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HYBRID GRID

TOWARDS A HYBRID AC/DC TRANSMISSION GRID

SAFER, SMARTER, GREENER

Cover image: HVDC and HVAC shown together
Power lines transmitting electricity from Hoover Dam to the greater Los Angeles metropolitan area, shown here crossing Interstate 15 near Primm, Nevada. On the right is Path 27, the Intermountain High Voltage Direct Current (HVDC) transmission line connecting the Intermountain Converter Station in Delta, Utah and Adelanto California. Path 27 is 785 km long and can transfer a maximum 2400 MW at ±500 kV. It is distinguished by two transmission wires, rather than the three required for transmission of AC power, shown on t he left of the photograph. Those are the two 500kV Los Angeles Department of Water and Power's McCullough - Victorville transmission lines, part of Path 46.
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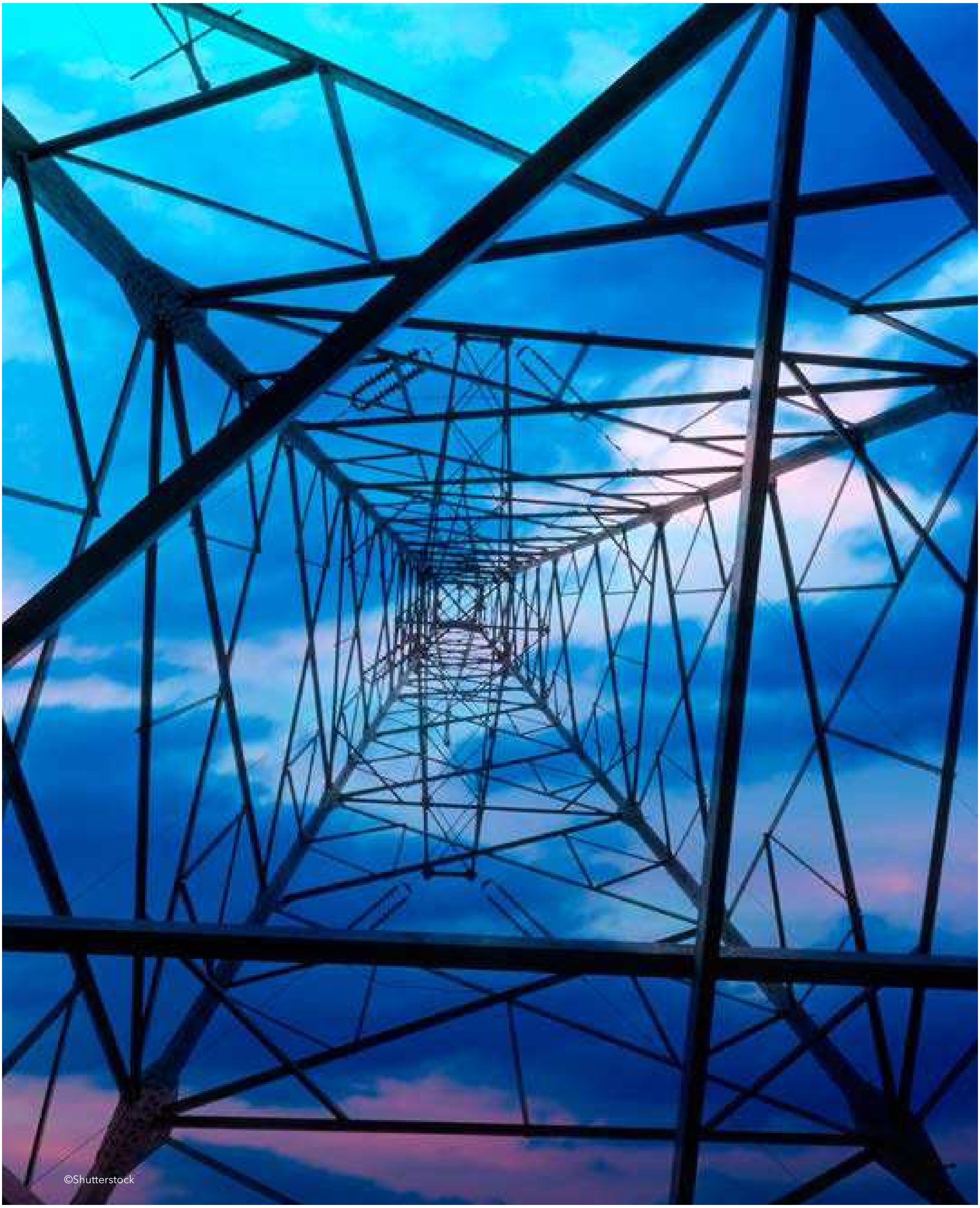
CONTENT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EXECUTIVE SUMMARY

Transmission grids will have to change fundamentally in order to deliver reliable, affordable, and sustainable electric energy in the right quantity (and quality), at the right time, and at the right place. As the share of renewables worldwide continues to grow, the major shift in the generation mix – large wind and solar capacities in combination with many small scale renewable generation systems – will lead to increased and more volatile power flows, over larger distances. These developments will create challenges in securing the reliability of supply. For example, in Europe 80% of the bottlenecks in the grid are related to integration of renewables, either in their direct connection to the grid or in transmission corridors to the load centres.

There will be large-scale grid expansion efforts worldwide over the next decade to bring power generated at locations near the "borders" of the grid to the load centres. The European Network of Transmission System Operators for Electricity (ENTSO-E) estimates the total investment costs for projects of pan-European significance at approximately €150 billion, of which €25 billion will be for subsea cables. New and cutting-edge technologies are being introduced to the grid. These include high-voltage direct current (HVDC) equipment, long AC cable routes, and the combined operation of HVDC and high-voltage alternating current (HVAC) systems. New electronic equipment, tools and digital systems are being installed to optimize the operation of existing assets, and to forecast, monitor, and control the emerging hybrid transmission grid and its connected equipment.

Large-scale deployment of HVDC is just beginning and we are convinced that it will play a vital enabling role in the Supergrid of the future. In fact, we argue that despite claims being made about the capabilities of 50 Hz/60 Hz or low-frequency AC, HVDC will play a central role in the transition to the future Supergrid in the next decade or two – in the form of so-called Hybrid Grids. But to realize this, there are immediate and anticipated challenges that must be overcome first. We show here that none of them is insurmountable, and we outline a role that third party and advisory organizations can play in shaping the new generation of power grids.

This possible path of evolution of the predominantly HVAC grid to a hybrid AC/DC grid is discussed in this position paper. The technologies that we think will make this possible are also introduced. The most important of these is HVDC technology, and this position paper gives insights into the state of the art, as well as the needs for possible future developments in HVDC in order to realize the Hybrid Grid for a reliable, affordable, and sustainable power supply to society.

INTRODUCTION

Society today is increasingly dependent on access to a reliable power grid. There are several drivers fuelling this dependency:

- Electrification – i.e. the shift of end-use consumption to electrical power (e.g. vehicles, appliances)
- The growing need for uninterrupted networking and electronic information exchange.
- The increasing size and complexity of modern power grids requiring sophisticated control mechanisms, which are predominantly electric / electronic.

At the same time, renewable power sources with variable nature have increased significantly. The combined effect of increased dependency and massive variable generation result in unprecedented changes in the power system.

The share of renewables will expand in the short-term – the rise in the use of renewable energy sources is a fact – and will continue to grow in the years to come. Ensuring reliability and affordability and safeguarding that power is delivered to the right place at the right time and in the right quantity, poses a huge challenge for a future power grid with a multitude of large, remote and small scale embedded renewable generation.

To ensure a reliable energy supply we need to bridge three gaps:

1. **Planning gap:** renewables sources, especially at customer premises, are usually built quickly, while changes in transmission and distribution grids require long planning cycles. For example, small-scale renewable systems can be built in a few months, while larger onshore wind and solar farms can be realized within a few years. Even offshore wind farms can be built within a timespan of five to seven years. By contrast, planning and permitting issues can lead to realization times for new transmission capacity of more than 10 years.
2. **Location gap:** large (renewable) power plants are increasingly being built at the "borders" of the grid and offshore, while more and more distributed renewables are usually installed in rural areas. Energy needs are highest in big cities and industrial locations, often far away from the generation locations.
3. **Flexibility gap:** wind speeds and sunlight intensities are variable; the increase in renewable sources calls for greater flexibility of the power system with more complex and advanced control mechanisms to maintain the balance between supply and demand, and to manage power-flow fluctuations due to this greater variability in the supply.

Power grids are expanding both geographically and in complexity. Regulations that aim to channel development towards sustainable energy systems, including renewable integration, add complexity,

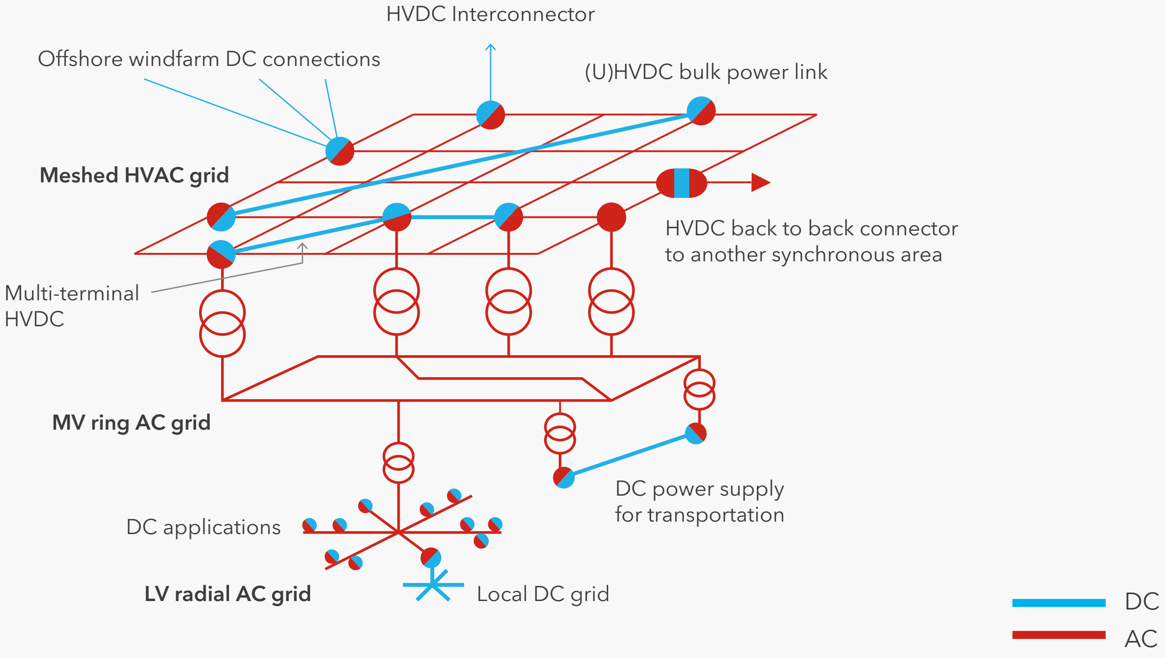

Figure 1. Power system grid architecture

as does new technology like power electronics and energy storage. Furthermore, despite consumers becoming more conscious about the energy that they consume, and its sources, they might still oppose the actual infrastructural changes required for efficient and robust grids.

In recent years, electric power systems around the globe have undergone significant development through the implementation of new high-voltage, direct current (HVDC) systems.

These systems:

- enhance bulk power transmission capability
- enable more effective transmission over long distances, including long submarine cables
- enable interconnection of regions and markets with different grid frequencies via back-to-back systems

What is the Hybrid Grid?
In this paper, the Hybrid Grid is defined as the addition of evermore HVDC connections within and between synchronized AC power systems. In this way, grids are evolving into combinations of AC and highly controllable DC systems that can be more active in providing end-users with affordable, reliable, and sustainable energy. Hybrid Grids hold considerable promise, but they also involve increasing levels of complexity; for example in combining relatively slow, mechanical controls typically associated with AC systems with faster electronically-controlled DC systems. Ultimately, the DC components of the Hybrid Grid will evolve into a highly meshed Supergrid, facilitating the transmission and trade of high volumes of electricity across great distances.

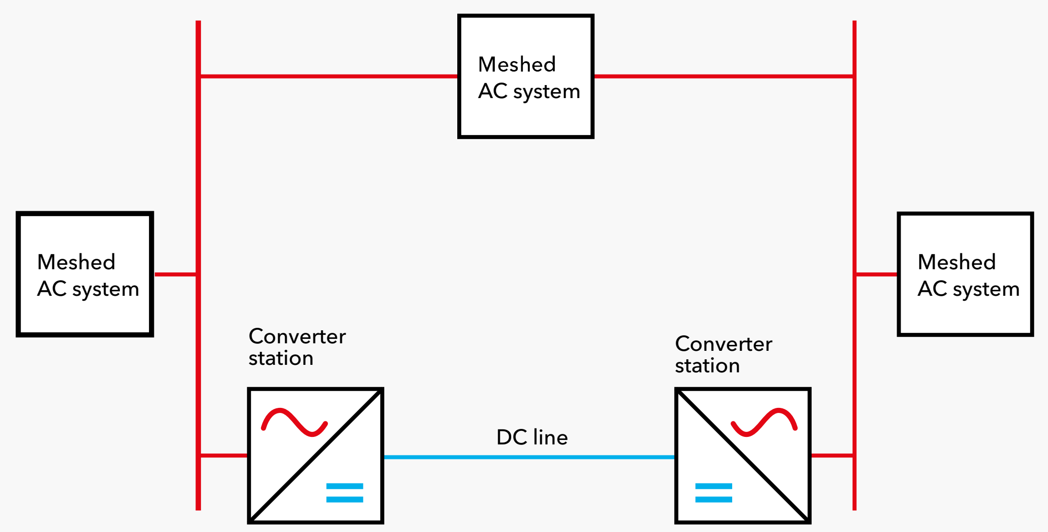

Figure 2. Layout of an embedded HVDC system.

- boost the integration of large-scale renewable energy sources
- improve the flexibility and controllability of AC systems
- can minimize environmental impact of transmission and distribution infrastructure.

Transmission grids are faced with more and bigger power flows over longer distances – nowadays, for example, approximately 15 % of all electricity used in Europe crosses one or more national border [1]. At these distances with significantly increased transmission capacity, enhanced availability and controllability are required.

Direct Current (DC) Technology
DC is the natural (technical) choice when bulk power has to be transmitted over long distances, connecting remote resources, such as coal and hydropower, to distant load centres, with low losses. HVDC dominates this space, and can be found at the highest voltage levels. HVDC applications also include subsea cable interconnectors, connections to offshore wind farms, and back-to-back connections of non-synchronous grid areas. All these applications use the superior power-flow steering and control functionality of HVDC technology.

