A Novel and Cost-effective Black Start Strategy of Anti-parallel Thyristor-Based DR-HVDC System for Offshore Windfarm

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***Abstract*—Diode rectifier (DR) has become an attractive option for offshore wind farm (OWF) transmission schemes due to its significant advantages in cost and volume. However, DR allows only unidirectional power transfer, meaning that reverse power from onshore is impossible, which creates a significant challenge for black-start operation. This paper proposes a novel and cost-effective black-start strategy for DR-HVDC systems based on anti-parallel thyristors. With only minor hardware modifications, specifically the addition of a few low-voltage anti-parallel thyristors, the onshore station is able to inject a composite current consisting of superimposed DC and AC components through the valve-side winding of the converter transformer, thereby establishing a single-phase voltage on the offshore AC side, which enables system black start. A complete startup sequence, including coordinated control strategies and switching actions, is developed for practical implementation. The feasibility of the proposed method is validated through detailed PSCAD/EMTDC simulations, demonstrating its effectiveness for OWF applications.**

***Index Terms*-- Anti-parallel thyristor(APT), black start strategy, diode rectifier(DR), offshore wind farm(OWF)**

I. Introduction

Offshore wind power has expanded rapidly and is now a key element of global energy transition strategies. Modular multilevel converter-based high voltage direct current (MMC-HVDC) transmission has been increasingly adopted for long-distance power delivery and grid-forming (GFM) control [1]. However, MMC-HVDC systems require substantial capital investment and large offshore platforms. As the required DC voltage rating, transmission capacity, and distance increase, further increasing cost and complexity.

Hence, diode rectifier-based HVDC (DR-HVDC) is proposed, which attracts considerable attention, to reduce the investment cost of the HVDC transmission system [2]. However, diode rectifier allows only unidirectional power transfer, meaning that the black start process is a significant challenge, and the valve lack of controllability would not operate without stable AC voltage, which restricts its application of DR-HVDC [3].

Several approaches, such as GFM control of wind turbine (WT) converters and auxiliary converters including small-capacity MMCs, have been proposed and analyzed in previous studies to mitigate the shortcomings associated with the uncontrolled characteristics of DR [4]. As for the challenge of black start, existing studies can be broadly categorized into two groups: back-feed schemes that rely on onshore power, and local dedicated schemes that deploy startup devices offshore. Back-feed solutions, such as using auxiliary AC or DC startup cables, auxiliary converters, or parallel operation with existing high-voltage AC or DC transmission systems for OWFs, can provide reliable power but often incur economic penalties, require complex coordination, or exhibit limited applicability [5]. Local devices such as diesel generators and energy storage devices are technically mature yet constrained by platform space, maintenance requirements, cost, and environmental conditions. To date, no existing approach achieves a satisfactory balance among feasibility, economics, and scalability for deep-sea OWF applications.

Against this background, this paper focuses on the back-feed way with higher reliability and proposes a startup strategy for the anti-parallel thyristor-based DR-HVDC system. This strategy introduces only a negligible increase in cost compared with conventional DR-HVDC schemes, because the added thyristors operate at very low current and voltage ratings and are not exposed to the high voltages present during normal operation. By superimposing an AC current component onto the DC current delivered from the onshore MMC, the thyristors remain conducting while AC current is injected into the valve-side windings of the converter transformer. Then,

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the single-phase alternating voltage is established on the offshore AC network, enabling energization of wind turbine auxiliary loads and the collection system. After startup, the OWF forms the AC grid using standard *P–U* and *Q–f* control strategies [6] and exports power through DR, achieving a compact and economical transmission architecture. The proposed strategy offers a practical and scalable solution tailored for deep-sea OWF transmission via HVDC.

The main contributions of this work are as follows:

- The anti-parallel thyristor-based DR-HVDC system is proposed as the enhanced DR-HVDC, enabling alternating current injection into the valve-side windings of the converter transformer and establishing a single-phase alternating voltage on the grid-side windings.
- A complete startup sequence is designed, comprising three stages, together with the required control strategies for each power electronics converter.
- The PSCAD/EMTDC simulation model is established to validate the feasibility and effectiveness of the proposed black start strategy.

