GREEN POWERED FUTURE
MISSION

NOVEL DC SOLUTION FOR EFFECTIVE RENEWABLE ENERGY INTEGRATION

GPFM INSIGHT REPORTS OF INNOVATION PRIORITIES

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ABOUT GPFM

Mission Innovation (MI) is a concept of multilateral cooperation in the field of clean energy that was initiated by multinational leaders at COP21 in 2015. In order to strengthen international scientific and technological cooperation and accelerate technological innovation in new power systems, the Green Powered Future Mission (GPFM) was launched as one of the first-wave Missions in MI's Second Phase (2021-2030).

The Mission, co-led by China, Italy and the UK, aims to "demonstrate that by 2030, power systems in different geographies and climates can efficiently integrate up to 100% variable renewable energies (VRE), like solar and wind, in their generation mix, and maintain a cost-efficient, secure and resilient system," with a focus on affordable and reliable VRE, system flexibility and market design, data and digitalisation for system integration.

INTRODUCTION

Currently, there are two primary methods for collecting and transmitting power from renewable energy (RE) power generation systems:

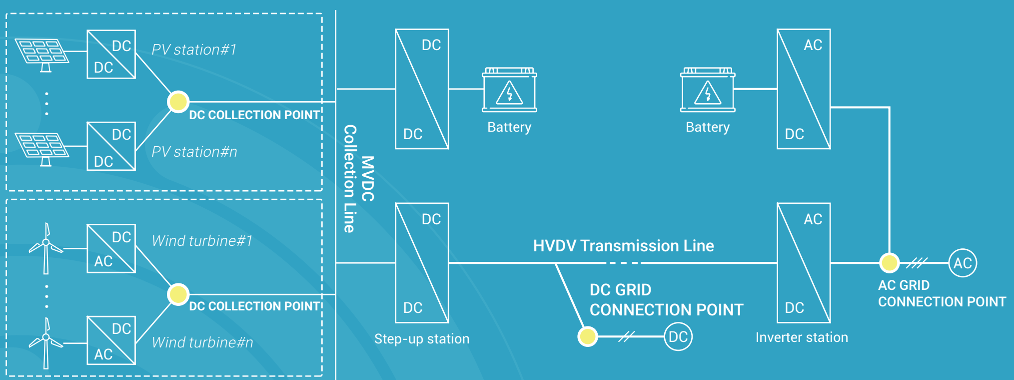
- AC Collection - AC Transmission: Alternating current (AC) is collected and transmitted directly.
- AC Collection - DC Transmission: Alternating current is collected and then converted to direct current (DC) for transmission.

This report introduces a novel approach: DC Collection - DC Transmission. This method involves collecting variable low-voltage DC electricity generated by wind or photovoltaic (PV) systems. This DC electricity is then converted into stable medium-voltage or high-voltage DC electricity using DC/DC converters, enabling collection and transmission without the need for a low-frequency AC link.

This report provides a comprehensive investigation into the key technologies of RE DC collection and DC transmission systems. By examining the current state-of-the-art, challenges, advancements, and future trends of relevant technical areas, this report aims to offer recommendations and strategies to drive technological progress, enhance engineering practices, and stimulate industry growth. Additionally, by analyzing case studies of demonstration systems, this report seeks to further these goals.

1) BENEFITS

- No phase stabilty problems as AC system.
- No reactive power compensation.
- Fewer conversion parts and high efficiency.



2) KEY FACTORS

- Fundamental theory breakthrough.
- Technological maturity.
- Cost of the critical equipment.
- Growing installation of renewable energy.
- Increase in DC application scenarios.

3) IMPLEMENTATION

- Stability analysis methods.
- System architecture.
- High-efficiency high-reliability DCDC converter.
- System operation control technology.
- Low coat fault prtection equipment

CHAPTER I
CONTRIBUTION TO POWER SECTOR TRANSFORMATION

The main technical routes for RE generation and grid integration systems include hybrid AC-DC grid systems, line-commutated converter high-voltage direct current (LCC HVDC) transmission, low-voltage direct current (LVDC) transmission, flexible DC transmission (VSC-HVDC), and AC microgrid systems. Each route has distinct characteristics and advantages concerning application scenarios, voltage levels, power capacity, and system efficiency.

A hybrid AC-DC grid system refers to the simultaneous operation of AC and DC transmission between two AC power systems. In this setup, both AC and DC transmission lines are connected in parallel. The starting points of AC and DC transmission can be the same in the sending-end power grid or located at different points. Similarly, the endpoints can either be at different locations in the receiving-end power grid or at the same point, as shown in Figure 1.

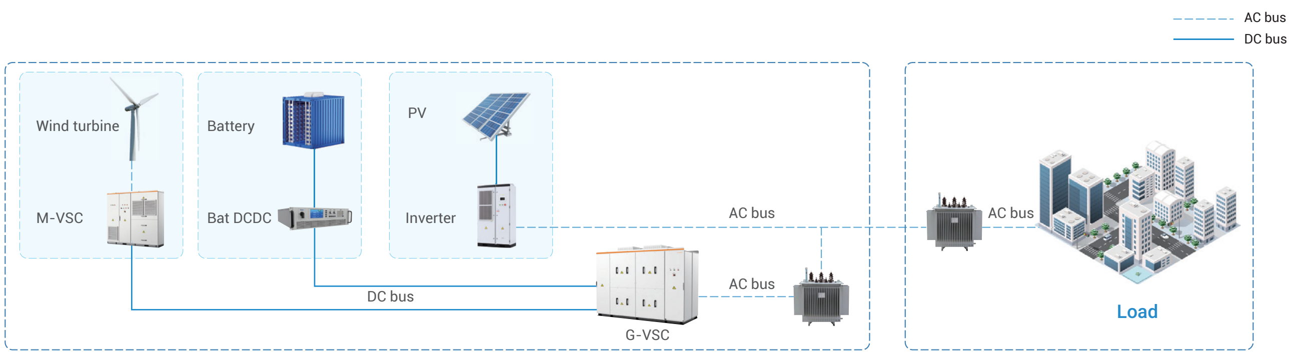


FIGURE 1: HYBRID AC-DC GRID SYSTEM

The working principle of LCC HVDC system is to rectify three-phase AC power into DC power through a converter station, and then send it to another converter station through a DC transmission line, and then reverse it into three-phase AC power show as figure 2.

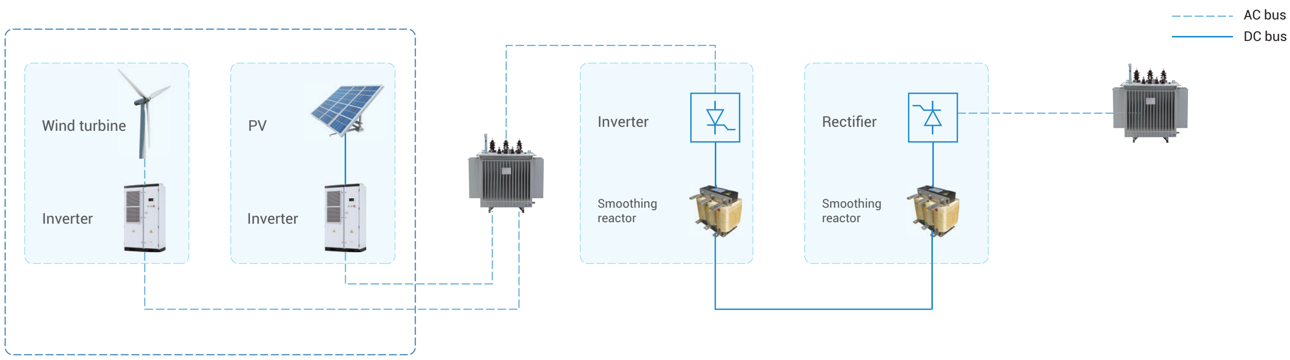


FIGURE 2: LCC HVDC SYSTEM

LVDC system is an independent power source used to provide DC power for signal equipment, protection, automatic devices, etc. It has the characteristics of "comprehensive perception, information sharing, digital intelligence, source load interaction, flexible and efficient", and has two main operating modes: full DC ecological operation mode and AC/DC common bus mode. The system achieves stable, reliable, green, efficient, and intelligent operation of the power grid through monitoring, protection, control, automation, distributed energy access, energy storage, and intelligent control technologies, as shown in figure 3.

