

Article

Differentiated Topology Configuration and Operating Characteristics of a Multi-Energy DC Collection System for Offshore Wind Power Integration

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Abstract

To meet the demand for large-capacity and long-distance transmission of deep-sea offshore wind power and coordinated export of multiple energy sources in coastal clean-energy bases, this paper investigates the topology configuration and operating characteristics of a multi-energy DC collection system for offshore wind power integration. Based on the characteristics of offshore wind power, nuclear power, onshore photovoltaic generation and pumped storage, a source-type-converter-topology-control-function matching relationship is established. A ± 800 kV true-bipolar DC large-bus system is then constructed, in which the four sources are configured as a lightweight offshore wind export branch, a stable power-export branch, a fast controllable renewable-energy branch and a system regulation resource, respectively. A polarity-interface conversion link is introduced to match the local offshore wind export structure with the main true-bipolar DC system, and the power-balance relationship among sending-end injection, receiving-end absorption and DC-bus voltage is formulated. PSCAD/EMTDC simulations are performed under steady-state operation, wind-speed step disturbance, a sending-end AC three-phase metallic grounding fault and a submarine-cable pole-to-ground fault. The results confirm that the proposed differentiated topology can support multi-energy collection, true-bipolar voltage coordination and continuous stable operation under typical disturbances.

Keywords: offshore wind power; multi-energy DC collection system; differentiated topology configuration; DRU-MMC series hybrid topology; operating characteristics



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1. Introduction

Under the carbon-peaking and carbon-neutrality targets and the construction of a new power system, wind power, photovoltaic generation, nuclear power, pumped storage and other clean-energy and flexibility resources are moving from dispersed integration toward base-oriented development, intensive collection and long-distance delivery. With the increasing installed capacity of renewable energy, the power-flow distribution, regulation demand and transient characteristics of power systems are changing. The export mode of clean-energy bases is also evolving from single-source and single-channel delivery to multi-energy collection, intensive transmission and coordinated receiving-end consumption.

Offshore wind power is an important component of coastal clean-energy bases. Early offshore wind farms commonly used power-frequency AC transmission, which is technically mature and structurally simple and is suitable for nearshore and medium-capacity

projects. However, as offshore wind development moves toward far offshore and deep-sea areas, the offshore distance, single-project capacity and cluster scale increase continuously. The charging reactive power of AC submarine cables becomes prominent, occupying transmission capacity and increasing the requirement for reactive compensation. Low-frequency AC transmission can reduce cable charging current by lowering the operating frequency, but it still requires frequency-conversion equipment and introduces additional requirements of protection, equipment design and system stability. When the transmission capacity and distance further increase, or when offshore wind power needs to be collected together with other clean energy sources, high-voltage DC transmission becomes more suitable in terms of long-distance capability, corridor utilization and multi-terminal interconnection [1,2].

Line-commutated-converter high-voltage DC (LCC-HVDC) has the advantages of high capacity, low loss and mature engineering experience, and is suitable for stable long-distance bulk power transmission. Nevertheless, LCCs rely on AC-system voltage for commutation and require sufficient short-circuit capacity and reactive-power support, making them unsuitable for direct connection to weak offshore AC systems. Sending-end AC faults and commutation-related disturbances in LCC-HVDC systems may cause rectifier-station overvoltage or commutation failure, and corresponding suppression and mitigation methods have therefore been investigated [3,4]. By contrast, voltage-source-converter HVDC (VSC-HVDC) can independently control active and reactive power and can support weak or passive AC networks [5]. Modular-multilevel-converter-based voltage-source-converter HVDC (MMC-HVDC) further provides high waveform quality, modular scalability and suitability for high-voltage, large-capacity applications [6]. However, for deep-sea large-capacity offshore wind farms, a full-capacity offshore MMC converter station usually leads to large platform size, high weight, high investment and difficult operation and maintenance.

To reduce offshore converter-platform requirements, diode rectifier units (DRUs) have been proposed for offshore wind DC transmission. A pure DRU solution can reduce offshore converter complexity, but the DRU is uncontrolled and cannot independently establish offshore AC voltage or provide black-start and dynamic support; thus, offshore AC voltage and frequency must be established by grid-forming wind turbines or other grid-forming equipment [7,8]. A hybrid structure combining a DRU and an auxiliary MMC can retain the lightweight advantage of the DRU while introducing controllability. DRU–MMC parallel and series hybrid structures have been proposed to combine DRU-based bulk rectification with MMC-based offshore AC voltage establishment, black-start capability and reactive-power support [9–12]. In the DRU–MMC-series hybrid topology, the DRU and the auxiliary MMC are connected in series on the DC side, so that the auxiliary MMC only withstands part of the DC voltage and provides grid-forming control, black-start capability and dynamic support [13–17]. Recent studies further indicate that the topology configuration, capacity allocation, DC-voltage sharing, power distribution and fault ride-through strategy of DRU–MMC hybrid converters directly affect the economy, stability and fault adaptability of offshore wind DC export systems [18–21]. Therefore, for deep-sea large-capacity offshore wind power transmission, it is necessary to form a reasonable converter-topology configuration strategy that balances offshore-platform lightweight design, AC-system support capability and DC export reliability.

The export demand of coastal clean-energy bases is not limited to offshore wind power alone. Offshore wind power may be developed together with nuclear power, onshore photovoltaic generation and pumped storage. If each source constructs an independent export channel, transmission corridors, landing points and receiving-end access resources may be repeatedly occupied. Connecting multiple types of energy sources to a high-voltage DC collection system can improve corridor utilization and receiving-end power accommoda-

tion. However, different sources have different output stability, regulation capability, safety constraints and grid-connection requirements. Inverter-based resources are required to provide voltage and frequency response, fault ride-through and active/reactive power control capabilities under transmission-level interconnection requirements [22]. Pumped storage can operate in generation, pumping and phase-modulation modes, and variable-speed pumped storage can further improve active-power regulation flexibility through power-electronic interfaces [23]. Therefore, a differentiated converter-interface configuration and a clear control-function division are required for multi-energy DC collection systems.

In addition, a high-voltage true-bipolar DC large bus provides a common interface for multi-source collection, positive–negative pole voltage coordination and receiving-end power sharing. Studies on pole-to-ground faults in true-bipolar MMC-HVDC grids and hybrid bipolar VSC–DRU offshore wind connections show that line coupling, pole-voltage response, fault-current evolution and interface polarity affect fault-current calculation, protection setting and non-fault-pole voltage response [24,25]. However, a true-bipolar DC large-bus structure also increases the complexity of DC fault-propagation paths and protection boundaries. HVDC circuit breakers and related hybrid, multiport, multiline and integrated breaker schemes are therefore important for current limiting, fast fault clearing and selective isolation in multi-terminal or meshed DC grids [26–32]. A multi-energy true-bipolar DC collection system therefore requires not only topology configuration but also assessment under renewable-power fluctuations, sending-end AC disturbances and DC line faults.

To summarize the above industrial background, Figure 1 compares three representative commercial HVDC configurations with the multi-energy DC collection topology investigated in this paper. Conventional LCC-HVDC is mainly used for long-distance and large-capacity bulk-power transmission, whereas MMC-based VSC-HVDC is more suitable for offshore wind integration, weak-grid connection and flexible active/reactive power control. Hybrid LCC/VSC-HVDC combines the high-capacity transmission capability of LCC terminals with the flexible regulation capability of VSC terminals. Different from these conventional point-to-point or station-level hybrid configurations, the proposed system integrates offshore wind power, nuclear power, onshore PV and pumped storage into a unified ± 800 kV true-bipolar DC collection platform through differentiated converter interfaces.

Based on the above comparison, this paper focuses on the system-level matching among source characteristics, converter topologies and control functions, rather than on the development of a single new converter topology.

Accordingly, this paper studies a multi-energy DC collection system for offshore wind power integration. The main contributions are as follows:

- (1) A source-type–converter-topology–control-function matching relationship is established for offshore wind power, nuclear power, onshore photovoltaic generation and pumped storage.
- (2) A differentiated topology configuration based on a ± 800 kV true-bipolar DC large bus is proposed.
- (3) A power-balance relationship among sending-end injection, receiving-end absorption and DC-bus voltage dynamics is formulated.
- (4) PSCAD/EMTDC simulations are conducted under steady-state operation, wind-speed step changes, a sending-end AC fault and a submarine-cable pole-to-ground fault.

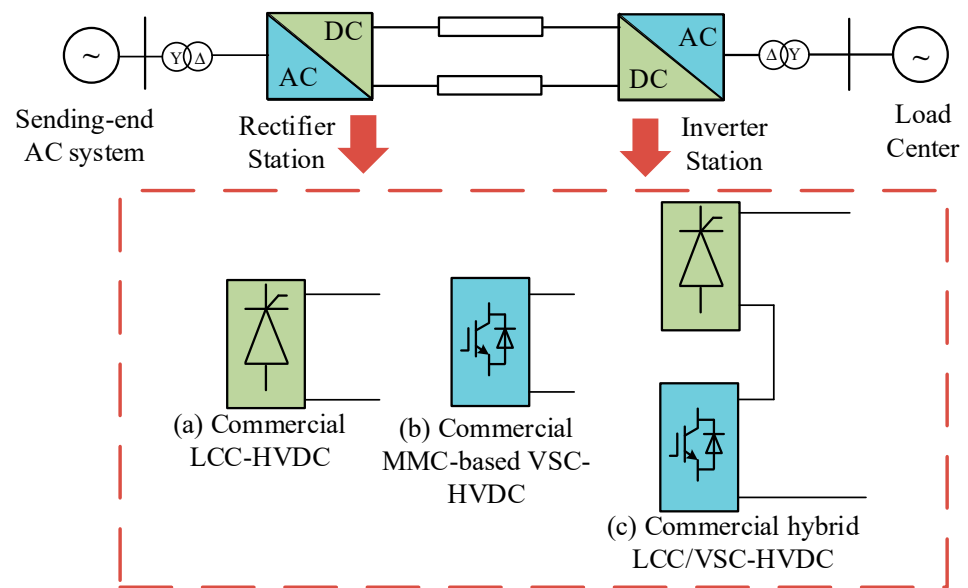


Figure 1. Representative commercial HVDC configurations.

2. Converter-Station Topologies and Mathematical Models

In a multi-energy DC collection system, converter-station topology determines the power-transmission mode, control capability, reactive-power support capability and fault response characteristics after a source is connected to the DC system. This section focuses on six topologies: DRU, MMC, LCC, DRU–MMC parallel hybrid, DRU–MMC series hybrid and LCC–MMC hybrid cascaded topologies. To facilitate subsequent operating-characteristics analysis, the basic mathematical models of these topologies are presented. Unless otherwise specified, this paper defines active power injected from the sending end into the DC bus as positive, and active power absorbed from the DC bus by the receiving end as positive.

The equivalent models used in this section are established based on classical average-value models of 12-pulse diode/line-commutated converters and dq-domain average-value models of MMC/VSC converters [33–36]. These equations are used to describe the system-level voltage, current and power relationships required for topology configuration and power-distribution analysis. They are not intended to reproduce detailed device-level switching processes.

The following assumptions are adopted unless otherwise specified: the three-phase AC-side voltage is balanced; only the fundamental-frequency component on the AC side and the average DC component on the DC side are considered; the DC-side current is continuous; converter valve losses, transformer resistance, DC cable losses and high-frequency harmonics are neglected in the basic equations; and internal switching dynamics, thermal behavior, protection-device operation and detailed submodule-voltage-balancing processes are not explicitly included. These simplifications are consistent with the system-level topology-comparison purpose of this paper.

