

Transport of direct current electricity: research and prospects

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ABSTRACT

The purpose of this study is to analyse the technical, economic, and environmental aspects of direct current electricity transport and to assess its potential in accordance with modern requirements for sustainable energy and infrastructure. The methods used include analytical method, classification, functional method, statistical method, synthesis. The study revealed that the use of direct current has the potential to increase the capacity of power transmission lines, which is especially important in a dynamically developing industrial sector. It should be noted that direct current networks have no phase shifts and no notions of static and dynamic stability, making them ideal for long-distance power transmission. As a result of the conducted research, it can be concluded that the use of direct current in technologies can increase the efficiency and reliability of energy systems, especially with an increase in consumption and load on the grid. Direct current power transmission technologies meet the requirements of sustainable energy supply, providing economic efficiency and reducing environmental impact.

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1. INTRODUCTION

The study of direct current power transmission is critical in today's world, where energy systems face the challenges of climate change and the need to ensure sustainable and reliable power supply for industry and the public. The use of direct current to transmit electricity allows for the efficient integration of renewable energy sources and reduces energy losses during long-distance transportation. A deep understanding of the technical, economic, and environmental aspects of this technology will contribute to the development of sustainable energy systems and meet the growing energy needs of the future. Therefore, studying this topic is an important step towards achieving sustainable development goals and modern energy strategies.

The study by Toishieva *et al.* [1], attention is paid to the importance of addressing the environmental aspects of direct current electricity transport and it is noted that this can contribute to reducing greenhouse gas emissions. However, the study does not consider the technical and economic aspects of the transport of direct current electricity, which remains an important unresolved issue in this line of research. In the study by Rakhimov [2], attention is focused on the fact that the effective use of direct current in energy networks will not only increase the efficiency of energy transmission, but also contributes to the integration of renewable energy sources into modern energy systems. The study does not sufficiently consider the issues of safety and reliability of power transmission using direct current, which is a poorly researched and key area in the context of the effective application of this technology.

The study by Kabulov and Adilbekov [3] discusses issues related to the adaptation of existing alternating current (AC) systems to the use of direct current and the need to develop standards to ensure compatibility. This study highlights that the adaptation of existing systems to the use of direct current requires the development of appropriate standards to ensure their mutual compatibility. The economic benefits and cost aspects of the adaptation of AC systems to direct current systems are not sufficiently considered in this study. This aspect is an important area that has been rather neglected. Researcher Kabduova [4] notes that the introduction of direct current power transmission technologies can lead to lower operating costs and increase the competitiveness of networks. The study suggests that the use of direct current can reduce maintenance costs and make power grids more competitive.

Research conducted by Shamsiyev and Sobitkhodjayev [5] highlights that increasing the capacity of direct current transmission (DCT) lines has the potential to significantly reduce energy losses during transmission over long distances, which is critically important for improving the efficiency of energy systems. However, the study does not address issues related to technical and economic problems that may arise when increasing the capacity of DCT lines. The study by Dosbolaev and Abdirakhmanov [6] emphasises an important aspect related to the impact of direct current technologies on the environment, including safety issues and their impact on ecosystems in the context of the expanded use of such systems in the field of energy. However, this study does not cover issues related to the economic and socio-cultural consequences of the introduction of direct current technologies. The research and opinions of these authors reflect the multifaceted nature of the topic of direct current electricity transport and emphasise the importance of a deeper study of this issue. The aim of this study is to explore the technical, economic, and environmental factors of direct current electricity transmission and evaluate its potential in light of current demands for sustainable energy and infrastructure.

2. METHOD

The analytical method helped in a deeper understanding of the technological, economic, and environmental aspects of direct current electricity transport. With the help of analytics, it was possible to identify several important areas in which this method of electricity transport can play a decisive role in the future. With the help of the statistical method, extensive analyses of the initial data related to the transport of direct current electricity were carried out, which revealed valuable trends and important patterns. These studies have shed light on various aspects related to direct current and have influenced the development of this field.

