

GE Vernova's
Electrification Systems Business

MVDC For Modern Grids:

ENABLING FLEXIBILITY AND RESILIENCE

Whitepaper

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INTRODUCTION

High-voltage direct current (HVDC) currently provides one of the most efficient ways to deliver enough decarbonized energy to meet the world's fast-growing electrification needs. Yet HVDC is only part of the story. **Medium-voltage direct current (MVDC) is the next chapter.**

Two things are driving this urgent interest in MVDC: first, the growth in distributed energy resources (DERs) and the need to integrate them into the grid and second, the high electricity provision needed to power heavy industry, transportation, and data centers.

For industries that use large amounts of electricity, avoiding energy losses associated with AC can amount to millions of dollars a year. While it's more efficient to use DC, a direct HVDC connection delivers a voltage that is too high for the techno-economic transfer of power in some cases. MVDC can bridge the gap by either stepping down HVDC for industrial use or stepping up solar and storage power to DC so it can travel long distances. There are many other cases where medium-voltage alternating current (MVAC) is converted to MVDC and then back again.

This paper will explore the role of MVDC in shaping the future of energy, examine real-world use cases, and share how GE Vernova is investing in technological innovations to support this critical transition.

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DC AND AC: HISTORY AND PARADIGM SHIFT



Thomas Edison



George Westinghouse

The war of the currents^[1] was a series of events surrounding the introduction of competing electric power transmission systems in the late 1880s and early 1890s. It grew out of two lighting systems developed in the late 1870s and early 1880s: arc lamp street lighting running on high-voltage alternating current (HVAC), and large-scale low-voltage direct current (LVDC) indoor incandescent lighting.

In 1886, the LVDC system was faced with new competition: an alternating current (AC) system that used transformers to step down from high voltage so AC could be used for indoor lighting. Using high voltage allowed an AC system to transmit power over longer distances from more efficient large central generating stations.

Direct Current

In 1878, inventor Thomas Edison saw a market for a system that could bring electric lighting directly into a customer's business or home, a niche not served by arc lighting systems. By 1882, the investor-owned utility Edison Illuminating Company was established in New York City.

Edison designed his utility to compete with the then-established gas lighting utilities, basing it on a relatively low 110-volt direct current supply to power a high-resistance incandescent lamp he had patented for the system. Edison's direct current systems would be sold to cities throughout the United States, making it a standard with Edison controlling all technical development and holding all the key patents. Direct current worked well with incandescent lamps, which were the principal load of the day. Direct current systems could be directly used with storage batteries, providing valuable load-leveling and backup power during interruptions of generator operation. Direct current generators could be easily paralleled, allowing economical operation by using smaller machines during periods of light load, improving reliability. Edison had invented a meter to allow customers to be billed for energy proportional to consumption, but this meter worked only with direct current. Direct current also worked well with electric motors; an advantage DC held throughout the 1880s. The primary drawback with Edison's direct current system was that it ran at 110 volts from generation to its destination, giving it a relatively short useful transmission range: to keep the size of the expensive copper conductors down, generating plants had to be situated in the middle of population centers and could only supply customers less than a mile from the plant.

Alternating Current

In 1884, inventor and entrepreneur George Westinghouse entered the electric lighting business when he started to develop an AC system. In 1885, he read an article in UK technical journal, *Engineering*, that described alternating current systems under development. By that time, alternating current had gained a key advantage over direct current with the development of a better, more industrialized version of transformers that allowed the voltage to be “stepped up” to much higher transmission voltages and then dropped down to a lower end-user voltage for business and residential use. The high voltages allowed a central generating station to supply large areas with up to 7-mile (11 km) long circuits^[1]. Westinghouse saw this as a way to build a truly competitive system instead of simply building another barely competitive DC lighting system.

MVDC: A Paradigm Shift

For over a century, AC has reigned supreme in transmission and distribution systems. However, the re-emergence of direct current (DC) brings forth a new era with **several compelling advantages**:

REDUCED POWER LOSSES

DC systems exhibit improved electrical conductivity, resulting in lower losses compared to AC.

HIGHER POWER-CARRYING CAPACITY

Fewer power cables are needed due to DC's ability to handle higher loads.

ENHANCED SAFETY

Hybrid DC protection devices and vacuum tubes combined with static switches enable faster fault detection and breaking speeds, enhancing safety.

SIMPLIFIED DESIGN

Integrated DC systems eliminate layers of power conversion hardware, leading to cost benefits, efficiency increase, and reliability gains.

Recent advances in semiconductor-based power electronics (such as wide-bandgap semiconductors, voltage source converters, and DC-to-DC converters) pave the way for greater utilization of DC in distribution and transmission.

APPLICATIONS RELEVANT TO MVDC AND PROSPECTS

A growing number of generation and load assets, including solar PV, energy storage, electric transportation, and consumer devices, all utilize DC power. Because of this evolving power landscape, estimates show that DC loads currently make up over 50% of total electricity consumption in the United States^[2].

Key Drivers

- Increasing demand for efficient and sustainable energy solutions
- Advancements in transportation and electric vehicle (EV) infrastructure
- Rapid growth of data centers and artificial intelligence computing

These drivers are shaping the future of power distribution systems, as businesses and industries seek more reliable, efficient, and environmentally friendly energy solutions.

The growing interest in MVDC systems can be attributed to several key developments and trends:

- Technological advancements: significant improvements in power electronics, including more efficient and reliable converters, have made MVDC systems more feasible and attractive. These advancements allow for better control and reduced energy losses, enhancing the overall efficiency of MVDC systems.
- Renewable energy integration: the rapid expansion of renewable energy sources, such as solar and wind, which naturally produce DC power, has increased the relevance of MVDC systems. These systems can directly integrate with renewable sources, minimizing the need for AC conversion, thus reducing losses and improving efficiency.
- Improved energy storage solutions: with the growth of battery energy storage systems (BESS), which operate on DC, MVDC systems are well-suited for efficient energy management. Direct connections between renewable sources and storage systems reduce conversion steps, enhancing overall system efficiency.
- Long-distance transmission: MVDC systems are advantageous for transmitting power over long distances with lower losses compared to AC systems. This is particularly beneficial for

connecting remote renewable energy sources to the grid or for offshore wind farms.

- Reduced infrastructure costs: MVDC systems can reduce infrastructure complexity and costs by requiring fewer components for power conversion and transmission. This can result in lower capital expenditures and operational costs.
- Enhanced power quality and reliability: MVDC systems can provide improved power quality and reliability, especially in applications with sensitive equipment or high-power demands. They reduce the number of conversion stages that can introduce losses and affect power quality.
- Environmental and regulatory drivers: growing environmental concerns and regulatory pressures to reduce emissions have intensified the focus on more efficient and sustainable energy solutions. MVDC systems contribute to these goals by supporting the integration of clean energy sources and reducing energy wastage.

In summary, the convergence of technological, economic, and environmental factors has revitalized interest in MVDC systems, positioning them as a promising solution for modern energy challenges^[2B].

Boundaries of the Applications Being Assessed, and their Relevance for MVDC

MVDC is primarily used for rail applications today, with voltages up to 3 kV; however, MVDC benefits extend to a variety of potential markets, including distribution networks (e.g., conversion of existing AC lines to DC), DERs, and integrated renewable energy.

In a group of interconnected loads and DERs (microgrids), DC offers significant advantages such as control simplicity and fewer conversion stages for energy storage, renewables, EV charging, and electronic load integration. These advantages have ignited

interest in DC microgrids for data centers, industrial facilities, office blocks, and electric ships; they may also be extended beyond the microgrid scale to higher-level MVDC distribution (e.g., primary distribution).

Sources of DC power supply currently include PV panels, battery storage and fuel cells, and could be easily extended to wind turbines if market demand existed.

A case study of an onshore distribution network^[3] showed that a DC link can be an efficient way to reinforce a network in which there are several issues that need to be addressed. It was found that in place of extensive 132 kV reinforcement, an MVDC link could be installed at 33 kV with much lower capital cost. In addition, the MVDC link dramatically improves the voltage profile throughout the case study network which decreases network losses. Over the asset's lifetime, the reduction in losses proves to be a significant benefit of the MVDC link compared to the conventional reinforcement scheme.

A general setup for an MVDC substation with representative energy supply, distributed resources, and loads is displayed in Figure 1.

As the MVDC market matures and technology enablement grows, meshed DC distribution and large-scale grid integration of renewables is expected to expand, driven by higher efficiency and flexible system operation. In countries with existing AC networks, an integrated multipoint DC grid could provide a backbone to the existing grid, resulting in greater grid resiliency.

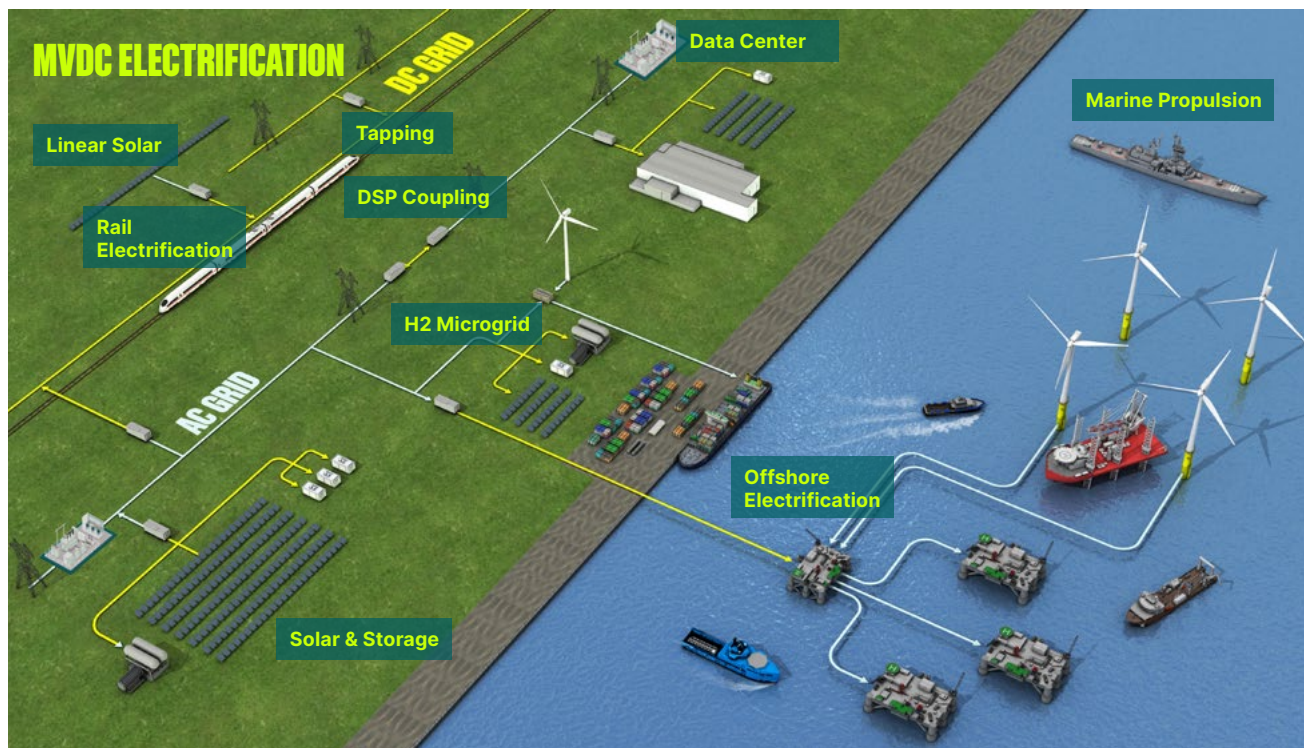


Figure 1: General setup for an MVDC landscape with representative energy supply, distributed resources, and loads

The applications being considered for MVDC include:

- MVDC solar & storage
- Data centers
- Transportation: rail and marine
- Oil and gas offshore electrification
- Distribution system operator (DSO) grids
- HVDC/MVDC tapping
- Microgrids and hydrogen electrolyzer power supply systems

For these applications, the power range would start from a few MW to reach ~100 MW. The voltage range would cover 10 to 100 kVdc. The other adjacent applications not considered at this stage are DC wind EV charging infrastructure.