2.1. DRU Topology

The diode rectifier unit (DRU) is an uncontrolled rectifier topology with a simple structure and low loss. It is suitable for lightweight offshore DC export, but its AC-side voltage and frequency must be established by external grid-forming equipment or an auxiliary converter. In this paper, the DRU is represented by a 12-pulse average-value rectifier model, in which the commutation effect is described by an equivalent commutation reactance. The corresponding 12-pulse DRU export topology is shown in Figure 2.

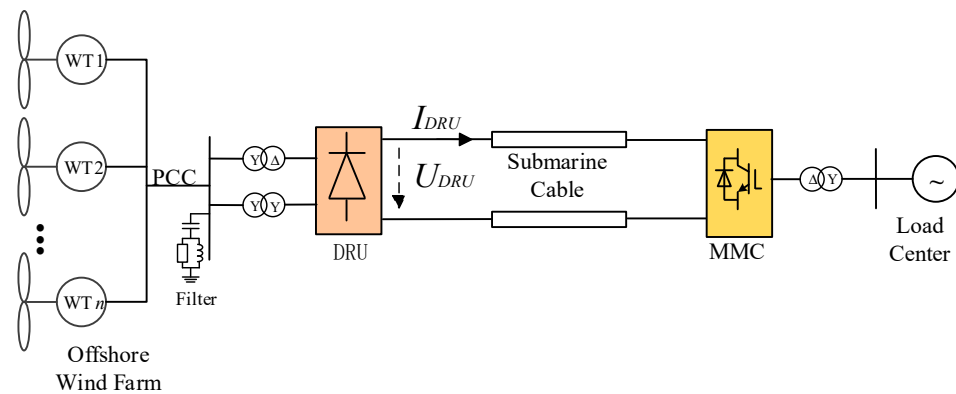


Figure 2. DRU export topology.

In Figure 2, the two converter transformers adopt different winding connections, namely Y/Y and Y/Δ. This arrangement is used to provide an approximate 30° phase shift between the two valve-side AC voltages and to form a 12-pulse diode rectifier. The two six-pulse rectifier bridges can therefore be combined on the DC side to reduce characteristic low-order harmonics and improve the DC output voltage quality. In this model, the diode valves are assumed to be ideal, the valve-side AC voltage is assumed to be balanced, the DC current is assumed to be continuous and the commutation effect is represented by an equivalent commutation reactance. Valve voltage drops, transformer resistance, converter losses and high-frequency harmonics are neglected.

Let U_v denote the valve-side line-voltage RMS value of the converter transformer, U_{DRU} the DRU DC voltage, I_{DRU} the DRU DC current, X_μ the equivalent commutation reactance, μ the commutation overlap angle and φ the power-factor angle. Then the DRU DC voltage can be written as [33,34]:

$$U_{DRU} = \frac{6\sqrt{2}}{\pi} U_v - \frac{6X_\mu}{\pi} I_{DRU} \quad (1)$$

From Equation (1), the DRU DC current can be obtained as:

$$I_{DRU} = \frac{6\sqrt{2}U_v - \pi U_{DRU}}{6X_\mu} \quad (2)$$

The active power transmitted by the DRU is:

$$P_{DRU} = U_{DRU} I_{DRU} \quad (3)$$

The relationship between the power-factor angle and the commutation overlap angle is:

$$\cos \varphi = \frac{1 + \cos \mu}{2} \quad (4)$$

It should be noted that φ in Equation (4) is not a DC-side power-factor angle. Since U_{DRU} and I_{DRU} are DC quantities, there is no phase-angle relationship between them. Here, φ represents the equivalent fundamental-frequency displacement angle on the AC side of the DRU caused by the commutation process. The reactive power absorbed by the DRU is:

$$Q_{DRU} = P_{DRU} \tan \varphi = P_{DRU} \sqrt{\frac{4}{(1 + \cos \mu)^2} - 1} \quad (5)$$

Equations (1)–(5) show that, when the DC voltage is fixed, the DRU transmitted power is positively related to the valve-side AC voltage. As the commutation reactance increases, commutation voltage drop and reactive-power absorption increase.

2.2. MMC Topology

The modular multilevel converter (MMC) has independent active- and reactive-power control capability and is suitable for offshore auxiliary support, onshore PV access, receiving-end DC-voltage control and post-fault dynamic support. The corresponding MMC export topology and the defined positive active-power direction are shown in Figure 3.

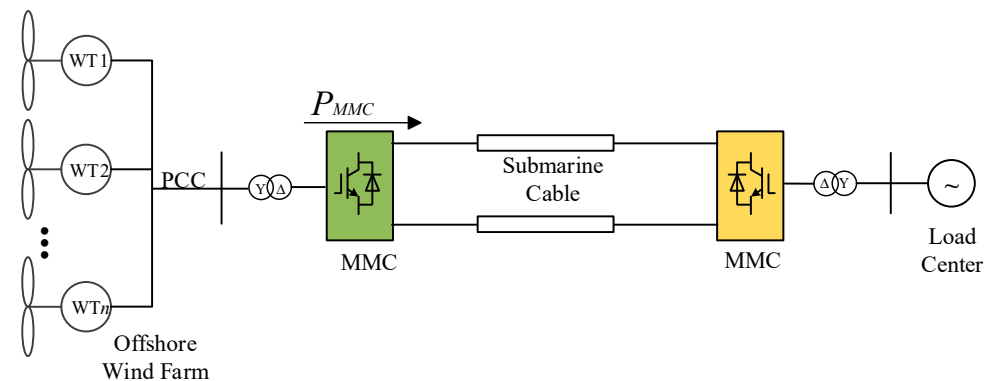


Figure 3. MMC export topology.

The MMC model is based on the dq-domain fundamental-frequency power model commonly used for VSC/MMC analysis [35,36]. Since this section focuses on the system-level power-regulation relationship of the MMC, the internal arm dynamics are not fully expanded. The three-phase AC-side voltage and current are assumed to be balanced, and the dq reference frame is adopted. The effects of circulating current, submodule capacitor-voltage balancing, switching harmonics and detailed modulation processes are not explicitly considered in the basic power equations. Under voltage-oriented control, the q-axis voltage component can be set to zero, so that active and reactive powers can be regulated mainly through the d-axis and q-axis current components, respectively.

In the dq reference frame, let u_d and u_q denote the AC-side voltage components of the MMC, and i_d and i_q the AC-side current components. In sending-end converter-station modeling, this paper defines the positive direction of the AC-side current as flowing from the AC system into the MMC. Under this positive-direction convention, the MMC AC-side active and reactive powers can be expressed as:

$$P_{MMC} = \frac{3}{2}(u_d i_d + u_q i_q) \quad (6)$$

$$Q_{MMC} = \frac{3}{2}(u_q i_d - u_d i_q) \quad (7)$$

When voltage-oriented control is adopted and $u_q = 0$, there are:

$$P_{MMC} = \frac{3}{2}u_d i_d \quad (8)$$

$$Q_{MMC} = -\frac{3}{2}u_d i_q \quad (9)$$

Thus, the MMC regulates active power mainly through the d-axis current and reactive power through the q-axis current. In this paper, the MMC equations are used to describe system-level power regulation.

2.3. LCC Topology

The line-commutated converter (LCC) is suitable for large-capacity and low-loss bulk power transmission supported by a strong AC system. The corresponding LCC export topology and the reference directions of the DC voltage and current are shown in Figure 4.

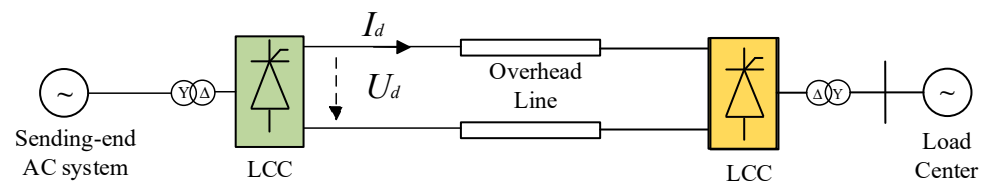


Figure 4. LCC export topology.

The LCC model is derived from the classical average-value model of a line-commutated HVDC converter [33,34]. The model assumes a balanced valve-side AC voltage, continuous DC current and steady-state operation under a given firing angle. The commutation process is represented by the equivalent commutation reactance, while valve losses, transformer resistance, DC smoothing-reactor losses and high-frequency harmonics are neglected. Therefore, the model is mainly used to describe the steady-state relationship among DC voltage, DC current, firing angle and transmitted active power.

In the steady-state average-value model, let U_d denote the LCC rectifier-side DC voltage, U_{d0} the no-load ideal DC voltage, α the firing angle, X_c the commutation reactance, I_d the DC current and U_v the converter transformer valve-side line-voltage RMS value. Then the LCC rectifier-side DC voltage can be written as:

$$U_d = U_{d0} \cos \alpha - \frac{3}{\pi} X_c I_d \quad (10)$$

$$U_d = \frac{3\sqrt{2}}{\pi} U_v \approx 1.35 U_v \quad (11)$$

The LCC active power is:

$$P_{LCC} = U_d I_d \quad (12)$$

Equations (10) and (11) show that the LCC DC voltage is jointly affected by the no-load DC voltage, firing angle, commutation voltage drop and DC current. Among these, U_{d0} is related to the AC-side voltage; therefore, an AC voltage sag directly reduces the LCC DC voltage and commutation margin. Although the LCC can regulate DC power through the firing angle and constant-current control, its control capability is constrained by AC-system strength, commutation conditions and reactive-power support capability. Therefore, the LCC is more suitable as a stable large-capacity power-transmission interface, while it is less suitable to serve as the main fast DC-voltage support and post-fault recovery control unit in weak AC systems.

2.4. DRU-MMC Parallel Topology

In the DRU-MMC parallel topology, the DRU branch and the auxiliary MMC branch are connected to the same offshore AC collection bus and are equivalently connected in parallel on the DC side. Different from the pure DRU topology, this topology introduces a controllable auxiliary MMC to establish offshore AC voltage and provide black-start capability and reactive-power support, while the DRU undertakes the main active-power rectification task. The corresponding DRU-MMC parallel export topology and the reference directions of the DC-side voltage and branch currents are shown in Figure 5.

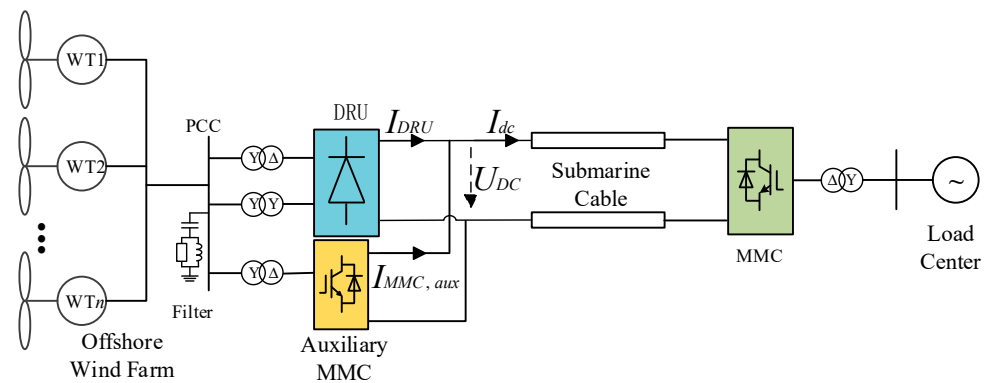


Figure 5. DRU–MMC parallel export topology.

Let U_{dc} denote the DC-side voltage of the parallel topology, I_{DRU} the DRU DC current and $I_{MMC,aux}$ the auxiliary MMC DC current. In the equivalent model that neglects branch losses and DC-side voltage differences, the total DC current is:

$$I_{dc} = I_{DRU} + I_{MMC,aux} \quad (13)$$

The total DC power is:

$$P_{dc} = U_{dc}(I_{DRU} + I_{MMC,aux}) = P_{DRU} + P_{MMC,aux} \quad (14)$$

Equations (13) and (14) describe the steady-state power-sharing relationship of the DRU–MMC parallel topology. Compared with the pure DRU topology, the auxiliary MMC improves controllability, but it still needs to withstand the common DC-side voltage of the parallel branch.

