

Article

Equivalent Modeling of Disconnecter Operation Based on Dynamic Arc Characteristics and VFTO Characteristic Analysis

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Abstract: To thoroughly analyze the high-frequency and high-amplitude electromagnetic disturbances generated during disconnector operation, this paper proposes an equivalent modeling approach based on dynamic arc behavior. The model incorporates the resistance, inductance, and capacitance characteristics of the arc and consists of four main modules: arc reignition, arc extinction, arc resistance control, and switch control. Complete logical coordination among these modules is designed to enhance the model's performance in terms of dynamic response and modeling accuracy compared to traditional methods. By systematically comparing simulation results with experimental data and conventional model outputs, the effectiveness and reliability of the proposed model in accurately reflecting the operational characteristics of disconnectors are validated. Furthermore, a comparative analysis of transient waveform characteristics from both experiment and simulation is conducted, with key parameters extracted and probability density functions constructed. The results demonstrate the high-precision fitting capability of the model and further reveal the statistical distribution patterns of very fast transient overvoltage single-pulse characteristics.



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Keywords: disconnector; equivalent arc model; very fast transient overvoltage; electromagnetic interference; statistical distribution; transient characteristics

1. Introduction

During normal power system operation, when a disconnector switches no-load transformers or transmission lines, small capacitive currents undergo multiple arc ignition and extinction cycles. This process generates high-frequency electromagnetic signals that propagate along conductors. Through continuous reflection and superposition, these signals ultimately develop into electromagnetic interference characterized by two parts: an amplitude reaching 2–3 times the phase voltage and a frequency spectrum extending to several hundred kHz [1–4]. Consequently, the very fast transient overvoltage (VFTO) and very fast transient current (VFTC) generated during disconnector operation present two major challenges: first, they significantly impair the performance of intelligent substation equipment; second, they introduce substantial risks to overall power system stability [5–7]. Developing precise equivalent simulation models for disconnector operations offers an effective approach to investigating these technical challenges, representing the predominant

methodology in current research. However, existing multi-operation simulation models exhibit notable limitations due to inadequate consideration of disconnecter structural features and operational characteristics, leading to significant discrepancies between the simulated and measured results. Given the increasing complexity of transient processes during disconnector operations, there is an urgent need to develop high-frequency dynamic arc equivalent models that accurately represent operational conditions, enabling a comprehensive analysis of rapid transient phenomena [8–10].

Although a variety of equivalent simulation models have been proposed for the fast transient process caused by the operation of the disconnector, these models rarely fully consider the influence of the structural characteristics of the disconnector and the operation mode on the accuracy of the simulation results, so the simulation results are directly different from the actual measurement results [11,12]. The cause of VFTO is closely related to the arc discharge process that occurs due to multiple breakdowns across the contact gap of the disconnector. The dynamic characteristics of the high-frequency arc have an important influence on the amplitude–frequency characteristics of the transient overvoltage. Therefore, when constructing the simulation model, accurately describing the dynamic characteristics of the high-frequency arc becomes a key factor in improving the simulation accuracy [13]. It is worth noting that the characteristic parameters of VFTO show obvious random dispersion, and its electromagnetic interference intensity is far beyond the current level of electromagnetic compatibility standards [14]. Although domestic and foreign scholars have accumulated a large number of transient interference data through field tests, there are still deficiencies in waveform feature identification, statistical law analysis, and analysis of the impact of various factors on the interference level. It is difficult to provide data support for the optimization design of the electromagnetic interference immunity of power equipment and for the research and development of simulated electromagnetic interference sources in disconnectors.

This research employs the ATP-EMTP simulation platform to model disconnector switching operations. The developed simulation framework incorporates five key functional modules: arc reignition modeling, arc extinction simulation, arc termination algorithm, switching control logic, and dynamic arc resistance regulation. Model validation is achieved through a systematic comparison between simulation outputs and experimental measurements, particularly referencing conventional modeling approaches. Subsequently, transient characteristics were analyzed, yielding significant findings regarding the statistical distributions of four critical parameters: single-pulse maximum peak value, duration, voltage rise time, and inter-pulse interval.