At the other end of the spectrum, we find DC applications predominantly at the power distribution and end-use level, at voltages well below 400 V; these include household appliances such as battery (charging) systems, LED lighting, electric vehicles, solar photovoltaic (PV) systems, and many others. The rapid development of power electronics and the availability of efficient AC-to-DC and DC-to-DC converters allow easy connectivity.

DC systems are presently mainly found in the "horizontal" layers of ultra-high and ultra-low voltage. (See Figure 1). At medium voltage, only isolated systems for traction (train, metro and tram) exist. When the different voltage levels are connected with DC/DC converters, similar to transformers in AC

systems, a true DC grid will be possible. However, cost-effective solutions must first be found for typical DC technical problems, which are not encountered in AC, concerning fault current interruption and galvanic isolation. This means that the electric power grid will not be converted to a DC grid in the near future. It is more probable that the power grids will gradually evolve into hybrid systems, combining the best of both AC and DC worlds.

Towards a Hybrid Transmission Grid

The trend towards a hybrid transmission grid with more HVDC systems is already visible in Europe and China and, to a lesser extent, the US. These HVDC systems can be interconnectors between asynchronous AC systems, back-to-back, or embedded HVDC (see Figure 2). The hybrid transmission grid will become more complex to manage, exhibit more unwanted system operation interventions, and have many different interacting control mechanisms that must be coordinated to ensure stability. A new suite of tools is needed to perform studies and simulations, to verify grid integrity, stability, and reliability, and to operate and maintain the grid within safe boundaries in a cost-effective manner.

As the price of power electronics continues to fall, and as converters become highly modular, efficient, and cheap, they can and will replace substation components to a certain extent and drive the "hybrid transmission grid". This will lead to LEGO-ized solutions in substations, where identical hardware building blocks will be installed to perform the desired functions through (software) controls.

DRIVERS AND CHALLENGES

DRIVERS

The high-voltage, high-power grid today is based on AC technology. The large conventional generators connected to this grid are responsible for supplying power, keeping the frequency within limits, and maintaining the voltage within boundaries throughout the nodes on the grid. The power flow has been predominantly uni-directional; i.e., from these large conventional generators to the consumers through the transmission and distribution system. The power flow, supply and demand balancing, and voltage control in such grids have been relatively simple, mainly because of the availability and predictability of the generators. In addition, transmission systems have been monopolies where the system security has been the main objective for control purposes. The level of interconnection between neighbouring power systems has also been limited, and used primarily for operational security rather than trading. This has changed and here we can identify a few drivers for the Hybrid Grid in which HVDC will play an increasingly important role.

Integration of renewables into power grids

The growth of the renewable share in the electricity generation mix creates more, bigger, and faster fluctuations in generation. In addition, renewable generation sites – especially wind and hydro – are generally located far from load centres. For example, offshore wind power plants (OWPPs) are being built further offshore, and AC transmission becomes technically unviable due to capacitive loading of the export cable. HVDC transmission does not suffer from this drawback and can be utilized for such connections.

The variability associated with renewables makes it difficult for the Transmission System Operators (TSOs) to maintain the supply-demand balance without unwanted frequency variations. Additional measures need to be taken for the transmission system to operate properly. This is leading to a paradigm shift in power system operation from “generation matches load” to “load matches generation”. This implies new challenges for power system operations, as well as the need for accurate forecasting.

Ageing and stressed AC grids

Transmission grids are not evolving as quickly as the generation and consumption of electricity. Generation has become more dispersed and diversified and, in the case of renewables, needs support from the grid rather than providing it. Consumers are now more active, as smart grid technologies and business models are rolled out. In order for grids to facilitate the power flows associated with these changes, they must be adequately equipped with fast power flow control capability and voltage control functions. HVDC is ideally positioned to fulfil these requirements.

Public opposition to new power lines

Large infrastructure projects, irrespective of their merits, are always likely to face some form of public opposition in the age of mass connectivity and the democratisation of information. The construction of new transmission lines is no exception, and public opposition has resulted in a rise in the number of new transmission systems being taken underground, in the form of cables; this increases the required investment, as high voltage cable systems are more expensive. This added cost burden may, however, accelerate the development of a hybrid transmission grid, as HVDC cable systems become an attractive alternative to high voltage AC cables. In addition existing HVAC lines can be converted to HVDC lines that can carry more power in a more controllable manner, while using the same right of way.

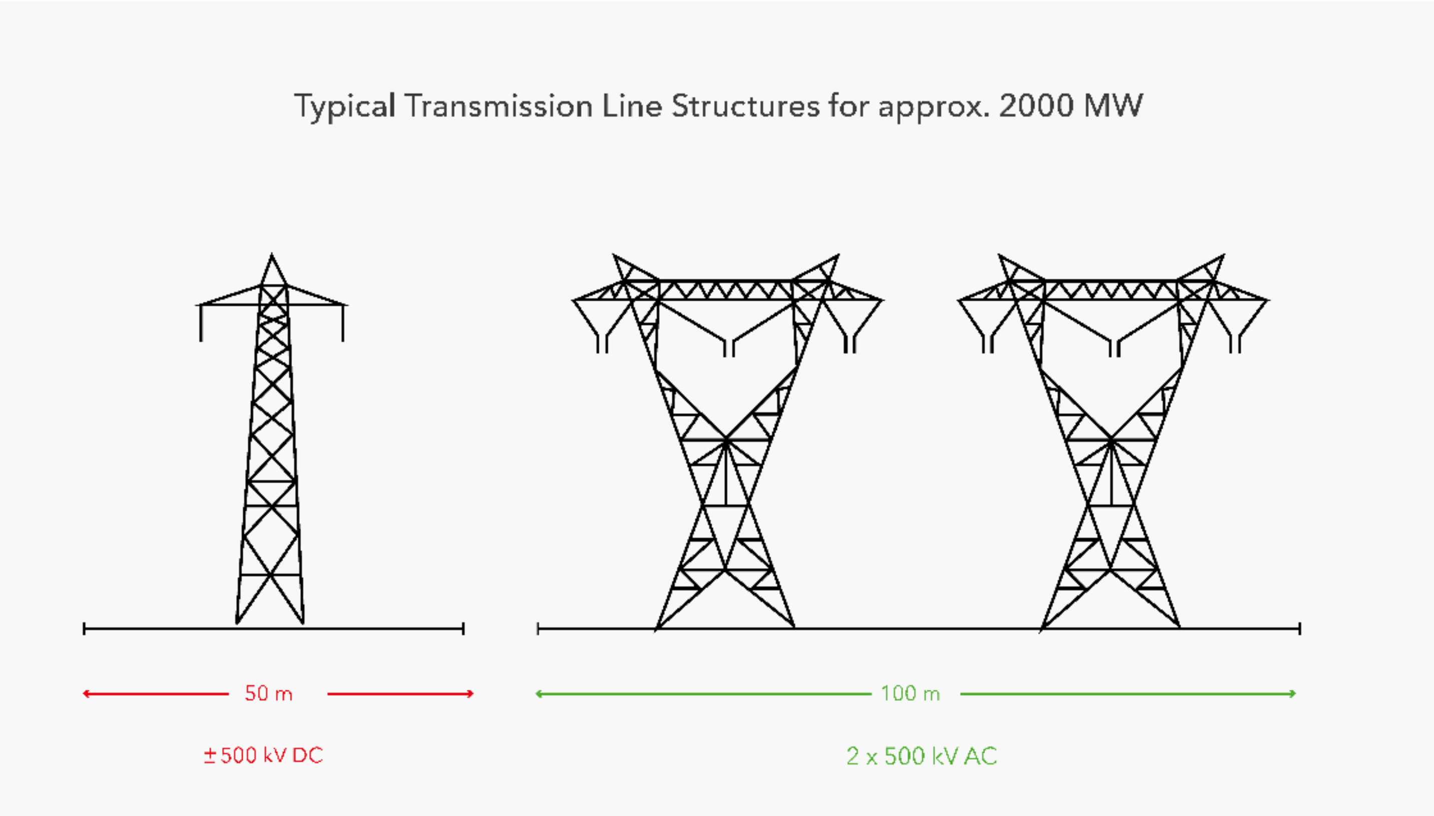

Figure 3. Comparison of tower infrastructure and right of way for similar power ratings using HVDC and HVAC technologies.

Increasing electricity trading between countries
The deregulation of power markets and the difference in energy prices (accentuated by the addition of renewables) are promoting increases in cross-border trading of electricity. Existing interconnection capacity (primarily HVAC) cannot sustain the rise in cross-border power flow associated with trading. Adding capacity by constructing new overhead transmission lines is not an easy solution owing to the high risk of public opposition combined with the fact that AC power flows are difficult to steer. New transmission capacity is therefore likely to go underground utilizing cables, which in turn demands an HVDC solution.

THE IMPACT OF DRIVERS ON THE GRID - WHY HVDC?

The drivers mentioned above have forced grid operators to adapt and improve functionality and controllability in order to maintain system stability. This includes increasing the power flow control capability to existing AC lines through the use of Flexible AC Transmission System (FACTS) technologies. Voltage control devices, such as static VAR compensators (SVC) and static synchronous compensators (STATCOM), are being frequently applied in the grids. A further solution is strategic and large-scale deployment of HVDC.

Infrastructure Cost
The most obvious advantage of HVDC over HVAC transmission is the higher current capacity for the same conductor cross-section and higher operation voltages at the same insulation level. This means that HVDC transmission infrastructure (be it overhead or underground) will have a smaller physical size and footprint than a comparable HVAC system. An example for overhead transmission line towers for HVDC and HVAC system is given in Figure 3.

However, any savings gained are offset by the high costs of HVDC terminal equipment. In terms of capital expenditure, the substation costs for HVAC transmission are less than for an HVDC converter station. The reason for this is the elaborate AC/DC converter and accompanying equipment for HVDC, compared with the simple configuration of transformers and switchgear found in an HVAC substation.

Therefore, above a certain transmission distance, HVDC becomes the cheaper option. The cost summary is illustrated in Figure 4. The variable costs include the costs of losses that are lower for HVDC. The break-even distance is between 600 and 800 km with overhead (O/H) lines [2] and between 60 and 100 km for cable transmission. This is because of even higher losses and the need for reactive compensation at very short intervals along the transmission route for HVAC cable.

Support services to the AC Grid

In addition to the obvious cost advantage for long transmission lines and cable transmission beyond a 60 km distance, HVDC possesses functionality that can help stabilize the predominantly HVAC grids of today. These functions are briefly mentioned below.

- **Active power control**
  HVDC offers greater control over the flow of active power. This control capability can be either scheduled manually by the operator or implemented as an automatic control where the set-point is automatically adjusted, for example, as a function of the difference of voltage angles at the two terminals of the HVDC link.

- **Reactive power and voltage control**
  Reactive power and voltage at the HVDC connection point are normally controlled by the use of switching filters in line commutated converter (LCC) based HVDC. It is possible to change the reactive consumption of LCC converters by varying their operating ignition and extinction angles. However, one drawback is the equivalent change in active power flow over the HVDC line. These techniques are ineffective during transient events, as filters cannot be switched during such instances. It is possible to add a STATCOM, SVC, or synchronous condenser to achieve this functionality, but this adds to the cost and footprint of the HVDC terminal. Voltage sourced converter (VSC) based HVDC, on the other hand, behaves as a STATCOM as the reactive power output can be regulated independently of active power flowing over the HVDC line, limited only by the current rating of the power electronics and the MVA rating of the converter transformers.

- **Frequency control**
  If the HVDC link connects two asynchronous power systems, the healthy system can assist in stabilizing the frequency of the disturbed system

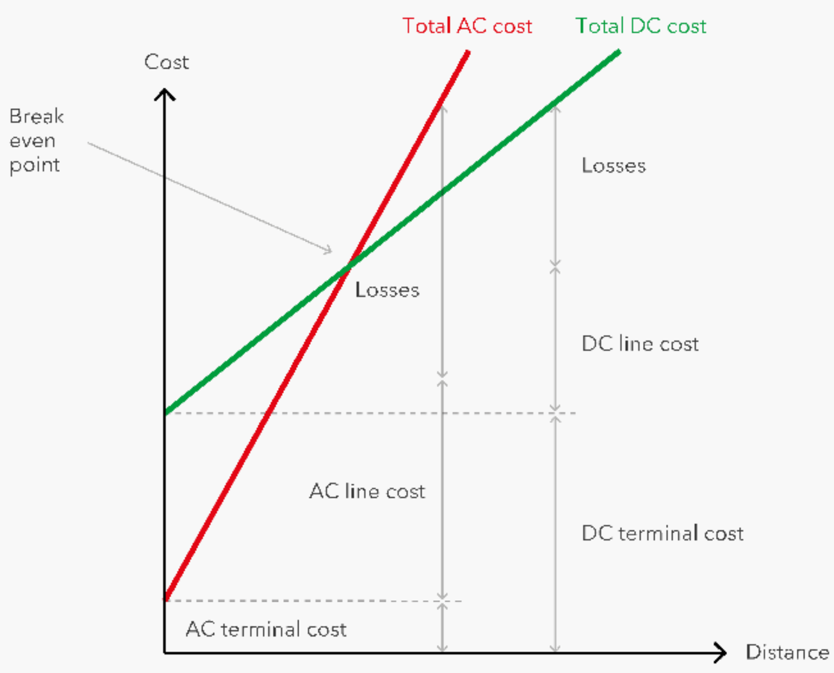

Figure 4. Comparison of fixed and variable capital costs as a function of transmission distance

by providing extra active power. The fast power controllability associated with HVDC ensures that this is achieved swiftly and efficiently. The change in frequency produces a proportional power signal that is added (or subtracted, based on the nature of the frequency event) to the active power reference for both terminals of the HVDC link. The switch modulation is accordingly adjusted by converter controls to provide adequate frequency support.

- Power Oscillation Damping (POD) and Emergency Power Control (EPC)
  Power oscillations are a result of generator response to variations in load on the system. If left uncontrolled, they can result in tripping of generators and transmission lines. The traditional solution for POD has been the use of Power System Stabilizers (PSS). These are controls that are added to the excitation systems of generators to control deviations in generator speeds. The same function can be achieved by devices that are connected to the power system such as HVDC and FACTS. A modulating signal is added to the power reference of the HVDC scheme after appropriate pre-processing to damp the oscillations.

  The fast power control capability offered by HVDC means that power transmitted over the DC line can be ramped up or down quickly. This capability helps relieve the system stress caused by power imbalance at either end of the HVDC line and is often referred to as EPC.

CHALLENGES

Although the ideal of a highly flexible Hybrid Grid is appealing, it brings its own challenges. In order to consider these more closely, we take as a starting point that the grid of the future will require fast and distributed response to changes in power demands, voltage disturbances, and rapid isolation of faults. This needs investment in HVDC and FACTS technologies that are largely based on power electronics. Some of the challenges associated with this development are dealt with below. It is also worth mentioning that the move from an inherently stable grid to grids that are held stable only through active control requires knowledge of advanced control theory, and this has to be gained ahead of large-scale grid hybridization.

