

Research on DC component decay time constant of 1000 kV AC filter circuit breakers in UHV converter station

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Abstract: In hierarchically connected UHV DC projects, the 1000 kV AC filter sub-bank in converter station is provided with two 500 kV circuit breakers. To determine the test DC component decay time constant when breakers break short-circuit current, relevant DC project was modelled in electromagnetic transient program (EMTP) for calculations. It is pointed out that for UHV AC filter circuit breakers, the decay time constant of DC component of short-circuit current should be determined solely based on the single-phase to earth fault current. Calculations and analyses were made of the AC and DC components and the DC component decay time constant of filter single-phase to earth fault current, and the time constant calculated was converted to the test value of breakers with rated short-circuit breaking current of 63 kA. According to the research results, a time constant of 75 or 90 ms is recommended for the two 500 kV circuit breakers, and it is lower than 120 ms as required by the relevant standards, providing technical support for future breaker tests.

1 Introduction

In recent years, China has witnessed rapid growth in ultra-high voltage (UHV) AC and DC projects. Several UHV AC and DC projects have been completed and operated safely and steadily, playing an important role in optimising the allocation of resources [1–4]. The UHV grid planning includes hierarchical connection of the inverter side to AC grid [5], that is, the higher-voltage end (HV-end) converter is connected to 500 kV AC grid, and the lower-voltage end (LV-end) converter to 1000 kV UHV AC grid. In hierarchically connected DC projects, the 1000 kV AC filter sub-banks at converter station use two series-connected 500 kV breakers instead of a 1000 kV breaker. This brings another problem. According to China's national standard GB/Z 24838—2009 *Specification for 1100 kV Alternating-current High-voltage Circuit-breakers*, the DC component decay time constant of 1000 kV AC breakers when breaking short-circuit current should be 120 ms [6]. According to this requirement, the scheme of two series-connected 500 kV breakers will be more difficult to test and costly. In order to properly determine the decay time constant, which could provide the two series-connected 500 kV breakers with adequate capability to break system short-circuit currents in both short- and long-term without causing any fault (e.g. burn of arc-extinguishing chamber due to the inability in breaking short-circuit currents containing large DC component) [7–9], it is necessary to conduct a specific study on the DC component decay time constant of filter breakers based on the system conditions of converter station and earth fault characteristics of 1000 kV AC filters. This will provide technical support to relevant tests on breakers and the operational safety [10, 11].

Here, the hierarchically connected UHV DC project and AC system were modelled in EMTP based on the Qingzhou Converter Station of Jarud—Qingzhou ±800 kV UHV DC link. In particular, the time constant of filter sub-bank breakers when breaking short-circuit currents was calculated according to earth fault characteristics of 1000 kV AC filters in converter station, based on which a recommended time constant was proposed.

2 DC component decay time constant of breakers and conversion of calculated value to test value

According to Section 4.101 of DL/T 402—2007 *Specification of High-voltage Alternating-current Circuit-breakers* [12], the rated short-circuit breaking current is the highest short-circuit current which the circuit breaker shall be capable of breaking under the conditions of use and behaviour prescribed in this standard. The rated short-circuit breaking current is characterised by two values, the r.m.s. value of its AC component and the percentage DC component (if the DC component does not exceed 20%, the rated short-circuit breaking current is characterised only by the r.m.s. value of its AC component).

The breaker shall be capable of breaking any short-circuit current up to its rated short-circuit breaking current containing any AC component up to the rated value and, associated with it, any percentage DC component up to that specified.

The percentage value of the DC component (dc%) at the instant of contact separation can be calculated using the following formula:

$$\text{dc}\% = 100 \times e^{-(T_{op} + T_r)/\tau}$$

where $\text{dc}\% = 100 \times e^{-(T_{op} + T_r)/\tau}$ is percentage value of DC component at contact separation; T_{op} is the shortest opening time specified by the manufacturer, which should not be longer than the measured opening time; T_r is time for relaying protection to operate, taken as one half-cycle of rated frequency, for example, 10 ms for 50 Hz (for self-tripping circuit breaker, T_r is set to 0 ms); τ is decay time constant of DC component of rated short-circuit current (standard values of 45, 60, 75 or 120 ms).

