Multi-Terminal HVDC System Control and Protection Standard Specifications

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New Energy and Industrial Technology Development Organization

(NEDO)

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1 Purpose

This document discusses the control function requirement specifications for each AC-DC converter station of the multi-terminal HVDC system and the high-order control system. “NEDO Project” in this document refers to the Next-Generation Offshore DC Power Transmission System Development Project.

2 Components and Main Functions of Multi-terminal HVDC System

This chapter defines the equipment of the multi-terminal HVDC system. The multi-terminal HVDC system has a hierarchical configuration and consists of subsystems. The subsystems are explained first, followed by the internal components of each subsystem, and then terms related to these components.

2.1 Entire System

Figure 2.1.1 is a schematic diagram of the entire multi-terminal HVDC system. The figure shows a four-terminal HVDC system that transmits power generated by three offshore WF on the left to two onshore systems on the right, or that interchanges power between the two onshore systems on the right. (This example system consists of five terminals, but the number of terminals is not limited to five in this NEDO Project.) The main function of each component is explained from left to right in the figure.

An **offshore wind farm** (WF) is a group of wind power generators (power generators are also called “windmills” if confusion with wind turbines is not anticipated) constructed offshore. Each wind power generator is interlinked with an offshore substation and outputs power generated by wind as a current source.

Offshore substations boost the output voltage from each wind power generator, and are linked to an offshore converter station through AC cables.

An **offshore converter station** converts AC power received from offshore substations, etc. through AC cables into DC power and outputs the power to a DC system. In this case, the offshore converter station operates as a current source for the DC system. This kind of operation is called “automatic power regulator (APR) operation on the DC side.” At the same time, the offshore converter station supplies an AC voltage of approximately constant amplitude and frequency to the offshore WF through an offshore substation. This kind of operation is called “constant-voltage constant frequency (CVCF) operation” or “independent operation” on the AC side.

A **DC system** is a DC power transmission network consisting of multiple DC cables. In this NEDO Project, a bipolar configuration with dedicated metallic return or symmetrical monopolar configuration is assumed. In addition, the world’s highest voltage of ±500 kVDC class is assumed in the project. Each DC cable of the DC system has stray capacitance with the ground. Therefore, even if the multi-terminal HVDC system stops, the potential immediately before termination is maintained unless the charge accumulated at the stray capacitance is discharged through a grounded circuit or other means.

An **onshore converter station** converts power received from the DC system again into AC and outputs it to the onshore system. One onshore converter station or more controls the DC system voltage in collaboration. This kind of operation is called “DC automatic voltage regulator (DC-AVR) operation.” Irrespective of offshore WF generated power, power can be interchanged between two onshore systems within the converter station rating.

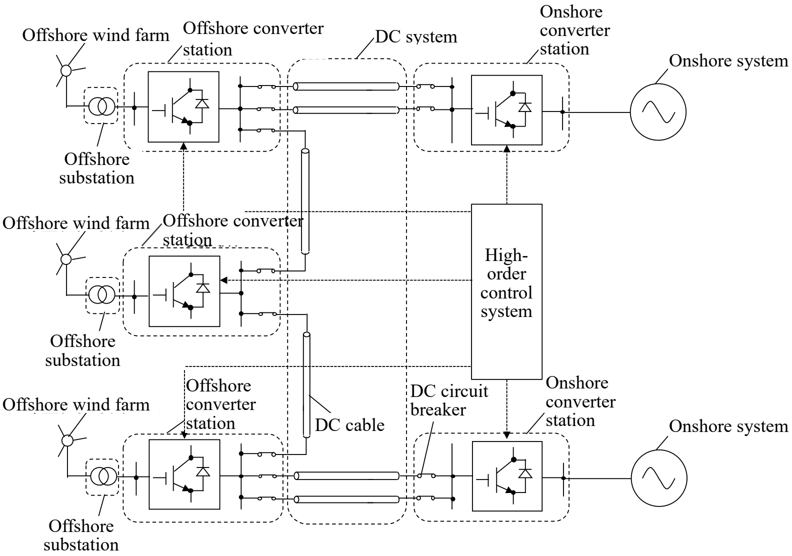


Fig. 2.1.1 Schematic of entire multi-terminal HVDC system

A combination of offshore converter station and onshore converter station is simply called a "converter station," "terminal" or "XX terminal" depending on the characteristic (for example, "AVR terminal", "Onshore terminal", etc.). Unintentional termination of a converter station in the operating multi-terminal HVDC system or disconnection from the DC system is called "terminal dropout" or merely "dropout." Reconnecting a dropout converter station to the DC system and starting its operation is called "re-interconnection." Unintentional disconnection of a converter station from the DC system is called "terminal parallel-off" or simply "parallel-off."

An **onshore system** is a general electric power system. Since 500 MW to 1,000 MW is assumed for an offshore WF in this NEDO Project, 500 kVAC is assumed for an AC system interlinking onshore converter stations to accept generated power.

The **high-order control system** controls the entire multi-terminal HVDC system by giving DC voltage and other command values to several converter stations (terminals). The control system optimizes the operation of the DC system (for example, minimizes losses) based on voltages and currents detected at several points of the DC system.

2.2 High-order Control System

Of the components of the multi-terminal HVDC system shown in Fig. 2.1.1, the high-order control system that controls the entire system operation is described in Chapter 3.

2.3 Converter Station (Terminal)

Figures 2.3.1 and 2.3.2 are schematic diagrams of an offshore converter station and onshore converter station. A bipolar configuration with return line is drawn with the AC side on the left end and the DC side on the right end. Figure 2.3.1 shows a bipolar configuration with return line and Fig. 2.3.2 shows a symmetric monopolar configuration.

Two AC-DC converters, positive and negative ones (or called "first pole" and "second pole" as illustrated), are interconnected again under the bipolar configuration with return line shown in Fig. 2.3.1. An AC-DC converter is also called a "pole." Each pole is connected to the DC bus. The first pole is connected to the positive main line and return line and the second pole to the return line and negative main line. The return line is also called a "neutral line." Unlike the monopolar configuration, the bipolar configuration can reduce the opportunity loss of power generation even if one pole or DC cable stops for some reason, because power can be transmitted up to 50% of the total rated capacity of the bipolar configuration.

One AC-DC converter is interconnected with the AC bus under the symmetric monopolar configuration shown in Fig. 2.3.2. On the DC side, positive and negative main lines are connected. A potential with the ground potential is secured by using the voltage dividing capacitor of the voltage divider on the DC bus.

Each converter station has a grounded circuit consisting of a grounding switch and a grounding resistor to ensure safety during termination or maintenance. The grounded circuit discharges a potential charged in the stray capacitance of the DC cables constituting the DC system.

In some converter stations, the return line of the DC bus may be grounded through a grounding circuit breaker.

In Fig. 2.3.1 and Fig. 2.3.2, the AC and DC buses are drawn as single buses. To achieve a balance between reliability and cost, the double-bus four-bus tie method or 1+1/2 circuit breaker method can be considered.

Each converter station has a converter station control device (or “terminal control device”) and exchanges various signals with the high-order control system, the converter station control devices of other converter stations, and the AC-DC converter control device (pole control device) mentioned later.

Under the bipolar configuration with return line (Fig. 2.3.1), unintentional pole disconnection from the DC system is called “pole dropout” or simply “dropout.” Intentional disconnection is called “pole parallel-off” or simply “parallel-off.”

An AC-DC converter (pole) consists of a main pole circuit breaker, an initial charging circuit, a converter transformer, and an AC-DC converter circuit. The AC-DC converter circuit is the main part for AC-DC conversion. In this NEDO Project, the use of a modular multilevel converter (MMC) is assumed.

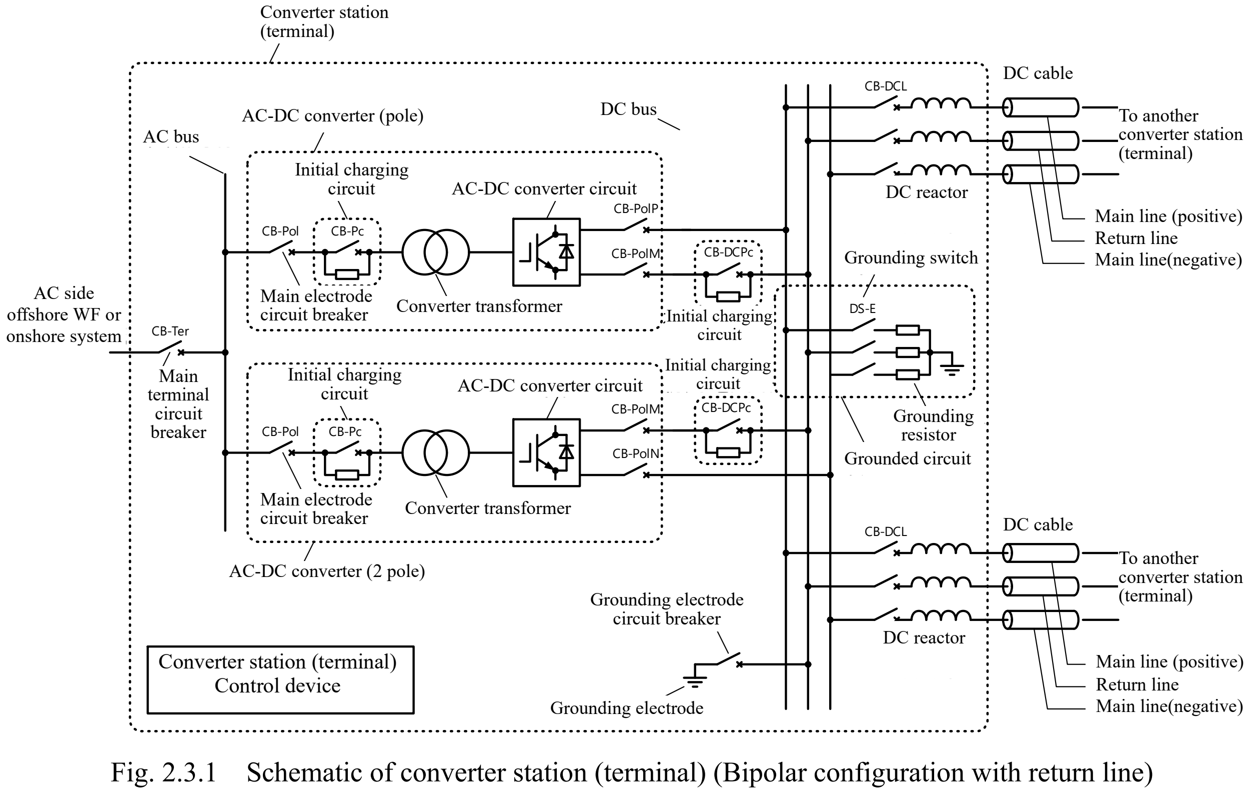


Fig. 2.3.1 Schematic of converter station (terminal) (Bipolar configuration with return line)

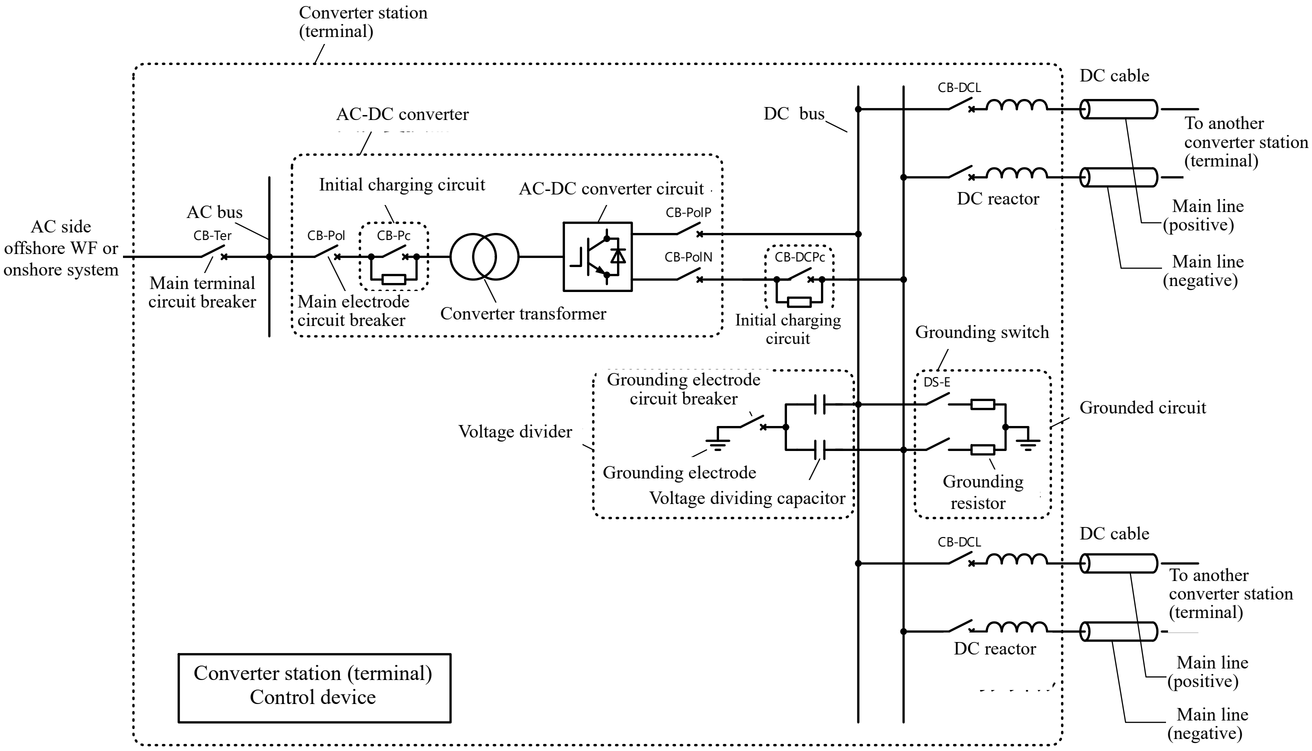


Fig. 2.3.2 Schematic of converter station (terminal) (Symmetric monopolar configuration)

2.4 AC-DC Converter (Pole)

Figure 2.4.1 is a schematic diagram of an AC-DC converter (pole). For ease of understanding, the initial charging circuit and converter transformer are the same as in Fig. 2.3.1 and Fig. 2.3.2. The AC-DC converter circuit is MMC. More specifically, the series circuits of arms and buffer reactors are connected in a three-phase bridge form. Each arm is a series circuit of multiple chopper cells.

A braking chopper is provided on the DC side as required. For example, the braking chopper consists of a resistor and IGBT. The resistor can consume DC power transmitted from the offshore WF for no longer than several ten to several hundred milliseconds. For example, a ground fault or short circuit of an onshore AC system may cause the AC bus voltage of the onshore converter station to decrease and disable the output of generated power from an offshore WF to the onshore AC system. However, power output (supply) from the offshore WF continues as a current source even in this case because the onshore AC system fault does not affect the offshore power collection system.

The capacitor voltage of each chopper cell constituting the MMC of the onshore converter station or the DC cable voltage keeps rising. To prevent the converter station from stopping upon detection of a cell capacitor overvoltage, the braking chopper is kept operating to consume generated power from the offshore WF as heat for as long as the ground fault or short circuit of the onshore AC system continues.

The HVDC interconnection of offshore WFs (not multi-terminal but point-to-point connection) is now in use in Germany and braking choppers are installed at onshore converter stations. A braking chopper is installed either by connecting positive and negative buses or by connecting positive and negative buses and the ground. The latter is used for a symmetric monopolar configuration.

Each AC-DC converter has an AC-DC converter control device (or “pole control device”) and exchanges various signals with the high-order control system and the converter station control devices (terminal control devices) of other AC-DC converter control devices (pole control devices) in the same converter station.

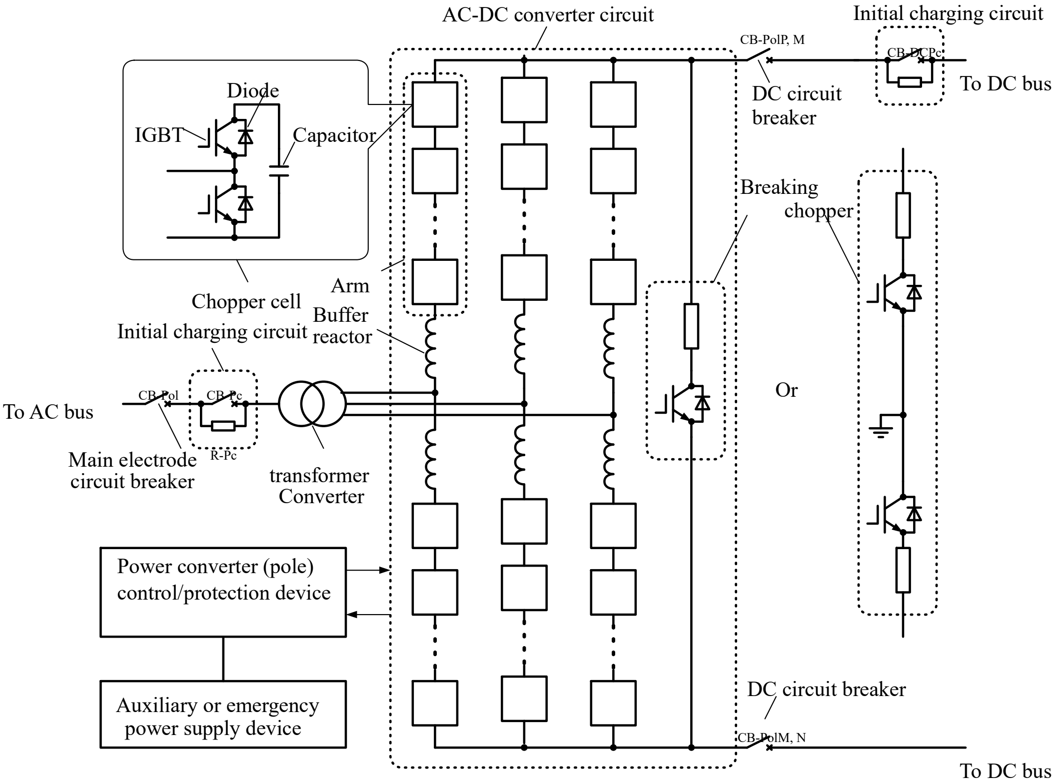


Fig. 2.4.1 Schematic of AC-DC converter (pole)

2.5 Offshore WF, Offshore System, and Power Collection System

Figure 2.5.1 is a schematic diagram of an offshore WF and offshore substation. The balloon shows an example internal configuration of each wind power generator.

As mentioned earlier, an offshore wind farm (WF) is a group of wind power generators constructed offshore. A wind power generator is divided into several strings; these strings are connected to the medium-voltage power collection bus of the offshore substation.

Each wind power generator consists of a wind turbine, gearbox, a power generator, a power conditioner (power conditioning system: PCS), an interconnection transformer, and a PCS circuit breaker (so-called full converter system or Type 4 under the WECC classification). Opening the PCS circuit breaker is called “wind power generator parallel-off” or simply “parallel-off.”

The offshore substation boosts the AC voltage of the medium-voltage power collection bus by using a step-up transformer and transmits it to the offshore converter station through the high-voltage power collection bus and AC cables.

The offshore WF is equipped with an offshore WF control device and receives output increase or decrease commands according to power curtailment or onshore system frequency by communication with the high-order control system and converter station control device (terminal control device) explained later.

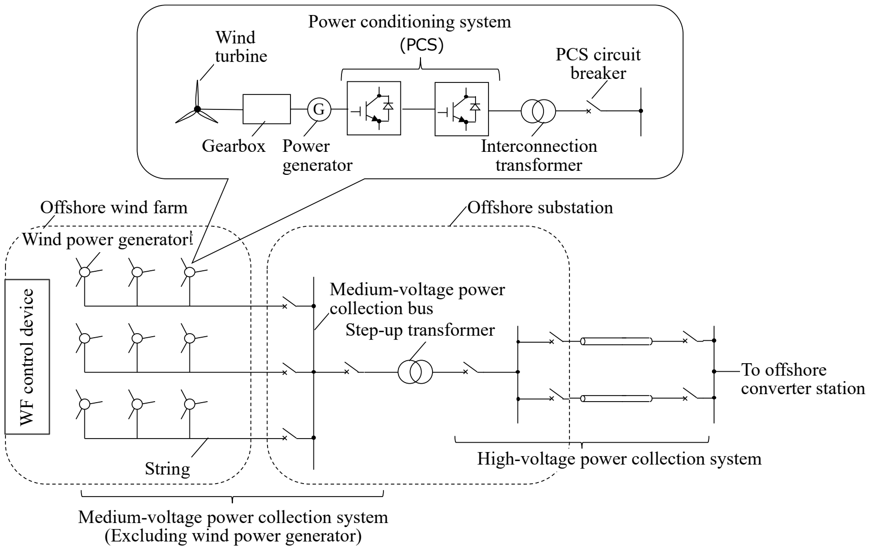


Fig. 2.5.1 Example configuration of offshore WF and offshore substation
(The two-stage boosting method of the power collection system and the voltage levels are examples.)

*1 In this NEDO Project, however, a model contracted from an offshore WF on a certain level is used. For example, an entire offshore WF is regarded as one current source. Alternatively, such mechanical elements as windmill, gearbox, and power generator are ignored by modeling up to PCS of each wind power generator. In fiscal 2015, a simulation was conducted by considering an entire offshore WF as one current source.

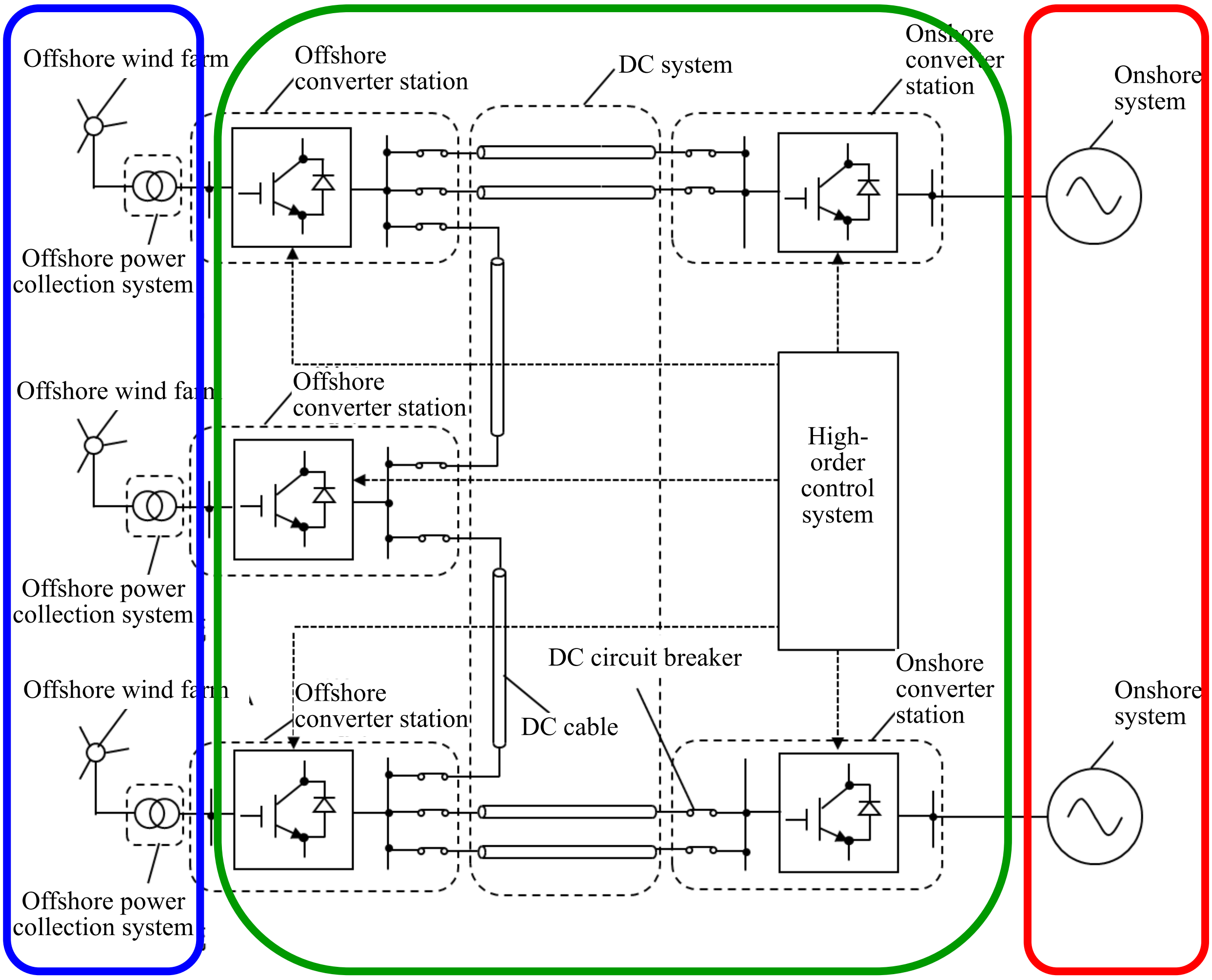
3 High-order Control System

3.1 Basic Principle of High-order Control System Power Distribution Functions

3.1.1 Overview of High-order Control Systems

In a multi-terminal HVDC system, there are the following planned values at the respective future timings: the "planned value for offshore wind power generation" and "planned value for offshore wind power reception" planned by the power provider at each offshore wind power plant; as well as the "planned value for power transmission between onshore terminals" planned by the onshore system operator (ISO etc.).

