The Impact of HVDC on the Current and Future Energy Markets

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***Abstract*—Obvious technological and economic advantages of High Voltage Direct Current (HVDC) systems over traditional High Voltage Alternating Current (HVAC) systems are becoming increasingly attractive for long-distance transmission. Several research papers on HVDC transmission networks have been published. However, most of them are focused on specific geographic locations or system components. Nonetheless, this study gives a brief yet thorough overview and international assessment of HVDC transmission systems. The following are the important points to be covered in the paper: The state of the art of HVDC technology development, the benefits, economic comparisons, and constraints of HVDC systems, as well as the size of the international HVDC industry market and the impact of COVID-19 on the market, are all explored in-depth, along with a mathematical model for forecasting the evolution of market demand. According to market statistics, the Asia-Pacific region (APAC) is the biggest market and technical leader in HVDC technologies. In addition, the market for HVDC will continue to grow in the forecasted period.**

***Index Terms*—HVDC, HVDC growth, HVDC growth mathematical model, HVDC market**

I. Introduction

By 2040, renewable energy sources are anticipated to account for more than 50% of the overall generated power, up from 30% present [1]–[3]. According to current policy and development forecasts, global renewable energy generation (solar photovoltaics PV, hydropower, and wind) is expected to increase by 8% in 2021 and more than 6% in 2022. According to a recent International Energy Agency (IEA) estimate, renewables will only be able to meet half of the expected surge in world power demand over the next two years, even with this strong growth [1]. Developing is necessary to continue and spend large resources to maintain effective energy production, transmission, and distribution. Because many big renewable energy power plants are located distant from crucial demand centers, efficient long-distance bulk energy transmission is required. Wind farms located offshore that recently increased their share in the energy market, especially in northern and western Europe, also need effective and cost-efficient transmission [4]–[6].

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On the contrary, regional and national electricity markets are becoming more and more connected with each other across the world. HVDC transmission systems are emerging as the foundation for developing and implementing a new energy system based on renewable sources. Solar and wind, which are one of the fastest-growing renewable energy resources in the world, for example, they are generally highly variable and located in remote locations. With long-haul HVDC transmission lines that can transfer electricity with optimum efficiency and the lowest losses, the ever-evolving HVDC technology is gaining traction in the new energy economy [7], [8]. The HVDC market is expected to grow in attention and effectiveness due to its relationship with renewable energy and the HVDC industry [9]. In recent years, the technology of HVDC witnessed an enormous development in its different components such as converter technology, cable, and overhead line, DC switchgear, DC/DC converter, system configuration and grounding, control Interaction, stability, and HVDC grid protection [10].

The two main converter technologies for HVDC transmission are Line Commutated Converter (LCC) and Voltage Source Converter (VSC). LCC outperforms the competition in terms of high power and voltage rating, which are essential for creating an overlay grid. The current most significant LCC connection has a power/voltage rating of 12GW/1100kV [11], while the Zhangbei four-terminal HVDC grid, rated at 3000MW/500kV [12], has the biggest VSCs in service. In the Kun Liu-Long three-terminal HVDC system, the biggest VSC under development is rated at 5000MW/800kV [13].

However, recent advances in power electronic devices, such as the Bi-mode Insulated Gate Transistor (BIGT), suggest that VSCs' power rating might be increased significantly [14]. Future advances in power electronic devices, such as high bandgap semiconductors, have the potential to bridge the gap between LCC and VSC technologies. Hybrid VSC technologies with embedded thyristors, such as those proposed in [15], could be a promising option for overlaying HVDC grids, as they combine the best of both worlds.

For converter technology, Mass Impregnated (MI) and cross-linked polyethylene (XLPE) cables are the most often utilized cable technologies for LCC and VSC HVDC systems, respectively, owing to a combination of

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cost and practicality. The Western link project, which connects Scotland and North Wales, uses MI underwater cables up to 600kV [16]. Due to space charge phenomena, XLPE cables, on the other hand, can only be utilized in VSC systems. XLPE cables have been employed in several HVDC projects up to 400kV [17]. Many manufacturers have recently revealed successful developments of XLPE cables up to 500Kv/3000MW polypropylene-based High-Performance Thermoplastic Elastomer (HPTE) cables have recently been produced with increased dielectric and thermomechanical performance [18], [19]. Gas-insulated transmission lines, which are currently being studied, may be able to provide the low losses required for extremely long transmission lines.

In the case of DC Switchgear, DC switchgear may be classified into four categories depending on its operations inside a DC substation: disconnecting, earthing, current transfer, and current interruption [20]. The function calculates the needed operating speed and interruption tolerance. DC Component-Based (DCCBs) and high-speed switches (HSSes) have been suggested for HVDC grid protection to swiftly interrupt and isolate the faulty element, respectively [10].

DC/DC converters will be critical in future HVDC grids because they allow connectivity of HVDC lines and terminals with varying voltage ratings. In an overlay HVDC grid, DC/DC converters are very useful since they enable tapping into and out of tiny renewable generating or load centers. Furthermore, DC/DC converters may include additional functions such as power flow control and DC fault management, reducing the number of power flow control devices and DC circuit breakers [21]. Enabling their practical use in HVDC grids, further study is needed into different areas of DC/DC converters, such as control and protection interactions and reliability improvement [22].

System Configuration and grounding are considered one of the most important components of an overlay HVDC grid to establish system design and grounding. These choices significantly influence the grid's operation, reliability, cost, and extendibility [23]. HVDC grids may be configured in one of the following ways, similar to current point-to-point HVDC links: 1) symmetrical monopole with ground/metallic return, 2) asymmetrical monopole with ground/dedicated metallic return, and 3) bipolar with ground/dedicated metallic return even though the symmetrical monopolar design has been the most popular for VSC HVDC systems, a bipolar configuration is the most promising alternative for an overlay HVDC grid owing to the needed power rating, reliability, and extendibility [24]. Voltage control, electromechanical torsional control, and electromagnetic control have all been recognized as kinds of control interactions [25].

