A EUROPEAN SUPERGRID: PRESENT STATE AND FUTURE CHALLENGES

Stijn Cole, Karim Karoui
Tractebel Engineering
Brussels, Belgium
stijn.cole@gdfsuez.com

Til Kristian Vrana, Olav B. Fosso
Norwegian Univ. of Science and Technology, NTNU
Trondheim, Norway
vrana@ntnu.no

Jean-Baptiste Curis, Anne-Marie Denis
RTE
Paris, France
anne-marie.denis@rte-france.com

Chen-Ching Liu
Univ. College Dublin
Dublin, Ireland
liu@ucd.ie

Abstract – Europe has a clear objective of obtaining a large share of wind power in the overall energy mix. A significant part of the installed wind power capacity will come from offshore wind farms. As an alternative to connecting every wind farm to the onshore grid separately, the 'supergrid' concept has been proposed. A supergrid would allow international trade and balancing, and can accommodate renewable energy sources, such as concentrated solar power and offshore wind energy. In this paper, we give an overview of technical challenges associated to meshed multi-terminal direct current supergrids, and present alternatives and a roadmap that could expedite the development of a European supergrid.

Keywords: Supergrid, HVDC

1 INTRODUCTION

The development of a 'supergrid' has been hailed as a means to attain the ambitious renewable energy targets Europe has set. The supergrid idea is finding acceptance in academic, industrial and political circles. The basic definition of a supergrid can be derived directly from the word's etymology: a supergrid is a grid which resides 'on top' of the existing grid. This basic definition is important in that it immediately makes clear that the supergrid is not just an extension of the existing grid, but a whole new layer or backbone, or at the very least a new independent structure, connected to the existing grid. The definition of supergrid as an overlaying grid is very broad. To arrive at a workable definition, it has to be further specified what is meant by a 'supergrid'. A supergrid could be based on Alternating current (AC) or Direct Current (DC), it could be offshore or onshore, fully meshed or with alternative topologies integrating point-to-point links, or a combination of all of the above. In section 2 it is argued that in the European context a number of key drivers will lead to many offshore developments such as wind farms and interconnectors. Therefore, a European supergrid will have a large offshore part that could rationalize the offshore developments. Voltage Source Converter High Voltage Direct Current (VSC HVDC) is often put forward as the ideal technology for supergrids, as VSC HVDC supports multi-terminal operation. However, as we will explain in section 4, many technological challenges associated to multi-terminal VSC HVDC systems remain. One should therefore not lose sight of other supergrid options (section 5). In view of the numerous offshore developments already existing, 'green field' approaches to the conception of a supergrid seem questionable. It is more likely that the development of the supergrid will follow an organic process as explained in section 6. It is finally argued that the alternatives could well expedite supergrid development as they are based on proven technology. In section 7, a selection of ongoing initiatives on supergrids is given. Special attention goes to the supergrid proposals of Friends of the Supergrid and Medgrid, which have a paper in the invited lecture on supergrids in the PSCC 2011 conference.

2 DRIVERS FOR THE SUPERGRID

The supergrid will not serve a single purpose. In fact, there is a wide variety of drivers, which are introduced in this section.

2.1 Offshore Wind Development

According to the European Wind Energy Association (EWEA) scenarios, 40 GW offshore wind farms will be installed by 2020, and 150 GW by 2030 [1]. The fast developing offshore wind projects call for a new type of electric infrastructure: offshore transmission systems. EWEA identifies the main markets for offshore wind farms as the United Kingdom, Denmark, The Netherlands, Sweden, Germany, Belgium, and Norway. It is thus expected that future offshore developments are mainly concentrated in the North and Baltic Sea. Instead of connecting each wind farm to shore by a dedicated connection, it could be more efficient to collect offshore wind energy in an offshore grid that is connected to shore, or directly to the main load centers.

2.2 Large-scale Concentrated Solar Power

The objective of a diversified energy supply and the observation that a small part of the desert has enough solar energy potential to cover the electrical energy needs of the whole world, make a case for Concentrated Solar Power (CSP). The idea is to install large-scale CSP in the Sahara region, and to transmit the electricity it generates directly to European load centers. This would require a supergrid structure, linking Europe to Africa and the Middle East.

