Research on Consistency of Transient Response Characteristics of Current Transformers for DC application in DC Engineering

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Abstract: In ultra high voltage(UHV) DC system, the transient characteristics for fault current monitoring of current transformers for DC application (DCCTs) and the consistency of response characteristics when different types of DCCTs are used for differential protection have become important factors affecting the safe and stable operation of DC system. In this paper, transient characteristics of all-fiber DCCTs and shunt DCCTs mainly used in DC system were studied, the main parameters of the transient characteristics including delay time and maximum peak instantaneous error were tested, and the key parameters influencing the response consistency of DCCTs were analyzed. The results show that the maximum peak instantaneous errors of all-fiber DCCTs and shunt DCCTs can meet ±5% limit requirement, meeting the demand for protection application in DC system. The delay time is the main factors affecting the maximum peak instantaneous error of DCCT. The longer the delay time is, the greater the maximum peak instantaneous error is, which may even exceed the limit value of ±5%. If necessary, the delay time of DCCTs participating in differential protection can be compensated. The research results provide a theoretical basis for preventing the malfunction of protection device caused by the inconsistent response characteristics of DCCTs in DC system.

1. Introduction
In UHV power system, the non-periodic component of short-circuit current decays for a long time, and the time required for removing short-circuit fault is very short. At this time, the current transformer is in a transitional working state. Therefore, the current transformer for transient protection must be used, whose sampling signal is input to the protection device. With the rapid operation of the protection device, the short-circuit fault is removed, so as to avoid the failure developing to the grid instability[1].

DCCT is an important device for monitoring the operation of DC system and an important signal source for sampling the control and protection information of DC system. Its transient performance directly affects the control and protection action and determines the safe and stable operation of DC system. At present, all-fiber DCCTs and shunt DCCTs are mainly used in DC system. Due to different structural principles, their transient performance has some differences. While different from traditional electromagnetic current transformers which easily saturate, all-fiber DCCTs and shunt DCCTs have good transient characteristics such as the transient response range is large, the overcurrent range can reach tens of thousands of amperes, and the secondary current has no saturation problem. Therefore,
when the DC system fault occurs, saturation does not need to be considered in differential protection application, which greatly improves the operation characteristics of the differential protection.

Much research has been done on transient characteristics of current transformers for transient protection. However, previous studies mainly focus on transient characteristics of current transformers for AC system, including the types of traditional electromagnetic current transformers and electronic current transformers. The difference in the transient characteristics between traditional electromagnetic current transformers and electronic current transformers was analyzed, and the method of differential virtually braking CT saturation open was proposed to solve the problem of saturation and false opening of line optical fiber in differential protection when different transformers were used in combination[2]. Experimental studies on transient characteristics of current transformers for transient protection with different principles were conducted, concluding that both traditional electromagnetic current transformers and electronic current transformers could meet the transient performance requirements specified in national standards[3]. The transmission characteristics of P-class, TPY-class and Rogowski coil current transformers under steady-state and transient conditions were studied, and the influence of the difference in transmission characteristics among different types of CTs on relay protection was analyzed[4]. The modular combination test technology based on different time scales was proposed. The transient test power supply for current transformers for protection was developed, and the performance indices met the requirements for transient test[5]. The response of the air-coil current sensor to the transient current of power system was analyzed and simulated. The results showed that the air-coil current sensor could fully meet the requirements for transient current measurement[6].

At present, there are few studies on transient characteristics of DCCTs in UHV DC system applications. Due to the strong inertia of DC grid, the characteristics of fault current mainly include the fast rising speed, which generally rises to steady-state current within 10 milliseconds after fault, and the high steady-state short-circuit current, which can reach dozens of times of the rated current[7]. Therefore, in order to ensure the safe and stable operation of DC system, high requirements are put forward for the transient performance of DCCTs. Due to the lack of research on the transient characteristics, some DCCTs in converter stations failed during operation. Some faults directly led to the unipolar blocking of DC system, which brings threats and hidden dangers to the stability and reliability operation of DC system.