Because the LCC cannot manage AC voltages, voltage-power stability may concern LCC systems, especially when connected to AC systems with a low short-circuit ratio. The AC voltage control of VSC systems may be improved [26].

In systems with low short-circuit levels, the VSC may need controller tuning or even a specific control configuration, such as power-synchronization control and direct-voltage control, as recommended in [27]. Fast controllability of HVDC systems, especially VSC kinds, creates a new control interaction and stability challenge with a considerably wider frequency range, as described in [28]. For HVDC Grid Protection, fast DCCBs with high short-circuit current interruption capability have been developed and deployed in the field, removing a key impediment to the realization of HVDC grids with DC-side protection. Intelligent electronic devices (IEDs) can detect a DC-side problem in a few milliseconds in labs and actual projects. This capability has been proven [29], [30] and in [31], used real-time simulations on a genuine industrial network to show interoperability of standalone DC protection IED prototypes. To locate the faulty line as rapidly as feasible, non-unit or single-ended protection techniques use traveling wave, current, and/or voltage derivative-based algorithms [32]. Fast IEDs and high-performance DC circuit breakers (DCCBs) have made it possible to build large-scale HVDC grids with high reliability [33]. The lack of available information about the HVDC market, most of which is exclusive, is the driving force behind this research. As a result, the aim of this paper is to make such information readily available to researchers. The paper presents a review of HVDC markets and their trends. We conclude that the HVDC market has the potential to grow in the future with steady and firm steps.

The remainder of the paper is organized as follows: The advantages of HVDC over HVAC are given in Section II. Then, in Section III and Section IV, the current and future markets for HVDC and a mathematical model of the HVDC demand are introduced. The segmentation of the HVDC market and the stations of HVDC converters were reviewed in Section V and Section VI. Then, the HVDC transmission cables and their demand and the strains of HVDC market growth have been outlined in Section VII and Section VIII, respectively. Finally, the effects of COVID-19 on the HVDC's global market and its future work have been discussed in Section X and Section XI respectively.

II. HVDC and Its Advantages Over HVAC

Compared to high voltage alternating current (HVAC), the utilization of HVDC transmission across large distances offers many technical benefits. The HVAC has capacitive and reactive effects on the transmission lines, which means that Direct Current transmission losses or costs are far lower than HVAC [34], [35]. These converters eliminate the need for expensive AC line-reactive compensators by converting transmission losses to line-resistive losses [36].

A. *Advantages of HVDC*

In comparison to HVAC transmission, HVDC offers several advantages [37]–[40]:

- Asynchronous systems, such as different frequency AC systems, can be connected.
- Overcoming technical barriers when an AC system fails, HVDC may provide power across a lengthy cable system. When AC transmission is used, cable capacitance increases with length leading to a significant capacitive current (flow of reactive power), the current capacity available for actual power transfer is reduced.
- There has been no increase in short-circuit capacity (Asynchronous systems, such as different frequency AC systems, can be connected).
- The transmission of power can be controlled flexibly and efficiently.
- It can meet any pre-determined criterion for power supply (the controller can be set to a variety of functions).
- Fewer losses.
- For a given conductor, it increases the transmitted power. There are no restrictions to transmit power over a long distance. Because there is no reactive voltage loss, voltage control is improved for heavy and light loads (no Ferranti effect).
- It requires a smaller right-of-way (better land use).
- It increases power transfer for a given conductor cross-section area.
- Optimized control characteristics can increase the AC system's stability and enable it to work as a generator.

B. *HVDC Power Flow Controllability*

HVDC transmission systems are more appealing due to their accurate, quick, and adaptive power flow management at any required value within that capacity limit. The HVDC station's core controls the converter switches, which are utilized to transfer the needed current and power. Converter valves are used to rectify or invert electrical current. The power flow of AC transmission, on the other hand, strictly follows Kirchhoff's principles and is reliant on network structure and impedances. There are worries about the lack of effective power flow controllability, rising network congestion, and issues with loop flow or parallel flow in the functioning of uncontrolled energy markets[41], [42]. Embedded HVDC transmission offers a viable approach for addressing these issues [43]. Complete controllability of HVDC transmission enables efficient power-sharing between parallel AC lines and DC connections and regulated power flows across areas or markets. System security and emergency reaction require HVDC transmission with rapid flow controllability.

C. *HVDC System Costs*

HVAC systems require at least three conductors, but HVDC systems only need two, resulting in a higher line cost for the same transmission capacity. The converter stations are much more costly in HVDC projects despite the lower line costs. The HVDC case has reduced transmission costs of cable, right-of-way, and operation and maintenance [44]. The break-even distance is the point where the costs of AC and DC systems are equal. Fig. 1 demonstrates that a DC line is more cost-effective over longer lengths than the break-even distance [45]. The HVDC option is always the most cost-effective, just above break-even distance. The transmission medium, permissions, local cost charges, and right of way are all elements that affect the break-even distance. For each given case, a project-specific study is required [46].

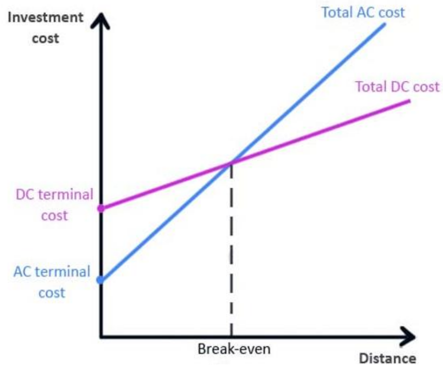

Fig. 1. Comparison of HVAC and HVDC system costs.

