e-HIGHWAY 2050

Modular Development Plan of the Pan-European Transmission System 2050

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Annex to D3.1 - Technology Assessment Report

Transmission Technologies: HVDC LCC, HVDC VSC, DC breakers, tapping equipment, DC/DC converters

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Document information

General purpose

This document is an annex of deliverable D3.1 focusing on the technology assessment (technical and economic performances) of generation, storage, transmission and demand-side technologies. It includes the assessment and outlook of the following key components of the HVDC technology (except cables and lines), i.e. converters (VSC, LCC) and other critical components (DC breakers, tapping equipment, DC/DC converters). It provides an explanation of the key variables selected, the methodology for the data construction as well as a technical outlook as of today and 2050.

The present document is complemented by an attached Excel file providing the data compiled according to the methodology described in the in the next sections.

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Legal disclaimer

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HVDC technology

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1 Introduction

High Voltage Direct Current (HVDC) is suitable for the transport of large amounts of power over long distances (by overhead transmission lines) as well as for long underground/submarine cable transmission and for interconnection of asynchronous systems.

The main advantages of HVDC over a conventional HVAC transmission are its ability to conduct more power for a given conductor/corridor, the overall system stability improvement thanks to its controllability, the higher undergrounding potential and the possibility to prevent cascading AC failures through the DC connection.

The key components of the two types of HVDC technologies used to convert electrical current from AC (Alternating Current) to DC (Direct Current) mode and vice versa are represented by:

- **Current Source Converters (CSC)**[1] are the conventional, mature and well established key component used to convert electrical current from AC to DC and vice versa. Such converters require a synchronous voltage source. Multi-terminal CSC connections are possible and exist (two schemes exist). However, larger systems with a more complex structure are not possible from a practical point of view (due to control complexity and problems with power reversals).
- **Voltage Source Converters (VSC**) are self-commutated converters using devices[2] suitable for high power electronics applications. The VSC technology can rapidly control both active and reactive power independently from each other. It allows a total flexibility to place converters anywhere in the AC network (no synchronous voltage source is required). As of today, the VSC-HVDC technology still needs to face some technology challenges, such as DC breakers, higher powers, losses reduction and further deployment in multi-terminal applications.

Both types of converters can be used in a full HVDC scheme (AC/DC converter – HVDC line or cable – DC/AC converter) or in a back-to-back (B2B) HVDC scheme (AC/DC converter – DC circuit - DC/AC converter, with all these components installed in a single station) as well as for multi-terminal applications, as described in the following sections.

Other critical components of the HVDC technology are the following:

- **DC breakers**, which will be needed for large HVDC grids to separate faulty parts of the grid during earth faults. The DC fault current breaking functionality will be needed for larger HVDC grids to enable more than one protection zone by separating 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 zero crossing current as in AC applications. This has been shown with full electronic breakers

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[1] CSC is also known as LCC (Line Commutated Converters). In the following they are used as equivalent terms

[2] Gate Turn-Off (GTO) thyristors, Integrated Gate Commutated Thyristor (IGCT) and Insulated Gate Bipolar Transistor (IGBT)

which operate very fast but have relatively high on-state losses. Recently, a hybrid DC breaker concept has been presented having a mechanical bypass path to reduce the losses to near zero (60 kW at 320 kV DC) while maintaining clearance time.

- **Tapping equipment**: Tapping is a converter that is connected to a point to point connection somewhere along the line or cable and a minor part of the active power is 'tapped' to supply a load. It is a variant of the multi-terminal system but highly cost/loss optimized for a minor power rating compared to the main power rating of the HVDC scheme which it is connected to.
- **DC/DC converters**: Unless the Supergrid[3] is specifically designed to operate at a common DC voltage and any scheme not at the common voltage is 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.

Key functions of HVDC are:

- Transmission capacity enhancement
- Power flow controllability
- Voltage control and stability
- Power oscillation damping
- Limitation of short circuit levels in AC systems

Key HVDC applications are:

- Long-distance bulk power delivery transmission
- Underground and long submarine cable transmission
- Interconnection of asynchronous systems
- Power delivery to large urban areas

2 Technology performance characteristics

2.1 Variables selected for HVDC converters

Four technical characteristics have been selected, the final one (security of supply) being itself measured by four specific technical variables.

2.1.1 Transmission losses – index of losses per converter station in percentage of rated power [%].

Computation: losses are measured in percent of the nominal rating of the converter station during load and no-load.

2.1.2 Transmission capacity – maximum power at which the transmission equipment can be operated [MW]

Computation: measuring voltage units X current capacity.

