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Comparative Assessment of HVDC Systems for Connecting Renewable Energy Sources to Urban Load Centers

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Abstract. This paper assesses the various high voltage direct current (HVDC) systems and topologies' suitability for connecting renewable energy sources with urban load centers in various geographical and pre-existing grid conditions. The three representative cases analyzed are the offshore wind connection of BorWin1 in Germany, the multi-terminal Zhangbei HVDC grid in which renewable energy generation is connected to multiple population centers and the ultra-high-voltage direct current (UHVDC) connection of Zhundong, which connects renewable generation with population centers in the middle of the country. There are several criteria that are assessed in the comparison: transmission capacity, distance, efficiency, voltage-control capabilities, protection against faults, offshore/onshore suitability, multi-terminal capability, renewable energy integration, expandability and economic factors in cases where reliable data are available. The paper finds that in a weaker grid or offshore connection, the flexibility required for an electrically weak existing AC system is provided by the Voltage-Source Converter (VSC) system, whereas in very high capacity and long-distance bulk transmission, the Line-Commutated Converter (LCC) type of HVDC systems is advantageous. With several renewable energy generation sources, storage plants, and load centers to exchange power, Multi-Terminal HVDC (MTDC) using Modular Multilevel Converter (MMC) can offer greater flexibility. Overall, it can be concluded that, contrary to the assumption that one converter technology is superior to the other, the choice of the converter technology best suited for a particular situation depends on the given circumstances.

Keywords: HVDC; LCC; VSC; MMC; Renewable energy.

1. Introduction

As renewable energy sources have gained traction, there's been a growing demand for efficient, dependable, and affordable solutions to transmit electricity. Some of the best renewable sources of energy, however, are far away from the population densities where electricity is utilized in the greatest quantities. Offshore wind and large wind and solar resources are often far from the coastal cities where wind farms are often built, and inland regions are often sparsely populated. This spatial disconnection results in the need to frequently transport electricity from renewable energy resources to the major cities and other load centers [1]. Meanwhile, traditional alternating current (AC) transmission networks can be subject to transmission losses, stability constraints and congestion when they are utilized for very long distance and large-scale transfer of renewable energy [1].

The use of HVDC transmission can be a solution to these challenges, as it has the potential to transmit large amounts of electricity over long distances with relatively low losses. When the share of renewables rises, HVDC can be a crucial link to connect geographically remote renewable resources with the existing urban electricity grid. But HVDC isn't one technology. The technical characteristics of different converter systems and network topologies vary, and consequently, they exhibit different performance in terms of distance, power capacity, network conditions, and type of renewable energy to be connected [1,2]. Specifically, LCC, VSC, MMC based systems have various pros and cons. LCC systems are proven for high capacity, long-distance transmission and VSC and MMC systems offer high flexibility and are more suitable for weak grids and variable renewable energy sources [1,3].

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The selection of HVDC system largely depends upon the application. For instance, an offshore wind farm feeding a coastal city can have very different transmission needs compared to a big wind or solar project feeding a city a long distance away. Likewise, if several isolated renewable sources are to be connected to a number of cities, this involves requirements for multi-terminal operation, coordination and fault protection. This poses a key issue for renewable-energy transmission: instead of asking the question about the overall best HVDC technology, it is more relevant to ask the question which technology and topology is the best under different geographical and grid conditions.

This paper thus addresses the following research question: What are the suitability of various HVDC systems and topologies when connecting renewable energy sources to major electricity load centers, such as cities, for various geographical and grid conditions? In order to answer this question, three typical scenarios are considered: offshore renewable energy feeding into urban centers; large inland renewable energy resource feeding into urban centers; multiple distributed renewable energy resources feeding into multiple load centers. Common technical and application considerations such as transmission capacity, distance, efficiency and losses, voltage-control capability, grid-strength requirements, fault protection, offshore and onshore suitability, multi-terminal capability, renewable-energy integration, expandability, and – if available – economic considerations are used to compare these cases. This paper compares the different HVDC systems and identifies the merits and demerits of such systems so that the suitability of each system can be decided.

