

### Раздел 3. «IT-технологии, энергетика, автоматизация и вычислительная техника»

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#### **HVDC Technologies: Operating Principles, Global Practices, and Prospects for Implementation in Qazaqstan**

High Voltage Direct Current (HVDC) technologies play a pivotal role in modern power systems by enabling efficient long-distance electricity transmission with minimal losses. This article explores the fundamental operating principles of HVDC systems, analyzes global implementation practices, and evaluates the prospects for deploying HVDC technologies in Qazaqstan. It highlights key technological trends, the advantages of HVDC over conventional alternating current (HVAC) systems, as well as the challenges associated with deployment. Drawing on the conducted analysis, this paper provides recommendations for integrating HVDC into Qazaqstan's power system, considering technical feasibility, economic viability, and environmental sustainability.

*Keywords:* HVDC, power transmission, energy sector, Qazaqstan, technologies, innovations, global practices, efficiency.

#### *Introduction*

High Voltage Direct Current (HVDC) transmission lines are gaining prominence due to their high energy efficiency and reliability [1]. Unlike traditional Alternating Current (HVAC) lines, HVDC systems enable long-distance power transmission with lower losses and facilitate the integration of renewable energy sources [2].

The application of HVDC is particularly relevant for countries with vast territories and remote generation sources, such as Qazaqstan. In recent years, Qazaqstan has been actively developing its energy infrastructure, aiming to enhance transmission efficiency and reduce its carbon footprint [3]. With the increasing penetration of renewable energy sources (RES), such as solar and wind power plants, HVDC presents an optimal solution for integrating them into the national power grid [4].

Moreover, Qazaqstan occupies a strategically important position between Europe, Russia, and China, making it a potential hub for cross-border energy projects based on HVDC technology [5]. Globally, major international HVDC interconnectors have already been implemented, ensuring power system stability and enabling electricity trade between countries [6]. Qazaqstan can draw upon this experience to strengthen its energy security and expand electricity exports.

The purpose of this paper is to review the operating principles of HVDC systems, examine global implementation practices, and assess the prospects for adopting this technology in Qazaqstan. The article discusses the advantages of HVDC over HVAC, the technological aspects of their deployment, as well as potential challenges related to financing and infrastructure development.

#### *Methods and Materials*

This study is based on an analysis of scientific publications dedicated to HVDC, including comparative studies on the efficiency of HVAC and HVDC systems [3, 5]. Materials from international organizations specializing in energy technologies were utilized, along with data on existing HVDC projects [4, 7].

#### *Results and Discussion*

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HVDC systems are designed for electric power transmission via direct current, which minimizes losses over long distances and enhances control over power flows [6]. The basic operating principle of HVDC involves converting alternating current (AC) into direct current (DC) at the sending end, transmitting it through the line, and then reconverting it into AC at the receiving end.

There are two main types of HVDC systems:

1. Line Commutated Converters (LCC-HVDC): These use thyristors that require a strong AC system for commutation. LCC-HVDC is widely used for interregional connections and long-distance bulk power transmission [8].

2. Voltage Source Converters (VSC-HVDC): These utilize insulated-gate bipolar transistors (IGBTs) or similar semiconductor switches, allowing them to operate without a strong AC grid. VSC technology provides more flexible power control and is commonly used for integrating renewable energy sources and linking power systems with different characteristics [9].

The key advantages of HVDC over traditional AC transmission:

- Reduced transmission losses over long distance.
- Independence from frequency synchronization between power systems.
- Capability to control power flow direction and volume.
- Enhanced power system stability due to rapid response to load changes [10].

HVDC technologies are currently being widely deployed across many countries, demonstrating their effectiveness in addressing long-distance transmission and renewable energy integration challenges. One of the global leaders in this area is China, which has implemented some of the world's largest HVDC lines connecting remote hydropower plants in the western regions to industrial hubs in the east. A notable example is the Ultra High Voltage Direct Current (UHVDC) project, capable of transmitting up to 12 GW of power over distances exceeding 3,000 km.

In Europe, HVDC is actively used to interconnect national power systems and ensure secure electricity supply. For instance, the NordLink project connects Germany and Norway, enabling bidirectional energy exchange between Norway's hydropower and Germany's wind energy. Such projects help balance the grid and mitigate fluctuations in renewable generation.

In North America, HVDC is applied in interstate energy corridors, such as the Pacific DC Intertie in the U.S, which links hydropower stations in the Northwest to major load centers in California. This project has significantly reduced dependence on conventional generation and improved power supply reliability.