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[3] Meshed HVDC Grid with multiple protection zones. See Friends of the Supergrid publications

2.1.3 Transmission distance – maximum transmission distance at an acceptable level of losses

Computation: depending on the level of losses that can be accepted from an economic point of view.

2.1.4 Security of supply – overall variable

Computation: result from four specific technical variables listed below. It is assumed that it is also impacted by the commercial availability and the integration in operation of other critical systems, such as DC breakers, tapping equipment, DC/DC converters.

2.1.4.1 Reliability – index of the likelihood of a contingency event

Computation: number of trips per station and per year [Nb/y].
A contingency event is defined by either loosing part of the power of the totality of it[4].

2.1.4.2 Availability – Probability of finding the component/device/system in the operating state at a random state.

Computation: scheduled energy availability as a percentage of the total number of hours per year [%].

2.1.4.3 Maintenance (frequency) – interval at which scheduled outages are planned. This variable impacts the Availability variable as well as the cost of maintenance.

Computation: interval of maintenance [scheduled outages frequency].

2.1.4.4 Maintenance (outage time) – amount of time required to perform scheduled maintenance

Computation: applies either to the whole equipment or to part of it [number of weeks or days per maintenance outage].

2.2 Variables selected for DC breakers[5]

The variables selected are the same as the ones identified above for converters (except for transmission distance).

2.3 Assumptions for the expected evolutions of technical data from 2013 to 2050 for HVDC technology

This section is organized in two subsections:

- The first one presents some technological insights for each of the above selected variables of the HVDC technologies[6] as seen by manufacturers at the current stage of development (2013).
- The second one is focused on the technical outlook at 2050 and the underlying assumptions to project trajectory of technical performances.

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[4] Traditionally the specifications of the network design might allow for some trips per year of part of the power; but losing all the power is allowed only in extreme cases.

[5] The tapping equipment for HVDC and the DC/DC converters are described in the current TAR; however, no datasheets will be provided since these are emerging technologies.

[6] Except for cables and lines (which are addressed in the reports related to passive transmission equipment)

2.3.1 Technical outlook today (2013)

The technical outlook for HVDC technology at the current stage is carried-out for the two representative technologies of HVDC converters (CSC converter and VSC converter) as well as for key components (such as DC breakers).

They are all detailed in the attached datasheets. The rationale for selecting these two particular technologies (with specific ratings) was based on the following assumption:

> *The representative of the CSC converter (respectively VSC converter) corresponds to the max power rating available today.*

Indeed such a selection (max rating for HVDC converters) allows covering the whole range of converters equipment commercially available and in operation today.

In the following sections a technical outlook for these two representative converters is presented per selected variable. The case of DC breakers, tapping equipment and DC/DC converters is examined at the end of the chapter.

2.3.1.1 Transmission losses in converter stations (CSC and VSC)

The use of Voltage Source Converters (VSC) for HVDC power transmission was first pioneered 15 years ago and since then there have been a number of evolutions of the converter technology used. The first projects were built with a 'simple' converter topology denoted 'two-level' converter but with an advanced technology voltage valve building on series-connected IGBT-valves. At this time (end of 90s) the station losses for the first commercial system with a power capability of 55 MW and DC voltage level of +/- 80 kV were around 3 %.

Today the losses per VSC station are still higher than those of the more mature CSC technology: 1% of rated power for VSC against 0.70% of rated power for CSC. Losses in transformers, reactors and auxiliary losses account for a major part of the losses.

It should be noted that in the general context of such loss reduction for VSC, the development 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.

2.3.1.2 Transmission capacity

This variable is the main parameter that system planners start with at the initial scanning of transmissions scenarios. The evolution of this parameter is fundamental in the additional planning state. It is irrelevant how good the other variables score if the capacity of the transmission solution does not meet the demand for the scenario. The technology has always strived for increase in sizes, but constraints, such as how big loss of power is acceptable at a single contingency, have to be addressed.

Transmission capacity is directly proportional to the voltage and current of the DC-circuit:

- The increase in voltage for the converter posed a challenge before the introduction of the multi-level converter since the converter valve was built on series-connection of IGBTs; the introduction of multi-level converter reduced the switching voltage at each time drastically and became independent from the DC-voltage level. This implies that the overall dielectrical properties do limit the DC-voltage from a converter perspective and all the findings concerning the CSC HVDC development where 800 kV exist can be reused.
- The current rating is dependent on the development of semiconductors. Today the step from 600 A to 2000 A has been achieved for IGBT technology. CSC installations use thyristors which can be used up to 4-4.5 kA.

