HVDC-Enabled Smart Grid Architecture for Long-Distance Renewable Power Transfer and Wide-Area Grid Interconnection

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***Abstract*—Conventional high voltage alternating current (HVAC) systems face technical limitations in transferring bulk renewable power over long distances, including transmission losses, reactive power limits, stability, and lack of control. To meet these challenges, the following smart grid architecture is proposed in this paper to enable the transfer of renewable power over long distances and to connect the grid across the entire country. In this context, this paper introduces an HVDC-enabled smart grid architecture for long-distance renewable power transfer and wide-area grid interconnection. The proposed architecture includes renewable energy sources, sending-end AC/DC converter stations, an HVDC transmission corridor, receiving-end DC/AC converter stations, receiving AC grid infrastructure, smart monitoring devices, communication networks, and SCADA/EMS-based control. The comparative investigation was performed in simulation mode for transmission distances ranging from 100 km to 1000 km, with a renewable energy power input of 1000 MW at the sending end. The assessment of the performance was done through the following metrics: transmission loss, power transfer efficiency, delivered renewable power, and extra renewable power delivered via HVDC. At 1000 km, HVAC loses 26.8%, while HVDC loses 15.0%. The efficiency of the power transfer has increased from 73.2% (HVAC) to 85.0% (HVDC). Likewise, the renewable power delivered rose from 732 MW to 850 MW, a rise of 118 MW of usable power delivered via HVDC. The results indicate that the HVDC smart grid architecture is technically better for long-distance renewable power transfer, grid controllability, and wide-area interconnection.**

Keywords— HVDC, smart grid, renewable power transfer, wide-area interconnection, HVAC, transmission loss, power transfer efficiency, SCADA/EMS

I. INTRODUCTION

Modern power systems face new challenges because of the rapid growth of renewable energy generation, rising electricity demand, and the need for efficient and reliable long-distance power transfer. Traditional power systems focus primarily on centralized generation and unidirectional electricity transmission from the power generation station to the load centre. The current energy landscape is increasingly complex, however, as the large-scale wind farms, solar photovoltaic parks, offshore renewable resources, and remote hydro resources are increasingly sited distant from major urban and industrial demand centres. This geographical separation necessitates advanced power transmission systems, which can transmit power over long distances with minimal losses and in large quantities [1].

Recent advancements in renewable energy systems and smart-grid-supporting technologies have further enhanced power system efficiency, thermal management, and operational sustainability in modern energy networks [2]. The smart grid is a combination of electrical infrastructure and digital communication, automation, sensors, protection systems, power electronic converters, and energy management platforms. They enable the monitoring and control of energy across the area, fault detection, coordination of renewable energy, and the efficient dispatch of energy in real time. There has been a recent emphasis on the importance of smart grid modernization to allow the integration of renewable energy resources, managing variable power generation, and supporting future power system transformation [3] [4]. Sustainable energy infrastructure and advanced energy storage technologies are increasingly recognized as essential components for improving renewable

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energy utilization and supporting future low-carbon power systems [5] [6].

High-Voltage Direct Current (HVDC) transmission has emerged as an important technology for the development of smart grids due to its characteristics of long-distance transmission of bulk power with less power loss and better control performance than high-voltage alternating current (HVAC) transmission. HVDC systems are particularly beneficial for interconnection of remote renewable energy areas, offshore wind farms, islanded or weak grids, and regional power networks. HVDC transmission does not have reactive power constraints and frequency synchronization problems over long-distance transmission and is more suitable to long-distance power system interconnection [7] [8].

Further growth is expected for HVDC as the hybrid AC/DC grids, multi-terminal HVDC systems, voltage source converter (VSC)-based HVDC systems, and meshed DC networks develop. These technologies enable flexible power flow control, asynchronous operation of the grid, and better integration of renewable energy sources. Distributed Optimal Power Flow (OPF) techniques for VSC-MTHDC have been demonstrated to enhance the power transfer capability and grid operation in multi-terminal AC/DC power systems [9]. Likewise, hybrid AC/DC transmission planning studies have been conducted previously, revealing that HVDC transmission lines and HVAC-to-HVDC conversion can contribute to power system expansion in the presence of high levels of renewable energy penetration [10].