2. Theoretical Basis of the Model

2.1. Analysis of Problems in Existing Models

At the initial stage of the disconnector's opening operation, the disconnector has not yet separated, and the voltages on both sides of the switch are equal, i.e., $U_S(t) = U_L(t)$. Once the disconnector contacts are fully separated, the source-side voltage follows the sinusoidal waveform of the power frequency. Due to the slow decay of residual charge, the load-side voltage retains the value it held just before arc extinction. The difference between the source-side and load-side voltages represents the recovery voltage across the disconnector gap, i.e., $\Delta U = U_S(t) - U_L(t)$. According to the gas discharge theory, the breakdown characteristics of the disconnector contact gap are determined jointly by the recovery voltage and the breakdown voltage of the gap.

During the opening operation of the disconnecter, the contact gap experiences dozens to hundreds of repeated breakdowns. Each breakdown triggers the ignition and extinction of an arc, causing a sharp voltage drop across the gap within nanoseconds and generating extremely steep voltage surges and traveling waves. These waves superimpose on the power-frequency voltage on the source side and on the residual voltage on the load side, forming transient overvoltage waveforms on both sides. Since the disconnecter contacts are not perfectly symmetrical, the breakdown voltage across the gap varies with polarity. In general, the breakdown voltage increases with the contact gap distance, and accordingly, the amplitude of VFTO also increases.

As shown in Figure 1, $U_S(t)$ denotes the source-side voltage, $U_L(t)$ denotes the load-side voltage, $S(t)$ represents the distance between the disconnecter contacts, and $U_B(t)$ represents the breakdown voltage across the gap.

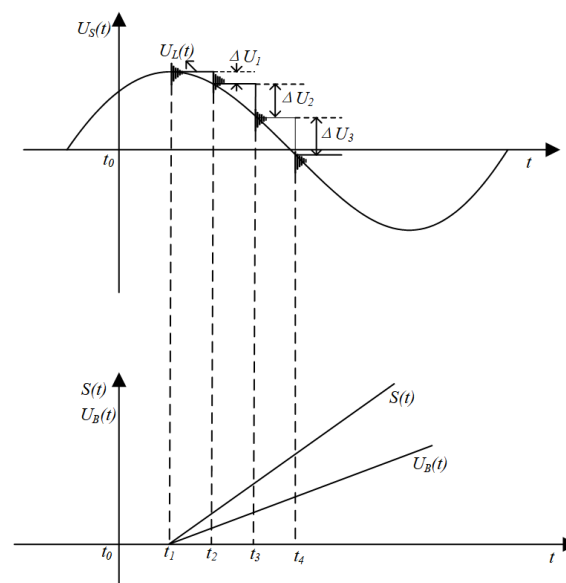


Figure 1. Relationship between repeated disconnecter breakdown events and corresponding breakdown voltages.

Specifically, the amplitude characteristics of VFTO are closely related to the breakdown process of the contact gap. Although existing modeling methods can simulate single breakdown events under opposite polarity conditions at the source and load sides, they fail to consider the influence of the breakdown characteristics of the contact gap and the dynamic behavior of arc resistance on the breakdown process. Current single and multiple breakdown arc models generally divide the discharge process into three stages: pre-breakdown, stable arcing, and arc extinction. However, these models still present significant limitations in practical applications. Firstly, during disconnecter operation, there is a lack of clear criteria for identifying gap breakdown and arc extinction, making it difficult to accurately determine the transitions into the pre-breakdown and arc extinction stages. Secondly, existing models are unable to accurately simulate the variation trend of arc resistance during the stable arcing stage. These issues hinder the ability of current arc models to accurately describe the dynamic evolution of the arc throughout the disconnecter operation process.