III. HVDC Current and Future Market

The benefits outlined in the preceding section were sufficient to encourage energy market companies and governments to invest in HVDC technology. Furthermore, HVDC transmission with quick flow controllability is required for system security and urgent response. The HVDC transmission systems market is predicted to develop at a Compound Annual Growth Rate (CAGR) of around 11.20 percent between 2020 and 2025. The capability of HVDC transmission technology to merge new generations with current infrastructure is boosting the industry as governments worldwide begin to adopt renewable power production. The HVDC industry is predicted to develop significantly over the next several years, especially with many new projects in 2019 or 2020 [47]. Over the estimated timeframe, HVDC transmission networks are predicted to observe a decline in demand as the percentage of the power generated grows for both off-grid and distributed generators, placing a strain on the market. A high voltage direct system is required for long-distance and high-voltage purposes, whereas an off-grid system is set up for on-site power generation and consumption with minimal demand. The following points summarize the HVDC market forecast in order to offer a comprehensive picture of future HVDC market potential [47], [48]:

- Due to the worldwide expansion of underwater power transmission systems, the submarine HVDC systems market is predicted to have the highest and the largest market share. Submarine energy transmission is becoming increasingly significant due to the rising focus on power exchange between countries.
- In the coming years, the HVDC transmission systems market is expected to benefit from increased energy demand in the Middle East and Africa and the growth of the renewable energy industry [41].

- Top global players dominate the European market, which is the biggest and most aggressive. Because of Chinese and Indian HVDC investments, the Asia-Pacific region (APAC) has gained much momentum in the last two years. It is projected that their market will continue to grow rapidly [49], [50].

IV. HVDC Market Growth

Fig. 2 depicts the current and expected growth of HVDC in the transmission market from 2020 to 2027.

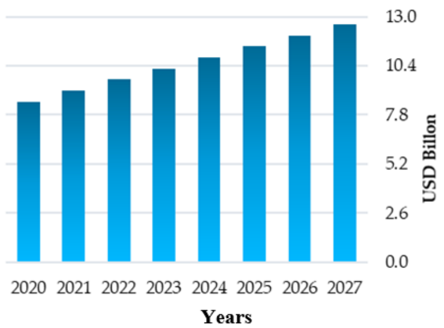

Fig. 2. Current and anticipated growth of the HVDC market (2020 - 2027). [53]

The worldwide market for HVDC transmission is expected to expand at a Compound Annual Growth Rate (CAGR) of 5.7% from 2020 to 2027, from roughly 8.5 USD billion in 2020 to a projected 12.6 USD billion by 2027, despite the COVID-19 epidemic, according to the data. The LCC market is predicted to develop at a 5.8% CAGR and reach 5 USD billion by the end of the research period. After an early evaluation of the pandemic's commercial repercussions and the resulting economic crisis, the VSC segment's growth is decreased to a 6.3 percent CAGR for the following seven years [51]–[53]. Compound annual growth rate (CAGR) may be computed using the following formula:

$$\text{CAGR} = \left[\left(\frac{\text{EV}}{\text{BV}}\right)^{1/n} - 1\right] \times 100\% \tag{1}$$

where EV is the ending value, BV is the beginning value, and n is the year's number. China and India are the primary contributors to the APAC, in which, due to their growing power demand, the market for HVDC is growing. This growth in the market can be attributed to the aging power infrastructure, the change in the pattern of energy consumption, uncertainty in the economy, and initiatives to reduce CO_2 emissions. One of the most important challenges in the power business today is the availability of high-quality energy as well as dependable and consistent power transmission. This aspect is moving the HVDC transmission market in the APAC region ahead.

V. Mathematical Model for HVDC Demand Calculation

The following assumption is considered when using the quantitative theory of demand [54]: While income is steady, the quantity of demand for specific goods or services declines as price rises, and vice versa. This assumption enables the development of numerical approaches for HVDC market demining, such as predicting the increase (reduce) the quantity of demand for a given price reduction (increase). Fig. 3 depicts a visual representation of the theory in which q_i represents the amount of quantity of demand for the HVDC, and p_i is the unit price for HVDC.

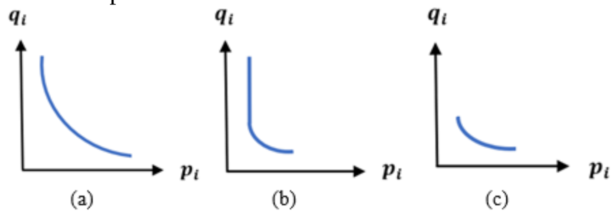

Fig. 3. Possible evolution of the price: (a) Curve of the demand-price function ($q_i = p_i$), (b) a fall in price leads to a rapid increase in the quantity of demand, and (c) price adjustments have a lower impact on the quantity of demand.

The elasticity of demand coefficient (c) of the price (p), which indicates the percentage change (in reverse) application of the HVDC if its price varies by 1%, illustrates the sensitivity of demand to price fluctuations.

The calculation formula is:

$$E_{c/p} = \frac{\Delta c}{c} : \frac{\Delta p}{p} \tag{2}$$

where ":" represents the proportional relation, ΔC is the demand growth and Δp is change (+/-) reference price in two periods.

For the scenario when demand for HVDC rises with rising income but falls with rising price, we assume f_v is the demand function for each level of income:

$$q_i = f_V(p_i) \tag{3}$$

As illustrated in Fig. 4, various variations in demand can be represented by numerous sequential demand curves.

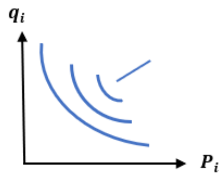

Fig. 4. Evolutions of demand.

The application may be stated as a function of revenue if the price is maintained constant:

$$q_i = f(v) \tag{4}$$

When income rises by 1%, the coefficient of elasticity of demand (C) to income (V) represents the percentage increase in demand. That is,

$$E_{c/v} = \frac{\Delta c}{c} : \frac{\Delta v}{v} \tag{5}$$

Changing pricing determines transmission demand curves. In the literature on Engel curves, they are a sort of curve that expresses the connection between demand and income. Product interchangeability influences the demand for unique items or product groups with a known saturation level.

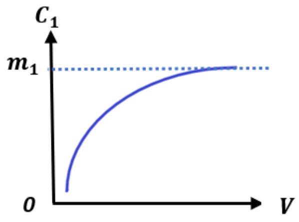

Fig. 5. Törnquist I function.

The following function is commonly used to express demand-income dependence:

$$C_1 = \frac{m_1 V}{V + n_1} \quad (6)$$

where C_1 is the demand for the product (or combination of products) under consideration, V is the income, and n_1, m_1 are econometric parameters, where n_1 is the demand amount (number of units), and m_1 is the unit price.