Another key aspect of HVDC smart grid architecture is converter technology. By employing a modern voltage source converter (VSC) and grid-forming converter (GFC), the voltage control, active and reactive power management, and stable operation between AC-DC networks can be enhanced. Advanced converter control in hybrid AC/DC grids has been shown to play a key role in ensuring stable grid operation and reliable interconnection in recent research [11]. Therefore, in addition to the transmission lines, the HVDC-enabled smart grid must have intelligent converter stations, protection schemes, monitoring systems, and communications.

In addition to power transfer, continuous sensing, monitoring, and control are essential for HVDC smart grids. The HVDC environment is characterized by high voltage, a high level of electromagnetic interference, strict insulation requirements, and a severe operating environment. Reliable sensor power supply and communication are critical for safe grid operations in these conditions. Huang et al. [12] presented the laser wireless power transfer system for powering sensors in HVDC smart grids and highlighted that HVDC is an important technology to realize modern smart grids because of its ability to transmit power over long distances with high efficiency, flexible renewable energy integration, and regional interconnection. Their work also highlighted the importance of reliable sensing and monitoring in an HVDC environment.

While several recent studies have addressed the integration of renewable energy sources, the change from HVAC to HVDC transmission, and the converter control, there is a need for an architecture-level study that directly compares the possibility of transferring renewable energy over long distances using HVAC or HVDC transmission. A large number of studies have been conducted on topics like the modeling of converters, weak-grid interconnection, transmission expansion planning, or even sensor support. There, however, must be an obvious smart-grid-oriented framework that demonstrates the benefits of HVDC architecture in terms of reduced transmission losses, increased power transfer efficiency, renewable power delivery, and wide-area interconnection capability.

Thus, the present work offers an HVDC-based smart grid structure for the interconnection of long-distance renewable power networks and wide-area power networks. The proposed architecture consists of renewable energy resources, SEND AC/DC conversion, an HVDC transmission link, receiving-end DC/AC conversion, a receiving AC grid, smart monitoring units, a communication network, and a SCADA/EMS control center. A simulation-based evaluation is carried out for HVAC and HVDC transmission with lengths of 100km, 500km, and 1000km. The analysis takes into account transmission loss, power transfer efficiency, delivered renewable power, and extra renewable power delivered via HVDC.

The key novelty of this article lies in the development of a structured HVDC-enabled smart grid architecture and its evaluation based on measurable performance indicators. The study indicates that power losses in long-distance transmission can be reduced, delivered renewable power can be enhanced, and it is possible to enable wide-area grid interconnections using HVDC transmission. Section 2 gives an overview of the literature, section 3 explains the methodology and modeling framework, section 4 talks about the simulation results, and section 5 sums up the main findings and suggests areas for future research.

II. METHODOLOGY

This research used a simulation-based comparative research method to assess the feasibility of an HVDC-based smart grid architecture for long-distance renewable power transfer and wide-area grid interconnection. The proposed system comprised renewable energy sources, a sending-end AC/DC converter station, an HVDC transmission line, a receiving-end DC/AC converter station, a receiving-end AC grid, smart monitoring devices, communication facilities, and a control center equipped with SCADA/EMS. The overall methodology was developed to compare the performance of conventional HVAC transmission with HVDC transmission for the transportation of bulk renewable power over various transmission distances.

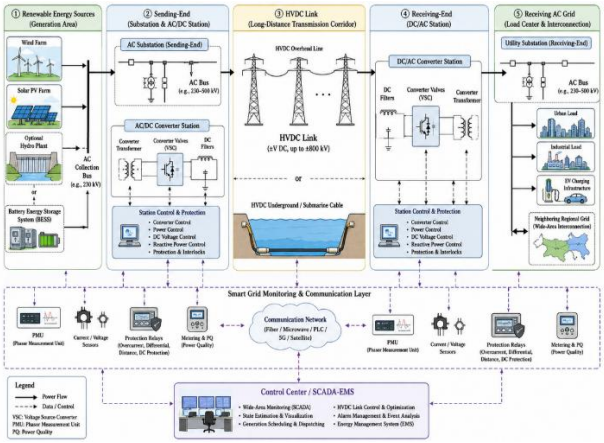

Fig. 1. Methodological workflow for evaluating HVDC-enabled smart grid architecture