Research on VFTO mainly focuses on the simulation modeling of the arc of the disconnecter. The accurate arc model is an important factor affecting VFTO research. At present, the commonly used arc models are mainly divided into fixed resistance arc model, time-varying arc resistance model, segmented arc resistance model, spark model, and black box model [15]. The constant resistance model is based on the ideal switching model, and

the arcing process is equivalent to a constant resistance of 2~5 Ω . However, the model cannot simulate the nonlinearity of the arc. Compared with the actual arcing process, there is still a lot of error, which is only suitable for simple calculations in engineering [16]. The time-varying arc resistance model considers the transition from pre-breakdown to arcing during a single breakdown of the disconnecter gap, but ignores the change in arc resistance during the arc extinguishing process, so it cannot accurately describe the change in arc resistance during a single breakdown [17]. In order to solve the above problems in the arc model, Reference [18] proposed a segmented arc model, which further considers the actual change trend of the resistance of the arc during the combustion process and divides the arc combustion process into three stages: pre-breakdown, stable arcing, and arc extinguishing. However, the judgment of the three stages of the model is very vague, and the assumption that the arc development always follows is too ideal.

In addition, for single arc models, analysis is typically limited to the most severe arcing scenarios, which cannot fully represent the transient waveforms generated during the entire disconnecter operation process. Moreover, most single arc models only perform dynamic simulation of the arc's equivalent resistance, without considering the influence of arc inductance, gap capacitance, and other factors on the simulation results. In a comprehensive model design, arc reignition criteria, arc extinction criteria, and switch state transitions are essential components of the complete arc reignition logic for a disconnecter. Although dynamic reignition arc models address the continuity of arc resistance and are capable of simulating the entire disconnecter operation process, they still suffer from certain issues related to phase division, program logic design, and the theoretical calculation of arc resistance.

2.2. Improved Simulation Approach for Full-Process Arc Modeling of Disconnecter Operation

VFTO waveforms are formed by the superposition of hundreds of individual breakdown events. Each breakdown generates a waveform exhibiting damped oscillation characteristics, with a typical duration ranging from several to several tens of microseconds. Since the interval between successive breakdowns is usually on the millisecond scale, individual breakdown events within a VFTO waveform can be considered non-overlapping. Most existing arc models for disconnectors focus primarily on the macroscopic characteristics of arc resistance, while neglecting the microscopic discharge processes. Experimental studies have shown that the variation trend of arc impedance during disconnecter operation can be equivalently represented by arc resistance, arc inductance, and gap capacitance. Based on existing dynamic arc models and multiple reignition arc models, this paper proposes an improved approach by incorporating the dynamic variation of arc resistance, arc inductance, and gap capacitance. The single breakdown process is divided into three stages: arc pre-breakdown, stable arcing, and arc extinction. In addition, criteria are introduced to determine both the occurrence of gap breakdown and the end of arc extinction. The overall disconnecter operation is modeled as a cyclic repetition of these three stages.

In the simulation, a single breakdown event in the disconnecter can be equivalently represented by the model shown in Figure 2: $R(t)$ represents the arc resistance, describing the time-varying impedance during the breakdown, L denotes the arc inductance, and C represents the gap capacitance. The dashed region in the figure indicates the breakdown stage, modeled as a series connection between arc resistance and inductance. In the arc pre-breakdown stage, a voltage difference exists between the disconnecter contacts and can be represented by a capacitive model. Once the models for each stage are defined, the complex transient process during disconnecter operation can be fully simulated by setting the corresponding start and end criteria for each stage.

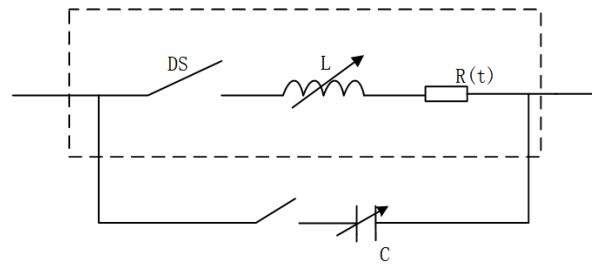


Figure 2. Equivalent model of a single breakdown event in the disconnector.

