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Multi-terminal DC grids: challenges and prospects

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Abstract A few multi-terminal direct current (MTDC) systems are in operation around the world today. However, MTDC grids overlaying their AC counterpart might a reality in a near future. The main drivers for constructing such direct current grids are the large-scale integration of remote renewable energy resources into the existing alternative current (AC) grids, and the promotion and development of international energy markets through the so-called supergrids. This paper presents the most critical challenges and prospects for such emerging MTDC grids, along with a foreseeable technology development roadmap, with a particular focus on crucial control and operational issues that are associated with MTDC systems and grids.

Keywords HVDC systems, MTDC grids, Control and operation, Integration of renewable energies, Supergrid

1 Introduction

DC technology has entered a new Renaissance period in recent decades, several generations after Edison and Westinghouse's public battles facing DC versus AC in the famous "war of currents", back by 1880 [1]. In the late 19th century, AC came to dominate power transmission design, as AC transformers offered a cost efficient solution to the problem of transferring bulk power from centralized power stations over long distances.

DC systems rebooting started in 1954, when ABB linked the island of Gotland to the Swedish mainland by a high-voltage direct current (HVDC) link, delivering the world's first commercial HVDC system [2]. The Gotland HVDC system (Gotland 1) used mercury-arc valves to convert and transfer 20 MW of power over its 98 km, with a 100 kV submarine cable—connecting Västervik on the mainland with Ygne on the island of Gotland. In 1970, the conversion stations were supplemented with thyristor valves connected in series with the mercury-arc valves, raising the voltage to 150 kV and the transmission capacity to 30 MW [2]. This was the first time worldwide that thyristor valve technology was used in a commercial HVDC transmission system.

Nowadays, we are in the infancy of a new paradigm for direct voltage power systems, as more than 180 HVDC projects are operational all over the world, being most of them two-terminal systems, although multi-terminal HVDC projects are getting into operation progressively. The question at the fore of this new paradigm is not that of a choice between AC and DC; it is now about how best to integrate both current formats. This change in the point of interest is due to the technology advances that are transforming the way in which electricity is produced and consumed. On the generation side, the amount of electricity generated from renewable energy sources is increasing, either in remote areas (hydropower plants far from urban centers, offshore wind farms, etc.) or locally (photovoltaic generation) [3]. On the demand side, changes in consumption patterns are calling for innovative technical and social solutions, such as the smart consumers and smart grids. Power electronics, control and information and

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communications are the key enabling technologies in this paradigm change. Particularly, high-power electronics devices and conversion systems are being developed at a rapid pace, incorporating an ever-growing list of technical capabilities while their price continues to drop [4, 5].

In this paper, MTDC system signifies a DC transmission system comprised of more than two terminals with no DC mesh in the associated transmissions lines, and MTDC grid denotes a DC transmission system of more than two terminals with at least one meshed DC path. With MTDC grids, normally there will be more than one power-flow path between two grid terminals.

In the following, Section 2 presents the status of HVDC and MTDC systems; Section 3 discusses progresses in high-voltage AC and DC integration; challenges along with the research pathways for the development of MTDC systems are presented in Section 4; and some recent research works on the control of MTDC grids are reviewed in Section 5, before concluding remarks that are provided in Section 6.

2 High-voltage and MTDC—The state of play

With rapid advancements in power electronic devices and control systems seen in recent years, electrical engineers and researchers have turned their attention to HVDC systems—with a particular focus on their application in coexistence with existing high-voltage AC (HVAC) grids.

While HVDC links were first sparked by the successful commissioning of Gotland 1 HVDC project, this original scheme was followed by several others that were orders of magnitude larger than their precursor, which triggered research and development into enhanced solid-state valves and power conversion topologies.