Solar and Storage Plants

Integration of Solar PV

By using MVDC, solar PV systems can reduce conversion losses typically associated with AC systems. This is because the DC output from solar panels can be directly transmitted through step-up converters from LVDC to MVDC (e.g., dual active bridge), as shown in Figure 2. MVDC systems can easily be scaled up, making them ideal for large solar farms, allowing for the integration of multiple solar arrays into a unified system and improving overall system coordination and management. MVDC systems facilitate easier connection to the grid, especially in cases where solar farms are located far from the main grid. This is because MVDC can efficiently transmit power over long distances with less loss compared to AC systems.

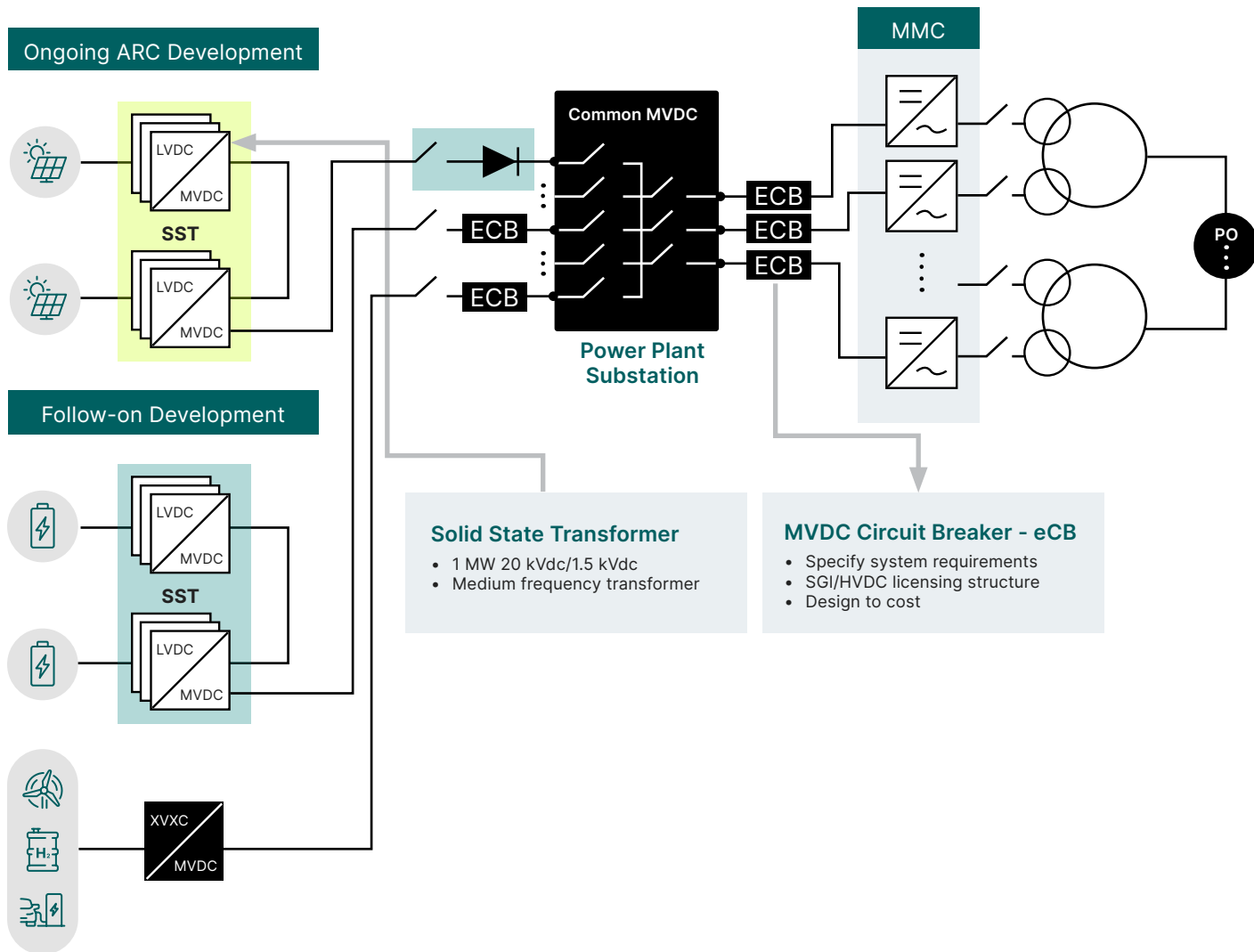


Figure 2: System architecture of MVDC solar & storage for utility scale plant

Integration of Energy Storage

MVDC systems provide a flexible platform for integrating various types of energy storage technologies, such as batteries and/or supercapacitors. This integration allows for better management of energy supply and demand, helping to stabilize the grid.

Energy storage systems can be used to balance loads and ensure a steady power supply, even when solar production is low, like at night or on cloudy days. This enhances the reliability and efficiency of the power system. Storage systems can be charged during periods of low demand and discharged during peak demand periods, improving energy usage and reducing costs and helping to manage peak shaving and load shifting.

Advanced control systems are crucial in MVDC grids to manage the flow of electricity between solar PV, storage, and the grid. This includes real-time monitoring and energy management systems to enhance performance and reliability.

In summary, MVDC electrification offers significant benefits for solar PV and energy storage systems by enhancing efficiency, scalability, and flexibility. It supports the growing demand for renewable energy integration and helps address challenges related to grid management and stability.

In utility-scale PV installations, integration of energy storage allows for an increase in plant capacity with aspirations to increase PV to 2000+Vdc.

MVDC can lower the cost of power electronics and improve efficiency due to the direct exchange of energy between BESS and PV without transiting through the grid.

A further option of energy storage integration could be considered at the voltage source converter (VSC) level featuring multi-level modular converter (MMC) topology. Energy storage could be distributed on the MMC cells via DC/DC converters as shown in Figure 3. Equipping the MMC cells with either batteries, for long duration energy storage, and/or supercapacitors for short duration energy storage would allow for efficient energy storage. Providing adequate voltage and frequency control adds grid-forming capability to the VSC. Centralized energy storage is also available. Selection of the centralized versus decentralized energy storage will hinge on maintenance, safety, and (degraded) operation considerations.

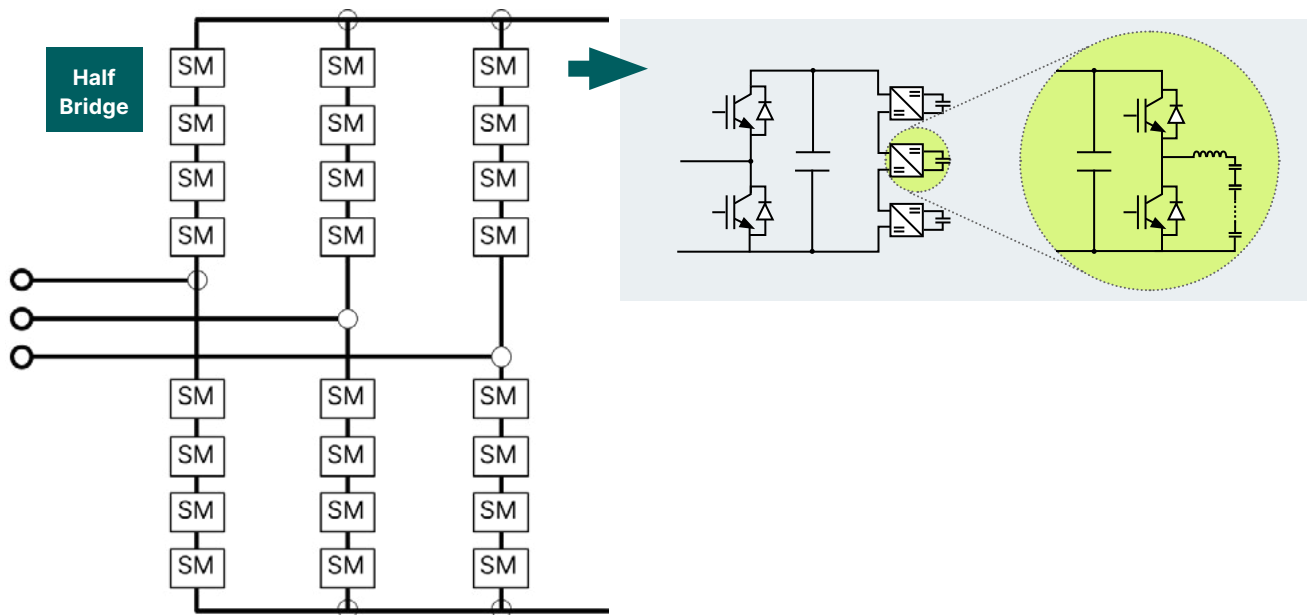


Figure 3: Integration of energy storage to VSC, distributed on the MMC cells

Oil and Gas Offshore Electrification

Electrification of oil and gas offshore platforms and floating production storage and off-loading (FPSOs) is driven by the reduction of CO₂ emissions (reduced carbon taxes), unmanned platforms (reduced OPEX), and further integration of offshore renewable resources. To electrify an offshore platform, a subsea cable is used for transmission of power from onshore to offshore in order to supply islanded and remote loads. This electrification removes two gas turbines from the platform and keeps only one for black start and back-up, as shown in Figure 4a. The trade-off is between:

- MVAC subsea cable: a static frequency converter is needed to convert onshore frequency from 50 Hz to offshore 60 Hz
- MVDC subsea cable: an offshore DC/AC converter is required

The technology relevant to the oil and gas MVDC market will need to investigate distributed DC power that suppresses the main DC/AC hub. In previous references, the technologies provided were bi-directional, while the power flows in one direction from onshore to an offshore load. This opens room for further simplification of the AC/DC converter.

Selection of the optimal system with the lowest CAPEX, including capitalized losses, is shown in Figure 4b and depends on both the length of the subsea cable and the power of the transmission. For example, for a 100 MW transmission on a distance of 200 km, the optimal range of voltage would be 50 kVdc. While for 150 MW, moving to 100 kVdc would drastically reduce the cost of the subsea cable.

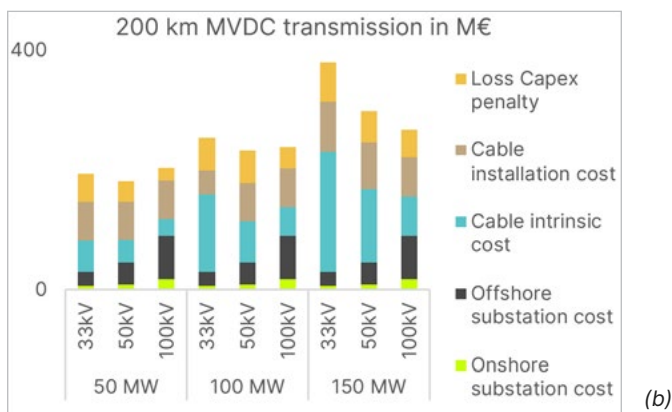
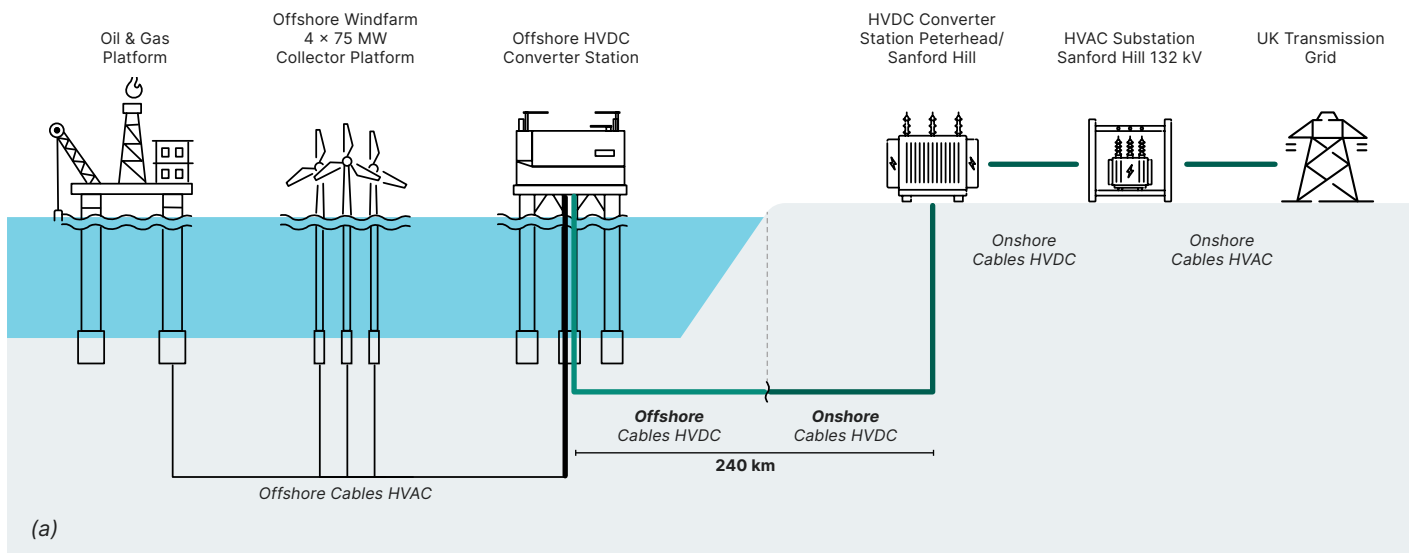