Considering the influence of arc resistance, arc inductance, and gap capacitance of the disconnector, the equivalent circuit for analyzing the electromagnetic transient process during contact gap breakdown is shown in Figure 3. In Figure 3, the equivalent arc model of the disconnector is indicated by a dashed box. R_S represents the arc resistance between the disconnector contacts, L_S denotes the arc inductance, and C_S represents the capacitance between the contacts. R_1 , L_1 , and C_1 correspond to the equivalent resistance, inductance, and capacitance of the source-side circuit of the disconnector, respectively, while R_2 , L_2 , and C_2 correspond to those of the load-side circuit. When no breakdown occurs across the disconnector contact gap, the power-frequency source forms an energy storage loop through the inductive and capacitive components of the system. At this stage, the contact gap can be modeled as capacitance C_S . Once breakdown occurs across the contact gap, its electrical characteristics change significantly. The discharge path is then equivalent to a time-varying resistance R_S in series with inductance L_S , which together form a parallel network with capacitance C_S . This model effectively describes the dynamic impedance characteristics of the gap after breakdown, as well as the flow path of high-frequency transient currents.

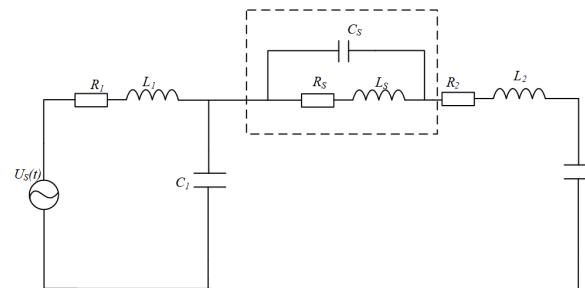


Figure 3. Equivalent circuit model.

2.2.1. Dynamic Arc Resistance Equivalence

During the arc pre-breakdown stage, the arc resistance rapidly decreases from the pre-arc resistance value to a stable arcing resistance value within an extremely short period. The transition from pre-breakdown to stable arcing in the disconnector gap exhibits significant time-varying characteristics and typically occurs within a few nanoseconds. To more accurately describe the dynamic behavior of the arc, a hyperbolic arc resistance model is adopted in the pre-breakdown stage to characterize the variation in arc resistance. In this model, the arc resistance drops sharply following the breakdown but does not immediately reach zero; instead, it gradually approaches steady-state arcing resistance. The expressions for arc resistance during the pre-breakdown and stable arcing stages are as follows:

$$R_a(t) = \begin{cases} R_0, t = 0 \\ Z_0 \left(\frac{t_\delta}{t} - 1 \right) + r_0, 0 < t < t_\delta \\ r_0, t_\delta < t \end{cases} \quad (1)$$

In the above expressions, R_0 denotes the initial breakdown resistance of the gap, approximately $1 \times 10^{12} \Omega$; r_0 represents the steady-state arcing resistance, which is set to 2Ω in this paper; Z_0 is the sum of the wave impedance of the disconnector line and that of the conducting rod; and t_δ indicates the breakdown delay time.

During the arc extinction stage, considering the influence of the recovery voltage, the complete Mayr arc model is typically adopted. The arc conductance equation of the Mayr model is given by

$$\frac{1}{g_m} \frac{dg_m}{dt} = \frac{1}{\theta_m} \left(\frac{i^2}{P_0 g_m} - 1 \right) \quad (2)$$

In this equation, g_m and θ_m represent the arc conductance and the time constant of the Mayr arc model, i is the arc current, P_0 denotes the power loss under steady-state conditions, and t is time.