Two major power conversion technologies have traditionally dominated by HVDC projects, namely, the line-commutated converter (LCC) and the voltage source converter (VSC); both have been commercialized and deployed and are standard technological solutions across today’s global networks. In LCC technology, a large smoothing reactors are connected at the power converters’ DC side, and pulses of DC current flow through the switching devices into the AC side to configure a current source converters (CSC) [6]. On the other hand, a DC link based on conventional VSC technology has large capacitors at the power converters’ DC side and the switching devices transfer the instantaneous DC voltage level to the AC side [7]. Two-and three-level power conversion topologies with symmetrical bipolar DC voltage respect to the earth electrode, in opposite polarity, have been generally used in VSC for HVDC applications [8, 9]. However, new modular multi-level converters (MMC), which synthesize the output AC voltage by combining direct voltages from multiple cascade connected cells, are becoming popular in recent years since they are a very flexible solution for processing high-power levels and they do not require any link filter at their AC side [10].

In the 80s, research alliances were forged between academics and power industry pioneers to extend HVDC technologies, mainly based on LCC, to develop multi-terminal systems. While conventionally, only point-to-point (two-terminal) solutions were possible with an HVDC link, this emergent research paradigm was seeking to interconnect more than two terminals via HVDC links to create multi-terminal HVDC systems [11–13].

Following successful research efforts, the Québec-New England HVDC Phase II was constructed and commissioned by ABB in 1990 as the first large multi-terminal HVDC system over the world [14]. It was based on LCC-HVDC technology and it was an extension of the existing two-terminal Québec-New England link into a five-terminal HVDC system, with a power rating of 2000 MW and a DC voltage rating of ±450 kV.

A limitation of the LCC-HVDC technology is the need to reverse direct voltage polarity to enact a change in the power flow direction; this limits the ability of an LCC-HVDC system to respond quickly to changing demand or market conditions [15–19]. On the other hand, the VSC-HVDC does not need to reverse direct voltage polarity to change the power flow direction, which enables it as a promising solution for constructing MTDC systems. VSC-HVDC technology can also address other conventional grid issues, such as bulk power transmission, asynchronous grid interconnections, back-to-back AC system linking, and voltage/frequency support [20–22] and it is also suited to facilitate the large-scale integration of renewable energy sources into the grid [23]. With this dawn of VSC-HVDC technology, the dream of implementing large-scale integrated MTDC systems/grids can become a reality in a near future.

The MTDC systems paradigm, however, is still being stretched at the research end. As an example, recent studies propose to combine LCC-HVDC and VSC-HVDC links into hybrid systems, which leverage the most interesting advantages from both technologies [6, 24, 25]. Taking into account that a significant number of LCC-HVDC systems are currently in operation, VSC-HVDC stations might be added to existing LCC-HVDC systems/grids by properly coupling their DC sides to form hybrid (LCC+VSC) MTDC systems/grids [26, 27].

Lately, different initiatives have been developed in order to integrate renewable energies using MTDC grids, such as the Medgrid project, which is focused on developing a Euro-Mediterranean grid to provide countries in Southern Europe and North Africa around the Mediterranean Sea with renewable energy, mainly from solar, and the Offshore Grid project, which is a scientifically based view on an offshore grid in regions around the Baltic and the North Sea, the English Channel and the Irish Sea along with a suited regulatory framework considering technical, economic, policy and regulatory aspects. Apart from initiatives in Europe, there are other international projects that have been announced in recent years, which have developed several important HVDC installations around the world. Some project examples include "Tres Amigas Super Station", which will provide a connection between the three major U.S. transmission networks (Eastern, Western and Texas networks), and the new electricity "superhighway" between Xiangjiaba and Shanghai, carrying 6400 MW of electricity over more than 2000 km to supply 31 million people [14]. Table 1 summarizes some relevant MTDC systems worldwide.

The single-line diagram of Zhoushan MTDC project is depicted in Fig. 1.

3 High-voltage AC and DC combination—Are they better together?

By interconnecting HVAC and HVDC networks, many technical advantages might be harnessed, which would definitively contribute to enable large-scale integration of offshore generation envisioned for the future; with key contributions in essential areas, such as generation capacity connection and grid stability.

Some advances and benefits that are crucial to achieve this potential include:

1) HVDC cables have lower power losses compared with HVAC cables.
2) The only practical way to connect remote offshore wind farms (more than 80 km from shore) to the AC mainland grid is via HVDC technology.
3) By using HVDC technology, instantaneous decoupled control of the transmitted power is possible.
4) HVDC systems support AC grids by providing several ancillary services, from voltage/frequency regulation to power oscillations damping.

