# Detection of DC-Cable Fault Location for HVDC Transmission Systems Integrated with Wind Farm

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## Abstract

This paper presents a method to find the fault location on the DC cables for the HVDC transmission systems which utilizes a hybrid topology of the diode rectifier and the voltage-source converter (VSC) in the wind farm (WF) side. First, the DC-cable fault occurring in this HVDC system is analyzed in detail. Then, the DC-cable fault location is detected from the two relative voltages located on the same section of the cable, which are estimated from a pair of DC-cable voltage and current measurements. The effectiveness of the method is verified by the simulation results.


## 1. Introduction

Nowadays, the HVDC power transmission systems are attracting more research interests. One of practical applications of HVDC is to integrate the offshore wind farm to the onshore grid, where long DC cables are required [1]. Cable faults occur more frequently compared with other parts of the system [2]. The main reason for the cable fault is an insulation deterioration and breakdown. It is extremely difficult to determine where a fault occurs in the DC cable. Therefore, the research on the accurate and fast fault-location detection techniques for HVDC transmission is of a great significance and of practical engineering values [3].

There have been researches about the detection of the DC-cable fault location on HVDC systems. The first approach is based on the travelling wave, where the time it takes for the travelling wave to propagate from the fault point to the terminals implies the fault distance [4]. However, when the system structure is complex (for instance, meshed for multi-terminal connection), many reflections occur, which will influence the location results. For this method, the accuracy in the fault location depends on sampling frequency since the speed of the travelling wave is extremely high. A method for the fault location detection was presented in [5] for the multi-terminal DC wind farm, which can overcome the drawback of the complex structure of the HVDC system for the fault location detection. The two voltage dividers are used for the distance measurement, which requires an additional reference voltage sensor located near the main DC-voltage sensor. Another technique was presented in [6], which extracts the fault signal by comparing the initial current change, the current rise time interval at different switch locations.

In this paper, analysis of the DC-cable fault occurring in the high-voltage DC (HVDC) transmission system which is a hybrid topology of the diode rectifier and the VSC in the wind farm side proposed in [7] is presented. Then, the fault location is detected by the two relative voltages located in the same section of the cable, which are estimated from a pair of DC-cable voltage and current measurements. The simulation results are shown to verify the validity of the presented method for finding the fault locations in the DC cables.

## 2. Analysis of DC-Cable Faults

Fig. 1 shows a single-line diagram of the HVDC link integrated with the offshore wind farm, which consists of the twelve-pulse diode rectifier and the VSC connected in series on the offshore side, whereas the fully-rated VSC is used to connect to the AC grid on the onshore side [7].

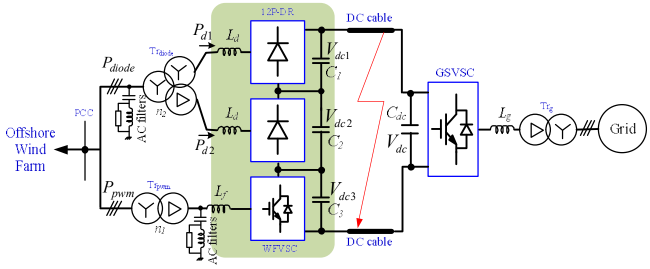


Fig. 1. Converter topology of HVDC link integrated with offshore WF.

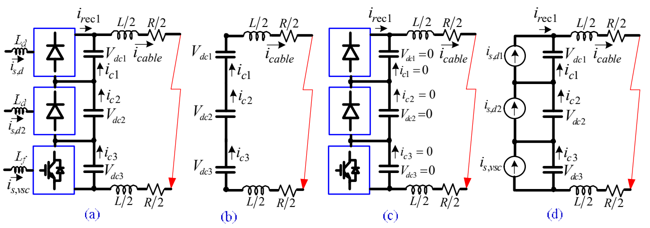


Fig. 2. HVDC converter at a short-circuit condition. (a) Equivalent circuit. (b) Capacitor discharging stage. (c) Diode freewheeling stage. (d) Current feeding stage in AC side.

