Study Committee B4
DC systems and power electronics

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Standard Specifications and Simulation Analysis on Control and Protection Scheme for Multivendor Offshore Multi-Terminal HVDC System

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INTRODUCTION

- Renewable energy sources are being adopted in Japan to contribute to the decarbonisation of society and enhance social resilience. The offshore wind farms (WFs) are expected to overcome geographical constraints for a large amount of onshore WFs to install.
- HVDC systems are used to transmit generated power of the large-scale offshore WFs to the onshore grid since they are suitable for long-distance cable transmission. The technology development for the multi-terminal HVDC (MT-HVDC) system is required to achieve the multi-directional power exchange among multiple offshore WFs and multiple onshore grids.
- An R&D project "Next-generation offshore HVDC system development project" started in fiscal 2015 as a five-year plan to promote the advanced technologies for the offshore MT-HVDC system.
- The R&Ds on system technologies included simulation studies on the control and protection scheme for multivendor interoperability of the offshore MT-HVDC system and business assessment etc.
- The R&Ds on component technologies included studies on the prototype dc circuit breaker aiming dc voltage 500 kV applications, studies on the dynamic rating technology for the dc submarine cable, and studies on the construction method for the offshore platform foundation etc.

SIMULATION MODELS OF MT-HVDC

Target system and simulation tools

- Digital real-time simulation studies were carried out using the five-terminal HVDC system model, as shown in Figure 1. The rated output power of the WF connected to the offshore terminal is 1,500 MW each. To avoid power output suppression of WFs even in case of a fault in one of the onshore converters, each onshore terminal comprises two sets of the converters rated at 1,500 MW. The power exchange between different onshore grids is assumed as the use purpose of this five-terminal system as well as power transmission between offshore WFs and onshore grid. The HVDC system configuration is the symmetrical monopole with rated dc voltage ±500 kV.

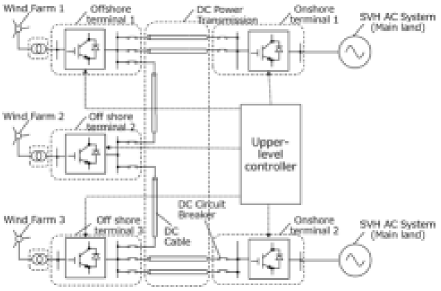

Figure 1 five-terminal HVDC system for power transfer from wind farms.

- The dc circuit breaker is connected to the dc bus of each terminal, and each terminal has the modular multi-level converter (MMC) type voltage source converter.
- Figure 2 shows a three-terminal HVDC model for the off-line instantaneous value analysis. The HVDC model has a monopole configuration with one offshore converter station and two onshore converter stations. These simulation tools enable easy modelling and share of the black-boxed power electronics equipment model between members without leakage of the vendors' intellectual property.

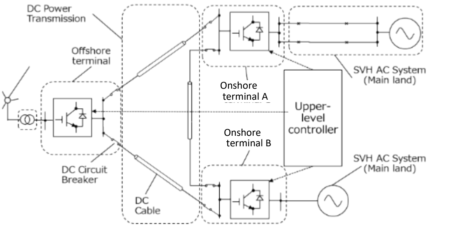

Figure 2 Three-terminal HVDC model for off-line instantaneous value analysis

AC/DC converter circuit and control

- Each terminal's AC/DC converter is an MMC (modular multi-level converter)-type voltage source converter. Each arm of the converter is composed of multiple chopper cells and an arm reactor.
- Figure 3 shows a control block diagram of the AC/DC converter. The power controller is used as a total integrated controller, including DC power-to-DC voltage characteristics, active power control, capacitor voltage batch control, reactive power control, AC connection point voltage control, and arm balance control. The DC power-to-DC voltage relation has a droop characteristic. The current and pulse controllers follow the power controller.

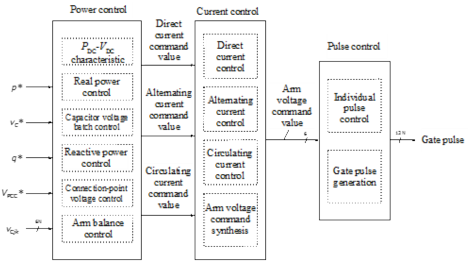

Figure 3 AC/DC converter (pole) control block diagram

Standard Specifications and Simulation Analysis on Control and Protection Scheme for Multivendor Offshore Multi-Terminal HVDC System continued

High-level control for coordination between terminals

- A high-level controller is designed in the project for coordination between the HVDC terminals. An offshore wind farm owner plans the wind powers sent from the offshore terminals and those received at the onshore terminals. On the other hand, an onshore AC power system operator plans the DC powers exchanged using the DC cables between the onshore terminals.
- A HVDC system operator plans the power references for the HVDC terminals, based on the flowchart for power dispatch between the terminals, as shown in Figure 4.
- The powers planned by the wind farm owner and AC power system operator, the installed capacity constraints of the terminals, the priority order assigned to the terminals, and the operating conditions are considered to plan the power references for the HVDC terminals. Those power references are sent from the high-level controller to the terminal controllers.