II. Topology of Anti-parallel Thyristor-Based DR-HVDC System

As shown in Fig. 1, the proposed anti-parallel thyristor-based DR-HVDC transmission system for OWFs is presented. Each direct-drive WT consists of a permanent magnet synchronous generator (PMSG), a machine-side converter (MSC), a grid-side converter (GSC), a box-type transformer, a dc-link capacitor, and a chopper. The conventional DR-HVDC system typically adopts a 12-pulse structure, consisting of two six-pulse DR valves and two converter transformers with different winding connections, along with AC filters installed at the AC bus. In the proposed scheme, only minor modifications to the conventional layout are required. One six-pulse DR valve is selected, where the small-capacity thyristor is connected in parallel to the upper arm of phase-A and the lower arm of phase-B. Other phase-arm combinations may also be adopted, provided that a closed loop can be formed through the offshore HVDC cable, the thyristor, and the converter-transformer winding, as shown in Fig. 1.

It is also worth noting that the onshore station employs a hybrid MMC consisting of 50% full-bridge submodules (FBSMs) and 50% half-bridge submodules (HBSMs) in each arm [7]. This configuration enables the onshore MMC to generate zero DC voltage, thereby providing inherent ride-through capability during DC faults [8]. Such capability is particularly valuable given the increasing voltage levels and transmission capacities of modern offshore wind farms. In particular, this hybrid MMC plays a key role in the proposed strategy.

III. Black Start Strategy and Control Scheme

The overall startup process consists of three stages: (a) reverse power from onshore, (b) silence the transmission channel, and (c) deliver power to onshore, as illustrated in Fig.2. For clarity, red lines indicate current-flow paths, whereas black lines indicate non-conducting paths. Only one turbine is shown for ease of explanation.

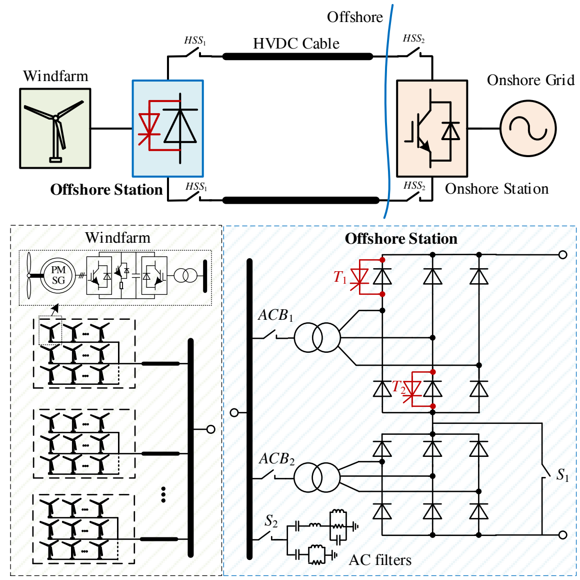

Fig. 1. Topology diagram of proposed anti-parallel thyristor-based DR-HVDC transmission system for OWFs

During startup, the MMC injects a current composed of a DC component superimposed with an AC component on the DC side. The AC component flows through the anti-parallel thyristors and the converter-transformer winding. Owing to electromagnetic induction, an AC voltage is generated at the transformer's grid-side winding, which subsequently charges the collection cable, auxiliary equipment, and the small battery units used by the auxiliary loads. Once these components are energized, the wind turbine can be started, after which the remaining steps of the startup sequence can be completed. For convenience, the key switches involved in the startup process are labelled in Fig.2. The thyristors are denoted as T_1 and T_2; the AC circuit breakers as ACB_1 and ACB_2; the sending-end high speed switch (HSS) as HSS_1; and the receiving-end HSS as HSS_2.