As a result, maximum transmission capacity of converters reaches the following levels:

- CSC technology schemes are now in service at DC voltages up to ±800 kV and power levels up to 8000 MW.
- In the last 15 years the VSC technology has arisen from some hundreds of MW to around 1 GW with one symmetric monopole transmission system.

2.3.1.3 *Transmission distance*

The maximum transmission distance for HVDC systems are resulting from techno-economic constraints. Today the maximum installed length of the line/cable is about:

- 2000 km (OHL) and 580 km (cables) for CSC
- 1000 km (OHL) and 300 km (cables) for VSC.

2.3.1.4 *Security of supply*

Four variables have been chosen to measure Security of supply as detailed in the table below. It should be mentioned that reliability, availability and maintenance variables are at about the same level in 2013 for both converter technologies (VSC and CSC).

Variables for Security of supply	**Today (2013)**
Reliability	2 trips per year per converter
Availability	99% for both types of converters.
Maintenance (frequency)	every 2nd year for both types of converters
Maintenance (outage time)	1 week/year for both types of converters

It is assumed that in order to secure a given level of supply, different measures could include strategies based on redundancy of system components, technology development of key equipment, processes and methodologies, etc.

2.3.1.5 *Converter arrangements for VSC (respectively CSC) technology*

HVDC converters are considered at the component level - e.g. only three phase converters between the AC (transformer) connection and the positive, negative, or zero DC voltage connection. They are thus not described at the detailed power electronic level.

Converter arrangements options are monopoles (symmetrical and asymmetrical) and bipole.

The choice will mainly rely on the need for power capability, redundancy and losses. The bipole configuration will result in higher maximum power capability since the number of converter is doubled and a better performance in terms of n-1 criteria but also in a more complex and costly solution.

The above choices apply to both VSC and CSC technologies.

2.3.1.6 *Converter topologies for VSC*

For existing applications of VSC HVDC, the modular multi-level converters (MMC) are typically arranged in half-bridge topology. In this case the valve levels consist basically of a combination of two IGBTs (and their associated diodes) and a storage capacitor. As a consequence the converter can produce dc voltages always in one polarity. Power reversal of the link is done by reversing the dc current.

However, for overhead line (OHL) applications of VSC HVDC, topologies in full-bridge arrangement are also available as already known from numerous other VSC applications. In this case the valve levels consists of twice the amount of IGBTs allowing to connect the storage capacitors to the dc terminals also in opposite polarity. Hence, the dc voltage can be reversed. This feature allows to operate OHL schemes at reduced dc voltages in case of insulation problems (e.g. due to pollution) as well as to reverse the voltage temporarily during dc faults (e.g. due to lightning strokes) in order to extinguish dc fault currents. Hence, the same performance regarding fault clearance and fault recovery as known from LCC technology can be obtained. The advantages of this solution have to be balanced by the fact that conducting losses will be doubled for the converters and that the cost will be increased due to the increased amount of semiconductors. The choice has to be evaluated for each project depending on functional requirements and cost/loss evaluation.

2.3.2 Technical outlook at 2050 for HVDC VSC and CSC converters

On several continents an evolution of the electrical grid is needed to enable the integration of remote large-scale wind and solar power generation and growing mega-cities. HVDC grids can leverage the fundamental benefits of VSC transmission with the additional value of integrating the point-to-point connections into an electric network, e.g. sharing of transmission capacity between generation, balancing and load resources as well as the creation of a larger market exchange of electric power. Furthermore, a grid design will reduce the total amount of equipment and capital cost compared to building multiple single links. The gradual introduction of HVDC grids during the next 15 years is foreseen to be the key enabling technology to match renewable targets on the global markets. The speed of introduction of more advanced VSC-schemes is heavily depending on the near term targets and development of market scenarios.

The evolution of the HVDC grid will be taken in steps. The first main development step foreseen to take place, in parallel to a few first *regional multi-terminal projects*, is that the customers planning a grid will require *grid-enabled point-to-point systems* that should be prepared for a future extension to a *three- or multi-terminal system*. Some recent *VSC point-to-point* projects, e.g. Nordbalt (SE-LT) and South-West Link (SE) have a "grid-enabled" feature as a specified requirement. In addition, plans for *regional Multi- Terminal HVDC (MTDC) Grids* have emerged on the market during 2011. Examples are projects such as Shetland (UK), Atlantic Wind Connection (US), and South-West Link (SE). Once one or a more of these breakthrough projects have been commissioned, it is likely that the market for Grid will expand, both as new multi-terminal projects and expansion of existing point-to-point systems to three or more terminals in one network.