For breakers with rated short-circuit breaking current I_k , the DC component $I_{dc,k}$ at the instant of contact separation ($T_{op} + T_r$) can be calculated using the formula:

$$I_{dc,k} = I_k \times \sqrt{2} \times e^{-(T_{op} + T_r)/\tau_k} \quad (1)$$

It can be concluded that the DC component that the breaker is capable of breaking during test is determined according to the decay time constant τ_k on the premise that the maximum DC component equals the peak AC component at 0 s.

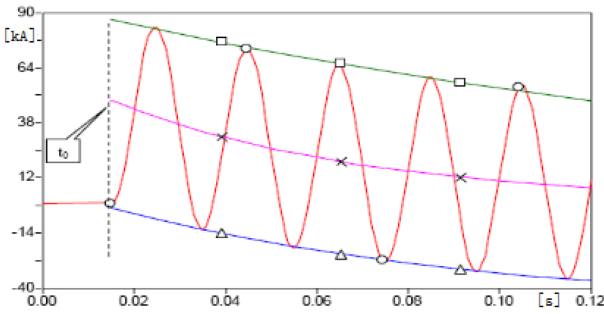


Fig. 1 DC component (x) calculated using Method I

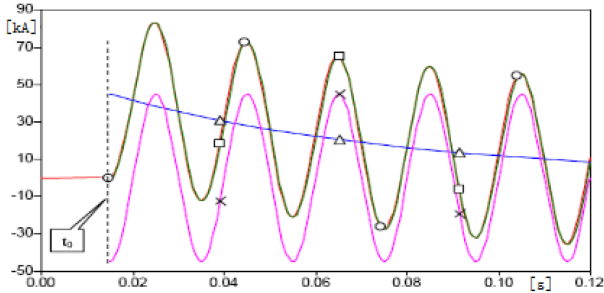


Fig. 2 AC component (x), DC component (Δ) calculated using Method II and their superposition (□) vs. short-circuit current (○)

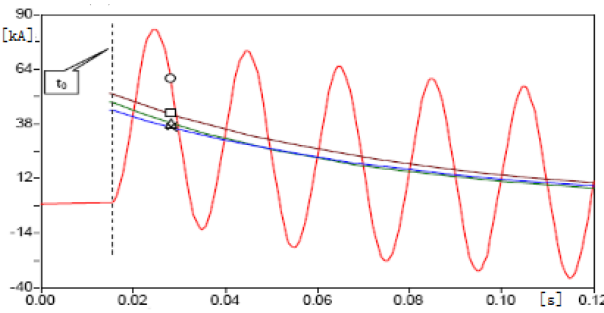


Fig. 3 Comparison of DC components calculated using two methods (Δ—Method I, □—Method II, x—formula method)

In simulation and calculation of system short-circuit faults, the DC component $I_{dc,s}$ of breaker at $T_{op} + T_r$ is expressed as:

$$I_{dc,s} = I_{dc,0} \times e^{-(T_{op} + T_r)/\tau_s} \quad (2)$$

where $I_{dc,0}$ is the DC component at the instant of fault occurrence (0 s); τ_s is the decay time constant of short-circuit current DC component calculated based on $I_{dc,0}$ which is different from the basis of Formula (1) that the peak AC component of rated short-circuit breaking current equals to its DC component at 0 s. Therefore, τ_s cannot be directly taken as the test parameter of circuit breaker and needs to be converted to the value under the test basis that the DC component equals the peak AC component of rated short-circuit breaking current [13].

According to the above principle, $I_{dc,k} = I_{dc,s}$, that is, the test time constant τ_k of circuit breaker with rated short-circuit breaking current I_k at $(T_{op} + T_r)$ when the breaker contacts just separate, is calculated as follows:

$$\tau_k = \left(\frac{(1/\tau_s) - \ln(I_{dc,0}/(I_k \times \sqrt{2}))}{(T_{op} + T_r)} \right)^{-1} \quad (3)$$

The selected test time constant should be greater than the time constant converted according to Formula (3).