C_1 is known as Törnquist function I (is a hyperbolic shape function that may be used to examine the demand for different commodities in relation to their price and prominence in the consumer basket), in which this function shows that with increasing income, the demand rises at a lower rate and tends to be capped. The graph is shown in Fig. 5.

From Fig. 5 it can be seen that $V \to \infty$ leads the level C_1 towards m_1. The function's first derivative is dropping and approaching zero when $V \to \infty$. Thus, the demand evaluation of the HVDC market can be described by the following equation:

$$C_1 = \frac{\partial c_1}{\partial V} = \frac{m_1 n_1}{(V + n_1)^2} \quad (7)$$

VI. Segmentation of the Global HVDC Market

The worldwide HVDC transmission system market can be categorized by technology, type, deployment, application, capacity, and geography, with regional segmentation being discussed in the following section due to its importance. The market may be divided into two types based on technology: LCC and VSC [55], [56]. In electrical engineering, voltage source converters are a relatively recent development. As a result, an increase in VSC demand is expected throughout the projection period. The market can be classified as a monopole system, a bipolar system, a back-to-back system, or a multi-terminal system based on its kind. By 2020, the worldwide HVDC transmission system market will be led by monopole and bipolar systems due to rising demand from end customers. Overhead, underground, submarine, and combination installations make up the world's HVDC transmission system market.

Due to increasing investment in various regions worldwide, underground and submarine transportation are major sectors, depending on the application. Interconnecting grids, feeding metropolitan areas, linking offshore wind, and other segments make up the market. Because there has been much growth in offshore wind energy projects worldwide, the industry that connects these projects is expected to grow quickly. The market for HVDC transmission systems is broken down into three groups: up to 400 kV, 401 kV to 800 kV, and more than 800 kV. 401 kV to 800 kV and beyond 800 kV markets are expected to grow a lot over the next few years. The HVDC transmission systems market covers the Americas, Europe, Asia, Latin America, the Middle East, and Africa. In 2020, Asia Pacific had led the global HVDC transmission systems market. HVDC transmission will grow at a 6.9% CAGR from 8.2 USD billion in 2018 to 12.3 USD billion by 2024. The growth in this market is attributed to the arability of long-distance transmission technologies and solutions, VSC technology demand, more renewable energy, and lastly, the support of governments for HVDC transmission [57], [58]. Fig. 6 displays the HVDC market by region from 2018 to 2024 for the USA, Europe, APAC, and the Rest of the World (ROW). The figure shows that the APAC region has the lead of the HVDC transmission market in the period under consideration, i.e., from 2018 to 2024. The APAC region is expected to be a very appealing region during the projection period.

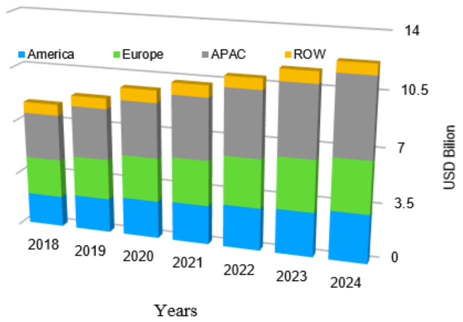

Fig. 6. HVDC transmission market by region (2018-2024).

Because countries like China, Japan, and India have invested much money in renewable energy, the growth is likely to continue over the next few years [59]. Europe is anticipated to be a large part of the global market for HVDC transmission systems in the next few years. Due to rising pollution and government laws, the region invests in renewable energy sources to satisfy the 2031 climate and energy framework. Since the region has advanced electrical transmission systems, North America will only make up a small percentage of the global market for HVDC transmission systems over the next few years. At some point, the market in this area should grow at a healthy rate [47].

As an example, China may be regarded as the most significant participant in the global HVDC market, as seen in Fig. 7, where HVDC technology is used in various applications. Fig. 7 depicts the Chinese HVDC market by application (telecommunications, medical, industrial, and oil & gas) and segment forecasts through 2022.

The Global Market Insights, Inc. report suggested that there is going to be a lot more demand for HVDC cables by 2027. The grid is being modernized, and more high-tech goods are being used in the T&D network. The rising power consumption will fuel the business landscape in emerging countries due to increasing industrialization and commercialization [60].

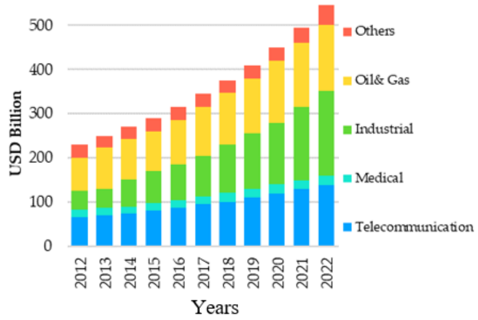

Fig. 7. Chinese HVDC power supply market by application (2012 – 2022).

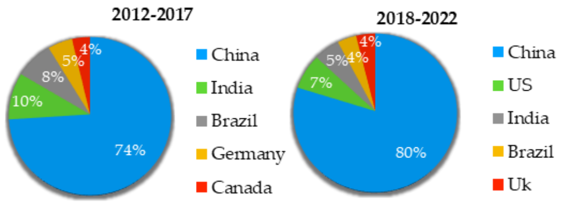

Fig. 8. HVDC Converter stations, key countries, market share 2012-2017, 2018-2022.

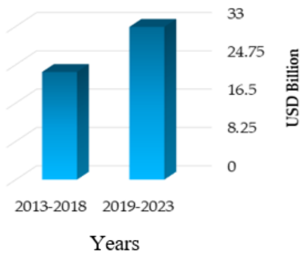

Fig. 9. Global HVDC converter stations market, (2013-2018), (2019-2023).

VII. HVDC Converter Station Market

The market for HVDC converters stations is likely to be led by China. An HVDC converter station is a type of substation that serves as the end of the line. They are land-based and offshore structures that convert direct current to alternating current or the other way around for offshore wind farms [61], [62].