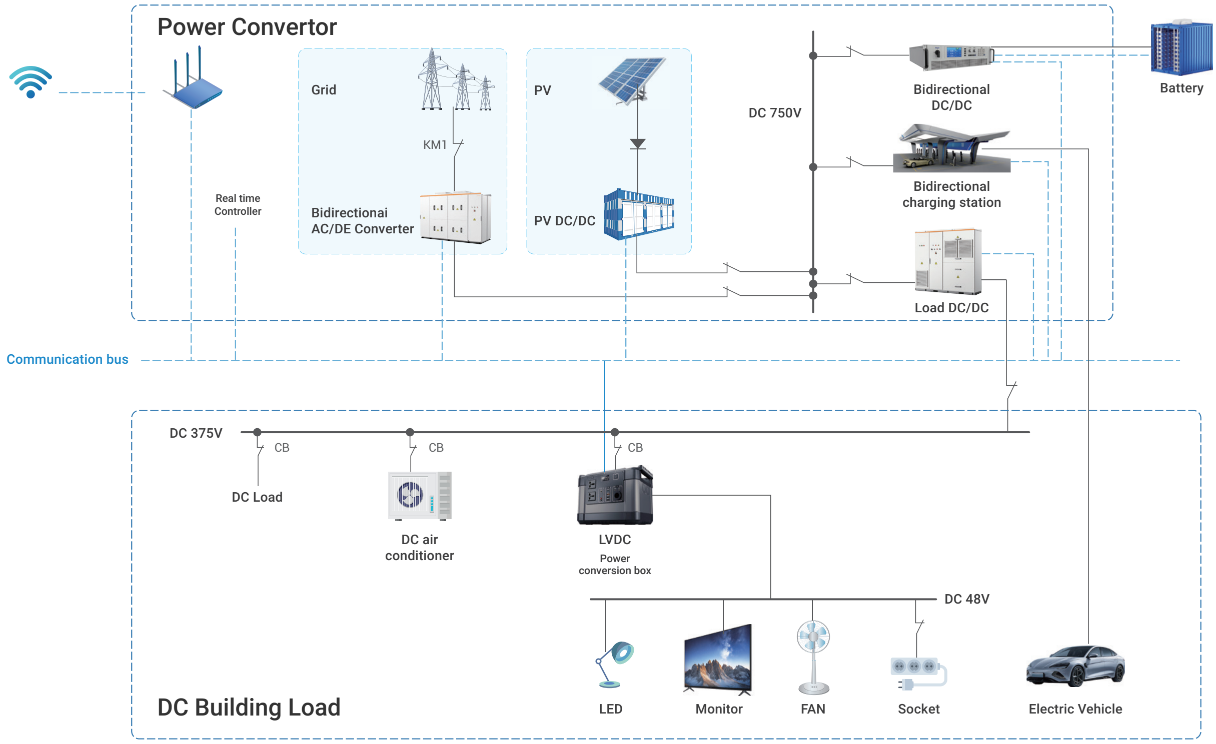


FIGURE 3: LVDC SYSTEM

VSC-HVDC (Voltage Source Converter High Voltage Direct Current Transmission) system is an advanced power transmission technology, whose core principle is based on Voltage Source Converter (VSC) to achieve direct current transmission. The working principle of VSC-HVDC system is to convert alternating current into direct current through a voltage source converter and transmit power through a direct current transmission line, as show in figure 4.

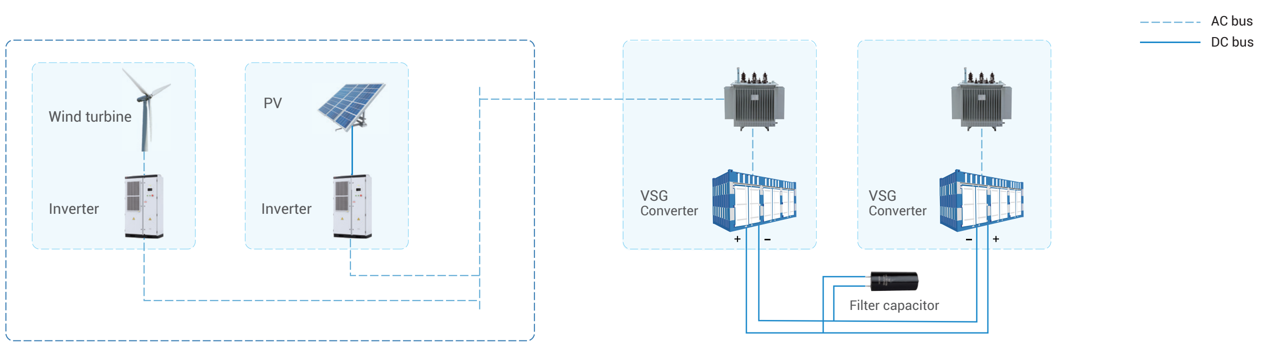


FIGURE 4: VSC-HVDC SYSTEM

AC microgrid is a micro power system composed of multiple small power systems, which are connected to form a large, mutually supportive power system. It adopts distributed generation, which can improve the reliability and power supply quality of the power system, as shown in figure 5.

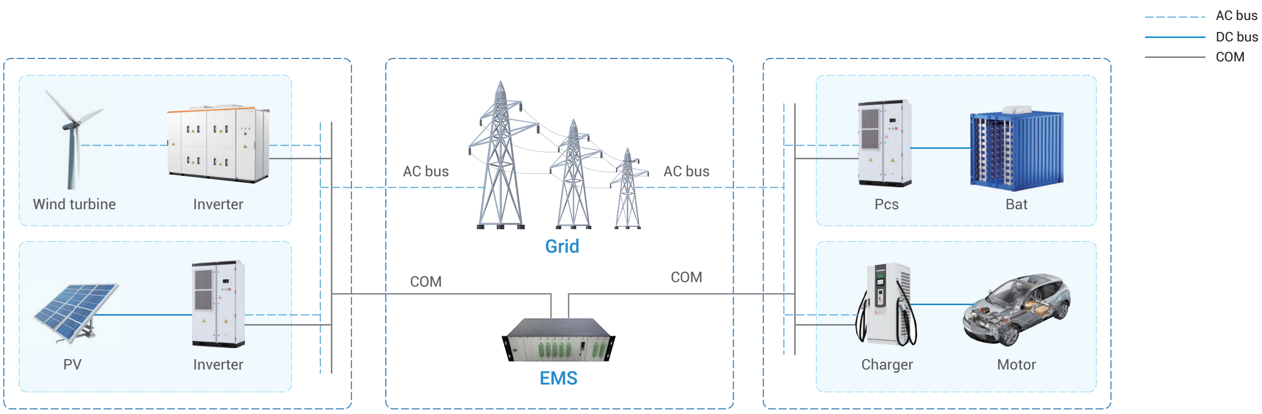


FIGURE 5: AC MICROGRID SYSTEM

Table 1. The mainstream technical routes for RE generation and grid integration systems

System	Description
Hybrid AC-DC Grid System	• These systems combine AC and DC technologies and are suitable for long-distance transmission scenarios, such as wind and solar power plants located far from load centers. • Voltage levels are typically 220 kV and above, with power capacity ranging from several megawatts to gigawatts.
LCC-HVDC System	• For long-distance power transmission. • Widely used in offshore wind farms and large-scale solar power plants transmitting electricity to load centers. • Voltage levels are typically 500 kV and above, with power capacity ranging from hundreds of megawatts to gigawatts.
LVDC System	• Primarily used in distributed energy systems and microgrids, including small-scale PV plants and mini wind farms. • Voltage levels range from 400V to 1.5 kV, with power capacity from kilowatts to megawatts.
VSC-HVDC System	• Based on voltage-source converters. • Suitable for integrating RE sources like wind and solar into multi-terminal DC grids. • Voltage levels typically range from ±320 kV to ±800 kV, with power capacity from hundreds of megawatts to gigawatts.
AC Microgrid System	• These small-scale grids use AC technology and are suitable for isolated operation or grid-connected distributed energy systems. • Voltage levels are typically low (below 400V) or medium (10 kV to 35 kV), with power capacity from kilowatts to tens of megawatts.

CHAPTER II

TECHNOLOGY FEASIBILITY TO INTEGRATE RE INTO GRID WITH DC

Each technical route exhibits its own advantages and disadvantages in different application scenarios.

Table 2. Application scenarios of the mainstream technical routes

System	Applicable scenarios	Challenges
Hybrid AC-DC Grid System	Suitable for long-distance transmission and various grid structures	System complexity and cost
LCC-HVDC Transmission	Suitable for long-distance, high-power transmission, such as offshore wind farms and large scale PV plants	Initial investment and maintenance costs.
LVDC Transmission	Suitable for small-scale distributed energy systems	Lack of technical standards, fault isolation and protection issues.
VSC-HVDC	Suitable for complex grid structures	VSC-HVDC excels in adaptability and multi-terminal connections.
AC Microgrid System	suitable for isolated or grid-connected distributed energy systems	The impact of high proportion and high uncertainty distributed RE is enormous.

As there are many technical routes for RE generation and grid integration systems, the different technology has its advantages and disadvantages.