As of now, there is no specific equivalent criterion or test method to demonstrate that the test conducted with rated short-circuit current and corresponding time constant is valid for different rated short-circuit currents and their corresponding time constants. For example, breaker test conducted with 63 kA and DC component decay time constant of 45 ms is not necessarily adequate for justifying the breaker performance under 50 kA and 60 ms [1, 14, 15].

Japan used an equivalent verification with breaking current of 63 kA and time constant of 70 ms to ensure the breaking capability of breaker under 50 kA and 150 ms [16]. In terms of breaking at 30 ms, the DC components of the two test methods 63 kA/70 ms and 50 kA/150 ms are, respectively, 58.04 kA and 57.89 kA, which are comparable. That is to say, the 50 kA/150 ms test can be converted to 63 kA/70 ms test based on the DC component of breaking at 30 ms. Whereas, 63 kA has larger AC component than 50 kA, so the equivalent verification is more rigorous in terms of thermal capacity.

According to the section 'Guide to the Selection of Circuit-breakers for Service' of DL/T 402—2007, as long as the AC component is equal or higher and the TRV conditions associated with lower DC component are met, then test with higher DC component covers the test with lower DC component. Thus, test time constant selected according to the above principles is sufficient to cover the simulated fault conditions with a proper margin.

3 Calculation of the DC component decay time constant of circuit breaker

The DC component decay time constant is usually calculated using two methods. Method I is fitting of the current waveform envelope where the average of upper and lower envelopes is the DC component decay curve, and the time constant can be obtained through exponential curve fitting. In Method II, the DC component decay curve is obtained according to harmonic analysis method, and the DC component decay time constant is obtained through exponential curve fitting [17]. Differences between the two methods are described with a simple electrical circuit.

In this circuit, R and L elements are series connected to the voltage source, and a short-circuit fault occurs on L side, where $L = 0.063$ H, $R = 1$ Ω, and time constant $L/R = 63$ ms.

Fig. 1 shows the DC component calculated using Method I, and Fig. 2 shows the AC and DC components calculated using Method II, the superimposed waveform of them, and the short-circuit current waveform. It can be seen from Fig. 2 that the latter two waveforms fit well. Fig. 3 is the comparison of the DC component decay curves obtained using Method I, Method II, and formula method.

As compared to the results calculated according to formulas, the DC component at 0 s calculated using Method II is 10% higher, and the time constant is 63.25 ms, showing a difference of 0.4%; the DC component at 0 s calculated using Method I is 8% higher, and the time constant is 62.62 ms, showing a difference of 0.6%. Results calculated using the two methods do not differ greatly, and Method II was adopted in this research. The AC and DC components were superposed and the calculated short-circuit current was fitted to correct the DC component.

4 DC component decay time constant of filter Sub-bank circuit breakers

4.1 Calculating conditions

Studies showed that AC component and DC component decay time constant of single phase to earth short-circuit current are related to the following factors:

(1) Resistance (R) and inductance (L) of power lines, transformers and generators in a transmission system. R/L ratios determines the proper DC component decay time constants of various elements, and the overall decay of DC component when fault occurs depends on the combined time constants of all fault sources.

Table 1 Single-phase to earth fault current of filter sub-bank busbar in converter stations of hierarchically connected projects in 2020

Project	Xilin Gol League— Taizhou/Taizhou end	Zhundong— Wannan/Wannan end	Longbin—Xuzhou/ Xuzhou end	Jarud—Qingzhou/ Qingzhou end	Shanghaimiao—Linyi/ Linyi end
short-circuit current, kA	40	32	37	53	48

Project	Yazhong— Nanchang/Nanchang end	Jinshang— Ganzhou/Ganzhou end	West Inner Mongolia— South Hunan/South Hunan end	Zhundong— Chengdu/Chengdu end	North Shaani— Wuhan/Wuhan end
short-circuit Current, kA	41	34	33	28	40

(2) Type of short-circuit fault. The time constant of DC component is the largest for three-phase to earth fault current.