The Chinese government has invested significantly in developing a nationwide HVDC transmission infra-structure to reduce electricity transmission losses via HVAC cables between energy-producing bases and load centers. Europe and Asia-Pacific accounted for the highest market shares in 2021.

Apart from India and China, other ASEAN countries such as South Korea, Japan, Pakistan, Indonesia, and others are likely to contribute considerably to multiple requests for HVDC transmission systems over the forecasted period [17].

Due to China's expansion, the market for HVDC converter stations is predicted to be more than double from 3.24 USD billion in 2018 to 6.88 USD billion in 2023, as shown in Fig. 8, from 74 % in 2012 to 2017 to 80 % to 2022. In line with the increase in China, the worldwide market for HVDC converter stations is predicted to be almost twice the size, from 3.24 USD billion in 2018 to 6.88 USD billion in 2023. Fig. 9 shows the Global HVDC converter stations market (USD billion), (2013-2018), (2019-2023). Due to growing power demand, increased cross-border power transmission, multiple global attempts to promote interest in renewable smart grids, and the need to decrease CO2, the global HVDC converter stations market are predicted to grow to 32.88 USD billion 2023 [63].

VIII. HVDC Transmission Cables and Demand

With the growing number of HVDC lines, HVDC cables have become increasingly important. Regardless of the high cost caused by building both ends terminals for HVDC and AC links, the line's per unit length cost can be considered low. To say it another way, when all other factors are equal, the link's cost per unit of energy goes down when its length grows. Over a break-even distance, HVDC becomes the most cost-effective option (about 600-800 km for current technology). Furthermore, an HVDC cable has no technological constraints in terms of length. The reactive power flow in a long AC cable transmission will limit the maximum practicable transmission distance due to the large cable capacitance [51], [47], HVDC does not have this limitation.

One of the most important projects in Africa is the Kenya-Ethiopia Electricity Highway. This bipolar 500 kV HVDC line is now being built and will run from Welaya Sodo in Ethiopia to Suswa in Kenya. It will cover 1068 km, with 437 km in Ethiopia and 631 km in Kenya.Egypt is expected to be the leader in Africa's HVDC transmission system market since it has spent much money on grid infrastructure. On the other hand, HVDC transmission has failed to gain pace globally, with only a handful of projects now under development.

The arrangement between Egypt and Cyprus to commission and develop the Euro-Africa Interconnector, which was achieved in May 2019, might be considered a significant project. Around 2.2 USD billion will be spent on the project, mostly built under the sea. The Egypt-Cyprus link will be built in two phases. There will be a transmission capacity of 1000 MW in the first phase, and it will be increased by 1000 MW in the second phase. There should be a finish date for the project 36 months after it began [64].

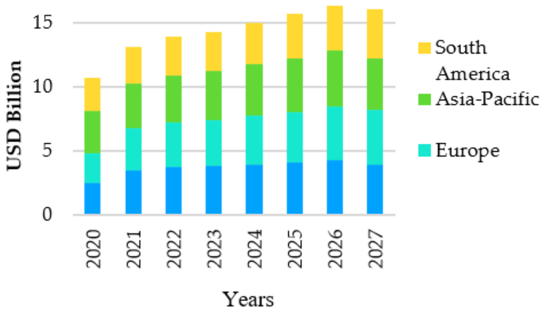

Fig. 10. Global HVDC cable by region 2020-2027.

The demand for cables can also provide crucial information about the HVDC markets and the major worldwide competitors. Fig. 10 depicts the Global HVDC Cable Market by Region from 2020 to 2027. This figure shows that the European region is the most significant player in this component market than APAC. These results may not be accepted when APAC, especially with countries such as China leading the world in HVDC technology.

IX. HVDC Market Growth Strains

Low cost, long-range transmission, and high-efficiency energy consumption are just a few benefits expected to help the business grow greatly throughout the forecast period. More design freedom and cheaper installation costs are projected to drive demand. Due to the increased need for grid expansion, the complexity of electric systems developed in conjunction with the number of feed-in nodes. Raises may turn on the possibility of outages, which happen when supply flow exceeds design parameters. HVDC may instantly alter the output polarity with a remote or switch control signal. It aids in the prevention of system outages, which are projected to increase product demand as a result of their failure. Because of the challenges of constructing and operating a multi-terminal HVDC system, expansion may be challenging.

Furthermore, the requirement for greater and much more costly filter-compensation systems to address concerns about reactive power usage may restrict expansion in the next seven years [65], [66].

X. Impact of Covid-19 on the Global HVDC Market

By 2040, the world is expected to produce 38,000 TWh of electricity a year, up from 27,000 TWh in 2019 [3], [67]. As the global economy recovers, global power consumption is predicted to climb by 5% in 2021 and 4% in 2022, after a little dip in 2020 due to the COVID-19 epidemic [1].

Because power delivery to grid systems is dependent on transmission lines, the power business is classified as an essential service. It is owing to the lockdown in several nations. At first, the COVID-19 pandemic had little impact on the HVDC transmission system business, affecting the logistic supply chain and workforce availability. For these reasons, the global economy might be involved in three ways by COVID-19: directly, by disrupting supply chains and disrupting markets, and financially, by impacting businesses and financial markets [68]. Governments and businesses have worked hard to rebuild the supply chain and get more people to work. It is expected to make the market better soon. Energy usage is shown in Fig. 11 for the years 2019-2021.

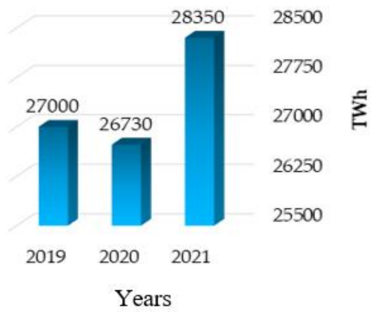

Fig. 11. Impact of COVID-19 on global power demand.