Table 3. Advantages and disadvantages of the mainstream technical routes

System	Description
Hybrid AC-DC Grid System	• While these systems offer high efficiency, the multiple conversion processes can impact overall efficiency. • Advantages include flexibility, compatibility with various grid structures, and low transmission losses over long distances. However, they are complex and have higher conversion equipment costs.
LCC-HVDC System	• HVDC offers high transmission efficiency due to low DC losses. However, initial investment costs are high, and maintenance can be complex.
LVDC System	• Although LVDC systems have relatively higher transmission losses due to lower voltage, they remain efficient for short-distance transmission. • Advantages include simplicity, low cost, and suitability for small-scale distributed energy systems. However, transmission distance is limited.
VSC-HVDC System	• VSC-HVDC offers rapid control and adaptability, high system efficiency, and compatibility with complex grid structures. However, it comes with higher costs and technical complexity.
AC Microgrid System	• Provide good compatibility and flexibility for diverse energy sources. • Advantages include simplicity, adaptability, and strong compatibility. • Long-distance transmission efficiency may be lower, requiring frequent voltage and frequency adjustments.

Choosing the right technology depends on practical needs, including considerations of efficiency, cost, application scenarios, technical complexity, and operational maintenance. As technology advances and market demand grows, these routes will be further optimized to support efficient integration of RE.

In areas with abundant sunlight (approximately 1200 hours per year), a conventional 5 MW AC PV power plant generates around 6 million kWh annually. By implementing a PV DC boosting system, which improves efficiency by approximately 5%, the annual electricity generation can increase by 300,000 kWh. Over the system's lifespan, compared to a conventional PV power plant, this approach can save a cumulative total of 2700 metric tons of standard coal, reduce carbon dioxide emissions by 7192.5 metric tons, decrease sulfur dioxide emissions by 48.75 metric tons, and lower nitrogen oxide emissions by 24 metric tons.

Large-scale PV power generation stations can aggregate advantageous resources, leverage economies of scale, and significantly reduce electricity generation costs. They are a crucial direction for RE generation. In conventional AC power systems, there are issues such as harmonic resonance, three-phase imbalance, and reactive power compensation at the grid's margins. Large-scale PV power stations are often located at the periphery of the grid, where stability issues related to harmonic resonance and sub-synchronous oscillations frequently arise when using AC grid connection technology. Therefore, a more reliable technical solution is urgently needed.

Some power plants use flexible DC transmission technology, but it has complex structures, multiple conversion stages, lower efficiency, and higher costs. Research and development are necessary to create a simple, efficient, and autonomously controllable new DC collection system.

Furthermore, the grid integration cost of large-scale PV power plants increases by more than 30% in high-altitude areas compared to flat regions. Medium-voltage (MV) DC collection and grid integration technology in large PV power stations involve boosting the low-voltage DC output from PV arrays to medium or high-voltage DC for collection and connection, as shown in Figure 6. Medium-voltage (10kV~50kV) DC collection and grid integration are the future trends, offering potentially fewer conversion stages, no harmonic resonance, and no reactive power transmission issues. This approach covers a wider collection range and longer transmission distances, reducing system equipment and cable requirements by over 30% and improving system efficiency by 4%-6%. This method is more conducive to aggregating advantageous resources, leveraging economies of scale, reducing electricity generation costs, and providing a simpler, more efficient, and stable solution.

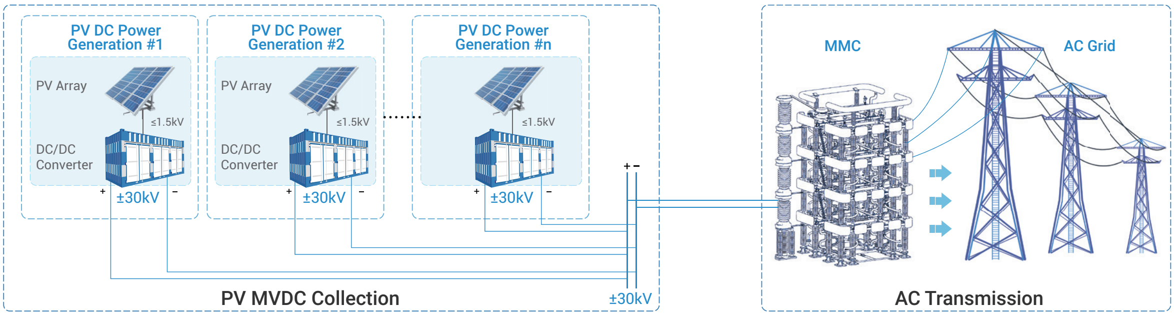


FIGURE 6: STRUCTURE OF THE PV DC BOOST COLLECTION AND GRID CONNECTION SYSTEM

Figure 7 compares two technical schemes for RE power plants: AC grid connection and full DC grid connection. Currently, large-scale collection of new energy primarily adopts the AC collection method, as illustrated in Figure 7(a). PV and wind turbine (WT) systems are connected to the step-up transformer through various multi-stage transformations such as DC-DC and DC/AC conversions. Alternatively, PV and WT systems are consolidated and connected to the step-up transformer after low-voltage AC collection, enabling the grid connection of new energy sources.

In contrast, the DC collection technology route is shown in Figure 7(b). Here, PV and WT systems are connected to the medium and high voltage DC grid through AC/DC and DC/DC boosting. Alternatively, these systems can be collected through a low voltage DC bus and then transmitted uniformly through a large capacity DC-DC boosting converter.

Compared to AC collection methods, DC collection technology can reduce the number of power electronic equipment and high-cost isolation transformers. From an economic perspective, whether transitioning from low voltage to medium voltage or from medium voltage to high voltage, the cost of using DC grid connection converters is higher than that of using AC grid connection inverters. Additionally, this does not account for the extra costs associated with numerous DC circuit breakers required in the internal collection system when using medium-voltage DC.

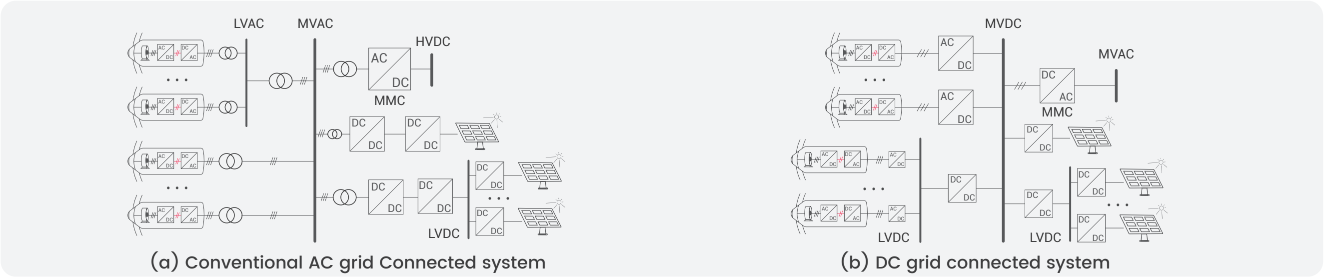


FIGURE 7: COMPARISON OF TWO GRID CONNECTED SYSTEMS

Overall, the new energy DC grid connected system exhibits the following characteristics.

Table 4. Characteristics of the RE DC system

Operating scenario	Characteristics
Small-Scale Distributed RE	Connecting to voltage levels around ±10 kV
	Systems are suitable for localized applications
Large-Scale RE	Systems may operate at voltage levels around ±30 kV
	Systems are likely to be part of grid-scale projects.
Challenges	Developing efficient and cost-effective DC boost transformer technology from low voltage to high voltage
	Achieving higher efficiency and lower costs is crucial
	Long-term operation is necessary to validate reliability
DC Transformer Volume Requirements	Interestingly, in RE grid integration scenarios, the volume requirements for DC transformer devices are not particularly stringent

However, DC grid integration systems for RE still face several challenges and complexities.

- **Efficiency and Cost of Converters**

  Enhancing converter efficiency and reducing costs are critical for overall system feasibility

  High-efficiency converters minimize energy losses and mitigate heat dissipation issues

  Achieving cost-effective solutions is essential for widespread adoption

- **Reliability of High-Voltage, High-Power Equipment**

  Ensuring reliable operation of high-voltage, high-power devices during extended periods of heavy load is crucial

  Stability under harsh environmental conditions is a priority

- **Standardization and Compatibility in Modular Designs**

  Modular multilevel converters (MMCs) pose challenges in achieving standardized designs

  Interchangeability of components and flexible system expansion require standardized approaches

- **Heat Dissipation and Efficiency Optimization**

  Managing heat generated during high-power operation is a significant technical hurdle

  Balancing efficiency improvements with effective cooling mechanisms is essential

- **Economic and Stability Considerations in Low-Voltage DC Systems**

  Achieving a balance between system economics and stability is vital for distributed energy systems

  Low-voltage DC systems highlight this trade-off

- **Indigenous Development and Technological Autonomy**

  Chinese companies face the challenge of enhancing indigenous research and development capabilities

  Reducing reliance on imported equipment will enhance international competitiveness

CHAPTER III
CURRENT STATUS AND DEMONSTRATION EXAMPLES

Existing large-scale new energy grid-connected systems exhibit multi-time-scale dynamic characteristics dominated by power electronic equipment. Their AC grid-connected stability heavily relies on the stable control of grid-connected converters, which are prone to oscillation problems. For instance, in 2009, a 20 Hz synchronous oscillation occurred between a doubly fed wind farm in Texas, USA, and a 75% series compensation line, resulting in the disconnection of wind turbines from the grid. In 2015, wind farms in Hami, Xinjiang, China, experienced multiple 20-80 Hz oscillations that interacted with weak synchronous power grids, leading to large-scale wind turbine disconnections. Similarly, in 2021, 8 Hz sub-synchronous oscillations were observed in an event in North Scotland.