2.2.2. Transient Capacitance Equivalence

During the steady-state stage of disconnector operation, the duration typically ranges from several hundred nanoseconds to several tens of milliseconds. During this period, the disconnector remains in the process of operation, and as the contacts continue to move, the variation trend of the gap capacitance and stray capacitance can be expressed by the following equation:

$$C_t = \left(73.741 - \frac{0.6278}{t_c + 0.01096} \right) \times 10^{-12} \quad (3)$$

In this equation, C_t is the gap capacitance of the disconnector, where $t_c = \left\{ \frac{d}{v} - t \right\}$, t is the duration of the disconnector operation process, in seconds; v is the movement speed of the moving contact during disconnector operation, in meters per second; and d is the initial distance between the moving and fixed contacts, in meters.

In the steady-state stage, the arc between the contacts of the disconnector is extinguished, and there is a gap between the two contacts. With the change in the power supply side voltage, the isolation switch gap will produce a voltage difference. It is worth noting that the steady-state phase of the disconnector lasts for a relatively long time, generally up to hundreds of ns or even tens of ms. During this process, the disconnector is still in the operation process, and its disconnector contact produces displacement. Therefore, in the steady-state stage, the value of the contact gap capacitance and the disconnector ground capacitance will change with the gap distance d , which should be regarded as the capacitance of the size change. The fracture capacitance is actually an energy storage element, and there is a buffer and delay in the release of energy. Therefore, the single VFTO peak does not necessarily appear on the first peak under the isolation switch model, considering the capacitance effect. The peak value of VFTO in the disconnector model considering the capacitance effect is higher, the rise time of VFTO is shorter, and the steepness is larger. The main reason is that the fracture capacitance under the disconnector model is used as an energy storage element. Compared with the model without considering the capacitance, the energy storage is higher. The larger the energy, the higher the VFTO amplitude generated, and the faster the rising speed.

2.2.3. Transient Inductance Equivalence

During the arcing stage of the disconnector operation, the value of arc inductance changes dynamically with the evolution of the arc. This section takes into account the real-time dynamic variation in arc inductance. The arc channel inductance in the transient arc stage of the disconnector is modeled using the empirical Martin formula, as expressed in the following equation:

$$L \approx 2d_L \ln(b/a) \approx 14d_L \quad (4)$$

In this equation, L is the equivalent inductance, in nanohenries (nH); d_L is the arc channel length, in centimeters (cm); and a and b represent the radii of the discharge channel and the return conductor, respectively, also in centimeters (cm). In practical arcing scenarios, the values of a , b , and d_L vary dynamically. The arc inductance can therefore be described by the relationship between inductance and arc channel length. The discharge channel length can be approximately considered the real-time distance between the moving and fixed contacts of the disconnecter. Thus, the time-dependent variation in arc channel inductance during the opening and closing operations of the disconnecter can be expressed by the following equation:

$$\begin{cases} L_{op} = 14v_{op}t \\ L_{cl} = 14(d_0 - v_{cl}t) \end{cases} \quad (5)$$

In this equation, L_{op} and L_{cl} represent the real-time equivalent inductance during the opening and closing processes, in microhenries (μH); v_{op} and v_{cl} represent the velocity of the moving contact during the opening and closing processes, in meters per second (m/s); and d_0 represents the initial distance between the moving and fixed contacts of the disconnecter, in meters (m).

2.3. Critical Breakdown Criteria for Disconnecter Contact Gap

During the operation of the disconnecter, the phenomenon of arc reignition after arc extinction is determined by the relationship between the recovery voltage and the gap breakdown voltage. Specifically, when the recovery voltage exceeds the critical breakdown voltage, the gap will be re-broken down, forming a new discharge path; otherwise, it will remain in the open state. This process repeats until the contacts reach a fully closed or open state. Taking the disconnecter closing process as an example, according to gas discharge theory, in the early stage of closing, because the contact distance is large, the gap breakdown voltage of the switch is significantly higher than the actual voltage it is subjected to, so the switch remains in the open state. As the contacts gradually move closer, the gap distance continues to decrease. When the contact distance reaches a certain critical value, the actual voltage across the gap exceeds the breakdown voltage, causing gas molecules to collide and ionize, forming a discharge path through the gap and ultimately completing the gap breakdown.