Figure 4 (a) MVDC transmission to offshore oil and gas platform (b) Cost breakdown

MVDC Transportation

Marine Power & Propulsion

For marine ship power and propulsion systems, there is a need to mutualize power generation, energy storage, propulsion systems, ship services, and other peak loads, as shown in Figure 5. The drivers to go DC are the following:

- Power stability and quality benefits: more simple synchronization of generators vs. AC grid. Opens for free selection of generator frequency.
- No reactive power interactions.
- No harmonic filter or shifting transformer installed: in DC grid systems, only inverters are needed for load. On AC onboard grids, diode rectifiers are used on the AC system for propulsion motors. Variable frequency drives (VFDs) could be eliminated, and so, power losses and harmonic distortions into the connecting load could be reduced and improve power quality.

The economics are:

- The DC grid diesel generators operate with variable frequency/speed system that reduce fuel consumption and emissions.

- Removing switchboards, transformers, and rectifiers in a variable frequency drive for motor control, reducing weight and volume.
- Easy integration of DC power sources to a DC-bus such as energy storage systems could be used for various purposes like reducing the running time of diesel generators and improving energy efficiency.
- Flexibility of reconfiguration

In summary, moving to DC reduces short circuit current, reduces part counts, increases efficiency, and reduces the size of cables.

The main technology innovations required to accelerate deployment and acceptance are:

- DC/DC converters for connection of BESS or integration of BESS at MV level.
- Converters for connection of future high-speed generators to MVDC bus.
- DC bus coupling protection (static switch).

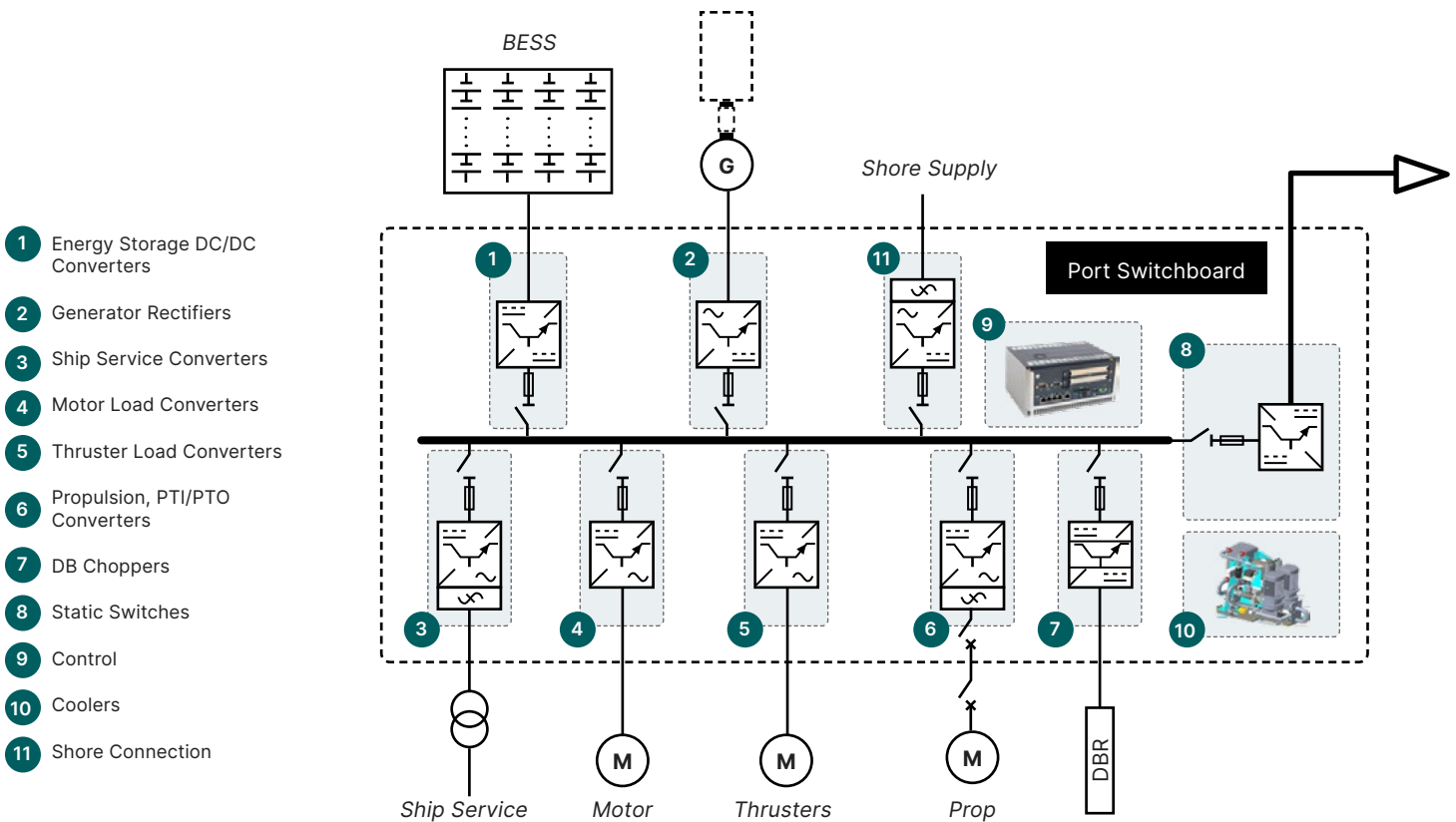


Figure 5: DC architecture for marine power and propulsion

Rail Electrification

MVDC systems enhance rail system efficiency by minimizing energy losses during power conversion and transmission. These systems effectively capture and reuse braking energy, reducing overall energy consumption. They support the integration of renewable energy sources, such as solar and wind, by allowing direct DC connections. MVDC can decrease the number of required substations, lowering infrastructure costs and maintenance. Additionally, they allow bidirectional power flow, improving grid stability and flexibility. MVDC networks are easily expandable, accommodating future demand increases without significant infrastructure changes. Advances in power electronics and control systems have made MVDC solutions more viable and cost-effective, promoting their adoption in rail networks. Key benefits include power sharing between substations, a three-phase power supply from the public grid, simplified

locomotive power converters, lightweight overhead lines, and no inductive voltage drop. MVDC is seen as a breakthrough enabler for rail transportation, offering solutions for electrification in undeveloped regions, DC line renewal, and the integration of smart grid concepts.

Switching rail catenary systems from LVDC to MVDC by increasing voltage from 1.5 kVdc to 9 kVdc, as shown in Figure 6, offers significant advantages. It reduces the copper requirement for overhead lines by 70%. It also decreases the number of substations needed, resulting in 60% less installed power and enhances efficiency by about 6%^[3B]. This transition can save approximately 2 GWh annually for every 100 km. The move is particularly beneficial for countries developing electrified railway networks.

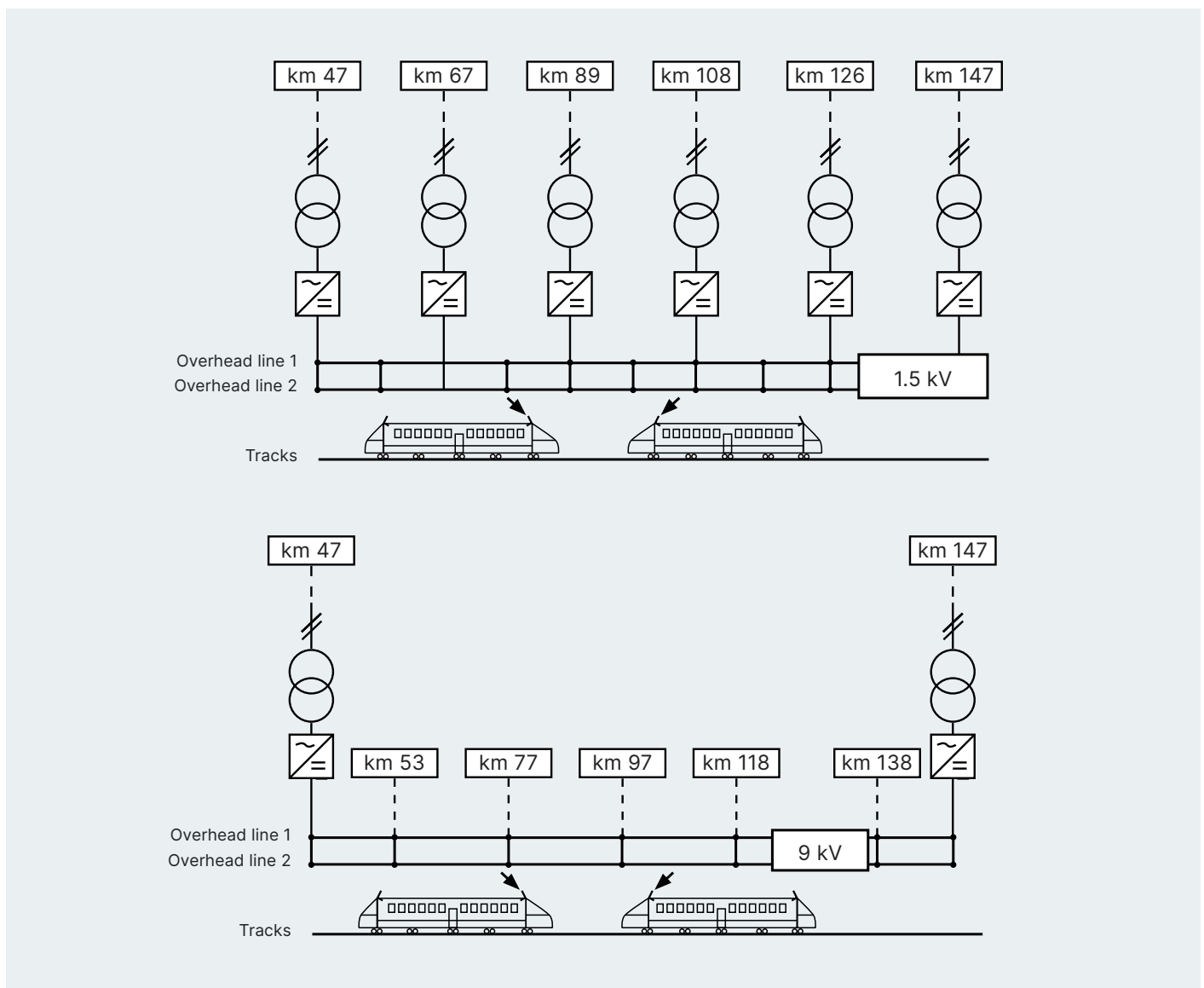


Figure 6: Comparison of a 1.5 kVdc versus 9 kVdc electrification system

MVDC Grid Distribution

MVDC systems offer significant advantages for electric grid distribution, similar to the benefits of HVDC for high-voltage transmission. The efficiency of DC systems is enhanced by the absence of reactive power losses, skin effects, corona losses, as well as “no-load” transformer losses.

In general, while exact breakeven distances can vary (see Figure 7), MVDC is often seen as more cost-effective than AC for distances typically around several hundred kilometers for overhead lines and shorter distances for underground cables (e.g., 500 km for overhead lines and 30 km for underground cables^[4]).