Compared to the stability issues faced by AC grid-connected systems, DC collection is easier for new energy access, offers long transmission distances, lower losses, and does not require consideration of voltage phase and frequency. It improves the stability and reliability of new energy grid connections and is the main development direction for future grid connections.

Multiple DC demonstration projects have been built domestically and internationally for the collection of new energy DC. The application scenarios and parameters of these projects are shown in Table 4. For example, the Hangzhou Jiangdong New City Flexible DC Distribution Project, which was put into operation in 2018 for the collection of wind and solar energy, adopts MMC AC grid connection, with a DC voltage of ±10 kV and a capacity of 2-40 MW. In 2019, the Institute of Electrical Engineering, Chinese Academy of Sciences, developed a ±30 kV/1 MW PV DC boost converter, which was the largest voltage class and capacity in China at that time. Additionally, the campus three-terminal medium voltage DC demonstration project built by RWTH Aachen University in Germany in 2020 has an input DC voltage of ±2.5 kV and a capacity of 1 MW.

However, DC collection technology relies on high-capacity and high-gain DC/DC converters and faces challenges such as low efficiency and immature technology.

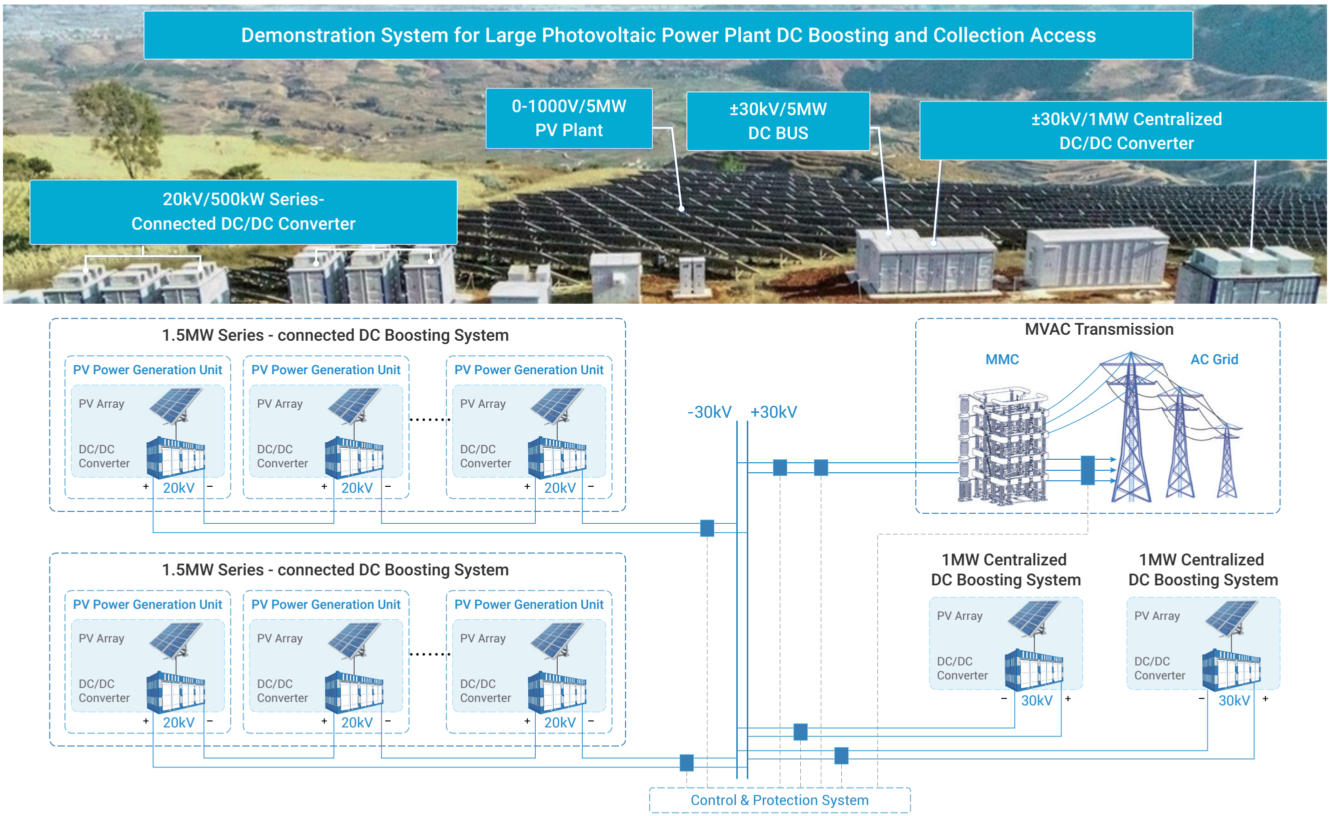
Table 5. Demonstration and research case studies of the DC collection and grid connection system

Location/Institute	Project introduction with its advantages description	Year
Guizhou, China	±10kV/±375V/0.5MW, DC transformer with DAB series parallel combination topology	2018
Jiangdong New City, China	±10kV/2-40MW, this project is used for wind and solar energy storage and collection, and adopts MMC AC grid connection	2018
Yunnan, China	±30kV/1MW PV DC boost converter with the highest voltage level and maximum capacity in China	2019
RWTH Aachen University, Germany	±2.5kV/0.5MW Campus Three Terminal Medium Voltage DC Demonstration Project	2020
Zhangbei, China	±35kV/0.5MW DC-DC topology technology solutions: intermediate frequency DC-DC converter, high-frequency series resonant DC-DC converter, and modular IPOS DC-DC converter	2020
Wenzhou, China	±10kV/0.6MW T^2-DAB converter, The first domestic medium voltage side LCC-CNPC hybrid DC distribution architecture project, DC power supply and new energy consumption	2023
Spain	(i) Planning, design and evaluation of transnational HV AC/DC hybrid transmission systems, as well as DC distribution grids. (ii) Improved grid forming control for hybrid AC/DC networks. (iii) Protection and control schemes for improved security, resilience and interoperability among multivendor and multi-terminal MVDC and LVDC systems. (iv) New switchgears and converters topologies for DC distribution and microgrids.	2024

PROJECT 1: THE INTELLIGENT FLEXIBLE DC PROJECT IN JIANGDONG NEW CITY, CHINA

In 2018, the intelligent flexible DC transmission and distribution demonstration project put into operation in Jiangdong New City, Hangzhou, adopted a three-terminal back-to-back MMC structure to achieve interconnection of two 10kV and one 20kV supply areas in the Jiangdong New City distribution network. The 10kV Xinwan substation, Changzheng substation, and 20kV Linxin substation are respectively connected to the ±10kV DC bus through MMC. The overall transmission capacity of the system is 3MW. MMC adopts 1.7kV/IGBT with parameters of 1.7kV/650A and submodule (SM) capacitor voltage of 0.91kV. The MMC arms of Xinwan Substation and Changzheng Substation are equipped with 22 half bridge submodules (HBSMs), while the MMC arms of Linxin Substation are equipped with 33 full bridge submodules and HBSMs. By adopting flexible straight technology, flexible ring closure of AC power grid can be achieved; Realizing power flow transfer under steady-state conditions and load transfer under fault conditions improves power supply reliability and capacity. In addition, the ±10kV medium voltage DC system adopts DC circuit breakers and DC transformers to form a DC power grid. DC charging piles, PVs, energy storage, smart streetlights, and hydrogen production are connected to the ±375V low-voltage DC system through DC transformers to improve the consumption of new energy and the power supply capacity for DC loads. Among them, the key equipment MMC in the demonstration project has an operating efficiency of up to 98.5%. In addition, the DC transformer adopts a series parallel combination topology based on a series resonant converter, and the DC transformer adopts open-loop control to achieve a fixed voltage transmission ratio.