Reference [6] analyzes and fits the breakdown voltages under different contact gaps, showing that the breakdown voltage and the switch gap length maintain an approximately linear relationship. Based on this finding, this paper adopts the simplified algorithm from Reference [19] to model multiple breakdown processes during disconnecter operation, assuming that

$$\text{During opening operation, } U_b(t) = Evt \quad (6)$$

$$\text{During closing operation, } U_b(t) = E(d_0 - vt) \quad (7)$$

In the equation, E represents the breakdown voltage per unit length of the switch gap, v represents the operating speed of the switch, d_0 represents the distance between the switch contacts, and t represents time.

3. Establishment of the Whole Process Model of the Disconnecting Switch

3.1. Functional Modules of the Complete Disconnecter Operation Model

Currently, the Electromagnetic Transients Program (EMTP-ATP) is widely used for transient process calculations. This program establishes accurate and reliable models based on theory, allowing for convenient modeling and simulation, and has become the primary

tool for overvoltage calculations in power systems. Figure 4a–d, respectively, represent the reignition arc module, arc extinction module, arc resistance control module, and switch control module in the complete disconnector simulation model.

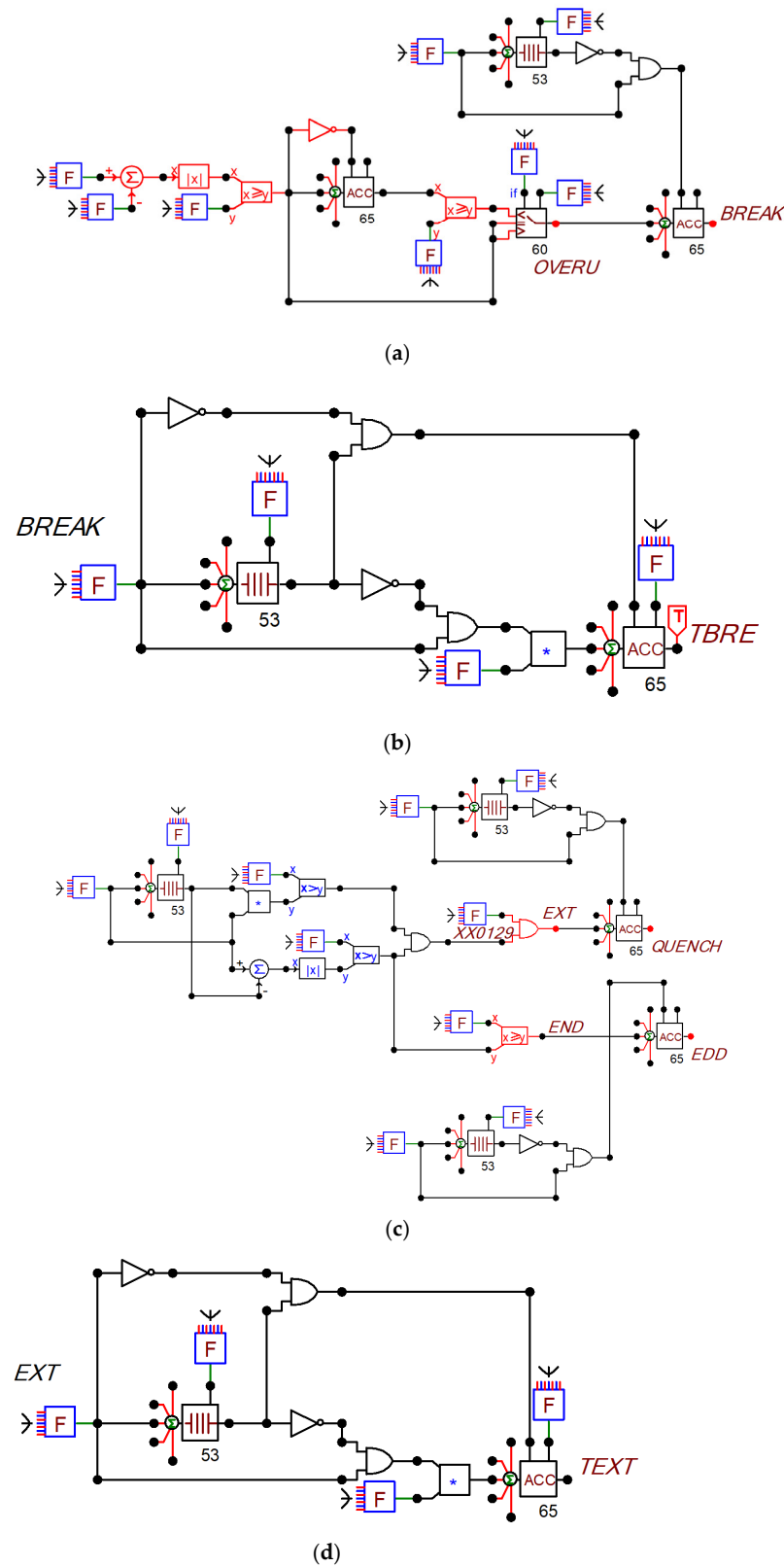


Figure 4. Simulation model of each module in the entire process of disconnecting switch operation. (a) Reignition arc module. (b) Burning arc time recording module. (c) The arc extinguishing module. (d) Aoff time recording module.

The core function of the reignition arc module is to determine whether the gap voltage during the disconnecter's opening and closing operations exceeds its insulation withstand level. This module works in coordination with the arc extinction module to control the conduction state of the circuit. When constructing a short-gap reignition arc model, criteria for re-breakdown must be defined, along with key parameters such as the disconnecter's operating speed and the gap breakdown voltage per unit length. The reignition arc module obtains the real-time recovery voltage (ΔU) and calculates the critical breakdown voltage of the gap (U_b). Comparing the two determines whether breakdown has occurred. If $\Delta U > U_b$, it indicates that a gap breakdown has occurred, and an arc ignition command is sent to both the switch control module and the arc resistance control module. Upon receiving the ignition signal, the switch control module performs the closing operation, while the arc resistance control module adjusts the resistance accordingly. At the natural current zero-crossing instant, the arc ignition command is immediately terminated.