The first small regional systems can be operated as one protection zone without interruption equipment, such as DC breakers; but as the size and complexity of DC networks increase, DC breakers may be introduced gradually. It is realistic to expect that the existing rated voltage and power will increase while losses will reduce during the next ten years. Significant incremental improvements of HVDC technologies are foreseen from the levels today.[7]

In a longer run, future developments foresee an extended domain of use of HVDC technologies, such as far-offshore and ultra-deep submarine connections (2000m+), ultra-high voltage and higher transmission distance, and combining HVDC and HVAC networks and related impact on reliability.

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[7] Organisations such as CIGRÈ, CENELEC and IEC are studying various aspects of HVDC. They are preparing guidelines and technical reports/standards on common operational procedures to facilitate an open market for future system expansions.

2.3.2.1 Transmission losses in converter station

The transmission losses of the HVDC VSC system have been reduced (from a level of 3 % in 1999) thanks to three main developments, which are expected to continue in the coming decades:

i. **Development of semiconductors** from the first generation silicon IGBTs for 2,5 kV with a current rating of 600 A with a rather high on-state losses due to optimization for high switching frequency, 2 kHz, until today's semiconductors of 4,5 kV and a current rating of up to 2000 A with a reduced on-state losses due to optimization of the lower switching losses in recent topologies resulting in almost 1 % loss reduction since 1999 figures. Further improvements due to the introduction of new components in silicon as well as future use of high bandgap semiconductors, such as SiC, will further drive the loss reduction in the coming years.

ii. The **use of improved topologies** from the basic *two-level converter* through the use of *three-level converter* and then to the recently introduced *multi-level converter schemes* have enabled a better utilization of the semiconductor and therefore a loss-reduction since the total power rating has been increased at the same absolute value of losses, thus reducing the losses in percentage. There are a lot of R&D activities among the academia and this might spark improved topologies until 2050 which will also drive a further loss reduction.

iii. The **modulation principle** that determines the switching pattern has been greatly improved and used resulting in a switching frequency for each device that has been reduced from 2 kHz to approx. 150-200 Hz. This has greatly reduced the switching losses.

The above developments explain that at 2050 the losses per VSC station are expected to reach the same values as those of the more mature CSC convert technology, i.e. 0,50% of rated power.

2.3.2.2 Transmission capacity

The use of Voltage Source Converters for HVDC power transmission is expected to grow as the transmission capacity increases. Applications for CSC will most likely be outside Europe. In Europe VSC will be the predominant technology for most applications; but the CSC will be used in Back-to-Back applications and other specific applications where the main purpose is to transmit bulk power with overhead lines and or subsea cables.

Regarding the improvement of transmission capacity, key challenges are the development of new types of semi-conductors, novel multi-level switching topologies with more parallel components and higher power ratings in operation. More specifically in the shorter term (i.e. the next decade) such HVDC techno-economic challenges will include:

- New types of semiconductors (SiC , diamond, etc.) which will allow the development of new thyristors;
- Development of novel multi-level switching topologies (architecture and switching modes, paralleling components) to enhance transmission capacity.

At 2050 power ratings in operation could reach levels of (13 GW at 1100 kV for CSC terminals (bipolar); at 1100 kV for VSC terminals (bipolar))[8] taking into account an economic/technical optimum at the system level.

In a longer run, it is expected that ultra-high HVDC will be implemented. Related technological challenges include: air insulation of water cooled thyristor valves, transformer oil/paper insulation, numerical analysis tools to UHVDC designs, etc. More futuristic challenges in cooperation with cable manufacturing industry relate to the development of SCDC (superconducting DC cable transmission).

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[8] Studies are now in progress to take CSC technology to ±1,100 kV DC voltage and scheme powers of 13,000 MW.

The transmission capacity for both technologies is a function of the voltage and current development. However, the demand for ultra-high DC transmission is limited to networks which can handle the sending and receiving of such amounts of power in single nodes without jeopardizing the overall reliability of the system.

2.3.2.3 Transmission distance

With increased voltage levels the longer transmission distances for CSC technology (with OH lines and cables) will be economically more feasible as the current and consequently losses can be reduced.

At 2050 the maximum length of the line/cable between two nodes of the system is expected to reach 3000 km (OHL) and 1000 Km (cables) both for CSC and VSC.) . The rationale behind these projections is that the losses in the cable/OHL shall be reasonable, i.e. they have to be tolerable for the complete system. Approximately 10% is an acceptable level in our view. This is true for bulk transmission. In case of a critical load that cannot be met in any other way, this level can be extended. For example in northern Canada, fuel for generating electricity is flown in by helicopter. In this case a higher figure can be acceptable.

2.3.2.4 Security of supply

All variables of security of supply are foreseen to have further development in order to reach higher system performance. Reliability, availability and maintenance variables are expected to reach about the same level in 2050 for both converter technologies (VSC and CSC).