A. Stage 1: Reverse power from onshore

The startup process begins by triggering the anti-parallel thyristors to establish a reverse path. The onshore MMC then injects the current defined in (1), which contains a DC component superimposed with an AC component. The DC component ensures that the current remains above the holding current, maintaining continuous conduction, while the AC component flows through the converter transformer valve-side winding. This induces an AC electromotive force on the grid-side winding, enabling reverse energization of the offshore system. Through this mechanism, the proposed method overcomes the inherent limitation of DR, which cannot naturally transfer power in the reverse direction.

$$i_{dc} = \underbrace{I_{dc0}}_{direct\ current} + \underbrace{I_{dcm}\sin\omega t}_{alternating\ current} \tag{1}$$

where i_{dc} is the DC-side current of onshore MMC. I_{dc0} is the DC component. I_{dcm} is the amplitude of the AC component. ω

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is the angular frequency of the AC component, which adopts $\omega=2\pi f$。

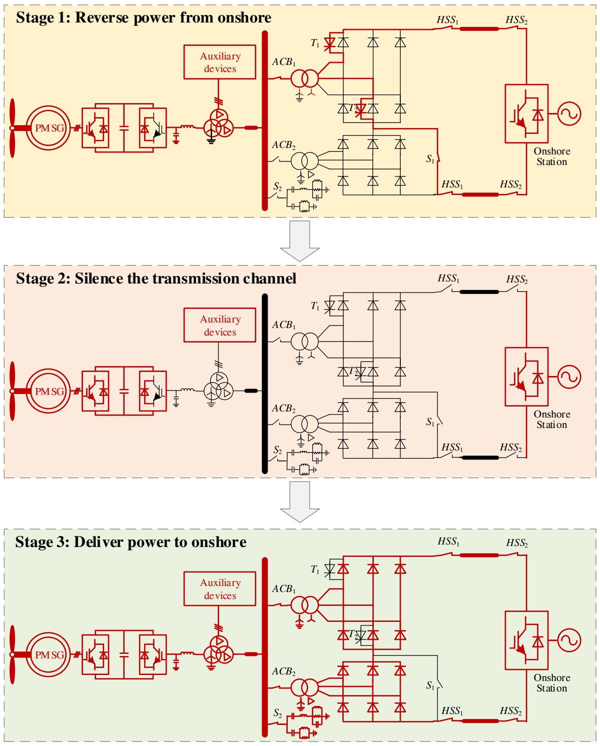

Fig.2. Proposed startup process diagram

Fig. 2 shows the control diagram of the onshore MMC, which is key to producing a special current at the DC side for startup. It adopts sub-module (SM) voltage balancing control, reactive power control, and DC current control. In addition, the reference value of the DC current command is assigned by different control modes depending on the specific stage of the startup sequence.

The single-phase induced voltage generated at the grid-side winding of the converter transformer charges the cable and, after passing through the WT box-type transformer, supplies power to the turbine auxiliary loads, which are supported by small battery units, and to the machine-side converter through an uncontrolled rectifier. This voltage also charges, through an uncontrolled rectification stage via the deblocked MSC, the DC-link capacitor of the WT.

Once the auxiliary equipment regains operational capability, the pitch-control mechanism is started. Following the control strategy shown in Fig.4, the pitch actuator regulates the turbine blades to achieve two objectives: (a) maintaining the rotor speed at a stable value to ensure mechanical stability, and (b) adjusting the wind-energy conversion coefficient (CP) so that the turbine produces no electromagnetic power [9]. Under these conditions, the PMSG operates in a no-load state. Then, the machine-side converter is deblocked and controls the DC-link voltage to rise to its rated level while maintaining the d-axis current at zero.

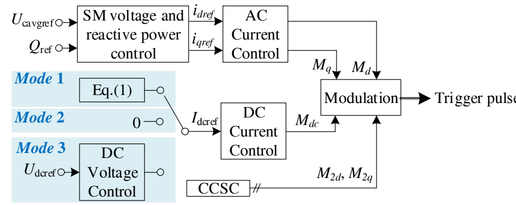

Fig.3. Control scheme of onshore hybrid MMC

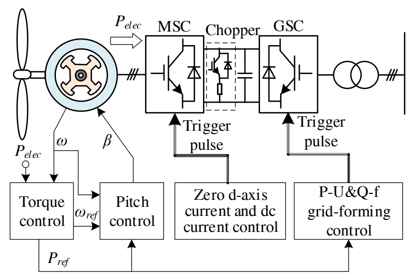

Fig.4. Control scheme of wind turbine

It is worth noting that the converter transformer windings are not ideal components but contain inherent resistance. When the special current flows through the winding, a corresponding DC voltage drop is produced. As a result, a DC component appears in the voltage between phase-A and phase-B of the valve-side winding of the converter transformer. This DC offset raises the potential level and prevents unintended diode conduction. Due to space limitations, a detailed discussion is not provided in this paper.