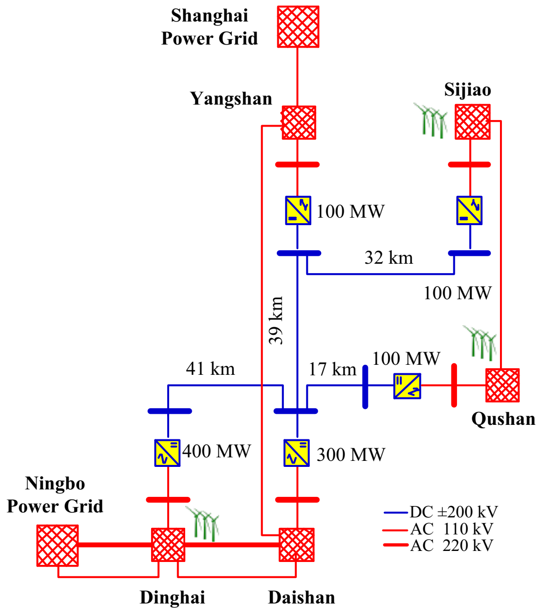

Fig. 1 The single-line diagram of Zhoushan MTDC system

5) HVDC systems do not increase the short-circuit level of connected AC grids.
6) Passive networks or passive-loads can be supplied by VSC-HVDC stations.

A typical representation of an AC overlaid MTDC grid containing several LCC-HVDC and VSC-HVDC terminals is simplistically illustrated in Fig. 2.

4 Challenges on operation and control of MTDC systems

In spite to the challenges on HVDC technology, which mainly deal with the development of new power devices and systems at high-power levels [28–30], research and development challenges regarding operation and control of MTDC systems/grid are very similar to those ones already seen for AC power system development. Thus, the most reasonable, cost-effective and practical approach is

Table 1 Some operational and under-construction multi-terminal HVDC systems around the world

Status	Location	Year	Capacity (MW)	Terminals	Voltage level (kV)
In operation	Italy-Corsica-Sardinia (SACOI)	1967, 1988, 1992	200, 50, 200	3	+200
	Québec-New England	1990, 1992	2250, 2138, 690, 690,1800	5	±450
	Nanao	2013	200, 100, 50	3	±160
	Zhoushan	2014	400, 300, 100, 100, 100	5	±200
Under-construction	North-East Agra	2017	6,000	4	±800
	Zhangbei	2018	1500, 1500, 1500, 3000	4	±500
	AWC	2021	7000	6	±320

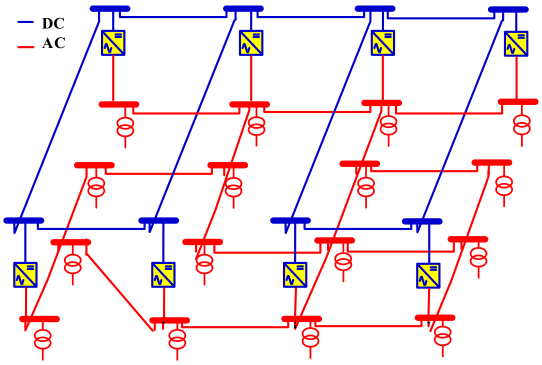

Fig. 2 A typical representation of an MTDC grid comprised of LCC-HVDC and VSC-HVDC technology

to take advantage of the experience and lessons learned over the decades of operation and control of traditional AC power systems. If any of these solutions, or concepts, can be applied or adapted to the DC case, then it would significantly shorten the route to a framework for operation and control of MTDC grids in cohabitation with existing AC power systems. In particular, issues such as designing a suitable hierarchical control structure, power-sharing, and voltage control, as well as power flow control in MTDC grids can be addressed more efficiently by building upon the lessons and experiences of AC system design.

In this overview, some critical challenges regarding operation and control of MTDC systems are identified and described in the following:

4.1 System integration

MTDC systems/grids will grow organically over time, mirroring the development of AC power systems—evolving from simple structures towards a final complex system in an incremental manner. However, this development will occur over a much shorter time than the development of AC power systems, which took almost one century.