In configuring the arc extinction module of the disconnecter, this study introduces an arc extinction termination determination mechanism based on traditional extinction criteria. The core function of this module is to determine the extinction state of the arc following a single breakdown. Once it is confirmed that the arc extinction process has been fully completed, the system maintains the switch in an open state until the next gap breakdown occurs. When constructing the arc extinction module, this study introduces a differential criterion: When the absolute value of the current difference $|I_t - I_{(t-\Delta t)}|$ between adjacent time steps is less than a preset threshold K , the current zero-crossing can be determined. This dual-criterion approach can effectively identify the moment of current zero-crossing and provides a reliable basis for accurately determining the entry into the arc extinction phase. When the absolute value of the monitored current signal $|I_t|$ is lower than a preset threshold I_k , the arc extinction process is deemed to be complete. Subsequently, the system enters a steady-state condition until the next dielectric breakdown occurs.

The arc resistance control module regulates the resistance variation in each stage. After a breakdown occurs in the disconnecter gap, the programming code for the hyperbolic arc model during the arc pre-breakdown and stable arcing stages, as well as the Mayr arc model expression for the arc extinction stage, is stored in the Models module. At the same time, the arcing signal from the restrike arc module and the arc extinction signal from the arc extinction module are also transmitted into the Models module, establishing the connection between the arc resistance control module, the restrike arc module, and the arc extinction module, thereby realizing the dynamic adjustment of arc resistance values in different stages.

The switch control module receives the breakdown arcing signal and arc extinction completion signal sent by the restrike arc module and arc extinction module, respectively, achieving the purpose of controlling the switch state.