The structural and functional method helped in the in-depth analysis and understanding of the complex system of direct current electric power transport. This research method focuses on the analysis of the structure of the system and its functional elements, which allowed the study to identify many aspects related to direct current, and contributed to the development of more advanced systems. The structural and functional method of analysis played a key role in research related to the transport of direct current electricity. It allowed systematically analysing complex systems and identifying their key elements and functions.

The deduction method is a powerful tool that has helped in the analysis and understanding of direct current electricity transport by identifying patterns and conclusions based on general principles and theories. The application of the deduction method in this area has led to important conclusions and expanded knowledge about direct current. The deduction method was important in the analysis and study of direct current electric power transport. Its ability to identify general principles and patterns contributed to a deeper understanding of direct current systems and their wide application. Deductive analysis allowed developing theories, models and standards that ensured efficient and reliable energy supply, and contributed to the development of innovations and improvement of technologies in this area.

Applying the synthesis, innovative research and solutions were developed in the field of direct current electric power transportation. This method of analysis allowed creating new concepts, technologies, and systems, considering various aspects of direct current. The synthesis played an important role in the development of direct current electricity transport. It enabled the creation of new technologies, systems, and concepts that increase the efficiency, reliability, and stability of direct current systems. These innovations contribute to the development of modern energy systems and provide an efficient and reliable energy supply for future generations.

3. RESULTS AND DISCUSSION

Efficient electricity transmission is crucial for modern energy infrastructure, and DCT technology, once limited, is now gaining attention as a solution to modern energy challenges. Originally developed for long-distance transmission, DCT minimizes losses and extends transmission distances. Current research focuses on applying DCT for shorter distances and integrating renewable energy sources like solar and wind into urban grids. DCT also supports international energy projects, such as the China-Kazakhstan transmission line, ensuring efficient resource use and stable energy supply. Additionally, DCT enhances control over active

and reactive power, improving grid flexibility and efficiency, especially within smart grid systems, contributing to a more sustainable energy future.

DCT circuits and direct current inserts use special converter devices that are based on controlled thyristors, such as gate turn-off thyristors (GTO), and bipolar transistors, known as insulated gate bipolar transistors (IGBT) [7]-[9]. In fact, these systems use essentially the same components to perform the rectification and inversion processes. Many substations are designed with such flexibility in mind that they are able to perform both the role of rectifiers and the role of inverters. The diagrams of DCT are shown in Figure 1(a) and direct current links (DCL) are shown in Figure 1(b).

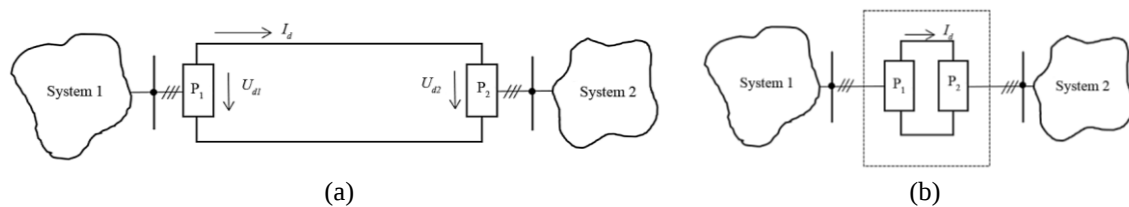


Figure 1. Structural diagrams of; (a) DCT and (b) DCL

A DCL is a station in which both inverters and rectifiers are located in the same place, usually in the same building. The length of the permanent line is minimised as much as possible. DCL are used to connect the main lines of different frequencies (as, for example, in Japan) and to connect two electrical networks with the same nominal frequency, but with different, non-fixed phase shifts [10], [11]. The conversion of electrical energy in the transmission systems of DCT is carried out using devices for changing current and voltage (Figure 2).