Precise calculations would require a detailed analysis of the specific project, including cost estimates and technical specifications.

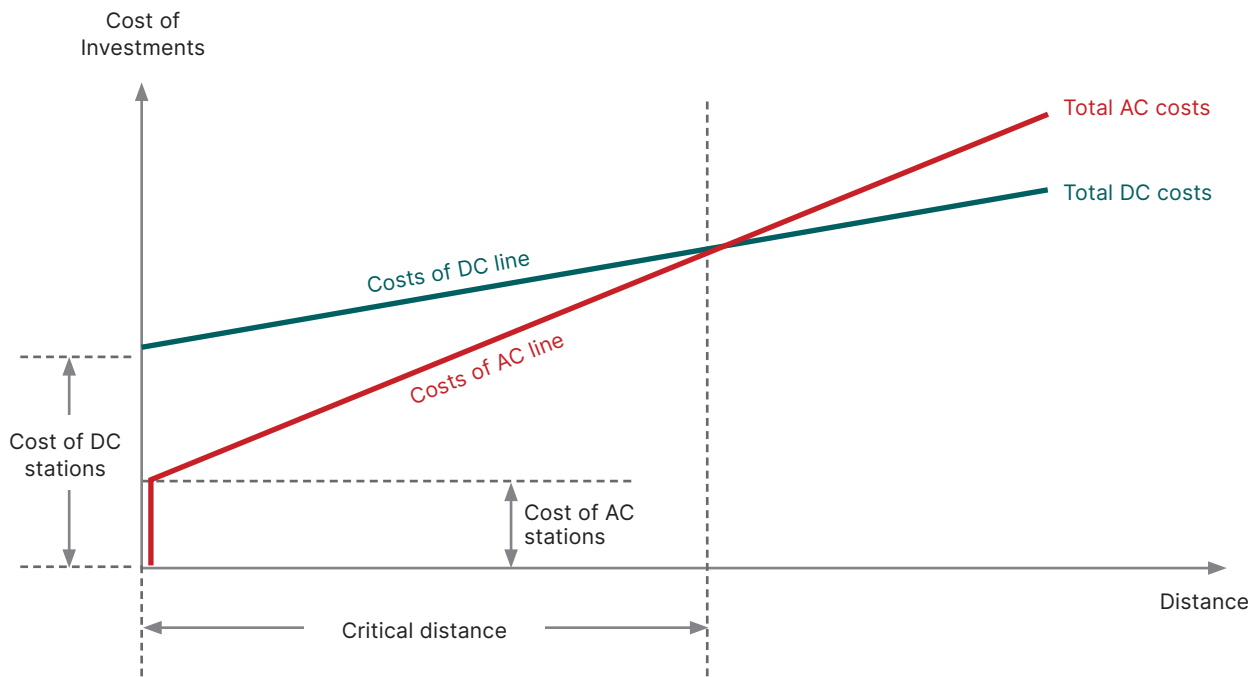


Figure 7: Cost of AC and DC investment versus distance of transmission line

MVDC multiterminal systems can be configured as either radial or meshed. Meshed MVDC grids feature a network of interconnected nodes, providing multiple power flow pathways that enhance reliability and flexibility. Protection of the MVDC terminals require current limiters and DC circuit breakers as shown in Figure 8. This configuration is ideal for complex networks requiring high resilience, such as urban areas or industrial complexes.

In contrast, radial multiterminal MVDC systems consist of several terminals connected to a central DC bus, as shown in Figure 9, facilitating power exchange between different points. This setup is easier to control and suitable for applications like integrating renewable energy sources or connecting remote locations to a central grid.

In summary, multiterminal MVDC grids are simpler to control. They provide a straightforward solution for specific distribution needs. While meshed MVDC grids are more complex to control and to protect, they provide enhanced flexibility and reliability. The choice between these configurations depends on system requirements such as complexity, reliability, and the nature of connected loads or sources.

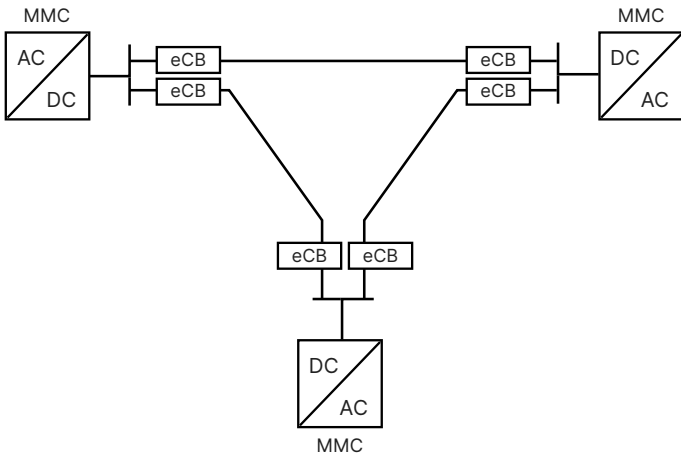


Figure 8. Meshed MVDC grids to connect multiple nodes

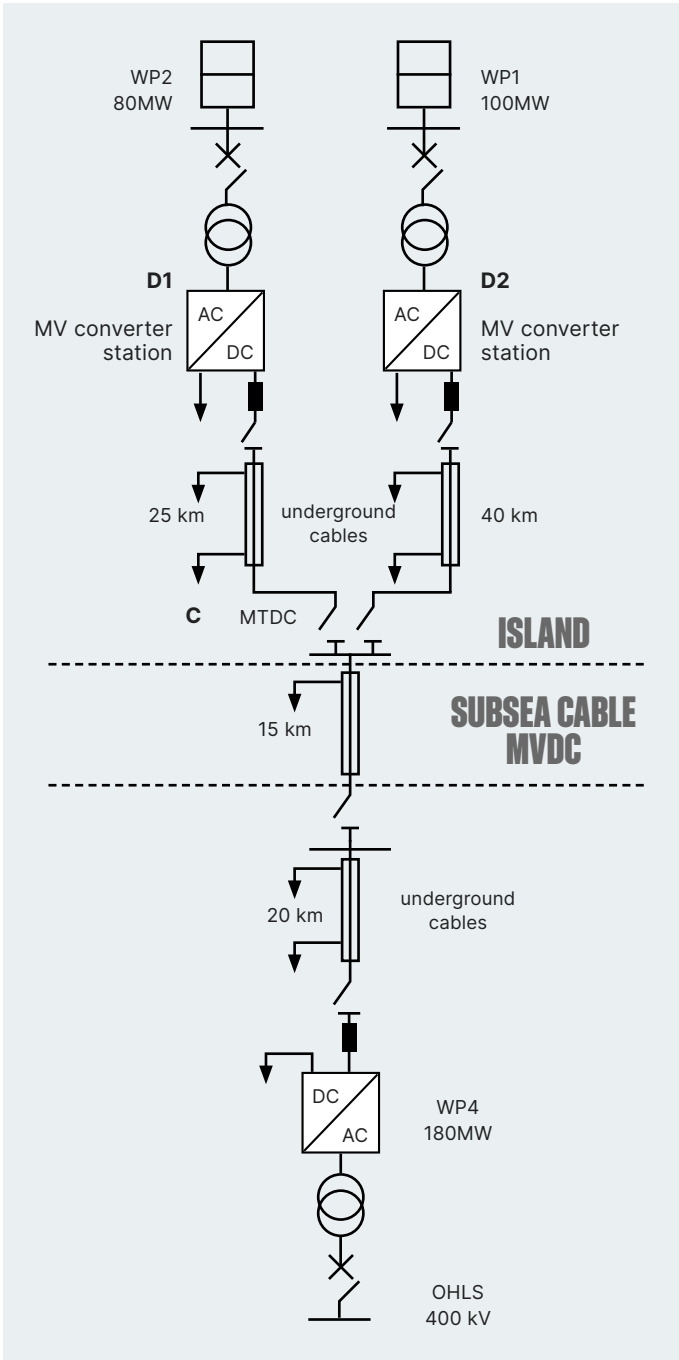


Figure 9. Multi-terminal MVDC grid to connect two wind power parks

MVDC for Electro-intensive Industries

The steel industry is seeking to reduce its global CO₂ emissions to align with global energy and climate objectives. As the demand for steel increases, electric arc furnaces (EAFs) are anticipated to exceed 150 MW in size, resulting in elevated energy quality requirements than traditional solutions, such as SVCs or STATCOMs, as shown in Figure 10a.

The Medium-Voltage Direct-Feed EAF solution^[5], utilizing MVDC technology, addresses these challenges by supporting new steel production processes such as Direct Reduced Iron (DRI) with reduced greenhouse gas emissions. This solution facilitates the transition to using more hydrogen in DRI facilities or constructing new plants with green hydrogen.

The direct feed system connects directly to the MVAC grid without step-down transformers, as shown in Figure 10b, to supply EAF through an indirect conversion system (MVAC to MVDC and vice versa) that decouples the EAF disturbances from the grid. It provides precise EAF electrode current management and qualitative monitoring through a digital control system. Key benefits of this technology include compatibility with greenfield and brownfield installations, a simplified EAF transformer, scalability up to 400 MW with aspirations to increase AC grid voltage to 66 kV, reduced power and electrode consumption, increased EAF production gain, and reduced electrical disturbances (flicker). Further development to decarbonize the steel industry consists of integrating renewable energy to the plant power supply. Connection of solar PV to MVDC bus of the direct feed is possible via DC/DC converters for better efficiency.

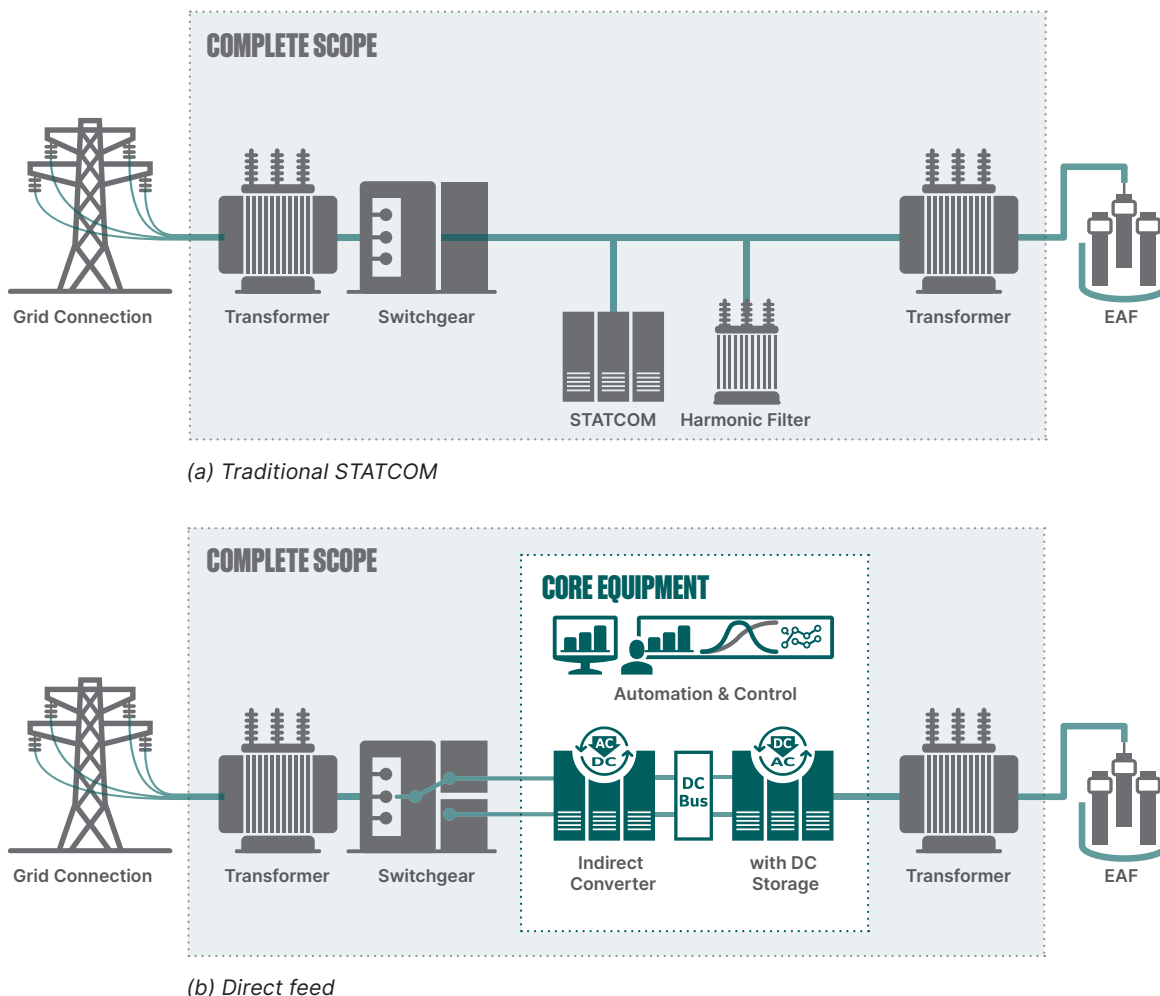


Figure 10: Power supply architecture of EAF from grid via MVDC bus



MVDC Data Center Power Supply System

Data centers continue to exhibit rapid growth in number and size. Hyper-scale data centers have become the most cost-efficient option for cloud operators due to economies of scale.