The multi-terminal HVDC system operator determines each terminal command value by considering these planned values, system capacity, priorities among planned values for each situation, and operational status of each terminal, among other factors. High-order control systems deliver operational orders based on the command value as determined above for each terminal as per Fig. 3.3.1, and then each terminal is operated in accordance with that command.



Operator name	Planned or command value
Blue: "Power provider at each offshore wind power plant"	**→ "Planned value for offshore wind power generation"**
Green: "Multi-terminal HVDC system"	**→ "Command value for each terminal"**
Red: "Onshore system operator (ISO) etc."	**→ "Planned value for power transmission between onshore terminals"**

Fig. 3.1.1 Roles of the multi-terminal HVDC system power provider, onshore system operator, and DC power transmission system operator

3.1.2 High-order Control System Power Distribution at Steady State and Transient State

Multi-terminal HVDC system terminals and DC cables can be either "within capacity" or "in excess of capacity." For planned values, priorities are decided among plans in advance as in Table 3.1.1, with the priorities being pre-agreed upon among the multi-terminal DC power transmission system operator and the other various providers. These priorities are required for making adjustments based on the various planned values when capacity is exceeded.

When capacity has not been exceeded, terminal command values are calculated based on overlap of planned values.

When capacity is exceeded, first the volume exceeding system capacity is limited to the limit value. In this limited state, the amount of power for each terminal and the amount of flow for each DC cable are calculated using the multi-terminal HVDC system flow formula (see Chapter 7), and the calculated amount of power for each terminal is set as that terminal's command value. To ensure that terminal command value comes next in order, planned values are adjusted from lowest priority to highest.

For the flowchart for this calculation, see Section 3.2 "Flowchart of High-order Control System Power Distribution Functions." For an example calculation, see "Case Study of High-order Control System Power Distribution."

3.1.3 Planned Value Priorities

When capacity is not exceeded as above, planned values are adjusted from lowest to highest priority as a way of limiting excess system capacity to within the bounds of the limit value. As an example of priorities, if there were a total of five terminals with three offshore and two onshore, then there would be six possible patterns of priorities as shown in Table 3.1.1. Receiving offshore wind power requires offshore wind power generation, and therefore an offshore wind power reception plan cannot rank as priority 1.

There may also be patterns that cannot be adjusted due to terminals' operational status, and such plans will be unusable.

Table 3.1.1 Patterns of Planned Value Priorities

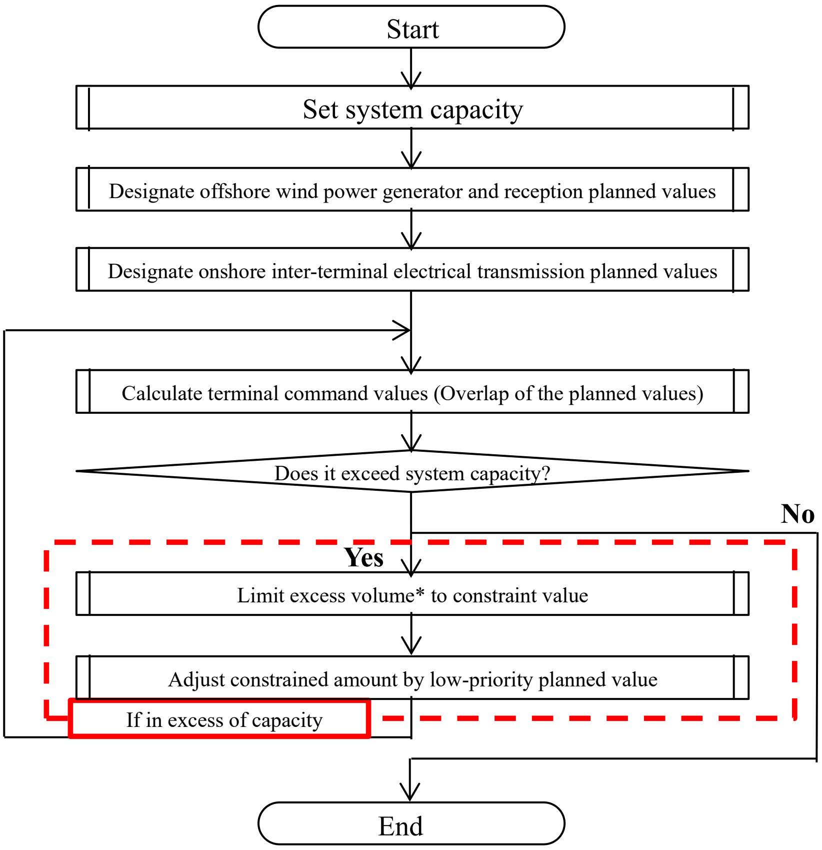
No.	Priority 1	Priority 2	Priority 3 (Adjusted)
Pattern 1	Offshore wind power generation plan	Offshore wind power reception plan (Terminal 1)	Onshore inter-terminal electrical transmission plan Offshore wind power reception plan (Terminal 2)
Pattern 2	Offshore wind power generation plan	Offshore wind power reception plan (Terminal 2)	Onshore inter-terminal electrical transmission plan Offshore wind power reception plan (Terminal 1)
Pattern 3	Offshore wind power generation plan	Onshore inter-terminal electrical transmission plan	Offshore wind power reception plan (Terminal 1) Offshore wind power reception plan (Terminal 2)
Pattern 4	Onshore inter-terminal electrical transmission plan	Offshore wind power generation plan	Offshore wind power reception plan (Terminal 1) Offshore wind power reception plan (Terminal 2)
Pattern 5	Onshore inter-terminal electrical transmission plan	Offshore wind power reception plan (Terminal 1)	Offshore wind power generation plan Offshore wind power reception plan (Terminal 2)
Pattern 6	Onshore inter-terminal electrical transmission plan	Offshore wind power reception plan (Terminal 2)	Offshore wind power generation plan Offshore wind power reception plan (Terminal 1)

*Terminal 1: Onshore terminal 1. Terminal 2: Onshore terminal 2

3.2 Flowchart of High-order Control System Power Distribution Functions

The previous section discussed the basic principles of high-order control system power distribution functions. This chapter will present a flowchart that portrays those basic principles.

For power distribution by high-order control system as described in the last chapter, as long as capacity is not exceeded, specify offshore wind power electrical transmission planned values and onshore inter-terminal electrical transmission planned values, and then calculate terminal command values based on overlap of the planned values. If capacity is exceeded, limit the excess volume to the limit value and adjust the portion subjected to the limit by the lowest-priority planned value. This adjustment process is repeated until the excess of system capacity is resolved. See Fig. 3.2.1 for a flowchart of the series of actions to be taken in the event that capacity is exceeded or if it is not exceeded.



*Volume: Transmission line flow or terminal power

Fig. 3.2.1 Flowchart of High-order Control System Power Distribution Functions

3.3 High-order Control System Interfaces

Table 3.3.1 lists the high-order control system functions, and Table 3.3.3 and Table 3.3.4 list the high-order control interfaces (IF). Undead-band droop control shown in Fig. 3.3.1 is assumed here as a characteristic of the terminal control system that transfers signals with the high-order control system. Table 3.3.2 lists information necessary for the high-order control system to provide the functions listed in Table 3.3.1, apart from the information listed in Table 3.3.3 and Table 3.3.4.

Table 3.3.1 List of high-order control functions

High-order control function	**Description**
Terminal activation function	Starts up an offshore converter after an onshore converter. (See Chapter 4.)
Terminal termination function	Shuts down an onshore converter after an offshore converter. (See Chapter 4.)
Reactivation function in case of terminal activation failure	Reactivates a terminal by re-command, etc. at failure according to each converter status.
Fallback continuation function	Interrupts offshore WF transfer according to converter or line status
Power distribution function if capacity is not exceeded	The high-order control system calculates the droop command value for onshore converters based on the basic principles of power distribution. Onshore converters distribute power according to the droop command values.
AC system voltage fluctuation suppression function	Executes terminal AC-AQR or AC-AVR.
AC system line status monitor function	Monitors onshore and offshore AC systems (power collection systems) to check line statuses and faults.
DC line status monitor function	Monitors DC circuit breaker open/close statuses to check line statuses.

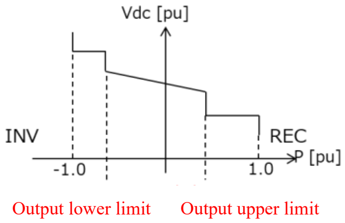


Fig. 3.3.1 Undead-band droop control

Table 3.3.2 Information necessary for high-order control system (Other than information in Table 3.3.3 and Table 3.3.4)

No.	**Item**	**Explanation**
1	Converter capacity	At operation start and converter implementation
2	DC voltage fluctuation range	Determined by the high-order control system at operation start or equipment tolerance change or wherever possible
3	DC line allowable current	Determined by the high-order control system at operation start or equipment tolerance change or wherever possible
4	DC system (onshore and offshore) information (failure and line information)	As required
5	DC system information (failure and line information)	As required

Table 3.3.3 High-order control system interfaces (Input signal)

Major category	**Minor category**	**Output destination**	**Input source**	**Related control function**	**Remarks**
Input signal	Status	-	Converter	-	0: Line interrupt 1: Termination 2: Startup status 3: Ordinary operation status 4: Shutdown status 5: Operation failure 6: Activation/termination failure
	Converter failure information	-	Converter	-	0: No failure 1: AC overvoltage 2: AC undervoltage 3: Arm overcurrent 4: AC frequency abnormal 5: DC overvoltage 6: DC undervoltage 7: DC overcurrent
	DC circuit breaker information	-	DC circuit breaker	-	Necessary for line status monitoring
	AC circuit breaker information	-	AC circuit breaker	-	
	Offshore WF status	-	Offshore WF	-	Necessary for transfer interrupt offshore WF status monitoring
	Predicted output value for offshore WF	-	Offshore WF, etc.	-	Necessary to calculate droop command value for each converter
	Onshore inter-terminal electrical transmission planned value		Onshore AC system, etc.		

Table 3.3.4 High-order control system interfaces (Output signal)

Major category	**Minor category**	**Output destination**	**Input source**	**Related control function**	**Remarks**
	Wind/onshore terminal setting switching	Converter	-	-	0: Wind terminal (CVCF)
Output signal					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
	Droop command value VDClimL	Converter	-	DC-AVR	Undead-band droop characteristics parameter

	Droop command value PDClimH	Converter	-	DC-AVR	Undead-band droop characteristics parameter
	Droop command value PDClimL	Converter	-	DC-AVR	Undead-band droop characteristics parameter
	Reactive power command value	Converter	-	AC-AQR	
	AC voltage command value	Converter	-	CVCF, AC-AVR	Onshore terminal AC-AVR AC voltage command value, Wind terminal CVCF voltage command value
	Frequency command value	Converter	-	CVCF	Wind terminal CVCF AC frequency command value
	DC circuit breaker close command	DC circuit breaker	-	-	
	AC circuit breaker close command	AC circuit breaker	-	-	
	Transfer interrupt	Offshore WF	-	-	Transfer interrupt signal to offshore WF
	Wind power output upper limit	Offshore WF	-	-	Upper limit output value for offshore WF

4 Stationary-state Control Plan

In this chapter, Section 4.1 explains the basic principle of multi-terminal HVDC system operation and control. Section 4.2 shows a control block diagram of the MMC which is an AC-DC converter circuit for each converter station and summarizes the MMC control functions on the AC and DC sides. Section 4.3 describes the technique of controlling the DC side of each converter station or controlling both the DC voltage and DC power. Section 4.4 covers collaboration of converter stations, and Section 4.5 covers the interfaces with offshore WFs.

4.1 Basic Principle of Multi-terminal HVDC System Control

The basic principle of the policy for controlling a multi-terminal HVDC system for steady operation is described below using an example. The basic principle of the policy for controlling a multi-terminal HVDC system for steady operation is described below using an example.

(1) Minimizing the opportunity loss of power generation

Power generation opportunity refers to the time of transmitting power generated by an offshore WF. In principle, the multi-terminal HVDC system is controlled so as to minimize the duration of non-transmission of power generated by an offshore WF during normal operation of the system.

(2) Minimizing power transmission loss

Power transmission loss refers to DC power transmission line loss. In principle, the multi-terminal HVDC system is controlled so as to minimize power transmission loss during normal operation of the system.

(3) Minimizing the impact of a failure

Failure mainly refers to an onshore system fault, power collection system fault, DC system fault, converter station fault, or converter failure. In principle, the multi-terminal HVDC system is controlled so as to minimize the impacts of these failures. It is preferable to provide a mechanism for minimizing the impact of a failure as required until the failure can be eliminated. Table 4.1.1 lists multi-terminal HVDC system failures.

Table 4.1.1 Multi-terminal HVDC system failures

No.	Item	Remarks
1	Balance fault (onshore side)	3LG: 70 ms for failure elimination and 300 ms for re-closing
2	Imbalance fault (onshore	1LG: 70 ms for failure elimination and 300 ms for re-closing
3	Imbalance fault (offshore	1LG: 70 ms for failure elimination
4	DC line fault	See Chapter 5 for an example of failure point.
5	Terminal failure	See Chapter 5 for an example of failure point.

(4) Minimizing adverse impacts on the onshore system

Adverse impacts on the onshore system refer to frequency fluctuations and voltage fluctuations mainly caused by converter output. In principle, the multi-terminal HVDC system is controlled so as to minimize these adverse impacts on the onshore system. For example, if the multi-terminal HVDC system is interconnected with more than one onshore system, a function may be added to change the real power distribution between onshore terminals immediately. This function may enable the real power distribution to an onshore system to be quickly increased in case of a quick frequency change. A reactive power control function (STATCOM function) may also be added to the multi-terminal HVDC system to suppress onshore system voltage fluctuations.

4.2 MMC Control Block Diagram

Figure 4.2.1 shows a control block diagram of an AC-DC converter station (pole). The terms used in the block diagram are approximately based on Reference [1]. In the figure, p^* is real power command value, v_C^* is capacitor voltage command value, q^* is reactive power command value, V_{PCC}^* is connection-point voltage command value, and v_{Cjk} is j-phase k-th cell capacitor voltage. If the number of cells per arm is N, the $6N$ capacitor voltage is detected for the entire MMC.

Table 4.2.1 gives local control modes on the AC and DC sides of the onshore converter station (DC-AVR terminal, APR terminal) and offshore converter station. The control in each mode is outlined below. Section 4.3 describes the DC-side control modes given in Table 4.2.1. See Table 4.3.1 for the P_{DC}-V_{DC} characteristics of Type I to III.

4.2.1 Power control

As Fig. 4.2.1 shows, the P_{DC}-V_{DC} characteristic, real power control, capacitor voltage batch control, reactive power control, connection-point voltage control, and arm balance control are generically referred to as power control. Power control is followed by current control described later.

The P_{DC}-V_{DC} characteristics include constant DC voltage control for DC-AVR operation which maintains the DC system voltage (more precisely, the DC bus voltage v_{DC} interconnected by the converter station). They also include a droop characteristic that varies the DC voltage v_{DC} with a certain inclination depending on real power p. See Section 3.3 for details.

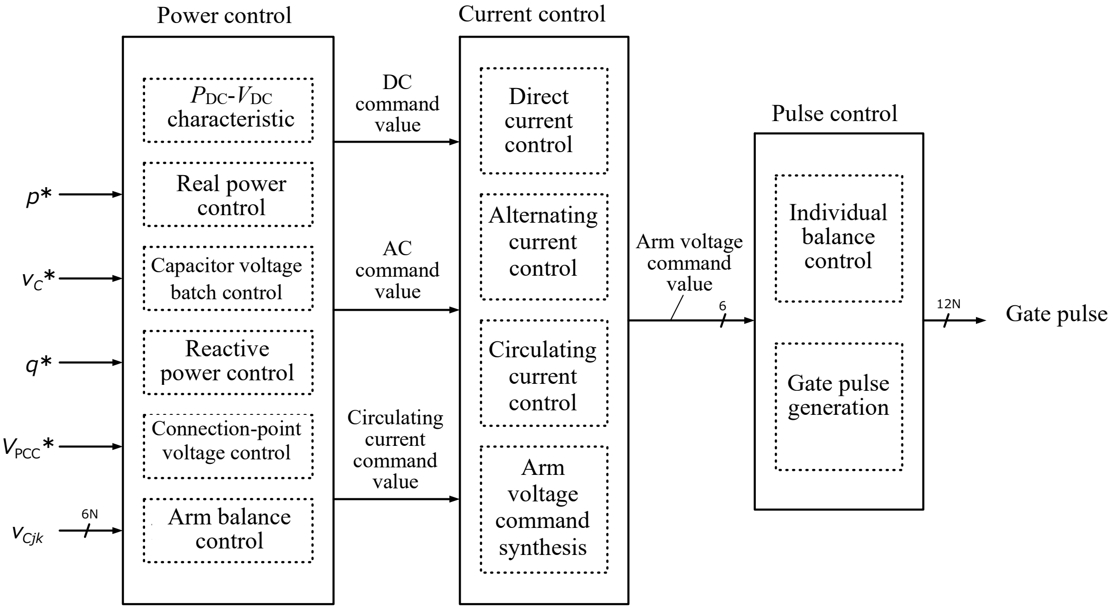


Fig. 4.2.1 AC-DC converter (pole) control block diagram

Table 4.2.1 Local control modes at each terminal

Converter station	AC side		DC side
	Real power	Reactive power	
Onshore converter station (DC-AVR terminal)	Capacitor voltage batch control	Reactive power control (AQR) or Connection-point voltage control (AC-AVR)	P_{DC}-V_{DC} characteristic Type I
Onshore converter station (APR terminal)	Capacitor voltage batch control	Reactive power control (AQR) or Connection-point voltage control (AC-AVR)	P_{DC}-V_{DC} characteristic Type II
Offshore converter station	CVCF control (independent operation) (Real and reactive power control determined by offshore WF)		Capacitor voltage batch control Type III

Real power control applies to AC-DC conversion interchange power p at the terminal. Power p can be controlled by using an alternating current. Capacitor voltage batch control maintains the average capacitor voltage v_C of all chopper cells of the MMC configuring an AC-DC converter (pole) within an allowable range (about constant). For v_C control, either AC-side real power or DC power is used.

Reactive power control applies to reactive power q exchanged between the AC bus and AC-DC converter (pole). Connection-point voltage control applies to the amplitude V_{AC} of AC bus voltage (hereafter, "connection-point voltage"). Arm balance control balances the average voltage of all capacitors configuring each arm of the MMC between six arms.

Power control generates command values to control direct current, alternating current, and circulating current for each type of control as described below.

4.2.2 Current control

As Fig. 4.2.1 shows, direct current control, alternating current control, and circulating current control are generically referred to as current control. Current control is followed by pulse control described later.

Direct current control applies to the feedback of a current flowing from the AC-DC converter (pole) to the DC bus. Alternating current control applies to the feedback of a current flowing from the AC bus to the AC-DC converter (pole), for example, on the d-q axis.

Circulating current control applies to the feedback of a current that circulates through each arm and flows out to neither the AC nor the DC side.

Three voltage command values from the current controls are synthesized to generate a voltage command that is given to the six arms for pulse control described below.

4.2.3 Pulse control

As Fig. 4.2.1 shows, discrete balance control and gate pulse generation are generically referred to as pulse control.

Discrete balance control balances the capacitor voltages of chopper cells configuring each arm within the arm. The algorithm may be integral with gate pulse generation from the perspective of operating voltage commands or IGBT gate pulses given to chopper cells.

4.3 DC System Local Control Characteristic (P_{DC}-V_{DC} Characteristic)

This section describes the P_{DC}-V_{DC} characteristic at each converter station in steady operation, or the DC system local control characteristic. There is also a method of mainly controlling not DC power P_{DC} but direct current I_{DC} [4]. Local control applies to the relationship between power P_{DC} rectified and inverted by a converter station and DC bus voltage V_{DC} of the converter station. The entire multi-terminal HVDC system can be expected to operate stably by setting the local control characteristic of each converter station appropriately.

4.3.1 Onshore converter station and offshore converter station

Since an onshore converter station is connected to an onshore system, it can control real power and reactive power freely within the allowable range of the onshore system. By using this characteristic, some or all onshore converter stations can be used as DC-AVR terminals to maintain the DC system voltage. (If there is more than one DC-AVR terminal, their collaboration and power sharing are issues to be solved.)

*2: Reference [2] describes the two-stage AVR method of a three-terminal system. This may be partially applicable to this NEDO Project but should be newly considered because an offshore WF is connected to an offshore converter station.

Meanwhile, since an offshore converter station is connected to an offshore WF, its real power is always changing depending on the weather, which means the station cannot operate according to certain command values. Power generated by the offshore WF flows into the capacitor of each MMC cell. To maintain a stable capacitor voltage, the MMC outputs generated power from the WF to the DC side by using capacitor voltage batch control. Therefore, an offshore converter station can be regarded as an APR terminal that operates according to command values output from capacitor voltage batch control.

The P_{DC}-V_{DC} characteristic described below can explain the control characteristic viewed from the DC side of converter stations, including DC-AVR and APR terminals. The control characteristic viewed from the DC side of each converter station can be illustrated with DC power P_{DC} (or I_{DC}) that is converted (rectified) from AC to DC by the converter station on the horizontal axis and the DC bus voltage V_{DC} of the converter station on the vertical axis. This is called the "P_{DC}-V_{DC} characteristic (or I_{DC}-V_{DC} characteristic)." Examples described in Reference [3] are given below.

4.3.2 Constant DC voltage control

Figure 4.3.1 shows an example of the P_{DC}-V_{DC} characteristic for constant DC voltage control. This is a typical example of a DC-AVR terminal. Regardless of the value of power P_{DC}, constant voltage control keeps DC voltage V_{DC} matching a certain command value V_{DCref} so long as the magnitude of direct current I_{DC} does not exceed I_{DCmax} and DC voltage V_{DC} is between the lower limit V_{DCmin} and the upper limit V_{DCmax} (which is why it is called "DC slack bus" in Reference [3]). However, if the magnitude of I_{DC} reaches I_{DCmax}, the mode changes from V_{DC} control to current I_{DC} control.

The multi-terminal HVDC system usually has one terminal for constant voltage control. In other words, only one terminal contributes to maintaining the DC system voltage as a DC-AVR terminal.

4.3.3 DC power control

Figure 4.3.2 shows an example of the P_{DC}-V_{DC} characteristic for DC power control. This is a typical example of an APR terminal. Power control keeps DC power P_{DC} matching an arbitrary command value P_{ref} so long as the magnitude of direct current I_{DC} does not exceed I_{DCmax} and DC voltage V_{DC} is between the lower limit V_{DCmin} and the upper limit V_{DCmax}. For example, an offshore converter station controls P_{DC} to keep the MMC capacitor voltage at a certain level.

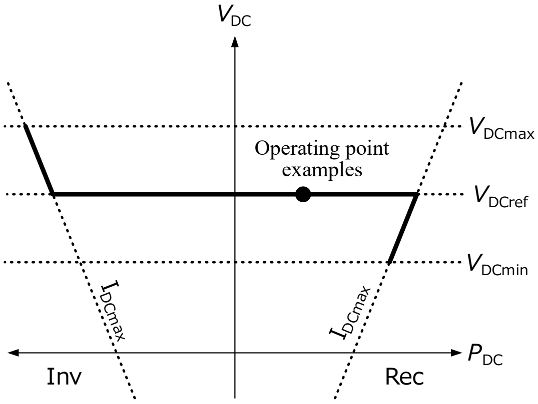


Fig. 4.3.1 Constant DC voltage control

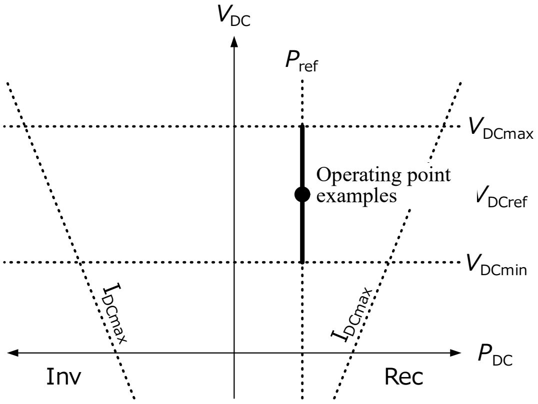


Fig. 4.3.2 DC power control

4.3.4 Droop control

Figure 4.3.3 shows an example of the P_{DC}-V_{DC} characteristic for droop control. This can be regarded as a kind of DC-AVR terminal. Droop control gives a certain inclination D to the relationship between P_{DC} and V_{DC} so long as the magnitude of direct current I_{DC} does not exceed I_{DCmax} and DC voltage V_{DC} is between the lower limit V_{DCmin} and the upper limit V_{DCmax}. However, a terminal such as an APR terminal determines P_{DC}, in which case V_{DC} is determined according to P_{DC} and D. By using the droop characteristic, two or more terminals can be prepared as DC-AVR terminals to contribute to DC voltage control. In addition, the degree of contribution to DC voltage control can be varied by assigning a different D to each converter station that becomes a DC-AVR terminal.