Cost of Equipment and Implementation

Very few manufacturers have been able to sustain the necessary resources for maintaining HVDC competence, and this has contributed to high input costs. Manufacturers from Asia have been working within their home countries, but this may change as they seek to expand. This may improve the capacity problem in the market. However, HVDC-associated technology is developing quickly, and manufacturers have incurred penalties arising from delays and downtime. Therefore, contractors are incorporating large safety margins in their pricing for future projects, especially offshore applications, increasing the price of HVDC projects.

AC/DC System Interaction

The flexibility offered by the fast controls in HVDC can result in adverse interactions between AC and DC systems, leading to instability and interruption of service. These can be harmonic interactions, Sub-Synchronous Resonance (SSR), and Sub-Synchronous Torsional Interactions (SSTI) with nearby turbine generator shafts. Studies investigating these interactions should be conducted prior to construction so that the design of control can be optimized. With properly designed controls HVDC systems can help mitigate the impact of such interactions.

Harmonic Pollution

Industrial and domestic customers are increasingly employing power electronic interfaces for connection with the grid. In addition almost all the renewable power from wind and solar PV is exported through power electronics. Power electronic equipment is a source of harmonic pollution and this can excite resonances leading to destabilization of the grid.

Reliability of Power Electronics

Power electronics is a major component of HVDC technology and remains comparatively less reliable than equipment that is based mostly on passive components employed in AC technology. The reason for this is the higher stress to which these are exposed owing to high frequency switching. Improved reliability data and proper modelling can help improve the situation and therefore reduce the life-cycle costs.

VSC HVDC technology has been in operation for 15 years, and is still immature compared with LCC HVDC technology. Due to the lack of operational data from VSC systems, simulation models, regulations, and standards were mainly adopted from LCC technology. This leads to inaccurate results from design studies, component testing, and system performance.

Few manufacturers are able to deliver turnkey solution for VSC HVDC systems at present. Each manufacturer has its own models and methods for system parameters and performance calculation. This means that it is difficult to evaluate results and assess a system's performance.

Technology gap

Power system experts agree that our dependence on fossil fuel-based power plants can only be reduced by increasing solar and wind generation capacity and at the same time levelling out the variability of those renewable energy sources. This involves high power transmission corridors over long distances, and can only be realized with HVDC technology. The term commonly used for such an overlay HVDC grid is "Supergrid". A Supergrid will essentially have the same mesh-like structure as that of the 50 Hz or 60 Hz HVAC grid. However, proper protection and branch power-flow control require equipment that has not yet been commercialized. HVDC circuit breakers are technological innovations and operational experience is not yet available. Branch power flow control can be achieved to some extent through coordinated power-voltage droop control at several buses. This control concept cannot be extended to systems with more nodes and lines. Eventually series devices, such as DC/DC converters, will be needed on specific lines to control individual line flows, such devices have not yet progressed beyond the stage of academic research.

Standardization

HVDC projects to date have been relatively few and far between because of the limited number of relevant scenarios for the application of the technology. These have been almost exclusively point-to-point connections, each built on a turnkey basis by a single manufacturer. This has led to a relately small niche market; with every project deemed unique and with manufacturers and developers not prioritizing standardization. This has now changed and owners/developers demand greater openness and standardization as the number of HVDC projects increase and competitors from Asia seek to internationalize their business. This will benefit manufacturers as the sizes and numbers of developments increase with the arrival of multi-terminal HVDC projects. Nevertheless, significant work must be done to standardize particular parts of the DC system, such as cables, and control and protection protocols. Standardization of system parameters, especially system voltage, and integration rules are crucial for multi-terminal systems and to reduce the barriers for new players to enter the market.

TSOs expect more HVDC connections between different grids and also for OWPP connections. However, hazardous AC/DC interactions can cause contingencies that should be avoided. Therefore TSOs are establishing grid codes that should be satisfied by HVDC connections in order for them to be allowed to connect to the AC system [3]. These grid codes have two dimensions; one is the guarantee that the HVDC connection will not disturb the AC grid operation and the other is the provision of a variety of AC system support services.

Regulatory Barriers

Interconnectors between isolated power systems are built with HVDC technology. OWPPs that are located far from shore, also need HVDC connections to the onshore grids. Integration of OWPPs into interconnectors requires multi-terminal HVDC configurations. Recent studies have revealed that integration of OWPPs into interconnectors between power systems can add significant value by reducing implementation costs and adding benefits such as allowing for higher penetration of renewables by reducing the need for spinning reserve. As the operational benefits may spread to the power systems far from the interconnectors, mechanisms and regulations for allocation of costs and benefits arising out of such implementations do not currently exist. The NorthSeaGrid project, funded by the European Commission, discusses these issues in detail [4].

Competition from 50 Hz/60 Hz and Low-Frequency AC

In the last couple of decades, the relatively young VSC HVDC technology has been promoted for OWPP integration, as well as for electrification from shore in offshore oil & gas production. Such projects have been very costly, and unforeseen operational problems have resulted in downtimes and loss of energy supplied from OWPPs. As a result, the industry has begun to explore other options, such as extending the range of traditional 50 Hz or 60 Hz technology for cable transmission. The range is limited because the cable behaves as a capacitor whose capacitance increases with the length of the cable. The current drawn by this capacitance thus also rises with length. This current is exchanged with the power system through the cable conductor and occupies some of the thermal capacity of the cable conductor. The capacitive current rapidly becomes so large that it takes up the entire thermal capacity of the cable, leaving no room for active power transmission between the two ends of the cable. Reactive compensation, either at the terminals or at suitable intervals on the cable route, helps to

eliminate this current exchange. Developers are now analysing the technical and financial details of such implementations.

Another solution lies in the use of low-frequency AC connection [5]. The current taken up by the capacitance of cables is proportional to the frequency, as well as the capacitance. This means that the capacitive current would be much lower at a lower operating frequency, and would extend the transmission distance proportionately without the need for intermediate compensation. However, frequency converters are needed for connection to the main grid, which operates at 50 Hz or 60 Hz. These converters are expected to be based on power electronics. If the offshore equipment operates at the reduced frequency, an offshore converter would be unnecessary, so the investment and operational costs of such connections would decrease. Equipment for a frequency that is one third of grid frequency exists (railway applications), but the voltage and current ratings are not as high as those needed for OWPP integration.

DEVELOPMENTS IN HVDC

Transmission grids today are predominantly based on HVAC, with a few HVDC connections acting as interconnectors to adjacent power systems. HVDC is also used to connect offshore wind farms and for offshore oil & gas platforms. HVDC will be discussed extensively as it will be the transforming agent from predominantly AC to a Hybrid Grid.

BUILDING BLOCKS OF AN HVDC SYSTEM

The major components of a point-to-point HVDC connection are shown in Figure 5. The converter stations at each end of the line provide the interface between the AC and DC systems. These extract power from the AC system (rectifier mode) or inject power to it (inverter mode). As power can be transmitted both ways over a transmission corridor, these converter stations have the ability to switch from rectifier to inverter mode. They are equipped with AC/DC converter valves made up of power electronic modules, switchgear, converter transformers, and AC & DC filters (refer to Figure 6). One of the most expensive components in such a system i.e. a submarine or underground cable is shown in Figure 7. Figure 8 gives a pictorial representation of a converter station for LCC HVDC. Figure 9 depict the IGBT valves in a converter hall.

The transmission medium can be either an overhead line or a cable. The materials employed are similar to those for AC power transmission. The major difference is that HVDC lines can operate with only two conductors in the line, compared with three for AC transmission. In some cases a metallic return is used to enable mono-polar operation in case of faults on one of the conductors. In such cases, up to 50% of the rated power can be transported.

The Converter

The individual valves are connected to form a complete converter. The construction of a converter is shown in Figure 10, in which six valves are configured in three phase legs to form a three-phase converter. This arrangement is also referred to as the 6-pulse bridge because of the six valves which receive separate firing pulses.

Another type is the 12-pulse converter, which has two 6-pulse converters connected in series on the DC side and in parallel on the AC side, and is often employed in LCC HVDC to effectively eliminate 5th and 7th harmonics on the AC side.

The converters are mainly characterized by their AC and DC voltages; and active power ratings.

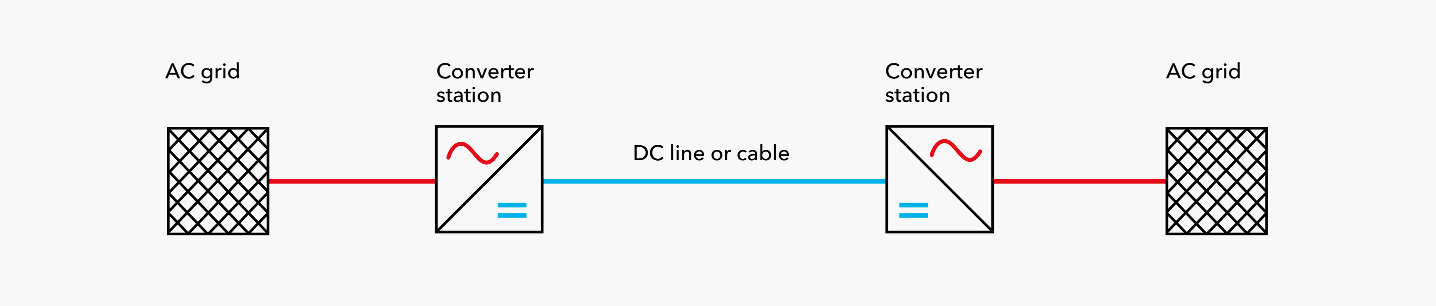

Figure 5. Point-to-point HVDC connection.

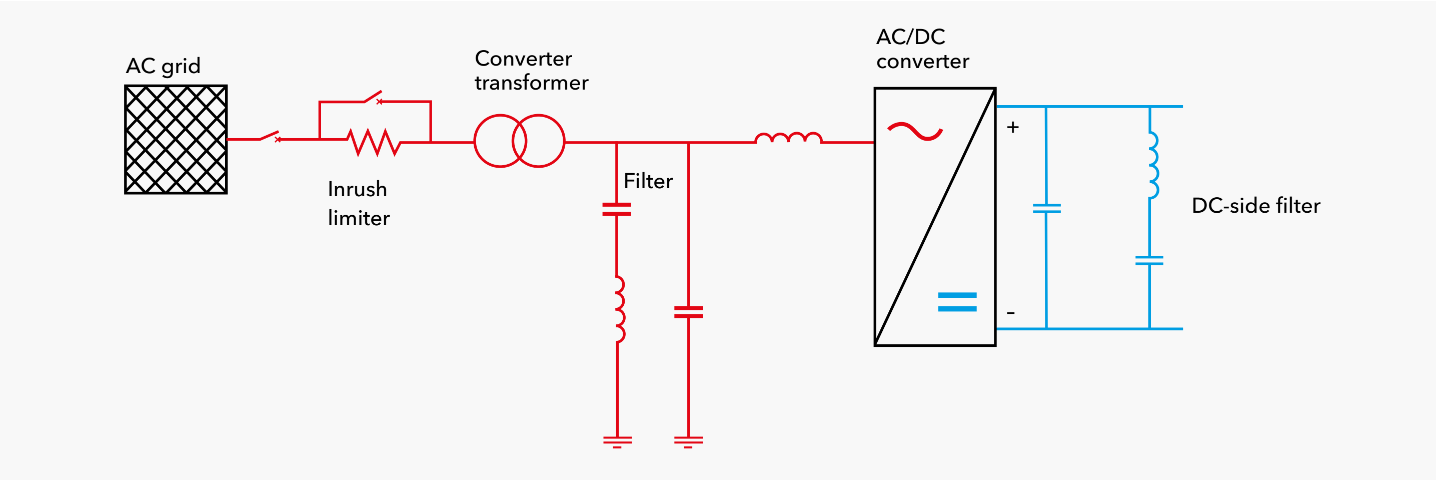

Figure 6. Schematic arrangement of a VSC HVDC converter station. Only major components are shown.