2.5. DRU–MMC Series Topology

In the DRU–MMC series topology, the DRU and the auxiliary MMC are connected in series on the DC side. The DRU undertakes the main rectification task, while the auxiliary MMC provides offshore AC-voltage support, black-start capability and dynamic regulation. The corresponding DRU–MMC series export topology and the reference directions of the DC-side voltage and current are shown in Figure 6.

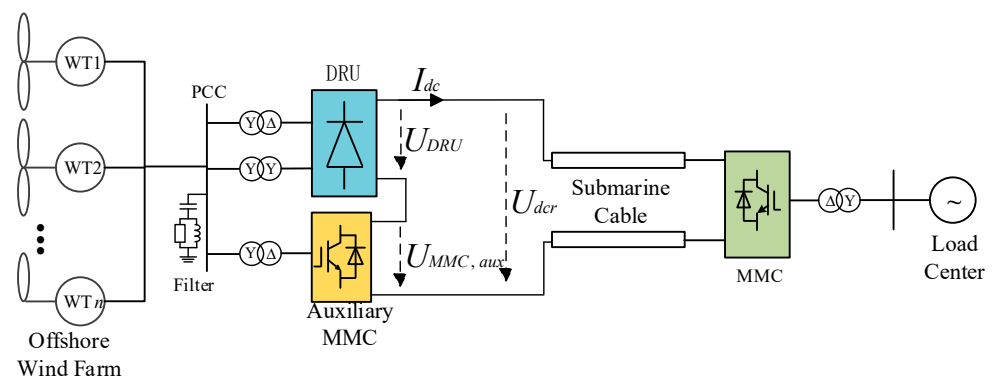


Figure 6. DRU–MMC series export topology.

Let U_{dcr} denote the DC voltage of the sending-end hybrid converter, U_{DRU} the DRU DC voltage, $U_{MMC,aux}$ the auxiliary MMC DC voltage and I_{dc} the DC current. In the steady-state model that neglects DC line voltage drop and converter losses, there is:

$$U_{dcr} = U_{DRU} + U_{MMC,aux} \quad (15)$$

Because the DRU and the MMC are connected in series on the DC side, their DC currents are identical:

$$I_{dc} = I_{DRU} = I_{MMC,aux} \quad (16)$$

The total DC power of the sending-end hybrid converter is:

$$P_{dc} = U_{dcr} I_{dc} \quad (17)$$

The active powers undertaken by the DRU and the auxiliary MMC are:

$$P_{DRU} = U_{DRU} I_{dc} \quad (18)$$

$$P_{MMC,aux} = U_{MMC,aux} I_{dc} \quad (19)$$

The voltage ratio of the auxiliary MMC is defined as:

$$k_{MMC} = \frac{U_{MMC,aux}}{U_{dcr}} \quad (20)$$

Then:

$$P_{MMC,aux} = k_{MMC} P_{dc} \quad (21)$$

$$P_{DRU} = (1 - k_{MMC}) P_{dc} \quad (22)$$

Equations (15)–(22) show that, in the series hybrid topology, the DRU and the auxiliary MMC have the same DC current, and their power sharing is mainly determined by the DC-voltage allocation between them. When the auxiliary MMC bears a lower voltage, the number of submodules and the platform scale can be reduced, but its dynamic support capability is limited by capacity and voltage ratio.

2.6. LCC–MMC Hybrid Cascaded Topology

The LCC–MMC hybrid cascaded topology combines the large-capacity and low-loss transmission capability of the LCC with the flexible control capability of the MMC. It is therefore suitable for branches requiring both bulk power transmission and dynamic regulation, such as the pumped-storage branch considered in this paper. The corresponding LCC–MMC hybrid cascaded topology and its connection with the polarity-interface conversion link are shown in Figure 7.

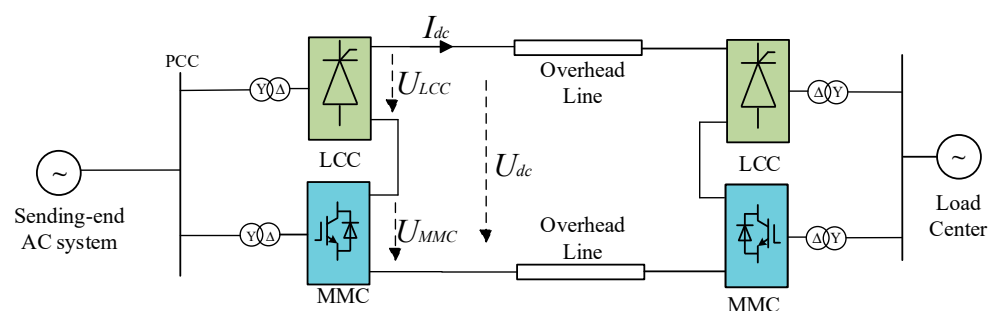


Figure 7. LCC–MMC hybrid cascaded topology.

Let U_{dc} denote the total DC voltage of the hybrid cascaded branch, U_{LCC} the LCC DC voltage, U_{MMC} the MMC DC voltage and I_{dc} the branch DC current. In the steady-state model that neglects converter losses and DC line voltage drop, there is:

$$U_{dc} = U_{LCC} + U_{MMC} \quad (23)$$

Because the LCC and the MMC are connected in series on the DC side, their DC currents are identical:

$$I_{dc} = I_{LCC} = I_{MMC} \quad (24)$$

The total active power of the branch is:

$$P_{dc} = U_{dc} I_{dc} = P_{LCC} + P_{MMC} \quad (25)$$

where:

$$P_{LCC} = U_{LCC} I_{dc} \quad (26)$$

$$P_{MMC} = U_{MMC} I_{dc} \quad (27)$$

Equations (23)–(27) are steady-state equivalent power-distribution relationships. Actual systems must also consider the capacity ratio between the LCC and the MMC, the strength of the AC access point, control and protection coordination, commutation-failure risk and fault ride-through requirements.

3. Control Strategy and Topology Configuration Scheme of the Multi-Energy DC Collection System

3.1. Differentiated Topology Configuration

To meet the intensive long-distance export demand of multiple types of clean energy, such as deep-sea offshore wind power, nuclear power, onshore PV and pumped storage, a DC collection system must not only satisfy large-capacity transmission and long-distance export requirements, but also consider the operating characteristics, regulation capability, grid-connection constraints and post-fault continuous-operation capability of different sources. Different sources differ significantly in output stability, dynamic response speed, dependence on AC-system strength and the system-support functions they can undertake. If a single converter topology is used for unified access, it is difficult to simultaneously satisfy multiple requirements, including offshore-platform lightweight design, stable large-capacity export, fast power regulation, dynamic reactive-power support and post-fault power recovery. Therefore, this paper proposes a source-type-converter-topology-control-function matching strategy: differentiated converter topologies are selected according to the physical attributes and operating requirements of different sources, and the functional positioning of each type of converter station in the multi-energy DC collection system is further clarified. The core of this strategy is not to propose a single new converter, but to establish, at the system level, an adaptation relationship between multiple types of sources and converter topologies, so that different sources can operate with functional division, complementary support and coordinated export on the same DC collection platform.

For the offshore wind DC branch, the main constraints include long offshore distance, large export capacity, high offshore-platform construction and maintenance cost, obvious wind-power fluctuation and limited offshore AC-system strength. A full-capacity offshore MMC-HVDC scheme can provide strong active/reactive power regulation and passive-network support capability, but it requires a large number of submodules, capacitors, arm reactors, cooling systems and auxiliary devices. Therefore, the full-capacity MMC scheme would significantly increase the size, weight, investment cost and operation-and-maintenance difficulty of the offshore converter platform.

A pure DRU scheme has the advantages of compact structure, low cost, high power density and simple operation control. Compared with a VSC-HVDC offshore transmission scheme, the DRU-based offshore transmission scheme can reduce the offshore converter platform volume by approximately 80%, the platform weight by approximately 65% and the total investment cost by approximately 30% [37]. However, the DRU is an uncontrolled

rectifier and cannot independently establish offshore AC voltage, provide black-start capability or offer dynamic reactive-power support. Therefore, although a pure DRU scheme is attractive in terms of platform lightweight design and economic efficiency, it is difficult for it to independently adapt to large-scale wind-power fluctuations and post-fault recovery requirements.

To further clarify the adaptability of different candidate topologies, the offshore wind branch is compared from the perspectives of converter rating, control freedom, offshore-platform lightweight characteristics, transient stability and loss level. If a full-capacity MMC scheme is adopted, the offshore converter station must withstand the full 2000 MW power rating and the full DC voltage level. This scheme has strong active-power control, reactive-power regulation and offshore AC-voltage support capabilities, but its submodule number, arm reactors, cooling equipment and platform burden are the largest. If a pure DRU scheme is adopted, the offshore converter equipment is the simplest and the loss level and platform burden are relatively low, but the scheme lacks active controllability and dynamic support capability.

By contrast, the DRU–MMC series hybrid topology allows the DRU to undertake the main rectification and bulk power-export task, while the auxiliary MMC is responsible for offshore AC-voltage establishment, reactive-power support and dynamic regulation. Taking the simulation parameters in this paper as an example, the rated power of the offshore wind branch is 2000 MW, in which the DRU is rated at 1500 MW with a rated DC voltage of 750 kV, and the auxiliary MMC is rated at 500 MW with a rated DC voltage of 250 kV. Therefore, the auxiliary MMC undertakes only about 25% of the branch power rating and about 25% of the local DC voltage. Compared with the full-capacity MMC scheme, this configuration can significantly reduce the offshore MMC rating, the number of submodules and the platform scale. Compared with the pure DRU scheme, it retains the necessary offshore AC-voltage support and dynamic regulation capability. Therefore, the DRU–MMC series hybrid topology provides a compromise among offshore-platform lightweight design, control capability and fault adaptability.

For the nuclear power branch, the main requirement is stable, large-capacity and low-loss power export. Nuclear power units have large unit capacity, stable output, high utilization hours and high reliability requirements, but they are constrained by reactor safety, thermal processes and equipment lifetime. Therefore, they should not frequently undertake fast deep regulation tasks or serve as the main fast power-balancing resource during short-term DC-system disturbances. From the converter-topology perspective, the LCC has the advantages of large capacity, low losses, mature engineering experience and suitability for long-distance bulk power transmission, which matches the stable export requirement of the nuclear branch. Thus, the nuclear branch adopts an LCC interface and is positioned for constant-power or constant-current stable export. However, because the LCC depends on AC-system commutation and requires sufficient AC-system strength and reactive-power support, it should not be assigned as the main resource for fast DC-voltage regulation or post-fault power recovery. These dynamic support functions should instead be undertaken jointly by MMC-type converter stations, the pumped-storage branch and receiving-end converter stations.

For the onshore photovoltaic branch, the output is affected by irradiance and meteorological conditions and may fluctuate rapidly, while the interface is highly power-electronic and has fast control potential. After the PV branch is connected to the multi-energy DC collection system, insufficient converter controllability may cause DC-bus voltage disturbance, receiving-end power redistribution and coupling effects on other sending-end branches. Therefore, the PV branch should not only export active power, but also participate in active-power limitation, reactive-power support and auxiliary DC-voltage control when necessary. For this reason, the

onshore PV branch adopts a true-bipolar MMC interface. The MMC can independently regulate active and reactive power and can respond rapidly to PV power variations. Compared with the LCC, the MMC does not rely on AC-system commutation; compared with the DRU, it has active regulation capability. Therefore, the PV branch is positioned as a fast controllable renewable-energy branch. During normal operation, it follows the active-power command for DC power injection; during renewable-energy fluctuations or local disturbances, it can reduce DC-bus voltage deviation through fast regulation.