4.3.5 Two-stage AVR

Figure 4.3.4 shows an example of the P_{DC}-V_{DC} characteristic for two-stage AVR. Two-stage AVR is a characteristic proposed in Reference [1]. This applies to a terminal that usually operates as an APR terminal but changes to constant voltage control if a DC system disturbance causes the DC voltage to deviate from the range between V_{DCrefH} and V_{DCrefL}. The two-stage AVR characteristic can be given to multiple terminals. Then a terminal having a smaller difference between the two DC voltage command values V_{DCrefH} and V_{DCrefL} has higher priority in transition to a DC-AVR terminal.

4.3.6 Dead-band droop control

Figure 4.3.5 shows an example of the P_{DC}-V_{DC} characteristic for dead-band droop control. The terminal can be regarded as an AVR terminal during steady operation. This resembles two-stage AVR in Fig. 4.3.4. However, the mode changes to not constant voltage control but droop control if the power deviates from the range between P_{limINV} and P_{limREC}.

4.3.7 Emergency constant DC voltage control

Figure 4.3.6 shows an example of the P_{DC}-V_{DC} characteristic for emergency constant DC voltage control. This resembles two-stage AVR in Fig. 4.3.4 and dead-band droop control in Fig. 4.3.5. However, the mode is droop control when the DC voltage is between V_{DCrefH} and V_{DCrefL} and changes to constant voltage control if a DC system disturbance causes the voltage to reach V_{DCrefH} or V_{DCrefL}. In case of a significant DC system disturbance, therefore, the terminal contributes to the maintenance of DC voltage wherever possible as a DC-AVR terminal of constant voltage control.

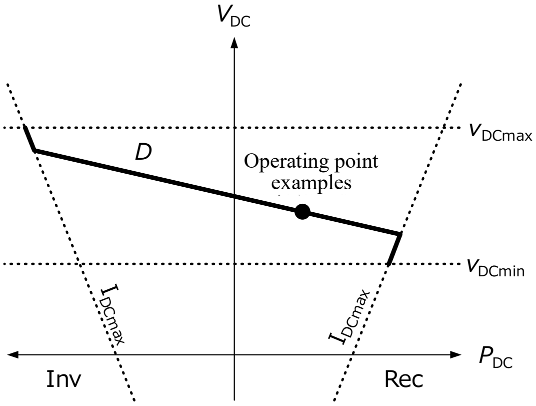


Fig. 4.3.3 Droop control

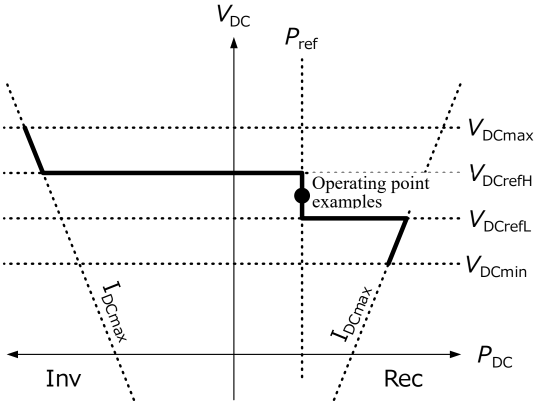


Fig. 4.3.4 Two-stage AVR

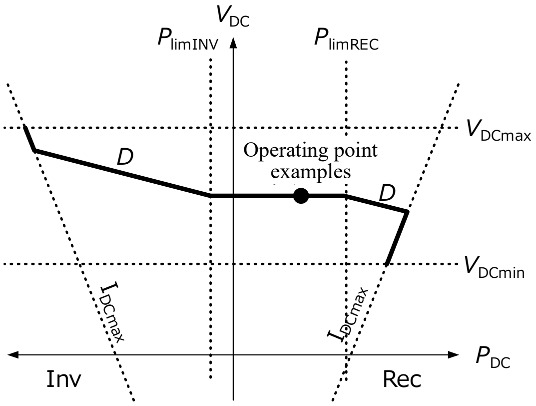


Fig. 4.3.5 Dead-band droop control

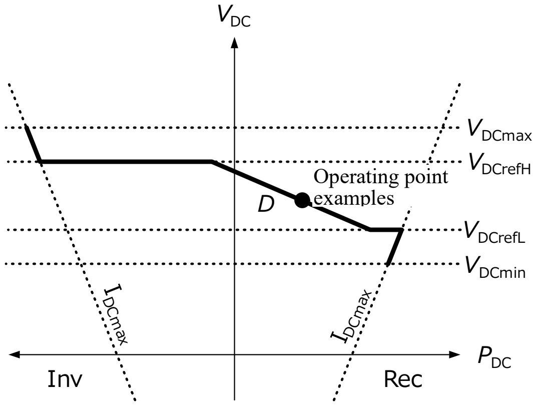


Fig. 4.3.6 Emergency constant DC voltage control

4.3.8 Emergency droop control

Figure 4.3.7 shows an example of the P_{DC}-V_{DC} characteristic for emergency droop control. Contrary to emergency constant voltage control in Fig. 4.3.6, the mode changes from constant voltage control during steady operation to droop control if the power deviates from the range between P_{limINV} and P_{limREC}. Therefore, the contribution to DC voltage maintenance is small because a significant DC system disturbance causes the mode to change to droop control.

Figure 4.3.8 shows an example of the P_{DC}-V_{DC} characteristic for undead-band droop control. The figure shows the transition from droop control of inclination D_1 in the range close to the operating point to droop control of inclination D_2 if the DC voltage deviates from the range between the lower limit V_{DClimL} and the upper limit V_{DClimH}.

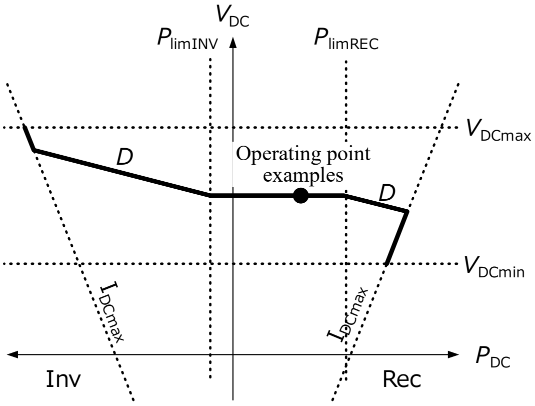


Fig. 4.3.7 Emergency droop control

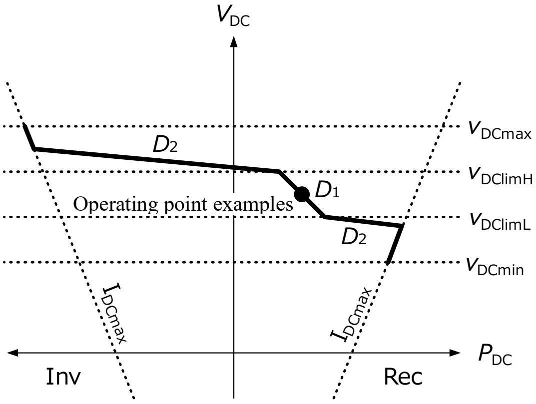


Fig. 4.3.8 Undead-band droop control

4.3.9 Classification of P_{DC}-V_{DC} characteristics

Table 4.3.1 classifies the aforementioned P_{DC}-V_{DC} characteristics into those suitable for an onshore converter station as a DC-AVR terminal (Type I), those suitable for an onshore converter station as an APR terminal (Type II), and those suitable for an offshore converter station (Type III).

Type I has a function to keep the DC voltage constant during steady operation. Therefore, this is suitable for an onshore converter station that becomes a DC-AVR terminal. According to the level of contribution to DC voltage maintenance, set the ranges of V_{DCrefH} and V_{DCrefL} for constant DC voltage control, droop control, and emergency constant DC voltage control. Emergency droop control reduces the contribution to DC voltage maintenance by drooping. Therefore, note the behaviors of a converter station under emergency droop control.

Type II has a function to control power arbitrarily during steady operation and keeps the DC voltage constant in case of an emergency. Therefore, this is suitable for an onshore converter station that operates as an APR terminal during stable operation and becomes an AVR terminal contributing to DC voltage maintenance in case of an emergency. However, there may be a converter station that is set to DC power control.

Type III uses DC power for capacitor voltage batch control to keep the MMC capacitor voltage constant.

Table 4.3.1 Classification of DC controls

Category	Converter station	Suitable P_{DC}- V_{DC} characteristic
Type I	Onshore converter station as DC-AVR terminal	・Constant DC voltage control (Fig. 4.3.1) ・Droop control (Fig. 4.3.3) ・Emergency constant DC voltage control (Fig. 4.3.6) ・(Emergency droop control) (Fig. 4.3.7) ・Undead-band droop control (Fig. 4.3.8)
Type II	Onshore converter station as APR terminal	・Two-stage AVR (Fig. 4.3.4) ・Dead-band droop control (Fig. 4.3.5) ・DC power control (Fig. 4.3.2)
Type III	Offshore converter station	・Constant capacitor voltage control

4.4 Collaboration of Converter Stations

This section describes the local control characteristic set to each terminal of the multi-terminal HVDC system, using DC voltage centralized control and DC voltage decentralized control as two examples.

4.4.1 DC voltage centralized control

Table 4.4.1 gives an example of DC voltage centralized control. Set one of the onshore converter stations to constant DC voltage control (Fig. 4.3.1) and the other onshore converter stations to two-stage AVR (Fig. 4.3.4), dead-band droop control (Fig. 4.3.5), or DC power control (Fig. 4.3.2). Set all offshore converter stations to DC power control (Fig. 4.3.2).

During steady operation, one converter station (terminal) set to constant DC voltage control (Fig. 4.3.1) contributes to DC system voltage maintenance as a DC slack bus (DC-AVR operation). Other onshore converter stations control DC power according to command values given from the high-order control system or generated themselves. An offshore converter station conducts capacitor voltage batch control on the DC side to handle power fluctuations according to power generated by the offshore WF.

If a DC-AVR terminal drops out for some reason, a converter station set to two-stage AVR or dead-band droop control among the onshore converter stations contributes to DC system voltage maintenance as a new DC-AVR terminal.

Table 4.4.1 Example of DC voltage centralized control

Converter station		Suitable P_{DC}- V_{DC} characteristic
Onshore converter station as DC-AVR terminal	One onshore converter station	・Constant DC voltage control □ (Fig. 4.3.1)
Onshore converter station as APR terminal	Other onshore converter station	・Two-stage AVR (Fig. 4.3.4) ・Dead-band droop control (Fig. 4.3.5) ・DC power control (Fig. 4.3.2)
Offshore converter station	All offshore converter stations	・Constant capacitor voltage control

4.4.2 DC voltage decentralized control

Table 4.4.2 gives an example of DC voltage decentralized control. Set *N* (which may be all) onshore converter stations to droop control (Fig. 4.3.3), emergency constant DC voltage control (Fig. 4.3.6), or undead-band droop control (Fig. 4.3.8). Set other onshore converter stations (which may be none) to two-stage AVR (Fig. 4.3.4), dead-band droop control (Fig. 4.3.5), or DC power control (Fig. 4.3.2). An offshore converter station conducts capacitor voltage batch control on the DC side to handle power fluctuations according to power generated by the offshore WF.

During steady operation, N onshore converter stations (terminals) contribute to DC system voltage maintenance in collaboration with multiple DC-AVR terminals in almost inverse proportion to the size of droop control inclination D. Other onshore converter stations control DC power according to command values given or generated themselves. An offshore converter station controls DC power according to power generated by the offshore WF.

If a DC-AVR terminal drops out for some reason, the other DC-AVR terminals contribute to DC system voltage maintenance. In case of a significant disturbance to the DC system, onshore converter stations which are to become APR terminals excluding those set to DC power control (Fig. 4.3.2) contribute to DC system voltage maintenance as new DC-AVR terminals.

Table 4.4.2 Example of DC voltage decentralized control

Converter station		Suitable P_{DC}- V_{DC} characteristic
Onshore converter station at the DC-AVR terminal	Onshore converter stations at N points (which may be all)	・Droop control (Fig. 4.3.3) ・Emergency constant DC voltage control (Fig. 4.3.6) ・Undead-band droop control (Fig. 4.3.8)
Onshore converter station as APR terminal	Other onshore converter station (which may be none)	・Two-stage AVR (Fig. 4.3.4) ・Dead-band droop control (Fig. 4.3.5)
Offshore converter station	All offshore converter stations	・Constant capacitor voltage control

5 Multi-terminal HVDC System Operation Statuses and Sequence

This chapter describes the multi-terminal HVDC system operation statuses roughly along the operation flow from termination, including startup from termination, to normal operation, and special operation statuses at and after failure of each component. Figure 5.1.1 is a schematic diagram of a converter station with the names of circuit breakers (Fig. 2.3.1 shown again) and Fig. 5.1.2 is a schematic diagram of status transition. The multi-terminal HVDC system statuses defined here may include multiple component statuses as detailed in the specifications of each component.

A bipolar configuration with return line is assumed in the explanation below. However, the sequence of a symmetric monopolar configuration is almost the same as that of the bipolar configuration except that the configuration has only one pole and no return line.

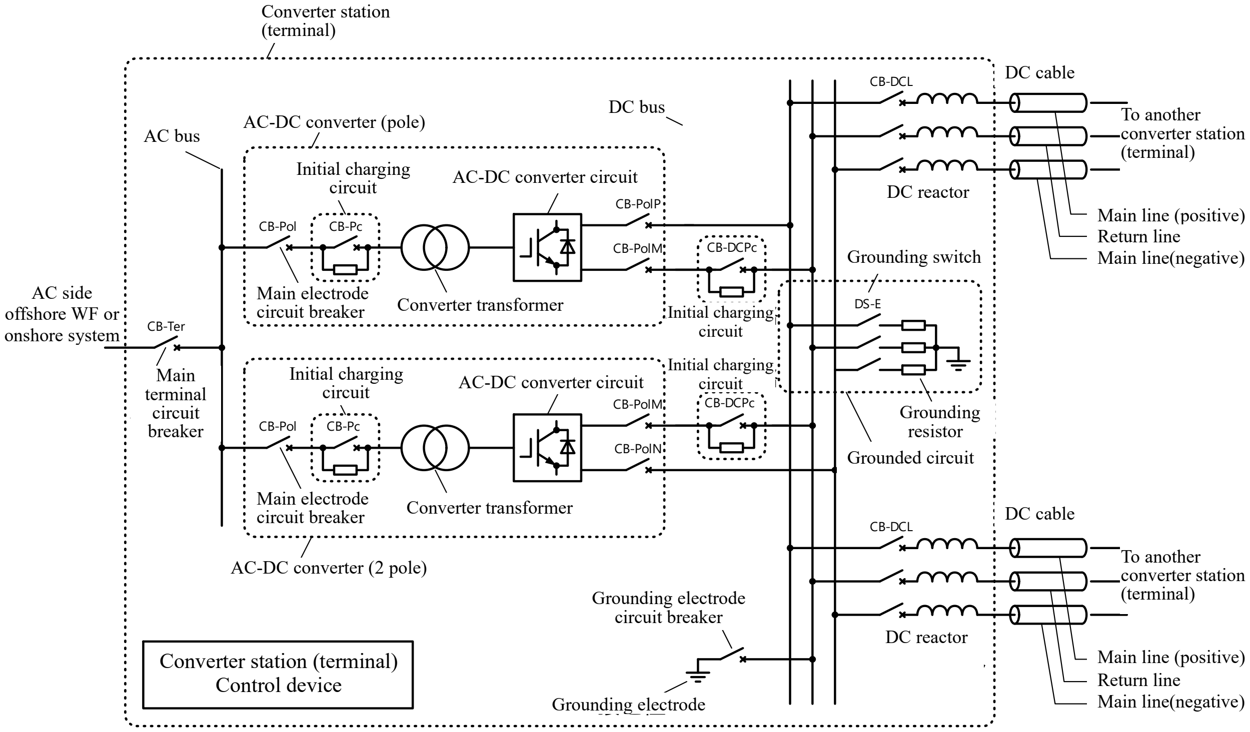


Fig. 5.1.1 Schematic of bipolar converter station (terminal) with return line (Fig. 2.3.1 shown for referencing circuit breaker names)

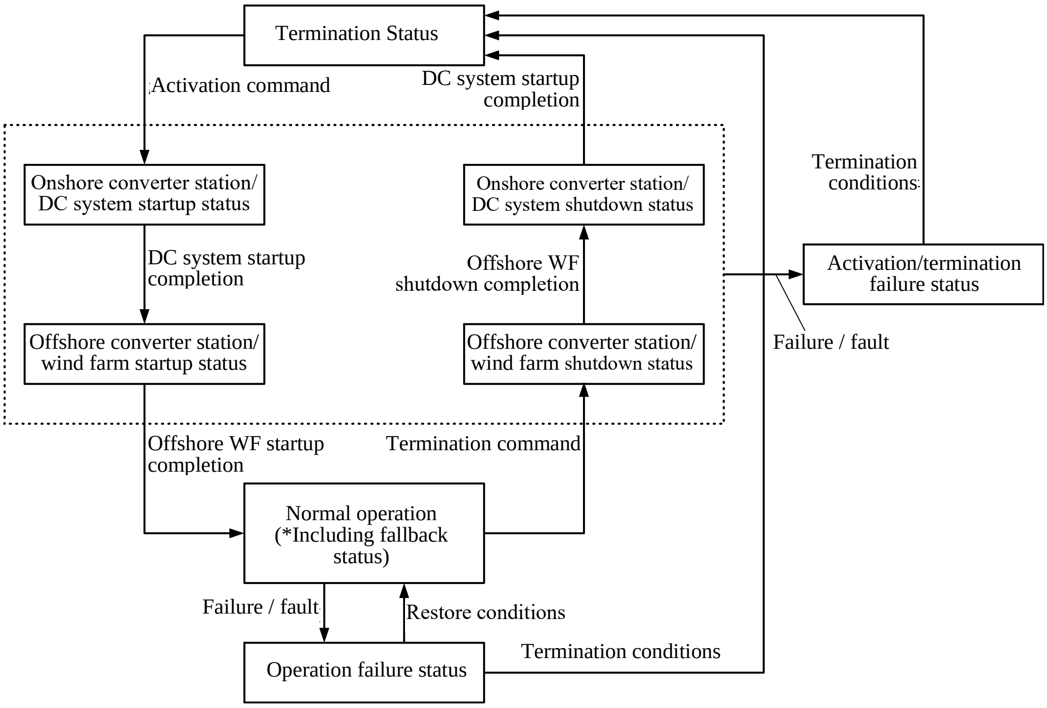


Fig. 5.1.2 Schematic status transition

5.1 Line Suspension Status

In this status, not only is a converter station terminated but the DC line grounding switch DS-E is on and the DC circuit breaker CB-DCL is open. Then the DC line is disconnected from the converter station.

5.2 Termination Status

In this status, every chopper cell configuring the AC-DC converter circuit of each converter station has IGBT off (hereafter, “gate blocking”). Both the main terminal circuit breaker CB-Ter and main pole circuit breaker CB-Pol are open and the grounding switch DS-E in the grounded circuit of each converter station is on. Charged potential is totally released from the stray capacitance of each DC cable configuring the DC system (to the ground potential). In addition, the PCS circuit breaker CB-PCS of every wind power generator configuring the offshore WF is opened.

5.3 Onshore Converter Station/DC System Startup Status

5.3.1 Initial charging

For one or more predetermined onshore converter stations, close the circuit breaker CB-DCL between the DC bus and DC cable and the circuit breakers CB-PolP, CP-PolM, and CP-PolN between the DC bus and each pole. In addition, open the grounded circuit installation switch DS-E and the initial charging circuit CB-ACPc. Every chopper cell configuring the AC-DC converter circuit of each converter station has IGBT off.

If the main terminal circuit breaker CB-Ter and main pole circuit breaker CB-Pol are closed in this status, each chopper cell capacitor of the onshore converter station is charged through the initial charging circuit resistor (initial charging resistor) to some voltage below the rating. In addition, each DC cable connected to the onshore converter station is also charged to some voltage below the rating.

If the capacitor voltage of each chopper cell or DC cable voltage exceeds a preset value or a preset time passes, the initial charging circuit CB-ACPc is closed. Operation from CP-Ter and CB-Pol closing to CB-ACPc closing is called “initial charging.”

5.3.2 DC voltage establishment

When the IGBT switching of each chopper cell is started (hereafter, "gate deblocking"), the AC-DC converter control device (pole control device) raises the capacitor voltage of each chopper cell and the DC cable voltage to their ratings. The capacitor charging energy is obtained from the onshore system. Raising the capacitor and DC cable voltages to their ratings by IGBT switching is called "capacitor voltage establishment" and "DC voltage establishment," respectively.

5.3.3 Notes and issues about this status

If only one onshore converter station is operated as above, not all DC cables configuring the DC system may be charged because some DC cables are not connected to the onshore converter station. The chopper cell capacitors of other AC-DC converter stations are not charged either. On the contrary, if CB-PolP, CP-PolM, and CP-PolN of all offshore and onshore converter stations are closed, the initial charging and DC voltage establishment of one converter station can charge all DC cables and chopper cell capacitors of other offshore and onshore converter stations.

5.4 Offshore Converter Station/Offshore WF Startup Status

The chopper cell capacitors of an offshore converter station are charged to some voltage below the rating by onshore converter station/DC system startup explained in the previous section. In this status, each chopper cell of the offshore converter station is gate-deblocked and the AC-DC converter control device (pole control device) raises the capacitor voltage of each chopper cell to the rating. The capacitor charging energy is obtained from the DC system. Raising the capacitor and DC cable voltages to their ratings by IGBT switching is called "capacitor voltage establishment" as with onshore converter stations. If the offshore converter station has an auxiliary or emergency power supply of enough capacity for capacitor voltage establishment, the power supply may be used to charge the capacitors. After capacitor voltage establishment, each chopper cell is gate-blocked.

At an offshore converter station with the capacitor voltage established, the main pole circuit breaker CB-Pol and main terminal circuit breaker CB-Ter are closed and IGBT is gate-deblocked again and AC voltage is supplied to the offshore WF through a converter transformer and a step-up transformer. This operation to supply AC voltage to an offshore WF is called "offshore WF startup" or "black start."

Each wind power generator configuring an offshore WF closes its PCS circuit breaker to start the power conditioner (power conditioning system: PCS) when AC voltage is supplied to the high-order side of the circuit breaker. Then the wind power generator shifts to normal operation.

5.5 Ordinary Operation Status

The series of operations described in Sections 5.3 and 5.4 interconnects all converter stations of the multi-terminal HVDC system. An offshore converter station outputs power generated by the offshore WF to the DC system and an onshore converter station receives power generated by the offshore WF from the DC system and outputs it to the onshore system. If there is more than one onshore converter station, power is interchanged between them.

In this status, each wind power generator configuring an offshore WF outputs (supplies) power as a current source under maximum power point tracking (MPPT) control. An offshore converter station outputs (supplies) power received from the offshore WF to the DC system as a current source.

Power from the offshore WF charges each chopper cell capacitor configuring the offshore converter station. The offshore converter station outputs power to the DC side as a current source to keep the capacitor voltage of each chopper cell approximately constant. In conclusion, an offshore converter station operates as CVCF for the

AC side (offshore WF). One or more onshore converter stations keep the DC system voltage approximately constant.

5.6 Offshore Converter Station/Offshore WF Shutdown Status

This is an operation status where an offshore WF or offshore converter station in ordinary operation is shut down. When a termination command is sent from the high-order control system to an offshore WF, each wind power generator configuring the offshore WF deblocks PCS and opens the PCS circuit breaker. Then the offshore converter station is gate-blocked, and the main pole circuit breaker CB-Pol and main terminal circuit breaker CB-Ter are opened, including CB-PolP, CP-PolM, and CP-PolN on the DC side. This disconnects the offshore converter station from both the AC side (offshore WF) and DC side (DC system) (parallel-off).

5.7 Onshore Converter Station/DC System Shutdown Status

In this status after the offshore WF and offshore converter station are terminated and disconnected as described in the previous section, the onshore converter station is terminated and disconnected, and the DC cable stray capacitance is discharged.

The onshore converter station is gate-blocked, and the main pole circuit breaker CB-Pol and main terminal circuit breaker CB-Ter are opened. This disconnects the offshore converter station from the AC side (onshore system) (parallel-off). If there is more than one onshore converter station, they are paralleled off sequentially. The parallel-off order is APR terminal first and DC-AVR terminal next.

After all onshore converter stations are paralleled off from the AC side (onshore system), turn on the grounded circuit installation switch at one or more arbitrary onshore converter stations. Accumulated charge is released from each DC cable of the DC circuit to reduce the DC cable potential to the ground potential level.

The series of operations described above changes the multi-terminal HVDC system to the termination status described in Section 5.2.

5.8 Operation Failure Status

This status arises if any abnormality is detected during ordinary operation, such as overvoltage or overcurrent attributable to a ground fault or short circuit fault of the onshore system or DC system or any other equipment failure. In this status, the AC-DC converter, circuit breaker, and switch of each converter station are operated according to predefined procedures (called “protective interlocking”).

Each conversion starts operation if a ground fault or short circuit fault is removed from the onshore system, the AC bus voltage recovers, and the components of each converter station and the DC cables of the DC system are normal (no failures). If a converter station (terminal), AC-DC converter (pole), or DC cable is abnormal (failure), only sound terminals, poles, and DC cables are used for fallback described later.

5.9 Activation/Termination Failure Status

This status arises if any abnormality is detected in the startup or shutdown status of an onshore converter station, DC system, offshore converter station, or WF, such as overvoltage or overcurrent attributable to a ground fault or short circuit fault of the onshore system or DC system or any other equipment failure. In this status, the AC-DC converter, circuit breaker, and switch of each converter station are operated according to predefined procedures (called “protective interlocking”). Even when the failure or fault is removed, the status does not return to the ordinary operation status but changes to the termination status.