The proposed architecture is depicted in figure 1. The sending end comprised renewable energy power plants, including wind farms, solar photovoltaic farms, an optional hydro generation point, and battery energy storage systems (BES) linked to an AC collection bus. The AC power collected was fed to a sending-end substation from which it was converted to DC at an AC/DC converter station. The HVDC link transmitted the converted power via HVDC cables (or overhead lines) over a long-distance transmission line. The received DC power was transformed back into AC power at the receiving DC/AC converter station and fed to the receiving AC grid, which consisted of urban loads, industrial loads, electric vehicles charging stations, and neighboring regional grids. A monitoring and communication layer for a smart grid was added for reliable operation. These units were phasor measurement units, current and voltage sensors, protection relays, metering devices, power quality monitoring units, communication networks, and a control center. The control center was assumed to be responsible for wide area monitoring, state estimation, generation scheduling, HVDC link control, alarm management, and energy management by implementing SCADA. This monitoring layer is vital because the operation of HVDC smart grids is conducted under high-voltage and electromagnetic environments, where the main requirement is reliable sensing and communication. The base article also notes the significant role HVDC plays in the modern smart grid: flexibility, long-distance transmission efficiency, renewable integration, and interconnection between regions are just a few of the attributes that make HVDC so essential in modern smart grids, and the reliability of sensing support is a critical requirement in HVDC environments.

To compare the HVAC and HVDC transmission performance in the comparison of long-distance renewable power transfer, a simulation-based dataset was developed. The distance of the transmission was changed from 100 km to 1000 km in 100 km steps. For all cases, it was assumed that a 1000 MW renewable power input could be sent from the sending end. The delivered power at the receiving end was determined using the transmission efficiency of each system.

The main variables used in the simulation were defined as follows:

- D=transmission distance in km
- P_{in} = renewable power injected at the sending end
- L_{AC} = transmission loss of HVAC system
- L_{DC} = transmission loss of HVDC system
- η_{AC} = power transfer efficiency of HVAC system
- η_{DC} = power transfer efficiency of HVDC system
- $P_{AC,out}$ = renewable power delivered through HVAC
- $P_{DC,out}$ = renewable power delivered through HVDC

The study assumed , $P_{in} = 1000\ MW$.

The values of HVAC and HVDC losses were used to calculate efficiency and delivered power at each transmission distance.

The HVAC and HVDC systems were modelled separately to calculate the amount of renewable power delivered to the receiving grid. In the HVAC model, renewable power was transmitted through a conventional AC transmission system. In the HVDC model, renewable power was first converted to DC at the sending-end converter station, transmitted through the HVDC link, and then converted back to AC at the receiving-end converter station.

The transmission efficiency was calculated using:

$$\eta = 100 - L \tag{1}$$

Where,

η = power transfer efficiency

L = transmission loss percentage

For HVAC transmission:

$$\eta_{AC} = 100 - L_{AC} \tag{2}$$

For HVDC transmission:

$$\eta_{DC} = 100 - L_{DC} \tag{3}$$

The delivered renewable power was calculated as:

$$P_{out} = P_{in} \times \frac{\eta}{100} \tag{4}$$

Therefore, the delivered power through HVAC was:

$$P_{AC,out} = P_{in} \times \frac{\eta_{AC}}{100} \tag{5}$$

The delivered power through HVDC was:

$$P_{DC,out} = P_{in} \times \frac{\eta_{DC}}{100} \tag{6}$$

To evaluate the advantage of HVDC over HVAC, the additional renewable power delivered through HVDC was calculated. This value represents the extra usable renewable power received at the load centre when HVDC is used instead of HVAC.

$$P_{add} = P_{DC,out} - P_{AC,out} \tag{7}$$

Where,

P_{add}= additional renewable power delivered by HVDC

$P_{DC,out}$= renewable power delivered through HVDC

$P_{AC,out}$ = renewable power delivered through HVAC

A higher value of (P_{add}) indicates greater benefit of HVDC transmission for long-distance renewable power transfer.