B. Stage 2: Silence the transmission channel

After the machine-side converter completes the establishment of the DC-link voltage, the onshore MMC begins to reduce its DC-side current toward zero and switches its control mode to Mode 2, which is zero-DC-current control shown in Fig.3. Once the current decreases below the allowable interruption threshold of the HSS, HSS_1, HSS_2, and the AC circuit breaker (ACB) ACB_1 (see Fig. 1) are opened isolate the offshore sending-end system from the onshore receiving-end system and to prepare the electrical conditions required for the next stage. At this moment, the auxiliary devices inside the WT have already recharged their small battery to a sufficient level to supply auxiliary loads. The turbine, therefore, continues operating with the MSC deblocked and the GSC remaining blocked.

C. Stage 3: Deliver power to onshore

Once both the single-phase AC component and the DC current in the transmission system have been fully cleared, HSS_2, ACB_1, and ACB_2 are reclosed. The onshore MMC then rapidly re-establishes the DC-side voltage, operating at Mode 3 shown in Fig.3 of the transmission system, controlling it to rise to the rated value. Then the GSC is deblocked and operated in a grid-forming control mode to raise the offshore system voltage to its rated level. As the offshore AC voltage increases, the DC-side voltage of the sending-end station rises correspondingly and, once it reaches the same level as the onshore DC-side, HSS_1 is closed. In addition, the AC filters are switched in sequentially according to the actual power level.

Meanwhile, the turbine torque controller and pitch controller shown in Fig.4 adjust the PMSG rotor speed and blade pitch angle according to ambient wind conditions. These controllers generate the active power reference that serves as the input to the GSC control loop, enabling the turbine to produce and deliver power.

IV. SIMULATION VERIFICATION

To verify the feasibility of the proposed startup strategy, a simulation model is built in PSCAD/EMTDC based on the system configuration shown in Fig. 1. The HVDC transmission system is rated at ±500kV/2000MW, and each WT string consists of five 12-MW WTs. The rated RMS line voltage of the offshore AC collection system is 66kV. The WT model is implemented using the detailed GE PMSG-based model [9]. In addition, to accelerate the simulation while preserving system dynamics, the entire 2GW windfarm is represented by one detailed WT string combined with the corresponding current multiplication element in PSCAD.

A. Simulation Results During Stage 1

The simulation sequence for Stage 1 is configured as follows. At 0.1s, the onshore MMC is deblocked and controlled according to the strategy shown in Fig.3 to inject a current containing both DC and AC components on the DC side. The current ramps up over a period of 2 seconds to prevent the system from overvoltage. In this study, the DC component is set to 0.3p.u., the amplitude of the AC component to 0.01p.u., and the AC frequency to 50Hz. It is assumed that the small auxiliary battery within the turbine has been fully recharged at 3s, and the auxiliary equipment has regained operational capability. At this moment, the pitch controller is deblocked. The MSC is subsequently deblocked at 5.5s. The simulation results for Stage 1 are shown in Fig.5.

As shown in Fig.5(a)-it(d), the DC-side current is well established, while the DC-side voltage, the DC modulation index, and average sub-module voltage remain stable throughout Stage 1, which is owing to the onshore MMC control. During the controlled onshore DC-side current ramp-up, the inductances within the system generate a DC-induced voltage. This induced DC component appears not only across the HVDC cable but is also transferred through the converter-transformer windings to the transformer's grid-side terminals, as illustrated in Fig.5(e)-(g). After 2 seconds, the DC-side current reaches its steady-state value, and the system operates normally. As shown in Fig.5(a)-(g), the AC component successfully passes through the thyristors and induces the single-phase voltage on the valve-side winding of the converter transformer. This voltage is then transferred to the grid-side winding, where a single-phase AC voltage is established. As shown in Fig.5(h)-(k), afterwards, the mechanical auxiliaries of WT are started. The blade pitch angle gradually decreases, and the rotor speed slowly increases. The stator begins to generate the three-phase voltage, which then charges the DC-link capacitor through the uncontrolled rectifier. As a result, the DC voltage rises gradually. Then, at 5.5s, the MSC controller is deblocked and rapidly controls the DC voltage of WT to rise up to the rated value.