5.10 Fallback Status

This section describes fallback that arises when any component is lost due to a failure in normal operation or any other status. In this status, remaining sound components are used to continue operation.

In this document, the fallback status is handled as an internal status of ordinary operation status.

5.10.1 DC cable disconnection

Figure 5.10.1 shows an example of DC cable disconnection. Depending on the DC system configuration, however, a different route may allow power transmission to continue. This is called bypass power transmission. In this case, generated power from two offshore WFs flows through the asterisked DC cable in Fig. 5.10.1 (hereafter, “bypass route”). Since the bypass route may be overloaded under certain weather conditions, it is necessary for the high-order control system to give an output limit command to each offshore WF. Note that DC cable inspection may cause this status.

5.10.2 Terminal dropout

In case of converter station (terminal) dropout, the multi-terminal HVDC system aspect (response) differs depending on the station type, offshore or onshore. If a DC-AVR terminal drops out, the DC system voltage may fluctuate and deviate from the allowable range. The DC system power flow may change and cause overload on some DC cables or onshore converter stations. This makes it necessary to keep DC system voltage and DC cable current within allowable ranges by local control at each converter station or the high-order control system.

Figure 5.10.3 shows an example of offshore converter station dropout. In the figure, the upper left offshore converter station dropped out and one offshore WF was terminated accordingly. Even in this case, power transmission between two or more DC cables is possible through the bus of the dropout offshore converter station as indicated by the blue arrow. The high-order control system detects converter station dropout by some means and reflects it in later multi-terminal HVDC system control.

Figure 5.10.2 shows an example of onshore converter station dropout. In the figure, the upper right onshore converter station dropped out. Even in this case of onshore converter station dropout, power transmission between two or more DC cables is possible through the bus of the dropout offshore converter station as indicated by the blue arrow. If the dropout onshore converter station was a DC-AVR terminal maintaining the DC system voltage, the load on sound onshore converter stations may increase. If the dropout onshore converter station was the only DC-AVR terminal, the DC system voltage can no longer be maintained. Therefore, each converter station should prepare droop characteristics by local control in case an onshore converter station operating as a DC-AVR terminal should drop out. The high-order control system detects converter station dropout by some means and reflects it in later multi-terminal HVDC system control.

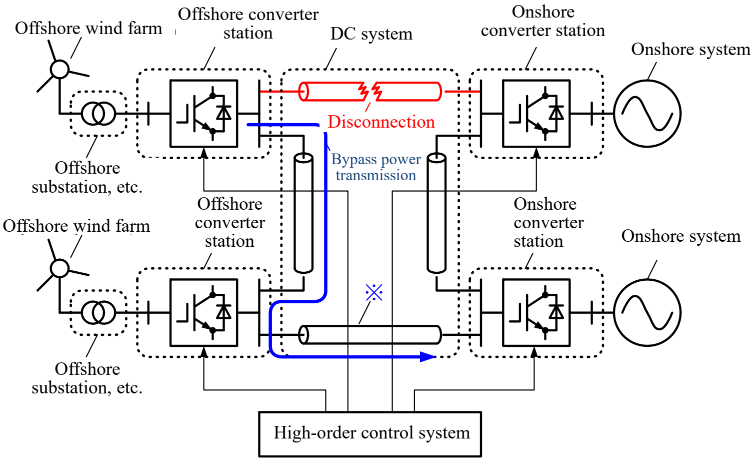


Fig. 5.10.1 DC cable disconnection

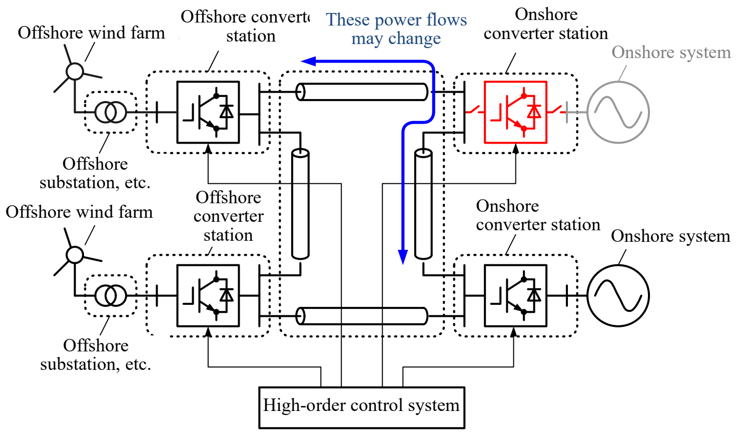


Fig. 5.10.2 Terminal dropout (Onshore)

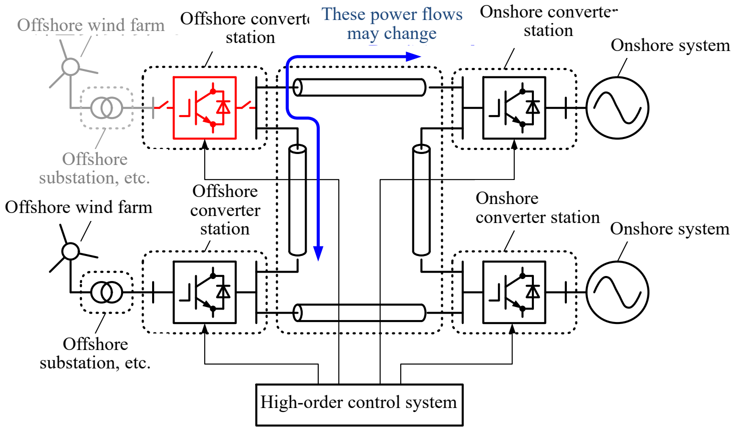


Fig. 5.10.3 Terminal dropout (Offshore)

5.10.3 Pole dropout

Pole dropout is a fallback status that arises only in a bipolar configuration with a return line. Figure 5.10.4 shows an example of single pole dropout from a converter station. In case of pole dropout, the converter station (terminal) can interchange power up to 50% of the total rated capacity of two poles. Since DC cables connected to the DC bus maintain interconnection with the DC system, power can pass through the converter station.

If pole dropout occurs at an offshore converter station, the entire power generated by an offshore WF cannot be converted from AC to DC under certain wind conditions. This makes it necessary to suppress offshore WF generated power by high-order control or terminate some wind power generators by terminal control.

If pole dropout occurs at an AVR terminal, the AC-DC conversion capacity of the converter station decreases to 50%. Then the DC system voltage may fluctuate and deviate from the allowable range. The DC system power flow may change and cause overload on some DC cables or onshore converter stations. This makes it necessary to keep the DC system voltage and DC cable current within allowable ranges by local control at each converter station or the high-order control system.

Since only the first or second pole operates at the converter station, a current difference is produced between the positive and negative main lines of the DC system and current flows to the return line (neutral line). If current flows to the neutral line, the power transmission loss may increase. Therefore, other converter stations may be controlled to reduce current to the neutral line.

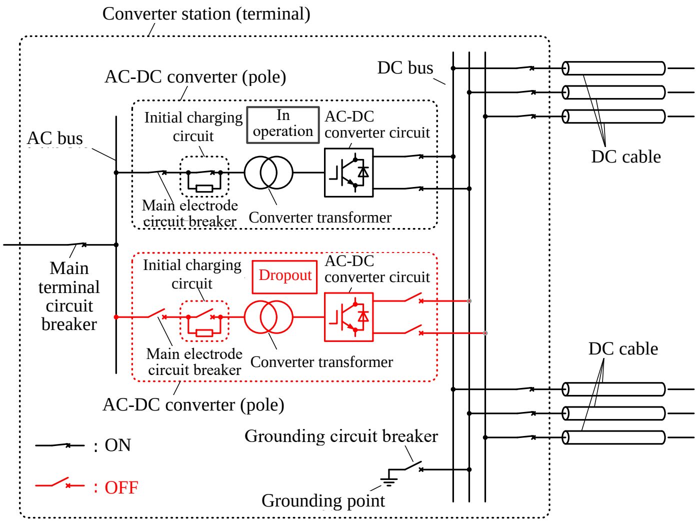


Fig. 5.10.4 Schematic of pole dropout

5.10.4 DC system separation

Figure 5.10.5 is a schematic diagram of DC system separation. Since two DC cables are disconnected, the DC system is separated into the upper half and the lower half in the figure, with each being a point-to-point HVDC system. This reference exemplifies a four-terminal system. If the DC system consists of five or more terminals, however, an HVDC system may have three or more terminals. If another DC cable is disconnected in Fig. 5.10.1, the status may change as shown in Fig. 5.10.5. In addition, DC cable inspection may change the status as shown in Fig. 5.10.5.

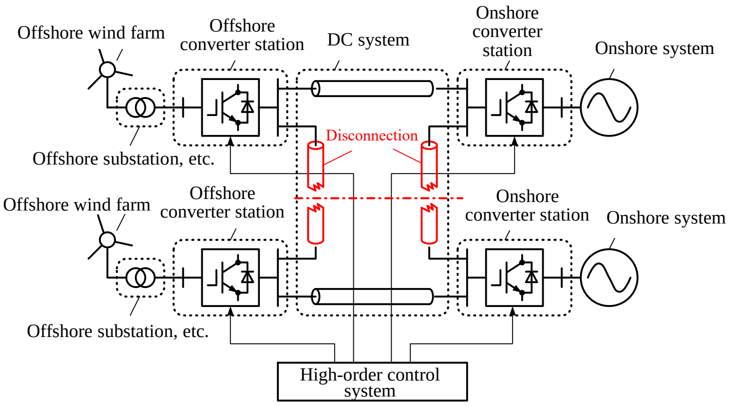


Fig. 5.10.5 Schematic of DC system separation

5.11 Re-interconnection

5.11.1 Terminal re-interconnection

Figure 5.11.1 is a schematic diagram of a bipolar converter station (terminal). In terminal dropout status, the AC-DC converter station of each converter station is gate-blocked, and the main terminal circuit breaker CB-Ter and main pole circuit breaker CB-Pol are opened. The circuit breakers to be opened include CB-PolP, CB-PolM, and CB-PolN between the DC bus and each pole, CB-DCL between the DC bus and DC reactor, and also AC initial charging circuit CB-ACPc and DC initial charging circuit CB-DCPc.

Terminal re-interconnection refers to a series of operations that restore a converter station of terminal dropout due to a system fault or converter failure to normal operation in the multi-terminal HVDC system.

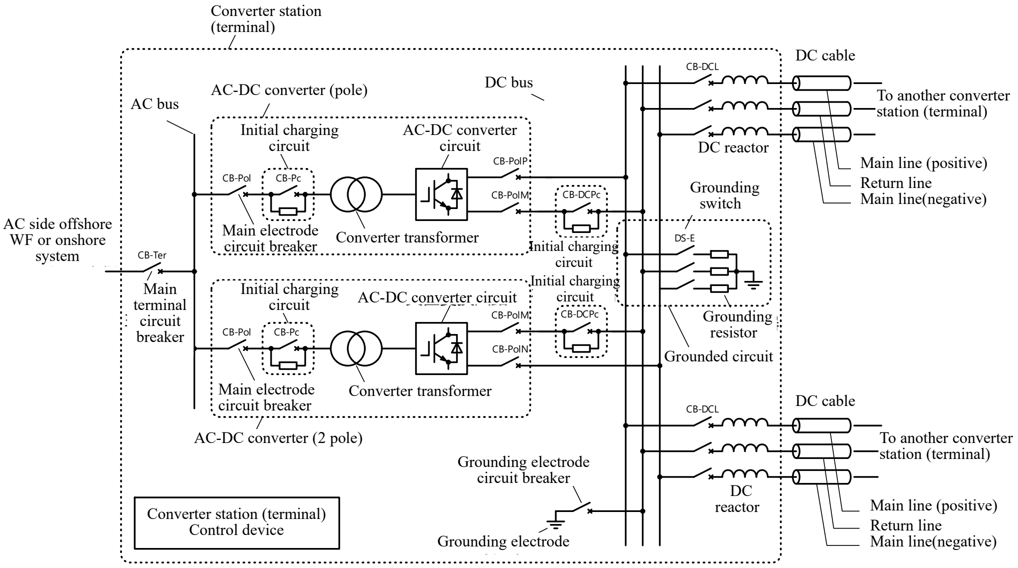


Fig. 5.11.1 Schematic of bipolar converter station (terminal) (Fig. 5.1.1 shown again)

When a re-interconnection command is received from the high-order control system, the terminal establishes the rated chopper cell capacitor voltage and interconnects the multi-terminal HVDC system again. The energy necessary for capacitor voltage establishment may be received from the AC side (offshore WF or onshore system) or the DC system.

For capacitor voltage establishment by charging from the AC side, execute initial charging and capacitor voltage establishment. After capacitor voltage establishment, close the circuit breakers CB-PolP, CB-PolM, and CB-PolN between the DC bus and each pole and the circuit breaker CB-DCL between the DC bus and DC reactor. If the voltage of each chopper cell capacitor exceeds the preset value at initial charging, the initial charging process may be skipped.

For capacitor voltage establishment by charging from the DC side, execute additional initial charging and capacitor voltage establishment. After capacitor voltage establishment, close the main terminal circuit breaker CB-Ter and main pole circuit breaker CB-Pol. If the voltage of each chopper cell capacitor exceeds the preset value at additional initial charging, the additional initial charging process may be skipped.

5.11.2 Pole re-interconnection

The energy necessary for capacitor voltage establishment is received from the AC or DC side for pole re-interconnection as with terminal re-interconnection. After the chopper cell capacitor voltage is raised to the rating, the pole is interconnected with the multi-terminal HVDC system again.

6. Assumed Faults of Multi-terminal HVDC System and Responses at Component Faults

The following pages describe various faults that are assumed to occur in the multi-terminal HVDC system connected to an offshore WF, and the responses in case of such component faults.

The multi-terminal HVDC system may have various configurations of equipment, such as AC-DC converter, AC circuit breaker, DC circuit breaker, DC bus, and DC cable. Therefore, the assumed fault and responses in case of component faults are mere examples.

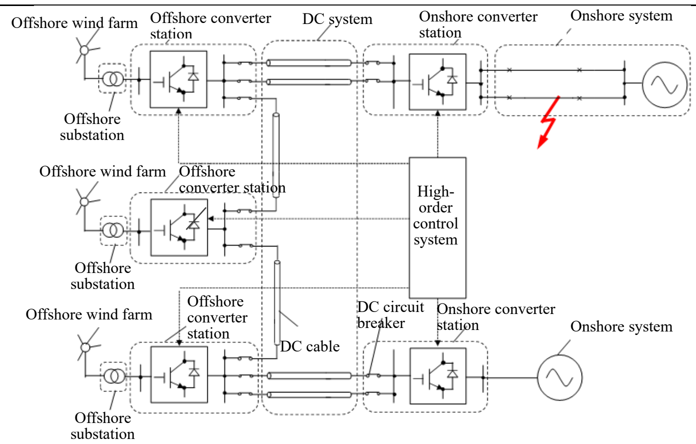
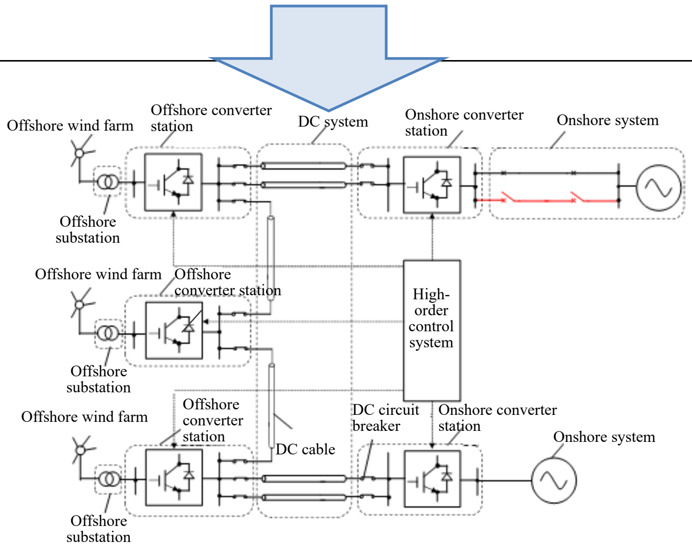
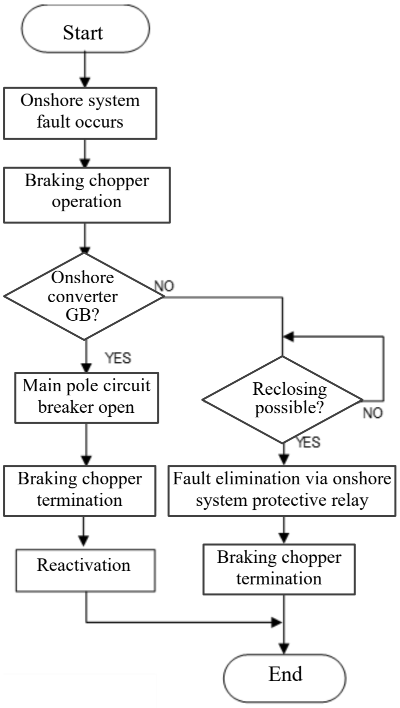
Assumed faults:

*Onshore system fault
*DC system fault (Main line ground fault)
*DC bus fault
*Offshore high-voltage power collection system fault (Power transmission cable)
*Offshore medium-voltage power collection system fault (String)
*Wind power generator internal failure
*Onshore converter station dropout
*Offshore converter station dropout
*High-order control system failure

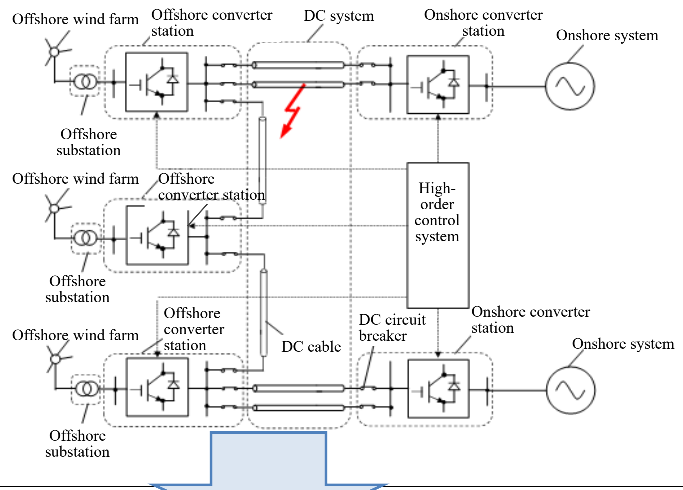
Components:

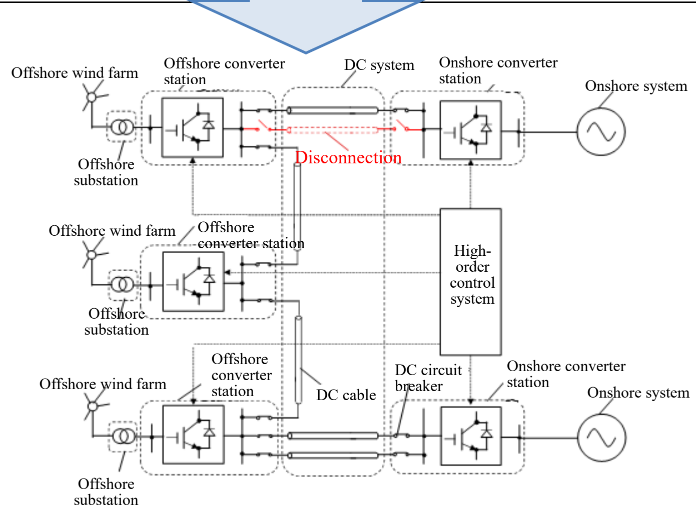
*Offshore WF (power generator, PCS)
*Offshore converter station - AC circuit breaker (medium-voltage power collection system)
*Offshore converter station - AC circuit breaker (high-voltage power collection system)
*Offshore converter station - AC-DC converter circuit
*Offshore converter station - DC circuit breaker between AC-DC converter circuit and DC bus (*)
*Offshore converter station - DC circuit breaker between DC bus and DC cable (*)
*Onshore converter station - DC circuit breaker between DC bus and DC cable (*)
*Onshore converter station - DC circuit breaker between AC-DC converter circuit and DC bus (*)
*Onshore converter station - AC-DC converter circuit
*Onshore converter station - AC circuit breaker
*Onshore system - Power transmission line AC circuit breaker

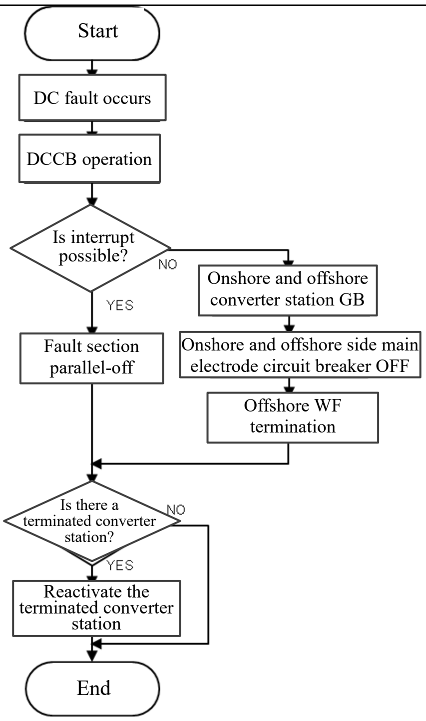
* “DC circuit breaker” constitutes examples of configuration and may be a switch like a DC disconnecting switch.