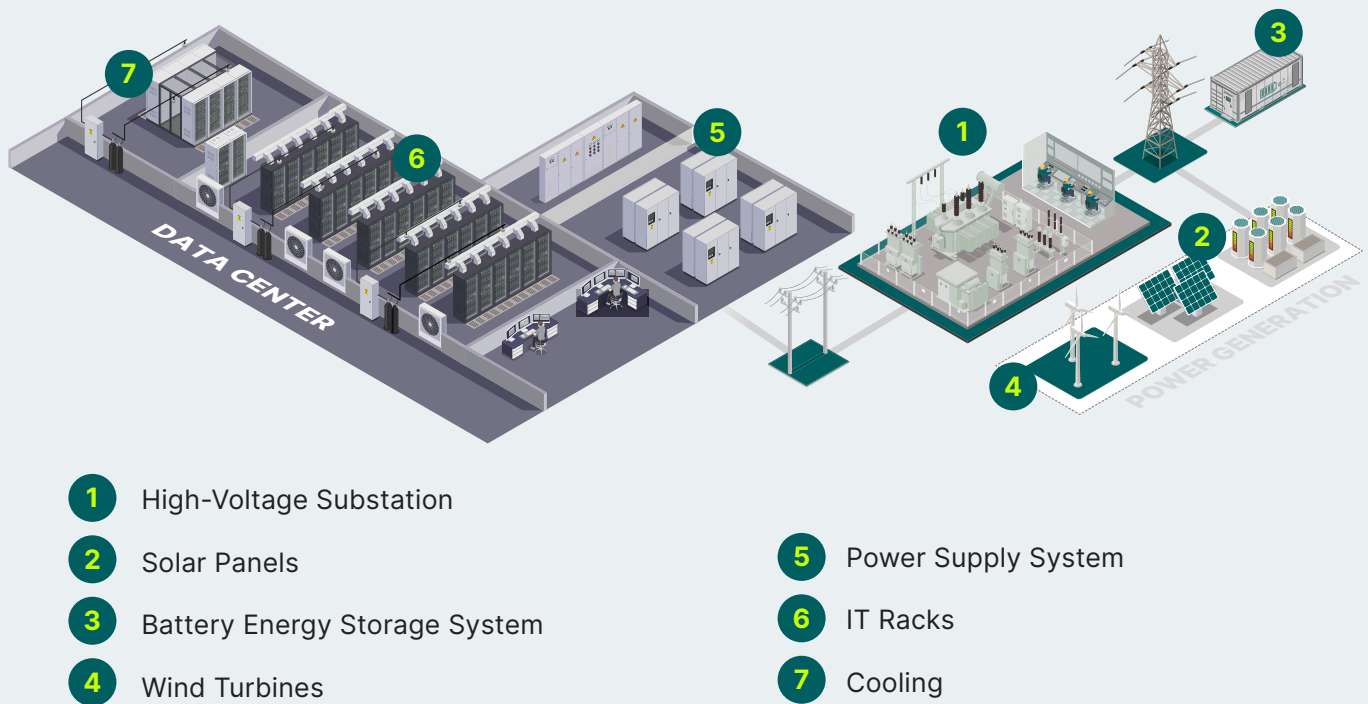


Figure 11: Data center power supply system

Power swing seen by the grid

The primary need is adequate sizing of electrical infrastructure, as shown in Figure 11, to support peak loads of AI data centers. Load profile shows high power swings of ~50% of peak load at GW levels for short cycles of 10 to 20s, step in three cycles of 60 Hz with a load that might even stop 10 times a day.

Due to these fast and large power swings of AI load, grid utilities are concerned by the risk of critical sub-synchronous torsional interaction frequencies (>0.5Hz) of turbine generator shafts. These oscillations could create damage as severe as shafts breaking, or other less severe effects such as islanding from unintended breaker(s) opening.

To prevent excitation of these critical frequencies, grid utilities require loads to contain very low power fluctuation magnitude in these critical frequencies. This turns into the need to filter the IT load centrally, using energy storage, on DC bus that distributes power to IT racks, in order to absorb instantaneous fluctuations.

IT rack voltage regulation

The worst foreseen load profile is shown below, where regular patterns of activity/lull/activity/lull during uninterrupted portions of a run occur with the load varying between 20% and 95% at a period of 50 or 100 seconds. It is not acceptable for this instantaneous load profile to be seen by the utility grid and needs to be smoothed out.

Hybrid energy storage, as shown in Figure 12, consists of battery storage that provides lower frequency components of the power profile and super capacitors that absorb higher frequency components. Combined with adequate control, the slope of load on ramp-up and ramp-down, seen by the grid, stays acceptable and its low frequency ripple content is damped. The distribution to the IT racks is made via DC bus. Due to large amounts of energy stored, protection against short-circuit (arc flash) will require static switch to disconnect the energy storage.

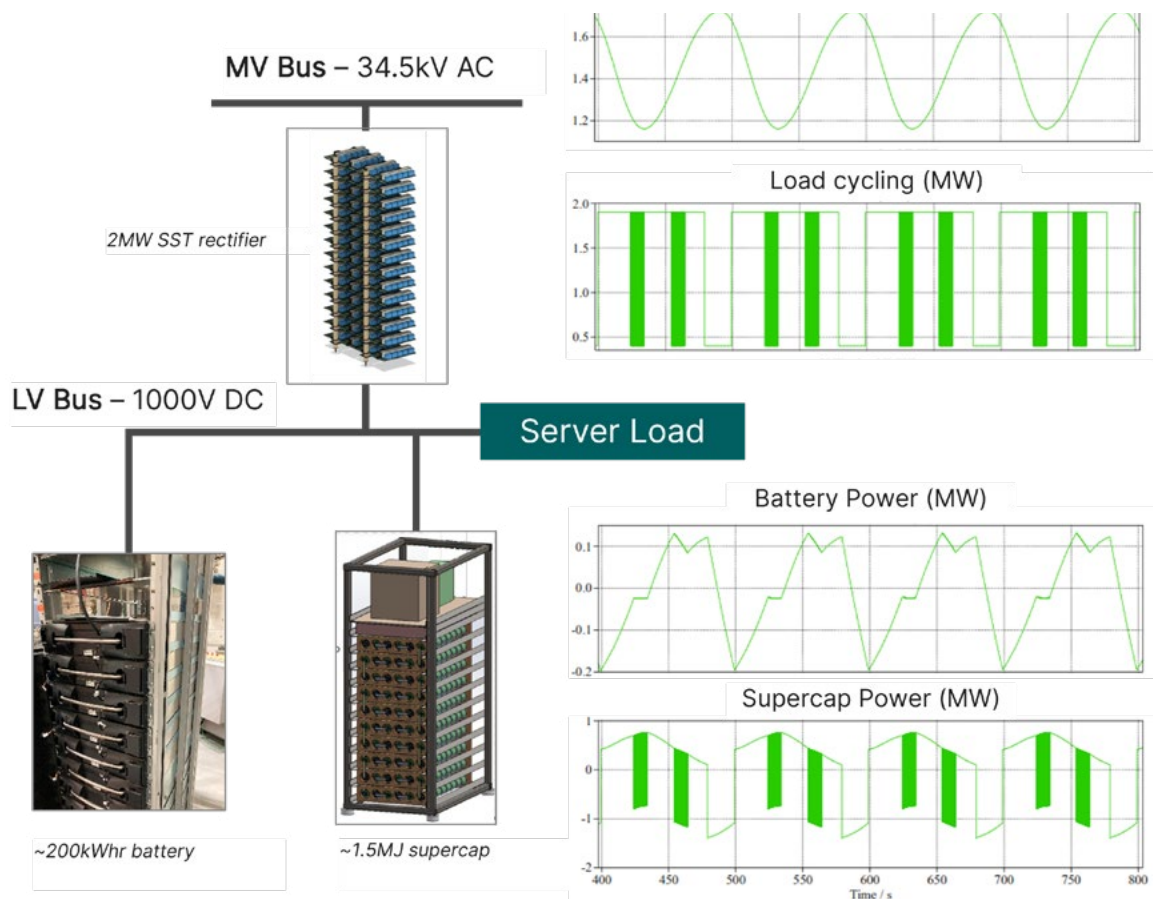


Figure 12: Power supply of IT rack with centralized energy storage to filter the load

There is limited possibility to extend data centers in urban areas above 100 MVA. Thus, the requirement is to design power supply systems using architecture that eliminates multiple power conversion stages.

A study for MVDC that considers economic metrics relevant to data centers was presented in North American Power Symposium (NAPS)^[6]. The results show that using a DC system at the medium-voltage level can substantially reduce the costs of data centers compared to the conventional AC architecture. A typical MVDC architecture of a power supply system is shown in Figure 13.

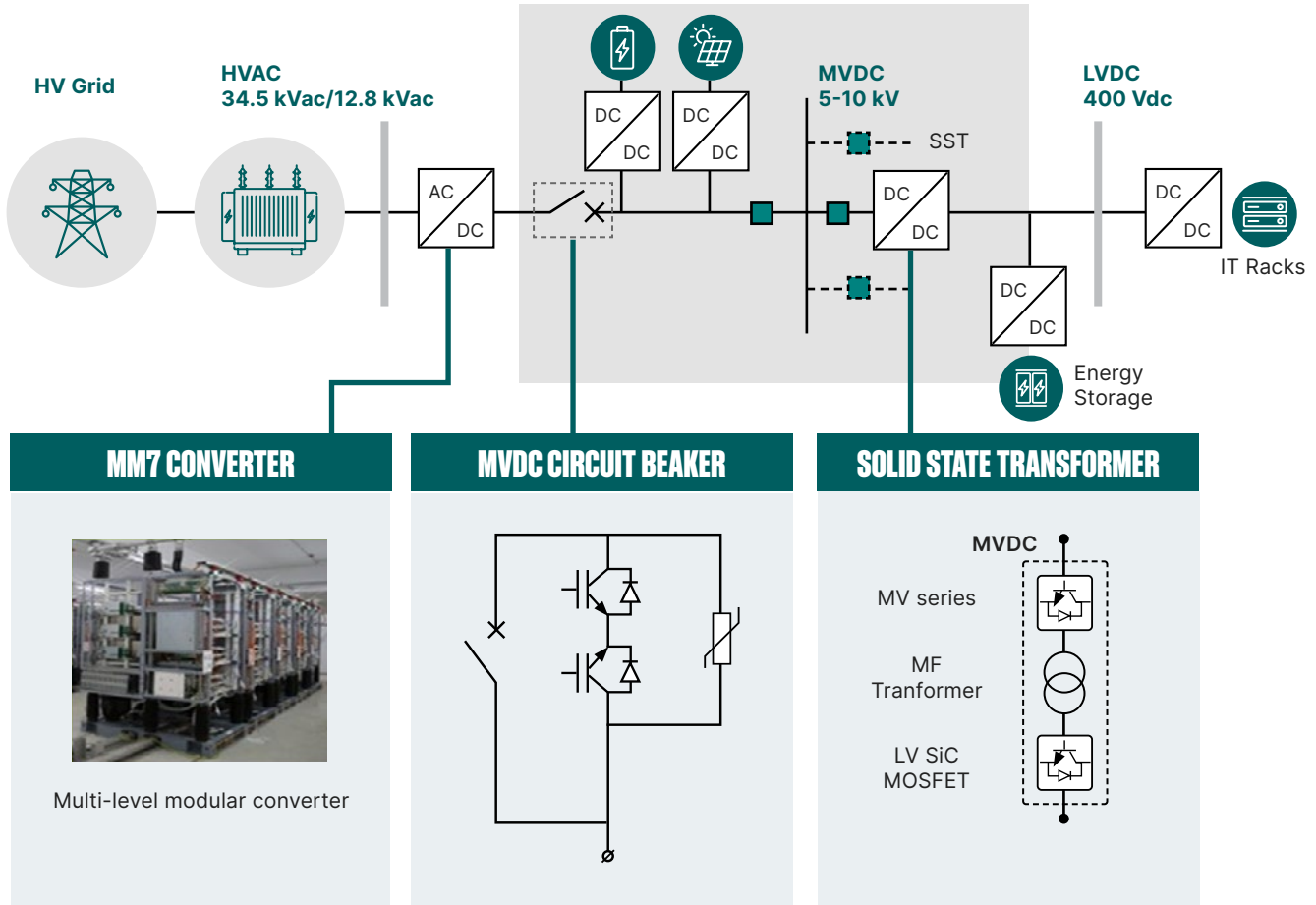


Figure 13: MVDC power supply system architecture from grid to IT racks

4

PRIOR EXPERIENCES

There are a number of pilot projects for MVDC distribution. GE Vernova's Power Conversion & Storage business delivered Europe's first MVDC link as part of Scottish Power Energy Networks' Angle-DC project between 2016 and 2020.

