Voltage Distribution and Regulation of Multi-interrupter SF6 Circuit Breakers for HVDC Grid

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Abstract. The multi-interrupter SF6 circuit breakers are widely used in High Voltage Direct Current (HVDC) station. The AC filter circuit breakers play an important role on the reliability of the grid. In this paper, the voltage distribution of the multi-interrupter circuit breaker is researched and the regulation method is obtained. First, the equivalent model of four-interrupter SF6 circuit breaker is established. The equivalent circuit is composed of controlled post-arc sources, post arc resistors and equivalent capacitors. The equivalent capacitance and stray capacitance across each interrupter were calculated by using finite element analysis software (ANSYS). Then voltage distribution was simulated under the condition that different measures were adopted. The measures include paralleling resistance, capacitance and resistance-capacitance. Comprehensive comparison of various voltage-sharing measures, paralleling capacitance and resistance-capacitance. Comprehensive comparison of various voltage-sharing measures, paralleling capacitance and resistance-capacitance is suitable for multi-break SF6 circuit breaker at the present condition. At last, experimental system was built based on Weil synthesis circuit to seek suitable scheme. The test results verify the simulation analysis, which indicates that the grading resistance-capacitance is suitable voltage regulation method.

1. Introduction

Convector station is very important in HVDC transmission system. Transverter can convert AC to DC or DC to AC. Harmonic is produced in the rectification or contravariant process. To avoid the AC system being invaded by harmonic, Alternating Current Filter (ACF) is needed to be installed in the AC side of convector station [1]. At the same time, in the running process 30%-60% rated reactive power is consumed. So a great quantity of reactive power is required to compensate the loss. The differences between ordinary circuit breakers and AC filter circuit breakers are as follows: opening capacitive load, enduring transient recovery voltage. When transmission power is changed, consumed reactive power also varies in pace with it [2]. To maintain the voltage of AC bus in converter station, ACF breakers close and open frequently. Meanwhile the breakers have to stand mixed-voltages (AC and DC). The mixed-voltages include AC voltages from AC bus and DC voltages from capacitors. These factors bring forward stricter requirements to ACF breakers [3].

The SF6 ACF breaker with four interrupters consists of two switches with double breaks. The effect of voltage balancing scheme determines whether or not the switch open successfully [4]. The equivalent capacitance of interrupter endures alternating voltage. The equivalent resistance stands DC
part. There is stray capacitance in parallel with interrupter. The rate of dielectric recovery and different arcing time could cause unequal voltage distribution on each break [5].

To improve uniformities of four breaks people often adopt grading capacitors. The higher the capacitance is, the better the effect is obtained in theory [6]. While transient recovery voltage becomes larger with the capacitance increasing. Especially when four breaks aren’t opened simultaneously, breakdowns occur in succession. That leads to the fail of SF6 circuit breaker interrupting. So the breaking capacity is greatly reduced. This paper aims to seek a kind of suitable voltage-sharing measure.

2. Voltage distribution mechanism of multi-interrupter circuit breakers

The static voltage distribution progress of multi-interrupter circuit breakers is different from the dynamic. The static voltage distribution is under the circumstance that the contacts don’t move and fault current doesn’t exist. The dynamic voltage distribution is in the breaking process that the contacts are moving [7-8]. Arc memory of the fault current exists in the dynamic voltage distribution process. The differences between the static and dynamic voltage distribution are the surface temperature of the contact and the remaining plasma in current zero, and both can be influenced by the arc memory. The static voltage distribution is usually analysed through the equivalent circuit. The dynamic voltage distribution can be got by finite element analysis.

![Figure 1. The breaking process of the circuit breakers](image)

The breaking process of the circuit breakers is shown in Figure 1. Breakers open after detecting fault current. The arc voltage appears when the contacts are separated. If the dynamic insulation recovery strength of the circuit breaker is greater than the transient recovery voltage (TRV), the fault current is extinguished at the current zero point. After the current zero point, high frequency TRV and system voltage exist across the circuit breakers. The peak of the TRV and du/dt are obtained in the opening process. The oscillation of the TRV is damped. After the oscillation is over, the system voltage is total voltage. The elliptical black circle shows a partial enlargement of the TRV. The TRV process can be defined as four phases: (i) the initial TRV process, between the current zero point and the first peak of the TRV; (ii) the oscillating TRV process, the damped oscillation process; (iii) the stable TRV process, from the end of the oscillation to the end of attenuation of the contact surface temperature and (iv) the power frequency voltage process.

3. Establish simulation model

3.1. Calculation of capacitance parameters

In order to choose the reasonable equalization measure, a specific system must be ascertained and parameters of each component should be figured out. By simulation regular pattern of the voltage balancing scheme is obtained. Then the advantages and disadvantages of each measure are compared and analysed.
In this paper, a SF6 four-break circuit breaker consisting of two double-break porcelain column circuit breakers is taken as an example, and the equivalent circuit shown as Figure 2. The electric field analysis model of four-interrupter SF6 circuit breaker is established in Ansys. The self-capacitance of the breaks and the stray capacitance to the ground are obtained. The results are showed as Table 1.

**Table 1. Capacitance of interrupter**

| Interrupter | #1     | #2     | #3     | #4     |
|-------------|--------|--------|--------|--------|
| Self-Capacitance/pF | 23.744 | 24.005 | 23.995 | 23.715 |
| Stray Capacitance/pF | 2.8372 | 6.6441 | 6.1180 | 6.7991 |

### 3.2. Arc resistance parameters

When dynamic resistance model of the interrupter was established, the breaking process is divided into three stages, as showed in Figure 3.