Assumed fault	Onshore system fault
Schematic	
When a fault occurs	
After fault elimination	
Flowchart	

Assumed fault		Onshore system fault
Response immediately after fault		・ An onshore converter station connected to the onshore system at which the fault occurred preferably continues operation without gate-blocking wherever possible (FRT: Fault Ride Through). However, temporary gate blocking is acceptable if an overcurrent or overvoltage is detected. ・ Notify the high-order control system that a fault has occurred in the onshore system. ・ If the converter station was operating in inverter mode before the fault, the braking chopper is activated as required. ・ The fault is eliminated by the onshore system protective relay and circuit breaker opening within a certain time. ・ The AC-side protective relay system and circuit breaker reclose after fault elimination.
Fault elimination method		The onshore system protective relay and circuit breaker disconnect the fault point. The power transmission line including the fault point is reclosed in a certain time.
Response after fault elimination		
	Onshore converter station	The onshore converter station braking chopper terminates within the operation time. If gate-blocking is caused by a fault, turn the main pole circuit breaker off. Reactivate the converter station if possible.
	Offshore converter station	Continues the pre-fault operation.
	Onshore system	Depends on the onshore system protective relay and circuit breaker.
	Power collection system	Continues the pre-fault operation.
	Offshore WF	Continues the pre-fault operation.
	High-order control system	Continues the pre-fault operation if the converter station continues to operate.
Remarks		

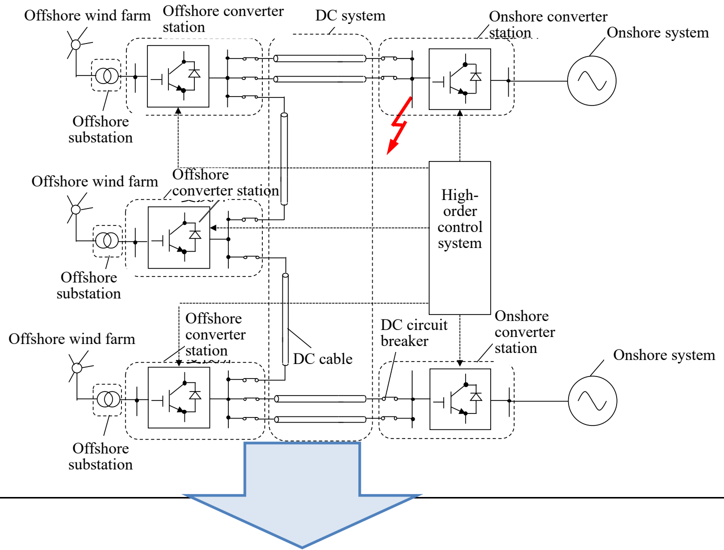
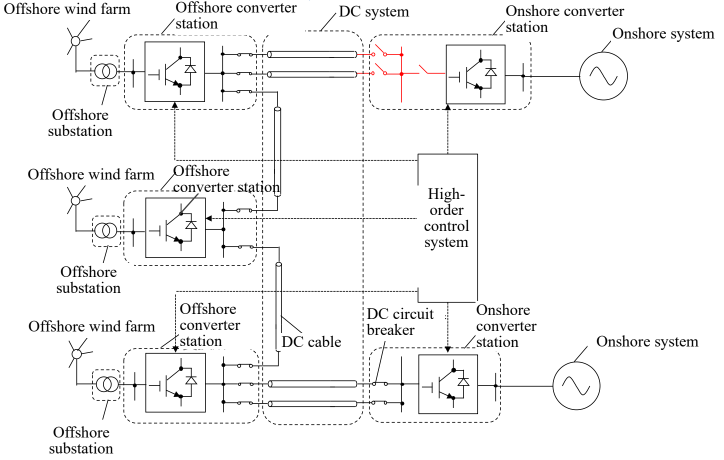
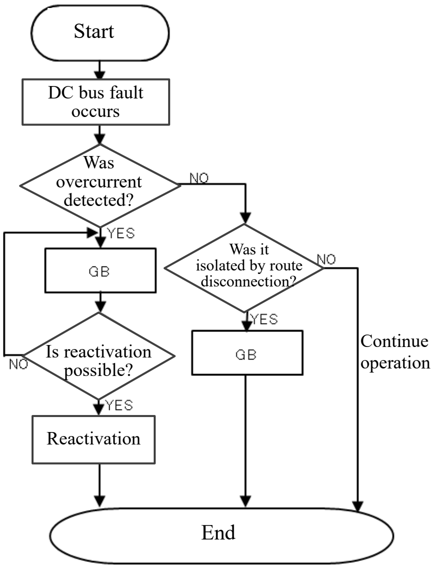
<table>
<tr><td colspan="2">Assumed fault</td><td>DC system fault (Main line ground fault)</td></tr>
<tr><td colspan="3">Schematic</td></tr>
<tr><td></td><td>When a fault occurs</td><td>


</td></tr>
<tr><td></td><td>After fault elimination</td><td>


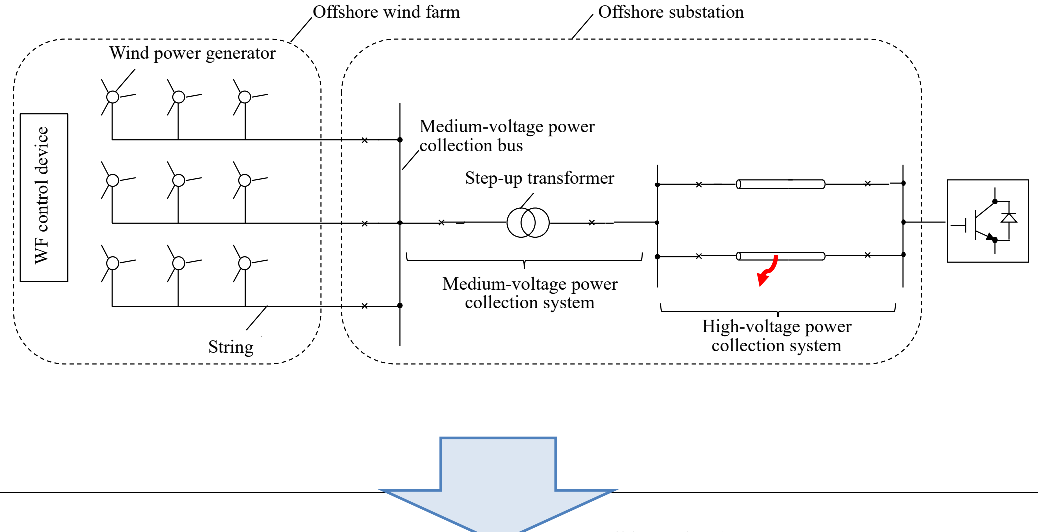
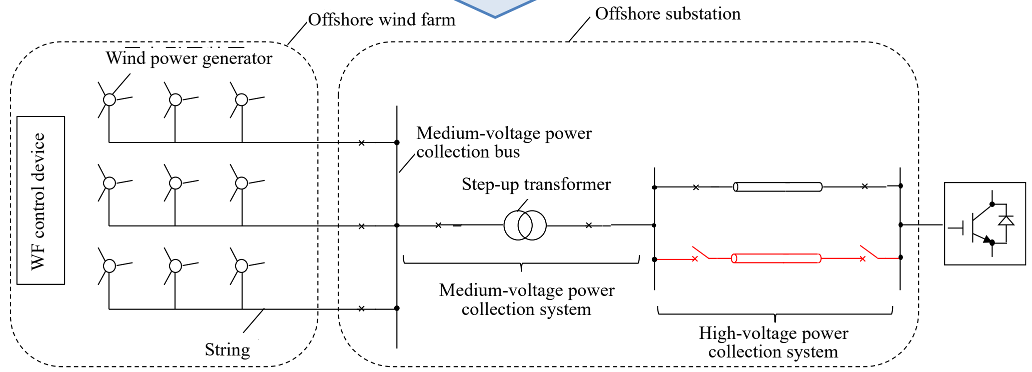
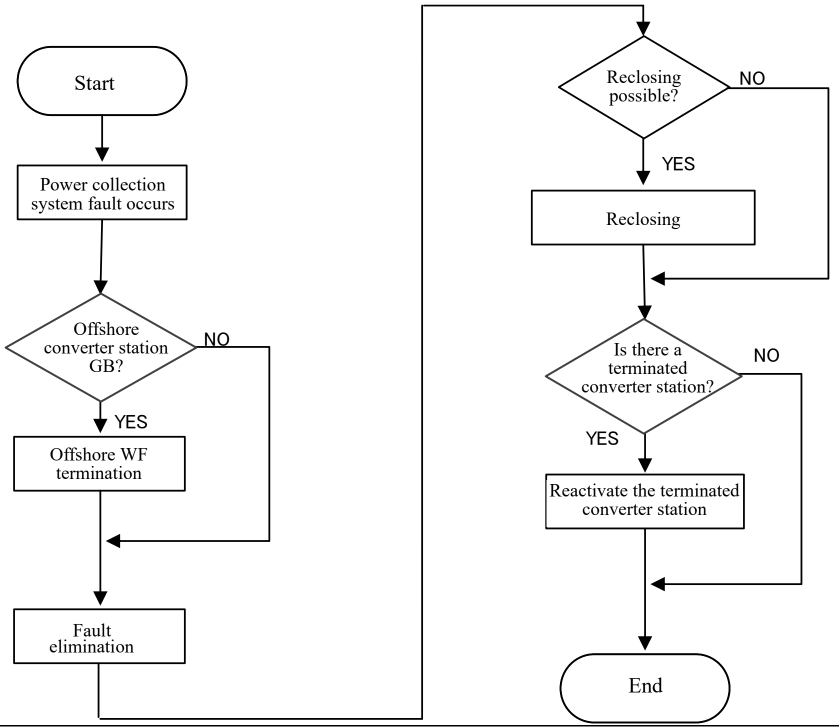
</td></tr>
<tr><td colspan="2">Flowchart</td><td>


</td></tr>
</table>

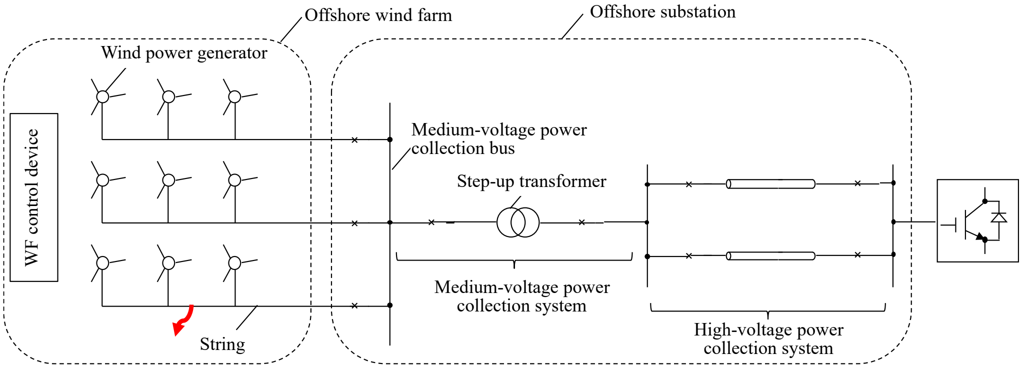
Assumed fault		DC system fault (Main line ground fault)
Response immediately after fault		・ Open the DC circuit breaker to interrupt the fault current and parallel off the fault section from the DC system. ・ Converter stations should remain in operation wherever possible after the fault, but onshore converter stations and offshore converter stations may be gate-blocked if overcurrent is detected. In this case, the amount of time gate-blocked should be as little as possible. ・ For bipolar or asymmetric monopolar configurations, open the main pole circuit breaker because the fault current will continue to flow in from the onshore system even after gate-blocking. For symmetric monopolar configurations, the earth potential level of normal poles theoretically increases to 2pu. If the increase in earth potential exceeds tolerance, a surge arrester or other countermeasure will be needed to control overvoltage. ・ If an offshore converter station is gate-blocked, the offshore WF detects an abnormal AC voltage (deviation from FRT requirements) and terminates.
Fault elimination method		Disconnect the grounded cable from the DC system by by opening the DC circuit breaker. Reopening is not assumed because this is a permanent fault. Opening the DC circuit breaker causes the converter station to drop out because of disconnection from another converter station.
Response after fault elimination		
	Onshore converter station	If possible, reactivate the station (deblock the gate) as soon as possible after gate blocking by a fault. If the station is isolated due to disconnection from other converter stations, this is a converter station dropout. After the dropout, STATCOM may be activated for the AC system.
	Offshore converter station	If possible, reactivate the station as soon as possible after gate blocking by a fault. If the station is isolated due to disconnection from other converter stations, this is a converter station dropout.
	Onshore system	Depends on the onshore system protective relay and circuit breaker.
	Power collection system	Depends on the power collection system protective relay and circuit breaker.
	Offshore WF	WF remains off if an interconnected offshore converter station is gate-blocked. If the converter station is then reactivated, AC voltage is restored and operation is restarted. However, if an output limit command is received, narrow down the output from each wind power generator or terminate some wind power generators.
	High-order control system	Use information on the opening/closing of the DC circuit breaker and converter failure information to locate the DC fault point and terminated terminal, then update the droop command value. If an onshore converter station dropout causes the power generated by an offshore WF to exceed transmission capacity, an output limit command can be issued to each offshore WF.
Remarks		Converter stations should continue operation after the fault and pre-fault flow status maintained as much as possible, but consider coordinating protection in accordance with the multi-terminal HVDC system operator’s approach to protection. Some cables may be overloaded before the high-order control system updates the droop command value, but this may be avoided through dynamic line rating or similar.

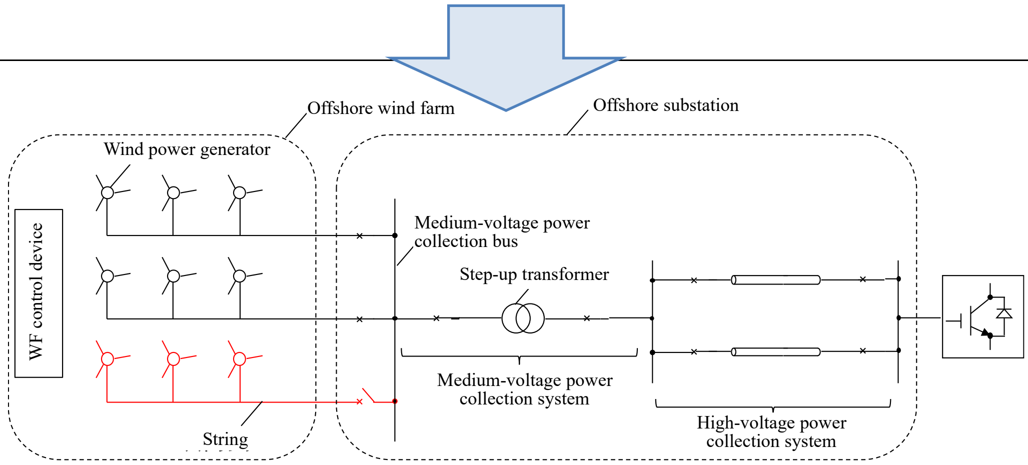
<table>
<tr><td>Assumed fault</td><td>DC bus fault</td></tr>
<tr><td colspan="2">Schematic</td></tr>
<tr><td>When a fault occurs</td><td>
</td></tr>
<tr><td>After fault elimination</td><td>
</td></tr>
<tr><td>Flowchart</td><td>
</td></tr>
</table>

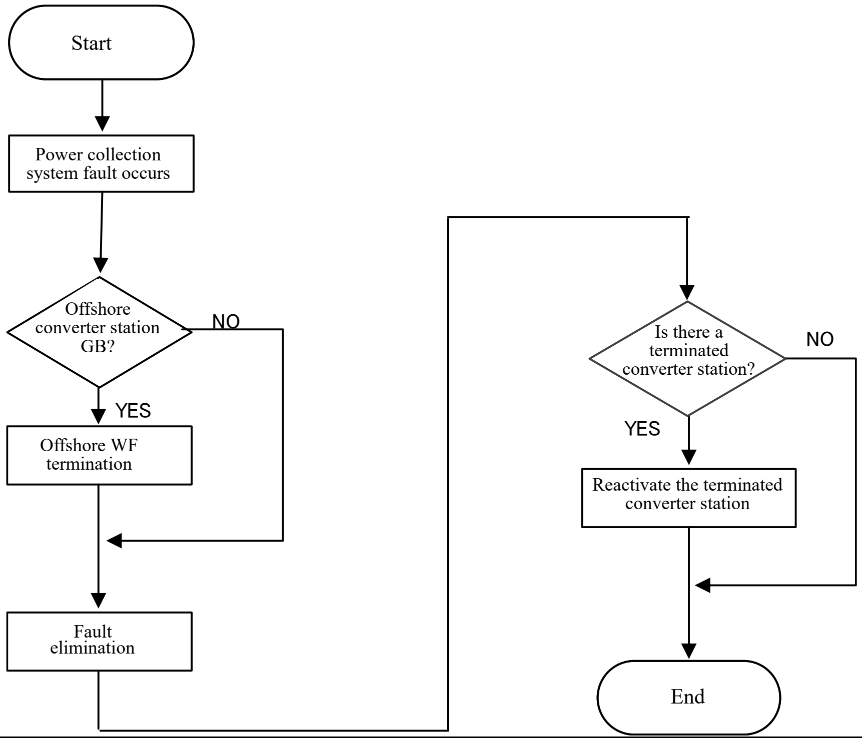
Assumed fault		DC bus fault
Response immediately after fault		・ Open a DC circuit breaker that can properly interrupt the fault current, and disconnect the faulty bus from the DC system. This DC circuit breaker is not necessarily one that is very close to the converter station at which the fault occurred. ・ Opening the DC circuit breaker causes the isolation of converter stations (including converter stations near the faulty bus) due to disconnection from other converter stations. Isolated converter stations are immediately gate-blocked and drop out. ・ Converter stations should remain in operation wherever possible after the fault, but onshore converter stations and offshore converter stations may be gate-blocked if overcurrent is detected. In this case, the amount of time gate-blocked should be as little as possible. ・ For bipolar or asymmetric monopolar configurations, open the main pole circuit breaker because the fault current will continue to flow in from the onshore system even after gate-blocking. For symmetric monopolar configurations, the earth potential level of normal poles theoretically increases to 2pu. If the increase in earth potential exceeds tolerance, a surge arrester or other countermeasure will be needed to control overvoltage. ・ If an offshore converter station is gate-blocked, the offshore WF detects an abnormal AC voltage (deviation from FRT requirements) and terminates.
Fault elimination method		Open a DC circuit breaker that can properly interrupt the fault current, and disconnect the faulty bus from the DC system. Reclosing of the DC circuit breaker is not assumed for a solitary bus without redundancy that has suffered permanent failure. Therefore, the fault bus converter station will drop out.
Response after fault elimination		
	Onshore converter station	If possible, reactivate the station (deblock the gate) as soon as possible after gate blocking by a fault. If the converter station drops out, STATCOM may be activated for the AC system.
	Offshore converter station	If possible, reactivate the station as soon as possible after gate blocking by a fault. If the converter station drops out, it shifts to termination status and is not reactivated.
	Onshore system	Depends on the onshore system protective relay and circuit breaker.
	Power collection system	Depends on the power collection system protective relay and circuit breaker.
	Offshore WF	WF remains off if an interconnected offshore converter station is gate-blocked. If the converter station is then reactivated, AC voltage is restored and operation is restarted. However, if an output limit command is received, narrow down the output from each wind power generator or terminate some wind power generators.
	High-order control system	Use information on the opening/closing of the DC circuit breaker and converter failure information to locate the DC fault point and terminated terminal, then update the droop command value. If an onshore converter station dropout causes the power generated by an offshore WF to exceed transmission capacity, an output limit command can be issued to each offshore WF.
Remarks		Before disconnecting the fault point, it is necessary to consider coordinating protection to ensure that non-fault bus converter stations do not drop out. If offshore WF power generation continues to exceed transmission capacity due to onshore converter station dropout, still-operational converter stations may be offline for an extended period due to overvoltage. To avoid this, it is necessary to consider countermeasures such as having the high-order control system issue an output limit command to each offshore WF.

Assumed fault	High-voltage power collection system fault (Power transmission cable)
Schematic	
When a fault occurs	
After fault elimination	
Flowchart	

Assumed fault		High-voltage power collection system fault (Power transmission cable)
Response immediately after fault		A fault current flows into the fault point from the offshore WF and/or offshore converter station. The offshore WF and offshore converter station continue operation without gate blocking wherever possible (FRT). However, gate blocking is acceptable in case of deviation from their requirements.
Fault elimination method		Disconnect the faulty cable by using the protective relay and circuit breaker of the power collection system. If the power collection system does not have redundancy, this may interrupt the route between the offshore converter station and offshore WF. Then the offshore converter station will drop out.
Response after fault elimination		
	Onshore converter station	Continue normal operation.
	Offshore converter station	Restart operation after gate deblocking if the converter station is gate-blocked during a fault except dropout.
	Onshore system	Depends on the onshore system protective relay and circuit breaker.
	Offshore system	Disconnect the faulty cable by using the protective relay and circuit breaker of the power collection system.
	Offshore wind power	If an interconnected offshore converter station has its gate blocked that is then deblocked and a power collection system voltage established, restart operation. WF terminates if an interconnected offshore converter station drops out.
	High-order control system	If a power collection system overload is expected to accompany a reduction in active lines, send an output upper limit command or termination command to offshore wind power.
Remarks		This fault corresponds to Figure 4.5 of CIGRÉ Technical Brochure 619. It is necessary to consider fault detection methods for power collection systems (fault current sources, whether to use a current differential relay, etc.).

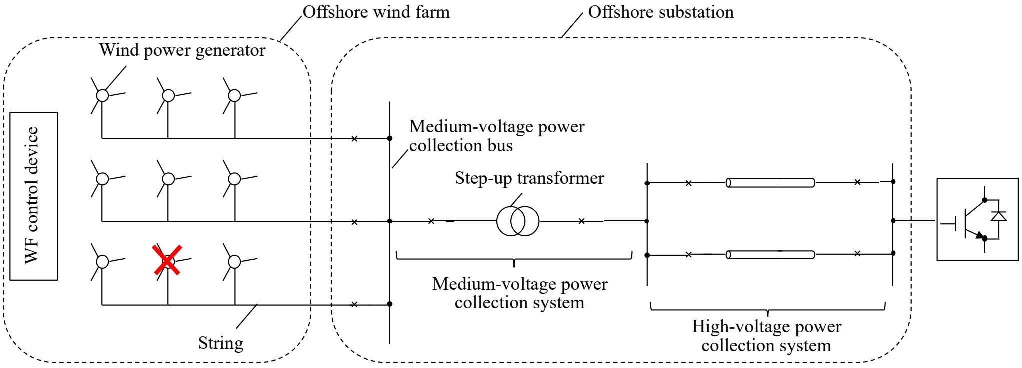
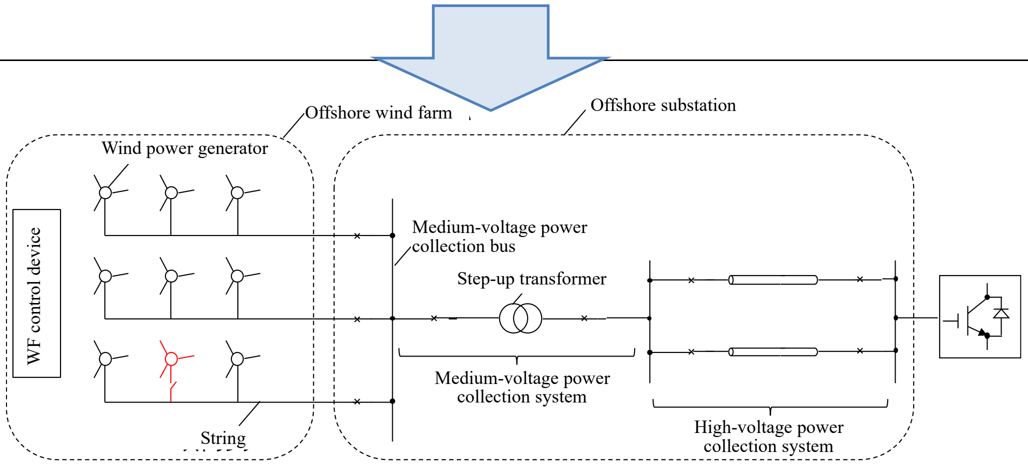
<table>
<tr><td>Assumed fault</td><td colspan="2">Medium-voltage power collection system fault (String)</td></tr>
<tr><td colspan="3">Schematic</td></tr>
<tr><td></td><td>When a fault occurs</td><td>


</td></tr>
<tr><td></td><td>After fault elimination</td><td>


</td></tr>
<tr><td>Flowchart</td><td colspan="2">


</td></tr>
</table>

Assumed fault	Medium-voltage power collection system fault (String)
Response immediately after fault	A fault current flows into the fault point from the offshore converter station and/or other string comprising offshore WF. The offshore WF and offshore converter station continue operation without gate blocking wherever possible (FRT). However, gate blocking is acceptable in case of deviation from their requirements.
Fault elimination method	Disconnect the faulty cable by using the protective relay and circuit breaker of the power collection system. Stop the wind power generator (wind turbine) belonging to the medium-voltage cable (string).
Response after fault elimination	
Onshore converter station	Continue normal operation.
Offshore converter station	Restart operation after gate deblocking if the converter station is gate-blocked during a fault except dropout.
Onshore system	Depends on the onshore system protective relay and circuit breaker.
Offshore system	Disconnect the faulty cable by using the protective relay and circuit breaker of the power collection system.
Offshore wind power	Stop the wind power generator (wind turbine) belonging to the medium-voltage cable (string). Other wind power generators (windmill) will continue normal operation.
High-order control system	Send a notice from the WF control device to the high-order control system regarding termination of some offshore wind power.
Remarks	This fault corresponds to Figure 4.4 of CIGRÉ Technical Brochure 619. It is likely also necessary to consider relay composition for fault point detection purposes.