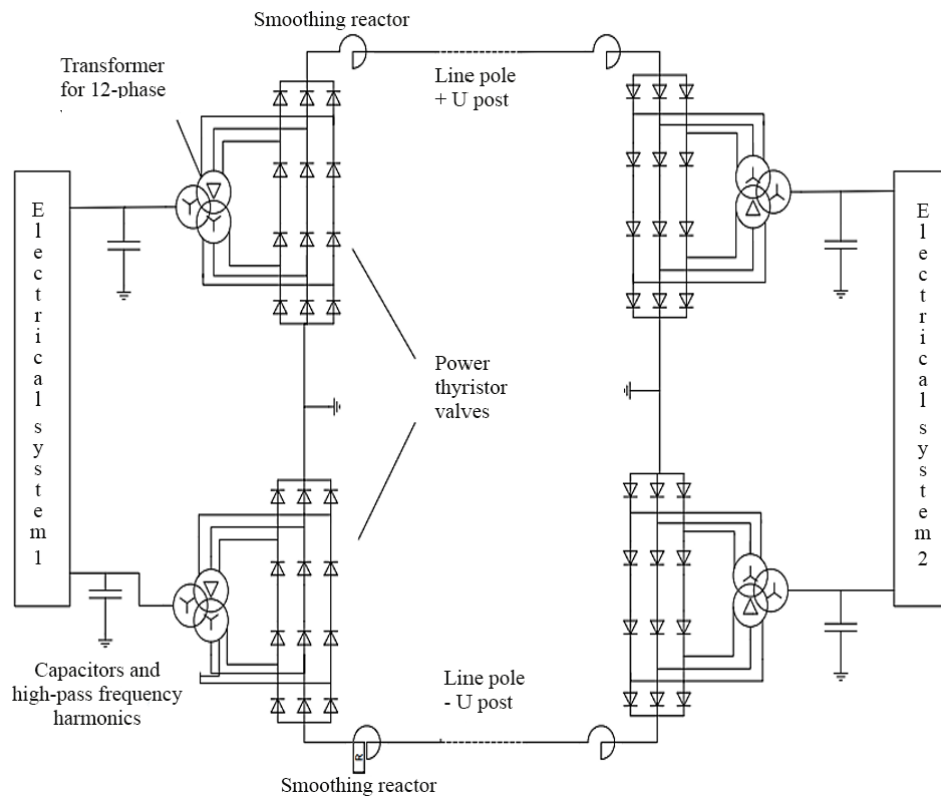


Figure 2. Schematic diagram of DCT between two alternating voltage power systems

Since the beginning of the 1970s, current converters with thyristor valves for DCT and inserts have been used commercially. These converters are used in the composition of high-voltage lines (HL) and cable lines (CL) of different voltage classes, starting from 250 kV and reaching 1,100 kV [12]. One of the current trends in the application of direct current technologies is the transmission of large capacities over long distances using high-voltage and ultra-high-voltage permanent transmission lines. China, India, and Brazil stand out as the leading countries in this area due to the specific features of their geographical location and the uneven distribution of resources and electricity consumers throughout the country. For example, at the moment there are already 14 ultra-high voltage direct current transmissions (UHVDC) in China with a voltage of ± 800 kV, and three more such projects are under construction.

The implementation of direct current electric transport in large-scale infrastructure involves substantial initial investment, long-term operational costs, and long-term benefits. A cost-benefit analysis of such systems must consider various factors, including the infrastructure requirements, energy transmission efficiency, scalability, and integration with existing power grids. The initial costs of implementing direct current electric transport systems are significantly higher compared to traditional AC systems. This is primarily due to the need for specialized equipment such as high-voltage direct current (HVDC) transmission lines, power converters, and substations. These systems require advanced converter technologies such as thyristors and IGBT, which are more expensive than conventional AC components. Moreover, the construction of HVDC infrastructure, especially for long-distance or large-scale transmission, involves high capital expenditure. For instance, the establishment of transmission lines with voltages of ± 500 kV or higher requires substantial investment in converter stations and supporting infrastructure [13].

