Simulation Research on the Post-arc Dielectric Recovery Characteristics of Multi-break Vacuum Circuit Breakers

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Abstract. The dielectric recovery characteristics are very important for the successful interruption of the vacuum circuit breaker. In order to explore the influence of the post-arc dielectric recovery characteristics of the multi-break vacuum circuit breaker on its breaking, this article establishes a simulation model of the multi-break vacuum circuit breaker and a 750kV short line fault simulation circuit in MATLAB. By adjusting the dielectric recovery characteristics of different breaks, the critical dielectric recovery rate (The minimum dielectric recovery rate of the break when the circuit breaker does not break down) under different conditions is finally obtained. In addition, the influence of the equalizing capacitor on the critical recovery rate is also explored. It is found that the smaller the grading capacitance, the greater the voltage of the break, and the greater the critical dielectric recovery rate.

1. Introduction

As a new type of switchgear in the power system, the vacuum circuit breaker has the advantages of strong arc extinguishing ability, small size, light weight, long service life, and no environmental pollution. However, due to the saturation effect of the breakdown voltage and the gap length, the development of vacuum circuit breakers to high voltage levels is restricted. The multi-break vacuum circuit breaker has become an effective means to push the vacuum circuit breaker into the high-voltage field because it maintains the excellent characteristics of vacuum short gap [1-4].

The development of multi-break vacuum circuit breakers involves many research topics. Among them, the study of post-arc dielectric recovery characteristics is particularly important. The reason is that the post-arc dielectric recovery characteristics of the multi-break vacuum circuit breaker will directly determine whether it can successfully break the fault current [5]. In recent years, the research on the post-arc dielectric recovery characteristics of multi-break vacuum circuit breakers has also made some progress. Minfu Liao et al. studied the static and dynamic breakdown characteristics of multi-break vacuum circuit breakers, and finally reached the conclusion that the more breaks in series is not the better [6]. Guowei Ge et al. explored the synergistic characteristics of dynamic medium recovery of double-break vacuum circuit breakers, and determined the best combination of double-break vacuum circuit breakers [7].
At present, the research on the post-arc dielectric recovery characteristics is mostly based on experimental methods. This article is to study the dielectric recovery characteristics of the multi-break vacuum circuit breaker by means of simulation. Based on the established simulation model of the multi-break vacuum circuit breaker and the simulation circuit of short line fault short-circuit breaking, this article finally obtains the critical dielectric recovery rate of the breaker under different conditions. The so-called critical dielectric recovery rate refers to the minimum dielectric recovery rate of the break to ensure the entire circuit breaker does not break down. In addition, the article also explores the influence of the grading capacitor value on the critical dielectric recovery rate.

2. The establishment of simulation model of the multi-break vacuum circuit breaker

In order to study the post-arc dielectric recovery characteristics of the multi-break vacuum circuit breaker, this article first established a multi-break vacuum circuit breaker model in MATLAB. The model considers the dielectric recovery and high-frequency interruption characteristics of the vacuum circuit breaker. By coupling the multi-break vacuum circuit breaker model with an external test circuit, the arc current and TRV (transient recovery voltage) waveforms can be obtained, and they can be used as the basis for making and breaking to simulate the breaking and breakdown process of the multi-break vacuum circuit breaker[8].

This multi-break vacuum circuit breaker simulation model consists of two parts: the circuit breaker module and the control module.

2.1. Circuit breaker module

According to the actual data, the voltage level of the multi-break vacuum circuit breaker is 750kV, which is composed of 12 arc extinguishing chambers. The voltage level of the arc extinguishing chamber is 63kV and each arc extinguishing chamber is connected in parallel with a grading capacitor of 9000pF. The specific structure of the multi-break vacuum circuit breaker is shown in Figure 1.

![Figure 1. Structure diagram of the multi-break vacuum circuit breaker](image)

The circuit breaker module uses 12 ideal switches to replace 12 breaks. It obtains data such as TRV and arc current through the measurement module and sends it to the control module. After that, the ideal switches will receive the opening or closing signal from the control module and react accordingly to simulate the breaking and breakdown process of the circuit breaker. The structure of a single break is shown in Figure 2.
2.2. Control module

The control module receives the voltage and current values from the circuit breaker module. When the vacuum circuit breaker is in the closed state, the control module will determine whether the current value meets the interruption characteristics. If so, it will issue an opening command to the ideal switch of the circuit breaker module. When the vacuum circuit breaker is in the open state, the control module will compare the TRV with the dielectric recovery withstand voltage value. If the TRV is greater than the dielectric recovery withstand voltage value, it will issue a closing command to the ideal switch.

The mathematical model of the control module mainly includes the following two parts:

1) Dielectric recovery

In the transient process of vacuum circuit breaker opening, the dielectric recovery strength increases as the opening distance becomes larger[9]. This article regards the post-arc dielectric recovery characteristics as a variable to explore the critical dielectric recovery characteristics when the circuit breaker is not broken down. The dielectric recovery characteristics of the 63kV arc extinguishing chamber are preliminarily determined as shown in formula (1):

\[ U_d = \begin{cases} 2.1t & 0 \leq t \leq 50 \\ 0.354(t - 50) + 115 & 50 \leq t \leq 300 \\ 2205.6906(t * 10^{-8})^{0.3} & 300 \leq t \leq 90000 \end{cases} \]  

(1)

In the formula(1), \( U_d \) is the breakdown voltage, in kV, and \( t \) is the breaking time, in \( \mu \)S.