For the pumped-storage branch, the LCC–MMC cascaded topology is adopted. The reason for retaining the thyristor-based LCC in this branch is not that the LCC is superior to the MMC in all aspects, but that the pumped-storage branch is characterized by large-capacity bidirectional power exchange, relatively stable power scheduling and a strong AC-side grid connection. Under this condition, the LCC can undertake the main bulk power-transfer task with mature engineering experience, high voltage and current capability, low converter loss and relatively low converter cost. By contrast, a full-capacity MMC scheme would provide stronger control flexibility, but it would also require a large number of submodules, capacitors, arm reactors, cooling equipment and auxiliary devices, thereby increasing the converter-station scale and investment cost. The MMC part in the LCC–MMC cascaded topology is used to compensate for the main limitations of the LCC. It provides flexible voltage regulation, reactive-power support, dynamic power adjustment and improved post-fault recovery capability. Therefore, the proposed LCC–MMC cascaded interface is a compromise between the high-capacity and low-loss characteristics of the LCC and the flexible control capability of the MMC. This configuration is especially suitable for source branches that require both bulk power transfer and dynamic regulation support, such as the pumped-storage branch considered in this paper.

To coordinate the differentiated converter interfaces of the four source branches, this paper proposes a hierarchical coordinated control framework for the multi-energy DC collection system. The framework consists of a source-side branch control layer, a DC-bus coordination layer and a receiving-end power accommodation layer. In the source-side branch control layer, each converter station is assigned different control functions according to its source characteristics and topology. The offshore wind DRU–MMC series branch uses the DRU for main active-power rectification and bulk power export, while the auxiliary MMC provides offshore AC-voltage and frequency support, black-start capability, reactive-power support and local dynamic regulation. The nuclear LCC branch mainly operates under constant-current or constant-power control and is responsible for stable large-capacity power export, rather than fast DC-voltage regulation. The onshore PV MMC branch follows the active-power command under normal operation and can participate in reactive-power support and auxiliary DC-voltage regulation when renewable-power fluctuation occurs. The pumped-storage LCC–MMC cascaded branch combines the large-capacity transmission function of the LCC with the dynamic regulation capability of the MMC, and therefore serves as an important controllable resource for power balancing and post-disturbance recovery.

In the DC-bus coordination layer, the main objective is to maintain the power balance of the multi-source DC collection system and the voltage coordination of the ± 800 kV true-bipolar DC large bus. The receiving-end MMC stations act as the primary DC-voltage regulation units. When the injected power from offshore wind or PV changes, the receiving-end MMCs adjust their absorbed power according to the DC-bus voltage deviation and their capacity margins. Meanwhile, the PV MMC and the MMC part of the pumped-storage branch can provide auxiliary regulation to suppress DC-voltage fluctuation. The nuclear LCC branch is kept as a relatively stable power-export branch to avoid frequent deep power adjustment. In

this way, fast controllable branches and receiving-end MMC stations undertake short-term power balancing, while stable sources mainly provide base power injection.

In the receiving-end power accommodation layer, the parallel receiving-end MMC terminals share the collected DC power and transfer it to different AC systems or load centers. Under normal operation, the receiving-end terminals share the absorbed power according to their scheduled power commands or capacity margins. When one receiving-end AC system is disturbed or its power-absorption capability is reduced, the remaining receiving-end MMC terminals can participate in power redistribution, thereby reducing the power imbalance on the main DC bus. During DC faults, multi-port DC circuit breakers are coordinated with converter controls to isolate the faulted branch, limit fault-current propagation and maintain the continuous operation of non-fault branches as much as possible. Through this hierarchical control framework, the differentiated source-side topology configuration can be transformed into coordinated system-level operation.

After the differentiated source-side converter topologies are configured, the main DC system needs a unified wiring form to reduce the interface complexity caused by multi-branch access. The true-bipolar DC structure has clear positive- and negative-pole transmission paths, explicit pole-to-pole voltage relationships and relatively clear fault boundaries. It is therefore suitable for unified access of multiple source branches and high-voltage DC collection. Compared with pseudo-bipolar or asymmetric local export structures, the true-bipolar structure provides clearer system boundaries for positive/negative pole-voltage coordination, pole-to-ground fault analysis, pole-to-pole fault identification and non-fault-pole continuous operation. Accordingly, the main DC system in this paper adopts a true-bipolar interface as the unified access form. For local branches such as the offshore wind DC branch, a pseudo-bipolar or asymmetric export structure may be adopted due to offshore-platform lightweight design, insulation configuration or converter-station structure simplification. Before connection to the main DC system, a polarity-interface conversion link is used to match the local branch with the main true-bipolar DC bus.

To further clarify the connection between the local offshore wind export branch and the main true-bipolar DC bus, the topology of the polarity-interface conversion link is shown in Figure 8. The interface consists of four MMC-based conversion units arranged in two pole branches. The upper branch is connected to the positive-pole side of the main DC bus, while the lower branch is connected to the negative-pole side. The neutral point of the main true-bipolar DC system is grounded, so that the positive and negative pole voltages can be explicitly established with respect to the ground reference. Through this interface, the local offshore wind DC export structure can be transformed into a true-bipolar form before being connected to the ± 800 kV main DC large bus.

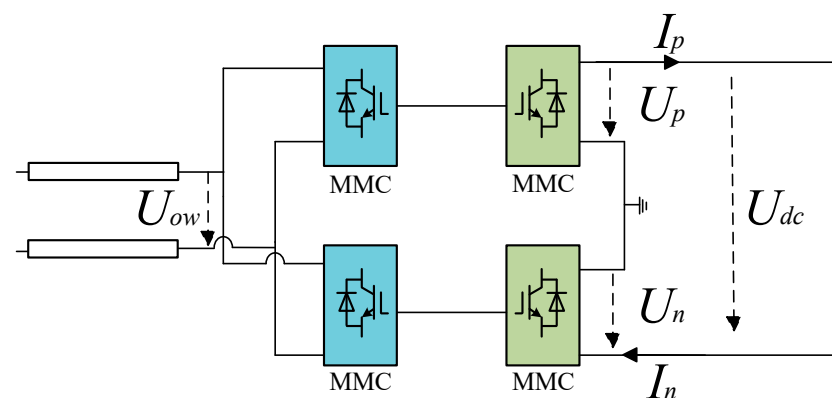


Figure 8. Polarity-interface conversion link between the offshore wind branch and the main true-bipolar DC bus.

Let U_p and U_n denote the positive- and negative-pole voltages of the main true-bipolar DC bus with respect to the grounding point, respectively. Under symmetrical operation, they satisfy:

$$U_p \approx +U_{dc}/2 \quad (28)$$

$$U_n \approx -U_{dc}/2 \quad (29)$$

The local offshore wind export branch may have a pseudo-bipolar or asymmetric DC-side structure because of offshore-platform lightweight design and insulation simplification. Therefore, the voltage of the local offshore wind branch cannot be directly regarded as identical to the pole voltage of the main true-bipolar DC bus. The polarity-interface conversion link provides voltage-level matching and polarity conversion between the local offshore branch and the main DC bus. If the local offshore wind DC-side voltage is denoted by U_{ow} , and the equivalent voltage conversion ratio of the polarity-interface link is denoted by k_{pic} , the voltage matching relationship can be expressed as:

$$U_{dc} = k_{pic} U_{ow} \quad (30)$$

When losses in the polarity-interface conversion link are neglected, the active power injected from the offshore wind branch into the main DC bus satisfies:

$$P_{ow} = P_{dc} = U_{dc} I_{dc} \quad (31)$$

The polarity-interface conversion link therefore does not change the basic power source of the offshore wind branch. Its main function is to complete the voltage-level matching, grounding reference establishment and polarity conversion between the local offshore wind export structure and the main true-bipolar DC large bus. In addition, because the interface is based on MMC conversion units, it can also provide auxiliary voltage regulation and improve the controllability of the connection between the offshore wind branch and the main DC collection system.

On the basis of the unified true-bipolar interface, a DC large bus is adopted as the multi-energy power collection platform. The DC large bus can collect offshore wind power, nuclear power, onshore PV and pumped storage at the same DC voltage level. This avoids repeated construction of independent export channels, repeated occupation of transmission corridors and scattered receiving-end access points. For coastal and nearshore clean-energy bases, different sources may be geographically concentrated at the sending end, while receiving-end load centers may be located far away. The DC large-bus structure is therefore conducive to multi-source collection at the sending end, intensive use of transmission corridors and coordinated accommodation at the receiving end. From the system-operation perspective, the DC large bus is not only an electrical connection node, but also the core platform for multi-energy power collection, cross-regional transmission, receiving-end accommodation and post-fault power redistribution.

At the receiving end, a parallel multi-terminal MMC structure is adopted to absorb the power collected by the DC large bus and distribute it to different receiving-end AC systems or load centers. Compared with a single receiving-end converter station, this structure improves receiving-end accommodation flexibility and operating redundancy. When one receiving-end AC system is disturbed or its power-absorption capability is limited, other receiving-end terminals can participate in power redistribution within their capacity margins.

However, the multi-energy DC large bus and the receiving-end parallel multi-terminal structure also increase the complexity of DC fault-propagation paths and protection boundaries. Once a DC line or branch fault occurs, the fault current rises rapidly and has no natural zero crossing. If the fault branch cannot be quickly identified and isolated, the

DC-bus voltage may drop significantly and affect the continuous operation of non-fault branches. Therefore, multiport DC circuit breakers are configured at key DC collection nodes or branches. They are used for selective isolation of DC fault branches, fault-current limitation, interruption and energy absorption, while maintaining the power-transmission capability of non-fault branches as much as possible.

3.2. Adaptability Analysis of the Topology Scheme

In the multi-energy DC collection system, the total sending-end injected power is composed of the offshore wind DC branch, nuclear branch, onshore PV branch and pumped-storage branch, and can be expressed as:

$$P_{in} = P_{WF} + P_N + P_{PV} + P_{PS} \quad (32)$$

where P_{in} denotes the total active power injected by the multi-source sending end into the main DC bus; P_{WF} , P_N , P_{PV} and P_{PS} denote the active powers injected into the main DC bus by the offshore wind DC branch, nuclear branch, onshore PV branch and pumped-storage branch, respectively.

The receiving-end parallel multi-terminal structure is used to accommodate the multi-energy power collected by the main DC large bus. Let P_{out} denote the total receiving-end absorbed power, P_{loss} the system loss and W_{dc} the equivalent electromagnetic energy storage of the main DC system. Then the system power-balance relationship can be written as:

$$P_{in} = P_{out} + P_{loss} + \frac{dW_{dc}}{dt} \quad (33)$$

It should be noted that W_{dc} is not the energy of an additionally configured energy-storage device. Instead, it represents the electromagnetic energy temporarily stored in the DC-side capacitive elements of the system. In a multi-terminal DC collection system, this energy is not only associated with the concentrated capacitance of the main DC bus, but also with the submodule capacitors of MMC converter stations and the distributed capacitances of long DC lines and submarine cables. Therefore, W_{dc} can be further expressed as:

$$W_{dc} = W_{bus} + \sum_{i=1}^n W_{MMC,i} + W_{line} \quad (34)$$

where W_{bus} denotes the energy stored in the equivalent capacitance of the main DC bus; $W_{MMC,i}$ denotes the equivalent DC-side energy contribution of the submodule capacitors of the i -th MMC station; W_{line} denotes the energy stored in the distributed capacitances of DC overhead lines and submarine cables; and n is the number of MMC stations connected to the DC system.