XI. Conclusion and Future Work

This study described the HVDC transmission systems market, presenting the current state and future growth of the HVDC market, covering its current condition and supplier environment, as well as obstacles and possible advancements. Furthermore, the advantages of HVDC may enable it to dominate the energy industry in the future. We can infer from the statistical data that HVDC technology will soon win the market due to its many advantages over HVAC. However, the sophistication of designing and managing a multi-terminal HVDC system may hinder growth. Furthermore, the growing demand for the construction of costly filter-compensation systems to address problems resulting from reactive power consumption would hinder expansion during the next seven years. Finally, this research reveals that the big international players are located in the APAC region, notably China. Future work aims to give a more in-depth analysis of the HVDC market, particularly for the Middle East and Africa, due to the shortage of information conferences in these two areas, using a mathematical model presented in this paper, an analysis study could be done to estimate the demand of HVDC systems.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Israa I. H. conducted the research; Israa I. H. analyzed the data; Sirine E. and Adel K. Validated the research; Israa I. H. wrote the paper; Sirine E. and Adel K. revised and edited the paper; all authors had approved the final version.

References

[1] IEA. Electricity market report - July 2021. [Online]. Available: https://www.iea.org/reports/electricity-market-report-july-2021

[2] Staff of the Federal Energy Regulatory Commission. Report on barriers and opportunities for high voltage transmission. (June 2020). [Online]. Available: https://www.congress.gov/116/meeting/house/111020/documents/HHRG-116-II06-20200922-SD003.pdf

[3] IEA. Electricity information: overview. IEA, Paris. (2021). [Online]. Available: https://www.iea.org/reports/electricity-information-overview.

[4] J. Sun, M. Li, Z. Zhang, T. Xu, J. He, and H. wang, "Renewable energy transmission by HVDC across the continent: system challenges and opportunities," *CSEE Journal of Power and Energy Systems*, vol. 3, no. 4, pp. 353–64, December 2017.

[5] A. Raza, D. Xu, X. Su, W. Li, and B. Williams, "A novel multi-terminal VSC-HVDC transmission topology for offshore wind farms," *IEEE Trans. on Industry Applications*, vol. 53, no. 2, pp. 1316-1325, April 2017.

[6] K. Sun, H. Xiao, S. You *et al*., "Frequency secure control strategy for power grid with large-scale wind farms through HVDC links," *Int. J. Electr. Power Energy Syst.*, vol. 117, July 2020.

[7] A. Yadwadkar. (2021). How HVDC transmission can be the future of renewable energy generation. Circuitdigest. [Online]. Available: https://circuitdigest.com/article/how-hvdc-transmission-can-be-the-future-of-renewable-energy-generation

[8] H. Acaroğlu and F. P. G. Márquez, "High voltage direct current systems through submarine cables for offshore wind farms: A life-cycle cost analysis with voltage source converters for bulk power transmission," *Energy*, vol. 249, 2022.