Variables for Security of supply	2050
Reliability	1 trips per year for both types of converters
Availability	99,9% for VSC converters and 99,5% for CSC converter [9]
Maintenance (frequency)	every 5th year for both types of converters
Maintenance (outage time)	2 days/ year for both types of converters

One of the main driving forces of many transmission networks is the need to improve the security of supply. This will impose more stringent requirements also on future HVDC systems. Therefore, there is a need to focus R&D on parameters influencing the security of supply. The figures in the 2050 projections are based on the assumption that the R&D work will lead to the development of HVDC systems with close to zero downtime. The rationale behind this is that this is mostly a cost/benefit problem. Thanks to work on innovative redundancy and maintenance schemes, security of supply will be improved. The TSO, as a customer of HVDC technologies will drive these future developments.

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[9] Such high levels might be seen by some players as a risky assumption for the availability of a converter station (see Cigre 2012: A Survey of the reliability of HVDC systems throughout the world during 2009 – 2010). However, at Cigre 2014, a very high availability for the Murray Link project was reported, therefore indicating that such levels might be achievable at the 2050 time horizon (similar improvements, in terms of reliability, have been achieved in the car industry during the period ranging from 1970 to today).

2.3.3 Technical outlook at 2050 for DC breakers

The 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 zero crossing current as in AC applications. This has been shown earlier with full electronic breakers which operate very fast but have relatively high on-state losses. Recently, a *hybrid DC breaker* concept has been presented having a mechanical bypass path to reduce the losses to near zero (60 kW at 320 kV DC) while maintaining clearance time.

The technology challenges are to enable the very rapid fault detection and current breaking, in the range of 5 ms, needed for a DC breaker since only the inductances will limit the di/dt of the fault currents and the fault levels will be extremely high if the breakers are too slow. The second issue is the DC-insulation that also poses a greater challenge than an AC-insulation case.

2.3.4 Technical outlook at 2050 for tapping equipment for HVDC

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. Tapping functionality is therefore foreseen to be a requested part of the HVDC technology.

For the tapping functionality the main challenge is to find a cost effective solution. The tapping is a special case of the multi-terminal system, where the power rating of the station is much smaller than the main converter station in the scheme. The initial cost for the ‘first’ MW is very high for an HVDC station and this makes the tapping solution a challenge mainly from a cost perspective.

2.3.5 Technical outlook 2050 for DC/ DC converters

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. 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 fulfill the same function.

2.3.6 Multiterminal HVDC (MTDC) systems

With respect to the already mentioned evolution of the HVDC grid (see 2.3.2), a critical stage will be the deployment of new multi-terminal projects as well as the expansion of existing point-to-point systems to three or more terminals in one network.

To that purpose, VSC technology is more adapted than CSC technology to the design of full meshed grid (since there is no need to power flow reversal, it is not subject to commutation failures, etc.).

As a matter of fact, in conventional CSC technology, reversing power flows requires reversal of the polarity of the converters. The complexity that this introduces into multi-terminal operation has limited the widespread use of multi-terminal systems. Today, 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 a real possibility of designing multi-terminal systems and hence fully meshed DC grids.

It is foreseen that meshed HVDC grids with multiple protection zones will be available from 2030 on (based on voltage source converters).

2.4 Methodology for data gathering

The methodology for data gathering has been consistent for all active technologies.

- For each technology a first set of data parameters were identified by a group of key experts within T&D Europe. These data parameters or variables were selected based on their economic and technical importance for the active technologies when it comes to choosing the future grid technologies from a planning perspective. The parameters reflect the key technical parameters that have and will be the base for specifying the transmission schemes during planning, construction and evaluation phases of each future project.
- This set of parameters were verified and approved in T&D Europe. The assumptions were verified by a larger group of experts inside T&D Europe that agreed on the link between the selected data set and the relevant parameters.
- An appointed expert group collected the data and prepared a first draft during several workshops with 5-10 experts from organizations in T&D Europe.
- The data gathering sources are reference projects, published articles and R&D plans that give the robustness needed to the figures. One element of concern in this approach can be the transparency for some partners and stakeholders outside of T&D Europe; however, T&D Europe believes that a combination of hard facts from relevant reference projects, including the history and some quantitative and qualitative assumptions, are a sound base for the dataset. Although such an approach will always lead to interpretation, T&D Europe believes that this is a fair and appropriate way of collecting data.
- The data gathering of VSC technology was presented in WP 3 group meeting as a dry-run test with all WP's to agree on the proposed approach to be used for the remaining active transmission technologies.
- After compilation of data parameters for all active transmission technologies, a second round of validation, with all the relevant stakeholders, is performed before submission of the present report to the e-Highway 2050 coordinator. The robustness will be further explained in the next section.