2.3 *Interconnection for Balancing*

A growing share of intermittent renewable in the grid leads to a number of problems, many of which were identified in The European Wind Integration Study (EWIS), a study conducted by the European TSOs [2]. In particular, the intermittent nature of renewable sources is considered as a huge problem. Balancing becomes more difficult as more uncontrollable sources such as wind energy are connected to the grid. Long distance transmission, interconnecting remote RES, are instrumental in balancing regional fluctuations. Harnessing the tremendous value of the storage capacity and flexibility of Norwegian hydro could be even more advantageous from a balancing perspective. A large European supergrid could not only connect offshore wind farms, but also a variety of other sources such as hydro power, CSP and even ocean energy in future.

2.4 *Interconnections/Trade*

A supergrid would not only be used for connecting offshore wind farms, but also for international trade. In Europe, a large number of submarine cables are already installed for international trading purposes, and more are planned. A supergrid spanning multiple and far away countries would increase the potential for international trade.

2.5 *Bootstraps*

TSOs are facing difficulties in getting permits to construct overhead lines. An alternative are offshore HVDC ‘bootstraps’ that link two onshore connection points. The idea has been proposed for the France-Spain interconnector, but was ultimately discarded. The UK Transmission System Operator (TSO), National Grid, considers two HVDC bootstraps, connecting Scotland and England on the west and east coast (Fig. 1). The bootstrap function is inherently present in a supergrid. A supergrid would combine the three functions of bootstraps, international trade and offshore wind farm connections.

Figure 1: Bootstraps (Figure extracted from [3]).

3 TECHNOLOGY

The main drivers described in the previous section give an indication of the requirements for the supergrid. The present section lists the requirements and the possible technological answers.

3.1 *Requirements*

Based on the applications that form the drivers for the supergrid, the technical requirements for a supergrid can be defined. A first requirement is long-distance transmission. A supergrid would connect renewable source from different, often remote regions. An example is concentrated solar power in the Sahara. A second requirement is that sufficient ratings can be achieved, to allow connection of large-scale renewable energy sources. A third requirement is the meshed nature of the supergrid. Meshing a transmission grid increases its overall reliability. When large-scale renewable energy sources are connected to the load centers, it is desirable that they do not rely on a single connection for the export of power. Lastly, it is clear that the European supergrid will have a significant offshore component. All equipment should therefore be suitable for offshore use.

3.2 *Technological Answers*

Much experience is gained in offshore power technology in the last years due to the increasing number of offshore projects, mainly offshore wind farms, but also offshore oil and gas rigs. In future commercial oceanic energy projects, harvesting tidal or wave energy may see the light of day. Moreover, vast experience exists in Europe on submarine connections, both in AC and DC technology. However, for supergrid applications, AC and classical HVDC systems reach their technological boundaries. AC cables require reactive compensation for large distance transmission, which is very inconvenient in offshore applications. Classical HVDC converter stations cannot be used offshore because they need a voltage source to commutate and because of their large footprint. VSC HVDC on the other hand, complies with all of the technological requirements for a supergrid. VSC HVDC can be used for long-distance transmission, it can be meshed and is used for the connection of offshore wind farms and oil rigs. While today the power ratings are not up to par with those of Current Source Converter (CSC) HVDC systems, they have been sufficiently developed to allow large-scale power transmission. VSC HVDC is therefore considered to be a major enabler of the supergrid.

4 CHALLENGES AND R&D NEEDS FOR MULTI-TERMINAL VSC HVDC BASED SUPERGRIDS

While VSC HVDC allows in theory easy multi-terminal operation, many technical challenges remain.

4.1 *Operation of AC-DC Systems*

Future HVDC transmission grids, either offshore or onshore, will have to be operated in parallel with AC transmission grids, thus creating hybrid transmission systems. The security and stability of those hybrid systems have to be handled both in normal and disturbed conditions, to maintain continuity of energy supply to domestic consumers and crossborder trade. Moreover, this continuity of service will have to be provided at “non-prohibitive” economic conditions for all parties involved. These are crucial pre-requisites for the feasibility of future HVDC grids, that might strongly influence the stakeholders decisions (TSO’s, regulators, governments, …) at the very beginning of the design process.

On one hand, HVDC grids will have to react “correctly” against disturbances affecting HVDC devices. On the other hand, as the DC and AC transmission grids will be operated in parallel, a harmonized and efficient coordination will have to be set up to control and limit any possible spreading of negative effects from AC to DC and vice-versa.

It should be kept in mind that dynamics will be the major key issue to deal with. This is the huge challenge TSO’s, developers and manufacturers have to meet together for a successful outcome in future decades.