2. Development and Types of HVDC Systems

The development of HVDC transmission technology has always been closely tied to advances in power electronics. The early direct current (DC) systems were not successful because of the problems with the conversion and control of HVDC. The introduction of mercury arc valves was another significant step towards the feasibility of HVDC, and then the semiconductor devices such as the thyristor were developed, which made large scale HVDC systems more reliable and efficient. In recent years, however, the creation of insulated-gate bipolar transistors (IGBTs) and MMC technology have made VSC systems more flexible [2].

Modern systems can be classified primarily into two types: LCC and VSC systems. LCC-HVDC is well known and employs thyristors for the conversion between DC and AC and vice versa; the advantage of LCC-HVDC is that it can transmit a very large amount of power over a very long distance with a low loss. It, however, requires a robust existing AC power grid for commutation and a great amount of reactive power support. This restricts their use in weak-grid applications and certain remote renewable energy applications [1,3].

VSC-HVDC is a new technology that utilizes semiconductors as AC-DC conversion devices. VSC systems are more flexible in controlling active and reactive power and can work well with weaker AC systems, compared to LCC systems. This can be very handy when renewable sources are involved, and grid may be weak relative to the location or the grid may be isolated. Another benefit of VSC converter stations is that they also can be smaller, where space is a concern [3]. But, conventional VSC systems have higher conversion losses and lower voltage ratings compared to large LCC systems [3].

MMC is a development of the VSC technology. MMC shapes the desired voltage waveform into multiple steps by employing a large number of smaller converter submodules. This enables the converter to generate a high-quality waveform, reduces the requirement for large filtering equipment, and improves overall converter performance. Therefore, MMC technology has become especially significant for modern VSC-HVDC systems and when it comes to offshore renewable energy applications and multi-terminal applications [2,4].

Another point to be taken into consideration is the physical structure of a HVDC network. A point-to-point system, where one transmitting station is connected to one receiving station, is the most common system for large scale transmission designs. Multi-terminal HVDC (MTDC) systems on the

other hand are able to tie multiple generation and receiving sites to a single DC system. These systems can have a radial configuration or be a complicated meshed configuration. Meshed MTDC systems have significant potential for connecting multiple renewable energy sources to multiple urban load centers due to the ability to offer multiple transmission paths and enhanced redundancy. However, there are difficulties in wider adoption such as the DC fault protection and the coordination between the different converters [4,5].

3. Evaluation Criteria

The technical, application, and economic criteria used in this paper are common criteria for comparing the suitability of different HVDC systems fairly. The technical requirements are rated transmission capacity, transmission voltage, distance of transmission, efficiency and losses, voltage-control capability, grid-strength requirement and fault response and protection. These factors are used to indicate the technical ability of a system to operate in a variety of transmission conditions [1,3].

Application criteria are considered, depending on the suitability of each system to practical situations. These involve offshore and onshore use, weak-grid connection, multi-terminal operation and integration with renewable energy and future network expansion. These criteria are especially relevant since the nature of the renewable source/grid that it is connected to can vary widely on a per project basis [3-5].

Lastly, economic and practical considerations will be considered, if there is adequate published information. These include the costs of the converter station, cable costs, maintenance, land use, and project complexity [6]. DC fault protection is treated separately because rapid fault isolation is still one of the major challenges in interconnected HVDC grids [7,8].

These criteria are used instead of examining each technology individually, to enable the advantages and disadvantages of different HVDC technologies to be evaluated depending on the requirements of each case study. Where a published project or study has provided quantitative values, they are included in the table, otherwise the table indicates that project-specific values are not available. This prevents generic technology estimates from being treated as measured performance for a particular project.

4. Case Studies

4.1. Offshore Renewable Energy to Onshore Load Centers

Often, offshore renewable energy, especially offshore wind energy, is situated far from major electricity load centers. This means that submarine cables and appropriate converters to connect the source of renewable energy to the existing AC grid are needed to transmit electricity from offshore. VSC-HVDC is particularly suitable for this application, since it is capable of controlling active and reactive power separately, and VSC-HVDC can run with comparatively weak AC networks. These are important properties of offshore renewable generation where the local electrical network may be relatively weak [3].

An example of such an offshore renewable connection is BorWin1 in Germany. The connection of the offshore wind generation to the onshore power grid in Germany is carried out by a VSC-HVDC system, known as BorWin1. The project has a rated capacity of 400 MW, ±150 kV and extends around 200 km with 125 km submarine and 75 km underground cables [9]. This case was summarized in Table 1, which includes key characteristics and assessment. The offshore converter platform BorWin1 is displayed in Figure 1.