Mode	Type of data gathering	Nature of data processing	Comment
Own expertise	Informal knowledge captured by interviews with internal experts	Modelling	Yes
		Data gathering	Yes
	Knowledge formalized in published articles	Modelling	Yes
		Data collection	Yes
Other experts of the field	Informal knowledge captured by interviews with external experts or workshops	Modelling	N/A
		Data gathering	N/A
	Knowledge formalized in published articles	Modelling	N/A
		Data gathering	Yes
	Knowledge structured in State of the Art studies	Modelling	N/A
		Data gathering	N/A
Other mode (please describe)	Not used	Modelling	N/A
	Not used	Data gathering	N/A

Modes for data gathering

2.5 Conclusions on robustness of the produced data

The methodology for verification of data robustness has been consistent for all active technologies. All data have been verified in several steps including workshops with experts from the T&D Europe organization to increase the confidence in the results.

All data corresponding to technical variables of the active technologies have been evaluated during the data gathering process based on their probable market readiness over the time horizon for the project.

As a consequence, the data has a high degree of confidence for each time horizon: today, 2020, 2030, 2040 and 2050.

For some of the key parameters in the data sheets uncertainty levels have been approached by including value ranges. The uncertainty is handled by providing min and max values, which shall contribute to increase the robustness of the data.

3 Technology readiness and maturity

3.1 Variables selected

The following characteristics representative of the technology readiness and maturity of technological variants for HVDC VSC and CSC converters have been selected.

3.1.1 **VSC – voltage source converter**
Computation: TRL index

3.1.2 **CSC – line commutated converter** or current source converter
Computation: TRL index

3.1.3 **Converter topology –** description of the topology of equipment which results from the need for power capability, redundancy and losses
Computation: monopole or bipole

3.1.4 **Multi-terminal HVDC –** planning options of such HVDC grids are either regional DC grids (multi-terminal systems with one protection zone) or interregional DC grids (several protection zones with sectionalization).
Computation: commercial availability of each of the above-mentioned planning options [Y/N]. If Y a TRL index is provided.

3.1.5 **DC/DC converters** – equipment changing the voltage in a DC network
Computation: commercial availability or no availability of such device [Y/N]. If Y a TRL index is provided.

3.1.6 **DC breaker** – such equipment is needed in large HVDC grids to isolate faulty parts of the grid during earth faults
Computation: commercial availability of a fault current breaker [Y/N]. If Y a TRL index is provided.

3.1.7 **Tapping equipment –** such functionality is needed in HVDC systems
Computation: commercial availability of such functionality [Y/N]. If Y a TRL index is provided.

3.2 Assumptions for the expected evolutions of technical data from 2013 to 2050 for HVDC technology

Technology readiness level is a quantitative index reflecting the degree of maturity of a given technology (and each of its components). The mark (from 1 to 9) synthesizes the expected evolutions described in the technical outlook as of today and in 2050.

Technology readiness and maturity	**Time horizon**				
	2013	**2020**	**2030**	**2040**	**2050**
Overall HVDC-VSC TRL	9	9	9	9	9
DC breaker TRL	7	9	9	9	9
Tapping equipment TRL	4	7	9	9	9
DC/DC converter TRL	4	7	9	9	9
MTDC Regional DC Grid TRL	9	9	9	9	9
MTDC interregional DC Grid TRL	4	7	9	9	9
Overall HVDC-CSC system TRL	9	9	9	9	9

From this table the following conclusions can be drawn:

- HVDC CSC (60 years commercial experience) and VSC (more than 15 years commercial experience) are already mature technologies.
- For the tapping equipment for HVDC technology, laboratory testing of prototypes are ongoing.
- DC breakers are under pilot demonstration as of today and should reach a status of readiness for full scale deployment by 2020.
- HVDC MTDC (interregional, VSC) are expected to be in operation from 2030 on.

3.3 Methodology for data gathering

Data gathering on maturity of technologies relies on expertise of T&D Europe members.

3.4 Conclusions on robustness of the produced data

See section 2.5

4 Possible implementation constraints

4.1 Variable selected

The selected variable is the following:

4.1.1 Converter station size

Computation: development in percentage of a selected average footprint for a VSC and CSC converter station respectively.

The physical sizing (surface occupation) is a constraint that is included in the “environmental impact and public acceptance” data type (see chapter 6).

Although other variables influencing implementation constraints could be evaluated, they are more related to the owner’s perspective rather than to the manufacturer’s side.