Infrastructure adaptation also plays a crucial role in the long-term cost and benefit analysis. The transition from AC to direct current systems requires significant upgrades to existing grids, including the installation of converter stations and adjustments to distribution networks [14]. However, the modular nature of direct current systems allows for phased implementation, where existing infrastructure can be gradually upgraded to incorporate direct current technology without requiring a full overhaul. This incremental adaptation process reduces the upfront financial burden and spreads the cost over several years. In terms of scalability, direct current systems offer the advantage of being easily expandable to meet growing energy demands. There are no minimum power restrictions for DCT and DCL systems based on voltage converters. These converters can also function as static reactive power compensators (STATCOM) when the direct current line is disconnected, helping to control reactive power and stabilize voltage in the electrical network. As a result, DCT and DCL systems using voltage converters are widely adopted to improve power supply reliability in weak and autonomous grids [15], [16]. They are also used on offshore oil and gas platforms to transmit electricity from wind farms at sea. Additionally, they can compensate for daily and seasonal power generation fluctuations and maintain voltage stability in AC networks. Voltage converters are integrated into high and ultra-high-voltage DCT lines, with voltages reaching up to 525 kV [17], [18].

All voltage converters intended for integration into the systems of DCT and DCL are built based on modular multi-level circuits, as indicated in Table 1. Modular multi-level voltage converters (MMVC) provide a number of advantages, including a modular structure, high reliability and minimal losses, which range from about 0.95% to 1%. When using such converters in DCT systems, it is possible to choose both symmetric and asymmetric monopolar arrangements.

Table 1. Some planned, constructed, and recently commissioned CL and HVDC and DCL transmission lines

No.	Country, year of commission	Voltage, kV	Throughput capacity, MW	Length of HL/CL, km	Main purpose
1	Eleck link. Norway – Germany, 2020	± 320	1000	51 (CL)	Integration of electricity markets.
2	A Ugro. Belgium – Germany, 2020	± 320	1000	75 (CL)	Increase in the reliability of power supply.
3	Nort Sea Network, Norway – England, 2021	± 525	1400	730 (CL)	Increase in the reliability of power supply.
4	Ultra-Net, Germany, 2022	± 380	2000	340 (CL)	Conversion of 380 kV high-voltage AC lines to direct current. Demonstration stand.
5	Dotwin 6, Germany, 2023	± 320	900	90 (CL)	Power collection from WPPs.
6	Kazakhstan, 2025	± 500	602	550	Increase in the reliability of power supply in the Atyrau region.

Currently, there is a tendency to integrate current converters and voltage converters in one node of the DCT system, and such complexes have been called “hybrid” [19]–[21]. Among the planned projects using such hybrid systems, it is possible to single out multilevel DCT in China, where the rectifier part is built using linearly switched current converters, and the inverter part is based on voltage converters. The total length of

HVDC transmission lines in such systems is approximately 1,500 km, the voltage reaches ± 800 kV, and the capacity is 5 GW. A simplified diagram of such a system is shown in Figure 3.