<table>
<tr><td>Assumed fault</td><td>Wind power generator internal failure</td></tr>
<tr><td colspan="2">Schematic</td></tr>
<tr><td>When a fault occurs</td><td>
</td></tr>
<tr><td>After fault elimination</td><td>
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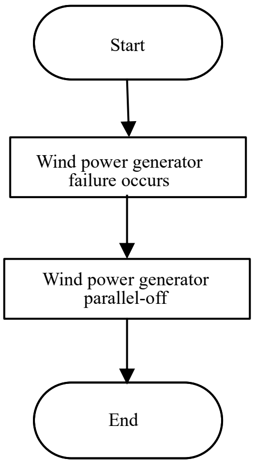
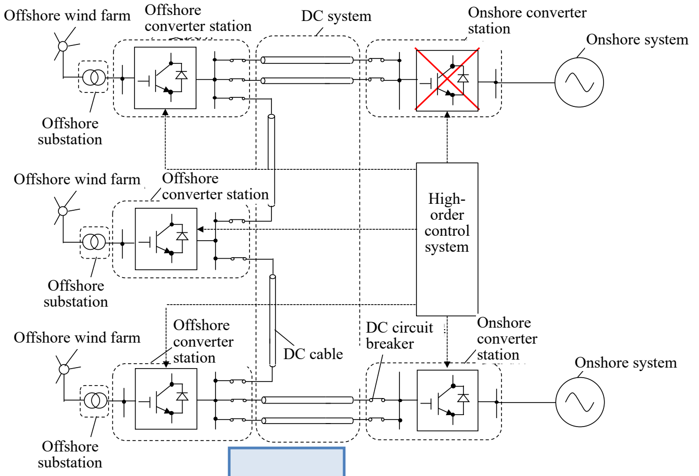
<tr><td>Flowchart</td><td>
</td></tr>
</table>

Assumed fault		Wind power generator internal failure
Response immediately after fault		An internal failure causes a wind power generator to trip. Depending on the nature of the internal failure, a fault current may flow in from the power collection system.
Fault elimination method		Disconnect the wind power generator (windmill) by using its protective system and PCS circuit breaker.
Response after fault elimination		
	Onshore converter station	Continue normal operation.
	Offshore converter station	Continue normal operation.
	Onshore system	Depends on the onshore system protective relay and circuit breaker.
	Offshore system	Continue normal operation.
	Offshore wind power	Disconnect the wind power generator (windmill) by using its protective system and PCS circuit breaker.
	High-order control system	Send a notice from the WF control device to the high-order control system regarding termination of some offshore wind power.
Remarks		

<table>
<tr><td>Assumed fault</td><td>Onshore converter station dropout</td></tr>
<tr><td colspan="2">Schematic</td></tr>
<tr><td>When a fault occurs</td><td>
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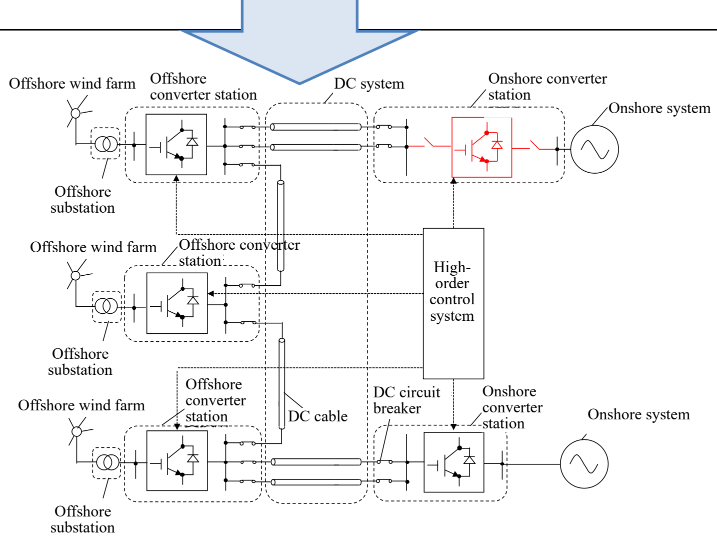
<tr><td>After fault elimination</td><td>
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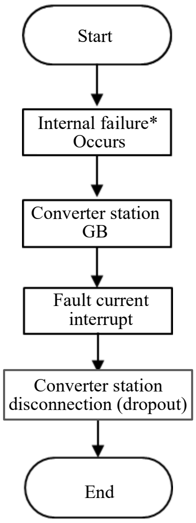
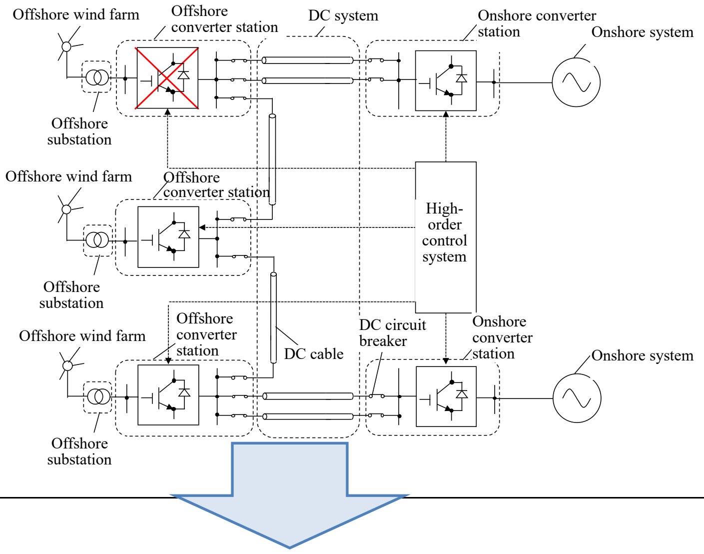
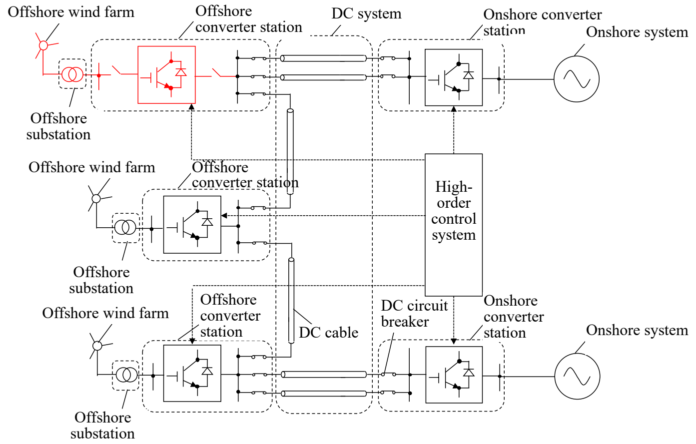
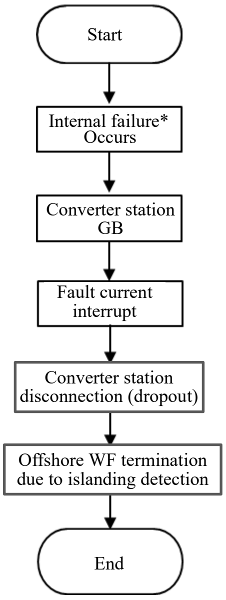
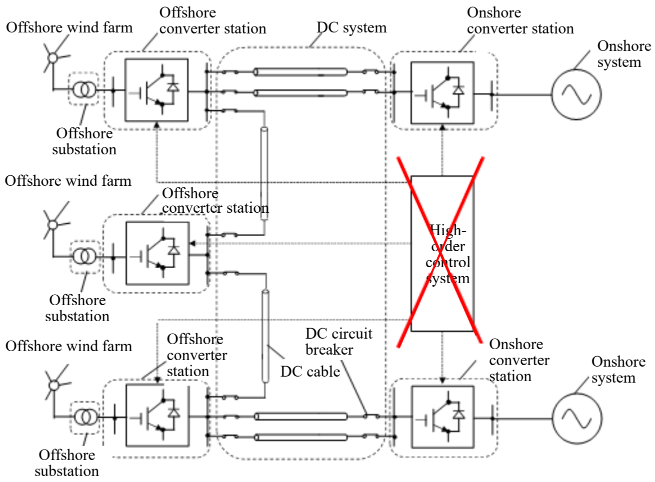
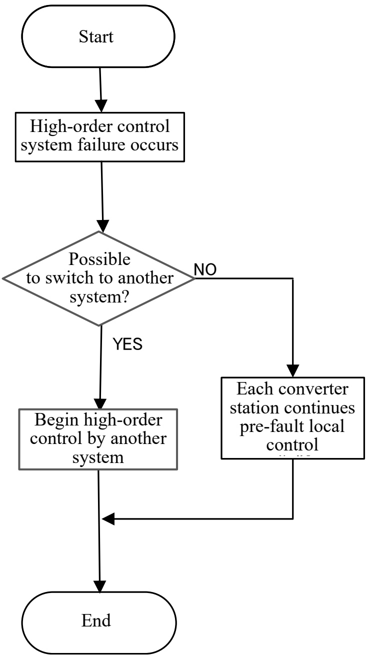
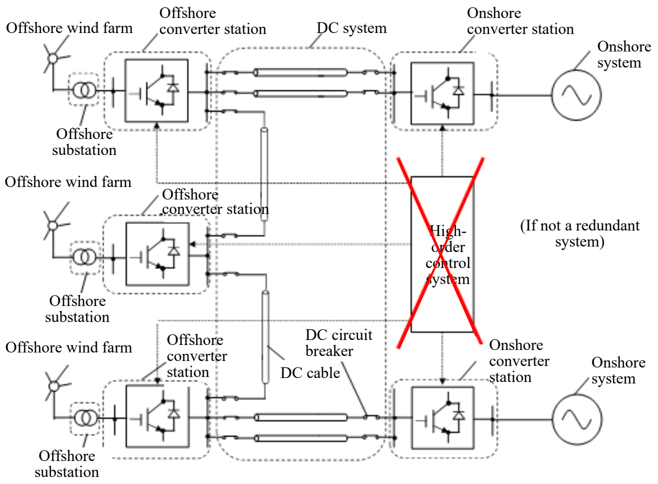
<tr><td>Flowchart</td><td>
</td></tr>
</table>

Assumed fault		Onshore converter station dropout
Response immediately after fault		・ The onshore converter station is gate-blocked by internal failure* and drops out. ・ Depending on the nature of the internal failure, a fault current may flow in from the AC or DC systems. ・ Open an AC or DC circuit breaker that can properly interrupt the fault current. This DC circuit breaker is not necessarily one that is very close to the converter station at which the fault occurred. ・ Open the circuit breakers for both the AC and DC sides within the converter station. That converter station will be disconnected from the AC and DC systems.
Fault elimination method		Disconnect the converter station using both the AC and DC side circuit breakers as well as the converter station protective relay system.
Response after fault elimination		
	Onshore converter station	Continue normal operation except when the converter station drops out. If a new voltage command or droop command is given by the high-order control system, continue operation in accordance with the new commands.
	Offshore converter station	Continue normal operation.
	Onshore system	Depends on the onshore system protective relay and circuit breaker.
	Power collection system	Continue normal operation.
	Offshore WF	Continue normal operation. However, if an output limit command is received, narrow down the output from each wind power generator or terminate some wind power generators.
	High-order control system	Update the droop command value. If an onshore converter station dropout causes the power generated by an offshore WF to exceed transmission capacity, there will be an offshore WF transfer interrupt. If an onshore converter station dropout causes the power generated by an offshore WF to exceed transmission capacity, an output limit command can be issued to each offshore WF.
Remarks		If an onshore converter station has only one DC-AVR terminal and that onshore converter station drops out, the DC system's voltage control functionality will be lost. It is likely necessary to use droop controls or similar to reconfigure systems to have another onshore converter station take over DC-AVR terminal functionality. *There are other causes than internal failure for converter station dropouts, but since converter station dropouts caused by DC system fault or DC bus fault have already been explained, this section will use internal failure as an example.

Assumed fault	Offshore converter station dropout
Schematic	
When a fault occurs	
After fault elimination	
Flowchart	

Assumed fault	Offshore converter station dropout
Response immediately after fault	・ The offshore converter station is gate-blocked by internal failure* and drops out. ・ Depending on the nature of the internal failure, a fault current may flow in from the AC or DC systems. ・ Open an AC or DC circuit breaker that can properly interrupt the fault current. This DC circuit breaker is not necessarily one that is very close to the converter station at which the fault occurred. ・ Open the circuit breakers for both the AC and DC sides within the converter station. That converter station will be disconnected from the AC and DC systems. ・ Power collection systems are offshore WF-only isolated systems.
Fault elimination method	Disconnect the converter station using both the AC and DC side circuit breakers as well as the converter station protective relay system.
Response after fault elimination	
Onshore converter station	Continue normal operation.
Offshore converter station	Continue normal operation except when the converter station drops out.
Onshore system	Depends on the onshore system protective relay and circuit breaker.
Power collection system	Continue normal operation except when the offshore converter station drops out. If an offshore converter station drops out, the system will be depend on the power collection system’s protective relay and circuit breaker.
Offshore WF	Continue normal operation except when the offshore converter station drops out. If the offshore converter station drops out, the system will become an offshore WF-only isolated system which is then terminated by the offshore WF power conditioning system’s islanding detection functionality.
High-order control system	Update the droop command value.
Remarks	*There are other causes than internal failure for converter station dropouts, but since converter station dropouts caused by DC system fault or DC bus fault have already been explained, this section will use internal failure as an example.

Assumed fault	High-order control system failure	
Schematic		Flowchart
When a fault occurs		
After fault elimination		

Assumed fault		High-order control system failure
Response immediately after fault		(If the system has no redundancy) The DC system voltage and flow depend on the local control of each converter station only and an overvoltage or overcurrent may arise in some cases. If an overvoltage or overcurrent is detected, the protective relay of each converter station or DC system may cause converter station dropouts or route disconnections in a chain reaction. (If the system has redundancy) Switch to the backup system.
Fault elimination method		(If the system has no redundancy) Depends on the protective relay of each converter station or DC system (However, it is considered necessary to ensure that the HVDC system does not have to operate without a high-order control system as much as possible, by including sufficient redundancy in the high-order control system). (If the system has redundancy) Switch to the backup system.
Response after fault elimination		
	Onshore converter station	Continues normal operation but stops (dropout) if an overvoltage or overcurrent is detected.
	Offshore converter station	Continues normal operation but stops (dropout) if an overvoltage or overcurrent is detected.
	Onshore system	Depends on the onshore system protective relay and circuit breaker.
	Offshore system	Depends on the offshore system protective relay and circuit breaker.
	Offshore wind power	WF terminates if an interconnected offshore converter station drops out. In this case, each wind power generator (windmill) will terminate operate using islanding detection functionality.
	High-order control system	(If the system has no redundancy) Depends on the protective relay of each converter station or DC system. (If the system has redundancy) Switch to the backup system.
Remarks		If there is a high-order control system failure, converter stations will operate under local controls based on command values assigned immediately prior. Therefore, there is the possibility of overvoltage or overcurrent resulting in dropout, depending on wind conditions and onshore system status. It is best to introduce redundancy to high-order control systems to prevent loss of functionality.

Assumed Faults of Offshore Multi-terminal DC Power Transmission System and Responses to Component Faults

	Offshore side						
	A. Offshore WF (Power generator, PCS)	**B. AC circuit breaker at offshore converter station (Medium-voltage power collection system)**	**C. AC circuit breaker at offshore converter station (Medium-voltage power collection system)**	**D. AC circuit breaker at offshore converter station**	**E. AC-DC converter circuit at offshore converter station**	**F. DC circuit breaker between offshore converter station and DC bus**	**G. DC circuit breaker between DC bus and DC cable**
1. Onshore system fault	-	-	-	-	-	-	-
2. DC system fault (Main line ground fault)	If an offshore converter station is gate-blocked, WF detects an abnormal AC voltage and terminates.	-	-	If an offshore converter station is gate-blocked, open the circuit breaker.	If gate-blocked by a fault, reactivate the converter station after deblock. If the station is isolated due to disconnection from other converter stations, it drops out from the DC system.	If offshore converter station dropout occurs, open the circuit breaker.	Open the DC circuit breaker of the DC cable. Reclosing is not assumed because this is a permanent fault.
3. DC bus fault	If an offshore converter station is gate-blocked, WF detects an abnormal AC voltage and terminates.	-	-	If an offshore converter station is gate-blocked, open the circuit breaker.	If gate-blocked by a fault, reactivate the converter station after deblock. If the station is isolated due to disconnection from other converter stations, it drops out from the DC system.	Open circuit breaker of that bus. Reclosing is not assumed. (Permanent fault)	Open circuit breaker of that cable. Reclosing is not assumed. (Permanent fault)
4. High-voltage power collection system fault (Power transmission cable)	WF terminates if an interconnected offshore converter station drops out.	-	Open circuit breaker for that cable.	-	Continue operation without gate-blocking wherever possible (FRT). GB is acceptable in case of deviation from FRT requirements.	-	-
5. Medium-voltage power collection system fault (String)	WF belonging to the string terminates. WF terminates if an interconnected offshore converter station drops out.	Open circuit breaker for that string.	-	-	Continue operation without gate-blocking wherever possible (FRT). GB is acceptable in case of deviation from FRT requirements.	-	-
6. Wind power generator internal failure	Disconnect the wind power generator by using its protection system and PCS circuit breaker.	-	-	-	-	-	-
7. Onshore converter station dropout	-	-	-	-	-	-	-
8. Offshore converter station dropout	WF terminates if an interconnected offshore converter station drops out.	-	-	Open circuit breaker for that converter station.	Continue operation except when the converter station drops out.	Open circuit breaker for that converter station.	-
9. High-order control system dropout	WF terminates if an interconnected offshore converter station drops out.	-	-	If offshore converter station dropout occurs, open the circuit breaker.	Switch to local control of converter station if the high-order control system has no redundancy Overvoltage or overcurrent detection causes dropout.	If offshore converter station dropout occurs, open the circuit breaker.	-

GB: Gate-block

GDB: Gate-deblock

Assumed Faults of Offshore Multi-terminal DC Power Transmission System and Responses to Component Faults

	Onshore side				
	H. DC circuit breaker between DC bus and DC cable	**I. DC circuit breaker between onshore converter station and DC bus**	**J. AC-DC converter circuit at onshore converter station**	**K. AC circuit breaker at onshore converter station**	**L. AC circuit breaker at onshore system power transmission line**
1. Onshore system fault	-	-	Continues operation without gate-blocking wherever possible (FRT). However, temporary gate-blocking is acceptable if an overcurrent or overvoltage is detected.	If an onshore converter station is gate-blocked, open the circuit breaker.	Open circuit breaker of that power transmission line. Reclose it after fault elimination.
2. DC system fault (Main line ground fault)	Open the DC circuit breaker of the DC cable. Reclosing is not assumed because this is a permanent fault.	If onshore converter station dropout occurs, open the circuit breaker.	If gate-blocked, reactivate the converter station after deblock. If the station is isolated due to disconnection from other converter stations, it drops out from the DC system.	If an onshore converter station is gate-blocked, open the AC circuit breaker to prevent a fault current inflow.	-
3. DC bus fault	Open circuit breaker of that cable. Reclosing is not assumed. (Permanent fault)	Open circuit breaker of that bus. Reclosing is not assumed. (Permanent fault)	If gate-blocked, reactivate the converter station after deblock. If the station is isolated due to disconnection from other converter stations, it drops out from the DC system.	If an onshore converter station is gate-blocked, open the AC circuit breaker to prevent a fault current inflow.	-
4. High-voltage power collection system fault (Power transmission cable)	-	-	-	-	-
5. Medium-voltage power collection system fault (String)	-	-	-	-	-
6. Wind power generator internal failure	-	-	-	-	-
7. Onshore converter station dropout	-	Open circuit breaker for that converter station.	Continue operation except when the converter station drops out.	Open circuit breaker for that converter station.	-
8. Offshore converter station dropout	-	-	-	-	-
9. High-order control system dropout	-	If onshore converter station dropout occurs, open the circuit breaker.	Switch to local control of converter station if the high-order control system has no redundancy Overvoltage or overcurrent detection causes dropout.	If onshore converter station dropout occurs, open the circuit breaker.	-

GB: Gate-block

GDB: Gate-deblock

7. Case Study of High-order Control System Power Distribution

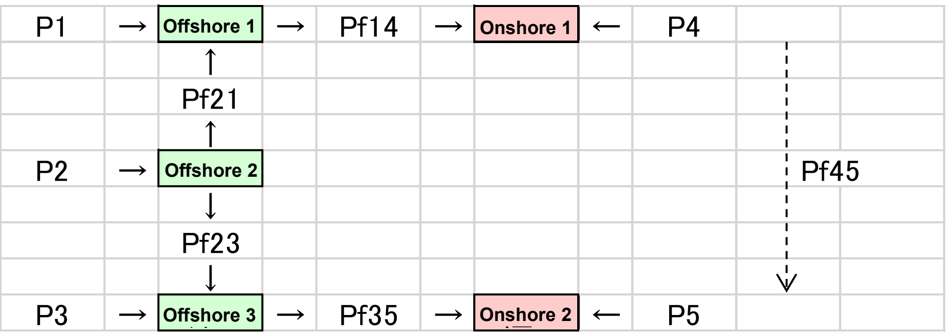
Section 3.1 discussed the basic principles of high-order control system power distribution functions. This chapter covers case studies in which those basic principles are applied: a case in which capacity is exceeded and a case in which capacity is not exceeded for a 5-terminal HVDC system.

The rated capacity for all equipment in this chapter's 5-terminal HVDC system is shown in Table 7.1, and the system configuration is shown in Fig. 7.1. In codes for terminal command values in this chapter, positive values represent power generation (transmission) and negative values represent power reception. Onshore inter-terminal electrical transmission planned values are positive (transmission) when moving in the direction from Onshore 1 to Onshore 2.

Table 7.1 Terminal command values and line flow for a 5-terminal HVDC system

No.	Terminal command values and line flow	Abbreviation	Code	Upper/lower limit [MW]
1	Offshore terminal 1 command value	Offshore 1	P1	0 to 1500
2	Offshore terminal 2 command value	Offshore 2	P2	0 to 1500
3	Offshore terminal 3 command value	Offshore 3	P3	0 to 1500
4	Onshore terminal 1 command value	Onshore 1	P4	-3000 to 3000
5	Onshore terminal 2 command value	Onshore 2	P5	-3000 to 3000
6	Offshore 2 Offshore 1 DC Cable Flow	Offshore 2 Offshore 1	Pf21	-1500 to 1500
7	Offshore 2 Offshore 3 DC Cable Flow	Offshore 2 Offshore 3	Pf23	-1500 to 1500
8	Offshore 1 Onshore 1 DC Cable Flow	Offshore 1 Onshore 1	Pf14	-3000 to 3000
9	Offshore 3 Onshore 2 DC Cable Flow	Offshore 3 Onshore 2	Pf35	-3000 to 3000
10	Offshore 1 Offshore 2 Electrical Transmission Flow	Offshore 1 Onshore 2	Pf45	-1500 to 1500

Code definitions	Terminal command value	・ Positive for direction of transmission from AC to DC
	DC cable flow	・ Positive for direction of transmission from Offshore 2 to Offshore 1 ・ Positive for direction of transmission from Offshore 1 to Onshore 1 ・ Positive for direction of transmission from Offshore 2 to Offshore 3 ・ Positive for direction of transmission from Offshore 3 to Onshore 2
	Onshore inter-terminal electrical transmission	・ Positive for direction of transmission from Onshore 1 to Onshore 2



*The arrow symbol → indicates the positive direction. (Ex) P4 = -3000 indicates the reception by Onshore 1 of 3000 MW.

Fig. 7.1 System configuration and code definitions for a 5-terminal HVDC system

7.1 If Not Exceeding Capacity

There are countless patterns for flow status that does not exceed capacity, among offshore wind power generation, offshore wind power reception, and onshore inter-terminal electrical transmission. This section will focus on flow status in a case in which there is considered to be a high potential for exceeding electrical transmission capacity in the event that excess of capacity does occur: full output from offshore wind power generation and uniform power reception by onshore terminals.

To ensure this flow status is achieved without exceeding capacity, the respective planned values are set as follows.

- Offshore 1 wind power generation plan: 1500 MW
- Offshore 2 wind power generation plan: 1500 MW
- Offshore 3 wind power generation plan: 1500 MW
- Onshore 1 wind power generation plan: -3000 MW
- Onshore 2 wind power generation plan: -1500 MW
- Onshore inter-terminal electrical transmission planned value: 750 MW

Terminal command values are calculated based on overlap of planned values, as follows. Offshore planned values apply only to offshore wind power generation, and offshore terminal command values line up with offshore wind power generation planned values.

- Offshore 1 terminal command value: 1500 MW = Offshore 1 wind power generation planned value: 1500 MW
- Offshore 2 terminal command value: 1500 MW = Offshore 2 wind power generation planned value: 1500 MW
- Offshore 3 terminal command value: 1500 MW = Offshore 3 wind power generation planned value: 1500 MW
- Onshore 1 terminal command value: -2250 MW = Offshore wind power reception planned value: -3000 MW
  + Onshore inter-terminal electrical transmission planned value: 750 MW
- Onshore 2 terminal command value: -2250 MW = Offshore wind power reception planned value: -1500 MW
  + Onshore inter-terminal electrical transmission planned value: -750 MW

Fig 7.2 shows the planned values and terminal command values for the above settings under the assumption that capacity is not exceeded.

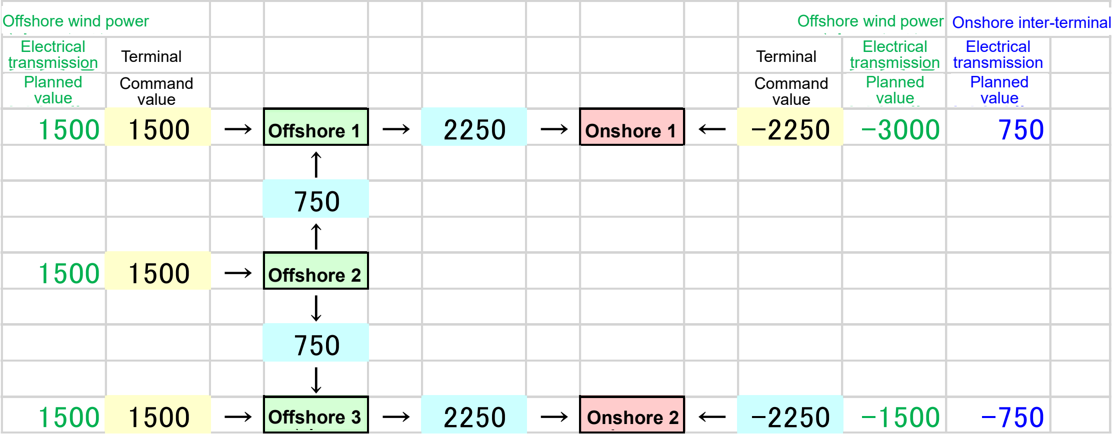


Fig 7.2: Planned Values and Terminal Command Values If Not Exceeding Capacity

7.2 If Exceeding Capacity

As a point of reference for flow status if not exceeding capacity, consider a case in which system capacity is exceeded. This section will look at two cases in which capacity is exceeded: an offshore terminal 1 dropout and onshore terminal 1 dropout.

[5-Terminal HVDC System Flow Formula]

As preparation for these case studies, this section will explain the flow formula needed for power distribution in the event that capacity is exceeded. In the event that system capacity is exceeded, the multi-terminal HVDC system flow formula is needed to calculate flow status when the volume exceeding system capacity is limited to the limit value. Fig. 7.3 shows the five-terminal HVDC system flow formula (hereinafter "flow formula") that is the focus of this chapter. The codes used in Fig. 7.3 are displayed in Table 7.1.

$Pf21 + P1 = Pf14$: Offshore 1 Bus
$P2 = Pf21 + Pf23$: Offshore 2 Bus
$Pf23 + P3 = Pf35$: Offshore 3 Bus
$Pf14 + P4 = 0$: Onshore 1 Bus
$Pf35 + P5 = 0$: Onshore 2 Bus

(Adding the five formulas above together yields the supply and demand equilibrium equation "$P1 + P2 + P3 + P4 + P5 = 0$".)

Fig. 7.3 5-Terminal HVDC System Flow Formula (System of 5 simultaneous equations with 9 variables)

Input known quantities (terminal command values, dropped-out system power amount of "0", amount of power limited to the limit value, etc.) into the flow formula in Fig. 7.3 to calculate the unknown quantities.