This first-of-its-kind project created a controllable bidirectional DC link between two sections of the UK's network: Isle of Anglesey (Ynys Môn) and North Wales. MVDC technology was a critical asset for the project, which aimed to demonstrate a novel network reinforcement technique by converting an existing 33 kV AC circuit to DC operation.

As electricity demand in the region increased, uncontrolled power flows risked exceeding the thermal limits of cables and overhead lines. The MVDC link enabled improved power flow and voltage control, converting AC assets to DC operation to improve the thermal capability of the circuit. MVDC also provides additional advantages over traditional reinforcement, including control of power flow direction and reactive power, voltage support, and the minimization of network losses.

Consequently, Angle-DC provides a smart and flexible method for reinforcing distribution networks, facilitating the integration of increasing volumes of renewable generation and accommodating the growth in electricity demand. Angle-DC has also built confidence in the deployment of MVDC technologies by other UK distribution network operators and initiated the MVDC supply chain.

The existing 33 kV AC distribution system was converted into a ± 27 kV DC distribution system. Benefits include the integration of renewable generation, the ability to accommodate growth in electricity demand with a 23% power capacity increase, and enhanced thermal capabilities of the circuit^[7].

Theoretical calculation of cable capacity increase and practical application

The concept consisted of switching three-phase MVAC overhead lines and cables to two-pole DC transmission. The theoretical calculation is as follows:

- The voltage withstand capability of a cable insulation is defined by the line to neutral voltage.
- The headline "nominal" rating quoted (here, 33 kV) is always the line-to-line voltage.
- 33 kV cable operates at a peak voltage stress across the insulation of $33 \times \sqrt{\frac{2}{3}} = 27$ kV. Angle DC used +/- 27 kVDC.

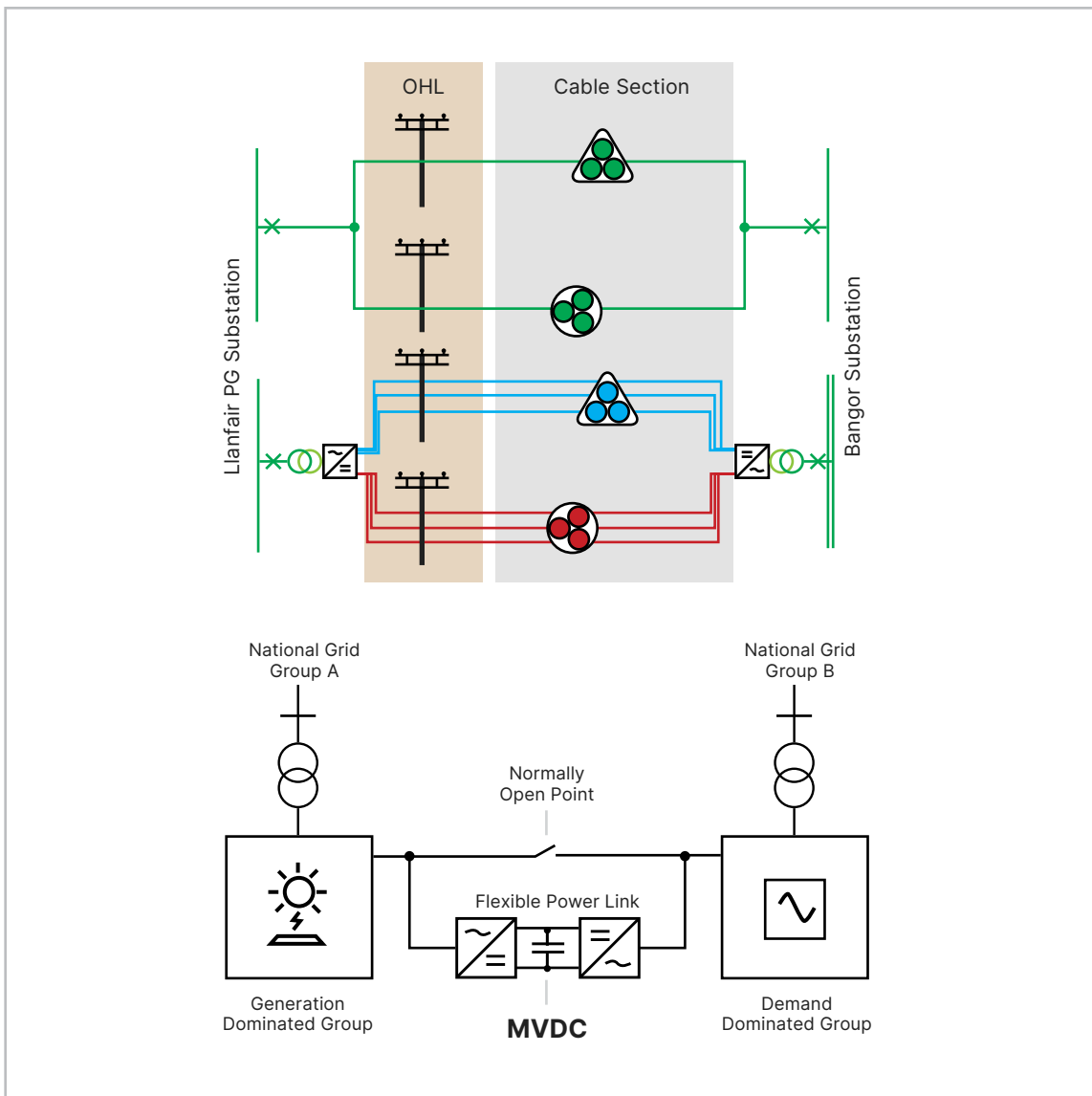


Figure 14: Angle-DC transmission system

Converting a double-circuit cable, using all three conductors of each circuit, giving a combined current rating of 3×217 , that is, 651 A and a potential total power of $2 \times 27 \times 651 = 35$ MW, ignoring any benefit you get from the absence of skin effect.

This theoretical calculation gives a potential increase of cable power capacity by 40%.

In practice, the 40-year-old double circuit from AC was converted to DC operation without replacing any assets. The AC amplitude of 33 kV was converted to ± 27 kV DC, giving a maximum theoretical increase in cable capacity of 43%. However, because the cables are old and not designed for DC operation, the maximum cable temperature will be kept, from the normal 65°C, to 50°C by reducing the maximum DC current from 219 A to 188 A. Even at this reduced current, the capacity of the cable can be increased by 23% from 24.8 MVA to 30.5 MVA. Therefore, the project will trial the use of voltage source MVDC converters as a DC link circuit.

Use of existing assets for future network expansion should minimize the capital investment significantly. The practical experience gained from this project will be valuable for removing system bottlenecks with rapid load growth together with ambitious low-carbon and net-zero emission goals.

5

PROSPECTS

The future market is anticipated to experience a rise in the adoption of DC microgrids utilizing low- or medium-voltage distribution, particularly in industrial environments where DC is already in place. This transition will require innovative architectural designs and protection systems to ensure flexibility and continuity of service.

For utility companies managing power distribution at voltages below 36 kV, DC must contend with the well-established and cost-efficient AC systems. However, the increasing prevalence of DC loads, driven by the need to distribute more power to homes as diesel vehicles are replaced by EVs, and the rise in DC generation from sources like solar PV systems, battery energy storage, and fuel cells, coupled with public and governmental efforts to reduce energy consumption, may lead to a reconsideration of the efficiency of DC-AC-DC conversions, potentially favoring direct DC distribution.

Currently, the DC distribution market is fragmented, with various consortia promoting DC use in diverse applications such as office buildings, shopping centers, homes, data centers, and telecommunications. Public utility companies have primarily invested in HVDC transmission lines to interconnect microgrids or remote grid areas, leveraging DC's advantages.

MVDC markets are expected to accelerate across the next decade with the changing landscape of generation and load types. The growth of solar PV and battery storage is expected to continue to accelerate, driven by forecasted reductions in material and manufacturing prices. Existing LVDC markets, including EVs, data centers, electric aircraft, and electric distribution will look to capitalize on DC-based generation as they transition to medium voltage due to increased electrification.

6

ENTRY BARRIERS

Barriers to Entry for MVDC Markets

Barriers to entry for MVDC markets include high adoption costs, technology availability, and safety concerns. As DC system-enabling technologies (e.g., DC-DC converters and DC circuit breakers) scale up, MVDC system deployment costs will fall through mass production. MVDC market demand will drive market competition, which will result in further cost reduction and a greater variety of technology solutions for MVDC developers.

Safety concerns in managing MVDC faults will be alleviated as DC circuit breaker technologies continue to be tested, validated, and brought into the market. It is worth mentioning that designing DC circuit breakers for MV is not as complex or demanding as it is for HV.

Technology innovation will be coupled with the introduction of new regulatory standards for MVDC safety protection globally to help facilitate smooth market adoption.

Regulators

MVDC distributions systems at a grid level are still at a nascent level. Early adoption applications where MVDC breakers have emerging standards include electric ships and marine applications. These are intended to assist in the procurement, design, safety, and practices that dictate effective operation of MVDC electrical power systems^[9]. Organizations such as CIGRE are actively assessing the applications and needs of the emerging MVDC space.

Key to the definition of a series of standards will be the type and architecture of switching equipment. Considerations will need to be made for closing functionality, commutation technology, speed, current and voltage ratings, and lifetime as a total number of cycles. The MVDC network topology may need to be considered as part of the standard definition, whether the connection is point-to-point or part of a multi-node/multiterminal system.

Standards will also be influenced by application. For instance, ship and rail operate at 6 kVdc and 3 kVdc, respectively, requiring different sets of standards. Specific standards may be required for hybrid DC-AC networked systems. Fusion energy applications, which would require rapid, high current breakers, would need not just electrical performance and safety standards, but also nuclear industry oversight. In this application, HVDC power would be used to control magnetic fields needed to heat plasmas, which are key for fusion energy realization.

Lastly, it is likely that certification organizations will leverage existing MVDC standards (used in transportation sectors) and HVDC protocols to meet the growing need for equivalent MVDC applications.