4.2 DC Breakers

In existing two-terminal or point-to-point VSC HVDC connection, a DC fault is cleared by opening the AC circuit breakers. This circumvents the need for DC breakers. Note that the current control loop cannot limit the DC fault currents as the IGBTs are blocked and the diodes connected in anti-parallel to the IGBTs keep feeding the fault. Keeping the same protection strategy in a multi-terminal system would mean that the whole grid has to be shut down in order to clear a DC fault, which is unacceptable. A large supergrid connecting diverse renewable energy sources and load centers would be a critical infrastructure. It would be desirable to have the same criteria as for AC grids regarding reliability and availability. One desired feature would be selectivity: only the faulted line should be isolated, while the rest of the DC grid keeps operating. This necessitates DC breakers.

DC breakers are currently not yet available. However, manufacturers acknowledge the importance of DC breakers for supergrids and are working hard to release a first prototype.

4.3 DC Voltage Control

In VSC systems, it is imperative that DC voltage remain very close to the nominal voltage. Therefore, in a point-to-point VSC HVDC transmission system, one converter always controls the DC voltage. When the other converter changes its active power, the voltage controlling converter automatically changes its active power in such a way that the DC voltage remains at the nominal value.

In a multi-terminal network, wherein many converters can change the setpoint of their injected active power, the voltage controlling converter cannot always provide the power required to balance the network. In Fig. 2, a meshed four terminal DC network is shown. The bottom right converter is the voltage controlling converter. If the bottom left converter fails, the voltage controlling converter has to compensate for the reduced output by increasing its output from 100 MW to 200 MW. If the converter rating is below 200 MW, the DC voltage could rise to an unacceptable level if no provisions were made.

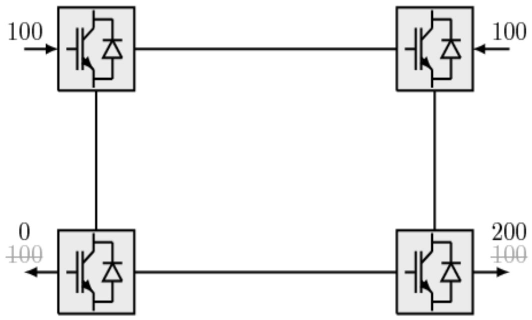

Figure 2: Voltage regulation in MTDC network.

It is obvious from the above discussion that a more elaborate voltage control method is needed in multi-terminal systems. Two methods are proposed in literature: voltage margin control and voltage droop control. In voltage margin control, the voltage is controlled by one converter, but aided by another one when it fails or when voltage becomes too low. In voltage droop control, all converters contribute to voltage control. The relative contribution of every converter to voltage control can be chosen [4].

4.4 Standardization and Interoperability

At present, standardization of HVDC systems is at its infancy and no initiative on standardization of multi-terminal DC systems exists. Nevertheless, standardization is an important issue, since the supergrid will incorporate a wide variety of facilities from different suppliers, some of them already existing, and has to cope with rapid advances in HVDC technology. Interoperability is a must, as different technologies and equipment from different manufacturers must be compatible. Moreover, the supergrid should be flexible and modular so that it can grow in an organic way.

Once the supergrid starts to emerge, a DC grid code must be available. At present, no attempt has been made to come up with a fully-fledged DC grid code. However, some grid codes, such as the grid code from the UK TSO, NGET, have been rewritten to cater for offshore grids. While still a far cry from a multinational supergrid grid code, such initiatives might spur the development of a DC grid code.

4.5 Protection

The availability of DC breakers is not enough to guarantee a high reliability of the DC grid protection. A suitable protection strategy needs to be available that can accurately detect and rapidly isolate the fault. The DC fault current will rise very rapidly in a DC network. Practically, the fault needs to be correctly detected within 1 ms and without using communication between the converter stations [5]. The problem is compounded by the fact that traditional AC protection methods are not applicable in HVDC networks.

Preliminary analyses on the protection of HVDC networks for off-shore wind farms have been discussed in the TWENTIES project (www.twenties-project.eu) launched in April 2010 and financed by EC funds in the FP7 framework ([6], [7]). The main concepts addressed and partial results achieved through first simulations, are summarized below.