For example, if the terminal command values of Offshore 1, Offshore 2, Offshore 3, and Onshore 1 (P1, P2, P3, P4) are knowns, they can be input into the flow formula (system of 5 simultaneous equations with 9 variables) to create a system of 5 simultaneous equations with 5 variables. Then the transmission line flow and Offshore 2 terminal command value can be found as shown in Fig. 7.4. The inputs and outputs of the flow formula in this example are shown in Fig. 7.5.

$Pf14 = - P4$: Offshore 1 Onshore 1 DC Cable Flow (Output)
$Pf21 = - P1 - P4$: Offshore 2 Offshore 1 DC Cable Flow (Output)
$Pf23 = P1 + P2 + P4$: Offshore 2 Offshore 3 DC Cable Flow (Output)
$Pf35 = - P5$: Offshore 3 Onshore 2 DC Cable Flow (Output)
$P5 = - P1 - P2 - P3 - P4$: Onshore 2 Terminal Command Value (Output)

P1, P2, P3, P4 : Offshore 1, Offshore 2, Offshore 3, Onshore 1 Terminal Command Value (Output)

Fig. 7.4 5-Terminal HVDC System Flow Formula (System of 5 simultaneous equations with 5 variables)

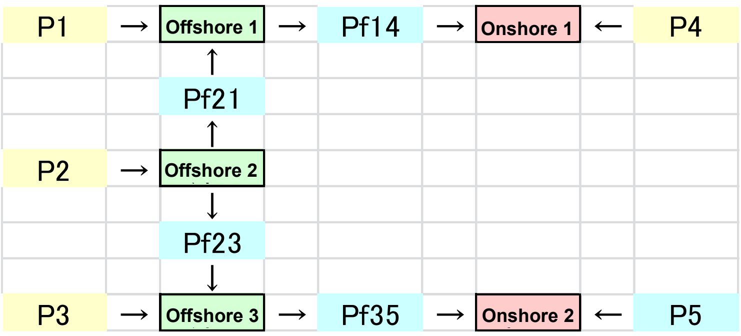


Fig. 7.5 Flow Formula Inputs and Outputs (Yellow: Input. Blue: Output)

7.2.1 Example: Offshore Terminal 1 Dropout

In contrast to cases in which capacity is not exceeded, this example scenario considers a case in which offshore terminal 1 (1500 MW power generation) drops outs.

In this case, an offshore terminal 1 dropout results in total power generation dropping from 4500 MW to 3000 MW, meaning that total power reception must also drop from 4500 MW to 3000 MW (a 1500 MW drop).

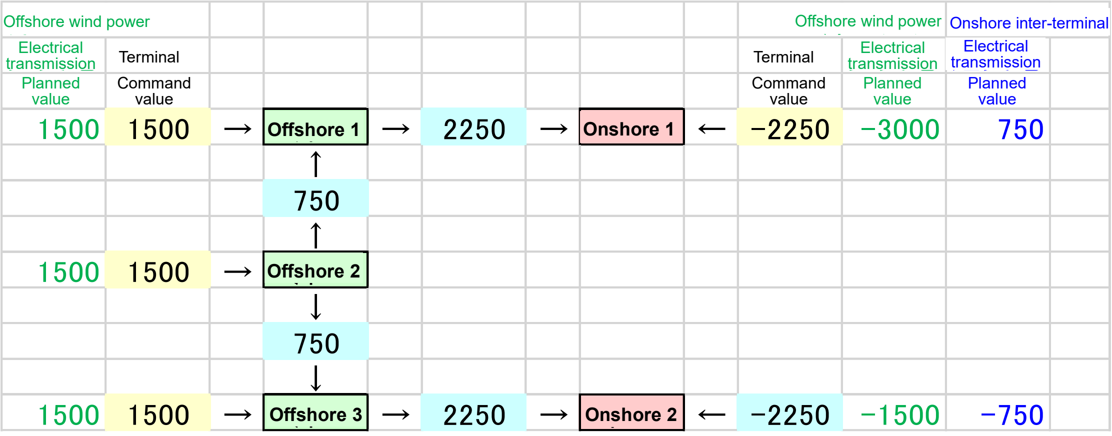


Fig. 7.6 If Not Exceeding Capacity

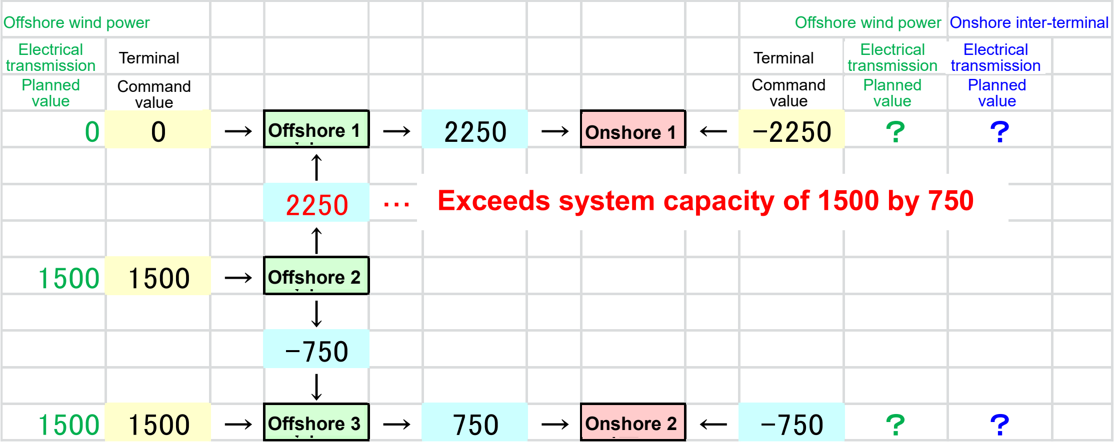


Fig. 7.7 Offshore Terminal 1 Dropout Case (Before Limitation of System Capacity to Limit Value)

For Fig. 7.7, use the flow formula (Fig. 7.3) to calculate flow status when the volume exceeding system capacity is limited to the limit value. The calculated flow status is shown in Fig. 7.8.

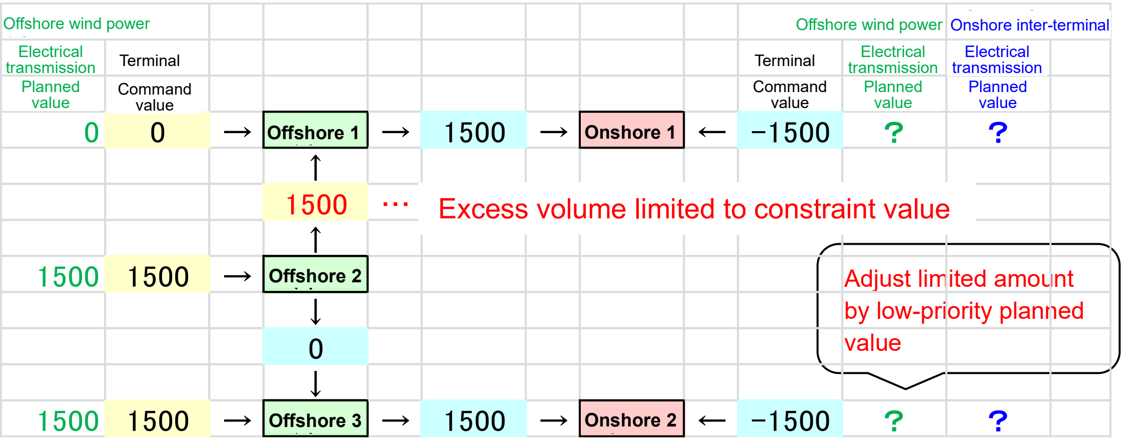


Fig. 7.8 Offshore Terminal 1 Dropout Case (After Limitation of System Capacity to Limit Value)

Next, adjust the limited amount by a low-priority planned value. Planned value adjustments will be described below for each pattern as shown in Table 3.1.1.

Pattern 1: Adjusted to prioritize the offshore wind power generation plan and offshore wind power reception plan (Terminal 1)

Since the offshore wind power generation plan and offshore wind power reception plan (Terminal 1) are given priority (fixed), change the onshore inter-terminal electrical transmission plan to 1500 MW to change the Terminal 1 command value to -1500 MW. After changing the onshore inter-terminal electrical transmission plan, make the Terminal 2 command value -1500 MW by changing the offshore wind power reception plan (Terminal 2) to -1500 MW.

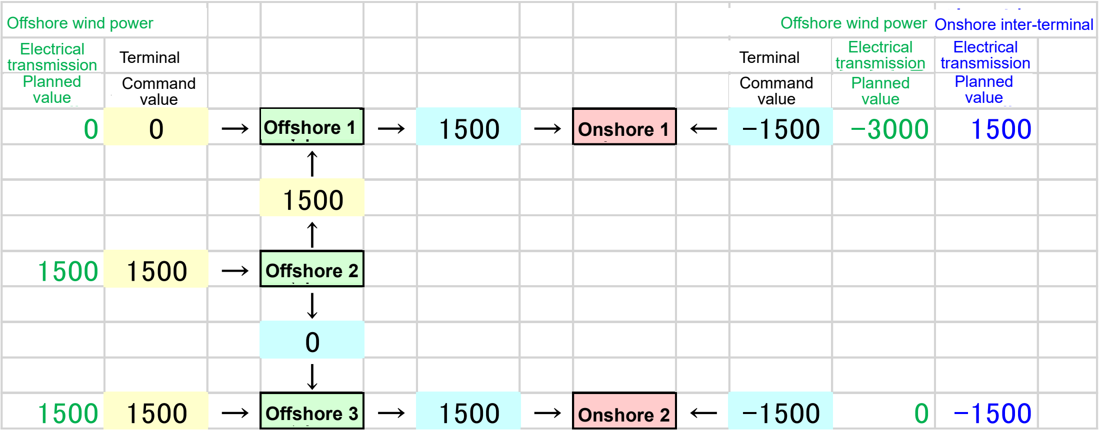


Fig. 7.9 Pattern 1: Prioritization of the offshore wind power generation plan and offshore wind power reception plan (Terminal 1)

Pattern 2: Adjusted to prioritize the offshore wind power generation plan and offshore wind power reception plan (Terminal 2)

Since the offshore wind power generation plan and offshore wind power reception plan (Terminal 2) are given priority (fixed), change the onshore inter-terminal electrical transmission plan to 0 MW to change the Terminal 2 command value to -1500 MW. After changing the onshore inter-terminal electrical transmission plan, make the Terminal 1 command value -1500 MW by changing the offshore wind power reception plan (Terminal 1) to -1500 MW.

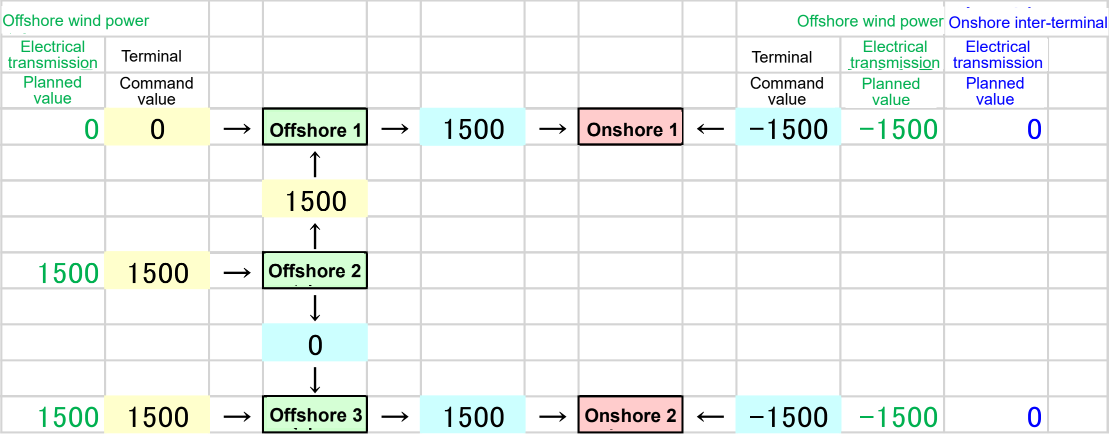


Fig. 7.10 Pattern 2: Prioritization of the offshore wind power generation plan and offshore wind power reception plan (Terminal 2)

Pattern 3: Adjusted to prioritize the offshore wind power generation plan and onshore inter-terminal electrical transmission plan (Terminal 1)

Since the offshore wind power generation plan and onshore inter-terminal electrical transmission plan are given priority (fixed), change the offshore wind power reception plan (Terminal 1) to -2250 MW to change the Terminal 1 command value to -1500 MW, and change the offshore wind power reception plan (Terminal 2) to -750 MW to change the Terminal 1 command value to -1500 MW.

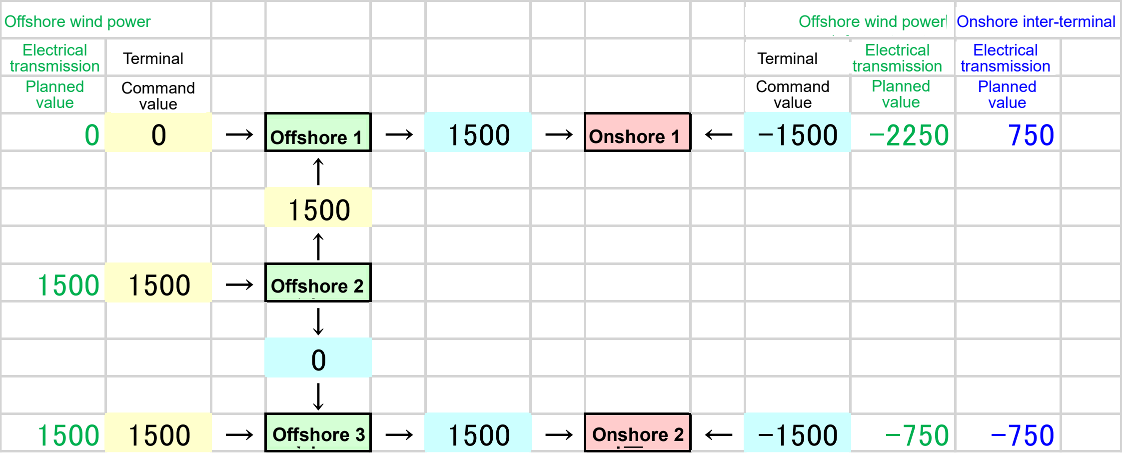


Fig. 7.11 Pattern 3: Prioritization of the offshore wind power generation plan and onshore inter-terminal electrical transmission plan

Pattern 4: Adjusted to prioritize the onshore inter-terminal electrical transmission plan and offshore wind power generation plan

Adjustment in this case is identical to Pattern 3 and therefore omitted here.

Pattern 5: Adjusted to prioritize the onshore inter-terminal electrical transmission plan and offshore wind power reception plan (Terminal 1)

Prioritizing (fixed) the onshore inter-terminal electrical transmission plan and the offshore wind power reception plan (Terminal 1) makes the Terminal 1 command value -2250 MW, and since it is not possible to adjust to -1500 MW, this plan is impossible to achieve.

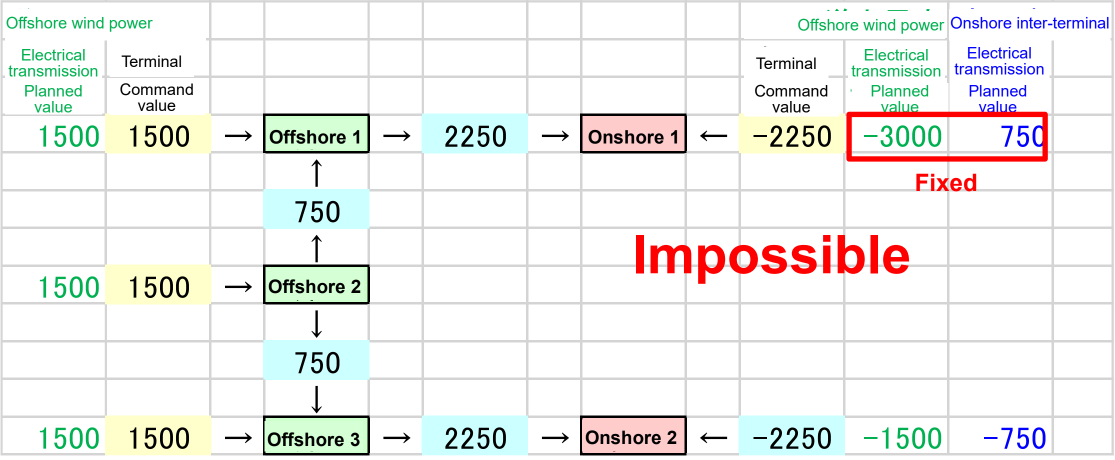


Fig. 7.12 Pattern 5: Prioritization of the offshore wind power generation plan and offshore wind power reception plan (Terminal 1)

Pattern 6: Adjusted to prioritize the onshore inter-terminal electrical transmission plan and offshore wind power reception plan (Terminal 2)

As in Pattern 5 above, it is not possible to adjust the Terminal 1 command value under this plan, making it impossible.

7.2.2 Example: Onshore Terminal 1 Dropout

In contrast to cases in which capacity is not exceeded, this example scenario considers a case in which onshore terminal 1 (3000 MW power reception) drops outs.

In this case, an onshore terminal 1 dropout results in total power reception being limited to 3000 MW from 4500 MW (a 1500 MW limit), meaning that total power generation must also be reduced from 4500 MW to 3000 MW.

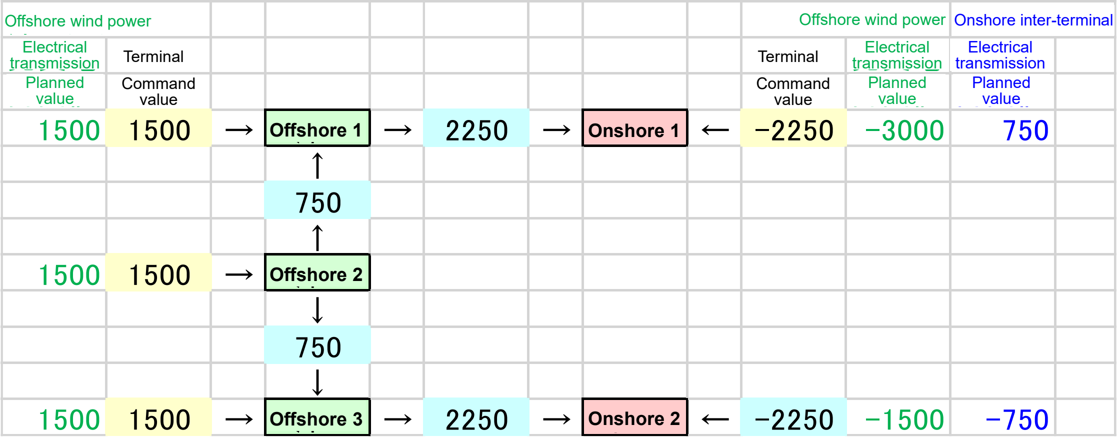


Fig. 7.13 If Not Exceeding Capacity

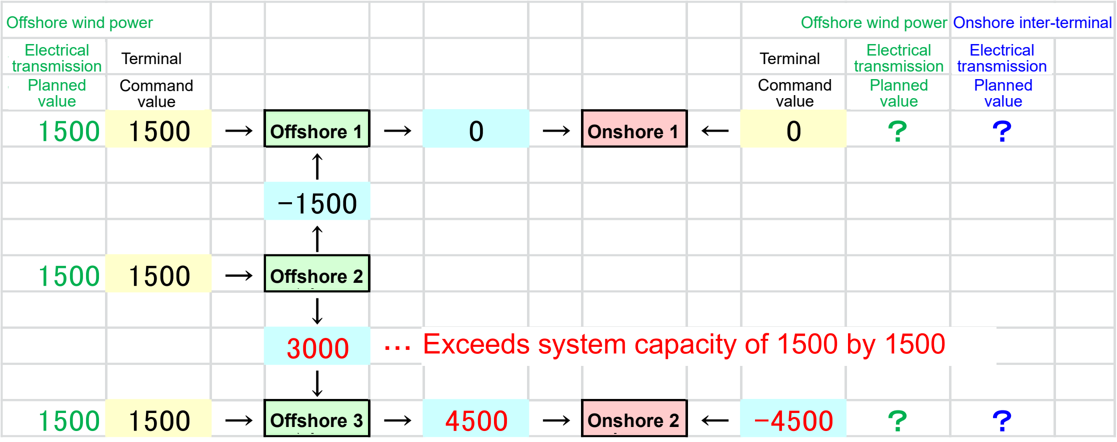


Fig. 7.14 Onshore Terminal 1 Dropout Case (Before Limitation of System Capacity to Limit Value)

For Fig. 7.14, use the flow formula (Fig. 7.3) to calculate flow status when the volume exceeding system capacity is limited to the limit value. The calculated flow status is shown in Fig. 7.15.

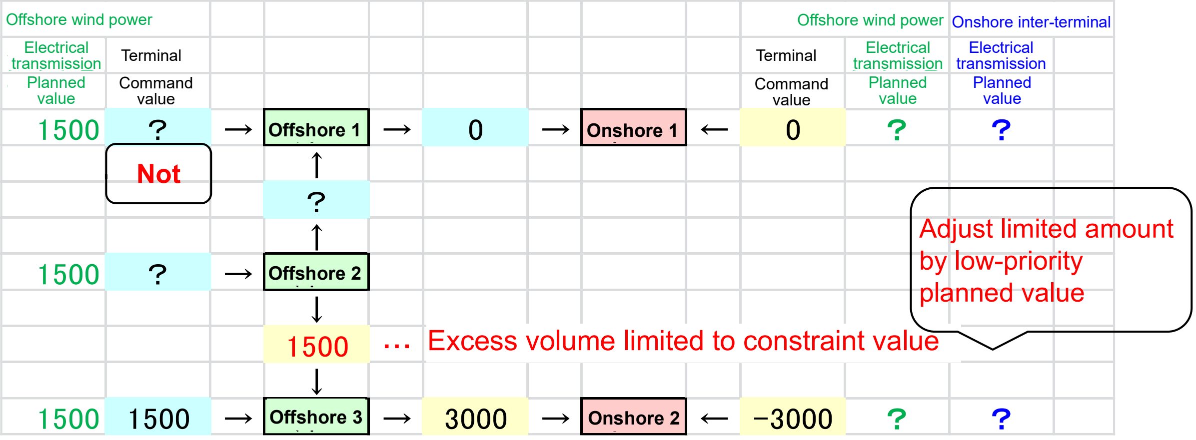


Fig. 7.15 Onshore Terminal 1 Dropout Case (After Limitation of System Capacity to Limit Value)

In the case in Fig. 7.15, the flow formula produces a non-fixed value and cannot be solved, which means that it is not possible to address the over-capacity using the flow formula alone. In this case, the system is adjusted based on the plan priorities.

However, if the offshore wind power generation plan is prioritized, rules are needed to determine which generator to prioritize, because there are three offshore wind power generators. These rules will be called the "Wind Power Generation Control Rules" in this document. The following are three ideas for such rules.

[Prerequisite] Wind power for which a solution can be found using the flow formula is not subject to these controls.

Example: Offshore 3 (P3) in Fig. 7.15 is not subject to these controls

a. Fixed-order controls: Decide a fixed order in which controls will be applied in advance.

Example: Controlled in the order Offshore 3 → Offshore 2 → Offshore 1.

b. Control by proximity to dropped-out facility: Control in order of proximity to the dropped-out facility

Example: If Onshore 1 drops out, control in the order Offshore 1 → Offshore 2 → Offshore 3

c. Uniform controls: Uniform controls applied to all wind power.

Example: Controlled uniformly among Offshore 1, Offshore 2, and Offshore 3

Fig. 7.16 Wind Power Generation Control Rules (Ideas)

Planned value adjustments after implementing Wind Power Generation Control Rules will be described below for each pattern as shown in Table 3.1.1.

Pattern 1: Adjusted to prioritize the offshore wind power generation plan and offshore wind power reception plan (Terminal 1)

Since the offshore wind power reception plan (Terminal 1) is given priority (fixed), it is necessary to change the onshore inter-terminal electrical transmission plan to 3000 MW in order to make the Terminal 1 command value to 0 MW. However, since the onshore inter-terminal electrical transmission capacity is 1500 MW, it cannot be changed to 3000 MW. Regardless of the Wind Power Generation Control Rules, this plan is impossible. Although shown here because this is a case study, the planned value for the dropped-out facility should be removed from the list of priorities.