Figure 1. BorWin1 offshore converter platform, Germany. Photo source: Windpower Monthly

Table 1. BorWin1 / VSC-HVDC assessment

Criterion	Information
Capacity	400 MW [9]
Voltage	±150 kV [9]
Distance	200 km total: 125 km submarine + 75 km underground [9]
Efficiency/losses	Project-specific losses are not reported in the selected project source. Offshore-wind studies indicate that HVDC becomes increasingly attractive for longer cable distances; one study found high-voltage alternating current (HVAC) had lower losses up to about 55–70 km, after which HVDC options became more favorable [10].
Voltage/control	Strong; VSC provides independent active and reactive power control [3,9].
Grid strength	Suitable for weaker AC grids than LCC [3].
Fault protection	DC fault protection remains an important challenge for VSC-HVDC and future MTDC networks [7,8].
Offshore suitability	Very high; specifically designed for offshore-wind transmission [9].
Onshore suitability	High; connects offshore generation to the onshore AC grid [9].
Weak-grid suitability	High relative to LCC because VSC does not depend on AC commutation in the same way [3].
Multi-terminal suitability	Not the main configuration; this is a point-to-point link [9].
Renewable integration	Very high; directly connects offshore wind generation to the onshore grid [9].
Expandability	Potentially high for future offshore networks, but expansion depends on coordinated control and DC protection [4,5].
Cost	No reliable project-specific cost figure used here. Published VSC cost studies show substantial variation and uncertainty, with costs depending strongly on converter rating and cable length [6].
Cable	125 km submarine + 75 km underground; cable route is a major practical consideration [9].
Maintenance	Requires specialized converter and cable maintenance; project-specific long-term cost data are not sufficiently reported in the selected sources [6].
Land use	VSC converter stations can be advantageous where converter footprint is constrained [3].
Complexity	Moderate for a point-to-point VSC link; lower network-control complexity than an MTDC grid [4,5].

Considering all aspects, VSC-HVDC is more suited than the traditional LCC for such offshore-renewable connections. The key reason is not simply efficiency, but the combination of flexible control, weak-grid capability, and compatibility with submarine transmission. Also, the BorWin1 project demonstrates the possibility of a direct connection of the offshore wind generation to the onshore AC grid using a VSC-HVDC. If the receiving network or offshore connection needs a higher level of controllability offered by VSC then LCC's low converter loss and high voltage would not be so beneficial [3,6,7,10].

4.2. Inland Connections Between Wind and Urban Areas

The situation is quite different for inland renewable-energy projects. The wind and solar resources are large, but they are generally located hundreds or thousands of kilometers from the big cities where electricity demand is concentrated. In this situation, the transmission system has to transport very large quantities of electricity over a very long distance. LCC-HVDC is especially suitable for this

application due to its high transmission capacity, high voltage ratings and its relatively low converter losses [1].

As a typical case, the Zhundong-Wannan ±1100 kV UHVDC project in China is presented. The rated transmission capacity of the project is 12, 000 MW and the transmission distance is 3, 324 km [11]. It uses bipolar ±1100 kV operation and was put into service in 2019 [1]. The main technical and application characteristics are summarized in Table 2. The Changji converter station is shown in Figure 2.



Figure 2. Changji Converter Station, Xinjiang Uygur autonomous region. Photo source: China Daily; photo by Ren Shijie

Table 2. Zhundong–Wannan / LCC assessment

Criterion	Information
Capacity	12 GW [11]
Voltage	±1100 kV [11]
Distance	3,324 km [11]
Efficiency/losses	Generally lower converter losses than VSC [1,3]; no directly comparable project-wide loss figure is identified in the sources used.
Voltage/control	More dependent on AC system [1,3].
Grid strength	Strong AC grid required [1,3].
Fault protection	Conventional HVDC protection is more challenging to interrupt than AC faults because DC current does not naturally cross zero [7].
Offshore suitability	Low; this is an onshore bulk-transmission project [1].
Onshore suitability	Very high [1].
Weak-grid suitability	Low [1,3].
Multi-terminal suitability	Low compared with MTDC arrangements [4,5].
Renewable integration	High for large, centralized generation [1,9].
Expandability	Limited compared with MTDC [4,5].
Cost	Well suited economically to very large, long-distance bulk transfer; project-specific cost data are not used without a directly comparable source [6].
Cable	Primarily onshore transmission [11].
Maintenance	Large converter and transmission infrastructure; long-term maintenance cost data vary substantially between projects [6].
Land use	Author assessment based on the large converter-station infrastructure required by an ultra-high-voltage bulk transmission system.
Complexity	High, but relatively straightforward compared with meshed MTDC; author assessment based on the point-to-point configuration [4,5].