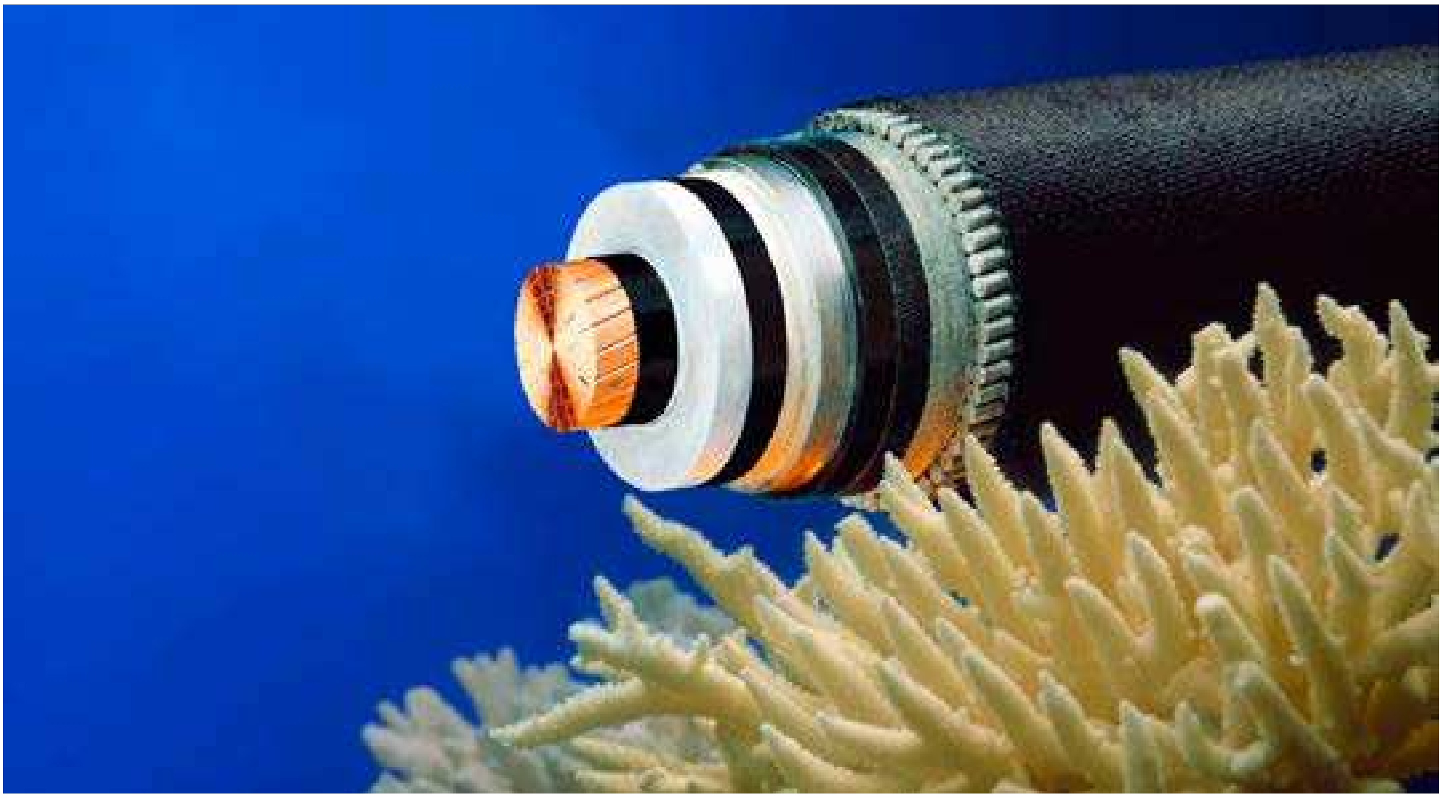

Figure 7. HVDC cable © Nexans

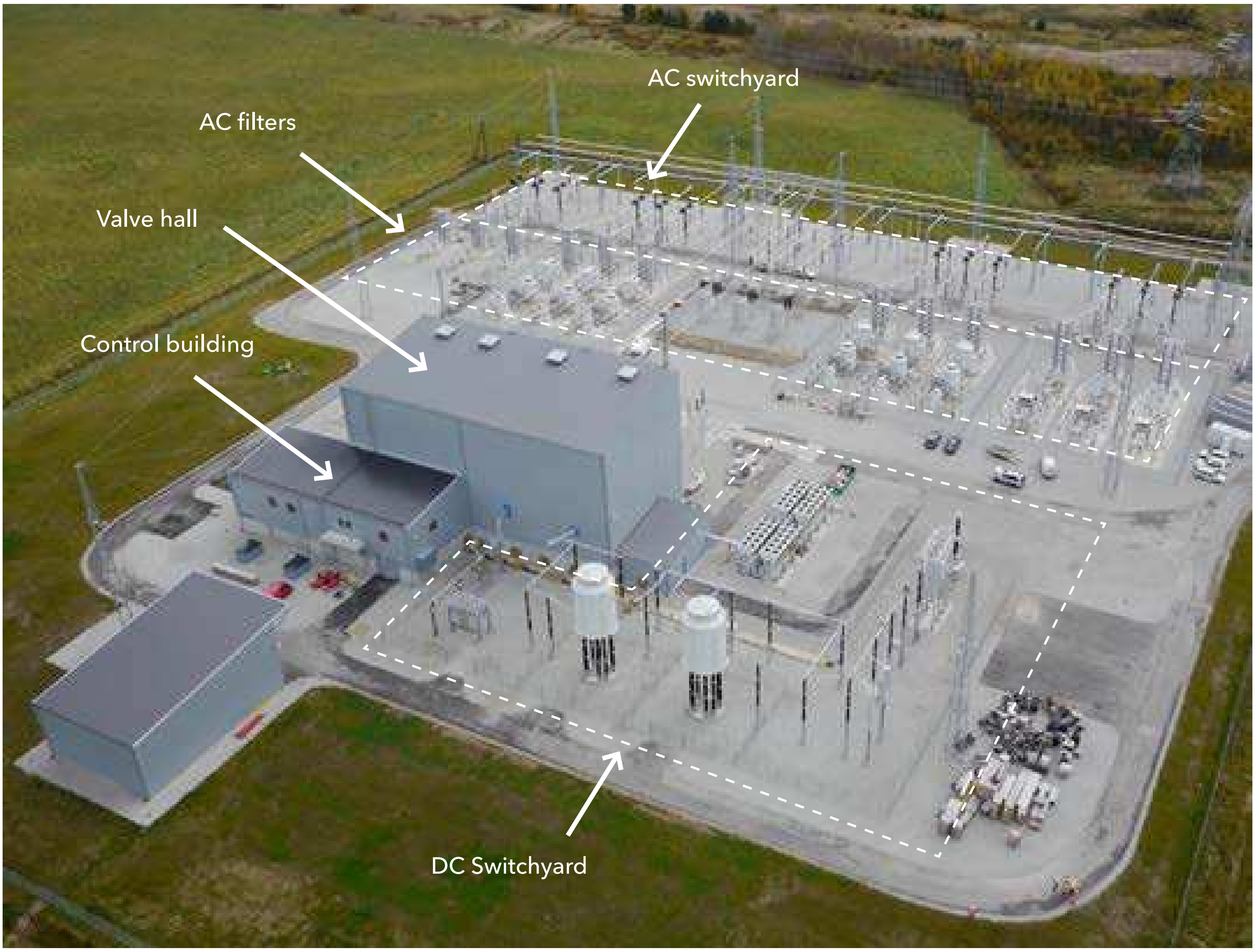

Figure 8. Bird's-eye view of an LCC HVDC converter station (in this instance the HVDC-converter station in Püssi, Estonia). Annotations added by DNV GL. Picture courtesy Siemens AG. www.siemens.com/press

The HVDC Conversion Terminal
In addition to the AC/DC converter, typical converter-terminal equipment may include :

AC and DC switchgear, AC and DC side filters, switching filters, DC choppers, surge arrestors, converter transformers, measurement systems, emergency power supply systems, cooling systems, and control & communication systems.

Comparison of Converter Technology
Two main converter technologies have been developed:

- Line Commutated Converter (LCC) HVDC
- Voltage Source Converter (VSC) HVDC

Figure 9. Valve hall in a VSC converter station ©ABB

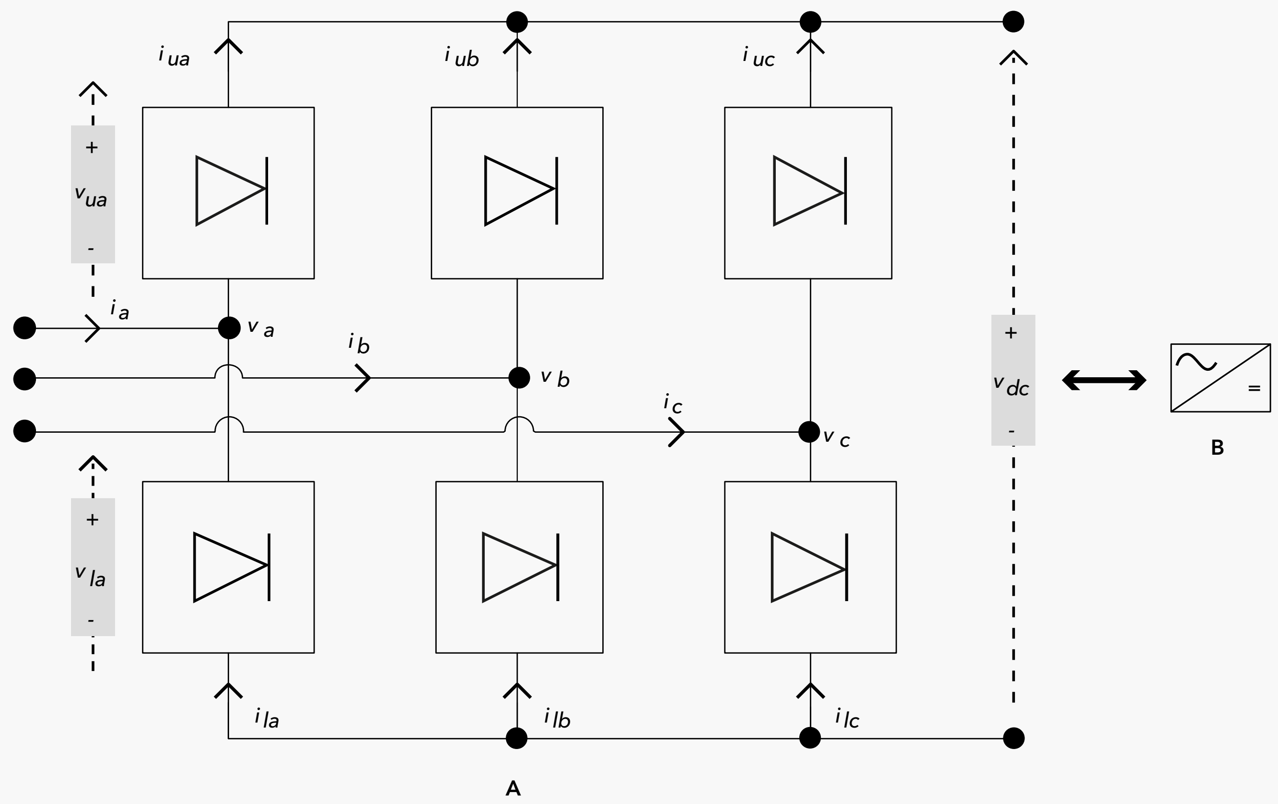

Figure 10. The 6-pulse, three-phase AC/DC converter (A) Schematic (B) Symbol. Valves may consist of line-commutated or self-commutated semiconductor switches.

Both technologies are suitable for the transmission of electric power and comprise of an underground cable or overhead transmission line (or a combination) and two converter stations.

LCC HVDC is based on solid-state thyristor technology and was first introduced in the 1950's. At present more than 100 projects are in service worldwide. LCC systems have power ratings in the range of several hundred to several thousand MW. The largest project to date is the Hami – Zhengzhou transmission system in China with a capacity of 8000 MW, it is operated at ±800 kV and covers a distance of 2210 km with overhead transmission lines. The longest LCC HVDC cable project is the 580 km long NorNed cable (in operation since May 2008) between Norway and the Netherlands, which has a transmission capacity of 700 MW at ±450 kV.

VSC HVDC technology is based upon insulated gate bipolar transistor (IGBT) and was developed during the 1990's. VSC HVDC is commonly used with underground or submarine cables with a transfer capacity in the range of upto 1000 MW and is suitable to serve as a connection to a wind farm or to supply a remote load. VSC HVDC technology is considered to be suitable for meshed HVDC grids.

LCC HVDC converters depend on the AC system voltage for commutation (switching), whereas VSC HVDC converters are self-commutating. For LCC HVDC—due to the nature of the technology—a

Line Commutated Converter (LCC)	Voltage Source Converter (VSC)
Bulk power 9000 MW	Building block up to 1000 MW
Voltage ±1000 kV	Voltage ±500 kV
Thyristor technology	Transistor (IGBT) technology
Strong AC grid needed	Also for weak grid / without generator
Voltage polarity reversal enables power flow reversal	Current direction reversal enables power flow reversal
Reactive power balance by shunt bank switching	Reactive power control
More suitable for point to point connection	More suitable for multi-terminal
Long distance 3000 km	Flexible: modular, expandable, grid restoration support
Generation of harmonics	Improved power network stability and power quality

Table 1. Comparison of converter technologies

typical minimum transmitted DC power of 5 –10 percent of rated power is necessary, but this can be zero for VSC HVDC. LCC HVDC converter stations consume reactive power, roughly 50 % of the active power transmitted, thus requiring reactive power compensation. On the other hand independent control of active and reactive power inherent in VSC HVDC means reactive power compensation is not needed. LCC HVDC requires larger switchable filters due to lower switching frequency, while for VSC HVDC less filtering is required. The comparison of LCC and VSC is summarized in Table 1.

APPLICATIONS

Long-Distance Bulk Power Transmission

The stable operation of HVAC transmission systems becomes complicated as the length of the transmission line / cable increases. This is due to reasons such as angle stability and voltage stability problems; such problems are not relevant for HVDC. Additionally, the losses in the transmission line are lower for HVDC than HVAC. However, the losses in the converter stations for HVDC are higher than in the equivalent substation for HVAC transmission. These station losses are not a function of the length of the transmission line; and total losses for HVDC are lower than those for HVAC as the transmission length increases beyond a certain point. Above this length, the HVDC alternative is economical in comparison with HVAC, at least in terms of losses.

Currently, the highest power transmission capacity is 8000 MW, achieved by the Hami–Zhengzhou project in China [6]. It also shares the highest voltage rating of ±800 kV DC along with several other HVDC projects, most of which are located in China. The longest HVDC line is the 2375 km Rio Madeira HVDC line in Brazil [7]. The trend of increasing voltages continues and manufacturers are developing equipment for ±1100 kV HVDC projects. The reason for the trend is the higher efficiency due to lower transmission line losses at higher voltages.

International Submarine Interconnectors

HVDC becomes comparatively economical at very short distances with cable transmission. Furthermore, it is easier to control the flow of power over HVDC lines, which is ideal for power trade from one country to another. Transmission grids of different countries do not always operate synchronously and may have different grid control strategies. The only way to transfer power between asynchronous grids is through HVDC.

Wind Power Integration

Wind resources, even onshore, may be located far from load centres. For offshore wind, HVDC becomes the preferred option at relatively short distances as shown in Figure 11. The presence of an HVDC link between a wind farm and a grid system prevents the faults in one network from disrupting safe operation in the other. The fast power controllability associated with HVDC is another plus when integrating intermittent wind resources. In brief, HVDC enables integration of wind power at lower costs, with reduced losses, and greater security.