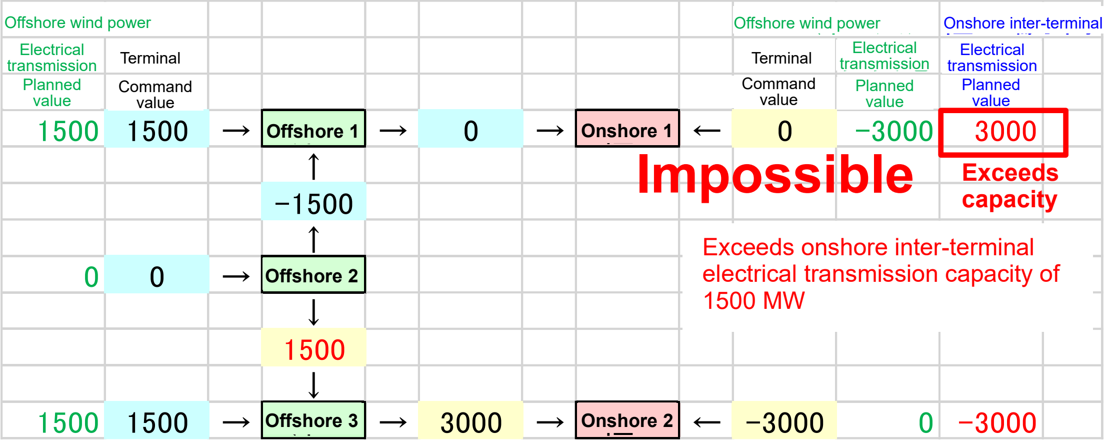


Fig. 7.17 Pattern 1: Prioritization of the offshore wind power generation plan and offshore wind power reception plan (Terminal 1) (Fixed-order controls)

Pattern 2: Adjusted to prioritize the offshore wind power generation plan and offshore wind power reception plan (Terminal 2)

a. Fixed-order controls (Offshore 2 → Offshore 1)

The offshore wind power generation plan controls Offshore 2 in accordance with the fixed-order controls. Since the offshore wind power reception plan (Terminal 2) is given priority (fixed), change the onshore inter-terminal electrical transmission plan to 1500 MW to change the Terminal 2 command value to -3000 MW. After changing the onshore inter-terminal electrical transmission plan, make the Terminal 1 command value 0 MW by changing the offshore wind power reception plan (Terminal 1) to -1500 MW.

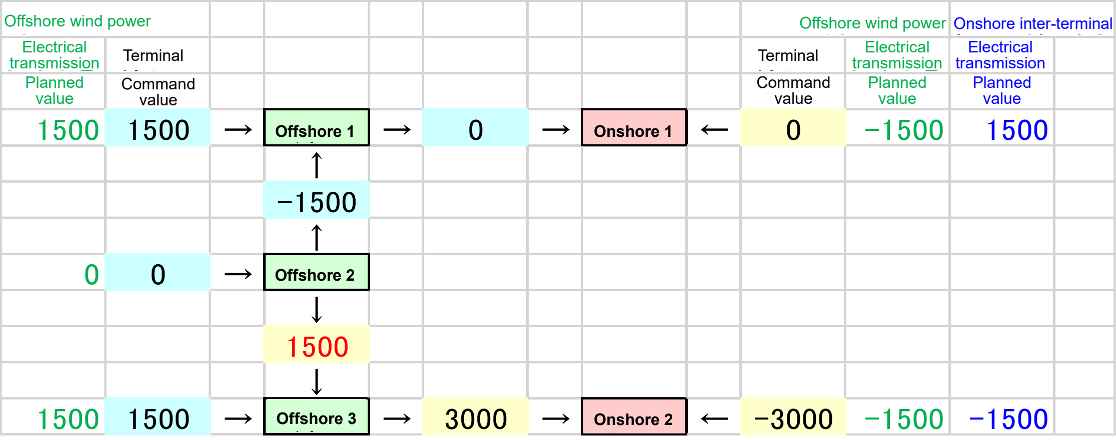


Fig. 7.18 Pattern 2: Prioritization of the offshore wind power generation plan and offshore wind power reception plan (Terminal 2) (Fixed-order controls)

b. Control by proximity to dropped-out facility

Power generation at Offshore 1 is controlled in accordance with order of proximity to the dropped-out facility. The offshore wind power reception plan and onshore inter-terminal electrical transmission plan work as shown in Fig. 7.18.

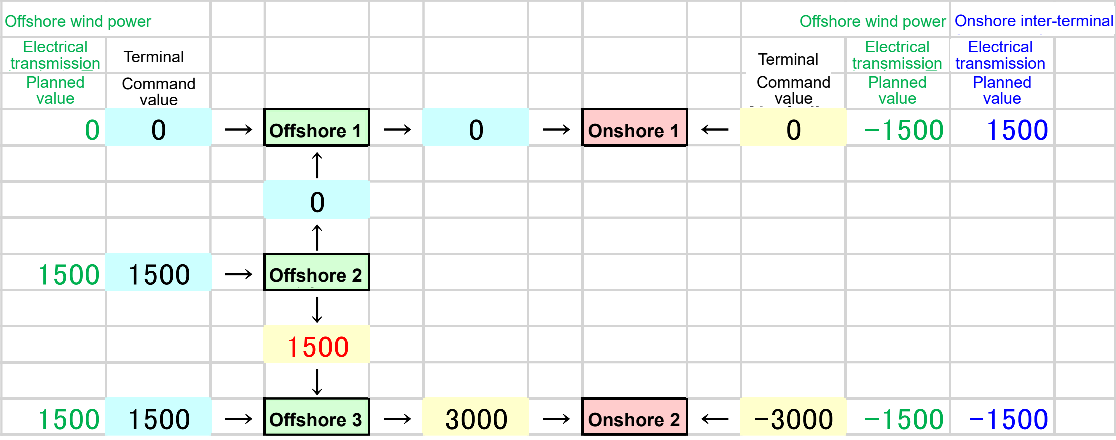


Fig. 7.19 Pattern 2: Prioritization of the offshore wind power generation plan and offshore wind power reception plan (Terminal 2) (Control by proximity to dropped-out facility)

c. Uniform controls

Uniform controls are applied to power generation at Offshore 1 and Offshore 2. The offshore wind power reception plan and onshore inter-terminal electrical transmission plan work as shown in Fig. 7.18.

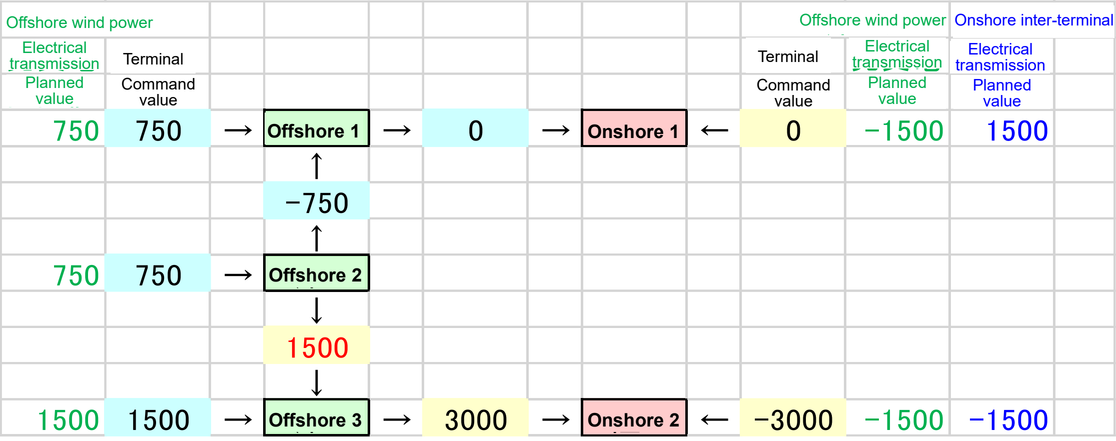


Fig. 7.20 Pattern 2: Prioritization of the offshore wind power generation plan and offshore wind power reception plan (Terminal 2) (Uniform controls)

Pattern 3: Adjusted to prioritize the offshore wind power generation plan and onshore inter-terminal electrical transmission plan (Terminal 1)

a. Fixed-order controls (Offshore 2 → Offshore 1)

The offshore wind power generation plan controls Offshore 2 in accordance with the fixed-order controls. Since the onshore inter-terminal electrical transmission plan is given priority (fixed), change the offshore wind power reception plan (Terminal 1) to -750 MW to change the Terminal 1 command value to 0 MW, and change the offshore wind power reception plan (Terminal 2) to -2250 MW to change the Terminal 2 command value to -3000 MW.

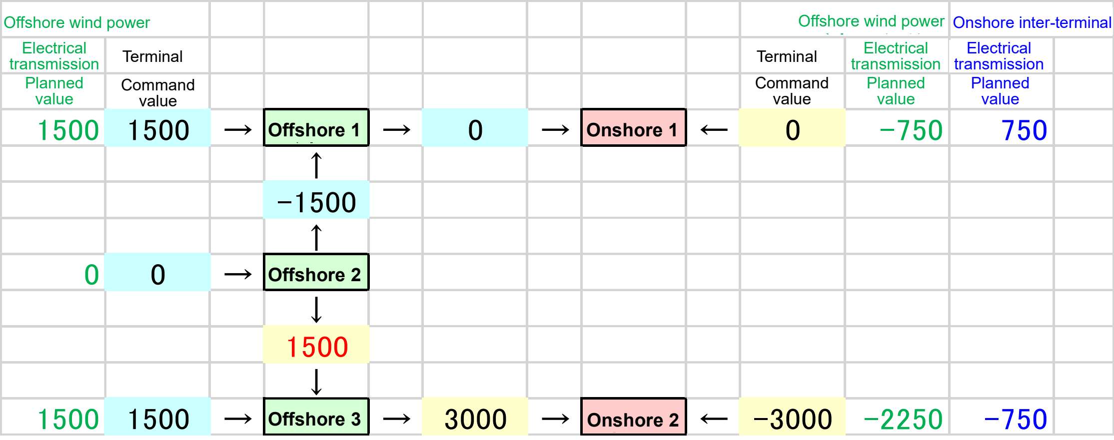


Fig. 7.21 Pattern 3: Prioritization of the offshore wind power generation plan and onshore inter-terminal electrical transmission plan (Fixed-order controls)

b. Control by proximity to dropped-out facility

The offshore wind power generation plan is controlled at Offshore 1 in accordance with order of proximity to the dropped-out facility. The offshore wind power reception plan and onshore inter-terminal electrical transmission plan work as shown in Fig. 7.21.

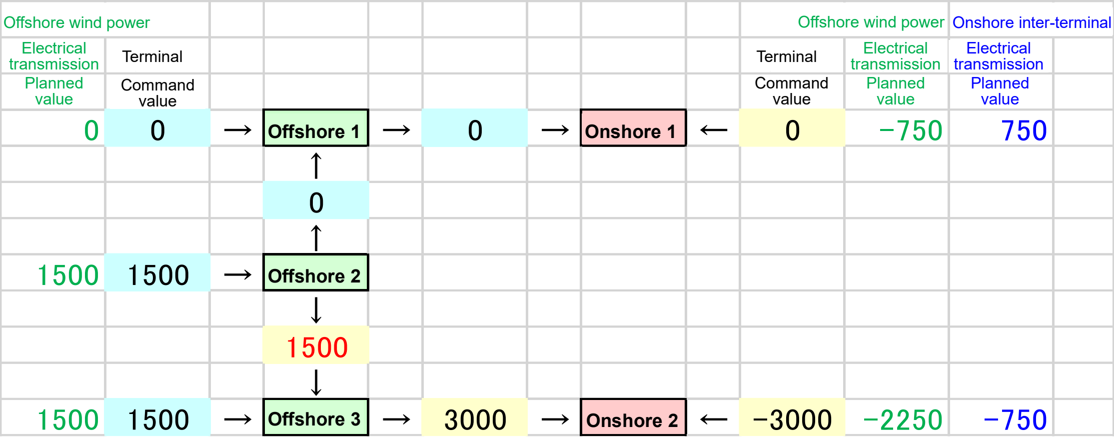


Fig. 7.22 Pattern 3: Prioritization of the offshore wind power generation plan and onshore inter-terminal electrical transmission plan (Control by proximity to dropped-out facility)

c. Uniform controls

The offshore wind power generation plan is controlled at Offshore 1 and Offshore 2 using uniform controls. The offshore wind power reception plan and onshore inter-terminal electrical transmission plan work as shown in

Fig. 7.21.

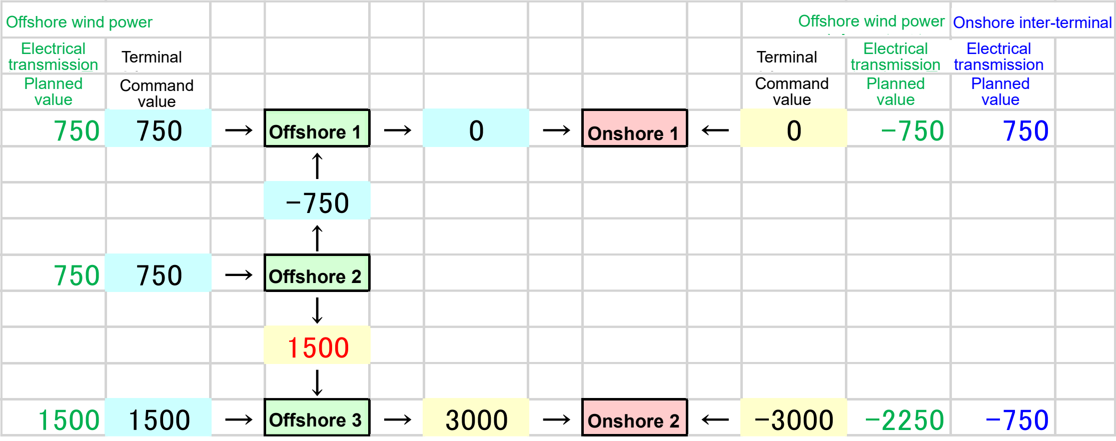


Fig. 7.23 Pattern 3: Prioritization of the offshore wind power generation plan and onshore inter-terminal electrical transmission plan (Uniform controls)

Pattern 4: Adjusted to prioritize the onshore inter-terminal electrical transmission plan and offshore wind power generation plan

Adjustment in this case is identical to Pattern 3 and therefore omitted here.

Pattern 5: Adjusted to prioritize the onshore inter-terminal electrical transmission plan and offshore wind power reception plan (Terminal 1)

Prioritizing (fixed) the onshore inter-terminal electrical transmission plan and the offshore wind power reception plan (Terminal 1) makes the Terminal 1 command value -2250 MW, and since it is not possible to adjust to 0 MW, this plan is impossible to achieve.

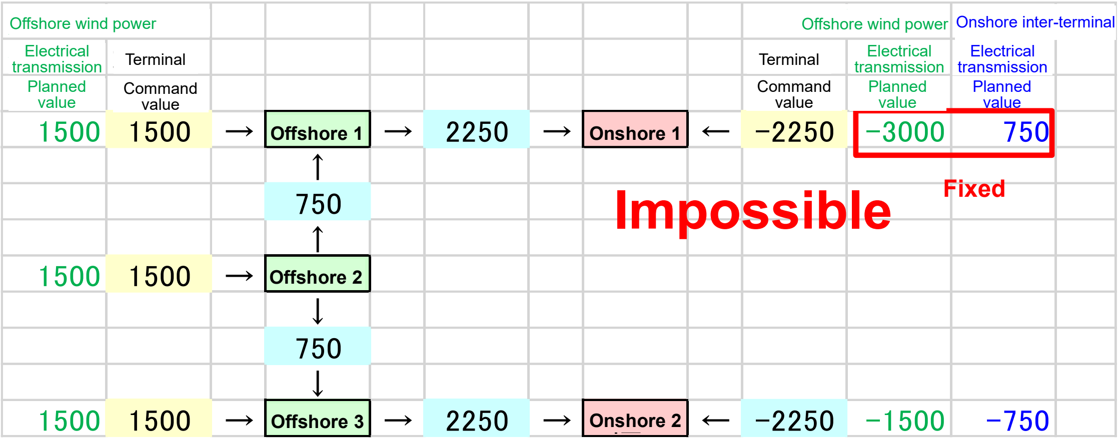


Fig. 7.24 Pattern 5: Prioritization of the offshore wind power generation plan and offshore wind power reception plan (Terminal 1)

Pattern 6: Adjusted to prioritize the onshore inter-terminal electrical transmission plan and offshore wind power reception plan (Terminal 2)

As in Pattern 5 above, it is not possible to adjust the Terminal 1 command value under this plan, making it impossible.

7.2.3 Conclusion

In the transient state cases described above, the flowchart for high-order control system power distribution functionality (Fig. 3.2.1) was applied to calculate planned values and terminal command values that eliminate states in which system capacity is exceeded. Whether adjustment was possible using each prioritization pattern for transient-state cases is shown in Table 7.2.

It was also confirmed that there are cases in which, depending on the conditions for facility dropout, adjustment is impossible using pre-determined prioritization schemes (Pattern 1 for the Onshore Terminal 1 dropout case). If a facility directly linked to the prioritized plan drops out, that plan should be removed from the list of priorities.

Table 7.2 Whether Adjustment Possible Using Each Prioritization Pattern (O: Possible. X: Impossible)

Pattern	Priority 1	Priority 2	Adjustment target	Offshore terminal 1 dropout case	Onshore terminal 1 dropout case	Remarks
Pattern 1	Power generation	Onshore 1 power reception	Onshore inter-terminal Onshore 2 power reception	○	×	Onshore inter-terminal Capacity exceeded
Pattern 2	Power generation	Onshore 2 power reception	Onshore inter-terminal Onshore 1 power reception	○	○	-
Pattern 3	Power generation	Onshore inter-terminal	Onshore 1 power reception Onshore 2 power reception	○	○	-
Pattern 4	Onshore inter-terminal	Power generation	Onshore 1 power reception Onshore 2 power reception	○	○	-
Pattern 5	Onshore inter-terminal	Onshore 1 power reception	Power generation Onshore 2 power reception	×	×	Impossible
Pattern 6	Onshore inter-terminal	Onshore 2 power reception	Power generation Onshore 1 power reception	×	×	Impossible

*Power generation: Offshore wind power generation plan. Onshore 1 power reception: Offshore wind power reception plan (Terminal 1). Onshore 2 power reception: Offshore wind power reception plan (Terminal 2). Onshore inter-terminal: Onshore inter-terminal electrical transmission plan.

8. Specific Example of Fallback (Five-terminal HVDC System)

Figure 8.1.1 shows a five-terminal HVDC system where fallback is assumed. Table 8.1.1 shows the fallback status at terminal termination. In Table 8.1.1, onshore terminal Nos. 1 to 3 and offshore terminal Nos. 1 and 2 are not identified as onshore terminals A to C or offshore terminals A and B. They are included in fallback because they are applicable to interchange between areas of onshore terminals A to C even when only onshore terminals operate. If the number of operating wind terminals exceeds that of operating onshore terminals, it becomes temporarily impossible to transmit the rated power generated by the WF to the onshore. However, fallback was made possible by assuming a WF transfer interrupt by high-order control. Table 8.1.2 shows the fallback status assuming DC bus line termination. A limited number of statuses are described here by considering the symmetry of the object system in Fig. 8.1.1 (vertical symmetry in the figure). For example, the line terminations of DC bus ① and DC bus ③ are considered as the same status. Even when the statuses of ① and ③ are exchanged, “Terminal status” and “Fallback Yes/No” in the table remain unchanged. The table gives the number of offshore terminals contributing to power transmission and the number of onshore terminals contributing to power transmission in the status item. If the termination of multiple DC buses is considered, the 14 kinds of statuses from A to N are assumed to allow fallback. Table 4.11.2 shows the fallback status at terminal termination.

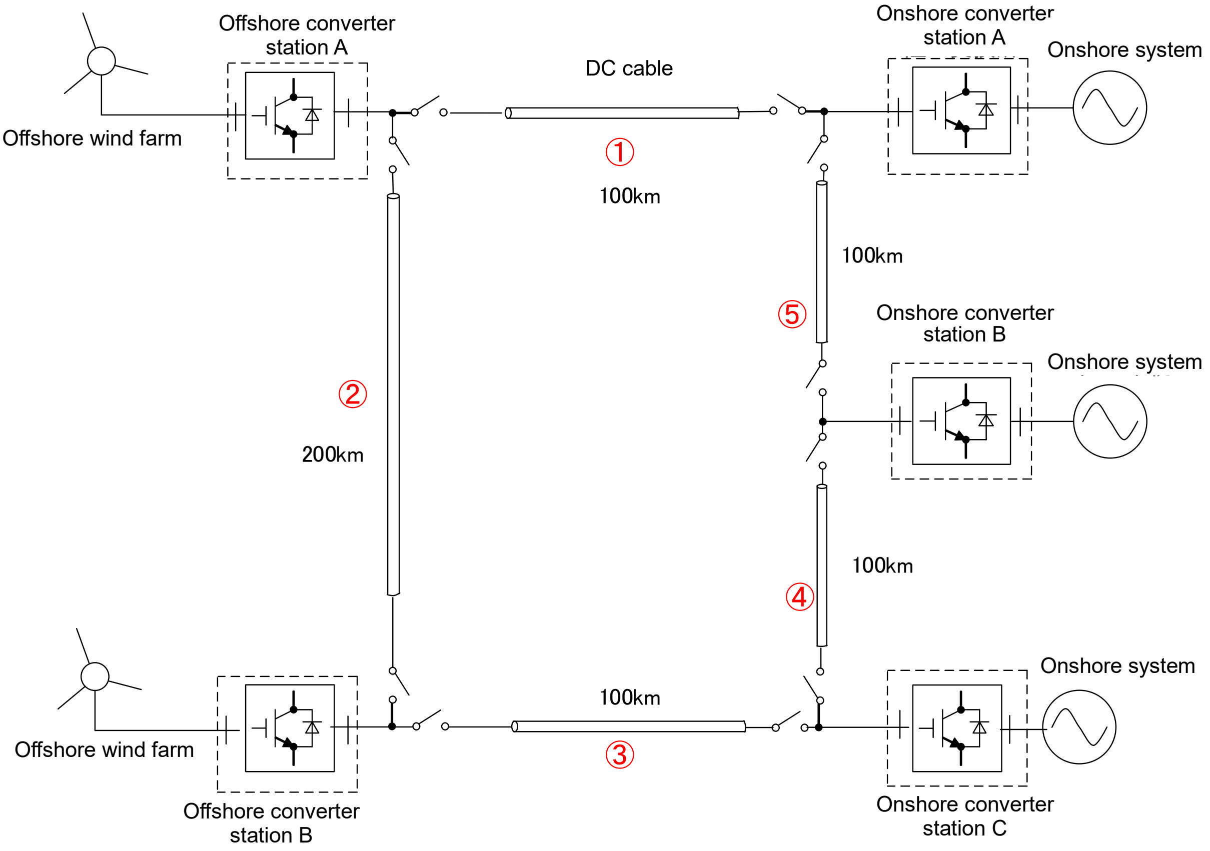


Fig. 8.1.1 Five-terminal HVDC system where fallback is assumed

Table 8.1.1 Fallback statuses at terminal termination

Status No.	No. of terminated terminals	Offshore terminal A	Offshore terminal B	Onshore terminal A	Onshore terminal B	Onshore terminal C	Terminal status	Fallback Yes/No
0	0	○	○	○	○	○	Normal operation	Yes
1	1	○	○	×	○	○	One onshore terminal terminated	Yes
2	1	×	○	○	○	○	One offshore terminal terminated	Yes
3	2	×	○	×	○	○	One onshore terminal terminated One offshore terminal terminated	Yes
4	3	×	○	×	×	○	Two onshore terminals terminated One offshore terminal terminated	Yes
5	3	×	×	×	○	○	Two onshore terminals terminated	Yes Interchange assumed between areas of onshore terminals
6	2	×	×	○	○	○	Three onshore terminals terminated	Yes Interchange assumed between areas of onshore terminals
7	2	○	○	×	×	○	Two onshore terminals terminated	Yes Offshore WF transfer interrupt and power curtailment necessary because generated power may exceed the transmission capacity
8	4	×	○	×	×	×	One offshore terminal terminated	No
9	3	○	○	×	×	×	Three onshore terminals terminated	No
10	4	×	×	×	×	○	One onshore terminal terminated	No
11	5	×	×	×	×	×	All terminals terminated	No

Table 8.1.2　Fallback statuses assuming DC line termination

Status No.	No. of terminated lines	DC line ①	DC line ②	DC line ③	DC line ④	DC line ⑤	Terminal status	Fallback Yes/No
--	0	○	○	○	○	○	Normal line status	Yes
A	1	×	○	○	○	○	One line terminated	Yes
B	1	○	×	○	○	○	One line terminated between offshore terminals	Yes
C	1	○	○	○	×	○	One line terminated between onshore terminals	Yes
D	2	×	×	○	○	○	Between one offshore terminal and three onshore terminals	Yes
E	2	○	×	○	×	○	Between one offshore terminal and two onshore terminals Between one offshore terminal and one onshore terminal	Yes
F	2	×	○	○	○	×	Two lines terminated	Yes
G	3	×	×	○	×	○	Equivalent of two-terminal operation	Yes
H	3	×	×	○	○	×	Between one offshore terminal and two onshore terminals	Yes
I	3	○	×	○	×	×	Between one offshore terminal and one onshore terminal	Yes
J	4	○	×	×	×	×	Between one offshore terminal and one onshore terminal	Yes
K	2	×	○	○	×	○	Between two offshore terminals and one onshore terminal (Offshore WF shutdown/ suppression necessary) Interchange between areas of two onshore terminals	Yes
L	2	×	○	×	○	○	No line between offshore and onshore	Yes
M	3	×	×	×	○	○	No line between offshore and onshore	Yes
N	4	×	×	×	○	×	No line between offshore and onshore	Yes
O	4	×	○	×	×	×	No line between offshore and onshore	No
P	5	×	×	×	×	×	All lines terminated (0:0)	No

References

Reference [1}: Niimura et al. “Decoupled Control of a Three-Phase Modular Multilevel Cascade Converter Based on Double-Star Chopper-Cells,” IEEJ Transactions on Industry Applications, vol. 132, no. 11, pp. 1055-1064 (2012-11)

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