PROJECT 2: THE PV MVDC POWER GENERATION PROJECT IN YUNNAN, CHINA



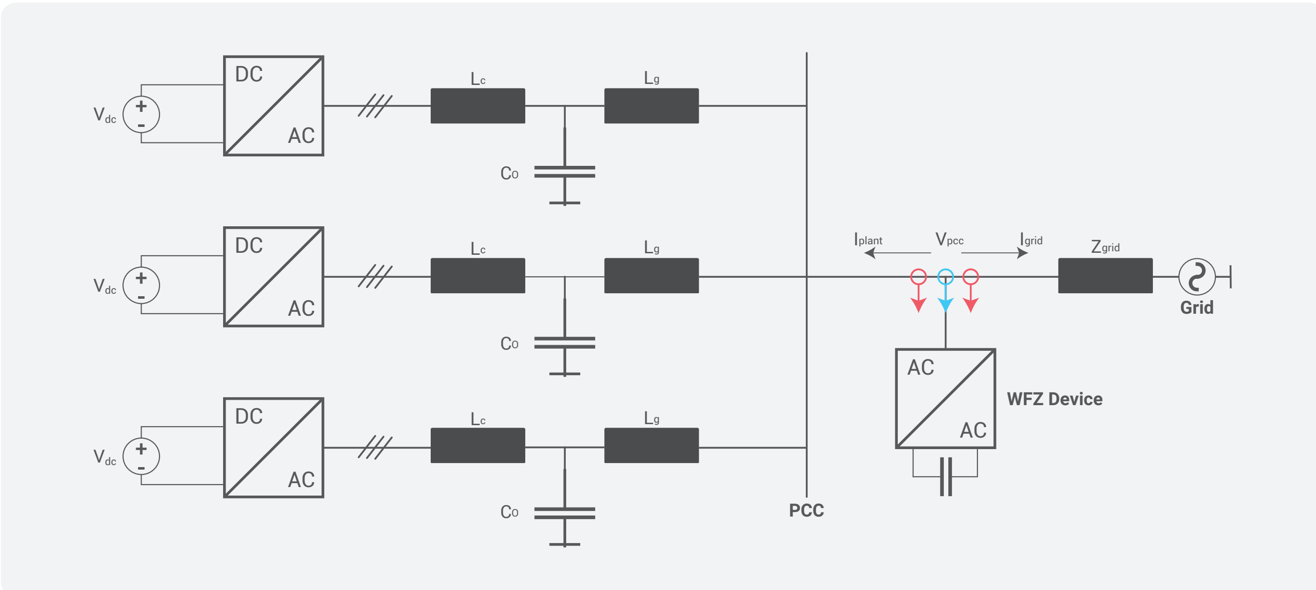
Photovoltaic (PV) power generation systems are evolving towards multi-scenario and high-efficiency directions. The PV MVDC power generation system is a new type of system that efficiently collects power over a large area using MV direct current. It offers advantages such as fewer conversion stages, low line losses, and easy integration with various energy sources or loads. This report focuses on the key technologies of PV MVDC power generation systems and equipment, high-reliability and low-cost system control and protection technologies, efficient operation, and control technologies across multiple scenarios. It also summarizes practical and industrial verification cases for PV MVDC systems.

In 2019, the Institute of Electrical Engineering, Chinese Academy of Sciences (IEECAS) established the world's first ±30 kV/5 MW PV DC boosting and collection grid integration demonstration system in Dali City, Yunnan Province, as shown in Figure 2. This system includes a 2 MW centralized PV DC boosting and collection system and a 3 MW series-connected PV DC boosting and collection system. IEECAS also developed a ±30 kV/1 MW centralized DC converter specifically for PV DC boosting and collection grid integration. This converter features maximum power point tracking for PVs and efficient DC grid connection with high voltage ratios. Third-party testing confirmed that the DC converter has an input voltage range of 450 V to 850 V, a maximum DC output voltage of ±33 kV, a DC voltage boosting ratio ranging from 88.5 to 143 times, soft switching over a wide power range (20% to 100%), and a maximum conversion efficiency of 97.46%. These achievements address technical requirements related to wide input voltage ranges, high power, large voltage boosting ratios, and overall efficiency.

To meet the on-site operational requirements of the system, the IEECAS team elevated the DC converters from Technology Readiness Level (TRL) 3 (feasibility validation of concepts and application ideas) to TRL 6 (completion of relevant environmental verification using system or subsystem prototypes). These individual converters have a rated power of over 1 MW and a voltage boosting ratio exceeding 60 times. Furthermore, by using a power segmentation control strategy, three 20 kV/500 kW PV DC converters are connected in series to form a ±30 kV/1.5 MW series-connected system, achieving coordinated operation within the series system.

At the end of 2021, IEECAS also established a 5 kV/1 MW 100% RE DC supply and distribution demonstration system in Huangdi City, Zhangjiakou, Hebei Province. This system successfully achieved stable operation during both grid-connected and off-grid scenarios.

PROJECT 3: THEUS PROJECT IN EU



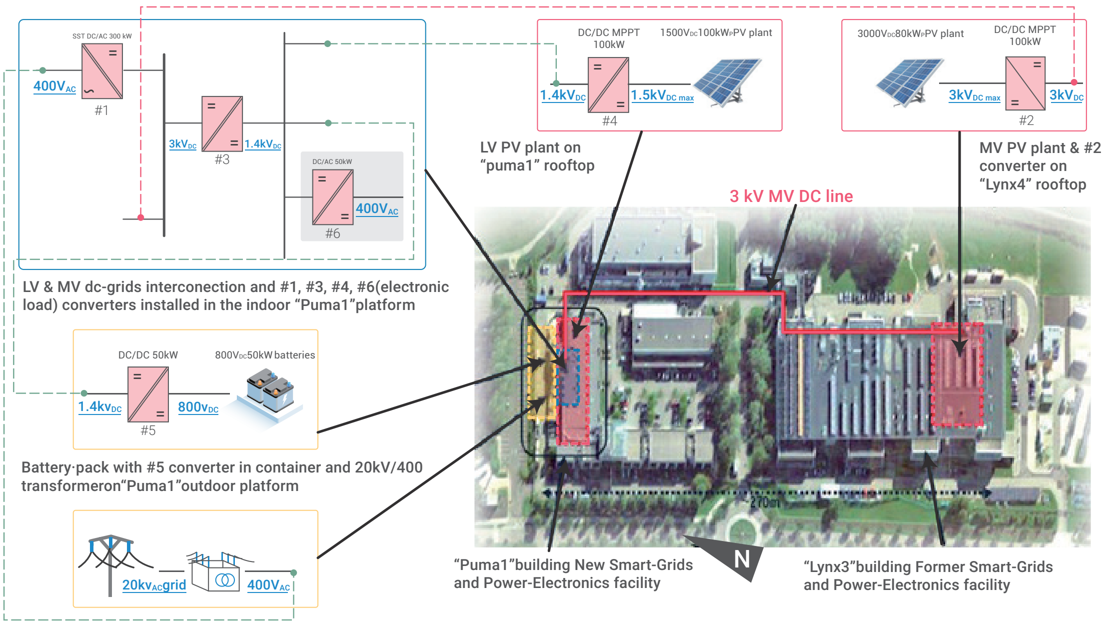
THEUS (Transmission and distribution Hybrid nEtworks with enhanced resilience and robUstnesS) is a Horizon EU project. It aims to demonstrate a range of advanced methodologies, models, and technologies that support the implementation and operation of hybrid grids across HV, MV and LV levels. These solutions will foster and pave the way for the future development of a pan-European AC/DC hybrid system, ensuring a reliable energy supply and an interoperable electrical network.

To successfully achieve its objectives, the project will develop a set of six planning and six operation solutions, that will be validated in three pilot environments. Moreover, five different use cases have been defined to validate the project developments against the most representative challenges faced by European grids. These use cases will rely on accurate models that will be fed with data from five real grids representing different project stages (exiting and under planification grids) and voltage levels. The validation will be conducted at some of the most relevant testing facilities in the EU, allowing to reach TRL 5 by the end of the project.

A set of solutions will be developed, categorized in two main innovation pillars focused on 1) facilitating design and planning of hybrid grids, 2) improving the operation of AC and DC systems, through a set of solutions focused on integrating grid forming capabilities of AC/DC converters and enhancing protection and control solutions.

These have been categorized according to their planning or operation purposes: 1) Methodology and tool for transnational HVAC/HVDC system expansion planning; 2) Reliability and resilience methodology and tool for transmission adequacy and CBA; 3) - Methodology for standardization of HV AC/DC smart substations; 4) PSA-ACDC (Power System Analysis under AC and DC operation conditions) tool for the planning and management of hybrid distribution grids; 5) Design strategies for standardization of MVDC networks; 6) - Methodology to evaluate MVDC links and their integration into AC distribution grids; 7) Advanced Virtual Oscillators-based GF converter; 8) Harmonic Stability Monitoring Technique for Renewable based Power Plants; 9) Advanced Active Damping Control Strategy for Grid-Connected Converters; 10) Selective protection algorithms for DC distribution and microgrids; 11) DC breakers with improved efficiency; 12) Direct AC/HF/DC converters.