In order to comprehensively study the transient characteristics of DCCTs and the performance of response consistency when different types of DCCTs used mixly for differential protection, transient characteristics of DCCTs including all-fiber type and shunt type were compared and studied, and the key parameters affecting the response consistency of DCCTs were studied. It provides a theoretical basis for preventing the malfunction of protection device caused by the inconsistent response characteristics of DCCTs in DC system, and provides technical support for the selection and configuration of DCCTs in future DC system.

2. Parameters of transient characteristics

The response performance of the secondary output to the transient change of the primary input of the current transformer is usually expressed by the delay time, the maximum peak instantaneous error and other parameters[8]. The consistency of response characteristics refers to the characteristics that the delay time and the maximum peak instantaneous error of current transformers of different principles meet the specified limits. Therefore, the delay time and the maximum peak instantaneous error are the main indices to measure DCCTs’ transient performance.

Delay time refers to actual time between the current taking place on the primary and its result(s) appearing in the output. For current transformers with analog output, delay time should be constant, as any deviation would result in phase error. For current transformers with digital output, delay time is difference between the time encoded by the field SmpCnt in a digital output message and the time this message appears at the digital output.
Maximum peak instantaneous error refers to the maximum instantaneous error current for the specified duty cycle, expressed as the percentage of the peak value of the rated primary short-circuit current, as shown in formula 1.

\[
\hat{\epsilon} = 100 \cdot \frac{i_i}{(\sqrt{2} \cdot I_{psc})} \%
\]  

(1)

Where, \( \hat{i}_i \) is the maximum instantaneous error current, \( I_{psc} \) is the r.m.s value of the symmetrical component of primary current.

Instantaneous error current is difference between the instantaneous values of the secondary output multiplied by the rated ratio and the primary current. For an analog output, the instantaneous error current is defined by formula 2:

\[
i_s(t) = k_r \cdot u_s(t) - i_p(t - t_n)
\]

(2)

For digital output, the instantaneous error current is defined by formula 3:

\[
i_s(n) = k_r \cdot i_s(n) - i_p(t_n)
\]

(3)

Where, \( k_r \) is the rated ratio, \( u_s \) is the secondary voltage, \( i_p \) is the primary current, \( t \) is the instantaneous value of time, \( t_n \) is the rated delay time, \( i_s \) is the secondary current, and \( t_n \) is the effective time where the primary current of the \( n^{th} \) data set have been sampled.

3. Principle of transient characteristic test

3.1. Test circuit

The transient characteristic test circuit consists of transient high current source, standard shunt, ADC, electronic transformer calibrator and test object, as shown in figure 1. The transient high current source generates transient high current to simulate the short-circuit fault of DC system. The standard shunt provides the standard analog signal which is converted to digital signal by the ADC. Then the digital output signal of ADC together with the digital output signal of the test object are input into the electronic transformer calibrator. After corresponding algorithm calculation, the values of delay time and maximum peak instantaneous error of the test object are obtained.

3.2. Transient high current source

The transient high current source adopts the DC energy storage and inverter technology, which consists of multi-stage electrolytic capacitors in series-parallel connection. The capacitors are charged with a small voltage transformer. The function of the current source is realized by controlling the output current waveform and amplitude of the capacitors. The output power is 15MW( VA ), and r.m.s value of the maximum output current is 63kA~80kA.

At present, the test and research on transient characteristics of DCCTs only focus on the duty cycle of C-O. However, considering the situation of reclosing, the fault current in actual DC system is often more severe than the duty cycle of C-O. The duty cycle C-O-C-O can comprehensively assess the transient performance of DCCTs. The transient primary current waveform generated by the transient high current source is shown in figure 2. According to GB / T20840.8-2007《Instrument transformers-
Part 8: Electronic current transformers, the duty cycle of double energization is \( C - t' - O - t_0 - C - t'' - O \) (Both energizations in the same polarity of magnetic flux when applicable), where \( t' \) is the duration of first fault, \( t_0 \) is the fault repetition time, \( t'' \) is the duration of the second fault, \( t'_{al} \) is the specified time to accuracy limit in the first fault, \( t''_{al} \) is the specified time to accuracy limit in the second fault.