For the main DC bus, the stored energy can be written as:

$$W_{bus} = \frac{1}{2} C_{bus} U_{dc}^2 \quad (35)$$

For the i -th MMC station, the submodule-capacitor energy can be described as the sum of the capacitor energies of all inserted and bypassed submodules:

$$W_{MMC,i} = \sum_{a=1}^6 \sum_{j=1}^{N_i} \frac{1}{2} C_{SM,i} u_{SM,i,a,j}^2 \quad (36)$$

where $C_{SM,i}$ is the submodule capacitance of the i -th MMC station, $u_{SM,i,a,j}$ is the capacitor voltage of the j -th submodule in the a -th arm and N_i is the number of submodules per arm. In system-level average-value analysis, the internal submodule-voltage-balancing

dynamics are usually not expanded explicitly. Therefore, the submodule-capacitor energy of each MMC can be equivalently mapped to the DC side as:

$$W_{\text{MMC},i} \approx \frac{1}{2} C_{\text{MMC},i,\text{eq}} U_{\text{dc},i}^2 \quad (37)$$

where $C_{\text{MMC},i,\text{eq}}$ represents the equivalent DC-side capacitance contribution of the i -th MMC station, and $U_{\text{dc},i}$ denotes the corresponding DC-side voltage of this converter station.

For long DC lines and submarine cables, the distributed capacitance also contributes to the DC-side transient energy. If the per-unit-length capacitance is denoted by $c'(x)$, the stored energy can be expressed as:

$$W_{\text{line}} = \frac{1}{2} \int_0^l c'(x) u_{\text{dc}}^2(x, t) dx \quad (38)$$

where l is the line or cable length, and $u_{\text{dc}}(x, t)$ is the instantaneous DC voltage distribution along the line or cable. For system-level analysis, the line and cable distributed capacitances can be further represented by an equivalent capacitance $C_{\text{line},\text{eq}}$.

Accordingly, the total equivalent capacitance of the main DC system can be written as:

$$C_{\text{eq}} = C_{\text{bus}} + \sum_{i=1}^n C_{\text{MMC},i,\text{eq}} + C_{\text{line},\text{eq}} \quad (39)$$

Then, the equivalent DC-side stored energy can be simplified as:

$$W_{\text{dc}} = \frac{1}{2} C_{\text{eq}} U_{\text{dc}}^2 \quad (40)$$

Substituting Equation (40) into Equation (33), the DC-bus voltage dynamic relationship can be obtained as:

$$C_{\text{eq}} U_{\text{dc}} \frac{dU_{\text{dc}}}{dt} = P_{\text{in}} - P_{\text{out}} - P_{\text{loss}} \quad (41)$$

Equation (41) shows that the dynamic variation of the main DC-bus voltage is determined by the instantaneous power imbalance among the sending-end injected power, receiving-end absorbed power and system losses, as well as by the equivalent DC-side capacitance of the whole system. Compared with a simplified model that only considers the main DC-bus capacitance, the expanded expression of C_{eq} explicitly includes the equivalent contribution of MMC submodule capacitors and the distributed capacitances of long DC lines and submarine cables. Therefore, the model better reflects the capacitive-energy coupling among converter stations, DC lines and the main DC bus.

When the sending-end injected power is greater than the sum of receiving-end absorbed power and system losses, the equivalent electromagnetic energy on the DC side increases and the main DC-bus voltage tends to rise. Conversely, when the sending-end injected power is lower than the receiving-end absorbed power and system losses, the stored DC-side energy decreases and the DC-bus voltage tends to drop. Therefore, the operating adaptability of the multi-energy DC collection system essentially depends on the coordination among source-side power injection, receiving-end power accommodation, MMC submodule-capacitor energy buffering, line distributed-capacitance effects and the dynamic regulation of controllable branches.

4. Numerical Simulation

4.1. Simulation System Parameters

To study the operating characteristics of the proposed multi-energy DC collection system, a system-level electromagnetic transient model based on a ± 800 kV true-bipolar

DC large bus was established in PSCAD/EMTDC. The model was compiled using the Intel Fortran compiler. A fixed simulation time step of 20 μ s was adopted, and the total simulation duration of each operating case was set to 15 s. The Euler method was used as the time-domain numerical solver. Since a fixed-step explicit time-domain solution was adopted, no additional nonlinear iterative convergence criterion was imposed. The numerical comparability of different cases was ensured by using the same simulation step size, solver setting, converter parameters, line parameters and control settings.

In the present study, the DRU, LCC and MMC stations were represented by system-level electromagnetic transient average-value models. These models focus on the main voltage, current, power and control-response characteristics of converter stations, rather than device-level semiconductor switching processes. Therefore, the model is suitable for evaluating DC-bus voltage dynamics, source-side power redistribution, receiving-end power accommodation and fault-response characteristics of the proposed multi-energy DC collection system.

It should be noted that the numerical model is not intended to exactly reproduce a specific commissioned power system or a particular industrial installation. Instead, it is used as an engineering-equivalent model to evaluate the system-level dynamic behavior and relative operating characteristics of the proposed topology under unified assumptions. The model can reasonably reflect the dominant electromagnetic transient responses related to DC voltage variation, branch power transfer, converter-interface coordination and post-fault recovery. However, detailed semiconductor switching losses, thermal behavior, submodule-level voltage-balancing dynamics, device-level protection actions and parameter deviations in practical engineering installations are not explicitly considered. Therefore, the simulation results are mainly used to verify the feasibility and comparative operating characteristics of the proposed topology, rather than to provide final equipment-level design parameters for a specific project.

The main system parameters are listed in Table 1. The offshore wind branch adopts a local DRU–MMC series hybrid export structure. According to the voltage allocation of this local branch, the DRU side is rated at 750 kV and the auxiliary MMC side is rated at 250 kV, forming a local 1000 kV DC export voltage. Before being connected to the main DC large bus, the offshore wind branch is interfaced through a symmetric/pseudo-bipolar conversion device, by which the local 1000 kV offshore DC export structure is converted and matched to the ± 800 kV true-bipolar main DC bus. In this way, the local offshore wind export branch can be connected to the unified true-bipolar DC collection platform together with the nuclear power, onshore PV and pumped-storage branches. The topology diagram is shown in Figure 9.

Table 1. Main simulation parameters.

Sending/Receiving Side	Equipment	Item	Parameter
Offshore wind side	Wind farm	Rated power	2000 MW
		Transformer ratio	0.69/66 kV
	12-pulse DRU	Rated power	1500 MW
		Rated DC voltage	750 kV
		Converter transformer ratio	66/300 kV
		Converter transformer leakage reactance	0.15 pu
	Auxiliary MMC	Rated power	500 MW
		Rated DC voltage	250 kV
		Link transformer ratio	66/125 kV
		Number of submodules per arm	100
Grid frequency		50 Hz	
Photovoltaic	PV unit	Rated power	2000 MW
	MMC (per pole converter group)	Rated power	1000 MW
		Rated DC voltage	800 kV
		Number of submodules per arm	100

Table 1. Cont.

Sending/Receiving Side	Equipment	Item	Parameter
Nuclear power	Nuclear unit	Rated power	2000 MW
	LCC (per pole converter group)	Rated power Transformer ratio Rated DC voltage	1000 MW 220/380 kV 800 kV
	Pumped-storage unit	Rated power	1800 MW
Pumped storage	LCC (per pole converter group)	Rated power Transformer ratio Rated DC voltage	400 MW 220/172 kV 400 kV
	MMC (per pole converter group)	Rated power Rated DC voltage Number of submodules per arm	500 MW 400 kV 100
Receiving-end AC system	Inverter-side MMC (per pole of each receiving terminal)	Rated power	2000 MW
		Rated DC voltage	800 kV
		Grid AC voltage	220 kV
		Grid frequency	50 Hz

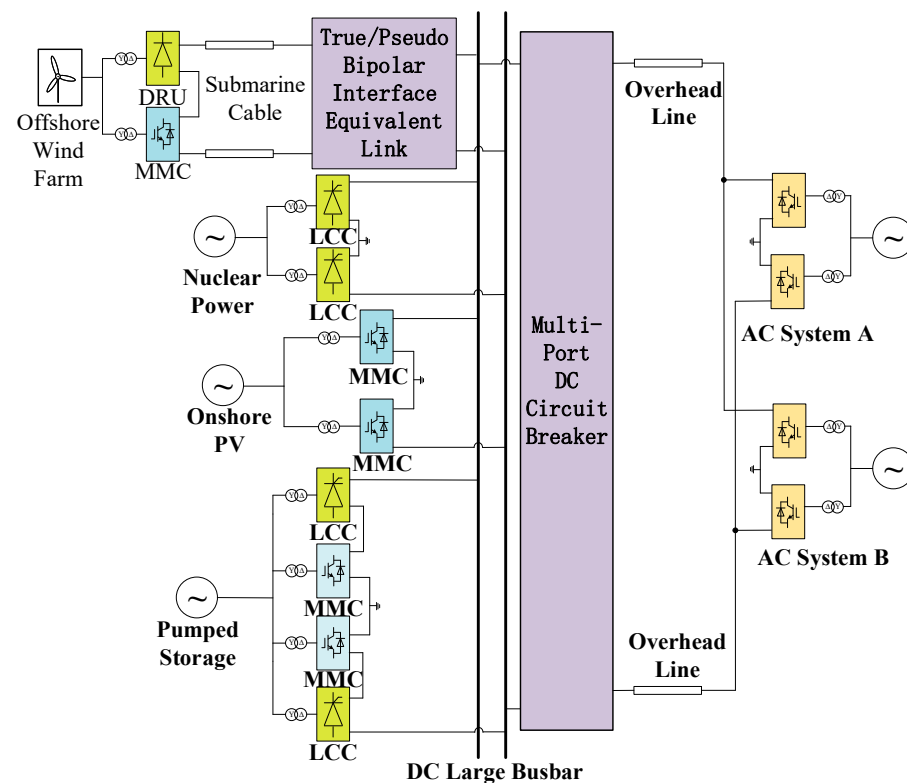


Figure 9. Topology of the multi-energy collection system.

4.2. Steady-State Operation Simulation

The steady-state operation case is used to verify the basic power-collection capability, DC-bus voltage stability and receiving-end power-sharing performance of the proposed multi-energy DC collection system. In this case, the offshore wind, nuclear, onshore PV and pumped-storage branches operate according to their scheduled power commands, while the receiving-end converter stations absorb the collected power and maintain the DC-bus voltage.

Figure 10 presents the steady-state waveforms of the main DC voltage, sending-end active powers, receiving-end power sharing and the internal voltage distribution of the offshore-wind DRU–MMC series branch. After the initial startup transient, the system gradually enters stable operation at approximately 1 s. The main DC line voltage stabilizes near 1600 kV, while the positive- and negative-pole voltages remain around +800 kV and

−800 kV, respectively. No sustained pole-voltage offset or low-frequency oscillation is observed, indicating that the ± 800 kV true-bipolar DC large bus can maintain coordinated bipolar voltage operation under multi-source power injection.