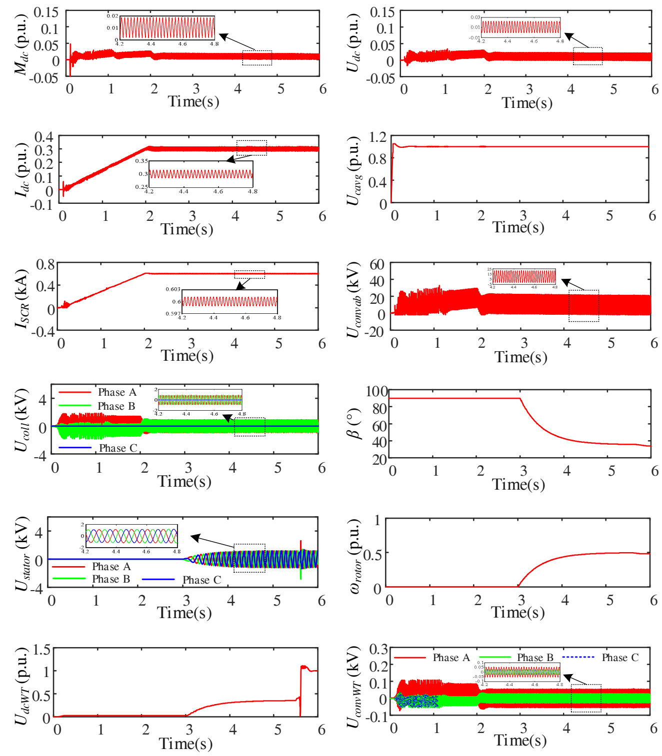

Fig.5. Simulation results during stage 1. (a) DC modulation index of onshore MMC. (b) DC-side voltage of onshore MMC. (c) DC-side current of onshore MMC. (d) Average SM voltage of onshore MMC. (e) Current of anti-parallel thyristors. (f) Valve-side line voltage of the converter transformer. (g) Three-phase voltage of PCC. (h) Pitch angle of PMSG. (i) Three-phase voltage of the PMSG stator. (j) Angular velocity of the PMSG rotor. (k) DC-side voltage of PMSG-WT. (l) Valve-side three-phase voltage of GSC.

It is worth noting that, on the valve-side winding of the turbine box-type transformer, the phase-A voltage is twice the magnitude of the phase-B and phase-C voltages, as shown in Fig.5, while the phase-B and phase-C voltages are in phase with each other and 180° out of phase with the phase-A voltage. This behaviour results from the delta connection type within the transformer grid-side winding.

B. Simulation Results During Stage 2

The simulation sequence for Stage 2 is arranged as follows. At 6.5s, the onshore MMC control mode is switched from Mode 1 to Mode 2. The simulation results for Stage 2 are presented in Fig.6.

As shown in Fig.6(a)-(d), the DC-side current, the DC-side voltage, the DC modulation index, and the current of the thyristor decrease stably. After clearing the current and cutting off the system between onshore and offshore, the valve-side line voltage of the converter transformer disappears, and a transient induced voltage appears because the opening of the switches causes the system inductances to discharge rapidly and then decay according to the behavior of a first-order RL circuit, as shown in Fig.6(e)-(f).