PROJECT 4: TIGON PROJECT IN EU



This Horizon 2020 EU TIGON project will design a hybrid alternating and direct current microgrid system, one that is decentralized and close to valuable sources of renewable energy. TIGON's technical, digital and business solutions will be developed at two demo sites located in France with emphasis on photovoltaics and in Spain with a focus on batteries. In addition, two use cases in the residential and urban railway sectors in Finland and Bulgaria will act as niche markets to increase replication potential.

TIGON proposes as a first step the design, modelling, building and demonstration of two DC-based grid architectures in CEA and CIEMAT facilities which will include a MV-LVDC-AC/DC architecture for the interconnection of different micro/nano-grids which will include alternative types of generation such us PV and wind, storage systems, EVs and AC loads such us building lighting. These grid architectures will include a set of hardware (SST, SiC WBG DC/DC converters, dedicated protection schemes) and software (WAMPAC system, smart EMS and DSS) technologies developed during the project, which will make up a complementary framework for the appropriate integration and operation of these DC-based architectures under different operation modes.

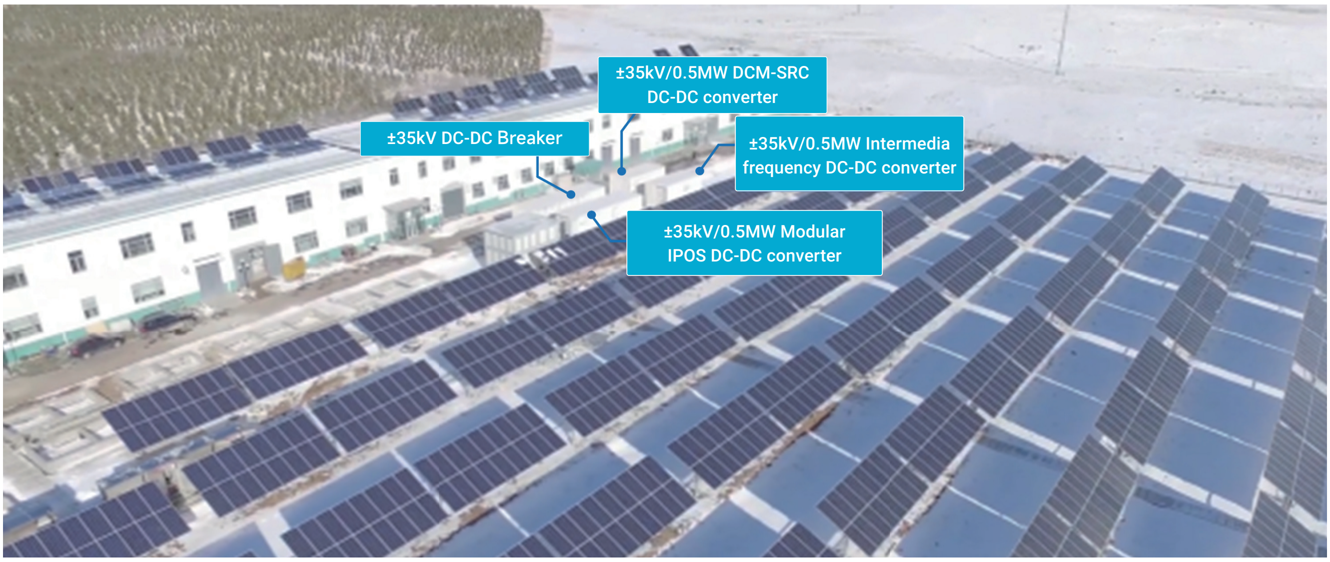
Pilot located in CIEMAT facilities in Soria (Spain), it will connect an AC/DC microgrid which include 15kWp of PV and 12,7 kW of wind generation, electrochemical energy storage and AC loads with MVDC microgrid which will include a BSS adapted to be connected at the MVDC line and provide different services to the whole micro-grid.

CIEMAT pilot will demonstrate the flexibility services provided by batteries connected to the MVDC grid and power electronics solutions with SiC technology, allowing better efficiency and digitalization of the grid. One of the main objectives is the enhancement of the system efficiency via the DC-based grid architecture deployment. Besides, a dedicated architecture for protections based on WAMPAC systems will be analyzed and tested.

Regarding the pilot located in CEA facilities in Savoie (France), it will compose of three micro grids, two DC and one AC, where dedicated DC protections and power electronics will be installed. All three microgrids are connected to the main AC grid through a PCC and they include a MVDC PV plant to be connected through a SiC based DC/DC converters developed during the project, a LVDC PV plant, buildings LVAC loads (lights, heating/cooling equipment, etc.), and electric vehicle chargers' infrastructure powered by a dedicated PV park along with a set of electrochemical batteries.

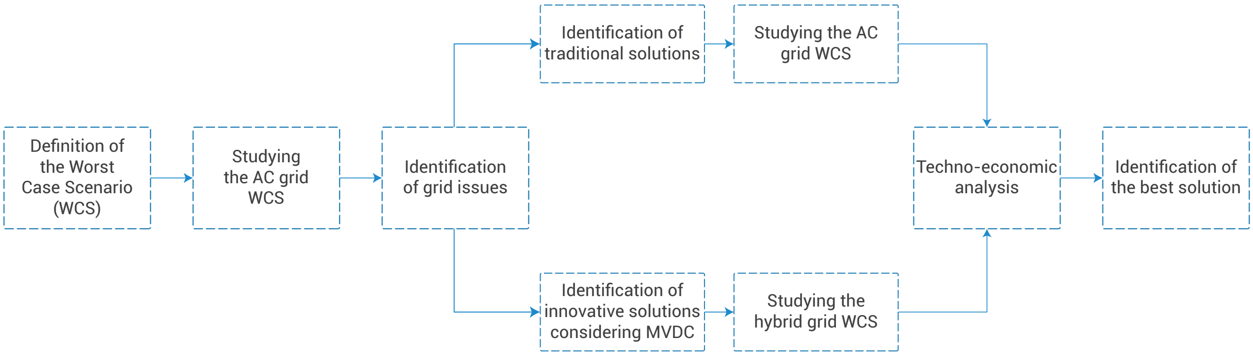
Expected outcomes of CEA pilot include a proof of concept for the connection of MV PV generation to a MV DC bus and a demonstration of cost benefit of MVDC applied to solar plants (LCOE analysis 0,02Euros/kWh). Furthermore, power electronics solutions with SiC technology will be characterized and demonstrated, allowing better efficiency and digitalization of the grid. Global losses with standard LV plants will be compared (reduction of 5-10%) with improvement of global efficiency (5-10%).

PROJECT 5: THE PV MVDC POWER GENERATION PROJECT IN ZHANGBEI, CHINA



In 2020, the State Grid Corporation of China (SGCC) built a ±35kV PV power generation medium voltage DC integration demonstration project in Zhangbei Test Base of the State Key Laboratory of New Energy and Energy Storage Operation Control. The Chinese Academy of Electric Power Sciences, in conjunction with Southeast University, Hefei University of Technology and Xuji Electric Co., Ltd., jointly developed three MW level DC/DC converters with different technical routes and demonstrated them in the test base. Southeast University has developed two high-frequency series resonant ± 35kV/0.25MW DC-DC PV boost converters, which adopt a master-slave control strategy. The MPPT converter converges the generated power of the PV array to the 820V low-voltage DC bus, and then boosts and collects it to ±35kV through a 250kW converter. Among them, the high-power DCM-SRC includes a high-power high-frequency transformer, two rectifier bridge boards, and two output stabilizing capacitors. The rectifier bridge board consists of 10 rectifier bridges. In order to achieve reliable power regulation of DCM-SRC and ensure that the maximum magnetic flux density of high-frequency transformers is not saturated, a fixed pulse width variable frequency control is adopted, which can achieve both ZCS of all switching devices and power regulation. Hefei University of Technology has developed a high-capacity intermediate frequency ± 35kV/0.5MW DC-DC boost converter. During steady-state operation, the input port voltage is controlled at 820V, and the input side DC bus is connected to four parallel inverter modules. The output end is connected in parallel to a 400Hz/24 pulse phase-shifting boost transformer, and the transformer output end is connected to a ±35kV DC bus. The intermediate frequency inverter consists of four power modules connected in parallel, each module is 125kW, with a maximum input DC voltage of over 1000V, a minimum input DC voltage and starting DC voltage of 550V, an output AC line voltage of 315V, a power factor of>0.99 at rated power, and a maximum efficiency of over 98.5%; The primary input line voltage of the intermediate frequency transformer is 315V, and the secondary output has four independent windings, each with a line voltage of 13.8kV. The working frequency is 400Hz, and the working efficiency is>98%. The modular IPOS ±35kV/0.5MW DC-DC grid connected converter has an input voltage of 750V~850V and an output voltage of ±35kV. The IPOS type consists of N LLC resonant converter modules, which adopt an interleaved control strategy between modules. The power module adopts a high-frequency isolation transformer, which adopts a double voltage rectification structure to reduce the transformation ratio of the isolation transformer. The rated power of a single LLC resonant converter module is 62.5kW, with an input voltage of 820V and an output voltage of 8750V. The use of DC-DC converters with three different technological routes has greatly promoted the efficient consumption of new energy and the industrial application of equipment.