4.2 Context of implementation constraints for HVDC

An important step needed to develop HVDC grids further is the aspect of **interoperability** of different individual projects and technologies of different manufacturers. Interoperability requires standardization of the basic principles of design and operation of HVDC grids. As a starting point for the standardization of HVDC grids some fundamental planning criteria need to be defined, leading to different types of HVDC grids (e.g. transmission and distribution HVDC networks, sometimes also referred to as "local" and "inter area" grids). A Grid Code for the pan European Overlay Grid needs to be defined. Based on the fundamental planning criteria, important questions to be answered with respect to HVDC grid standardization include:

- Standardization of DC voltage levels
- Concepts for interconnecting local and inter -area DC grids, probably with different DC voltage levels
- DC grid topologies
- Control and protection principles
- Fault behaviour
- (Typical block sizes for converter stations)
- Connection requirements
- Communication requirements
- Behavior during emergency operation and restoration.

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

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

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

The degree of interoperability (from 0 to 100 %) is hard to evaluate today; but the most critical issues can be solved before 2020 by grid codes and standards if the involved stakeholders; such as manufacturers, TSOs and regulators; join efforts to make this happen. Complex multivendor point-to-point schemes are under construction or already commissioned constituting an early indicator of possible interoperability problems for the future HVDC grids. Customers' specific issues will still exist as they do on the AC-side after more than 100 years of operation of the AC-grid.

The permitting issue is still very country specific and a general number (such as an average number of months to obtain a permit) cannot be given. A reduction is expected since the VSC based HVDC is more flexible and adaptive but this is to a large extent a legal issue and not a technical one.

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

4.3 Methodology for data gathering

All data on “converter station size” projections are based T&D Europe experts' assessment.

4.4 Conclusions on robustness of the produced data

The degree of confidence of “converter station size” of HVDC components for a time horizon after 2030 is however subject to uncertainty.

5 Costs

5.1 Variables selected

5.1.1 CAPEX – Capital investment in Euros per kW installed [€ /kW]

Data to be provided at a later stage

5.1.2 OPEX – Operational costs in Euros per kWh produced [€ /kWh]

Data to be provided at a later stage

5.1.3 Lifetime – Economic useful lifetime of converters in [years]

The lifetime of the converter stations for CSC and VSC technology refers to the expected economical operational duration, in years, of the converter stations. The lifetime of the converter stations includes refurbishments to replace certain components which have shorter lifetime expectancy than the overall converter station.
Computation: number of years

5.2 Underlying assumptions

As above.

5.3 Methodology for data gathering

All data on lifetime projections are based T&D Europe experts' assessment.

5.4 Conclusions on robustness of the produced data

See 2.5 above

6 Environmental impact and public acceptance

6.1 Variables selected

6.1.1 Land use - surface occupation of the HVDC converter (or any other component) [m^2].

Computation: typical surface occupied for the considered equipment.

6.1.2 Noise generation

Computation: dB

6.1.3 EMC - electromagnetic field generated by the considered component

Computation: issue or no issue.

6.1.4 CO2 emissions

Computation: issue or no issue

6.1.5 Health and safety [months on site].

Computation: months on site means the amount of time needed on the converter station site to construct the converter stations. The period starts from the beginning of civil works and ends when converter stations are ready for commercial operation.

6.2 Environmental impact today and in 2050

One of the main reasons to use the HVDC technology is the reduction of transmission losses in the energy system. Losses in the energy system have a significant environmental impact. Therefore, the continuous development of HVDC technology to reduce losses has a much larger impact on the environment rather than the environmental impact of the HVDC plants themselves.

HVDC plants can be decommissioned after end of life. It is assumed that the net value of the recycled plant will be greater than the dismantling costs associated with the converter installation.

An HVDC plant consists of the following materials to be handled properly at end of life disposal:
Metallic materials

- Construction steel
- Stainless steel
- Cast iron
- Galvanized steel
- Electrical steel
- Copper
- Aluminum

Return to a recycling company.

- Insulating oils
- Sulphur hexafluoride (SF6)

Shall be recycled or sent for destruction in line with environmental agencies.

- Cellulose (paper and wood): to be sent for incineration at very high temperature.
- Silicone: to be sent for incineration at very high temperature.
- Glass fibre, laminated. Should be sent to landfill.
- Drying agent. Sent for destruction.
- Other Components. The components should be taken care of in view of the content.

Although manufactures are continuously working to reduce the environmental impact, specific figures are very hard to predict at this stage.

In terms of public acceptance, the main advantages of the VSC based HVDC solutions are the following:

- VCS HVDC station have a much smaller footprint than CSC HVDC stations
- The power density for each HVDC OHL-line is double, which makes the necessary number of lines much lower than HVAC.