(3) The time of occurrence of single phase short-circuit, that is, the statistical relationship between the instant when ground faults occur and the voltage phase.

(4) Resistance of ground point or short-circuit point. The larger the resistance is, the faster the DC component decays.

The following calculating conditions are determined based on these factors and the characteristics of 1000 kV AC filter.

(1) *Type of short-circuit fault*: In calculation of the DC component decay time constant of EHV/UHV line circuit breakers when breaking short-circuit current, many fault types need to be taken into account, including single phase to earth short-circuit, two-phase to earth short-circuit, phase-to-phase short-circuit, three-phase to earth short-circuit, and even three-phase short-circuit [18]. These faults mostly occur on transmission lines, for example single phase to earth fault caused by lightning strike, two-phase or three-phase short-circuit caused by icing, galloping, wildfire, tower collapse, etc.

However, 1000 kV AC filter sub-bank circuit breakers in converter station only need to break faults occurring in the AC filter sub-banks but not line faults. As to the study of DC component decay time constant, the dominant fault found in UHV AC filters is single-phase to earth fault, and there is a tiny probability of earth fault involving more than one phase which is thereby ignorable. The reasons to this are discussed below.

Two-phase or three-phase short-circuits (including ground faults) on transmission lines are mainly caused by tower collapse as a result of icing, flood and other natural disasters, or by galloping, wildfire or lightning strike. These short-circuit faults will not occur in UHV AC filter sub-banks. Also according to studies [13] of China Electric Power Research Institute (CEPRI), the minimum phase-to-phase air clearance is 11.4 m [19, 20] for UHV AC filter sub-banks, which is large enough to prevent phase-to-phase short-circuit and three-phase short-circuit faults due to lightning strikes.

Therefore, as to the DC component decay time constant of UHV AC filter sub-bank breakers, it should be determined solely based on the single-phase to earth short-circuit current.

(2) *Time of occurrence of single-phase to earth fault and break time*: The filter sub-bank breaker model is an ideal breaker. In calculations, the time for relaying protection to operate is taken as 10 ms and the shortest opening time of breaker 20 ms, so the minimum opening time is 30 ms from the time of fault occurrence, and the breaker contact separation time is 30–60 ms.

(3) *Earth resistance*: Single-phase to earth fault occurs on the filter side, and the earth resistance is rigorously taken as 0.1 Ω .

(4) The object of study is the filter sub-bank circuit breaker of Qingzhou Converter Station.

Table 1 lists the single-phase to earth fault currents of 1000 kV filters in converter stations of some hierarchically connected UHV DC projects. The maximum single-phase to earth fault current

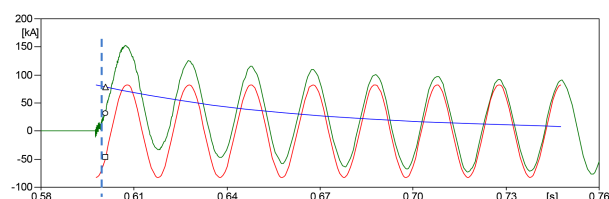


Fig. 4 DC component of breaker short-circuit breaking current during single-phase to earth fault of AC filter at Qingzhou Converter Station (\circ —short-circuit current, \square —AC component, Δ —DC component)

occurs with the 1000 kV AC filters in Qingzhou Converter Station. To this reason, Qingzhou Converter Station was taken as the object of study on DC component decay time constant of breakers breaking short-circuit current.

4.2 Test DC component decay time constant of filter Sub-bank breaker

The expected single-phase short-circuit current on the filter side is 50.8 kA (r.m.s.) through EMTP steady-state calculations in 2020. The single-phase short-circuit current of phases A, B, and C was calculated separately. The maximum short-circuit current waveform and the DC component decay time curve obtained through Fast Fourier Transform (FFT) are shown in Fig. 4.

At the instant of fault occurrence (0 s), $I_{dc,0} = 82.19$ kA; 30 ms after fault occurrence when breakers break the short-circuit current, $I_{dc,s} = 52.08$ kA. According to Formula (2), DC component decay time constant $\tau_s = -0.03/\ln(I_{dc,s}/I_{dc,0}) = 65.75$ (ms).