PROJECT 6: THE POTENTIAL RESEARCH OF MVDC LINKS IN ITALY



This research presents a methodology developed for carrying out distribution network planning and reinforcement studies considering DC links as possible alternatives to traditional grid upgrades. The perimeter of the analysis is the distribution grid, and the objective is to compare solutions based on the integration of MVDC links with the baseline option of using conventional AC-based grid upgrades. The first step of the proposed methodology is to model the existing distribution network to identify the grid portions that would benefit the most from the deployment of DC links. The comparison with traditional, AC-based grid reinforcements is then carried out considering also costs and potential savings associated with each evaluated solution. The selection between MVDC or AC grids reinforcement is, in fact, dependent on a variety of different technical and economic factors that need to be considered from a system-level point of view.

The first step of the methodology consists in the identification of a Worst-Case Scenario (WCS) for the existing AC grid under investigation. For the purpose, one or more realistic future scenarios for the grid development are necessary, considering the current grid configuration and by assuming the evolution of the electrical load and distributed generation. Based on the results of the simulations carried out for the WCS, the new operating conditions are checked to technically quantify non-compliance with the operational constraints defined by the network operator or by design parameters of network components.

The most promising solutions for upgrading the existing AC network are then identified among the state-of-the-art traditional solutions (AC-based), without considering the adoption of DC connection. In the perimeter of MV distribution grids such candidates typically are: 1) grid reconfiguration, 2) upgrading of conductor cross-sections, 3) installation of synchronous condensers, D-STATCOMS, etc., 4) replacement of circuit breakers or 5) creation of new links between transformers.

In parallel with the previous phase, the most suitable DC-based solution (involving the integration of a MVDC link) is then selected. To help in this selection, the most promising basic schemes for the DC-based solutions have been individually categorized for the application as distribution grid reinforcement candidates. The possible solutions can be then selected among the following list: 1) DC conversion of an existing MVAC grid portion (such as a line or an interconnection); 2) Installation of AC/DC converters in back-to-back configuration, to divide the AC grid in two sub-grids; 3) Installation of AC/DC converters at the substations to build point-to-point connections between grids that were previously independent; 4) Installation of AC/DC converters in edge nodes that are far away from the primary substation, to create edge DC grid branches; 5) Construction of new DC lines.

Technical and economic indicators to identify the most appropriate solution are then derived from the results comparison of the different sets of calculations and simulations developed. This helps in identifying the solution that, in addition to solving the problem identified in the initial WCS, will have a better overall impact from a system-level point of view. In fact, possible secondary technical issues (not being part of what was identified as WCS) or additional services that the DC-based solution may provide to the existing network could be considered and play an important role in the decision-making process. If it is the case, it will then be necessary to carefully evaluate the actual impact and worthiness from the network operator's point of view. A weight should be assigned to each of those indicators (likely to be assessed on a case-by-case basis), considering both the initial objectives of the network planning and reinforcement study and the characteristics associated with the considered grid structure.

CHAPTER IV

IS IT READY FOR THE PROMOTION TO INTEGRATE RE INTO GRID WITH DC?

The International Electrotechnical Commission (IEC) has released a series of standards for RE DC collection and DC transmission systems to guide the application of DC power generation systems. In 2022, the IEC released the standard "Electromagnetic Performance of High Voltage Direct Current (HVDC) Overhead Transmission Lines" (IEC TR 62681:2022), which stipulates the electromagnetic environmental characteristics of HVDC overhead power transmission lines in steady-state operation. It includes requirements and test methods for ground synthetic electric field, audible noise, and radio interference, helping designers and operators assess the impact of transmission lines on the surrounding environment.

In 2020, IEC TR 63179-1: "High Voltage Direct Current (HVDC) Transmission System Planning Guide - Part 1: HVDC Transmission Systems with Line Commutated Converters," developed a technology pathway for the standardization of smart grid user interfaces, aiming to promote effective interaction and communication between users and smart grids.

In 2022, IEC TR 63363-1: "Performance of Voltage Sourced Converter (VSC) Based High Voltage Direct Current (HVDC) Transmission – Part 1: Steady-State Conditions," specified the performance requirements of converter-based HVDC transmission systems in steady-state operation. This includes system topology, rated parameters, active-reactive power, overload capacity, operation modes of converter stations, DC transmission line parameters, control systems, communication systems, auxiliary systems, noise, AC and DC harmonics, high-frequency interference, reliability, and losses. It provides a reference basis for the performance indicators of HVDC transmission equipment.

IEC 62344: "Design of Earth Electrode Stations for High Voltage Direct Current (HVDC) Links - General Guidelines," stipulates the general guidelines for the design of earth electrode stations for HVDC links. It includes site selection of the earth electrode, the type and arrangement of the electrode, the calculation of earth resistance, and the assessment of step voltage and touch voltage, providing a basis for the safety of HVDC transmission.

In 2023, the IEC released "Integrating Distributed PV into LVDC Systems and Use Cases" (IEC TR 63534), which refers to China's research and engineering experience in medium and low voltage DC power systems. It lists typical application scenarios of distributed PV for DC systems, providing a reference for PV energy collection and DC power transmission.

Table 6. List of the standards

Organization	Item	Description
International Electrotechnical Commission (IEC)	IEC TR 62681:2022	Electromagnetic performance of HVDC overhead transmission lines
IEC	IEC TR 63179-1	HVDC Transmission System Planning Guide - Part 1: HVDC Transmission Systems with Line Commutated Converters
IEC	IEC TR 63363-1	Performance of voltage sourced converter (VSC) based HVDC transmission – Part 1: Steady-state conditions
IEC	IEC 62344	Design of earth electrode stations for HVDC links - General guidelines
IEC	IEC TR 63534	Integrating distributed PV into LVDC systems and use cases
China Electricity Council	GB/T 35692-2017	Guide for System Planning of HVDC Transmission Projects

Organization	Item	Description
Standardization Administration of the People's Republic of China (SAC)	GB/T 35703-2017	Specification of system design for HVDC transmission using voltage sourced converter (VSC)
SAC	GB/T 35711-2017	Analysis, restrain and measurement of harmonics of DC side of HVDC transmission system
National Energy System Operator for Great Britain (NESO)	Betta GC Planning Code	Specification of the technical and design criteria and procedures to be applied in the electricity transmission system and user end.
SP Energy Networks	MVDC Link Technical Specification	Specification of the requirements for a MVDC Link, involving the AC to DC conversion on MV AC circuit.

China has released a series of supplementary standards for RE DC systems. GB/T 35692-2017: "Guide for System Planning of High-Voltage Direct Current Transmission Projects" stipulates the basic principles, methods, and contents of system planning for high-voltage direct current (HVDC) transmission projects, including planning requirements for transmission capacity, transmission distance, and converter station location. GB/T 35703-2017: "Specification of System Design for High-Voltage Direct Current (HVDC) Transmission Using Voltage Sourced Converter (VSC)" guides the basic principles, methods, and contents of the complete set design of flexible DC transmission systems, including design requirements for the transmission wires, equipment selection, and control and protection systems. GB/T 35711-2017: "Analysis, Restraint, and Measurement of Harmonics on the DC Side of High-Voltage Direct Current (HVDC) Transmission Systems" specifies the basic principles, methods, and requirements for the analysis, suppression, and measurement of harmonics in high-voltage direct current transmission systems.