HVDC is also employed in submarine interconnectors that link the power systems of different countries. Examples include the BritNed interconnector between the United Kingdom and the Netherlands, and the Baltic Cable between Sweden and Germany, demonstrating how HVDC enhances reliability and efficiency in international electricity trade.

Thus, global experience shows that HVDC technologies provide effective solutions for enhancing power system reliability, integrating renewable energy sources, and transmitting electricity over long distances. Qazaqstan can leverage these examples to develop its own HVDC implementation strategy.

Qazaqstan has significant potential for HVDC development due to its vast territory and large generation facilities [13]. The deployment of HVDC could facilitate the integration of renewable energy sources such as solar and wind power [14]. This technology would help reduce electricity losses during long-distance transmission and improve the reliability of power supply in remote regions.

One of the most promising areas is the creation of HVDC lines connecting major renewable energy clusters, such as those in the Zhambyl and Mangystau regions, with industrial centers in the central and eastern parts of the country. This would allow Qazaqstan not only to optimize domestic energy supply, but also to strengthen its position as an electricity exporter to Central Asian countries and China [15].

Another promising direction is the development of cross-border HVDC interconnectors. Qazaqstan could play a key role in establishing an energy corridor between Europe and Asia, linking the power systems of Russia and China via high-voltage direct current lines. This would expand electricity trade volumes and enhance the resilience of the national power system to external fluctuations [16].

However, successful HVDC implementation requires significant financing, infrastructure development, and training of qualified personnel. Government support programs and international investment will play a crucial role in this process. Qazaqstan has already launched several projects to modernize its energy system, and HVDC integration could become a pivotal step toward a more sustainable and efficient energy future [17].

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#### *Conclusion*

HVDC technologies represent a critical area in the development of modern power systems, offering high transmission efficiency and reduced energy losses. The implementation of HVDC in Qazaqstan would enable the integration of renewable energy sources, enhance the reliability of power supply, and strengthen the country's position in international energy trade. However, the successful realization of HVDC projects requires substantial investments, infrastructure modernization, and active involvement from both public and private sectors. If these conditions are met, Qazaqstan stands to significantly enhance its energy security and the resilience of its power system.

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#### **HVDC технологиялары: жұмыс істеу принциптері, әлемдік тәжірибе және Қазақстанда енгізу перспективалары**

Жоғары кернеулі тұрақты ток (HVDC) технологиялары заманауи энергетикада маңызды рөл атқарады, себебі олар электр энергиясын алыс қашықтықтарға тиімді және аз шығынмен жеткізуге мүмкіндік береді. Бұл мақалада HVDC жүйелерінің негізгі жұмыс істеу принциптері қарастырылады, әлемдік енгізу тәжірибесі талданады және Қазақстанда HVDC технологияларын дамыту перспективалары бағаланады. Негізгі технологиялық үрдістер, тұрақты токтың дәстүрлі айнымалы ток (HVAC) жүйелеріне қарағанда артықшылықтары және енгізу барысындағы мәселелер сипатталады. Жүргізілген талдау нәтижесінде Қазақстанның энергетикалық жүйесінде HVDC-ны қолдану бойынша техникалық, экономикалық және экологиялық аспектілерді ескере отырып ұсыныстар әзірленді.

*Түйінді сөздер:* HVDC, электр энергиясын жеткізу, энергетика, Қазақстан, технологиялар, инновациялар, әлемдік тәжірибе, тиімділік.

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#### **Технологии HVDC: принципы работы, мировая практика и перспективы внедрения в Казахстане**

Технологии высоковольтного прямого тока (HVDC) играют ключевую роль в современной энергетике, обеспечивая эффективную передачу электроэнергии на большие расстояния с минимальными потерями. В данной статье рассматриваются основные принципы работы HVDC, анализируется мировой опыт внедрения, а также оцениваются перспективы развития HVDC-технологий в Казахстане. Рассматриваются ключевые технологические тенденции, преимущества HVDC перед традиционными системами переменного тока (HVAC), а также проблемы внедрения. В результате проведенного анализа предложены рекомендации по применению HVDC в энергетической системе Казахстана с учетом технических, экономических и экологических аспектов.

*Ключевые слова:* HVDC, передача электроэнергии, энергетика, Казахстан, технологии, инновации, мировая практика, эффективность.

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