A DC short-circuit fault is the most serious condition for the converter, which is illustrated in Fig. 1. Regardless of the location of the DC short-circuit fault, the HVDC converter can be represented by an equivalent circuit shown in Fig. 2(a), where R and L are the equivalent resistance and inductance, respectively, of the DC cable from the HVDC converter to the short-circuit point. The response of this nonlinear circuit is analyzed as follows.

*i) DC capacitor discharging stage (stage 1, natural response)*

During this stage, the DC capacitors are discharged through the cable resistance with the converter current neglected, where the equivalent circuit is shown in Fig. 2(b). The natural response under the initial conditions of $v_{dc}(0)=V_{dc0}=V_{dc10}+V_{dc20}+V_{dc30}$ and $i_{cable}(0)=I_0$ is [2], [5]

$$v_{dc}=V_{dc1}+V_{dc2}+V_{dc3}=\frac{V_{dc0}\omega_0}{\omega}e^{-\delta t}\sin(\omega t+\beta)-\frac{I_0}{\omega C}e^{-\delta t}\sin\omega t \quad (1)$$

$$i_{cable}=C\frac{dv_{dc}}{dt}=-\frac{I_0\omega_0}{\omega}e^{-\delta t}\sin(\omega t-\beta)-\frac{V_{dc0}}{\omega L}e^{-\delta t}\sin\omega t \quad (2)$$

where $C$ is an equivalent capacitance of $C_1$, $C_2$, and $C_3$ connected in series, $\delta=R/2L$, $\omega=\sqrt{1/LC-(R/2L)^2}$, $\omega_0=\sqrt{\delta^2+\omega^2}$, $\beta=\arctan(\omega/\delta)$.

*ii) Diode freewheeling stage (stage 2, natural response)*

When the DC capacitor is discharged up to the zero voltage, this stage is initiated as the cable current flows through the freewheeling path of the converter. This is the most challenging stage for the HVDC converter due to a very high value of the freewheeling current. Fig. 2(c) shows the equivalent circuit during the diode freewheeling stage.

*iii) Current feeding stage in AC side (stage 3, forced response)*

Fig. 2(d) shows the equivalent circuit during this stage, where the DC capacitors and cable inductor have a forced current-source response. The DC voltages are not equal to zero.

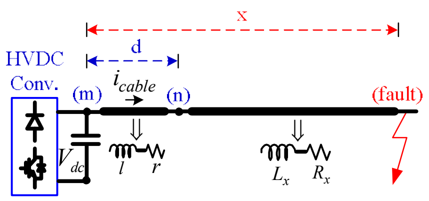

Fig. 3. Detection scheme of fault location in HVDC system.

Table I. Parameters of HVDC Converters

| Components | Parameters | Values |
|---|---|---|
| Base values | Power | 500 MW |
| | DC-link vol./cur. | 300 kV / 1.67 kA |
| VSC | Power rating | 166 MW |
| | Input inductance | 46.5 mH |
| | DC capacitance | 300 μF |
| Diode rectifiers | Power rating | 334 MW |
| | Input inductance | 35 mH |
| | DC capacitances | 300 μF each |

## 3. Detection of DC-Cable Fault Location

In a DC system, a mho characteristic of DC cable can be used to represent the distance from the relay point to the fault point [2]. Fig. 3 shows the detection scheme of fault location in the HVDC system, which illustrates the measurements and distance relationship. It is assumed that the cable resistance and inductance per kilometer, $r$ and $l$, respectively, are constant and the fault resistance is zero. From Fig. 3, the fault distance is calculated in (3), which uses two measured voltages at the main relay and additional relay in the same section of the DC line located near the main relay.

$$x = \frac{V_{dc(m)}}{V_{dc(m)} - V_{dc(n)}} d \tag{3}$$

where $V_{dc(m)}$ and $V_{dc(n)}$ are the voltage at relays m and n, respectively, the distance, $d$, between them is known.