2) High frequency arc extinguishing ability

When the circuit breaker is broken down, due to the oscillation of the system, a high-frequency current will be generated. At this time, the high-frequency current will be superimposed on the power frequency current. When the high frequency current is greater than the power frequency current, the current will have a forced zero crossing. The rate of change of the current at the current zero point determines whether there is a successful zero-crossing extinguishment. The high-frequency arc extinguishing capability of a typical vacuum circuit breaker is in the range of several hundred amperes per microsecond. This value can be a constant or a function of the time after the contact is separated. This simulation takes it as 300A/\( \mu \)S.

3. The establishment of simulation for the short circuit breaking test of the short line fault

After establishing the simulation model of the multi-break vacuum circuit breaker, it is also necessary to establish a short circuit breaking simulation. Since the TRV in the early stage of the short line fault has a high rate of rise and the dielectric recovery characteristics have a more obvious impact on the breaking of the circuit breaker. Therefore, this study established a short-circuit breaking test simulation for short line faults.
3.1. Characteristics of the short line fault

Short line fault refers to a short circuit that occurs on the overhead line close to the circuit breaker (usually tens of meters to several kilometers). The TRV waveform of a short line fault is different from the TRV waveform of an ordinary short circuit. It has an initial part with a high rising speed. This is because when the current crosses zero, the voltage on the line side of the circuit breaker is not zero. The voltage on the overhead line will traveling on the transmission line at a traveling wave speed. Since the fault point of the short line fault is closer to the circuit breaker, the voltage wave is quickly reflected back, and the recovery voltage rises to a fairly high peak in a short period of time. At this time, if the dielectric recovery withstand voltage of the vacuum switch is low, breakdown will occur [10].

3.2. The establishment of the main circuit of the short line fault

According to GB1984 regulations, three-pole circuit breakers with a rated voltage of 72.5kV and above and a rated breaking current exceeding 12.5kA that are directly connected to the overhead line should be subjected to a single-phase short line fault test. The breaking current during the test should be 75% or 90% of the rated breaking current[11]. Finally, the breaking current of this simulation is taken as 90% of the rated breaking current, and the amplitude of the voltage source is 653.2kV. The main circuit of the short line fault breaking test simulation is shown in Figure 3.

![Figure 3. Main circuit of the short line fault breaking](image)

3.3. TRV adjustment for the short line fault

After the main circuit of the short line fault is determined, the most important task is to adjust the TRV of the vacuum circuit breaker. GB1984 has made strict requirements on the TRV of the short line fault, which is mainly divided into two parts: the power side and the line side.

The power-side TRV uses a four-parameter method, and the initial transient recovery voltage (ITRV) must also be considered. The so-called ITRV considers the impact of the voltage wave reflected by the bus on the circuit breaker[12]. The line-side TRV adopts the two-parameter method. Since the fault point of the short line fault is closer to the circuit breaker, the TRV change rate on the line side is very large.

Finally, by adjusting the component parameters of the TRV control components, a standard TRV that meets the requirements of the national standard is obtained. The waveform is shown in Figure 4.
4. Simulation results

4.1. The critical dielectric recovery rate under ideal conditions
After running the simulation, the circuit breaker is not broken down. By turning down the dielectric recovery characteristics of all the breaks, it is found that the breakdown time is in the linear region of dielectric recovery. Under ideal conditions (the dielectric recovery characteristics of all the breaks are all the same), the critical dielectric recovery rate is \(2.1\text{kV/\mu S}\). Figure 5 shows the TRV waveform and dielectric recovery curve of a single break when the circuit breaker is not broken down.

4.2. The critical dielectric recovery rate considering the dispersion of dielectric recovery
Since the dielectric recovery characteristics of vacuum switches are very random and vary widely, it is impossible for all breaks to have the same dielectric recovery characteristics. In order to explore the influence of the different dielectric recovery characteristics of breaks on the short-circuit breaking, this article modified the dielectric recovery characteristics of some breaks to make them broken down, and then adjusted the dielectric recovery characteristics of other breaks. Finally, the critical dielectric recovery rate of other breaks when the breaker does not break down is found.

1) Modify the dielectric recovery characteristics of a break to make it broken down
This article reduces the dielectric recovery characteristics of one of the breaks, making it into:

![Figure 4. TRV waveform of the circuit breaker](image)

![Figure 5. TRV and dielectric recovery curve of a single break when the circuit breaker is not broken down](image)
In the formula (2), $U_d$ is the breakdown voltage, in kV, and $t$ is the breaking time, in μS. After running the simulation, it is found that the circuit breaker is broken down. The corresponding simulation waveform is shown in Figure 6.