[9] A. Tosatto, T. Weckesser, and S. Chatzivasileiadis, "Market integration of HVDC lines: Internalizing HVDC losses in market clearing," *IEEE Trans. Power Syst.*, vol. 35, no. 1, pp. 451–461, 2020.
[10] M. Wang, T. An, H. Ergun, *et al*., "Review and outlook of HVDC grids as backbone of transmission system," *CSEE Journal of Power and Energy Systems*, vol. 7, no. 4, pp. 797–810, July 2021.
[11] H. Lv, X. Abuduwayiti, L. Meng, and C. Shi, "Rapid power compensation-based VSC-HVDC control strategy for low-frequency oscillation suppression of the island power system," *Frontiers in Energy Research*, vol. 9, 2021.
[12] C. Zhao, Q. Wang, and R. Yang, "Research on demonstration project of Zhangbei Flexible DC Grid," in *Proc. IEEE 2020 10th Int. Conf. Power Energy Syst.,* Beijing, China, 2020, pp. 77–82.
[13] H. Rao, Y. Zhou, S. Xu, and Z. Zhu, "Research and development of ultra-high-voltage VSC for the multi-terminal hybrid ±800kV HVDC project in China southern power grid," *Proceeding Cigre'Paris Sess.,* Paris, Fr., pp. 23–28, 2018.
[14] ABB. (Sep. 2020). 5SJA 3000L520300 StakPak BIGT module. [Online]. Available: https://search.abb.com/library/download.aspx?documentID=5SYA1467&LanguageCode=en&DocumentPartId=&Action =Launch
[15] P. D. Judge, M. M. C. Merlin, T. C. Green, D. R. Trainer, and K. Vershinin, "Thyristor-bypassed submodule power-groups for achieving high-efficiency, DC fault tolerant multilevel VSCs," *IEEE Trans. Power Deliv.*, vol. 33, no. 1, pp. 349–359, Feb. 2018.
[16] P. F. C. S. Achenbach, V. Barry, and C. H. Bayfield, "Increasing the GB electricity transmission networks' power transfer capability between north and south–the western HVDC link," presented at 10th IET Int. Conf. AC DC Power Transm., 2012.
[17] G. Mazzanti, "Issues and challenges for HVDC extruded cable systems," *Energies*, vol. 14, July 2021.
[18] G. Lagrotteria, D. Pietribiasi, and M. Marelli, "HVDC cables-The technology boost," in *Proc. IEEE 2019 AEIT HVDC Int. Conf*., Florence, Italy, May 2019, pp. 1-5.
[19] M. Syatirah, N. Muhamad, K. Halim, M. Zakariya, M. Anuar, and A. Zaidi, "A review: Polymer-based insulation material for HVDC cable application," in *Proc*. *IOP Conference Series: Materials Science and Engineering*, vol. 932, no. 1, p. 012064, 2020.
[20] Technical requirements and specifications of State-of-the-art HVDC switching equipment. Cigre'Technical Brochure, Tech. Rep. TB683. (2017). [Online]. Available: https://e-cigre.org/publication/683-technical-requirement
[21] F. Zhang, Z. Zhang, S. Xiao, *et al*., "Design and implementation for the high voltage dc-dc converter of the subsea observation network," *J. Mar. Sci. Eng.*, vol. 9, no. 712, pp. 1-21, Jun 2021.
[22] J. D. Páez, D. Frey, J. Maneiro, S. Bacha, and P. Dworakowski, "Overview of DC-DC converters dedicated to HVDC grids," *IEEE Trans. Power Deliv.*, vol. 34, no. 1, pp. 119–128, Feb. 2019.
[23] I. Alwazah, R. Nasyrov, and F. Shaban, "The importance of grounding in HVDC power transmission systems," in *Proc. of IEEE 2020 Int. Ural Conf. on Electrical Power Engineering*, October 2020, pp. 131–135.
[24] P. Sun, F. Arrano-Vargas, H. R. Wickramasinghe, and G. Konstantinou, "Benchmark models for HVDC systems and DC-Grid Studies," in *Proc. IEEE 2019 9th Int. Conf. on Power and Energy Systems*, June 2020, Perth, Australia, pp. 1-6.
[25] A. S. Bayo, "Control interactions in power systems with multiple VSC HVDC converters," Ph.D. dissertation, Elect. Eng., KU Leuven University, Belgium, August 2018.
[26] J. Sreedevi, V. Anuradha, and P. Manohar, "Performance evaluation of VSC-HVDC link for varying AC system strengths," *Power Research*, vol. 14, no. 1, pp. 105–113, 2019.
[27] L. D. Zhang, L. Harnefors, and H. P. Nee, "Interconnection of two very weak AC systems by VSC-HVDC links using power-synchronization control," *IEEE Trans. Power Syst.*, vol. 26, no. 1, pp. 344– 355, Feb. 2011.
[28] F. Dugal, A, Baschnagel, M. Rahimo, *et al*., "The next generation 4500 V/3000 A BIGT stakpak modules," presented at PCIM Europe 2017, International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management, Nuremberg, Germany, May 2017.
[29] G. P. Chaffey, I. Jahn, R. Loenders, *et al*., "Requirements for functional testing of HVDC protection IEDs," presented at CIGRE International Council on Large Electric Systems; CIGRÉ B4 Colloquium, Johannesburg, South Africa, 2019.
[30] P. Rault, S. Dennetière, H. Saad, M. Yazdani, C. Wikström, and N. Johannesson, "Real-time simulation with an industrial DCCB controller in a HVDC grid," *Electric Power Systems Research*, vol. 189, p. 106593, 2020.
[31] M. Wang, G. Chaffey, D. Van Hertem, *et al*., "Multi-vendor interoperability tests of IEDs for HVDC grid protection," in *Proc. 15th Int. Conf. Developments in Power System Protection*, Liverpool, UK, March 2020.
[32] M. J. Perez-Molina, D. M. Larruskain, P. E. López, and A. Etxegarai, "Analysis of local measurement-based algorithms for fault detection in a multi-terminal HVDC grid," *Energies*, vol. 12, no. 24, pp. 1–20, 2019.
[33] I. Cowan, G. Chaffey, B. Ponnalagan, *et al*., "Demonstration of partially selective HVDC grid protection system with hardware-in-the-loop IEDs," in *Proc. 15th Int. Conf. on Developments in Power System Protection (DPSP 2020)*, Liverpool, UK, March 2020.
[34] A. Tosatto, M. Dijokas, T. Weckesser, S. Chatzivasileiadis, and R. Eriksson, "Sharing reserves through HVDC: Potential cost savings in the Nordic countries," *IET Gener. Transm. Distrib*., vol. 15, no. 3, pp. 480–494, 2021.
[35] I. Hussein, S. Essallah, and A. Khedher, "Improvement of the Iraqi super grid performance using HVDC/HVAC links by the integration of large-scale renewable energy sources," *Energies*, vol. 15, no. 3, 2022.
[36] E. Pierri, O. Binder, N. G. A. Hemdan, and M. Kurrat, "Challenges and opportunities for a European HVDC grid," *Renew Sustain Energy Rev.*, vol. 70, pp. 427–456, April 2017.
[37] N. Wehbring, R. Bleilevens, J. Saat, M. Rose, and A. Moser, "Benefit of a HVDC back-to-back station in a real distribution grid," in *Proc. 5th IEEE Work. Electron. Grid*, Aachen, Germany, Nov. 2020.
[38] Conclusions of workshop: Horizon 2050 power system and the role of HVDC technologies in a highly decentralised RES generation. Brussels. (February 2020). [Online]. Available: https://energy.ec.europa.eu/system/files/2020-03/200302_1_hvdc_workshop_conclusions_0. pdf
[39] N. R. Watson and J. D. Watson, "An overview of HVDC technology," *Energies*, vol. 13, no. 17, pp. 1-35, August 2020.
[40] A. D. Andersen and J. Markard, "Multi-technology interaction in socio-technical transitions: How recent dynamics in HVDC technology can inform transition theories," *Technol. Forecast. Soc. Change*, vol. 151, October 2019.
[41] IEA (2021). Global energy review 2021. IEA Paris. [Online]. Available: https://www.iea.org/reports/global-energy-review-2021.
[42] IEA (2019): Global energy review 2019. [Online]. Available: https://www.oecd.org/fr/publications/global-energy-review-2019-90c8c125-en.htm
[43] S. Wang, J. Zhu, L. Trinh, and J. Pan, "Economic assessment of HVDC project in deregulated energy markets," in *Proc. IEEE 2008 Third Int. Conf. on Electric Utility Deregulation and Restructuring and Power Technologies*, Nanjing, 2008, pp. 18–23.
[44] C. K. Kim, V. K. Sood, Jang, G. S. Jang, S. J. Lim, and S. J. Lee, *HVDC Transmission: Power Conversion Applications in Power Systems*, John Wiley & Sons, 2009.
[45] K. Sharifabadi, L. Harnefors, H. P. Nee, and S. Norrga, *Design, Control, And Application of Modular Multilevel Converters for HVDC Transmission Systems*, John Wiley & Sons, 2016.
[46] C. J. Pillay, M. Kabeya, and I. E. Davidson, "Transmission systems: HVAC vs HVDC," in *Proc. Int. Conf. Ind. Eng. Oper. Manag*., Michigan, USA, August 2020, pp. 2061–2077.
[47] HVDC transmission systems market growth, trends, covid-19 impact, and forecasts (2022 - 2027). *Research and Market*. (2022). [Online]. Available: https://www.researchandmarkets.com/reports/4520164/hvdc-transmission-systems-market-growth#src-pos-1
[48] G. A. Ludin, A. Nakadomari, A. Yona, *et al*., "Technical and economic analysis of an HVDC transmission system for renewable energy connection in Afghanistan," *Sustainability*, vol. 14, no. 3, 2022.
[49] L. Michi G. Donnini, C. Giordano, *et al*., "New HVDC technology in Pan-European power system planning," In *Proc. IEEE 2019 AEIT HVDC Int. Conf.*, Florence, Italy, May 2019.
[50] M. V. Czernorucki, M. B. Salles, E. C. Costa, A. S. Melo, and L. Piegari, "Comprehensive overview on HVDC converter transformer design: additional discussions to the IEC/IEEE 60076-