(i) When the contact is not separated, closing resistance play a major role.

(ii) In electric arc combustion phase, variable controlled resistance is used to equal arc resistance.

(iii) Post-arc procedure contains post-arc current phase and dielectric recovery phase.

For SF6 circuit breaker, post current can reach hundreds of mA and last a few microseconds. Then dielectric recovery phase begins. The resistance of interrupter increases from MΩ level to several GΩ rapidly.

### 3.3. ATP-EMTP system model

The focus of this paper is on the breaking process of the AC group filter circuit breaker. In the study, the AC power grid is simplified. The equivalent circuit model is used to calculate the system short-circuit impedance through short-circuit current. Proper voltage source is set to ensure that export voltage is the highest in the AC system. The system is established as Figure 4.

AC rated phase voltage is 461.88kV. Resistance and capacitance are paralleled to simulate the opening process of circuit breakers. Static voltage distribution is simulated by use of capacitance. Dynamic opening is simulated with paralleling variable resistance and capacitance.
According to the load variation of the DC side, filters with different capabilities need to be cast. In this paper, the maximum capability of the filter is selected as 288Mvar. HP24/36 double tuned filter is taken as an example to set up a model. The Parameters are as in Table 2.

| Type     | $C_1$ / μF | $C_2$ / μF | $L_1$ / mH | $L_2$ / mH | $R_1$ / Ω |
|----------|------------|------------|------------|------------|------------|
| HP24/36  | 1.5444     | 9.2604     | 7.5975     | 1.2658     | 500        |

4. Simulation and test results

4.1. Simulation results

In this paper, three kinds of measures are adopted: paralleling capacitance, paralleling resistance, paralleling capacitance and resistance. The degree of voltage irregularity is usually characterized by $r$. That is, the ratio of the voltage to the voltage when the voltage is evenly distributed. The ratio is the actual voltage of each break to the voltage that is uniformly distributed uniformity. Generally $r$ is no more than 1.1.

According to the calculated distributed capacitance parameters, the static voltage distribution ratio is simulated under different conditions.

As can be seen from Figure 5, $r \leq 1.1$, grading capacitance is no less than 400pF. When grading capacitance is more than 600pF, the effect of improving static voltage distribution is not obvious. In engineering application, the grading capacitance is usually 500-2000pF. The frequency is 50Hz. Equivalent condensance $X_C$ about 1.59～6.37MΩ. Comparing with line resistance and load, the branch containing capacitance is open. The paralleling resistance must be no less than the condensance that affects the normal opening.

As shown in Table 3, the lower the paralleling resistance is, the better the voltage-sharing effect is obtained. While the smaller the paralleling resistance is, the more heat is generated. When the paralleling resistance is less than 3MΩ, the capacitance of interrupter can be ignored. Because the equivalent capacitance of interrupter is about 20～30pF. The condensance is 159～106MΩ. If the
paralleling resistance is more than 24MΩ, the voltage-sharing effect also determined by the capacitance of interrupter. So the range of paralleling resistance is from 3MΩ to 24MΩ.

| Paralleling resistance/ MΩ | Voltage percentage/ % |
|----------------------------|------------------------|
| 3                          | 25.02                  |
| 6                          | 25.01                  |
| 12                         | 24.99                  |
| 24                         | 24.98                  |
| 48                         | 24.93                  |
| 100                        | 24.79                  |

Table 3. The voltage distribution of each interrupter

For paralleling resistance and capacitance, when the resistance is less than 24MΩ, the properties of voltage-sharing are mainly determined by resistance. Increasing the capacitance is bad for the uniformity of voltage distribution. If the resistance is higher than 24MΩ, the voltage across each interrupter is withstood by capacitance.

4.2. Test results

Under the condition that the main current is 15kA and the TRV is 36.5kV, the entire opening waveform can be seen in Figure 7. Voltage non-uniformity is defined as the percentage of the distinction between the voltage of one breaker and the average voltage, as shown in formula 1:

\[
K_{ni} = \frac{U_i - \overline{U}_i}{\overline{U}_i} \times 100\%
\]

\(U_i\) is the average voltage. \(U_i\) is the voltage of one breaker which you want to analyse. The voltage non-uniformity of circuit breakers with double-break can be calculated by formula 2. \(U_{V1}\) and \(U_{V2}\) represent the voltage of the low side and high side respectively. \(K_n\) represents the non-uniformity of the voltage distribution.

\[
K_n = \frac{U_{V2} - U_{V1}}{U_{V1} + U_{V2}} \times 100\%
\]
As shown in Figure 7, paralleling resistance and capacitance across each interrupter, the voltage of the high breaker is higher than the low one. The peaks of the high breaker and the low one are 21.54 kV and 15.17 kV respectively. The voltage non-uniformity of the circuit breakers with double-break is starting from 17.5% and finally to 7.0% in damped oscillation.

5. Conclusion
The equivalent circuit of the four-break circuit breakers is proposed, and the mechanism is described by introducing a controlled post arc current source. The effect of equivalent capacitance, post arc conductance and post arc charge on voltage distribution is considered. At last, experiments were conducted to verify the results:

Because of the change of arc resistance by stage, TRV distribution is mainly affected by the equivalent impedance of interrupter during the post arc stage.

The voltage-sharing effect of paralleling resistance measure is more stable than usage of paralleling capacitance under static condition. While the dynamic characteristics of the paralleling capacitance measure are better than paralleling resistance measure.

Comprehensive comparing of various voltage-sharing measures, paralleling resistance and capacitance is more suitable for four-interrupter SF6 circuit breaker. In the experiment condition, the resistance is no more than 24MΩ and the capacitance is no less than 600pF.

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