The performance of the proposed architecture was evaluated using the following indicators. Transmission loss represented the percentage of generated renewable power lost during transmission.

$$L = \frac{P_{loss}}{P_{in}} \times 100 \tag{8}$$

Power transfer efficiency represented the percentage of sending-end renewable power successfully delivered to the receiving grid.

$$\eta = \frac{P_{out}}{P_{in}} \times 100 \quad (9)$$

Delivered renewable power represented the usable power received at the load centre after transmission losses.

$$P_{out} = P_{in} - P_{loss} \quad (10)$$

The percentage-point reduction in transmission loss achieved by HVDC was calculated as:

$$L_{red} = L_{AC} - L_{DC} \quad (11)$$

The percentage-point improvement in power transfer efficiency was calculated as:

$$\eta_{imp} = \eta_{DC} - \eta_{AC} \quad (12)$$

The additional delivered renewable power was calculated as:

$$P_{add} = P_{DC,out} - P_{AC,out} \quad (13)$$

These metrics were used to analyse the results shown in the transmission loss graph, efficiency graph, delivered renewable power graph, additional delivered power graph, and the 1000 km performance summary.

III. Results and Discussion

A simulation-based comparative model of the proposed smart grid architecture with HVDC was used to evaluate it. The analysis considered long-distance renewable power transmission, ranging from 100km to 1000km. A renewable power sending end of 1000 MW was assumed, and the transmission loss, power transfer efficiency, renewable power delivered, and additional renewable power delivered via HVDC were compared to show the performance of HVAC and HVDC transmission. The results validate the viability of using HVDC architecture for long-distance renewable power transfer and wide-area grid interconnection.

The comparison of transmission loss between HVAC and HVDC systems for various transmission distances is shown in fig. 2. The results reveal that in both systems, the transmission loss is observed as a function of distance. The HVAC system has a greater rate of increase than the HVDC system, however. The HVAC system had 4.5% loss at 100 km, and the HVDC system had a lower loss of 3.2%. With an increasing distance of 1000 km, the transmission loss of HVAC rose to 26.8%, while the transmission loss of HVDC remained capped at 15.0%.

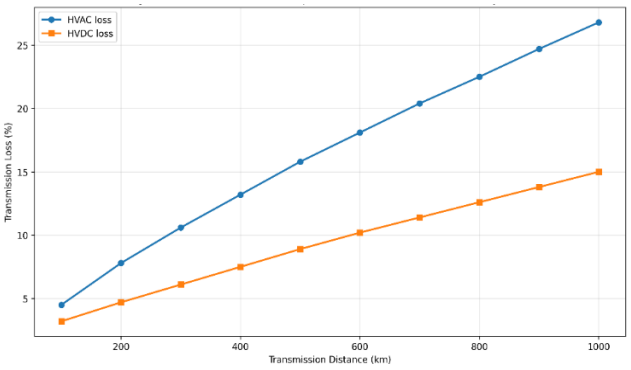

Fig. 2. Transmission loss comparison between HVAC and HVDC systems

This result shows that HVDC transmission is more appropriate for long-distance bulk power transmission due to the reduction in cumulative transmission losses. HVDC's low loss characteristics are especially significant for renewable energy facilities in remote locations from load centers like offshore wind farms, desert solar power farms or distant hydroelectric power stations. The discovery reinforces the HVDC's ability to be an enabler of modern smart grids, particularly in the context of long-distance transmission of renewable energy and regional interconnection.

Fig. 3 shows the variation in power transfer efficiency with increasing transmission distance. Both HVAC and HVDC systems operated at reasonably high efficiency at shorter distances. However, as the transmission distance increased, HVAC's efficiency decreased more rapidly than that of HVDC. The efficiency of the HVAC increased from 100 km to 95.5% and the HVDC to 96.8%. The efficiency of HVAC dropped to 73.2% at 1000 km, while HVDC remained at 85.0%.