Provided the MTDC system architecture is well defined, the next step is to clearly establish objectives, primary functions, and operational procedures and, critically, identifying feasible interactions between AC and DC systems. Exploiting all the advantages and functionalities that can be provided by the MTDC grid and assuring its optimal performance can only be accomplished through a sound integration of both AC and DC systems.

4.2 Power flow control

In AC grids, flexible AC transmission system (FACTS) devices are employed to support power flow control. In MTDC grids, the system state is different, since DC bus voltages are only characterized by their amplitude, and not by their phase-angle, and the transmission line impedances do not present any imaginary component in steady-state at zero frequency. Therefore, the only magnitudes to be used for controlling power flow in MTDC grids are the voltage and current amplitudes. In point-to-point HVDC transmission systems, power flow control is typically arranged with one terminal controlling the dc-link voltage, while the other terminal controls the active power, i.e., the current flowing through the HVDC transmission line. Although this simple control philosophy could be extended to MTDC grids, this is neither an optimal nor a flexible control solution for modern power systems. Thus, in order to fulfill requirements of tomorrow's networks—with improved performance, reliability, and safety, future MTDC grids need to integrate other devices able to make power flow control flexible [31, 32].

4.3 Dynamic behavior

In AC grids, arguably the most vital component, providing both active and reactive power, is the synchronous generator. The appropriate modeling of the synchronous machine dynamics is a crucial factor in assessing the dynamic behavior of the AC power system.

In a MTDC grid, the most vital component, providing power exchange to and from the grid, is the power electronics-based power converter. In comparison to synchronous generators, power converters have a time response that can be several orders of magnitude faster, due to the additional control capabilities and the lack of mechanical inertia. Precise modeling of power converters and their controllers is, therefore, a key aspect for assessment of the MTDC grid's dynamic behavior. This is an important challenge because, due to their switched operation, power converters are systems with a variable topology, characterized by discontinuous dynamic equations difficult to manage in analyses. To simplify integration of power converters in power systems analyses, averaged dynamic models can be employed. The advantage of using averaged models is that they simplify analyses, while still allowing sufficient detail to understand the power converter dynamics and to develop effective control strategies.

4.4 Stability

In MTDC grids, there is no synchronous frequency component for voltages and currents. In addition, reactive power flow is not available and active power flow depends on differences between DC bus voltages. Stability analysis for an MTDC grid, which only relies on the DC bus voltage magnitudes, has to be approached in a different way than in traditional AC power systems. In this sense, detailed state-space models for the MTDC grid, the power converters' controllers and the AC network, should be elaborated and systematic analyses should be carried out to define the ranges for the gains of the VSC controllers in order to ensure dynamic voltage stability at the MTDC grid and to know how fast the VSC controllers and protections should react in order to avoid a collapse of the MTDC grid.

4.5 Protections and HVDC breaker

Three main fault types are expected to take place in MTDC grids. Firstly, faults can occur on the AC side of the power conversion stations. This fault type can be single- or multi-phase, leading to a loss of generation or load in the MTDC grid. For the successful development of MTDC grids, it is imperative that a fault in one AC power system does not propagate through the MTDC grid to another AC system. Secondly, faults may occur at the power converter DC side. This fault type is much more challenging to handle than AC faults. During a DC fault, all interconnected power converters' DC buses severely contribute to the fault current and, due to the low impedance characteristic of DC cables, the direct bus voltages in the MTDC grid are thereby substantially reduced, nearly stopping the power flow. Finally, a fault can occur inside the power converter station itself, which can trip a section of the MTDC grid, and may lead to loss of generation or load.

The development of appropriate protection devices and strategies for MTDC grids is a challenging issue, and the lack of efficient protection strategies is a biting constraint on the pace of development of MTDC technology. In this regard, ABB has launched the world's first HVDC breaker as a promising device for MTDC grid protection [33]. As shown in Fig. 3, the ABB hybrid breaker combines an ultrafast mechanical actuator with IGBT valves to form a hybrid HVDC breaker.