Safety Aspects

The electrification of systems using MVDC technology presents several safety challenges that must be managed to ensure safe operation. Key safety considerations include:

- **Electrical Shock and Arc Flash:** high voltages in MVDC systems pose risks of electrical shock and arc flash, necessitating proper insulation, grounding, and protective equipment.
- **Fault Detection and Isolation:** MVDC systems require advanced protection systems and fault detection technologies due to the challenge of identifying and isolating faults without zero-crossing points.
- **Overvoltage Conditions:** surge protection devices and appropriate system design are needed to protect against transient over-voltages caused by switching operations or lightning strikes.
- **System Stability and Control:** sophisticated control systems and real-time monitoring are critical to maintaining stability and preventing unsafe operating conditions.
- **Thermal Management:** effective cooling and ventilation systems are necessary to manage heat generation and prevent overheating and fire hazards.
- **Equipment Insulation and Materials:** selecting suitable insulation materials and designing equipment to withstand electrical stresses is crucial to prevent insulation failure and associated safety incidents.
- **Personnel Training and Procedures:** adequate training and clear safety protocols are essential to minimize risks during operation and maintenance.
- **Interference with Communication Systems:** proper shielding and grounding techniques are required to prevent electromagnetic interference with nearby communication systems.

Addressing these concerns involves comprehensive **system design**, advanced **protection and control technologies**, and adherence to **safety standards and regulations**, along with regular **safety audits** and **risk assessments**.

7

TECHNOLOGY OVERVIEW

The technology enablers of MVDC development are summarized below. The objective is to maximize technology synergies across the applications relevant for MVDC and accelerate introduction to the growing demand of industry electrification.

Solid-State Transformers

During the last fifteen years, the price per kVA of power electronic converters lessened by almost half. In the same period, the price per kVA of power transformers has doubled mainly due to capacity of supply chain (see Figure 15a).

Since frequency in a solid-state transformer (SST) is not bound to the frequency in the grid, this provides the possibility of building a small medium-frequency transformer that would be easier to transport, produce, use less material, and take up less space in a substation (see Figure 15b).

SST technology can handle various types of power conversion, including:

- DC to DC (for high-efficiency DC grids)
- AC to DC (for integrating renewable energy sources or EV charging)
- AC to AC (for voltage transformation and regulation)

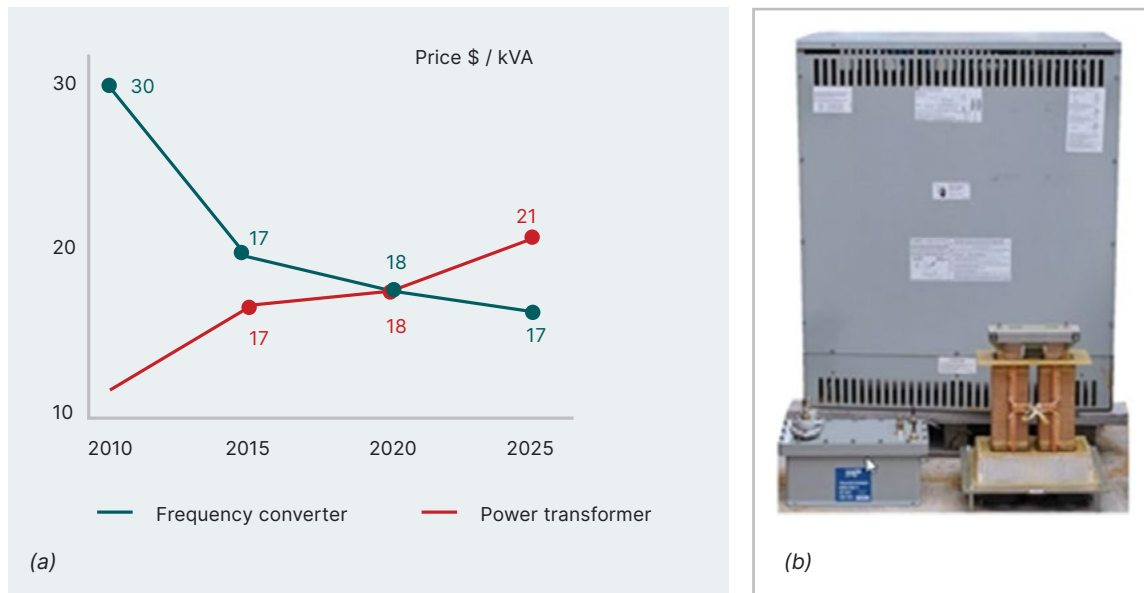


Figure 15: (a) Transformer / Power electronic prices. (b) 250 kVA transformer – 60 Hz dry-type (back). 20 kHz oil-filled water-cooled (front left) and 20 kHz dry-type forced air cooled (front right)

The goal is to build a MV SST in the most optimal way. The idea is to build this transformer based on a modular solution. The transformer needs to be built in a most efficient way and support redundancy to be able to still operate even if some component fails N-1 criteria. The transformer needs to be as small as possible and be built off less material.

Figure 16 shows an example of a medium-frequency transformer with volume and weight reduction compared to a current 60 Hz transformer.

SSTs can actively manage power flow, improve grid stability, and support DERs. By operating at higher frequencies and enabling direct DC links, SSTs reduce energy losses and improve system reliability, especially in applications involving renewable energy and DC load like rail and data center IT racks.

SST based on Series In / Parallel Output Converters

Figure 16 shows an arrangement of series connection of SST modules on the input to reach medium-voltage levels. On the output, the modules are connected in parallel to fit low-voltage levels⁹. This technology is suitable for 100 kW to 1 MW bricks using resonant capacitor circuits for soft switching, i.e., zero voltage crossing (ZVS) or zero current crossing (ZCS).

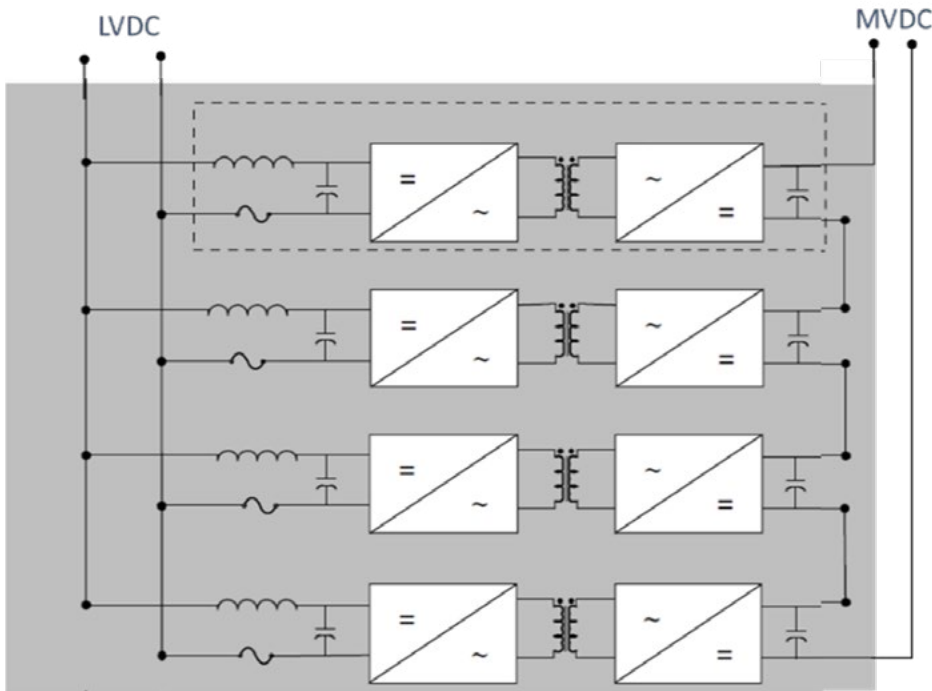
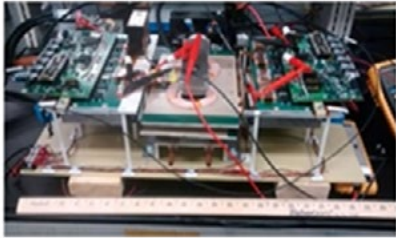


Figure 16: SST based on modular concept series IN - parallel OUT

The power of single SSTs is limited to below 1 MVA due to constraints on the resonant capacitor. The size-reduction potential enabled by the medium frequency is limited by the loss, cooling rate, and insulation level. The insulation plays an especially important role when a high isolation level is needed¹⁰.

SST based on Modular Multilevel Converter

For high power of 10 MW+, the objective is to reduce the number of SSTs that require high-voltage insulation. An MMC full bridge can be used for converting DC to DC at high voltage¹¹ in power HV transmission. For MV distribution, taking into account the lower level of power and unidirectional load, the MMC converter can be simplified as shown in Figure 17b, using less branches.



150kVa, 1kVdc - 1kVdc
250kHz SST (2018)



1MW, 6kVdc - 1kVdc
250kHz SST (2020)

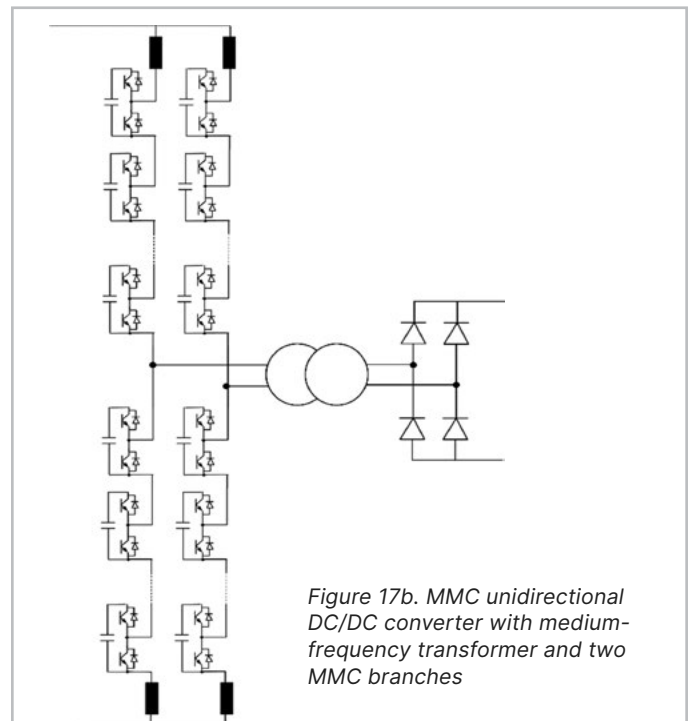
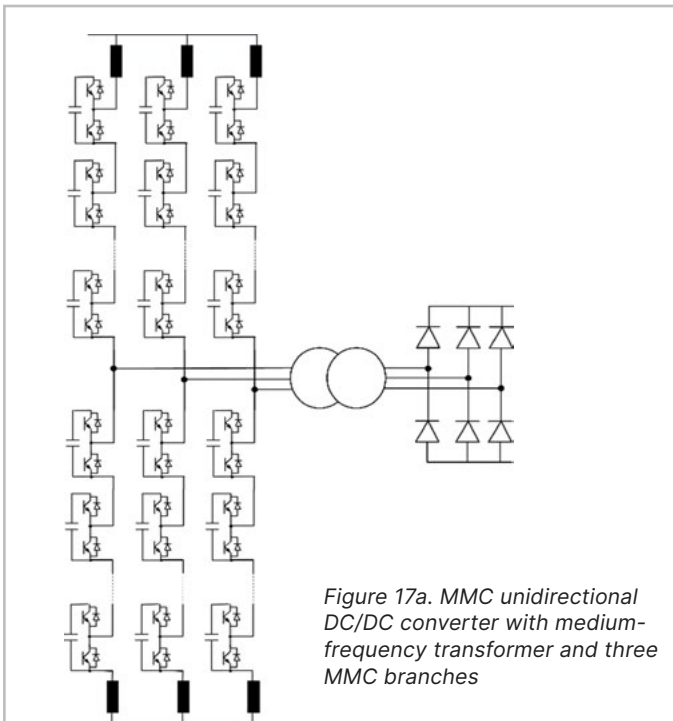


Figure 17: DC/DC converter using MMC and single medium-frequency transformer

The input stage of the converter is MMC-based, supplying a single medium-frequency transformer. The output stage is a diode bridge, necessary for the unidirectional power flow. Possible shifting of MMC cell switching can further make smaller voltage steps on the primary transformer, reducing the stress on insulation, providing a novel control of submodule capacitor voltage balancing is developed.

A DC/DC converter, using medium-frequency transformer (up to 200 Hz), reduces the weight of a transformer in a ratio of 2 (see Figure 18), while keeping current technology of grain-oriented silicon steel (GOSS) and Continuous Transposed Conductors (CTCs). On one hand, the estimated cost is reduced compared to known 50 Hz transformers. On the other hand, the power density in the core will be much higher than for a 50 Hz transformer and cooling will be a significant challenge.