These advantages are expected to improve public acceptance.

The introduction of the XLPE-cable for underground transmissions systems on-shore will also greatly increase public acceptance.

6.3 Methodology for data gathering

All data on environmental aspects are based on T&D Europe experts' assessment.

6.4 Conclusions on robustness of the produced data

See 2.5 above

7 Market and supply chain issues

7.1 Variables selected

7.1.1 Market issues - cumulated number of units installed [Nb.]

Computation: existing market studies.

7.1.2 Operation experience - cumulated number of years in operation for a given equipment [Nb.]

Computation: starting date is the first integration of the technology by a TSO (corresponding to a TRL of 9)

7.2 Underlying assumptions

See section 2.3.2. Please note that interoperability issues are discussed in chapter 4.

7.3 Methodology for data gathering

All data on market projections are based T&D Europe experts' assessment.

7.4 Conclusions on robustness of the produced data

See 2.5 above

8 Dynamic performance of technology

8.1 Variables selected

One of the main reasons to use HVDC technology is the enhancement of transfer capability in the grid. One key feature that enables this is the dynamic performance of HVDC that allows TSOs to operate the transmission system closer to its limits, relieving congested lines, taking part in voltage and frequency control, etc. The flexibility of the HVDC control enables an adaptation to changing network conditions when the grid is reconfigured. Today these cases must, most often, be studied off-line and then added as Modes of Operation. In the following paragraphs we have chosen some of the important features that are crucial for evaluation of the technology.

8.1.1 Adaptive control

This means that the control parameters and the control performance is changed on-line if any network parameter is changed. This will be based on the use of modern control theory. The greatest challenge is to handle new situations for these complex systems and to deploy adaptive control in an industry that is rather conservative since the security of supply is vital.

Computation: commercial availability of adaptive control at considered time period for each type of HVDC component [Yes/No/Not applicable].

8.1.2 Self-tuning control

This means that the control parameters would be set at an optimal position from a base case through a system configuration at commissioning, like plug and play. This would save a lot of project and commissioning time since it will not have to be tested off-line before commissioning.

> Computation: commercial availability of self-tuning at considered time period for each type of HVDC component [Yes/No/Not applicable].

8.1.3 Grid code compliance

This means that the network codes that will be imposed on the systems will have to be fulfilled. The factors with special relevance for HVDC are:

- Planning code
- Technical performance requirements
- Operational code
- Connection code
- Communication and data exchange code

> Computation: ability to comply with existing grid code at considered time period for each type of HVDC component [Yes/No/Not applicable].

8.1.4 Virtual rotating mass

This means that the HVDC converter is able to support instantaneously with additional power at fault cases exactly as a synchronous generator until the converter goes to current limitation.

> Computation: commercial availability of virtual rotating mass function at considered time period for each type of HVDC component [Yes/No/Not applicable]

8.1.5 Network models / simulations

Network models and simulations will be needed in order to do a proper design. In the future we expect that measures such as improved control, etc. will relax the need for this type of simulations[10].

> Computation: necessity of network/model simulations at the considered time period for each type of HVDC component [detailed/generic]. The word "detailed" means that the TSO needs to provide HVDC manufacturers with detailed inputs on the grid properties needed to perform the hardware and control design of the system. In the future, since the system will be more robust and flexible, the variations in the AC-system to which the DC system is connected needs to be described in a less detailed way.

8.1.6 DC side fault clearing

This means that the HVDC converter, with HVDC Breaker or through the use of full-bridge converter, is able to clear the fault if a fault appears on the DC-side.

> Computation: duration of the fault clearing phase [in ms].

8.1.7 DC fault ride through

This means that the HVDC converter will be able to continue to operate and stay connected to the AC-grid if a fault on the dc-side occurs without tripping.

> Computation: commercial availability of DC fault ride through function at considered time period for each type of HVDC component [Yes/No/Not applicable].

8.2 Underlying assumptions

See section 2.3.2.

8.3 Methodology for data gathering

All data are based T&D Europe experts' assessment.

8.4 Conclusions on robustness of the produced data

See 2.5 above

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[10] Two opposite points of views can be observed: on one side, an increased need for simulations – since the system is assumed to be very flexible, it will be necessary to model and simulate some extreme conditions in order to verify that it will remain functional and in operation. In addition, from TSO's perspective, it is always valuable to have appropriate models to perform necessary analyses even if the system is meant to be self-reliant. On the other side, since the cost of studies impact the costs of equipment, there is a trend in the long term to try minimizing such studies and to develop as much as possible plug and play approaches.

Bibliography

The main reference is T&D expert competence pool.