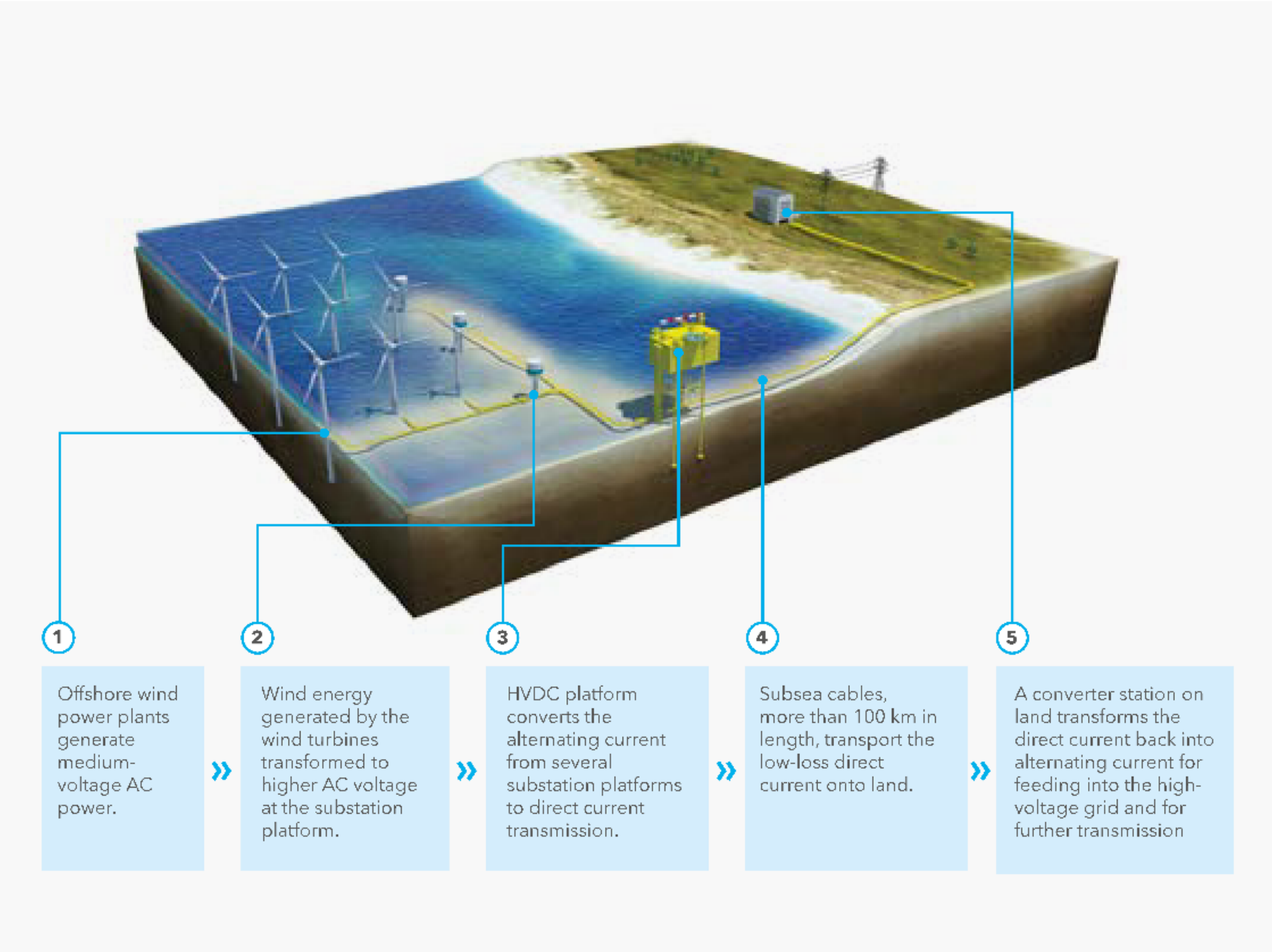

Figure 11. Offshore Wind Integration with HVDC, ©Siemens

Offshore Electrification
Offshore oil & gas production facilities have to employ fully redundant gas turbines for their power demand. These occupy valuable space on the platform that could otherwise be used for adding to the production and storage capacity of the facility. This solution also entails high cost of production due to full-throttle operation of the standby generating unit. The emission of CO_2/NOx/SOx caused by these turbines is another cause for concern in certain countries. Norwegian authorities may ask offshore field developers to provide an economic comparison between offshore power production and powering from shore solutions, and may employ the latter if they hold socioeconomic benefits. Due to this, some offshore oil & gas facilities on the Norwegian continental shelf have been powered from the shore, the first one being the Troll platform operated by Statoil with a connection capacity of 80 MW operating at a voltage of ± 60 kV as shown in Figure 12.

Back-to-Back
This solution is used where the rectifier and inverter converters are located within the same site, and when there is a need to exchange power between two grids operating at two different frequencies, or with the same frequency but not in synchronism with each other. In addition, HVDC back-to-back can be used for conversion from a three-phase 50 Hz supply to a single-phase 16.7 Hz supply for applications such as railway traction.

Figure 12. VSC HVDC power supply to Troll A production platform

IMPORTANT STAKEHOLDERS

Important stakeholders are shown in Figure 13, along with their involvement at different stages of HVDC projects.

Transmission System Operator (TSO): A TSO manages the planning, development, and operation of high-voltage high-power electric power systems, typically at state/national level. More than one TSO can operate parts of the power system in a country. In most cases, high-voltage transmission infrastructure constitutes a natural monopoly, and therefore the activities of TSOs are highly regulated.

Developer: In the main, TSOs are also developers - adding power infrastructure within their system. Two or more TSOs may jointly develop interconnectors between countries. However, there may be occasions when a merchant connection could be developed by another organization. The term 'developer' is used in such instances for the organization that invests in, and benefits from the difference in prices of the two power systems connected by the merchant link.

Advisory: Organizations that advise investors about various aspects of the project during its lifecycle take up the advisory role. These aspects may include technical, financial, regulatory, policy, and environmental.

Third Party: Testing, inspection and certification entities take up the third party role. Their activities help boost the confidence of other stakeholders about the ability of the new system to cope with all the requirements and allied regulations.

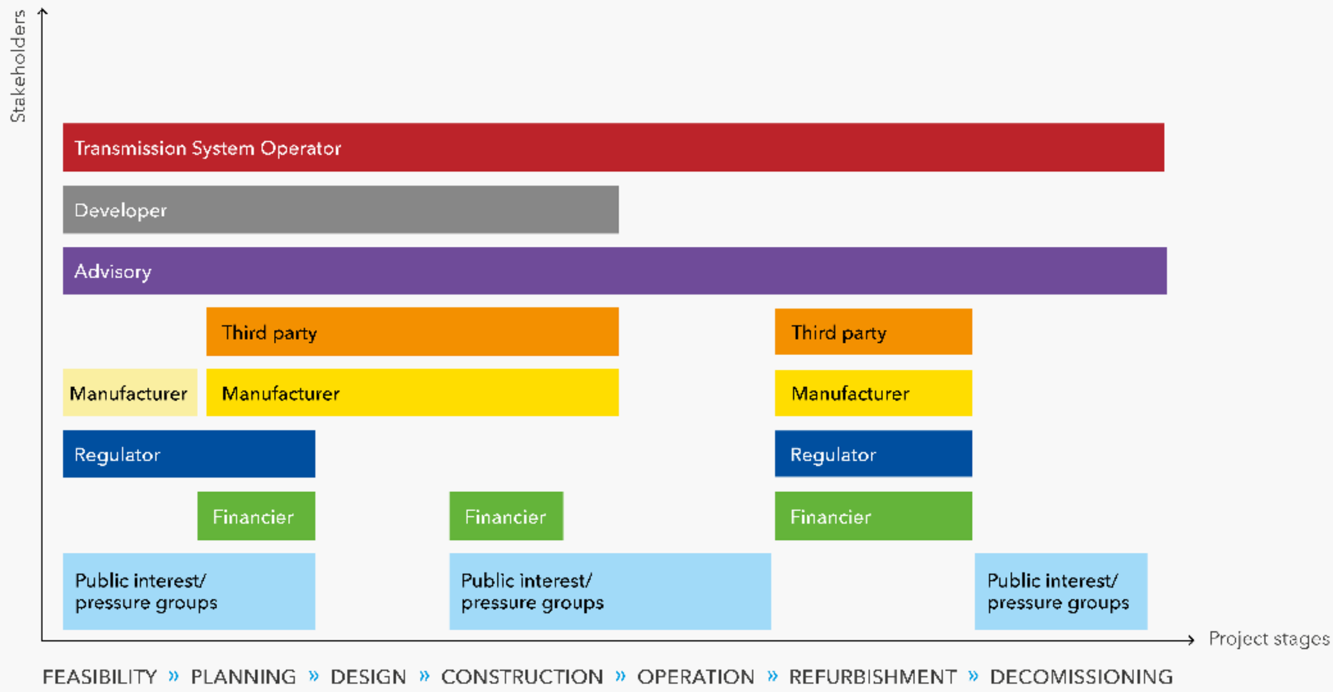

Figure 13. Important stakeholders during the lifecycle of a typical HVDC system

Manufacturer: These organizations produce the components of the project such as cables, converter stations, circuit breakers, transformers, and control and communication equipment.

Regulator: The oversight bodies established by governments to regulate various aspects of power systems under their jurisdiction.

Financier: Banks, capital holdings, and other financial institutions take on the financier role, benefiting from interest, fees and other returns that may accrue from their investments.

Public interest/pressure groups: These include any association of individuals or organizations, either formally or informally organized, attempting to influence public policy at either a micro (e.g. local infrastructure) or macro (e.g. national/regional regulatory) level. The power market is traditionally very politically sensitive and public opinion and pressure – potentially affecting market mechanism, technology choice etc. – should be factored in at every stage of the life cycle.

VISION FOR THE FUTURE

EMERGING TECHNOLOGY

HVDC technology has been evolving steadily during the past few decades; this can be partially demonstrated by Figure 14 and Figure 15, where the development of power ratings of HVDC cables and converter stations over time are plotted. In Figure 16, the cumulative powers and cumulative transmission lengths are plotted versus the commissioning years. It clearly shows that HVDC technology has been applied to the power grid in an increasingly accelerated manner. We expect that these trends will continue due to improvements in existing technologies and by applying emerging technologies; these include:

1. **New Devices such as DC circuit breakers and DC/DC converters:** Reliable and efficient operation of multi-terminal HVDC systems is difficult without fault clearance capabilities. Rapid, reliable and accurate protection systems must be developed, in which DC circuit breakers are crucial components. Circuit breakers for HVDC systems must operate over the system lifetime, protecting equipment from fault currents and maintaining operability of the system after fault clearance. Future HVDC grids should integrate both new and existing HVDC links, which might be operated at different voltage levels. Therefore, DC/DC converters will be necessary to connect HVDC systems with different voltage levels. When properly designed, DC/DC converters can also provide power flow control functionality and fault clearance capability.

2. **New Control strategy:** As the mutual interaction between HVDC converters and with AC system becomes increasingly important, where (slower) AC and (faster) DC controls as well as analogue and digital controls will need to work together in a coordinated way, new control strategies have to be developed for the Hybrid Grid. In comparison with today's EMS/SCADA system, the control centre for the Hybrid Grid is envisaged as being more extensive, with higher communication capacity and demanding higher computing power.

3. **Novel semiconductor materials:** Silicon carbide (SiC), gallium nitride (GaN), graphene, and other materials have superior electrical properties than silicon. Lower power losses and higher current capabilities of these new materials will increase the efficiency and capacity of future HVDC systems, enabling them to be more compact, and providing new opportunities for applications.

4. **Superconductive technology:** This technology can provide an attractive alternative for underground and submarine power transmission at multiple gigawatt level. Research institutes worldwide are working on increasing the temperature at which certain materials attain the superconductive state to make it more attractive in power grids [8]. Lower conductor resistance will reduce losses in transmission, and power transfer capacity will be improved several folds using the same cross-section of the conductor. Advances in superconductive technology will enable feasible intercontinental power transmission to be built, allowing for optimal utilization of energy sources on a global scale.

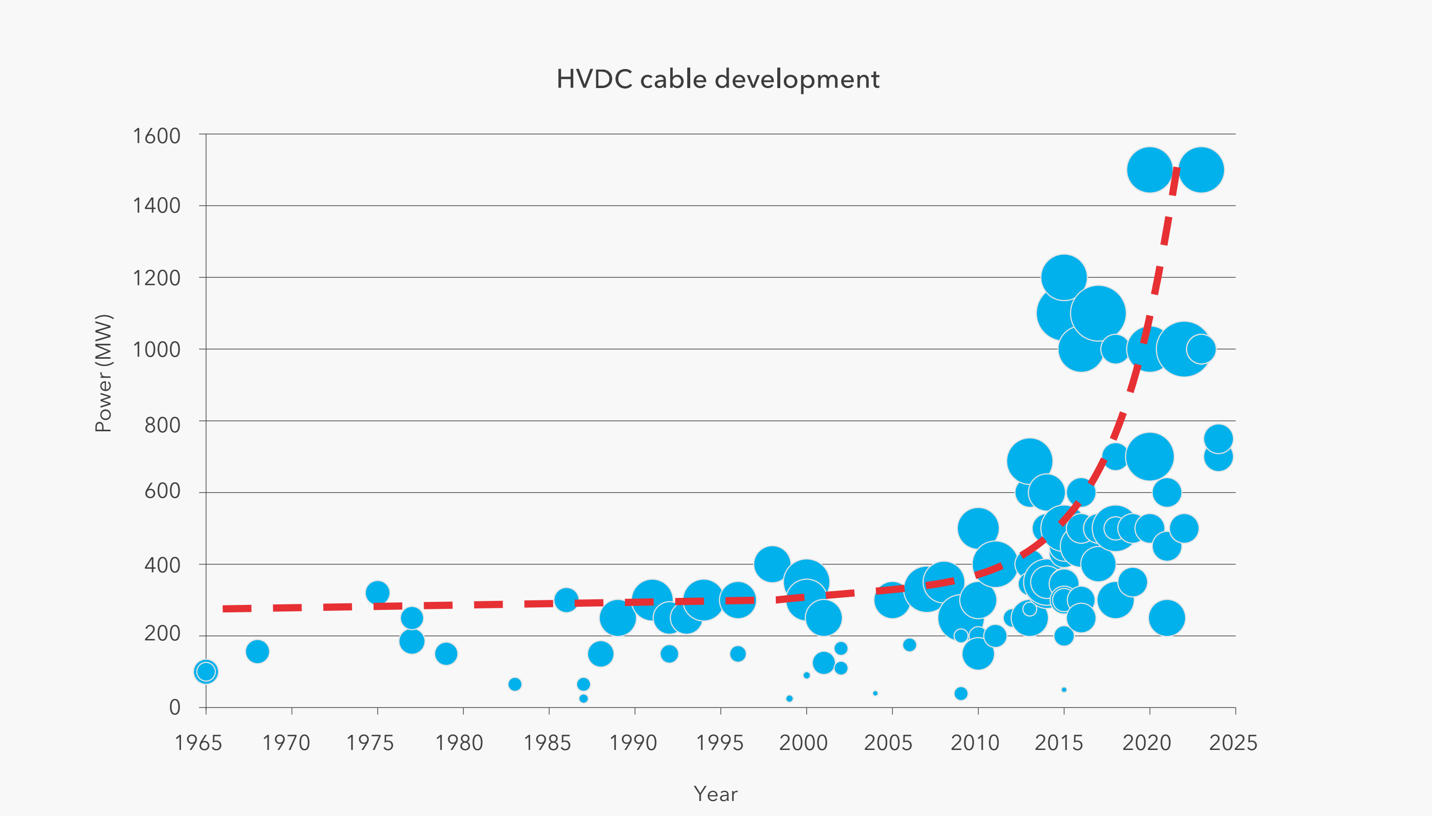

Figure 14. Development of HVDC cable power rating, the sizes of the bubbles are proportional to voltage levels