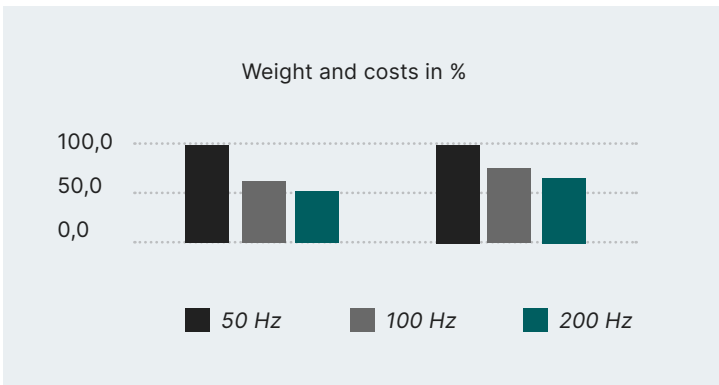


Figure 18: Estimation of transformer weight and cost versus frequency

DC Breaker for MVDC

Moving to MVDC, protection becomes critical for safety. There is a need to develop fast, compact MVDC breakers for the protection of new applications against electrical faults.

However, no commercial solution is currently available at medium/high voltages. The concepts being developed are shown in Figure 19.

- a. Interruption with static switch: the intrinsic advantage of circuit breakers based on this technology is that since they are ultra-fast, they can interrupt the current without waiting for it to cross zero (Patent US10389262B2).
- b. Interruption with hybrid technology: a hybrid-breaking solution uses both solid-state and mechanical breaking technologies. Circuit breakers are composed of IGBT semi-conductors and a vacuum interrupter associated with an ultra-fast actuator^[12].
- c. Interruption assisted with resonant current: a concept of assisted resonant current (VARC) circuit breaker that uses a mechanical vacuum interrupter (VI) together with auxiliary circuitry that creates a current zero-crossing in the internal arc during contact separation. There are others, such as the "adjustable current injection" type.

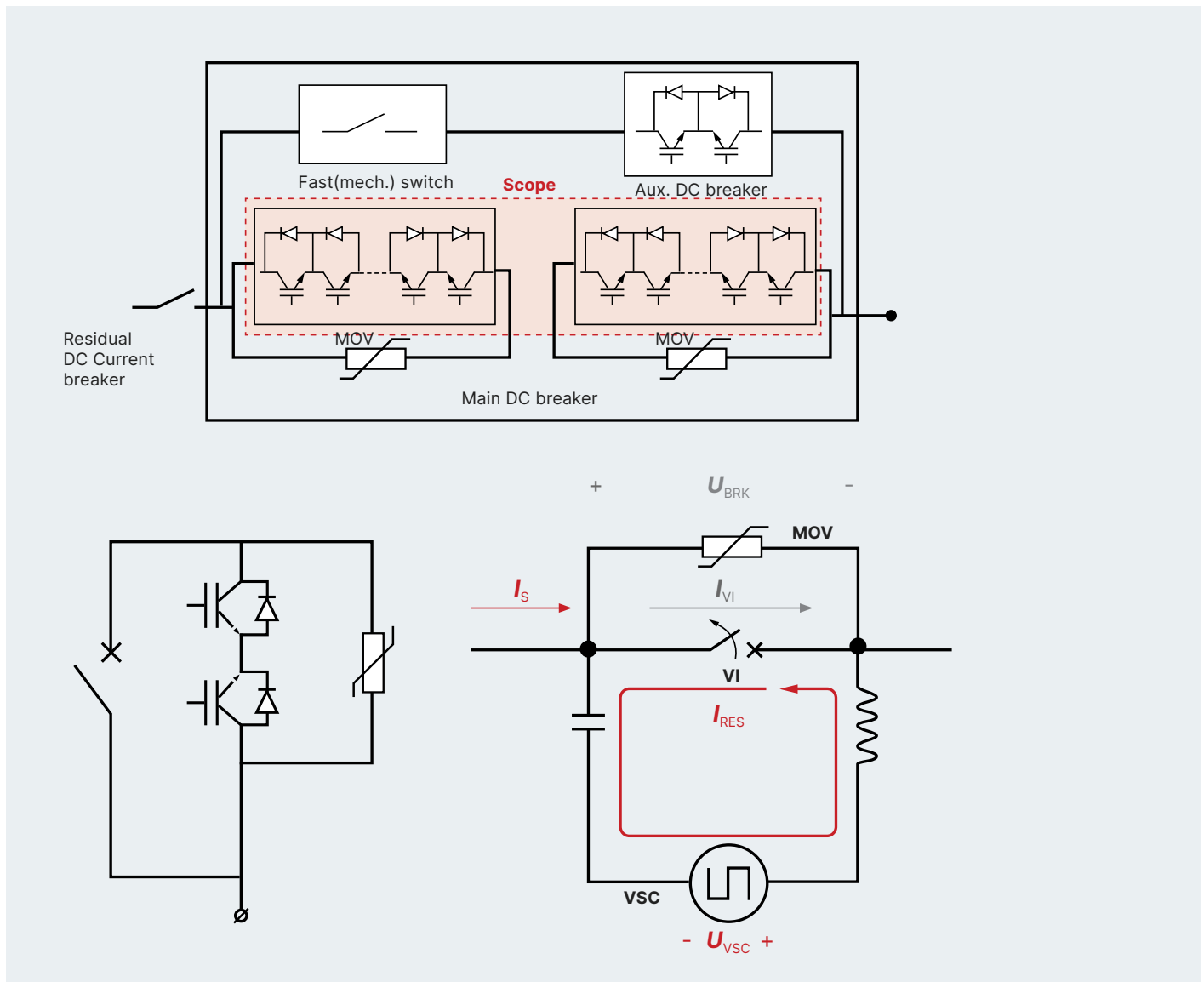


Figure 19. MVDC breaker concepts

8

CONCLUSION AND CALL FOR ACTION

MVDC is designed to enable industries to make the most out of every electron. It will help to truly harness the power of solar energy, our most abundant and reliable renewable energy source, and wind power, which is a growing contributor to the energy mix. MVDC, by regulating voltage, has significant potential to power data centers, green hydrogen gigaplants, and other electricity-intensive industries such as steel, metals, and petrochemicals. It could transform transportation by electrifying rail grids and powering ship power distribution and propulsion.

Our customers may realize savings by achieving greater energy efficiency and by eliminating costs for the equipment needed to switch between DC and AC.

At GE Vernova, we are at the forefront of driving the electrification and decarbonization of industries and power systems around the world. As the energy landscape rapidly evolves, the need for more efficient, flexible, and sustainable solutions is greater than ever. One key technology that supports this transformation is MVDC electrification ^[13].

To open this next chapter, we need to invest in more MVDC distribution infrastructure and surmount a few key technical challenges. More distribution infrastructure would allow high-intensity industries to tap into the direct current line via a substation that steps down the voltage to a range that the industrial application can use – but without converting it to AC. These lower power rating tap-off points could enable more access to DC power for remote communities or a city infeed, as well as for industrial applications.

The technology should also allow for DC connections between the photovoltaics, storage, and the grid without the loss of energy from the AC conversion, enabling better usage of solar energy.

GE Vernova is investing time, talent, and research into developing MVDC technology and DC circuit breakers. We are also working with major customers and partners to understand the technical and economic benefits of MVDC installation.

GE Vernova's Advanced Research Center's initiative to demonstrate the elements of a MVDC system at their Schenectady, NY facility is an important endeavor in advancing energy technology. By focusing on MVDC systems, the center aims to validate and showcase various system components such as converters, energy storage solutions, and potentially renewable energy sources integration. Such efforts are essential for driving innovation in energy systems and supporting the transition to more sustainable and efficient energy infrastructures.

REFERENCES

^[1] “Notes on the Jablochhoff System of Electric Lighting”. Journal of the Society of Telegraph Engineers. IX (32). Society of Telegraph Engineers: 143. March 24, 1880. Retrieved January 7, 2009 War of the currents - Wikipedia

^[2] S. Frank et al., Energy Design and Scoping Tool for DC Distribution Systems (U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, 2017)

^[2B] Daniel W. Cunningham, Isik C. Kizilyalli, and David Zhang Techno-Economic Aspect and Commercialization of MVDC Power Systems, Chapter 20. Direct current fault protection - Springer 2023

^[3] TNEI, MVDC technology study–market opportunities and economic impact (2015). [http://www.evaluationsonline.org.uk/evaluations/ Browse.do?ui=browse&action=show&id=562&taxonomy=BUI](http://www.evaluationsonline.org.uk/evaluations/Browse.do?ui=browse&action=show&id=562&taxonomy=BUI)

^[3B] “New Medium Voltage DC railway electrification system”, A. VERDICCHIO, P. LADOUX, H. CARON, C. COURTOIS
IEEE transaction on transportation electrification Vol: 4, Issue 2, June 2018, (p. 591-604)

^[4] Remote Community Supply Using DC Transmission. N M KIRBY 1, D A JACOBSON2, A G ADAMCZYK3, C D BARKER3, R S WHITEHOUSE3, 1GE Energy Connections USA, 2Manitoba Hydro Canada, 3, GE Energy Connections UK. CIGRÉ Winnipeg 2017 Colloquium, Study Committees A3, B4 & D1., Canada

^[5] Kevin Delsol, Duro Basic, Cyrille Baviere, Laurent Fahrner, Pierre-Louis Garmier, Nicolas Lapassat, Christof Sihler, Franck Terrien, “New Multi-Level Converter System for Electric Arc Furnace Applications”, AISTech 2024 — Proceedings of the Iron & Steel Technology Conference, 6–9 May 2024, Columbus, Ohio., USA, DOI: 10.33313/388/046

^[6] Y. Chen, S. Grijalva, L. Graber, Y. Seyedi, Techno-economical assessment of AC and DC power distribution architectures for Data Centers, North American Power Symposium (NAPS), Salt Lake City, Oct 9–11, 2022

^[7] Application to Angle DC: SPEN_Angle_DC_V3.pdf(spenergynetworks.co.uk)

^[8] 1709-2018-IEEE recommended practice for 1 kV to 35 kV MVDC power systems on ships; Naval Power and Energy Systems (NPES) Technology Development Roadmap (2015)

^[9] A Modular SiC High-Frequency Solid-State Transformer for Medium-Voltage applications: Design, Implementation, and Testing. Dong Dong , Member, IEEE, Mohammed Agamy , Senior Member, IEEE, Jovan Z. Bebic, Member, IEEE, Qin Chen, Member, IEEE, and Gary Mandrusiak. IEEE JOURNAL OF EMERGING AND SELECTED TOPICS IN POWER ELECTRONICS, VOL. 7, NO. 2, JUNE 2019

^[10] High Frequency Transformer Insulation in Medium Voltage SiC enabled Air-cooled Solid-State Transformers. Qin Chen, Ravisekhar Raju, Dong Dong, Mohammed Agamy General Electric Global Research Center. Schenectady, NY, 12303, USA. 2018 IEEE

^[11] High-Frequency Operation of a DC/AC/DC System for HVDC Applications
Thomas Lüth; Michaël M. C. Merlin; Tim. C. Green; Fainan Hassan; Carl D. Barker
IEEE Transactions on Power Electronics. Year: 2014 Volume: 29, Issue: 8 Journal Article Publisher: IEEE

^[12] SuperGrid Institute link to website: MVDC circuit breaker: our breakthrough HyBreak technology

^[13] TB 793 - Medium voltage direct current: (MVDC) grid feasibility study. Reference: 793 CIGRE WG C6.31. 2020

10 ACRONYMS

HVDC High-voltage direct current
MVDC Medium-voltage direct current
VSC Voltage source converter
IGBT Insulated gate base transistor
DSO Distribution system operator
PV Photovoltaic
BESS Battery energy storage solutions

EAF Electrical arc furnace
DER Distributed energy resource
SiC Silicon carbide
WBG Wide bandgap semiconductor
GOSS Grain-oriented silicon steel
FPSO Floating production storage and offloading

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governova.com/power-conversion

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