirements on the AC side concerning the maximum power loss in any one incident, and operational margins for dynamic disturbances Assessing different grounding concepts, converter topologies (symmetrical/non symmetrical, half-bridge/full-bridge, etc.…)
- Studying economic aspects of harmonization of DC voltages :
    - Comparison of strategies including initial optimization of the voltage or choice of recommended values with respect to initial cost and costs of interconnection or future integration of new terminals
    - Availability and cost assessment of upgrading (changing DC voltage) or interconnection (connecting two systems with different DC voltages) schemes
- Present case studies illustrating the process
- Derive from the items above possible recommendations for voltage levels to be used in DC grids in the near future

It should be noted that future HVDC schemes, which are not expected to become part of a DC Grid should not be constrained to the use of the recommended DC voltages.

The JWG is expecting to complete its work in 2015 and their report will be published as a Technical Brochure.

5 European Standards Activities

<u>CENELEC TC8x Working Group 6</u>

The CENELEC TC8x Working Group 6, "System Aspects of HVDC Grids", elaborates standards for HVDC Grid Systems on a European level. It started in April 2013 based on the New Work Items elaborated by the European HVDC Grid Study Group (2010 to 2012) [Ref 4-1]

By November 2013, the Working Group has 24 registered members representing, TSOs, manufacturers, Universities and Institutions.

HVDC Grid Systems are in an early stage of development. In particular, a broad number of applications do not yet exist, which would be needed as a basis for standardisation. Supporting the development and planning of multi-vendor HVDC Grid applications, the Working Group focuses first on preparing the ground for a competitive supply chain of HVDC Grid System components and solutions.

The work builds on the findings of the European HVDC Grid Study Group with the following objectives in chronological order:

- Elaborating technical guidelines and Functional Specifications for HVDC Grid Systems, which are characterized by having exactly one connection between two converter stations, often referred to as radial systems.
- Elaborating technical guidelines and Functional Specifications including applications in meshed HVDC Grid Systems
- Identification of items for HVDC Grid System standardisation
- Elaboration of the HVDC Grid System standards

As markets and technologies mature, new Work Items will be identified and elaborated by the Working Group.

Aiming at the best benefit to the technological development, the Working Group liaises or exchanges information with other organisations working in the same field, or actively contributes to their work as appropriate. By November 2013, this includes

- CIGRE B4 Working Groups on HVDC Grids
- ENTSO-E HVDC User Group
- IEC 73 MT3, DC Short Circuit Calculation
- FOSG WG 2, Technology

As one of its first activities, the Working Group finalised the Technical Report prepared by the European HVDC Grid Study Group "Technical Guidelines for Radial HVDC Networks" [Ref 4-2] including the feedback received from the National Committees of CENELEC. The report was then formally released by CENELEC and is now publicly available from the National Committees.

The draft Functional Specification presented in the above mentioned Technical Report was further detailed and partly restructured and will now be elaborated in detail. For that purpose, the Working Group has formed 5 Subgroups dealing with different topics of the Functional Specification, which are:

- Coordination of HVDC Grid and AC Systems
- HVDC Grid Control
- HVDC Grid Protection
- HVDC Grid System Characteristics and HVDC Grid Equipment
- Models and Validation, HVDC Grid System Integration Tests

For elaborating the Functional Specification close cooperation with the European Transmission System Operators is considered highly important. Therefore, a workshop with ENTSO-E is planned for mid-2014 to discuss technical aspects of the specification and to receive feedback from the TSOs.

The results of the work shall be made available to the public as soon as possible. Therefore, the Working Group intends issuing draft versions of the Functional Specification document on a yearly basis starting at the end of 2014.

References

[4-1] FOSG WG 2; Supplementary Report No. 1, “Overview of work in CIGRE and CENELEC related to the Supergrid vision”; March 2013