(a) TRV waveform of the circuit breaker during breakdown

(b) TRV and dielectric recovery curve of the modified break
It can be seen from the simulation results that after reducing the dielectric recovery rate of one of the breaks, the break is broken down. Since then, the remaining five breaks in series with it are also broken down. Finally, the entire circuit breaker is broken down.

What’s more, due to the large TRV rise rate in the early stage, the circuit breaker is broken down a few microseconds after the current crosses zero. At this time, the dielectric recovery characteristic of the circuit breaker is close to linear. Because the moment of breakdown is very close to the moment of arc extinction, the amplitude of the high-frequency current generated after breakdown is not large. Therefore, there is no forced zero crossing and no multiple failures. Eventually, the faulty circuit is broken in the next cycle, and the breaking time becomes longer.

Finally, by increasing the dielectric recovery rate of the break in series with the modified break, it is found that when the dielectric recovery rate of the break in series with it is greater than 2.3kV/μS, the entire circuit breaker is not broken down.

2) Modify the dielectric recovery characteristics of multiple breaks to make them broken down

After discussing the influence of the reduction of the dielectric recovery rate of one break on the breaking of the circuit breaker, this article also modified the dielectric recovery rate of multiple breaks in series to make them broken down. The critical dielectric recovery rate of the break in series with the
modified break is also found when the entire circuit breaker is not broken down. The specific results are shown in the table below.

Table 1. Simulation results when the modified dielectric recovery characteristics are same

| The number of modified breaks | Dielectric recovery rate of modified break (kV/μS) | The critical dielectric recovery rate of the break in series with the modified break (kV/μS) |
|-----------------------------|-----------------------------------------------|--------------------------------------------------|
| 2                           | 2                                             | 2.8                                              |
| 3                           | 2                                             | 3.3                                              |
| 4                           | 2                                             | 4.4                                              |
| 5                           | 2                                             | 7.1                                              |

Table 2. Simulation results when the modified dielectric recovery characteristics are different

| The number of modified breaks | Dielectric recovery rate of modified break (kV/μS) | The critical dielectric recovery rate of the break in series with the modified break (kV/μS) |
|-----------------------------|-----------------------------------------------|--------------------------------------------------|
| 2                           | 2,2,2                                        | 2.8                                              |
| 3                           | 2,2,2,2.5                                    | 3.3                                              |
| 4                           | 2,2,2,2.5,3                                 | 4.2                                              |
| 5                           | 2,2,2,2.5,3,3.8                            | 6.6                                              |

It can be seen from the table that the greater the number of breaks that are broken down, the greater the impact on the entire circuit breaker. To prevent breakdown of the entire circuit breaker, the break in series with the broken break needs to have a higher dielectric recovery rate. And the greater the dielectric recovery rate of the broken-down break, the smaller the impact on other breaks of the circuit breaker.

4.3. The influence of grading capacitor on the critical dielectric recovery rate

The above simulation results are obtained when the grading capacitors are all the same. In order to explore the influence of the grading capacitor on the critical dielectric recovery rate of the break, this article reduces the value of the grading capacitor of one of the breaks. The critical dielectric recovery rate when this break is not broken down is found. The results are shown in Table 3.

Table 3. The critical dielectric recovery of the break under different grading capacitance values

| Grading capacitance value (pF) | The critical dielectric recovery rate of the break (kV/μS) |
|---------------------------------|--------------------------------------------------|
| 8700                            | 2.1                                              |
| 8300                            | 2.2                                              |
| 7800                            | 2.3                                              |
| 7400                            | 2.4                                              |

It can be seen from the above table that when the grading capacitance decreases, the critical dielectric recovery rate of the break increases. The reason is that when the grading capacitor is smaller, the voltage value of the break is larger. Therefore, the requirements for the speed of dielectric recovery are higher.

5. Conclusion

In order to explore the multi-break vacuum circuit breaker’s post-arc dielectric recovery characteristics, this article established a multi-break vacuum circuit breaker model in MATLAB and established a
750kV short line fault breaking simulation circuit according to GB1984. The critical dielectric recovery rate of the break when the circuit breaker is not broken down under different conditions is obtained. In addition, this article also explored the influence of the value of grading capacitor on the critical dielectric recovery rate. The specific conclusions are drawn as follows:

- For the short line faults, the rate of increase in the initial stage of TRV is very high, even reaching the peak value in about ten microseconds. So the breaker is broken down in the early stage of breaking. At this time, the dielectric recovery characteristic is approximately linear at this time.
- When the early dielectric recovery rate of the break is less than 2.1kV/μS, the break will be broken down.
- When some breaks are broken down due to the low dielectric recovery rate, they will have a great impact on the breaks connected in series. The more the number of broken breaks or the smaller the dielectric recovery rate, the greater the impact on the breaks connected in series with the broken break.
- Since the breakdown time is early, the amplitude of the high-frequency current is not large. So there is no forced zero crossing and multiple breakdown. The fault circuit is broken in the next cycle, so the breaking time becomes longer.
- When the grading capacitance value of a break is reduced, the voltage value of this break will increase, which will eventually lead to an increase in the critical dielectric recovery rate.

6. References
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