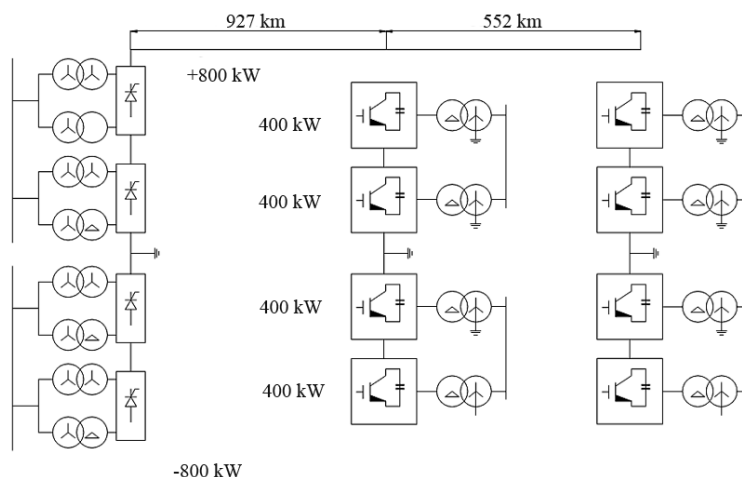


Figure 3. Hybrid DCT arrangement

There is a tendency to develop a multi-terminal direct current transmission (MDCT) using ultra-high voltage, including three or more converter substations [22]. MDCTs have a number of advantages over two-terminal DCTs, including the possibility of gradual expansion based on two-terminal transmission systems, the integration of several power systems, and flexible regulation of transmitted power. One of the most complex and interesting projects in this area is the Champa-Kurukshetra substation with a voltage of ± 800 kV and a length of 1,300 km high-voltage line. This system is designed to transfer electricity from power plants in the Champa region to consumption centres in the Kurukshetra region in India. The specific feature of this DCT is that the transmitting and receiving converter substations consist of two bipoles connected in parallel, which is essentially a four-terminal DCT system. The capacity of each bipole is 3000 MW [23].

The option of building a 500 kV HVDC line between Atyrau and Aktobe is a notable event in the development of Kazakhstan's energy infrastructure. This project is important from several key points. First of all, it contributes to strengthening the energy independence and reliability of the region. 500 kV HL are designed to transmit large volumes of electricity over long distances, and their implementation in the Aktobe region can help ensure stable and reliable power supply to both domestic consumers and industrial enterprises [24], [25]. The construction of a direct current line of this voltage level can help increase the network capacity. This is important to maintain the growth of electricity consumption in the region and to ensure the possibility of connecting new sources of generation. Based on the high efficiency of direct current lines, such a project can also contribute to saving energy resources and reducing operating costs on a long-term basis (Figure 4).

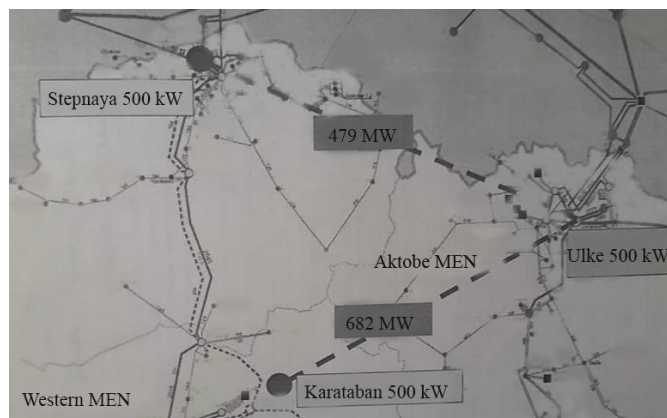


Figure 4. The option of building a 500 kV HVDC line Atyrau-Aktobe

In general, the construction of a 500 kV HVDC line Atyrau-Aktobe underlines the importance of modernisation and expansion of energy infrastructure in Kazakhstan to ensure stability and development of energy supply to the regions. This is an important step to maintain economic growth and improve the quality of life of the population.

According to Shair *et al.* [26], the problems of sustainability of power systems are becoming more and more urgent in light of the growing use of renewable energy sources and power electronics technologies. One of the key issues is the fluctuation of energy production from renewable energy sources depending on weather conditions, such as solar radiation and wind conditions [27], [28]. This creates uneven loads on the network and can cause overloads in power systems, which threatens their stability. Referring to the definition of Chen *et al.* [29], the development of direct current circuit breakers in China represents a significant technological and engineering challenge, given the growing importance of DCT systems in the country. These challenges include the development of highly efficient and reliable circuit breakers capable of ensuring the stability and safety of power systems when operating with direct current and reducing energy losses during long-distance transmission. These data are consistent with the theses given in the previous section.

Research by Zhang *et al.* [30] identify the assessment of the transient stability of power systems as an important aspect of ensuring the reliability of energy supply in modern conditions, especially given the growing introduction of renewable energy sources and power electronics. The principles of transient resilience assessment include an analysis of the dynamics of power systems in response to various disturbances, such as short circuits or equipment outages [31], [32]. These conclusions are consistent with the results of the study, which also emphasizes the importance of assessing transient stability in the context of the integration of renewable energy sources and new technologies, in particular power electronics. The use of data and modern modeling techniques becomes an important part of this assessment. Both studies emphasize the need to develop more accurate and realistic models of energy systems, as well as the use of the latest technologies for monitoring and management.