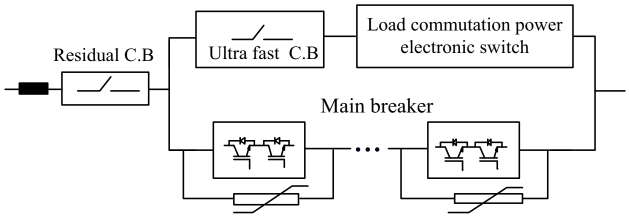

Fig. 3 Illustration of ABB's hybrid HVDC breaker

4.6 Economic aspects

In order to bring the benefits of MTDC grid technology into practice, solutions based on such a technology have to be economically viable. The initial capital investment of an MTDC grid is higher than the one for an HVAC grid solution since power conversion stations are a high-cost plant item in today's market. On the positive side, however, HVDC transmission lines or cables are normally less expensive than HVAC lines, and the lower MTDC grid losses should also be taken into account in long-term studies of investment return. Moreover, power flow control is greatly enhanced in an HVDC solution, which enables better utilization of the lines (closer to thermal limits) and can overcome loop flow problems—a well-known phenomenon in AC grids. The topology of future MTDC grids is not yet categorically defined, and different control/protection schemes are proposed by the main manufacturers and technology providers. Consequently, MTDC grids planning is a quite complex process that must consider multiple aspects, such as system technical performance, market aspects, security, reliability, safety, environmental considerations, economics and other factors. As a rough initial guide, Table 2 provides approximate costs for the basic building-blocks of an MTDC grid.

4.7 MTDC grid ownership and management

Multiple players will get into the MTDC grids future marketplace, including manufacturers and technology providers. Therefore, it is crucial to promote proper organizational mechanisms in such an emergent market, ensuring public and political support and establishing competition, which will lead to enhancing technical and economic system performance. In this regard, if a complete terminal is individually developed by a single manufacturer, its integration into an existing MTDC grid might entail a significant challenge, since it must be compatible with the rest of terminals connected to such grid, which would be produced by other manufacturers. Moreover, considering interoperability at the component low levels, for example, considering interchangeable DC circuit breakers from different manufacturers, there is a clear need for substantial further work on standardization. In addition, the development of grid codes for MTDS systems and, in particular, international codes are essential to inspire confidence to different grid operators for interconnecting each other through MTDC grids, which in turn will underpin MTDC grid development in the power industry [14].

4.8 Standardization

Several organizations have initiated multiple research activities through their study committees in the field of MTDC grids [24, 34]. As an example, the CIGRE study committee B4 on HVDC and power electronics has several working groups (WGs), some held jointly with other study committees (such as B5), which are currently

Table 2 Approximate cost of some key MTDC grid components [25]

Component	Cost per MW	Cost for 1 GW
Power converter station	€0.11 m	€110 m
Cable (pair)	€0.013 m/km	€140 m for 100 km
Hybrid HVDC circuit breaker	€0.25–0.35 m	€27–38 m
Mechanical circuit breaker	€0.002–0.005 m	€0.23–0.55 m
DC/DC converter (low stepping ratio)	€1 m	€110 m
DC/DC converter (high stepping ratio)	€1.5–1.8 m	€165–200 m

actively studying different aspects of MTDC grids. The aims and objective of some of these WGs include the following:

1) Guidelines for preparation of connection agreements or grid codes for MTDC grids (B4-56).
2) Guide for the development of models for HVDC converters in MTDC grids (B4-57).
3) Devices for load flow control and methodologies for direct voltage control in an MTDC grid (B4-58).
4) Designing HVDC grids for optimal reliability and availability performance (B4-60).
5) Definitions of reliability and availability for MTDC grids (B4-60).
6) Control and protection of MTDC grids (B4/B5-59).
7) Control and protection of MTDC grids (B4/B5-59).
8) Technical requirements and specifications of state-of-the-art DC switching equipment (JWG A3/B4.34).
9) Recommended voltages for HVDC grids (JWG B4/C1.65).

5 Prospects of MTDC systems/grids

As pointed out in previous sections, VSC technology is a critical building block in the future of MTDC grids. In order to realize such advanced DC grids, effective control techniques are necessary to exploit all the VSC technology potentials. In the following, the most relevant existing control techniques are reviewed. In particular, a special focus is placed on control methodologies for MTDC grids, concentrating on DC voltage control—the most crucial control task in the context of MTDC grids.