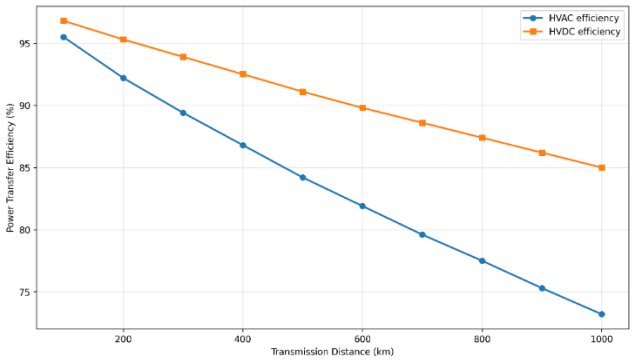

Fig. 3. Power transfer efficiency under different transmission distances

The difference in efficiency becomes more significant at longer distances. At 1000 km, HVDC achieved an efficiency improvement of 11.8 percentage points compared with HVAC. This demonstrates that HVDC transmission can preserve a larger portion of generated renewable power during long-distance transfer. Therefore, HVDC-enabled architecture is more appropriate for smart grid applications that require high-capacity and long-distance renewable power delivery.

Fig. 4 illustrates the amount of renewable power delivered to the receiving grid after transmission losses. Since the sending-end renewable power was assumed to be 1000 MW, delivered power was calculated according to the transmission efficiency of each system. At 100 km, HVAC delivered 955 MW, while HVDC delivered 968 MW. As distance increased, the delivered power decreased in both cases due to rising transmission losses.

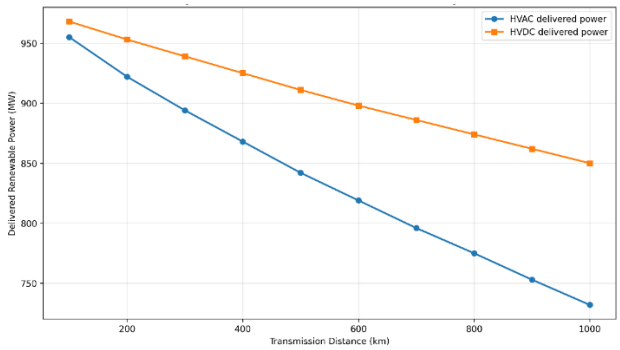

Fig. 4. Renewable power delivered to the receiving grid

At 1000 km, the HVAC system delivered only 732 MW, whereas the HVDC system delivered 850 MW. This means that HVDC delivered an additional 118 MW of usable

renewable power compared with HVAC at the same distance. This result is important because even a small percentage improvement in transmission efficiency can produce a large absolute power gain in high-capacity renewable power corridors. Hence, HVDC technology can improve renewable energy availability at the receiving-end grid and support more reliable power supply to urban, industrial, and regional load centres.

Fig. 5 presents the additional renewable power delivered by HVDC compared with HVAC at different transmission distances. The additional delivered power increases continuously as the transmission distance increases. At 100 km, HVDC delivered 13 MW more power than HVAC. At 500 km, the additional delivered power increased to 69 MW. At 1000 km, the additional renewable power delivered through HVDC reached 118 MW.

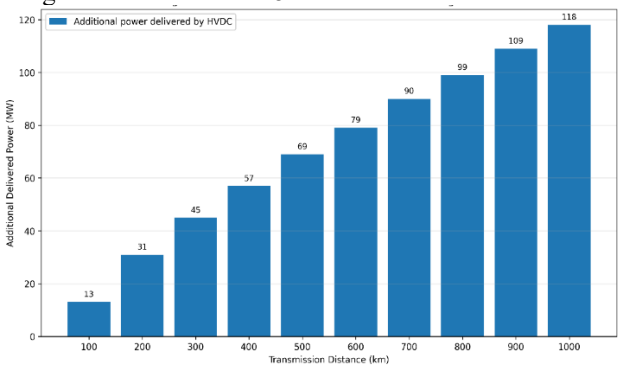

Fig. 5. Additional renewable power delivered through HVDC transmission

This trend confirms that the benefit of HVDC becomes more pronounced at longer transmission distances. For large-scale renewable energy integration, this additional delivered power can reduce energy wastage, improve grid utilization, and support wider interconnection between generation areas and demand centers. Therefore, HVDC-enabled smart grid architecture provides a stronger technical foundation for long-distance renewable energy corridors.