- The simplest MTDC system is the three-terminal one, the most complex a meshed network. Many intermediate topologies can be designed in between. Radial connections of wind farms or point-to-point interconnectors are not HVDC grids, as they do not offer alternative paths to power flows in case a fault occurs on a cable. However they have to be considered up to 2020, as preliminary steps for further off-shore grid developments beyond 2020 and towards a “target network” still to be designed.
- Short-circuits on DC cables, and mainly pole-to-pole ones are the most severe faults to get through, in very few ms (<10ms). Substantial research work based on detailed dynamic simulations is therefore mandatory to better understand and characterize the physical phenomena occurring in a DC grid affected by a short-circuit.
- DC short-circuits can be subdivided into several classes, depending on the magnitude of the peak fault current and the range of di/dt. These parameters vary according to fault location on the DC grid and characteristics of the AC grid to which the DC grid is connected. Each class will require specific current breaking functions and / or different types of DC breakers.
- Protections commonly used for AC grids cannot be simply transposed to DC grids and have to be adapted to DC needs (overcurrent, distance, line current differential, cable directional, busbar current differential, ...). More specific protections coordinated with converter actions will probably have to be designed. Back-up and reclosing also need to be addressed in future work.
- The DC grid protection system has to be specifically designed for the DC technology (CSC, VSC, specific converters architecture) and grid topology (from three-terminal MTDC to a meshed network) under concern. It has to integrate the detection, selection and elimination of the faulty section in very few ms, taking into account the short-circuit classes (item 3).
- A robust and fast DC breaker is a crucial component of the protection system. However, the DC breaker alone will not be sufficient to properly clear short-circuits in future meshed DC topologies. The whole protection system including sensors, actuators and signal processing units also have to meet the required dynamics and accuracy.
- The converters and other equipments such as inductors can help limiting the fault peak current, leaving thus more room to the selective fault elimination process and making it easier and more reliable. The first generation of DC breakers will probably have to benefit from this conjunction of actions.
- Finally, the coupling of DC grids to AC grids will require careful coordination of protection schemes on both sides. More simulation work on reference events is still needed, and might show that AC protections have to be adapted to avoid fault current infeeds from AC to DC and vice versa.

5 ALTERNATIVE SUPERGRID STRUCTURES

However, a meshed, multi-terminal VSC HVDC system is not the only option for a supergrid. Especially in the North Sea, where new transmission infrastructure is needed in the near future, other concepts can be applied. This future offshore transmission system can generally be described by four levels (Fig. 3). The first level consists of the individual wind turbines. The second level is the wind farm collection grid that connects all wind turbines in the same wind farm. The third level is the cluster grid, which interconnects several wind farms. The third level can also accommodate loads such as oil rigs as shown in the figure, or other generation such as solar power or ocean power. Finally, long distance transmission to the main load centers or to other clusters is the fourth level. The levels three and four could constitute the first step of a supergrid. Levels one to three can use AC or DC technology, while level four uses DC due to the long distances involved. Taking into account the possibility of gradual organic growth of the supergrid, it is likely that it will contain AC parts.

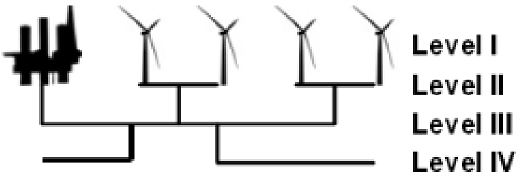

Figure 3: Offshore grid levels.

5.1 *Collection grid known concept*

The wind farm collection grid connects all the wind turbines in a farm to a common transformer (or converter) station. A wind farm with all turbines is usually planned in a single process, enabling good coordination of the activities. The system is constructed in one step and not changed significantly afterwards.

5.1.1 AC Collection Grids

The state of the art regarding collection grids is AC technology, and is applied to all existing wind farms. Far offshore wind farms with HVDC interconnection are a special challenge, since they are operated as an electrical island. Even though a lot of experience exists for the operation of AC grids, it is not possible to directly transfer all proven operation principles to offshore AC collection grids. Since no direct AC coupling to shore exists, the grid is an electrical island with its own frequency. This grid frequency is not linked to the rotational speed of electrical machines, and consequently it does not need to be the same as the main grid's frequency. Operational experience and knowledge on purely power converter based AC grids is limited. Control schemes for the operation of parallel inverters have been developed [8], but have so far been applied only in small scale. The feasibility for real life systems will hopefully soon be demonstrated at the Bard Offshore I wind farm.