57-129 standard," *IEEE Access*, vol. 10, pp. 40165–40180, April 2022.

[51] H. Acaroğlu, A. Najafi, Ö. Kara, and B. Yürük, "An economic and technical review for the utilization of HVDC in Turkey and in the world," *Konya Journal of Engineering Sciences*, vol. 9, no. 3, pp. 809–835, 2021.

[52] A. Nishioka, F. Alvarez, and T. Omori, "Global rise of HVDC and its background," *Hitachi Review*, vol. 69, no. 4, pp. 50–55, 2020.

[53] HVDC Transmission - Global Market Trajectory & Analytics. *Research and Market*, 2021. [Online]. Available: https://www.researchandmarkets.com/reports/4805530/hvdc-transmission-global-market-trajectory-and

[54] D. Nicolae, V. Pau, M. Jaradat, *et al*., "Mathematical model for forecasting and estimating of market demand," in *Proc. American Conference on Applied Mathematics*, 2010, pp. 629-634.

[55] Imdadullah, B. Alamri, A. Hossain, and M. S. J. Asghar, "Electric power network interconnection: A review on current status, future prospects and research direction," *Electronics*, vol. 10, no. 17, pp. 1–29, 2021.

[56] Global High Voltage Direct Current (HVDC) transmission market report, history, and forecast 2016-2027. (2021). [Online]. Available: https://www.360researchreports.com/global-high-voltage-direct-current-hvdc-transmission-market-18369488

[57] N. Hadjsaid and S. Jean-Claude, *Power Systems and Restructuring*, John Wiley & Sons, 2013.

[58] HVDC Transmission Market by Component (Converter Stations, Transmission Cables, and Others), Project Type (Point-to-Point, Back-to-Back, and Multi-Terminal), Technology (CCC, VSC, and LCC), Application, and Geography - Global Forecast to 2024. *Markets and Markets*. (2021). [Online]. Available: https://www.marketsandmarkets.com/Market-Reports/hvdc-grid-market-1225.html

[59] A. Hove, W. Qian, K. Zhao, and N. K. Fuerst. China energy transition status report 2020. Sino-German Energy Transition Project commissioned by Federal Ministry for Economic Affairs and Energy (BMWi). (2020). [Online]. Available: https://www.energypartnership.cn/fileadmin/user_upload/china/media_elements/publications/China_Energy_Transition_Status_Report.pdf

[60] HVDC Cables Market Revenue Worth $4 Billion by 2027, Says Global Market Insights Inc. (2021). [Online]. Available: https://www.prnewswire.com/news-releases/hvdc-cables-market-revenue-worth-4-billion-by-2027-says-global-market-insights-inc-301252685.html#:~:text=SELBYVILLE%2C Del.%2C March 22, products across the T%26D network

[61] J. Larsson, "Transmission systems for grid connection of offshore wind farms HVAC vs. HVDC breaking point," MS thesis, Uppsala University, Uppsala, Sweden, 2021.

[62] A. Follo, O. Saborío-Romano, E. Tedeschi, and N. A. Cutululis, "Challenges in all-DC offshore wind power plants," *Energies*, vol. 14, no. 19, pp. 1-15, 2021.

[63] China will continue to lead global high-voltage direct current converter stations market between 2019 and 2023. Global Data. (2021). [Online]. Available: https://www.globaldata.com/china-will-continue-to-lead-global-high-voltage-direct-current-converter-stations-market-between-2019-and-2023-says-globaldata/

[64] Africa high voltage direct current (HVDC) transmission systems market - growth, trends, covid-19 impact, and forecasts (2021 - 2026). Morder Intelligent. (2021). [Online]. Available: https://www.mordorintelligence.com/industry-reports/africa-high-voltage-direct-current-hvdc-transmission-systems-market-industry

[65] High voltage direct current power supply market size, share & trends analysis report by voltage (1,000 V, 1,000-4000 V, >4,000 V), by application (telecommunication, medical, industrial, oil & gas) and segment forecast to 2022. *Research, Grand Review*. (2021). [Online]. Available: https://www.grandviewresearch.com/industry-analysis/high-voltage-direct-current-hvdc-power-supply-market.

[66] A. Kumar and D. Hussain, "HVDC (high voltage direct current) transmission system: A review paper," *Gyancity Journal of Engineering and Technology*, vol. 4, no. 2, pp. 1 -10, 2018.

[67] A. Alassi, S. Bañales, O. Ellabban, G. Adam, and C. MacIver, "HVDC Transmission: technology review, market trends and future outlook," *Renew. Sustain. Energy Rev.*, vol. 112, pp. 530–554, 2019.

[68] High Voltage Direct Current (HVDC) Transmission System Market 2021: Impact of Covid 19 on Industry Share, Size, Price, CAGR. *Market Watch*. [Online]. Available: https://www.marketwatch.com/press-release/high-voltage-direct-current-hvdc-transmission-systemmarket-2021-impact-of-covid-19-on-industry-share-size-price-cagr-growth-rate-and-future-prospects-with-dominant-regions-and-countries-data-2021-12-13.

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