Fig. 6 summarizes the key performance indicators at a transmission distance of 1000 km. The HVAC system recorded a transmission loss of 26.8%, while the HVDC system reduced the loss to 15.0%. Similarly, the power transfer efficiency improved from 73.2% in the HVAC system to 85.0% in the HVDC system. For a 1000 MW renewable power input, the delivered power increased from 732 MW under HVAC transmission to 850 MW under HVDC transmission.

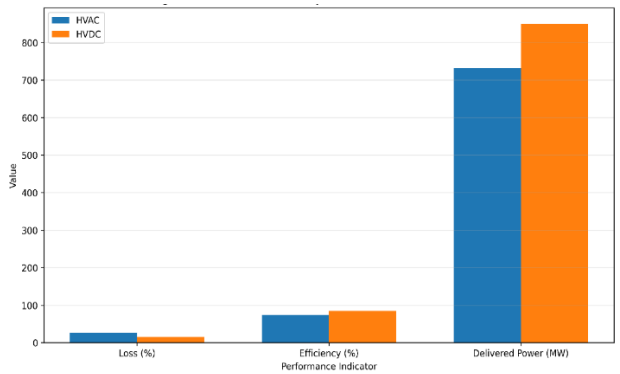

Fig. 6. Performance summary of HVAC and HVDC systems at 1000 km transmission distance

These findings clearly demonstrate the advantage of HVDC for long-distance renewable power transfer. The reduced transmission loss and improved delivered power indicate that HVDC can enhance the effectiveness of smart grid interconnection. The base reference also supports this direction by describing HVDC as a key enabling technology for smart grids because of its suitability for long-distance transmission, renewable energy integration, system flexibility, and regional interconnection.

The overall comparison between HVAC and HVDC transmission is presented in Table 1. The results confirm that HVDC-enabled smart grid architecture provides better performance for long-distance renewable energy transfer.

TABLE I. COMPARISON BETWEEN HVAC AND HVDC TRANSMISSION

Performance Indicator	HVAC System	HVDC-Enabled Smart Grid	Improvement
Transmission loss at 1000 km	26.8%	15.0%	11.8 percentage-point reduction
Power transfer efficiency at 1000 km	73.2%	85.0%	11.8 percentage-point increase
Delivered renewable power at 1000 km	732 MW	850 MW	118 MW additional delivered power
Long-distance transfer capability	Moderate	High	Improved
Wide-area grid interconnection	Limited by AC stability constraints	Better controllability	Improved
Renewable power utilization	Lower	Higher	Improved

The simulation results show that HVDC transmission is more efficient than HVAC transmission for long-distance renewable power transfer. The HVDC-enabled smart grid architecture reduces transmission losses, increases delivered renewable power, and supports stronger wide-area grid interconnection. These advantages make HVDC a suitable technology for smart grid modernization, especially in systems where renewable generation is located far from major load centers.

IV. CONCLUSION

This research has introduced an HVDC smart grid architecture for long-distance renewable power transfer and wide-area grid interconnection. The proposed architecture includes renewable energy generation, AC/DC conversion at the sending end, an HVDC transmission corridor, DC/AC conversion at the receiving end, infrastructure for the receiving AC grid, smart monitoring devices, a communication network, and SCADA/EMS-based control. The primary aim of the study was to assess the feasibility of HVDC transmission for bulk power transmission from remote generation sites to load centers further away. A simulation-based evaluation was performed to make a comparison between HVAC and HVDC transmission over a 100 km to 1000 km distance, considering a sending end renewable power input of 1000 MW. The results indicated that HVDC

transmission had superior performance to HVAC transmission at a longer distance. The HVAC system experienced 26.8% transmission loss at a 1000 km distance, while the HVDC system had 15.0% transmission loss at the same distance. Likewise, the efficiency of the power transfer was enhanced from 73.2% to 85.0% for the HVAC system and the HVDC system, respectively. The delivered renewable power also rose from 732 MW for HVAC transmission to 850 MW for HVDC transmission, representing an additional 118 MW of usable renewable power via HVDC.

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