These standards have standardized the technologies for RE DC power generation and transmission, facilitating the application of DC power systems. However, the promotion and application of DC power generation and transmission still face several challenges:

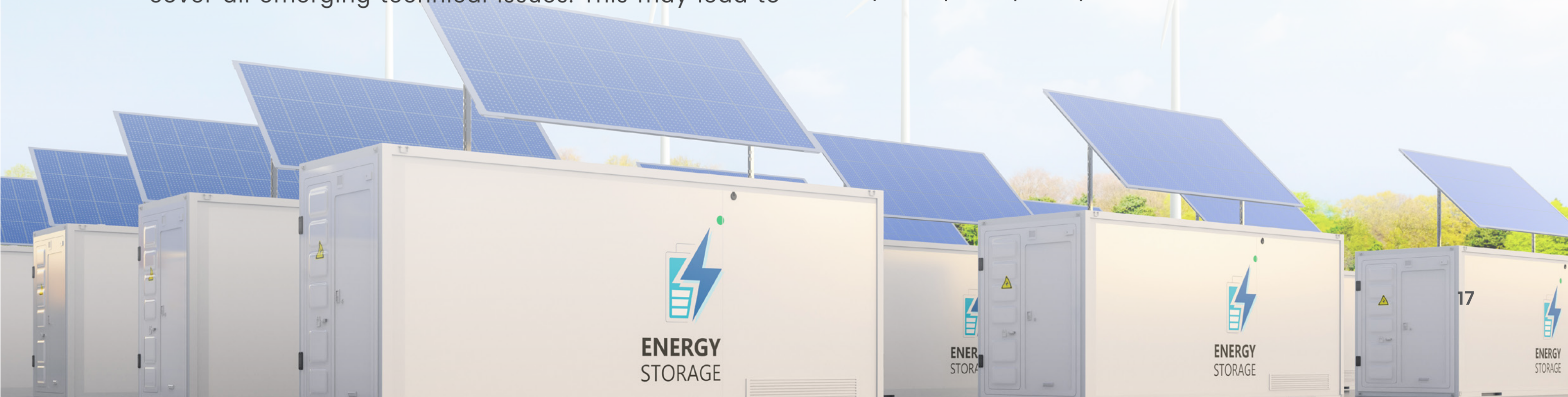
1) Incomplete Technical Standards: With the rapid development of RE DC collection and transmission technologies, existing technical standards may not fully cover all emerging technical issues. This may lead to incompatibility between different equipment, uncertainty in operation modes, and difficulty in accurately evaluating risks.

2) Insufficient Policy Support and Incentives: Despite the evident advantages of RE DC transmission technology, its promotion still requires government policy support and incentives. Short-term subsidy policies may affect the investment confidence and long-term planning of enterprises. Insufficient tax preferences may weaken the attractiveness of RE projects, and market restrictions may hinder new enterprises from entering the RE field.

3) Inflexibility and Poor Regulation Capacity: The intermittency of new energy poses great challenges to the power system. DC power systems may lack flexibility and regulation capacity. Insufficient energy storage facilities cannot smooth out the fluctuations of RE. This could lead to the DC grid not having enough capacity for matching and rapid power regulation of power supplies and load demands, resulting in low power supply reliability and high risks.

4) Cost and Benefit Issues: The initial construction cost of RE DC collection and transmission systems is high. Due to the immature technology, maintenance costs may also be high, making it difficult to achieve financial returns in the short term. This could dampen investor enthusiasm.

5) Low Social Awareness and Acceptance: Society has not deeply understood the advantages of DC power systems. Concerns about its stability, safety, and resistance to the construction of RE facilities may arise, leading to project delays, low public participation, and even social conflicts.



CHAPTER V

KEY ISSUES AND RECOMMENDATIONS FOR THE NEXT STAGE OF DEVELOPMENT

The promotion of DC power systems for RE will be progressively expanded, influenced by factors such as policy support, technological advancements, and cost reductions. As the demand for RE grows, the scale of DC power systems will correspondingly increase. DC power systems for RE can be combined with other energy systems to achieve multi-energy complementation and enhance energy efficiency, such as through combined cooling, heating, and power. They can be integrated into the energy internet to realize the sharing and optimal allocation of energy, thus promoting sustainable energy development. With the progression of DC power systems for RE, relevant standards and specifications will be continuously enhanced to ensure compatibility, safety, and reliability.

The core issue in developing full DC RE systems remains the cost. The high cost is mainly due to the immaturity of the DC ecosystem, where all devices are customized. Additionally, part of the cost increase is due to technical factors, such as the higher cost of DC circuit breakers compared to AC circuit breakers. Therefore, further efforts are needed to reduce costs. In terms of promotion, independent RE microgrids, such as off-grid hydrogen production systems powered by RE, have good potential for widespread adoption. Moreover, the cost of DC power systems for RE is expected to decrease in the future, making them more competitive. The development of power electronics will improve the efficiency of RE systems and reduce losses. DC power systems will become more intelligent, achieving better monitoring, control, and management, thereby enhancing the reliability of power supply.

In addition to large-scale centralized RE power plants, distributed DC power systems for RE will be more extensively applied, such as rooftop solar PV systems and community energy micro-grids. Integrating DC power systems for RE with energy storage systems will address the intermittent nature of RE and provide a more stable power supply.

For the next stage of development, the following suggestions should be considered:

1) Establish a Dedicated Mechanism for Standard Setting and Updates: It is necessary to create a dedicated mechanism for setting and updating standards. Countries should cooperate to share technology and policies. Research institutions and enterprises should be encouraged to participate in the formulation of standards, promptly incorporating the latest research results and practical experience into the standard system.

2) Provide Continuous Government Support: The government should provide continuous, stable, and sufficient subsidies, or increase tax incentives. Additionally, an effective supervision and evaluation mechanism should be established to ensure the effective implementation and timely adjustment of policies.

3) Enhance Research and Development: It is essential to enhance the research, development, and application of energy storage technology, promote the flexibility of power electronics converters, expedite the development and application of smart grid technology, establish a more flexible and efficient electricity market mechanism, and facilitate the optimal allocation and coordinated operation of various resources.

4) Encourage Technological Innovation: Through technological innovation, it is possible to improve the performance and reliability of equipment and reduce costs. Optimizing operation management can enhance system efficiency and reduce operation and maintenance costs. Additionally, a comprehensive evaluation of the social, environmental, and economic benefits of the RE system should be conducted.

5) Boost Social Awareness and Acceptance: To increase social awareness and acceptance, it is necessary to actively carry out public participation and communication activities. Listening to the views and suggestions of the public and addressing their concerns is crucial. Demonstration projects can help the public experience the benefits of RE, encouraging societal support for the development of RE systems.

Keywords and Explanations	
AC	Alternating Current
BSS	Battery Storage System
CBA	Cost-Benefit Analysis
CNPC	Cascaded Neutral Point Clamped Three-Level Converter
DC	Direct Current
DCM	Discontinuous-Conduction Mode
DSS	Decision Support System
D-STATCOMS	Distribution Static Synchronous Compensator
EMS	Energy Management System
GF	Grid-Forming
HBSMs	Half Bridge Submodules
HF	High Frequency
HVDC	High-Voltage Direct Current
IGBT	Insulated-Gate Bipolar Transistor
IPOS	Input Parallel Output Series
LCC	Line-Commutated Converter
LCOE	Levelized Cost Of Energy
LLC	Inductor-Capacitor-Inductor
LVDC	Low-Voltage Direct Current
MMC	Modular Multilevel Converter
MPPT	Maximum Power Point Tracking
MV	Medium-Voltage
PSA-ACDC	Power System Analysis Under AC and DC Operation Conditions
PV	Photovoltaic
RE	Renewable Energy
SiC	Silicon Carbide
SM	Submodule
SRC	Series Resonant Converter
SST	Solid State Transformer
THEUS	Transmission and Distribution Hybrid Networks with Enhanced Resilience and Robustness
TIGON	Towards Intelligent DC-Based Hybrid Grids Optimizing the Network Performance
TRL	Technology Readiness Level
VSC	Voltage Source Converter
WAMPAC	Wide Area Monitoring, Protection and Control
WBG	Wide Bandgap
WCS	Worst-Case Scenario
WT	Wind Turbine
ZCS	Zero Current Switching

GREEN POWERED FUTURE MISSION

Green Powered Future Mission Coalition

CHINA – Ministry of Science and Technology (MOST)

ITALY – Minister for Environment and Energy Security (MASE)

UNITED KINGDOM – Department for Energy Security and Net Zero (DESNZ)

AUSTRALIA – Department of Industry, Science, Energy and Resources (DISER)

INDIA – Department of Science and Technology (DST)

SAUDI ARABIA – Ministry of Energy

IRENA – International Renewable Energy Agency
World Bank Group
Alperia SpA, Italy
Areti SpA, Italy
Enel Global Infrastructure & Networks, Italy
National Grid Group, United Kingdom
Icebreaker One, United Kingdom
LONGi Green Energy Technology Co., Ltd., China
Xinjiang Goldwind Science Technology Co., Ltd., China

AUSTRIA – Federal Ministry for Climate Action, Environment, Energy, Mobility, Innovation and Technology (BMK)

BRAZIL – Energy Research Office (EPE)

CANADA – Natural Resources Canada/Ressources Naturelles Canada (NRCan/RNCan)

EUROPEAN COMMISSION – Directorate-General for Research & Innovation

GERMANY – Federal Ministry for Economic Affairs and Climate Action (BMWK)

JAPAN – Ministry of Economy, Trade and Industry (METI)

NETHERLANDS – Ministry of Economic Affairs and Climate Policy (MINEZK)

REPUBLIC OF KOREA – Ministry of Trade, Industry and Energy (MOTIE)

IEA – International Energy Agency
Energy Networks Association (ENA), United Kingdom
Gestore dei servizi energetici (GSE), Italy
BSI Group, United Kingdom
Terna SpA, Italy

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