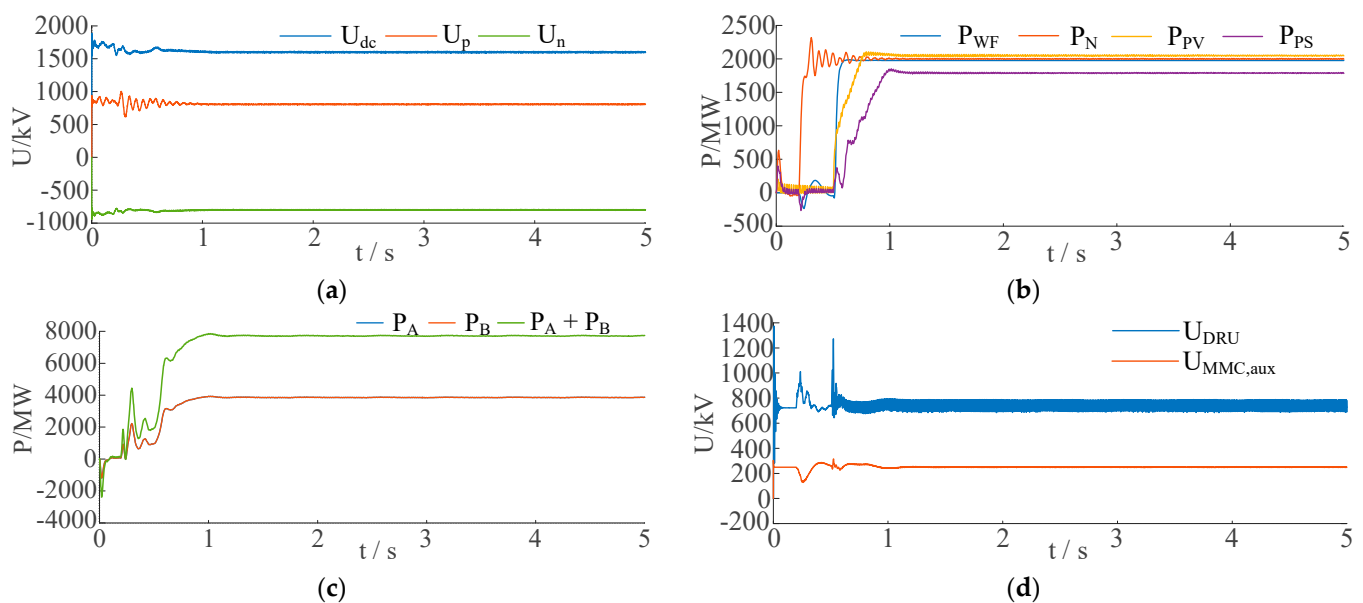


Figure 10. Steady-state waveforms: (a) main DC line voltage waveforms; (b) active power waveforms at sending ends; (c) power-sharing waveforms of parallel receiving ends; (d) offshore-wind DRU-MMC-series-branch internal voltage waveforms.

The sending-end active powers also converge to their scheduled operating points after a short transient process. The offshore wind, nuclear, onshore PV and pumped-storage branches stabilize at approximately 2000 MW, 2000 MW, 2000 MW and 1800 MW, respectively. This result shows that the differentiated converter interfaces can support the parallel access and stable power injection of multiple source types. Meanwhile, the total receiving-end absorbed power stabilizes at about 7600–7800 MW after system losses are considered, and the two receiving-end terminals share the collected power with similar magnitudes. This indicates that the receiving-end parallel MMC structure can effectively accommodate the power collected by the DC large bus and realize stable power sharing.

For the offshore-wind DRU-MMC series branch, an obvious transient voltage peak appears on the DRU-side voltage during the initial energization stage. The peak value is approximately 1.3 MV, which is higher than the steady-state DRU-side voltage. This peak occurs before the system enters the stable operating point and is mainly caused by the transient charging process and electromagnetic energy exchange among the converter equivalent capacitors, DC-line distributed capacitances and branch inductive elements during startup. Therefore, this peak should be interpreted as an initial energization transient of the system-level electromagnetic transient model, rather than as the normal steady-state voltage of the DRU-MMC series branch.

After the initial startup transient is damped, the DRU-side voltage gradually stabilizes around 750 kV, while the auxiliary MMC voltage remains near 250 kV. According to the voltage-sharing relationship of the series hybrid topology, the auxiliary MMC voltage ratio is approximately 0.25. This confirms that the DRU undertakes the main rectification voltage and power-export task, while the auxiliary MMC only bears part of the DC voltage and provides offshore AC-voltage support and dynamic regulation. In practical engineering applications, pre-charging control, voltage-ramp control and overvoltage limitation should be further designed to suppress the initial transient overvoltage. Therefore, the steady-

state results verify that the proposed topology can realize multi-energy power collection, true-bipolar voltage coordination and stable receiving-end power accommodation after the startup transient.

4.3. Wind-Speed Variation Simulation

To evaluate the influence of offshore wind-power fluctuation on the proposed multi-energy DC collection system, a wind-speed step-change case is conducted. The system is assumed to reach rated operation at $t = 2$ s. The wind speed decreases stepwise from 12 m/s to 10 m/s, 8 m/s, 6 m/s and 4 m/s at 4 s, 6 s, 8 s and 10 s, respectively, and then recovers to 12 m/s at 12 s. This case is used to examine whether the system can maintain DC-bus voltage stability, multi-source coordinated operation and receiving-end power accommodation under large offshore wind-power variation.

Figure 11 presents the overall dynamic response of the system under the wind-speed step changes. As the wind speed decreases, the active power of the offshore wind branch decreases accordingly and enters the corresponding operating points. When the wind speed recovers to 12 m/s, the offshore wind power also returns to the rated level. During this process, the internal voltage distribution of the DRU–MMC series branch remains basically stable after the initial startup transient. It should be noted that the high voltage peak in Figure 10c appears mainly during the initial energization stage before the wind-speed step sequence, rather than at the wind-speed step instants. Since the system is assumed to reach rated operation before the wind-speed variation process, this initial peak is associated with DC-side charging and converter-control establishment. After the startup transient, the DRU continues to bear the main DC voltage, while the auxiliary MMC remains at a lower voltage level. At the wind-speed step instants, only limited transient voltage disturbances occur, and the voltage-sharing relationship between the DRU and the auxiliary MMC is maintained.

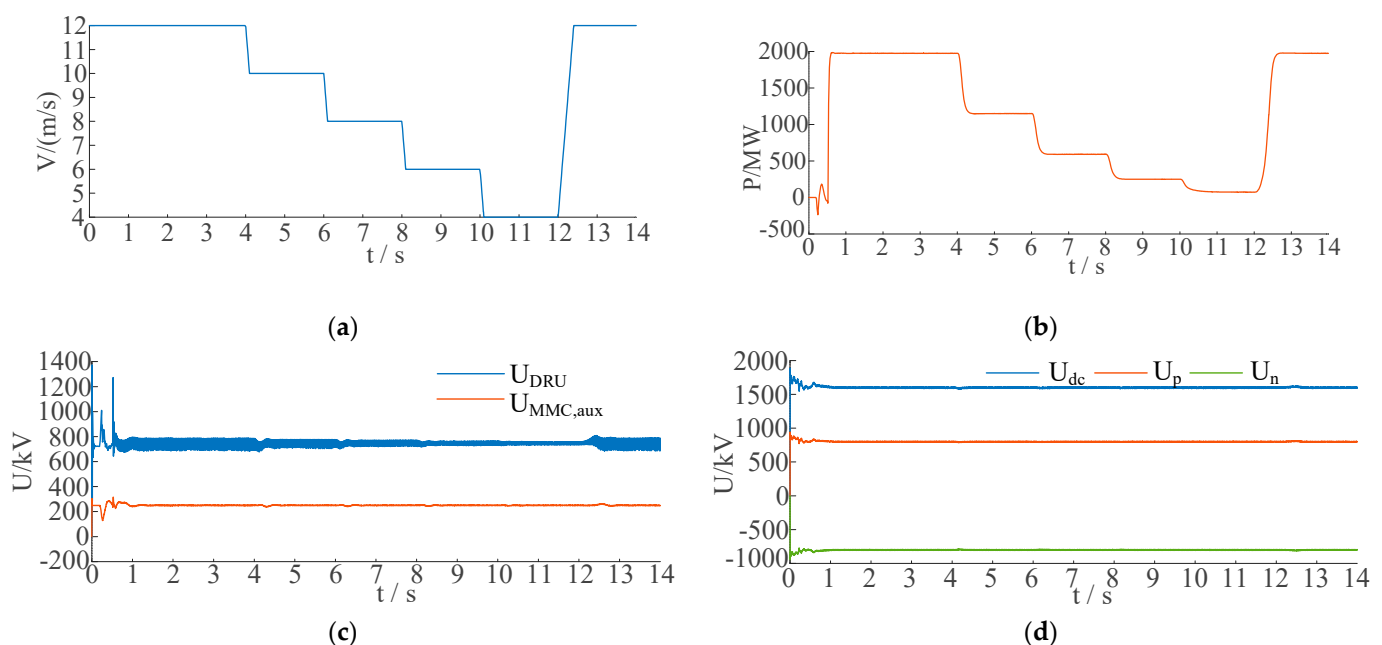


Figure 11. Cont.

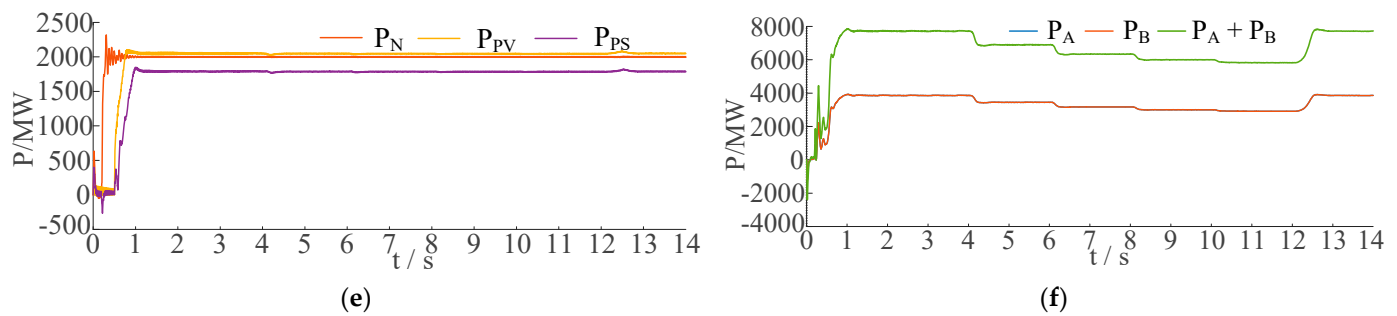


Figure 11. Wind-speed step-change waveforms: (a) wind speed step-change waveform; (b) active power of offshore wind farm; (c) offshore-wind DRU–MMC-series-branch internal voltage waveforms; (d) main DC line voltage waveforms; (e) active power waveforms at other sending ends; (f) power-sharing waveforms of parallel receiving ends.

Although the offshore wind power changes significantly, the main DC line voltage remains close to 1600 kV, and the positive- and negative-pole voltages remain around +800 kV and −800 kV, respectively. Only small transient fluctuations appear at the wind-speed step instants, and no sustained voltage deviation or oscillatory instability occurs. From the power-balance perspective, the decrease in offshore wind power reduces the total sending-end injected power. However, the stable DC-bus voltage response shows that the receiving-end power adjustment and the coordinated operation of other source branches can suppress the resulting power imbalance.

The nuclear, onshore PV and pumped-storage branches remain generally stable during the wind-speed variation, with only slight transient deviations at the step instants. This indicates that the wind-speed disturbance is mainly confined to the offshore wind branch and does not cause obvious power instability in the non-disturbed source branches. At the receiving end, the total absorbed power changes consistently with the offshore wind-power variation, while the two receiving-end terminals maintain similar power-sharing behavior. Therefore, the receiving-end parallel MMC structure can adjust its absorbed power according to the collected sending-end power and maintain coordinated receiving-end operation.

Overall, the wind-speed step-change simulation shows that the proposed system can accommodate large offshore wind-power fluctuations. The offshore wind branch can move to the corresponding operating points with wind-speed variation, the true-bipolar DC large bus can maintain voltage coordination, the non-disturbed source branches can continue operating and the receiving-end parallel terminals can share the varying collected power. These results verify the operating adaptability of the proposed multi-energy DC collection system under renewable-power fluctuation.