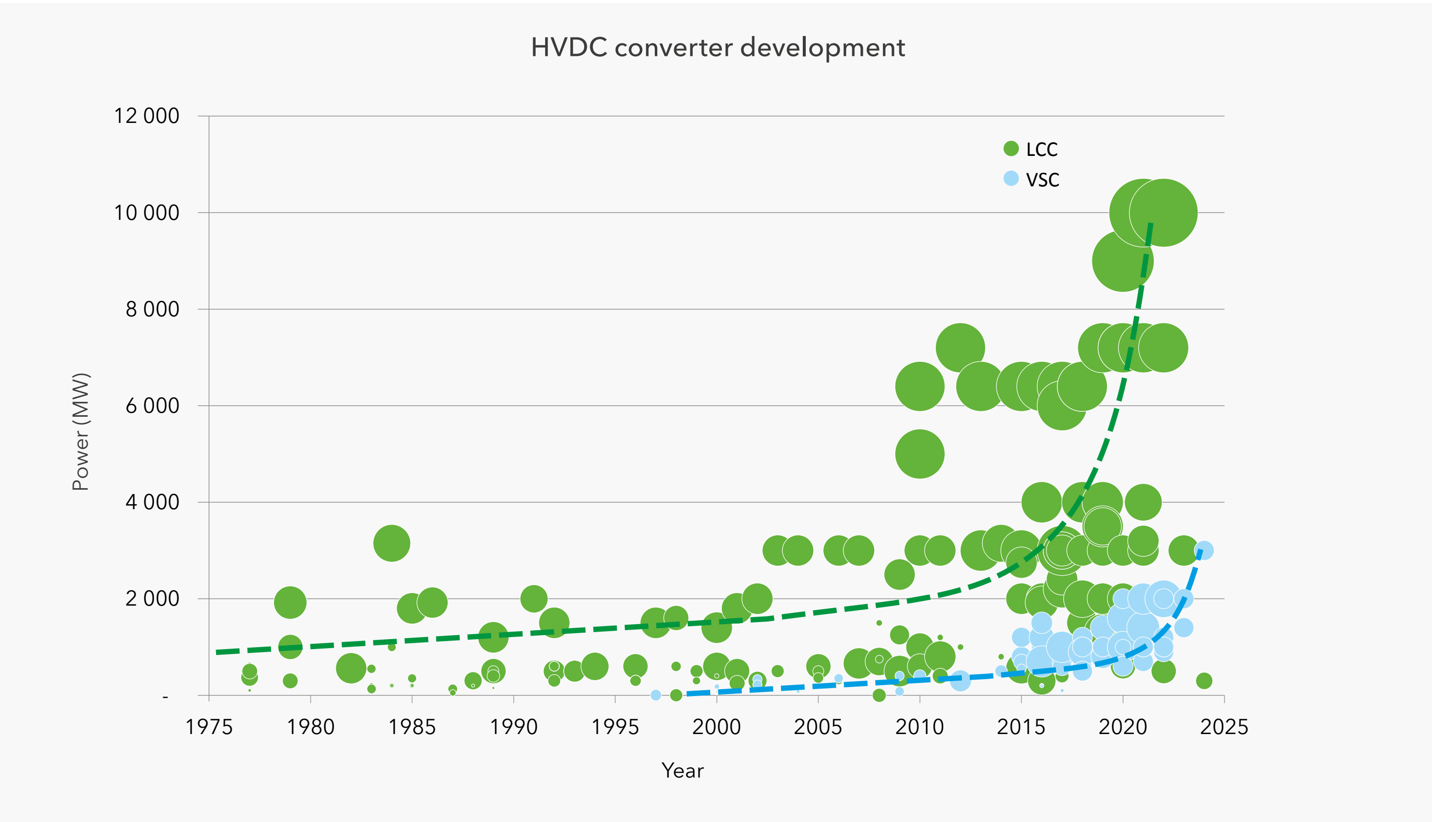

Figure 15. Development of HVDC converter power rating the sizes of the bubbles are proportional to voltage levels

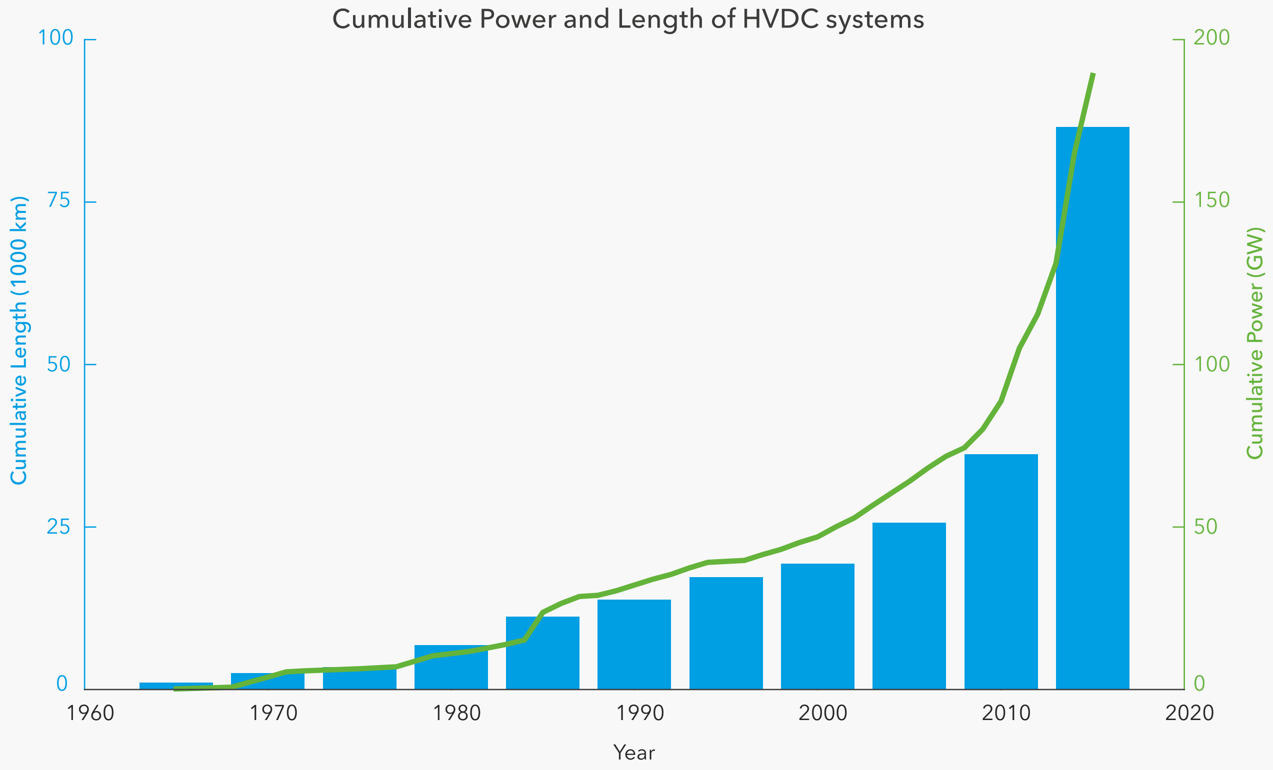

Figure 16. Cumulative power (green line) and cumulative length (blue bar) of HVDC projects

FUTURE APPLICATIONS

Interconnectors

Deregulation of power market and difference in energy prices lead to increase in cross-border energy flows. Historically, the power systems world-over were designed/constructed based on the principle that each country balances its own generation with demand and utilizes cross-border connections as a system support mechanism. Existing transmission capacity will not sustain increasing cross border power trading and HVDC interconnectors can provide the required capacities. Moreover HVDC interconnectors are capable of providing more flexibility for power flow control. HVDC is also the only option for interconnection between asynchronous power systems such as the UK, Nordic Region, and the continental Europe power system.

Embedded DC in AC grid

So far most of the existing HVDC projects were constructed to link between separated and unsynchronized AC grids, however there are an increasing number of projects being built or planned where both ends of the HVDC system are physically connected within one synchronous AC grid [9], such as the Cobra cable [10] , Suedlink [11], Fenno-Skan [12]. In addition to the basic function of bulk power transmission, an embedded HVDC system can provide control functions such as power flow control for optimal system operation, system stability improvement and mitigation of cascading line tripping.

Offshore grids

A huge amount of wind power generation (some 30 to 60 GW) may yet be built in the North Sea and Irish Sea. These wind farms must be connected to the national grids of different countries in a flexible and economical way. Individual connection is straightforward but, for technical and economic reasons, may not be the best choice. A high capacity North Sea transnational grid connecting wind farms to the national grids and simultaneously connecting the national grids to each other, as

Figure 17. Illustration of offshore grid in North and Western Europe.

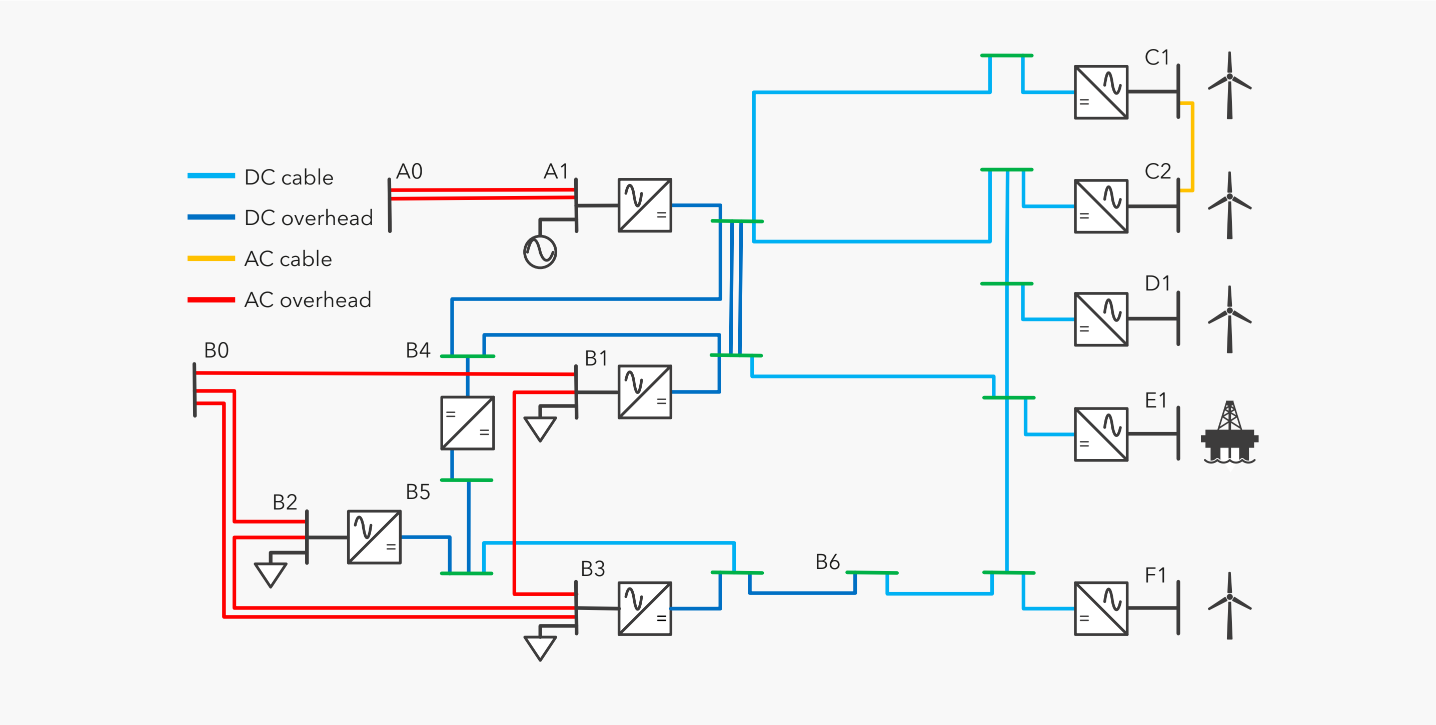

Figure 18. Meshed HVDC Grid connecting AC grids , offshore wind, and offshore oil&gas platform.

Figure 19. One of the growing number of solar power 'farms' in the Californian desert. Picture: iStock, © trekandshoot

shown in Figure 17, is probably a better solution than individual point-to-point connections. This can be explained by the likely improvement in energy efficiency, availability, controllability, lower investment & maintenance costs, and the possibility of trading/exchanging electricity offered by a full fledged offshore grid [4].

Solar grids

Solar PV is quickly on its way to become the most cost effective generation technology. In countries where space is available, large power plants (e.g. Figure 19) can and will be built. Similar to offshore wind, these power plants will likely not be close to the load centres. Therefore a similar pattern as seen in offshore wind may be envisaged; at first point to point and later a grid like structure, possibly including storage facilities such as pumped hydro plants. Such combinations could become interesting already in the near future; where both the solar flux and sufficient water is available; the transmission infrastructure can be shared and investment cost reduced.

Supergrids

Combining activities in offshore and onshore HVDC systems could pave the way for a continental-scale Supergrid, allowing integration of renewable resources and free energy trading. A fictive Supergrid is depicted in Figure 18 [13]. Long-term plans for development of Supergrids have been discussed for Europe, Asia, and, the globe (see e.g. Figure 20, Figure 21, and Figure 22). A Supergrid will not be built in one single step; rather it will materialize through the integration of multiple individual projects. In addition, the construction of such Supergrids will have to overcome many challenges along the way. Such challenges will be technical, economic, and, not least, political as international cooperation and benefits for all stakeholders will be essential.

THE WAY FORWARD

The emerging technologies presented above will facilitate novel applications of Hybrid Grids and accelerate the transition of today's power grid.
A depiction of such a transition is given in Figure 23. As controllability of HVDC systems advances and more and more renewable resources are integrated, the world's energy supply should gradually become more affordable, reliable and sustainable.