This case is thus an illustration of how distance and capacity may affect the choice of technology. The 12 GW connection is long (3,324 km) and the low converter losses of LCC are extremely valuable. The downside is that the surrounding AC systems have to work with these converters. Here, LCC-HVDC would be preferable to VSC/MMC due to the very high transmission distance and power

requirement that would offset the benefits of the flexibility of VSC. This is very different from the offshore case and illustrates why basing the choice of HVDC technology on a single parameter, such as converter efficiency, would be misleading.

4.3. Dispersed Energy Sources and Multiple Load Centers

The third scenario is more complicated: A number of renewable-energy sources and load centers are linked to each other via the same HVDC grid. This is only possible with an MTDC system, and possibly a meshed network. It can enable power from various renewables to be shared across multiple sites and storage or other balancing resources can be used to cover renewable intermittency.

An important example is the Zhangbei ±500 kV four-terminal HVDC grid in China. The system links the renewable power generation at Zhangbei and Kangbao with the receiving stations located in Beijing and Fengning [5]. MMC-based VSC technology is used in the system, which operates at ±500 kV. Zhangbei and Kangbao can host renewable generation and Fengning has pumped-storage generation, which can help balance the system. The outcome is summarized in Table 3. The Zhangbei converter station is shown in Figure 3.



Figure 3. Zhangbei flexible DC power grid, Zhangjiakou, Hebei province. Photo source: China Daily.

Table 3. Zhangbei / MMC-MTDC assessment

Criterion	Information
Capacity	3 GW at Beijing station [12]
Voltage	±500 kV [12]
Distance	Multiple overhead DC connections [12]
Efficiency/losses	No consistent project-specific loss figure is identified in the selected material; efficiency should not be inferred from converter type alone. Author assessment based on the absence of a directly comparable project-wide figure.
Voltage/control	Very strong control requirements [2,4,5].
Grid strength	Good suitability for renewable/weak-grid connections [2,3,12].
Fault protection	Major challenge; requires rapid DC protection [7,8,13].
Offshore suitability	Possible, but not the main application [3,9].
Onshore suitability	High [5,12].
Weak-grid suitability	High [2,3,12].
Multi-terminal suitability	Very high [5,12].
Renewable integration	Very high [5,12].
Expandability	High potential [4,5,12].
Cost	Higher complexity can increase investment requirements; reliable cost estimates depend strongly on network configuration [6].
Cable	Multiple DC connections [12].
Maintenance	More complex than point-to-point systems because several converter stations and coordinated controls must be maintained; author assessment based on the multi-terminal configuration [4,5,12].
Land use	Distributed across several terminals [12].
Complexity	Very high because coordinated control and DC fault protection are required across multiple terminals [2,4,5,12,13].

Based on the comparison criteria, Zhangbei performs very well on the aspects of renewable-energy integration, multi-terminal suitability, controllability, and expandability. But it's more complex than the previous two examples. Coordinated control of multiple converters and renewable generators is required for the system and the protection system needs to react extremely quickly to any DC fault. Therefore, the superiority of a meshed MTDC system due to flexibility should not be assumed. However, its extra complexity is worthwhile if multiple renewables are to be utilized and multiple load centers in real need of power sharing exist [2,4,5,12,13].

The Zhangbei case may therefore represent a possible direction for future renewable-energy networks. MTDC systems could enable renewable generation, storage, and large-scale loads to help each other instead of establishing large numbers of independent point to point connections. The technology, however, is more challenging to operate and to safeguard, and further development of the technology requires more advancements in DC fault protection and coordinated control technology [7,8,12,13].

4.4. Overall Comparison

As can be seen from the three cases, the choice of the HVDC technology must be based on the features of the transmission problem and not on a single performance measure. The three scenarios are compared directly in Table 4.