5.1.2 DC Collection Grids

Long distance subsea power transmission has to be realized with HVDC. Wind turbines with permanent magnet generators directly rectify the generators output to DC. Considering both turbine output and transmission being DC, it is a logical consequence to question if a conversion to AC is needed.

This concept seems promising, avoiding unnecessary conversion steps, reactive power flows, the need for a third pole, and other known advantages of DC technology.

The feasibility of DC collection grids has been studied in literature and might gain importance in the future [9].

5.2 Offshore Cluster Grids

An offshore cluster grid connects several wind farms together. The future offshore clusters will be much larger than a single wind farm. The planning and operation of an offshore cluster grid can be challenging, since it will incorporate several wind farms of different operators and manufacturers that might use different types of collection grids.

5.2.1 AC Cluster Grids

Since the wind farm collection grids are usually realized with AC technology, it is convenient to realize a cluster grid also with AC. This choice is advantageous, since AC technology is mature, and a lot of components are available. Circuit breakers enable reliable and cost effective protection and sectioning schemes.

If the chosen frequency is set by the largest converter, control is easy but vulnerable if the reference unit fails. In larger systems the frequency should be determined by all units (like in a regular AC grid). Wind farms that have been constructed as stand-alone farms, creating their own frequency, will have to adapt to synchronizing with the other farms.

Wind farms with DC collection grid, and an HVDC converter station would need an extra converter to be able to connect to the AC cluster grid. The same applies for wind farms which use a different frequency.

5.2.2 DC Cluster Grids

In theory, both the internal wind farm collection grid, as well as the wind farm cluster grid could be realized using DC technology.

Wind farms with DC collection grids could connect more easily to such a cluster grid, possibly using the same converter, which was used for connection to shore via HVDC. Wind farms with AC collection grid also already have a HVDC converter, which might be used to connect to the cluster grid, rather than to a radial link to shore. All AC wind farms could also maintain their own frequency, avoiding the need for synchronization (but also loosing the benefits).

The operational experience with DC grids is still limited, which makes AC a more attractive technology for this task today. On the other hand, the construction of large offshore cluster is not happening today, so DC technology might improve and be ready, when it is needed.

In the future, when several DC cluster grids are interconnected with several HVDC lines, cluster grids and long distance transmission might merge to a single structure, dissolving the distinction between level III and IV.

6 ROADMAP

A question that naturally arises once the need for a supergrid has been established, is what the supergrid should look like. A plethora of topologies have been proposed. Czisch, who makes the remarkable claim that a supergrid would allow a 100% CO_2 free, affordable electricity supply for Europe in the near future [10], proposes a supergrid that is the outcome of a large-scale mathematical optimization (about 2.45 million constraints and 2.2 million control variables) [11]. Such a 'green field' approach would require perfect coordination between member states. Moreover, it fails to recognize that there are already a large number of offshore equipment installed, such as HVDC cables, offshore wind farms, and oil rigs. It is more realistic that the supergrid will develop in an organic way.

A second argument for the gradual development of the supergrid is that many technical challenges remain, before a meshed multi-terminal supergrid will become a reality. Moreover, multi-terminal operation of VSC HVDC is hitherto unproven. Between a first pilot project and a full-blown supergrid, many years will pass.

A first realistic intermediate scenario between point-to-point connections and a meshed multi-terminal HVDC grid could be a wind farm or CSP unit connected to different countries (Fig. 4).

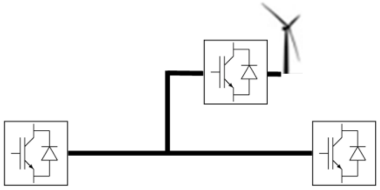

Figure 4: Three-terminal MTDC system.

A pilot project in the Baltic Sea is currently under study. It is studied whether the Kriegers Flak offshore wind development area in the Baltic Sea with a potential of 1800 MW could be connected to three countries Sweden, Denmark, and Germany. Recently, Sweden has withdrawn from the project.

A second example of an intermediate step is a system of two point-to-point connections between wind farms or CSP units and load centers that are interconnected at the generation side (Fig. 5).

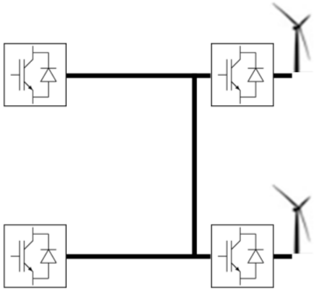

Figure 5: Four-terminal MTDC system.