![Fig.2 C-O-C-O duty cycle](image)

3.3. Standard shunt
The standard shunt is coaxial cylinder type with low inductance value. The coaxial cylinder structure can eliminate skin effect. The highly stable resistance material is used to ensure high annual stability and long-term stability. The rated ratio is 40kA: 2V, the transient accuracy level is 0.5 class, the measurement range of primary current is 1A ~ 40000A, the rated secondary voltage is 150mV.

The accuracy level of the ADC is 0.05 class.

The error of the measurement system is introduced by errors of the standard shunt and the ADC, and the accuracy level of standard shunt and ADC can meet the requirements for transient characteristic test.

4. Transient characteristic test
4.1. Test object
At present, all-fiber DCCTs and shunt DCCTs are mainly used in DC system. All-fiber DCCTs can be divided into modulation principles of open-loop and closed-loop types. DCCTs with different principles are selected for transient characteristic test, and the information of test objects is shown in Table 1.

| Manufacturer | Principle | Serial number | Sampling rate /kHz | Secondary output mode | Rated primary current/A |
|--------------|-----------|---------------|--------------------|-----------------------|------------------------|
| A            | All-fiber (Type of open-loop) | 1 | 10 | Digital output | 5000 |
|              |           | 2 | 100 |                          |                        |
| A            | All-fiber (Type of open-loop) | 3 | 10 | Digital output | 5000 |
|              |           | 4 | 100 |                          |                        |
| B            | All-fiber (Type of closed-loop) | 5 | 10 | Digital output | 5000 |
|              |           | 6 | 50 |                          |                        |
|              |           | 7 | 100 |                          |                        |
| C            | All-fiber (Type of closed-loop) | 8 | 10 | Digital output | 3000 |
|              |           | 9 | 100 |                          |                        |
| C            | Shunt     | 10 | 10 | Digital output | 3000 |
|              |           | 11 | 50 |                          |                        |
| D            | All-fiber (Type of closed-loop) | 12 | 10 | Digital output | 5000 |
|              |           | 13 | 100 |                          |                        |
4.2. Test parameters
According to the requirements in company standard of the state grid corporation“Specification for consistency of response characteristics of current transformers for HVDC”, primary current in transient condition of rated frequency and required offset shall be applied. The experiment shall be carried out under the specified C-100ms-O-500ms-C-250ms-O duty cycle. The primary constant shall be not less than 80 milliseconds. The first peak value of primary current in transient condition shall be $K$ times ($K \geq 6$) of the rated primary current. The recommended values of $K$ are 6, 10 and 15, which are determined by users according to actual DC engineering. Therefore, according to the rated primary current of the test objects, the peak value of primary current in transient condition applied to the test objects is 30 kA.

The delay time, the maximum peak instantaneous errors of the first duty cycle and the second duty cycle were tested.

4.3. Test results
The transient characteristic test results are shown in table 2. Figures 3 ~ 5 are current waveforms of the standard shunt and the test objects.