Voltage-droop control is the most commonly employed technique for direct voltage control of MTDC grids according to the literature [35]. This very simple control technique can be also used in a generalized manner to bring enhanced flexibility to the control and operation of the MTDC grid [36]. Moreover, the operation and control structures of an MTDC grid should be hierarchized in a similar manner as traditional AC power systems do [37]. As an example, a direct voltage control and power-sharing scheme for MTDC grids, based on applying optimal power flow and generalized voltage-droop strategies, is briefly described in the following section. In the highest control level of MTDC grids, control of power flow is, without any doubt, one of the most important issues, since it directly impacts on security, flexibility, and economics of MTDC grid applications. Innovative power flow control schemes based on ICT and computational intelligence provide improved flexibility to the grid operator, which brings carbon and financial savings by lowering the marginal cost of electricity in a market-based system. The greater the degree of power flow control flexibility, the greater the extent to which the system operator can capitalize on this aspect—securing the system for a lower cost to consumers.

6 Overview of some recent research topics in the operation and control of MTDC grids

In recent years, some of the main challenges in the control of MTDC systems are identified and investigated by the Academia and the Industry. In this regard, the main research efforts are focused on i) improving the performance and robustness of power converters by developing accurate and robust low-level controllers, ii) warranting the MTDC grid regulation by developing control systems for grid interactive power converters, and iii) optimizing and making the operation of MTDC grids flexible, as well as their interconnected AC systems, by using advanced control techniques based on ICT and computational intelligence. This research layers can be illustrated in the form of an MTDC grid automation pyramid as shown in Fig. 4.

In this regard, some recent research topics in the operation and control of MTDC grids can be summarized as follows.

6.1 MTDC grids control framework inspired by AC grids

When designing the hierarchical control structure of MTDC systems, those control approaches inspired by AC

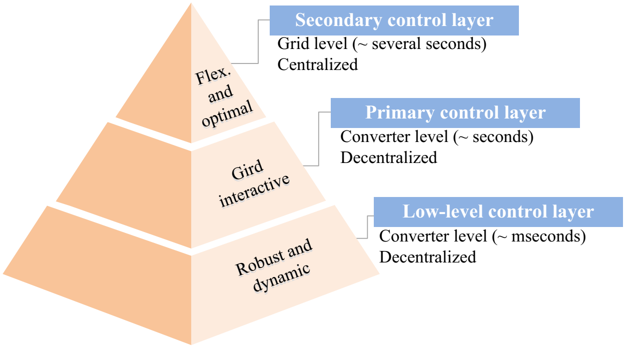

Fig. 4 Illustration of recent research layers in the format of automation pyramid

grids allow power converters to operate independently, in a similar manner to AC power generators, without the need for inter-station communications [38]. A MTDC grid operating analogously to AC power systems permits the connection of power converters of different ratings, supplied by different vendors and considered for different applications. This idea is presented and discussed in detail in [14], where it is demonstrated that a two-layer control structure can achieve stable operation of the MTDC grid.

As a step forward, the concept of AC/DC supergrid and its related challenges are discussed in [19]. The supergrid will allow the connection of renewable energy sources, possibly even up to a level that they might fully supply all the electric power demand.

6.2 Voltage-droop control

Despite the popularity of the voltage-droop control technique, inspired by frequency-droop control in AC power systems [35, 39, 40], it suffers from some drawbacks. The main one lays on the fact that it cannot perform fixed power control for a particular power converter station or fixed direct voltage control in some operation modes. In order to overcome the mentioned shortcoming, a control approach that deals with a unified control strategy for direct voltage control and power-sharing in VSC-based MTDC grids is presented in [36]. In this technique, a Generalized Voltage Droop (GVD) control is implemented at the primary level of a two-layer hierarchical control structure for an MTDC grid and constitutes an alternative to the conventional voltage-droop characteristics of voltage-regulating VSC stations—providing a higher degree of flexibility and thereby controllability to these grids. The GVD control strategy can operate in three different control modes: conventional voltage-droop control; fixed active power control; and fixed direct voltage control by adjusting the GVD characteristics of the voltage-regulating VSC power converters. Such adjustment is carried out in the upper layer of the hierarchical control structure of the MTDC grid. In this line, a power-dependent droop-based control strategy was recently proposed in [41]. In this approach, a droop controller structure maintains the DC voltage close to its nominal value and, at the same time, preserves the power flow in the MTDC grid, overcoming contingencies, such as faults or disconnection of stations. Likewise, a methodology for analyzing the impact of different types of droop control structures, by using small-signal stability analysis and considering all possible combinations of droop gains, was presented in [42].