After conversion to the value under the test basis that DC component equals the peak AC component of rated short-circuit breaking current according to Formula (3), the test time constant corresponding to rated short-circuit breaking current of 63 kA is 55.89 ms.

$$\tau_{s0} = \left(\frac{(1/\tau_s) - \ln(I_{dc,0}/(50 \times \sqrt{2}))}{0.03} \right)^{-1} = 55.89 \text{ (ms)}$$

Obviously, breakers whose time constant is 56 ms for rated short-circuit breaking current of 63 kV is capable of breaking DC component of 52.08 kA. In practice, the break time of breakers should be 30–60 ms, thereby needing a higher time constant. For example, the time constant may be taken as 75 ms. It can be seen from Fig. 5 that if the time constant is 75 ms, the breaker's breaking capability within 30–60 ms is above the system DC component decay time constant, and therefore, the breaker can break the system DC component. Besides, r.m.s value of the AC component of system short-circuit current is smaller than that of the rated breaking current of breaker, providing a margin for its breaking capacity Table 2, Fig. 6.

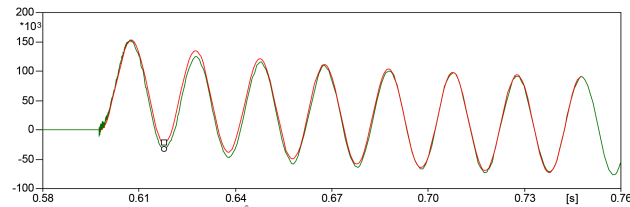


Fig. 5 Fitted curve of AC and DC components vs. calculated short-circuit current waveform of AC filter single-phase to earth short-circuit current at Qingzhou Converter Station (○—calculated short-circuit current waveform; □—fitted curve of AC and DC components)

Table 2 DC component and decay time constant when filter sub-bank breakers break single-phase to earth fault at Qingzhou Converter Station (earth resistance 0.1 Ω)

Converted Breaking Current of Breaker (kA)	Short-circuit current at 0 s (peak, kA)		Short-circuit Current at 30 ms (peak, kA)		Time constant τ_s , ms	Converted time constant, ms
	$I_{ac,0}$	$I_{dc,0}$	$I_{ac,s}$	$I_{dc,s}$		
63	82.91	82.19	82.06	52.08	65.75	55.89

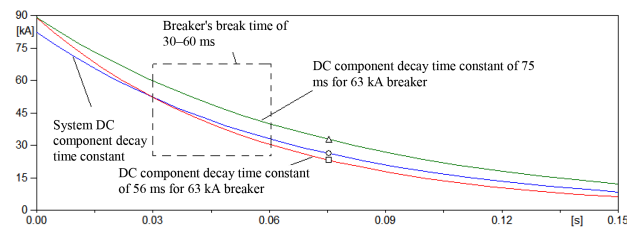


Fig. 6 Calculated DC component decay time constant vs. converted breaker test value (○—calculated time constant; □—converted time constant; △—selected time constant)

5 Conclusion

(1) The minimum phase-to-phase air gap of UHV AC filters is about 11.4 m, and there is a tiny probability of phase-to-phase short-circuit or three-phase short-circuit. So in determining the DC component decay time constant of filter sub-bank breaker, it is only necessary to consider single-phase to earth fault during test.

(2) The calculated decay time constant of short-circuit current DC component cannot be directly used for breaker test, and must be converted to the value under test basis that the DC component equals the peak AC component of the rated breaking current according to Formula (2) with necessary margin reserved. The final test time constant should be larger than the converted time constant.

(3) The calculated maximum DC component decay time constant of filter breaker at Qingzhou Converter Station when breaking single-phase to earth short-circuit current is 65.75 ms, and the AC component is about 50.8 kA (r.m.s.). After converted to UHV circuit breaker with rated short-circuit breaking current of 63 kA, the test time constant is 56 ms. Considering that the break time of breaker varies within 30–60 ms and to allow a proper margin, a larger time constant, say 75 ms, may be used.

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