| Manufacturer | Principle                  | Serial number | Sampling rate /kHz | Maximum peak instantaneous errors of the first duty cycle/% | Maximum peak instantaneous errors of the first duty cycle/% | Delay time/μs | Test waveform |
|--------------|----------------------------|---------------|-------------------|-------------------------------------------------------------|-------------------------------------------------------------|---------------|---------------|
| A            | All-fiber (Type of open-loop) | 1             | 10                | 4.56                                                        | 4.46                                                        | 150.58        | Fig.3         |
|              |                            | 2             | 100               | 4.51                                                        | 4.51                                                        | 147.67        |               |
| A            | All-fiber (Type of open-loop) | 3             | 10                | 3.42                                                        | 3.83                                                        | 60            |               |
|              |                            | 4             | 100               | 3.10                                                        | 4.16                                                        | 60            |               |
| B            | All-fiber (Type of closed-loop) | 5             | 10                | 1.49                                                        | 1.49                                                        | 49.88         |               |
|              |                            | 6             | 50                | 2.92                                                        | 3.02                                                        | 16.46         |               |
|              |                            | 7             | 100               | 1.94                                                        | 1.95                                                        | 48.67         |               |
| C            | All-fiber (Type of closed-loop) | 8             | 10                | 3.95                                                        | 4.03                                                        | 20.67         |               |
|              |                            | 9             | 100               | 3.80                                                        | 3.82                                                        | 20.67         |               |
| C            | Shunt                      | 10            | 10                | 11.3                                                         | 11.4                                                         | 352           |               |
|              |                            | 11            | 50                | 1.80                                                        | 1.90                                                         | 75.7          |               |
| D            | All-fiber (Type of closed-loop) | 12            | 10                | 7.9                                                         | 7.8                                                          | 237.7         |               |
|              |                            | 13            | 100               | 8.24                                                        | 8.16                                                         | 246           |               |
According to the requirements in company standard of the state grid corporation “Specification for consistency of response characteristics of current transformers for HVDC”, the maximum peak instantaneous error limit of current transformers with different principles is ±5 % under specified duty cycle. Table 1 shows that the transient performance of all-fiber DCCTs and shunt DCCTs is basically consistent with the theoretical analysis. The maximum peak instantaneous errors of all-fiber DCCTs and shunt DCCTs can reach the limit value of ±5%, which can meet the protection application requirements for DC system. However, according to the definition of the maximum peak instantaneous error, it is affected by the delay time. To a certain extent, the longer the delay time is, the greater the maximum peak instantaneous error is. The results in table 2 are tested without delay time compensation. For the test objects 10, 11 and 13, the delay time is 352μs, 237.7μs and 246μs respectively, and the corresponding maximum peak instantaneous errors exceed the limit value of ±5%. Therefore, it’s necessary for delay time compensation of the three test objects. Test results are shown as table 3.

### Tab.3 Test results after delay time compensation

| Serial number | Maximum peak instantaneous errors of the first duty cycle (before delay time compensation) /% | Maximum peak instantaneous errors of the first duty cycle (after delay time compensation) /% | Maximum peak instantaneous errors of the second duty cycle (before delay time compensation) /% | Maximum peak instantaneous errors of the second duty cycle (after delay time compensation) /% | Compensation time/μs |
|---------------|---------------------------------------------|---------------------------------------------|---------------------------------------------|---------------------------------------------|---------------------|
| 10            | 11.3                                        | 0.48                                        | 11.4                                        | 0.49                                        | 352                 |
| 11            | 7.9                                         | 1.26                                        | 7.8                                         | 1.33                                        | 237.7               |
| 13            | 8.24                                        | 1.26                                        | 8.16                                        | 1.31                                        | 246                 |

Table 3 shows that after delay time compensation, the maximum peak instantaneous error of DCCT can reach the limit value of ±5 %, which meets the protection application requirements for DC system. Current waveforms of transient characteristic test before and after delay time compensation are shown in figure 4 ~5.
5. Conclusions

(1) The maximum peak instantaneous errors of all-fiber DCCTs and shunt DCCTs can reach the limit value of ±5%, which can meet the protection application requirements for DC system.

(2) The maximum peak instantaneous error of DCCT is slightly affected by the sampling rate. The delay time is the main factor affecting the maximum peak instantaneous error. The longer the delay time is, the greater the maximum peak instantaneous error is. When the delay time reaches a certain value, the maximum peak instantaneous error may exceed the limit value of ±5%.

(3) The differential current is calculated by the protection device in DC system. In the case of no delay time compensation, high differential current may cause misoperation of the protection device if the delay time of one DCCT is too long. Therefore, it is necessary to determine whether the DCCTs participating in differential protection are necessary for delay time compensation.

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