Research by Najafzadeh *et al.* [33] found that recent advances in the management of interconnected converters in hybrid AC/DC microgrids are associated with the development of more integrated and intelligent control systems. These systems can dynamically optimise power distribution and regulate voltage in real time, considering variable loads and energy sources. Another important achievement is the development of control algorithms that consider weather forecasting and generation from renewable sources, which makes it possible to better manage energy in hybrid microgrids [34]. Future prospects in the management of interconnected converters include the wider adoption of artificial intelligence technologies, such as machine learning and neural networks, to optimise processes in microgrids. In addition, research in the field of energy flow management and energy storage is becoming more and more relevant.

The results of the study by Mikhailova *et al.* [35], Wei *et al.* [36] emphasize the importance of protection methods in HVDC power transmission systems to ensure the reliability and security of power grids. They note that these methods include a variety of approaches and technologies to detect and limit possible failures. This is in line with the results obtained, which confirm the continuous improvement of protection methods in HVDC transmission systems due to the development of new technologies and monitoring methods. An important component is that the level of protection and the choice of methods may vary depending on the specific conditions and requirements of a particular power system [37], [38]. This emphasizes the importance of adapting protection systems to different scenarios, which is also reflected in this study.

Research by Brown and Botterud [39] emphasizes the central role of interregional coordination and energy transmission in the process of decarbonizing the US electric power system. The authors note that the country is facing an ambitious task of reducing greenhouse gas emissions and transitioning to cleaner and more sustainable energy sources. Interregional coordination and transmission are critical to ensure efficient distribution of renewable energy sources and maintain grid stability. These conclusions are consistent with the results of the study, which also emphasizes the importance of interregional coordination in the context of renewable energy integration. Thus, the results of both studies confirm the importance of coordinating interregional energy networks for the sustainable development of the energy system and achieving decarbonization goals.

In conclusion, interregional coordination and transmission play an important role in maintaining the stability and reliability of the U.S. electric power system during the decarbonisation period. These measures help to reduce greenhouse gas emissions by ensuring the efficient use of renewable energy sources, and contribute to the creation of a more sustainable, clean, and efficient electric power system.

4. CONCLUSION

The main conclusions of the study emphasize that direct current power transmission technologies have great potential for modernizing global energy systems, particularly through the integration of renewable energy sources and the reduction of energy losses over long distances. Given these advantages, such as independent control of active and reactive power, no restrictions on the minimum transmitted power, and the ability to

handle different types of loads, direct current power transmission can significantly increase the efficiency and flexibility of power grids. This, in turn, opens up new opportunities for stable long-distance power transmission, especially between regions with different sources of electricity generation.

The introduction of multi-terminal DCT systems with a voltage of ± 800 kV, which combine several substations, as well as the development of hybrid systems that combine current and voltage converters, are new steps towards optimizing the power transmission network. This allows to significantly increase the transmission capacity to 11-12 GW, which is an important factor for ensuring reliable energy supply in countries with large territories. The study also shows that work is currently underway to eliminate technical limitations and improve the efficiency of DCT systems.

One of the promising areas for further research in the field of direct current electric power transport is the development of more efficient and economically feasible technologies for converting AC to direct current and vice versa. This is crucial for enhancing the overall efficiency and stability of DCT systems, as the ability to effectively convert between alternating and direct currents is fundamental for seamless integration into existing energy networks.

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AUTHOR CONTRIBUTIONS STATEMENT

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Akmaral Konarbayeva	✓		✓			✓		✓	✓		✓			✓
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C : Conceptualization

M : Methodology

So : Software

Va : Validation

Fo : Formal analysis

I : Investigation

R : Resources

D : Data Curation

O : Writing - Original Draft

E : Writing - Review & Editing

Vi : Visualization

Su : Supervision

P : Project administration

Fu : Funding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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