6.3 Droop control parametrization for optimal power flow

A step forward for optimal operation of AC+MTDC grids deals with performing optimal power-flow (OPF) calculations at the highest level of the grid control structure [43]. In this regard, the MTDC grid can be efficiently controlled under the voltage-droop scheme in case of variations in demand and generation. References [44] and [45] propose an effective DC voltage and power-sharing control structure for MTDC grids based on coordinating the OPF calculation and the voltage-droop control in the hierarchical control layers of the system. In this approach, an OPF algorithm is executed at the secondary control layer of an MTDC grid to find the optimal reference values for the direct voltages, and active power of the voltage-regulating power converters. Then, at the primary control layer, the voltage-droop characteristics of the voltage-regulating converters are tuned based upon the OPF results. In this control structure, the optimally tuned voltage-droop controllers enable optimal operation of the MTDC grid. In the event of variations in load or generation in the grid, a new stable operating point is achieved based on the voltage-droop characteristics. Then, by executing a new OPF, the voltage-droop characteristics are re-tuned for optimal operation of the MTDC grid after any load or generation change. This study also considers the integration of a frequency support loop into the proposed control framework to assist with connection to weak AC grids.

6.4 Flexible DC transmission systems (FDCTS)

As mentioned before, there is a wealth of experience on AC systems operation and control from which we can learn in order to accelerate progress toward optimized operation and control of MTDC grids. The concept of flexible DC transmission systems (FDCTS) based on using dedicated power converters has been introduced in several works [32] inspired by the successful operation of flexible AC transmission system (FACTS) devices, to provide voltage

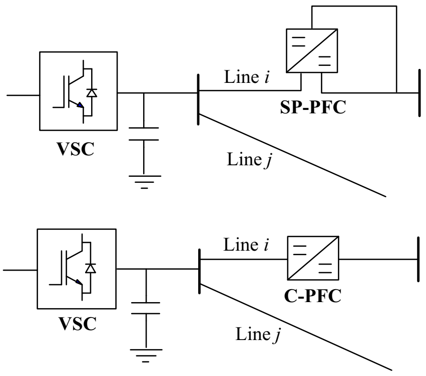

Fig. 5 Two connections of DC power flow controllers

regulation, power control, and load flow control within MTDC grids.

Considering recent advancements in the field of high-power electronics, the DC/DC converter is a prime candidate to be the first FDCTS device, providing voltage and power control in MTDC grids. By demonstrating success with DC/DC converters, the development of other FDCTS devices can flourish [31]. Fig. 5 shows two possible types of DC power flow controllers, namely–Serial-Parallel Power Flow Controller (SP-PFC) and Cascaded Power Flow Controller(C-PFC)–based on the DC/DC converter technology, for control of power flow in MTDC grids [32].

7 Conclusion

For the power grids of tomorrow, challenges such as remote connection of large-scale renewables and the formation of offshore supergrids require a new paradigm in transmission technology. MTDC systems/grids, combining the benefits of AC and DC technologies, offer a potentially game-changing paradigm in HVDC deployment, which can unlock the full potential of this technology, opening the door to new devices and systems, such a DC circuit breakers and FDCTS, that can bring benefits to the security, reliability, performance and economics of tomorrow's network.

The prospects for the emergent technology of MTDC grids are presented and summarized in this paper. The pivotal issues are discussed, with a detailed appraisal of potential control solutions at the system level—critical to overcoming the challenges to progress and achieving the full potential of MTDC grids.

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