When more generation such as wind farms, solar power and load centers are added, a three- or four-terminal HVDC system could gradually evolve into a meshed supergrid.

7 ONGOING INITIATIVES

A variety of initiatives on supergrids planning and development are launched in recent years. This section gives a brief overview, and covers the two projects “Friends of the Supergrid” and “Medgrid” in more detail. Both projects present an invited paper to the PSCC 2011 session on supergrids ([12], [13]). They exemplify the growing interest of industry in supergrids.

7.1 Friends of the Supergrid

The Friends of the Supergrid (FOSG) is an organization pushing for an offshore supergrid in the North Sea. Their definition of a supergrid is “an electricity transmission system, mainly based on direct current, designed to facilitate large-scale sustainable power generation in remote areas for transmission to centres of consumption, one of whose fundamental attributes will be the enhancement of the market in electricity.” [12].

FOSG has proposed a roadmap in three steps to 2050. Phase I of the roadmap would link the UK with Belgium, Norway, and Germany. It recognizes the growing offshore wind projects in UK, Belgium and Germany, and balancing potential of the Norwegian hydro power.

FOSG believes that the first phase should be under development before 2020. This tight timing is deemed viable because the ‘supernode’ concept will be used. In terms of the terminology introduced in the previous chapter of this paper, a supernode can be regarded as several AC collection grids, connected to an AC cluster node. Several point-to-point HVDC links connect the node to shore. The supernode concept would circumvent technical problems related to multi-terminal DC grids, such as DC breakers, fast fault detection, etc. A major drawback of this concept, recognized by FOSG, is that a large number of AC/DC conversions stations are needed.

7.2 Medgrid

While FOSG concentrates on a North Sea supergrid, the Medgrid initiative focuses on the Mediterranean. Medgrid pursues a better interconnection of North Africa and Europe. Currently, only Spain and Morocco are linked. Proposed links are e.g. Algeria-spain or Tunisia-Italy. Medgrid committed to five main tasks:

- Design the Mediterranean grid master plan for 2020;
- Promote a regulatory framework for the exchanges of green electricity;
- Assess the benefits of investment in grid infrastructures;
- Develop technical and technological cooperation with South and East countries in the area of power grids;
- Promote advanced HVDC technologies for power transmission.

At this moment, no details on technical concepts are given, and the proposal is not backed by economical studies. However, Medgrid has established five working groups: master plan, economic studies, finance, regulation, technology. The time horizon of the Medgrid project is 2020, with a target of 5 GW of interconnections.

7.3 Various

The many ongoing activities and initiatives on supergrids indicate that the supergrid is seen as an important concept for the future. Among the many initiatives, we mention the following four:

- Twenties: one of the goals of the Twenties project’s demo DCGRID is to analyze the technical feasibility of several topologies for future offshore DC networks, and to set out for each of them the technical challenges that need to be met before they can be operated in a safe way. (http://www.twenties-project.eu).
- The Desertec project proposes a supergrid to collect CSP from Africa and transmit it to Europe. The idea is based on studies from the German Aerospace Center [14], [15], [16].
- OffshoreGrid is a European project focusing on a regulatory framework for offshore grids

including technical, economical, policy, and regulatory aspects (www.offshoregrid.eu).

- The North Seas Countries’ Offshore Grid Initiative is a framework for regional cooperation on possible future grid infrastructure developments in the North Seas. Deliverables are expected on: grid configuration and integration, market and regulatory issues, and planning and authorization procedures [17].

8 CONCLUSIONS

In future, an increase in offshore activities is expected. Offshore connections and wind farms, driven by trading and renewable energy agenda. An offshore grid infrastructure could serve the needs for trading and for connecting wind farms to shore. Furthermore, it would allow balancing renewable energy sources and create additional transmission capacity. Meshed multi-terminal VSC HVDC systems have been proposed as a solution to the technical requirements of a supergrid. However, we have shown that a large number of exciting technical challenges still remain, leading to the conclusion that a large meshed supergrid based on multi-terminal VSC HVDC will not be constructed at once. Rather, the meshed supergrid is the final step in a gradual process consisting of intermediate steps that can be based on a combination of AC and DC technologies, or on multi-terminal schemes that are not meshed. These configurations are better known than multi-terminal VSC HVDC. Their implementation could expedite the development of a European supergrid.

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