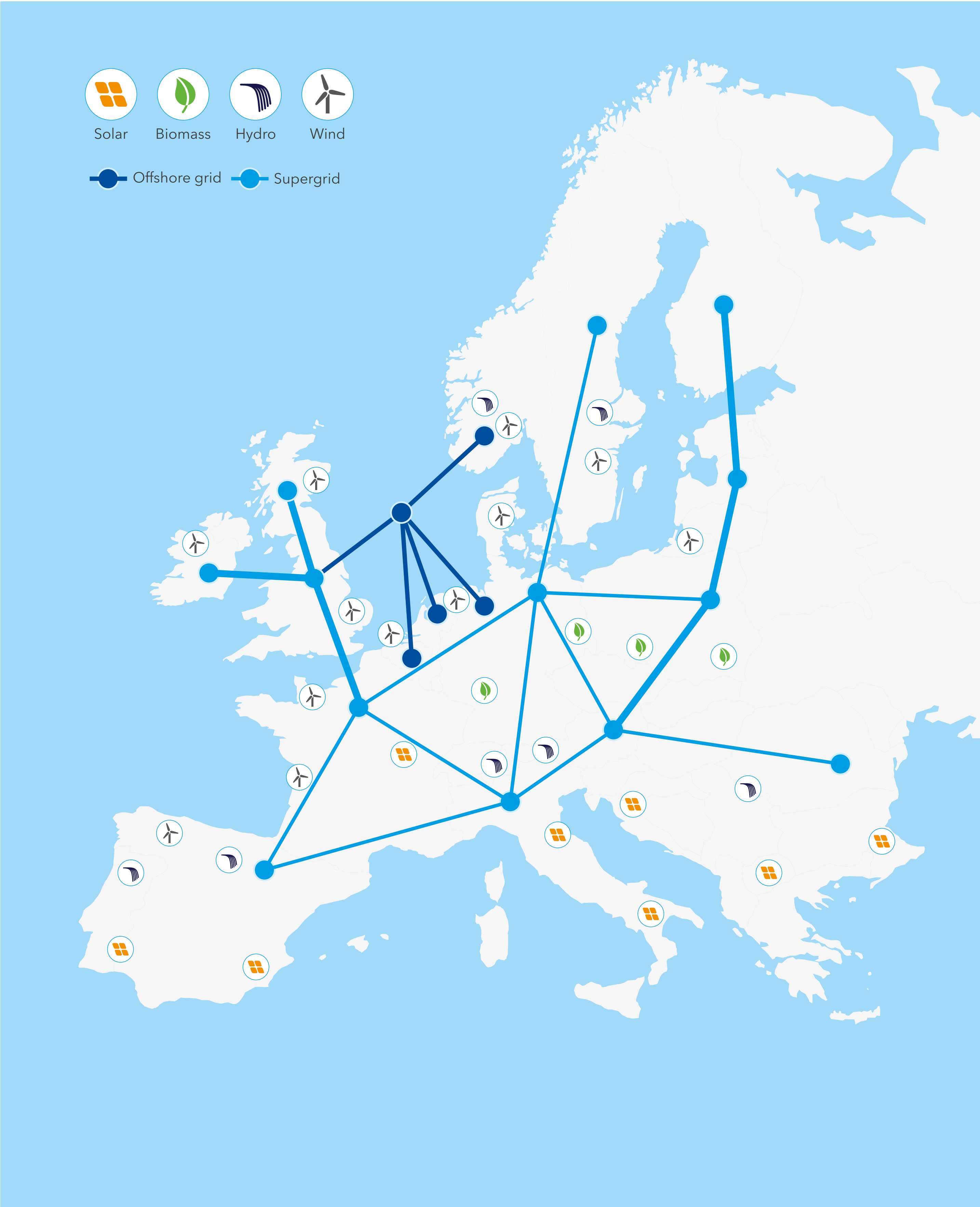

Figure 20. Vision for the European Supergrid

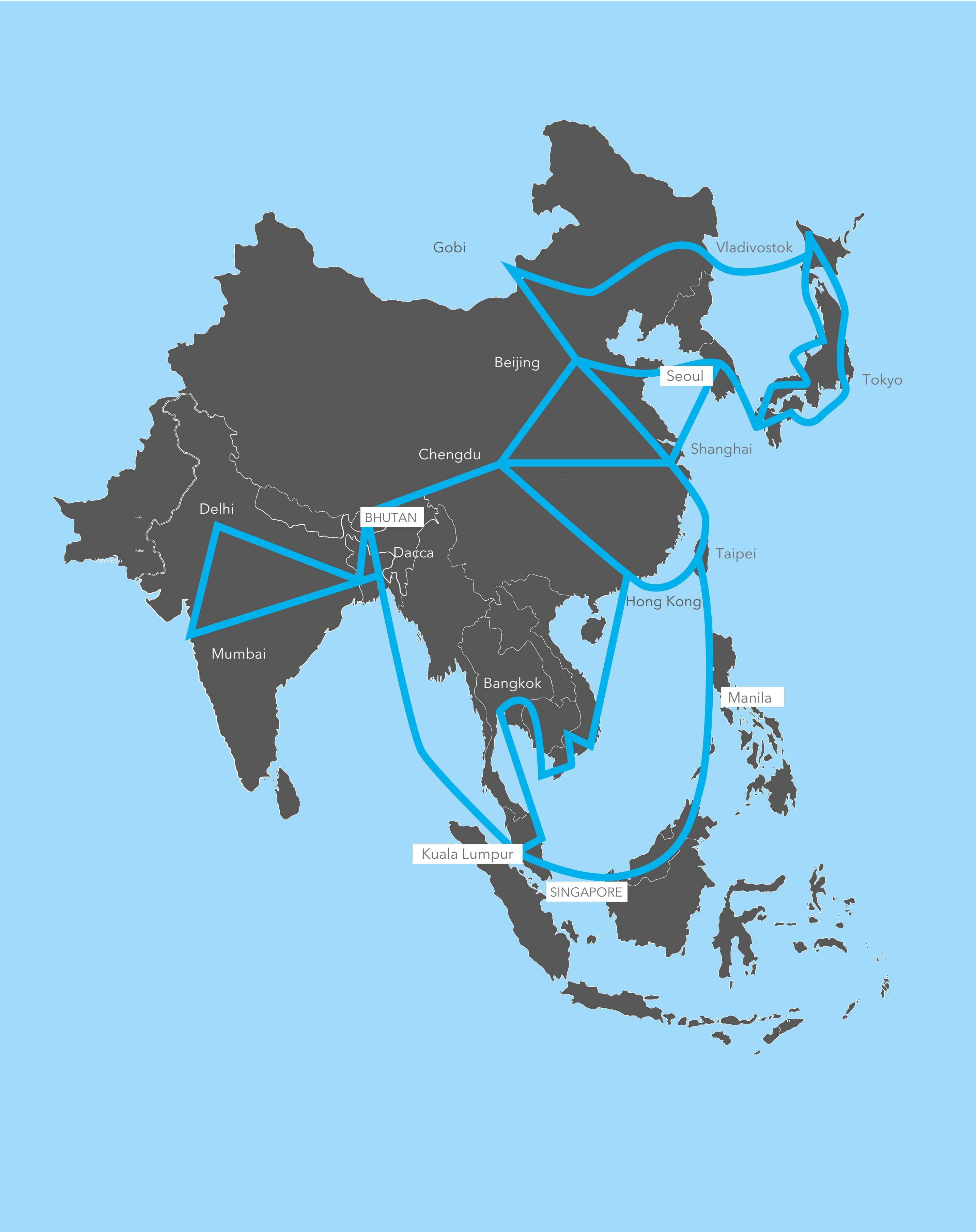

Figure 21. Asian Supergrid

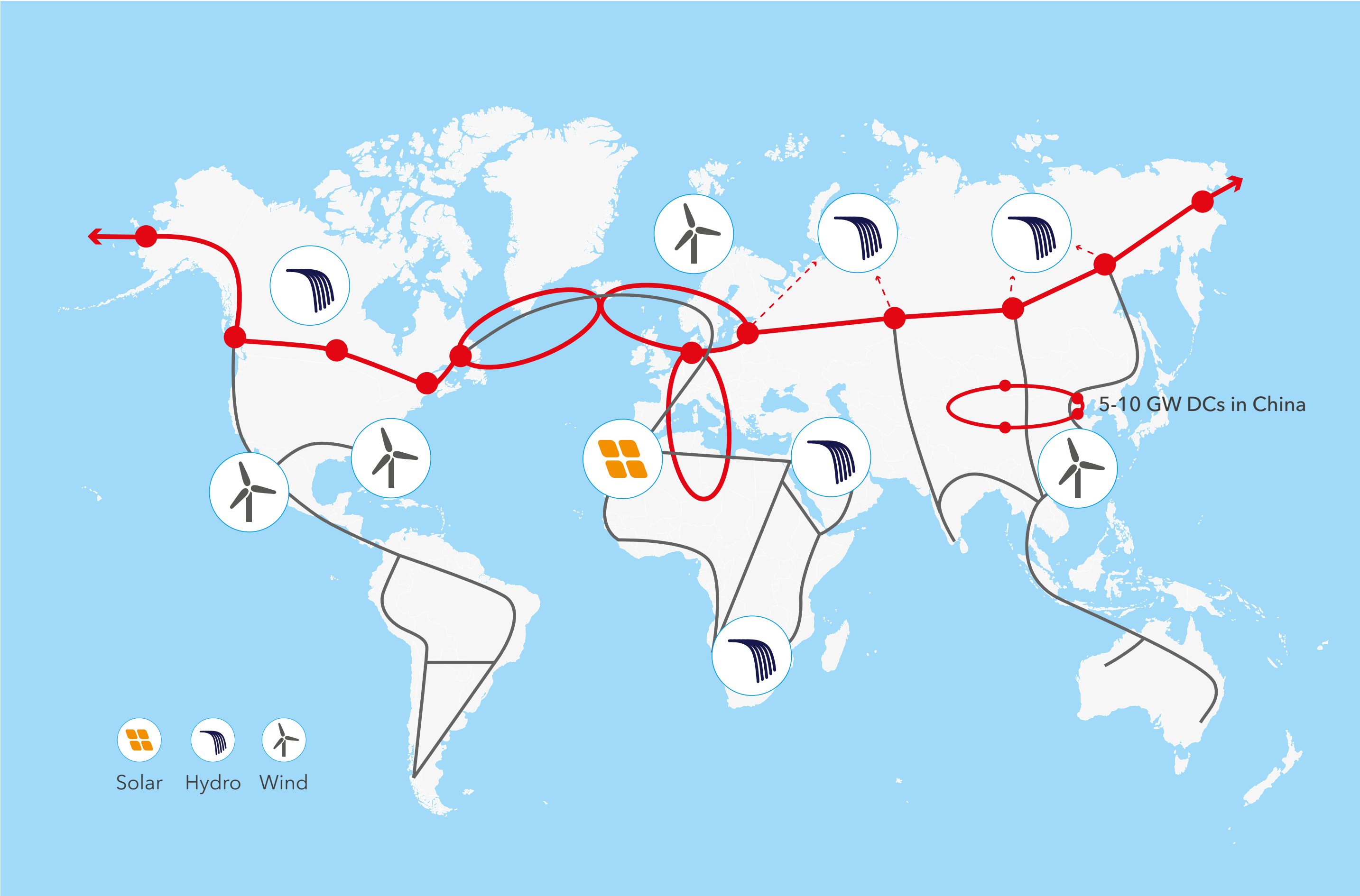

Figure 22. Global Supergrid

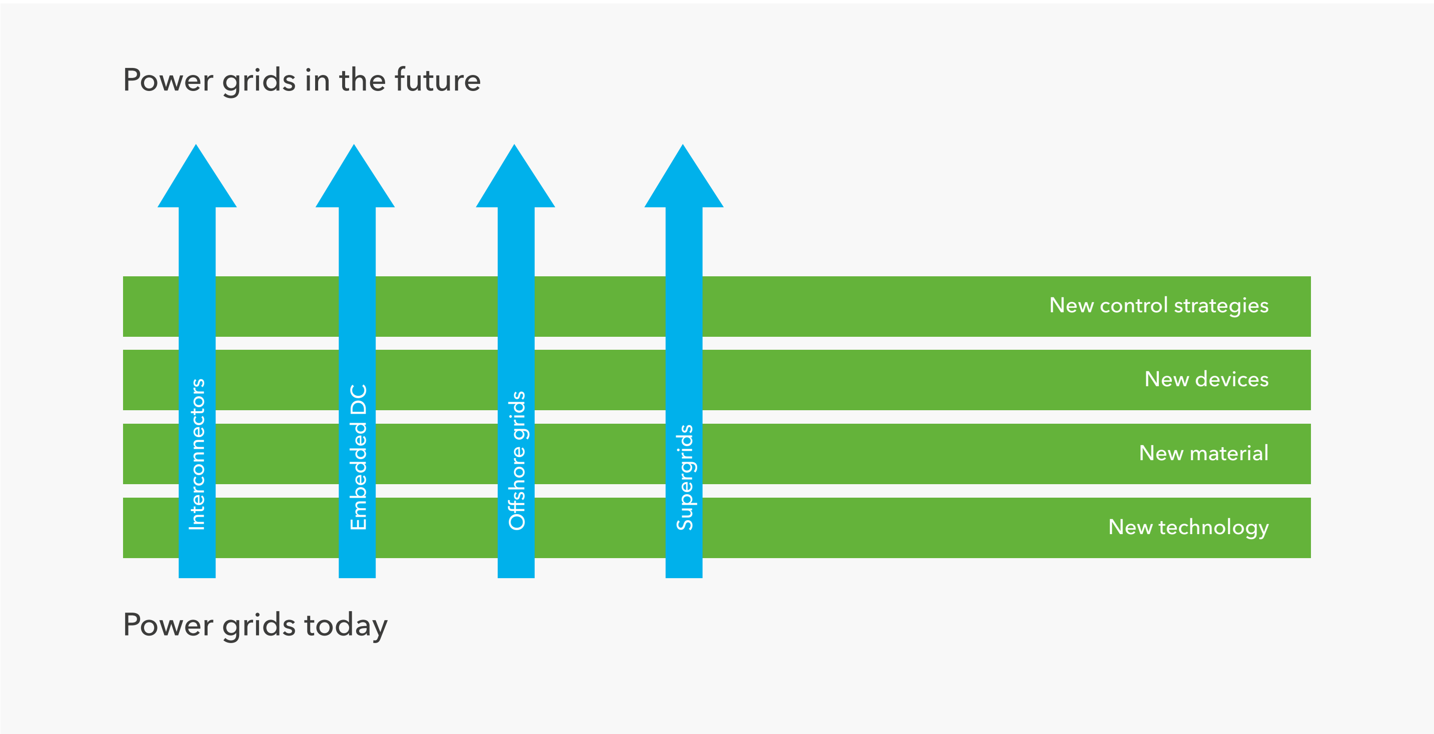

Figure 23. Transition from today's grid into the future

THE ROLE OF THIRD PARTY AND ADVISORY

In the transition from a predominantly HVAC to a Hybrid Grid, a gradual building-up of HVDC systems is anticipated, starting with regional multi-terminal HVDC systems, probably in the form of offshore grids for integration of offshore wind. Later, these regional HVDC systems will be interconnected to form continental-scale Supergrids.

Achieving this transformation will take decades, and the design and operation of the future grid will differ substantially from today. There are many opportunities for traditional and new advisory and third party testing, inspection, and certification (TIC) services brought about by the transition towards the Hybrid AC/DC Grid.

EXISTING SERVICES

System Studies

With many HVDC systems to be built, a large number of system studies are needed during various stages of HVDC projects, from pre-feasibility studies to detailed design studies. The scope of studies includes normal steady state assessment, short circuit calculations, dynamic stability analyses, and interaction and interference studies.

The most important questions to be addressed include:

- Where is the optimal location within the AC grid for connecting the HVDC system?
- How should the AC and DC system work together (systems operation, protection settings, how to address redundancy etc.)
- Can the HVDC system cope with the most severe faults originating from the AC grid?
- Can HVDC provide the necessary support for the AC system to recover from faults?
- Can the AC grid continue normal operation during the most severe DC fault?
- Which additional control functionalities should be incorporated in the HVDC system in order to address these challenges?