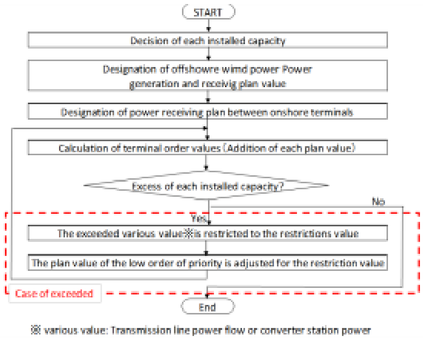

Figure 4 Flow chart for power dispatch between HVDC terminals by high-level controller

DRAFT OF STANDARD SPECIFICATIONS

- The draft standard specification includes
(1) definition of MT-HVDC equipment (MMC, DC circuit breaker, initial charger of cell capacitor, breaking chopper, etc.),
(2) concept of high-level control (flow chart of power dispatch function),
(3) steady-state control (droop characteristic between DC power and DC voltage),
(4) signal interface between the terminal controller and high-level controller,
(5) classification of fault locations such as offshore AC feeders, AC/DC converters, DC bus, DC cables, onshore AC grids and responses required for the equipment during and after the fault.
- The draft standard specification describes the list of signal interfaces between the high-level and terminal controllers (DC voltage reference and upper/lower limits, power reference and upper/lower limits, droop slope, etc.) and the signal attributes (analogue or digital), Table I shows the list of signal interfaces sent by the high-level controller and received by the terminal controller.

Table I List of signal interface sent from high-level controller to terminal controller

Minor category	Output destination	Related control function	Remarks
Wind/onshore terminal setting switching	Converter	—	0: Wind terminal (CVCF) 1: Onshore terminal (DC-AVR and AC-AVR, or AC-AQR)
Control switching	Converter	AC-AQR AC-AVR	0: AC-AQR 1: AC-AVR
Activation/ termination	Converter	—	0: Line interrupt 1: Termination 2: Startup status 3: Ordinary operation status 4: Shutdown status
Droop command value D1 Pref	Converter	DC-AVR	Undead-band droop characteristics parameter
Droop command value D1 Vdcref	Converter	DC-AVR	Undead-band droop characteristics parameter
Droop command value D1 inclination	Converter	DC-AVR	Undead-band droop characteristics parameter
Droop command value D2 inclination	Converter	DC-AVR	Undead-band droop characteristics parameter
Droop command value VDClimH	Converter	DC-AVR	Undead-band droop characteristics parameter
Reactive power command value	Converter	AC-AQR	—
AC voltage command value	Converter	CVCF AC-AVR	Wind terminal CVCF voltage command value Onshore terminal AC-AVR AC voltage command value
Frequency command value	Converter	CVCF	Wind terminal CVCF AC frequency command value
Transfer interrupt	WF	—	Transfer interrupt signal to WF

- On the other hand, the control blocks and control parameters for terminal control (converter control) are not specified in the standard specifications.

DIGITAL REAL-TIME SIMULATION

- Digital real-time simulation studies were carried out using the five-terminal HVDC system model, as shown in Figure 1. The five-terminal HVDC system model comprises two terminals modelled by one of the two vendors and the other three modelled by the other vendor. Table Ⅱ shows the vendor allocations selected for the simulations.
- The digital real-time simulations with the simplified AC grids cover start and stop processes, steady-state operation, change in the terminal power reference, and sudden change in the offshore wind power output, faults in the onshore AC grid and those in DC cable faults. Figure 5 shows the locations of various DC faults; a positive line-to-ground fault at the DC cable, a positive bus-to-ground at the terminal DC bus, and a short circuit fault between the positive and negative DC buses.

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Paper 10729_2022

Standard Specifications and Simulation Analysis on Control and Protection Scheme for Multivendor Offshore Multi-Terminal HVDC System continued

- Table III shows the simulation results of all the DC fault cases. In the table, offshore terminals 1, 2 and 3 are expressed by F1, F2 and F3, and N1 and N2 define onshore terminals 1 and 2. The terminals stopped automatically by the protecting action during the DC fault are indicated in the table cells. The terminals which are restarted immediately after stopping are enclosed in parentheses.
- The results show a difference between the stopped terminals in the single-vendor cases and those in the multi-vendor cases. The operational continuity depends on the vendor allocation in the five terminals. For example, in case B-10, offshore terminal F2 is stopped in the vendor allocation of ABAAB. However, terminal F2 continues operation in the vendor allocation of ABBAB.
- Figure 6 compares the AC voltage and current, DC voltage and current, cell capacitor voltage and AC powers of offshore terminals of F1, F2 and F3 in the vendor allocations of ABAAB and ABBAB in the case of B-10. It is considered that the difference in operational continuity is caused by the fact that the interoperability between the terminals is designed more optimally in the single-vendor MT-HVDC system than in the multivendor MT-HVDC system. The difference in operation is also caused by the difference between the control and protection blocks and parameters designed by vendors A and those by vendor B.