4.4. Three-Phase Short-Circuit Simulation of the Sending-End AC System

To analyze the response of the proposed topology under a severe AC-side disturbance, this paper sets a three-phase metallic grounding short-circuit fault at the sending-end AC bus of the offshore wind branch. Although single-phase-to-ground faults occur more frequently in practical AC systems, a three-phase metallic grounding fault causes the deepest symmetrical voltage depression at the offshore AC bus and almost completely removes the AC voltage required for DRU rectification. Therefore, it is used in this study as a conservative stress case to examine the fault-withstand capability of the DRU–MMC series branch, the voltage coordination of the true-bipolar DC bus and the power redistribution capability of the receiving-end parallel MMCs.

In the simulation, the system has reached rated operation at $t = 2$ s. A three-phase metallic grounding fault with a fault resistance of 0.01Ω occurs at $t = 3$ s and is cleared after lasting for 0.5 s. The fault waveforms are shown in Figure 12. The fault resistance of 0.01Ω

is used to approximate a metallic grounding short-circuit fault. This value represents a severe low-impedance fault condition rather than a high-resistance grounding fault. The fault resistance directly affects the residual AC-bus voltage and fault current. A larger fault resistance would result in a higher residual AC-bus voltage, a smaller reduction in DRU rectification power, weaker disturbance of the internal DRU–MMC voltage sharing and milder receiving-end power redistribution. In contrast, the near-metallic fault considered here leads to the most severe voltage-collapse condition at the offshore AC bus. Therefore, the case with $R_f = 0.01 \Omega$ is adopted as a conservative evaluation condition for the fault response of the proposed topology.

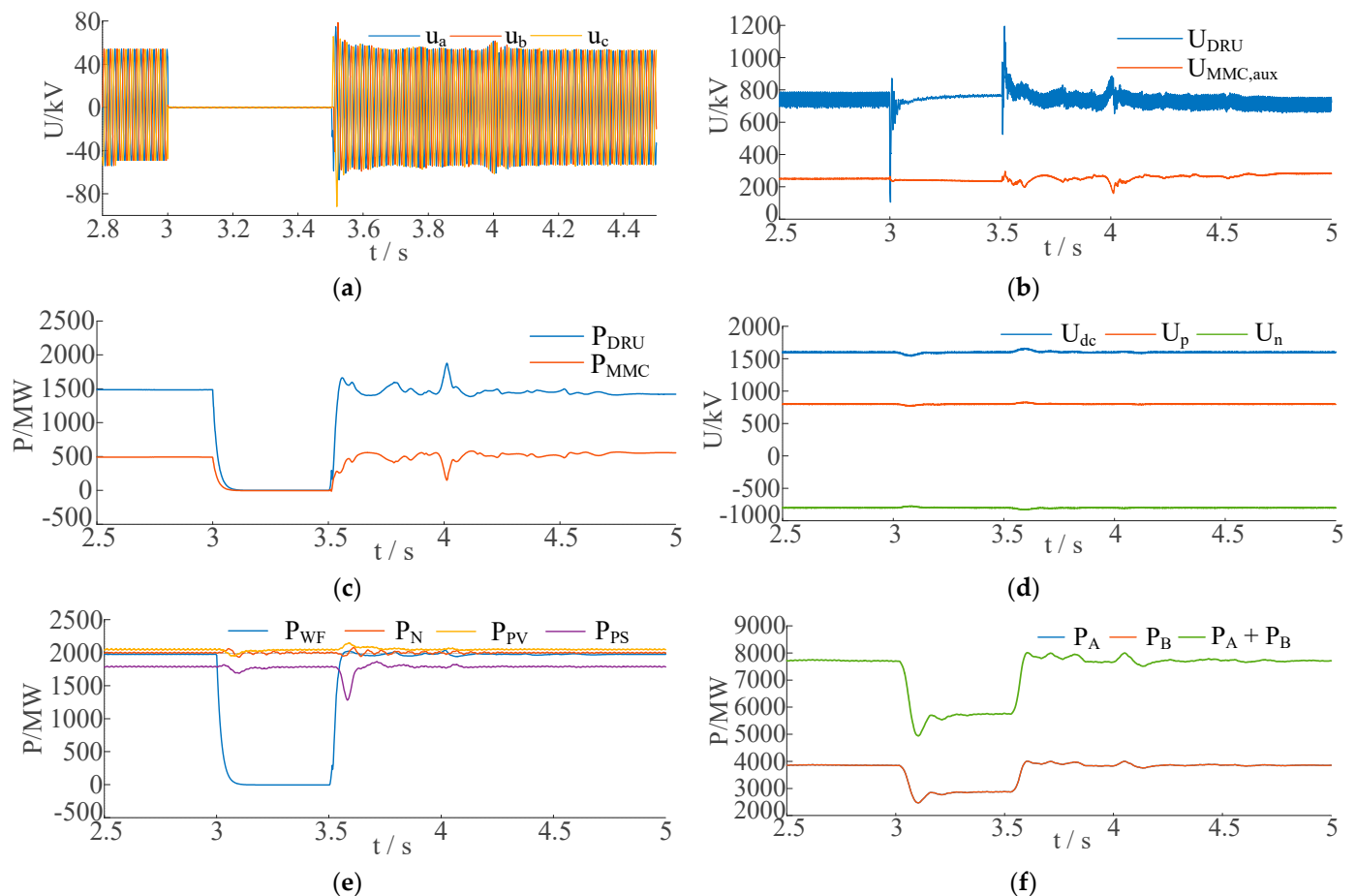


Figure 12. AC fault waveforms: (a) voltage waveform of the AC bus at the fault location; (b) internal voltage waveforms of the offshore-wind DRU–MMC series branch; (c) active-power waveform of the faulty branch; (d) main DC line voltage waveforms; (e) active-power waveforms at other sending ends; (f) power-sharing waveforms of the parallel receiving ends.

Before the fault occurs, the offshore wind DC branch is in the rated export state. The DRU undertakes 1500 MW of active power, and the auxiliary MMC undertakes 500 MW of active power; together they form the offshore wind export power. At the same time, the main DC bus voltage is stable near 1600 kV, and the positive- and negative-pole voltages remain near their rated values.

When the three-phase metallic grounding short-circuit occurs at 3 s, the three-phase voltage of the AC bus at the fault point rapidly drops from the pre-fault phase-voltage peak of 54 kV to nearly zero, and the AC-side voltage-support condition of the offshore wind branch is destroyed. Because the rectification capability of the DRU depends on the AC-side voltage, the AC-bus voltage collapse directly causes the DRU rectification power to decrease rapidly. Meanwhile, although the auxiliary MMC has grid-forming and dynamic

support capabilities, during the three-phase metallic grounding fault, its AC-side voltage support is constrained by the fault and it is difficult to maintain the original active-power transmission level. Therefore, after the fault occurs, the DRU power and the auxiliary MMC power both rapidly decrease to nearly zero, and the active-power export of the offshore wind DC branch is interrupted.

The sudden power drop of the offshore wind branch further causes significant changes in the internal voltage sharing of the DRU–MMC series branch. Before the fault, the DRU-side DC voltage is approximately in the range of 700–780 kV, and the auxiliary MMC DC voltage remains around 250 kV. After the fault occurs, the offshore AC-bus voltage collapses rapidly, and the rectification condition of the DRU is almost lost. As a result, the DRU-side DC voltage drops sharply. When the fault is cleared at 3.5 s, the AC-bus voltage recovers and the DRU rectification condition is re-established, leading to a rapid recovery of the DRU-side DC voltage. It should be noted that the steep change of U_{DRU} in Figure 12b is caused by the ideal fault switching process and the very small fault resistance used in the electromagnetic transient model. It does not indicate numerical discontinuity or missing simulation data. Instead, it reflects the rapid loss and re-establishment of the DRU rectification voltage when the offshore AC-bus voltage collapses and recovers. The auxiliary MMC-side DC voltage changes more gradually because the AC-side short-circuit fault does not directly short-circuit its DC-side energy-storage elements. Its voltage response is mainly determined by converter control and DC-side electromagnetic energy redistribution.

From the response of the main DC system, although the export power of the offshore wind branch is nearly interrupted during the fault, the main DC bus voltage does not suffer large-scale instability. The influence of the offshore wind sending-end AC fault is mainly concentrated in the faulted branch, while non-fault branches such as nuclear power, PV and pumped storage can still maintain continuous operation, thereby preventing a complete loss of total sending-end injected power.

The receiving-end parallel multi-terminal structure also adjusts power accommodation according to the sending-end power change. Before the fault, the total absorbed power of receiving ends A and B is about 7700 MW, and the two ends share power in approximately the same proportion. After the fault occurs, because the offshore wind branch power is nearly interrupted, the total sending-end injected power decreases and the total receiving-end absorbed power decreases accordingly, with the minimum falling to about 5000 MW. The decrease is about 35%, corresponding to the power loss of the offshore wind branch, indicating that the receiving-end power accommodation can follow sending-end power variation and reduce the DC-bus power imbalance. The power variation trends of receiving ends A and B are basically consistent, indicating that the parallel receiving ends still maintain the power-sharing relationship and that no single receiving end bears the entire power disturbance.

After the fault is cleared at 3.5 s, the AC-bus voltage at the fault point recovers rapidly and shows certain transient overshoot and oscillation in the early recovery stage. As the AC voltage recovers, the DRU rectification condition is re-established, and the active power of the offshore wind branch rises rapidly. The main DC bus voltage increases briefly with the recovery of offshore wind power and then returns near the rated value. The total receiving-end absorbed power also gradually stabilizes to the pre-fault level. After the offshore wind branch resumes export, the receiving-end parallel multi-terminal structure can again accommodate the increased DC power, and the DC large-bus voltage can also recover stability after a brief fluctuation.

This case shows that, under a severe sending-end AC fault in the offshore wind DC branch, the multi-energy DC collection system constructed in this paper can confine the main disturbance to the faulted offshore wind branch and its adjacent converter links. The

main true-bipolar DC large bus maintains good voltage coordination capability, non-fault sending-end branches have continuous-operation capability and the receiving-end parallel multi-terminal structure can participate in power redistribution. This result verifies the operating adaptability of the differentiated topology configuration under sending-end AC faults.

4.5. DC Line Fault Simulation

To analyze the operating adaptability of the multi-energy DC collection system when a pole-to-ground fault occurs on the submarine cable of the offshore wind DC export branch, this paper sets a monopolar grounding fault on the DC line at the submarine-cable side of the offshore wind branch. A pole-to-ground fault is set to occur on the submarine-cable-side DC line at 3 s. Once a submarine cable fault occurs, it is regarded as a permanent fault, so fault clearing and recovery do not need to be considered. The fault waveforms are shown in Figure 13.