These questions can only be answered through detailed system studies using suitable models of the whole hybrid power grid, including HVDC systems. These investigations should be conducted for new HVDC lines as well as for existing HVDC lines when there are substantial changes in the connected AC grids.

With the increasing application of HVDC technology and the advent of multi-terminal, or even meshed

Figure 24. Extensive analysis and study is essential for the safe and stable transition to the Hybrid Grid

HVDC grids, it will be particularly important to study the mutual interactions among the HVDC converters, i.e., the internal transient and dynamic stability of the HVDC systems and their interactions with the connected AC grids.

These studies can be performed by the owners (e.g., TSOs), but consultants and contractors may often be employed, particularly when allocation of available internal resources is difficult or when companies want to harvest from international experience. Such cases are predicted to occur more frequently, as the owners are increasingly challenged by the growing construction project work load.

Testing and Inspection

Development of new technologies brings new uncertainties and unpredictable risks to power systems. There are no reliability data for new components, and estimates can only be based on similar items. This is particularly the case with the transition to the Hybrid Grid and testing becomes more crucial with the possibility of verifying

Figure 25. High voltage and high power testing facility of DNV GL in Arnhem

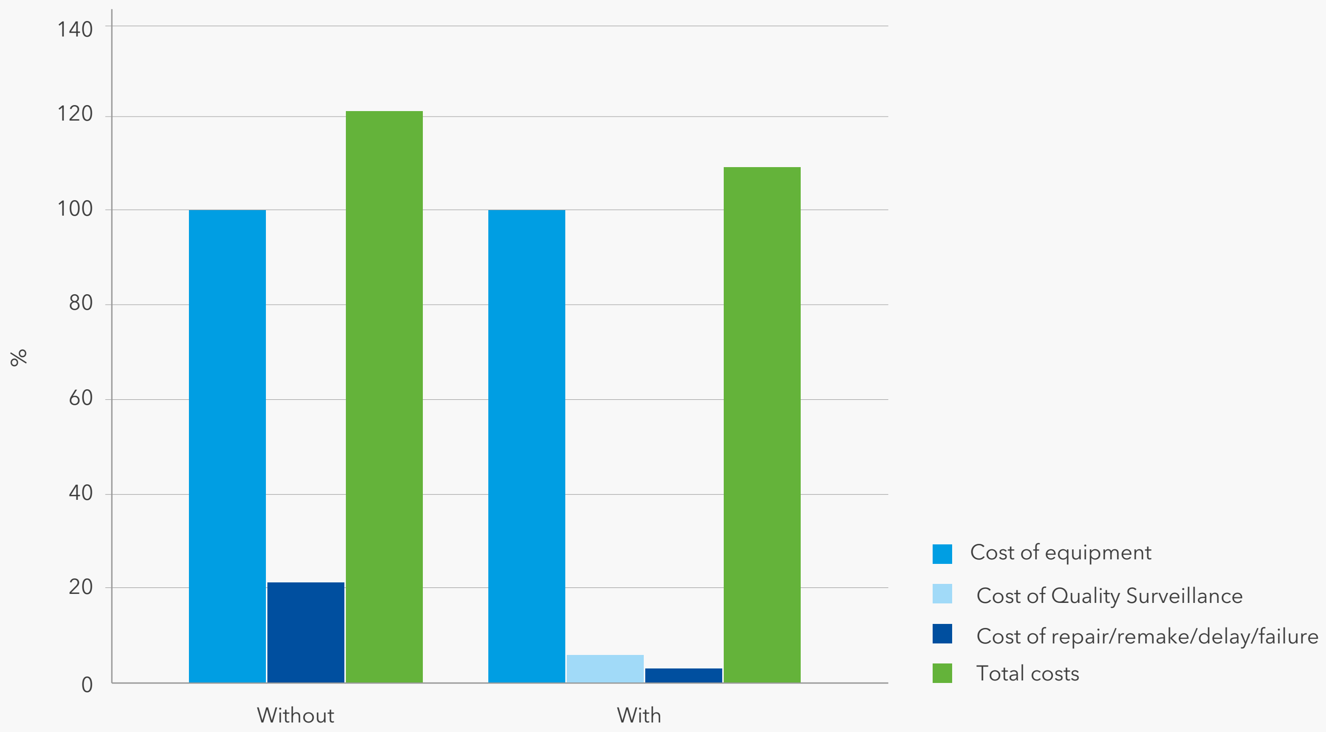

Figure 26. A sample depiction of project costs with and without QA.

equipment performance in conditions close to real-life operation. Testing helps in the identification and prevention of possible failure during the design and pre-commissioning stage. This is particularly important for HVDC equipment production as we foresee greater interdependence of AC and HVDC systems.

As well as detecting mistakes during the design stage, testing can assist in identifying sub-optimal production methods or materials. This is particularly important for bulk equipment production, and when design mistakes may lead to high risks in the power system during the operation of equipment.

Quality Assurance

Quality Assurance (QA) refers to the efforts and activities designed to make sure that the purchaser's quality requirements are met. It is a part of quality management, and is focused on delivering confidence through witness of evidence that quality requirements have been fulfilled. QA cannot guarantee the product quality, but means that inadequate quality is less likely to be encountered.

QA activities are often justified by the following considerations:

- Reduction of technical risks i.e. the failure of a component and possible flaws in the design
- Requirement for (independent) evidence of quality by law, grid codes or regulations
- Reduction in the risk of late delivery
- Reduction in financial risks

- The trust between parties involved, based on experience

- Demonstration of quality awareness to clients

The costs of re-work or solving problems during the construction stage of a new substation or connection are limited compared with the costs resulting from failure, see Figure 26. For the utility or the project management organization, the costs may not be actually visible, but consist of extra man-hours for discussions, project management, travelling costs, on-site repair, delays, etc.

Typical QA activities related to HVDC systems include:

- Review of key technical design specifications/ criteria/parameters for the key components like HVDC converters.

- Witness of type tests of key equipment, such as converter transformer, valves, reactors, bushings, and DC switchgear.

Experience shows that putting emphasis on the witness of all tests, including type tests, routine and special tests during the QA work is very important. This is because the production of key equipment still involves significant manual work. Successful pass of type tests does not always mean successful pass of routine tests, because human error is a significant factor. The factory acceptance test (FAT) is the most crucial QA phase where most of the problems from the previous processes can be identified.

ADDRESSING FUTURE CHALLENGES

As power grids progress towards the future Hybrid Grids, they will require new types of advisory and third party services in addition to various conventional services.

Modelling and Analysis of Combined AC/DC Systems

With the increasing number of HVDC lines integrated into AC power grids and the expected advent of multi-terminal HVDC systems, new modelling and analysis tools must be developed to deal with the increased complexity. This includes the extensive interactions between the AC and DC systems and the higher level of non-linearity.

From Component Testing to System Testing

In future power systems, with high penetration of individually controlled units, interoperability of components is an increasing concern. Nonlinear behaviour of power-electronic components, and the dynamic response of components which are deemed reliable in isolation, could lead to unexpected phenomena when installed in power systems. This is an issue increasingly of concern, for example, in offshore wind integration, where the mutual interaction of wind turbine converters and the HVDC system may be underestimated and result in significant problems. Thus, verification of the interoperability of components and subsystems by testing them together in the intended environment or simulated real-world conditions should be considered.

Interoperability

With the prevailing contract model for HVDC projects changing gradually from turnkey to multi-vendor, with multiple vendors providing different components, the system integrator (often the owner itself) will have the final responsibility for guaranteeing interoperability among the various sub-systems. The interoperability of sub-systems within the Hybrid Grid will become even more important with the implementation of multi-terminal HVDC, or even meshed HVDC grid, as the system will rely upon coordinated control actions from multiple HVDC converters to maintain system balance and stability. Standardization of communication protocols and system testing are among the most effective methods of ensuring interoperability.

Operation of Hybrid Grids under Increased Complexity

In a future grid that will be dominated by increased variability of power production, more commercial grid use and deregulation, higher societal expectations on reliability, more cross-border TSO cooperation, and changing market designs, it should be expected that system operations will change dramatically. These changes increase the complexity of the role for control room staff during normal and disturbed operation. The once relatively predictable grid will be subjected to more cases of aggressive use and greater uncertainty, both of which require rapid reaction and well-informed decision making by grid operators as well as by the control systems in order to maintain power balance and operation security.

Current tools and processes might not suffice. New IT technologies provide access to more data and thus, potentially, more information about the grid. Tools and processes that address this challenge must be developed.

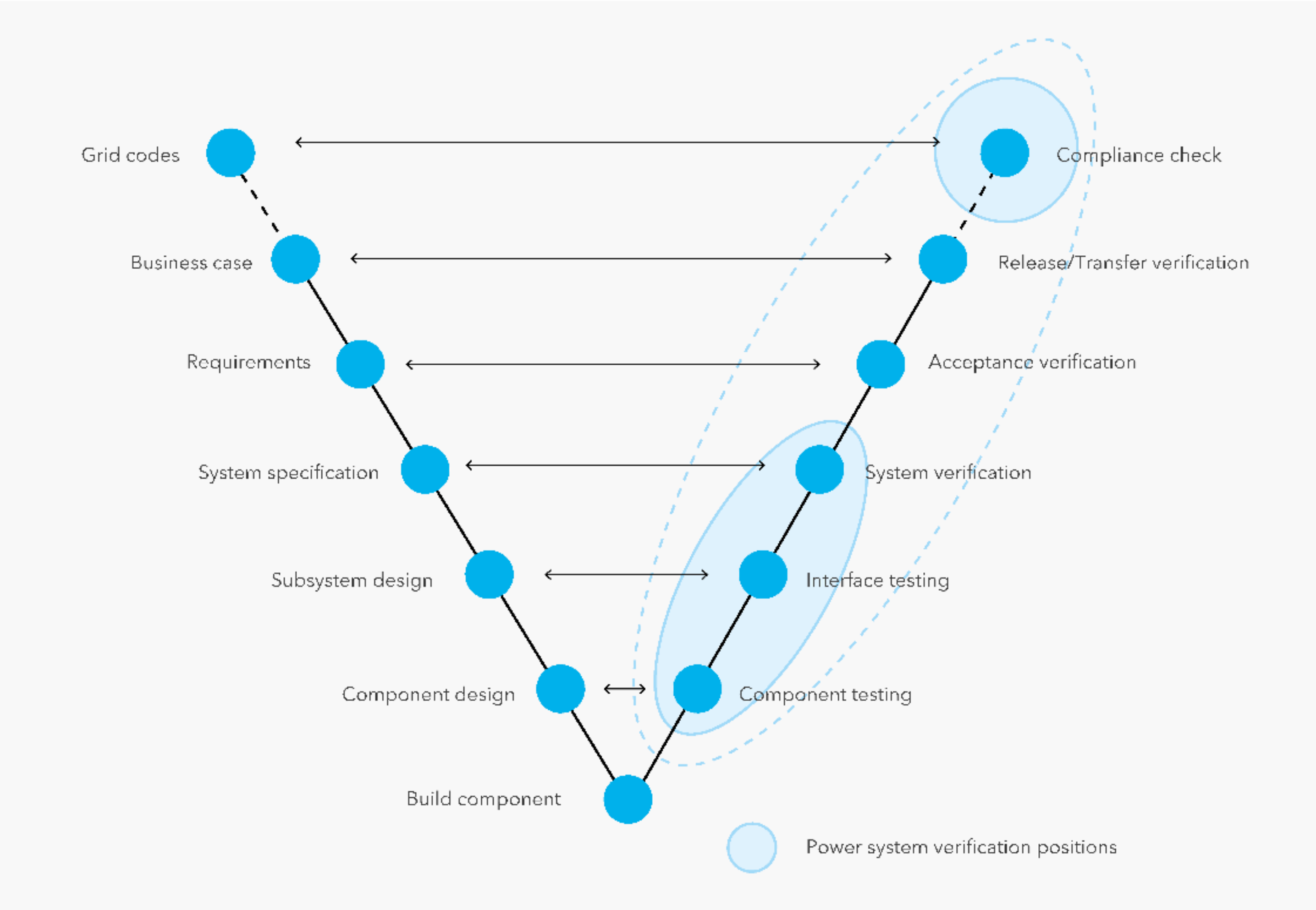

Figure 27. The system development V-model

Verification of Power System
A Verification Service includes the process of verification and reporting of the verification results and a clear conclusion regarding the status of the verified component or system. The scope of verification may be described by reference to a component or system specific service specification or a set of technical standards specified by, or agreed upon with, the customer.

With power grids developing towards a Hybrid Grid, new territories will be covered, e.g. offshore (wind) generation, and new technology and markets are being introduced. This means that advanced control functionality is added and more interdependencies with other systems (e.g., IT and telecom) are created. Power systems will develop from "passive stable" highly predictable top-down systems to hugely complex "actively held stable" integrated systems, evolving over time. This development clearly calls for a more holistic view; i.e. "does the (HVDC) system function correctly in this wider/bigger environment and is its functionality adequate over time?" (That is, does it still function as intended after upgrading with new HVDC equipment or software?). These client questions call for (repeatable) OPEX services and a broader "system requirements evolution over time" view. As a consequence, in order to meet client demand and contribute to solving the energy trilemma*, a set of power system verification services must be developed. These power system verification services are located along the right-hand side of the well-known system development V-model as shown in Figure 27.

* The energy trilemma refers to the challenge of delivering affordable, reliable, and sustainable energy.

CONCLUDING REMARKS

In the next few decades the world will see significant changes in power grids as they evolve in response to the growing challenges placed on power systems. The forces of globalization, combined with policy and market responses to climate change and the changes in energy mix, will result in:

- more trading of electricity across regions, subcontinents and continents
- greater demand for grid flexibility
- ever longer transmission distances
- increasing number of connections with (often remote) renewable sources

There is no doubt that power grids will become hybridized by integrating more HVDC systems to meet these expectations, which means that the composition and operation of grids will become fundamentally different from today. This brings both challenges and opportunities for all stakeholders, not least TSOs, manufactures, and advisory and third party bodies.

In order to seize the opportunities and address the challenges faced by the power grids of today, we need to take a broader view in which the performance assessment of the grid component is not only done on an individual basis but increasingly seen as a part of the bigger system. We have therefore recommended in this paper that the interaction of components and sub-systems within power grids should be analysed and tested in much greater detail than they are at present. This becomes even more important with the increased complexity of the Hybrid Grid characterized by more HVDC systems and extensive control functionality. The role of third party and advisory bodies will become increasingly valuable for enhancing trust in safeguarding reliability, flexibility, and resilience towards deployment and operation of the future Hybrid AC/DC Transmission Grid.

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