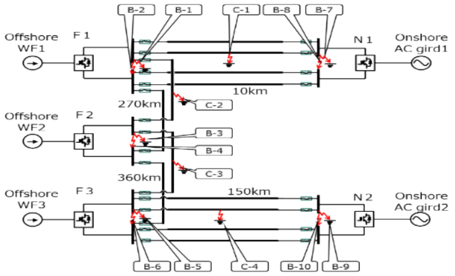

Figure 5 Fault locations in DC system

Table Ⅱ Vendor allocation in five-terminal HVDC system model

Case	Offshore terminal 1	Offshore terminal 2	Offshore terminal 3	Offshore terminal 1	Offshore terminal 2
1	Vendor A	Vendor B	Vendor A	Vendor A	Vendor B
2	Vendor A	Vendor B	Vendor B	Vendor A	Vendor B
3	Vendor B	Vendor A	Vendor B	Vendor B	Vendor A
4	Vendor B	Vendor A	Vendor A	Vendor B	Vendor A

Table III Fault cases and results in multivendor five-terminal HVDC system

Fault location	All A	All B	ABAAB (case 1)	ABBAB (case 2)	BABBA (case 3)	BAABA (case 4)
C-1	None	None	None	None	None	None
C-2	None	None	None	None	None	None
C-3	None	None	None	None	None	None
C-4	None	None	None	None	None	None
B-1	F1 N1	F1 N1	F1 N1	F1 N1	F1 N1	F1 N1
B-2	F1, (F2) N1	F1 N1	F1, F2 N1	F1 N1	F1 N1	F1 N1
B-3	F2	F2	F2	F2	F2	F2
B-4	(F1), (F2) (N1), (N2)	F2	F2, F3 N2	F2	F2	F1, F2 N1
B-5	F3 N2	F3 N2	F3 N2	F3 N2	F3 N2	F3 N2
B-6	(F2), F3 N2	F3 N2	F2, F3 N2	F3 N2	F3 N2	F3 N2
B-7	F1 N1	F1 N1	F1 N1	F1 N1	F1 N1	F1 N1
B-8	F1, (F2) N1	F1 N1	F1, F2 N1	F1 N1	F1 N1	F1 N1
B-9	F3 N2	F3 N2	F3 N2	F3 N2	F3 N2	F3 N2
B-10	(F2), F3 N2	F3 N2	F2, F3 N2	F3 N2	F3 N2	F3 N2

Conclusion

- In Japan, the verification process for multivendor interoperability of the offshore MT-HVDC has been progressing smoothly.
- Series of activities, such as cautious brushing up of standard specification documents, standardizing of control signal interfaces, as well as frequent communication regarding the results of waveforms simulation, shared with all of the participating organizations, including two vendors, have achieved good results so far.
- Project members confirmed that the operation of the MT-HVDC system does not evoke any significant problem regardless of several differences in simulated waveform response such as overshoot height and convergence time that were found depending on the combination of vendors.

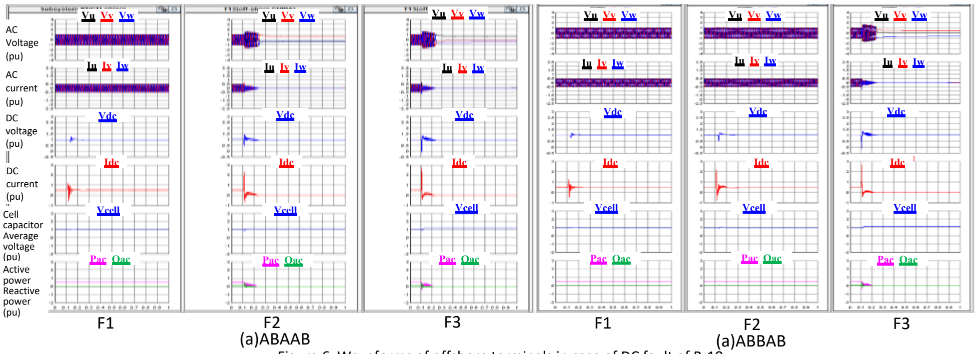

Figure 6 Waveforms of offshore terminals in case of DC fault of B-10