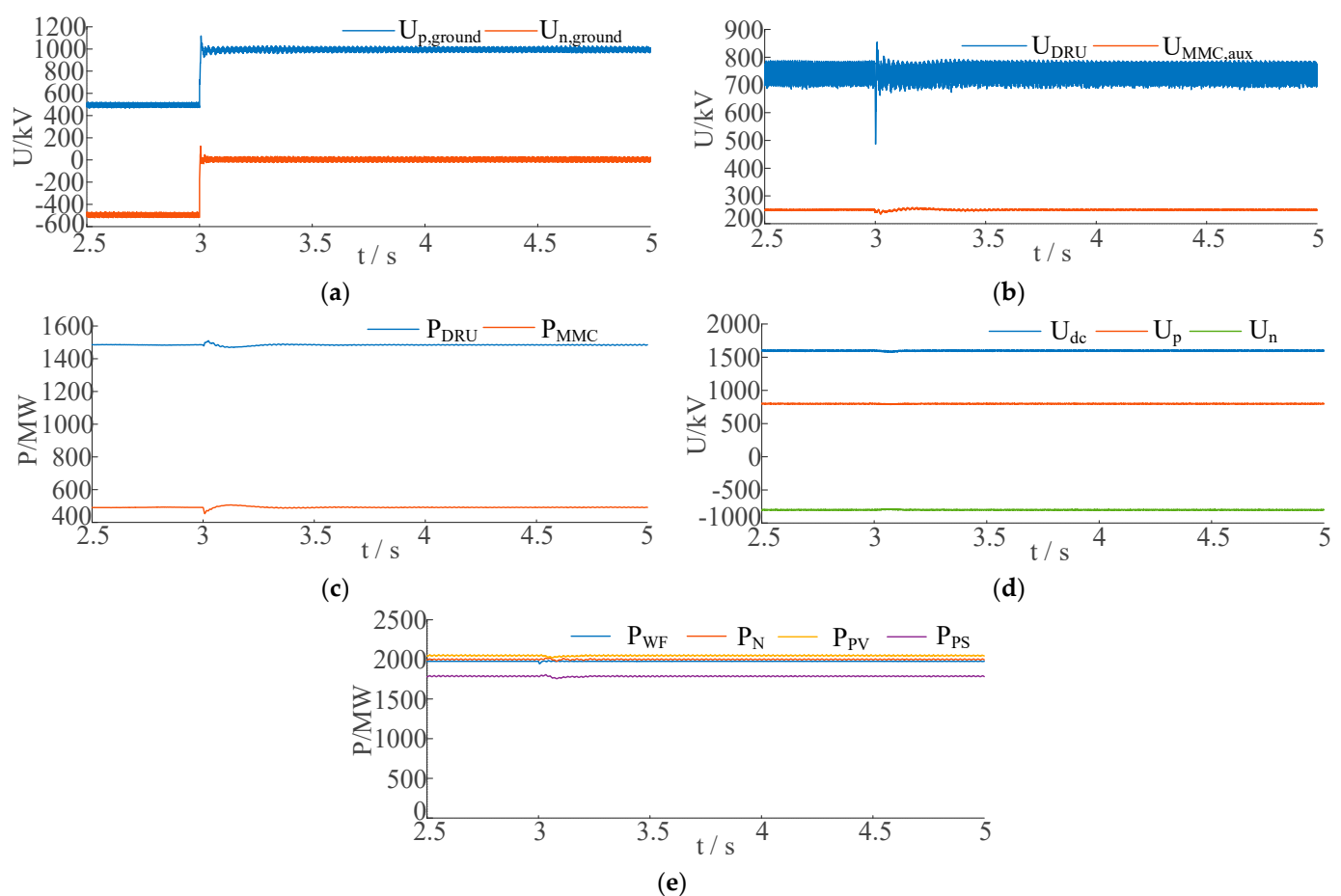


Figure 13. DC fault waveforms: (a) submarine-cable-to-ground voltage waveform; (b) internal voltage waveforms of the offshore-wind DRU-MMC series branch; (c) active-power waveform of the faulty branch; (d) main DC line voltage waveforms; (e) active-power waveforms at other sending ends.

Before the fault occurs, the multi-energy DC collection system is in rated operation. When a pole-to-ground fault occurs on the submarine-cable side at $t = 3$ s, the faulted pole-to-ground voltage rapidly changes to near zero potential. The abrupt change in the faulted pole-to-ground voltage further affects the internal voltage sharing of the offshore wind DRU-MMC series branch. At the moment of the fault, the DRU-side DC voltage experiences a short-term drop and overshoot, with the minimum falling to about 480 kV and then rising briefly to about 840 kV before returning to the original rated oscillation

range after transient oscillation. The disturbance amplitude of the auxiliary MMC-side DC voltage is relatively small; after the fault, it decreases briefly from 250 kV to 240 kV and then recovers to about 250 kV. The submarine-cable pole-to-ground fault has a more obvious influence on the DRU-side DC voltage, while the auxiliary MMC-side voltage can remain at a lower voltage level after a short-term disturbance, and the DRU–MMC series branch can still maintain the basic voltage-sharing relationship.

From the power response of the faulted branch, the pole-to-ground fault does not cause complete interruption of active power in the offshore wind DC branch. Before the fault, the DRU active power is about 1500 MW, and the corresponding auxiliary MMC power is about 500 MW. After the fault occurs, the transmitted powers of the DRU and MMC show small transient fluctuations and then recover; neither sustained instability nor power interruption occurs. From the response of the main DC system, although a permanent pole-to-ground fault occurs on the submarine-cable side, the main DC bus voltage remains relatively stable. U_{DC} decreases briefly from about 1600 kV to about 1580 kV, corresponding to a voltage deviation of about 1.25%. The positive- and negative-pole voltages remain basically symmetrical overall. Meanwhile, the fault influence is mainly concentrated in the faulted offshore wind DC branch, and other non-fault branches maintain continuous operation. Their transmitted powers show small changes but quickly recover to rated values.

In summary, the submarine-cable pole-to-ground fault mainly causes an abrupt change in the faulted pole-to-ground voltage and a disturbance in the internal voltage sharing of the offshore wind DC branch, but it does not cause obvious instability of the main DC bus voltage or power interruption of non-fault sending-end branches. In the simulated post-fault interval, the main DC bus voltage deviation remains about 1–2%, the positive- and negative-pole voltages remain basically coordinated and no sustained instability is observed in the non-fault branches.

4.6. Validation of the Main Contributions

The simulation results in this section support the main contributions of this paper within the scope of system-level electromagnetic transient analysis.

First, the steady-state simulation verifies the feasibility of the differentiated converter-interface configuration. As shown in Figure 9, offshore wind power, nuclear power, onshore PV and pumped storage can be connected to the same ± 800 kV true-bipolar DC large bus through different converter interfaces. The main DC-bus voltage, positive- and negative-pole voltages and receiving-end absorbed powers all reach stable operating states, which indicates that the proposed topology can realize coordinated multi-source power collection under a unified DC platform.

Second, the steady-state and wind-speed step simulations verify the operating adaptability of the DRU–MMC-series offshore wind export branch. The DRU undertakes the main rectification voltage and active-power export task, while the auxiliary MMC bears only part of the DC voltage and provides offshore AC-voltage support and dynamic regulation. Under wind-speed step variation, the offshore wind branch power changes with wind speed, but the main DC-bus voltage and the voltage-sharing relationship between the DRU and the auxiliary MMC remain within the expected operating range. This confirms that the hybrid offshore wind branch can accommodate wind-power fluctuation while reducing the required rating of the auxiliary MMC.

Third, the voltage responses of the positive and negative poles verify the true-bipolar DC bus integration and polarity-interface matching method. The local offshore wind export branch is converted and matched to the ± 800 kV true-bipolar DC large bus through the symmetric/pseudo-bipolar conversion interface. The simulation results show that the

positive- and negative-pole voltages can remain coordinated under normal operation and typical disturbances, supporting the feasibility of the proposed interface-matching scheme.

Fourth, the sending-end AC fault and DC pole-to-ground fault simulations verify the disturbance-withstand capability of the proposed system. During the sending-end three-phase short-circuit fault, the disturbance is mainly concentrated in the offshore wind fault branch, while the main DC bus and receiving-end power accommodation can recover after fault clearing. During the submarine-cable pole-to-ground fault, the faulted pole voltage is clamped locally, but the main DC bus and the non-fault branches do not suffer sustained instability. These results indicate that the proposed topology can maintain basic voltage coordination and multi-source power accommodation under representative local fault conditions.

Therefore, the simulation results support the main contributions of this paper, including the differentiated converter-interface configuration, the DRU–MMC series offshore wind export branch, the true-bipolar DC bus integration method and the system-level operating-characteristics analysis under representative disturbances.

5. Conclusions

This paper studied the topology configuration and operating characteristics of a multi-energy DC collection system for offshore wind power integration, oriented toward the demand for large-capacity DC export of deep-sea offshore wind power and its coordinated export with multiple types of coastal clean energy. The focus of this study is not to propose a single new converter or a new DC circuit-breaker topology. Instead, on the basis of lightweight DC export for offshore wind power, nuclear power, onshore PV and pumped storage are incorporated into a unified DC collection platform as a stable source, a fluctuating renewable source and a regulation resource, respectively. The converter-interface configuration, control-function division and system operating characteristics under typical disturbances are analyzed for different source branches.

From the perspective of the offshore wind branch, the DRU–MMC series hybrid export structure can realize the functional division of DRU main power rectification and auxiliary MMC dynamic support. The DRU undertakes the main active-power rectification task, which helps reduce the equipment scale of the offshore converter platform. The auxiliary MMC bears part of the DC voltage and provides voltage, frequency, black-start and dynamic regulation support for the offshore AC system, thereby compensating for the insufficient active control capability of the pure DRU scheme. The simulation results show that, under steady-state operation and wind-speed step conditions, the offshore wind branch can enter corresponding power operating points with wind-speed variation, and the DRU and auxiliary MMC can maintain the basic voltage-sharing relationship, indicating that the hybrid branch can adapt to a certain range of offshore wind power fluctuations.

From the perspective of the multi-energy collection structure, this paper adopts a ± 800 kV true-bipolar DC large bus as the main DC collection platform and realizes interface matching between the local offshore wind export structure and the main true-bipolar system through a polarity-interface conversion link. The nuclear branch is positioned as a stable power-export resource, the onshore PV branch as a fast controllable renewable-energy access branch and the pumped-storage branch as a system support resource with dynamic regulation capability. This differentiated configuration enables multiple types of sources to realize power collection under the same DC bus and provides a system foundation for main DC-bus voltage stability, positive- and negative-pole voltage coordination and receiving-end power accommodation.

From the perspective of typical disturbance response, wind-speed steps mainly cause power variation in the offshore wind branch, while the main DC bus voltage and positive-

and negative-pole voltages can still remain stable, and non-disturbed branches such as nuclear power, PV and pumped storage do not suffer sustained power instability. A three-phase metallic grounding short-circuit fault at the sending-end AC side of the offshore wind DC branch causes collapse of the AC voltage of the offshore wind branch, temporary loss of DRU rectification conditions and short-term interruption of active power in the offshore wind branch. After fault clearing, however, the offshore wind branch power, main DC bus voltage and receiving-end power can gradually recover, and the fault influence is mainly concentrated in the offshore wind fault branch and adjacent converter links. Under a submarine-cable pole-to-ground fault, the faulted pole-to-ground voltage is clamped and local voltage mutation occurs, but the main DC bus voltage and non-fault branch powers do not suffer sustained instability, indicating that the system has certain disturbance-withstand capability for local DC submarine-cable grounding faults.

Overall, the multi-energy DC collection system for offshore wind power integration constructed in this paper forms a relatively clear system-level configuration relationship among lightweight offshore wind export, unified multi-source power collection, true-bipolar DC voltage coordination and continuous operation after typical faults. The research results can provide a reference for topology configuration, control-function division and operating-characteristics analysis of deep-sea offshore wind power integrated into coastal multi-energy DC collection systems.

Although the present study verifies the feasibility of the proposed differentiated topology under steady-state operation, wind-power fluctuation, sending-end AC fault and DC line fault conditions, more comprehensive comparative studies are still required. Future work will further compare full-MMC, pure-DRU, DRU–MMC parallel and DRU–MMC series offshore wind input topologies under unified system parameters, control settings and disturbance conditions. The comparison will focus on economic performance, offshore-platform weight and volume, converter rating, transient stability, DC-voltage fluctuation range, post-fault recovery capability and receiving-end power redistribution.

Moreover, the energy consumption and loss characteristics of different topologies will be investigated in detail. Converter loss models including DRU conduction loss, LCC thyristor-valve loss, MMC submodule switching and conduction losses, converter-transformer loss and DC cable loss will be introduced to evaluate the efficiency differences among candidate schemes. These studies will help clarify the trade-off among platform lightweight design, loss level, control capability and fault adaptability, and will provide further support for the engineering application of the proposed multi-energy DC collection system.

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