To eliminate the additional voltage sensor at the relay n, which causes a complicated structure level of the measurement circuit due to the distance aspect, a pair of DC voltage and current is measured instead of two voltage sensors. Then, the fault distance can be calculated as

$$x = \frac{V_{dc(m)}}{r \cdot i_{cable} + l \cdot \frac{di_{cable}}{dt}} \tag{4}$$

## 4. Simulation Results

Simulations are performed on the model shown in Fig. 1, where the parameters of the system are listed in Table I. As cable parameters, $r$ = 0.06 Ω/km and $l$ = 0.28 mH/km. Cable grounding resistance is neglected. It is assumed that a short-circuit fault occurs at the distance of 41 km from the main relay.

Fig. 4 shows the response of the HVDC converter on the offshore side at the short-circuit condition. Fig. 4(a) shows the HVDC-link voltage, which also indicates three stages of the converter responses. The capacitor discharging stage lasts about 3 ms as seen in Fig. 4(a). The response of three DC voltages of the rectifiers and VSC is the same as the HVDC-link voltage, which is shown in Fig. 4(b). The rectifiers, VSC, capacitor and cable currents are shown in Fig. 4(c) and (d), which correspond to the analysis in section 2. The phase currents of rectifier are shown in Fig. 4(e). Fig. 5(a) shows the DC voltages at two relay points, which are different due to the cable resistance. The fault distance can be calculated from either the two measured voltages or the main relay voltage and the cable current, which is shown in Fig. 5(c). The detected distance is 40.92 km, of which error is 0.2%.

## 5. Conclusions

This research has investigated a short-circuit fault condition in the DC lines for the hybrid topology of the HVDC links. The response of the HVDC converter at the fault condition is analyzed in detail. For detecting the fault location, the scheme which utilize the measured voltage and current at the DC-link relay gives a good result with the estimation error of 0.2%.

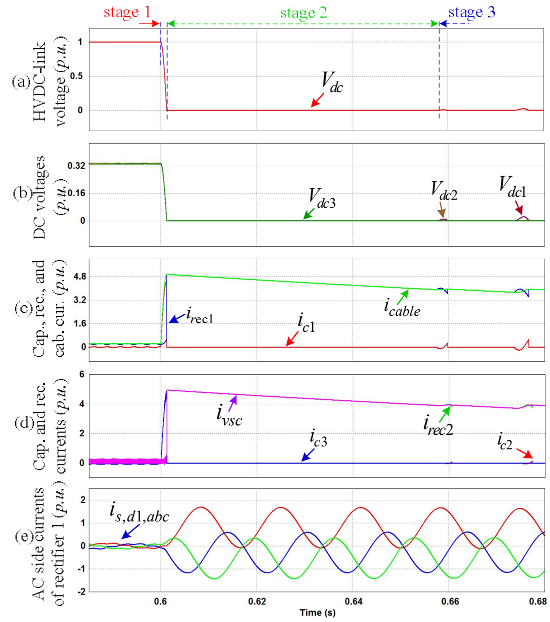

Fig. 4. Responses of HVDC converter under a short-circuit fault. (a) HVDC-link voltage. (b) DC voltages of rectifiers and VSC. (c) Currents of capacitor, rectifier, and DC cable. (d) Currents of capacitors, rectifier, and VSC. (e) Phase current in AC side of rectifier.

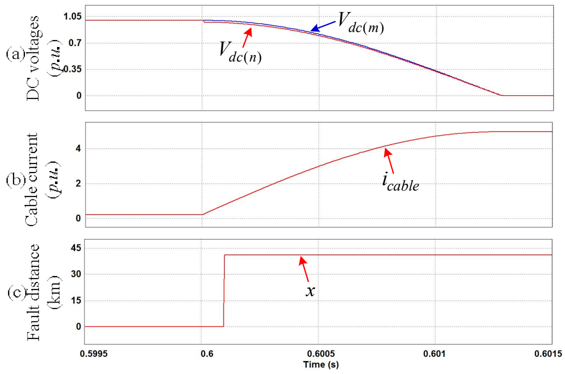

Fig. 5. Detection of fault location. (a) DC voltages at two relays. (b) DC cable current. (c) Fault distance detected.

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