[4-2] CENELEC TR HVDC Grid, CLC TR 50609

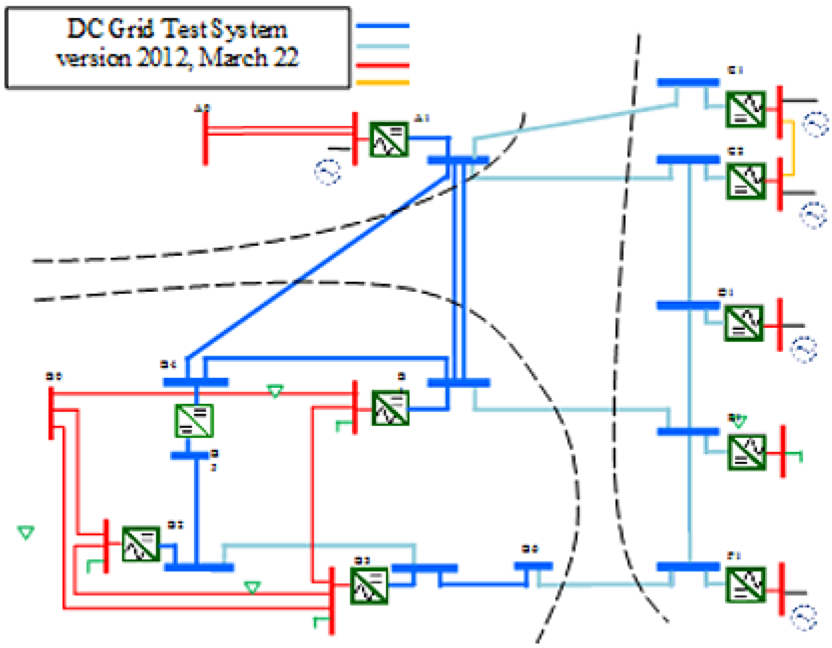
5 Conclusions

The aim of this supplementary report has been to collate the on-going activities, external to the FOSG, which impact in the work of WG 2. It is clear from the level of activity related to DC grids that the contents and conclusions of the FOSG report are still valid and that other workers in the field are pursuing these ideas in ever increasing depth. All of the on-going study activity identifies challenges in the implementation of a DC grid, but to date none have identified impassable technical obstacles, which could invalidate the concept of a Supergrid. The work of CIGRE has identified two key areas where further work is needed, and is presently on-going, to bring the Supergrid to a reality. One is the need for a power flow control technique, which can receive commands from a dispatch centre and be implemented by any vendor of HVDC technology. The other is a fast acting protection system, which can detect and discriminate faults on the DC network and isolate the faulted circuit, enabling the remainder of the grid to recover to a stable operating power flow.

Since the first issue of this Supplementary report CIGRE has instigated a new Working Group to look into the needs for the creation of standard DC voltage levels for application on DC grids. This work will consider the merits and de-merits of adopting standard DC voltages. It is anticipated that the results of this work will be published in 2015..

However, the Supergrid is not simply a technical challenge, the economic, logistical, supply chain, skills and social aspects must also be considered to ensure that the Supergrid becomes a reality. These are the subjects which will be reported on by other FOSG WGs.

Annex 1 – Test system for DC grid evaluation



Buses:

Bus	AC [kV]	DC [kV]	Power [MW]	Frequency
A0	380	------	Slack bus	50Hz
A1	380	±400	-1500	50Hz
B0	380	------	Slack bus	50Hz
B1	380	±400	900	50Hz
B2	380	±400	1500	50Hz
B3	380	±400	1500	50Hz
B4	-----	±400	0	------

B5	-----	±400	0	------
B6	-----	±400	0	------
C1	155	±400	-500	50Hz
C2	155	±400	-500	50Hz
D1	155	±400	-1000	50Hz
E1	155	±400	100	50Hz
F1	155	±400	-500	50Hz

Lines:

Line	Type	Circuits	Voltage [kV]	Construction	Length [km]
A0-A1	AC	2	380	Overhead	300
A1-B1	DC	2	±400	Overhead	400
A1-B4	DC	1	±400	Overhead	500
A1-C1	DC	1	±400	Cable	200
A1-C2	DC	1	±400	Cable	200
B0-B1	AC	1	380	Overhead	400
B0-B2	AC	1	380	Overhead	300
B0-B3	AC	1	380	Overhead	400
B1-B3	AC	1	380	Overhead	200
B1-B4	DC	1	±400	Overhead	200
B1- E1	DC	1	±400	Cable	200
B2-B3	AC	1	380	Overhead	200
B2-B3	DC	1	±400	Cable	200
B2-B5	DC	1	±400	Overhead	300

Line Parameters:

Line type	R' [Ω/km]	L' [mH/km]	C'[µF/km]	Power Rating* [MW/MVA]
400kV DC Cable	0,010	1,40	0,00	2400
400kV DC Overhead	0,006	1,00	0,00	2400
380kV AC Overhead	0,020	1,018	0,0116	2340
155kV AC Cable	0,0354(AC)	1,40	0,16	275

*Values for power ratings are calculated assuming nominal voltages, and bipole values are specified for DC overhead lines and cables.

ACDC Converters:

Bus	R	L	G	C	Tap changer range	Power Rating[MW]
A1						2400
B1						2400
B2						2400
B3						2400
C1						500
C2						500
D1						1000
E1						100
F1						500

DCDC Converter:

Line			
B4-B5			

Slack Buses:

Bus	S	T	Frequency Droop
A0		12	
B0		15	

About Friends of the Supergrid

The Friends of the Supergrid (FOSG) is a group of companies which have a mutual interest in promoting and influencing the policy and regulatory framework required to enable large-scale interconnection in Europe. With a special insight into the technology needed to create Supergrid the Friends will be empowered to build the know-how to deliver it in practice.

FOSG combines companies in sectors that will deliver the High Voltage infrastructure and related technology, together with companies that will develop, install, own and operate that infrastructure. The risks of providing this new transmission service will be reduced by the early knowledge gained during the policy formation and design stages. FOSG is able to present 'cradle to grave' interconnection solutions to policy makers and others looking to develop energy policy across Europe through to 2050.

FOSG counts on 19 members including: ABB, ACS-Cobra, ALSTOM, Bernard Energy Advocacy, CESI, DONG Energy, Elia Group, General Electric, Hochtief Solutions, Intel, Mainstream Renewable Power, National Grid, Nexans, Parsons Brinckerhoff, Prysmian Group, REN, RTE, Siemens and Visser & Smit Marine Contracting.

www.friendsofthesupergrid.eu