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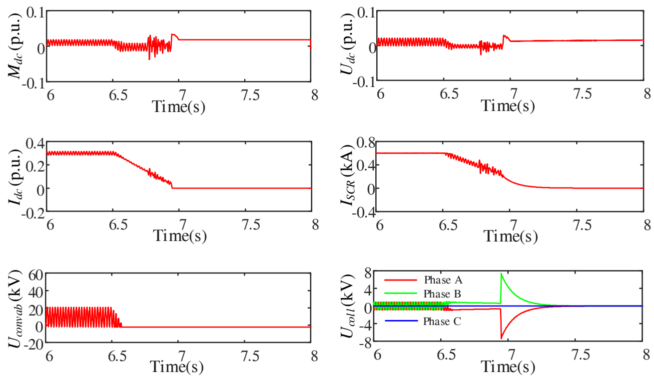

Fig.6. Simulation results during stage 2. (a) DC modulation index of onshore MMC. (b)DC-side voltage of onshore MMC. (c) DC-side current of onshore MMC. (d) Current of anti-parallel thyristors. (e) Valve-side line voltage of the converter transformer. (f) Three-phase voltage of PCC.

C. *Simulation Results During Stage 3*

The simulation sequence for Stage 3 is arranged as follows, in line with existing studies. At 8s, the DC-side voltage is established by the onshore MMC by switching its control mode to Mode 3, and the GSC is deblocked at 9s. The simulation results corresponding to Stage 3 are illustrated in Fig.7.

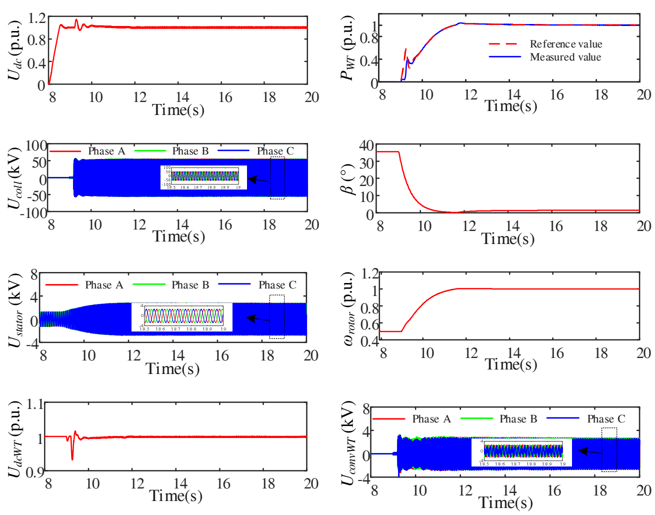

Fig.7. Simulation results during stage 3. (a) DC-side voltage of onshore MMC. (b) Reference and measured value of PMSG active power. (c) Three-phase voltage of PCC. (d) Pitch angle of PMSG. (e) Three-phase voltage of the PMSG stator. (f) Angular velocity of the PMSG rotor. (g) DC-side voltage of WT. (h) Valve-side line voltage of the converter transformer.

As shown in Fig.7(a), at 8s, the onshore MMC rapidly establishes the DC voltage at 1p.u. and maintains a stable value thereafter, with a peak deviation below 10%. At 9s, the turbine GSC is deblocked and starts constructing the AC grid, while the WT is operating at maximum power point control. The active-power reference begins to rise gradually and reaches 1p.u. in approximately 4 seconds, assuming rated wind speed during this period, as shown in Fig.7(b)-(c). According to Fig.7(d) and (h), the pitch angle decreases in accordance with the active-power reference, while the GSC successfully establishes a balanced three-phase AC voltage and its valve-side voltage remains stable. As shown in Fig.7(e)-(g), meanwhile, the PMSG stator voltage increases as the rotor speed rises. The MSC continues to regulate the DC-link voltage at a stable level, with its fluctuation kept within 10%.

V. Conclusion

This paper has proposed an anti-parallel-thyristor-based DR-HVDC transmission scheme, which enables reverse power transfer from the onshore grid without any high-cost auxiliary devices and thereby overcomes the key limitation of conventional DR-HVDC systems. A complete startup process was designed, including coordinated control strategies and the switching sequences of all relevant devices. The feasibility of the proposed strategy was validated through PSCAD/EMTDC, and the results confirm that the novel strategy provides an effective means for initiating DR-HVDC systems.

The work reported here represents an initial step toward practical implementation. Future research will focus on developing enhanced schemes capable of supporting higher single-phase voltage and conducting a more rigorous theoretical analysis of the underlying operating mechanisms.

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