Table 4. Comparison of the three renewable-energy transmission scenarios. Note: Qualitative rankings are a synthesis of the author based on Tables 1-3

Criterion	Offshore to Onshore	Inland to Urban	Multiple Sources to Multiple Cities
Representative case	BorWin1	Zhundong–Wannan	Zhangbei
Preferred technology	VSC-HVDC	LCC	VSC/MMC
Capacity requirement	Moderate	**Very high**	High
Distance requirement	Medium–long	**Very long**	Medium–long
Weak-grid capability	Important	Less important	**Important**
Multi-terminal capability	Low	Low	**Very high**
Renewable integration	Very high	High	**Very high**
Main strength	Offshore-wind grid connection	Bulk long-distance transmission	Flexible sharing between sources and loads
Main limitation	Converter/cable cost and DC protection	Strong AC-grid dependence	Complex control and DC protection

On the whole, the comparison confirms the conclusion that there is no universally superior HVDC technology. Offshore transmission, weak-grid operation and flexible control are important features that make VSC-based systems particularly attractive. LCC is more beneficial for transmission of very large amounts of power over very long distances. In this context, multi-terminal MMC-based systems are gaining in popularity, especially considering the need to exchange power between renewable sources and load centers, which are geographically distributed. Finally, it is important to recognize that the best choice for the HVDC configuration depends on the renewable resource, transmission distance, grid situation, desired network configuration and economic factors, and that not every configuration is necessarily better.

5. Limitations and Future Outlooks

5.1. Limitations

Although there are many benefits to the use of HVDC for electricity transmission, there are still a few issues that need to be overcome in order for it to become standard practice for electricity transmission as opposed to the conventional AC system. Fault protection is one of the most critical issues of DC systems. In a DC application, the current does not change direction with each cycle as it does with AC systems, but instead is constant, making it harder to quickly interrupt faults. This can be a problem in multi terminal and meshed networks. The lack of mature HVDC circuit-breaker technology and the stringent response demands for VSC-MTDC protection are challenges to a reliable and scalable

interconnected DC grid [7,8,13]. Another major limitation is the different requirements of LCC and VSC systems. LCC has a high transmission capability and is capable of achieving relatively low losses but is not as well-suited to some remote renewable-energy projects because it requires a strong AC network. VSC and MMC systems are more flexible and better suited for weak grids and for variable renewable generation, but are associated with higher converter losses and complexity, which can lead to higher costs [1-3]. Also, renewables are intermittent, which means that a stable power flow and voltage at the receiving end remains an ongoing challenge.

5.2. Future Outlooks

Future HVDC development is more likely to be directed towards increasing interconnection, flexibility and reliability of the system than to increasing the transmission capacity. Onshore wind power generation continues to grow in geographically rural locations, and larger offshore wind farms could drive a greater need for multi-terminal and meshed HVDC networks which can connect one or more generation sites and cities. New technologies of DC fault detection and circuit breakers will be particularly significant as they could provide a means of isolating faults without disrupting an entire network, thereby enhancing reliability and overcoming one of the major challenges for achieving MTDC on a large scale [7,8,13]. Changes in semiconductor devices and MMC technology may also help to increase efficiency and control. More advanced control strategies may also be able to enhance the coordination of renewables and loads [2,4]. A plausible scenario of future development is a hybrid network where LCC will still be useful for mass, long distance transmission as well as VSC/MMC systems for flexible connections to renewables and urban networks. This would allow the strengths of each technology to be combined, making it a more practical and attractive system [1,2,4].

6. Conclusion

The three cases show that the most suitable HVDC technology for renewable-energy transmission is not necessarily a single one. BorWin1 demonstrates the value of flexible power control, compatibility with submarine cables, and suitability for weaker AC grids in offshore wind applications. The Zhundong–Wannan case demonstrates why LCC-HVDC remains attractive for very long-distance transmission because of its high capacity and relatively low converter losses. The Zhangbei case shows the possibility of MTDC using MMC, when multiple renewable energy sources, energy storage and urban load centers have to share energy through the same network.

In general, the most suitable configuration should be based on the required transmission distance and capacity, receiving and sending grid strength, and offshore/multi terminal requirements and economics. Future developments of DC fault protection, converter technology, and coordinated control will be important to make HVDC a mainstream option.

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