3.2. Functional Coordination Logic of Each Module

By integrating the restrike arc module, arc extinction module, arc resistance control module, and switch control module, the logical coordination among these functional modules is illustrated in Figure 5. The process is as follows: When the disconnecter begins to close, the voltage between its two contacts and the air breakdown voltage are transmitted in real time to the restrike arc module. If the breakdown condition is met, a restrike signal is sent to the arc resistance control module and the switch control module. At this point, a breakdown occurs across the contact gap, and the switch control module outputs a closing command to drive the closing operation of the disconnecter in the model. The formation of the arc causes the arc resistance to enter the arcing stage. As the current passes through the arc extinction module, it continuously determines whether the arc extinction conditions are met. If the conditions are satisfied, an arc extinction signal is sent to the arc resistance control

module, and the arc resistance equation for the extinction stage is used for calculation. When the current decreases to the preset value IKI_KIK, the arc extinction process ends. An end signal is then sent to the switch control module, which issues an opening command, causing the disconnecter to open. At this time, the arc resistance remains unchanged until the next breakdown occurs.

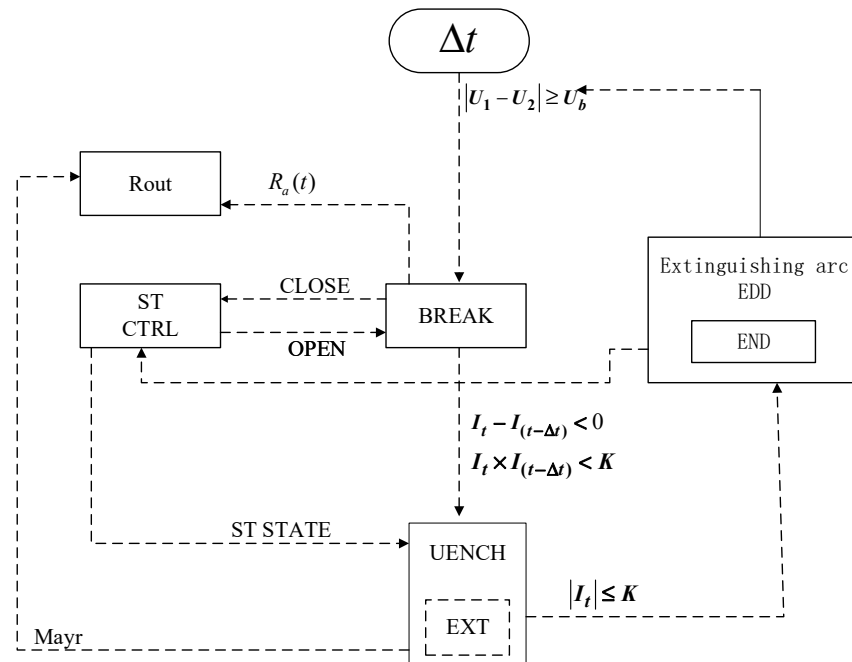


Figure 5. Logic coordination of each module.

3.3. Simulation of the Entire Disconnecter Operation Process

According to the frequency range classification of the International Large Power Grid Conference (CIGRE), the isolating switch operation process belongs to the field of fast wavefront overvoltage [20]. According to the CIGRE standard, when building the simulation model for the bus in the main circuit, the lossless uniform transmission line model can be replaced by the wave impedance. The power-side ground capacitance and the load of the small current can be used equivalently. According to the parameters of commonly used open isolation switch equipment and theoretical calculations, the main component parameters used in the simulation are shown in Table 1.

Table 1. Equivalent models and parameters of the main components.

Element	Parameter Declaration
Aerial conductor	T1 = 4.5 m, wave impedance 266 Ω, wave speed 300 m/μs T2 = 3 m wave impedance at a 121 Ω wave velocity of 300 m/μs
Power supply side to ground capacitor capacitive divider	6300 pF 411 pF, variable ratio of 2000:1
Dynamic and static contact guide wave impedance	130 Ω
Potential transformer	1000 pF
Load capacitor	10,000 pF

At the same time, according to the test circuit and the corresponding parameters, considering the inductive and capacitive effects during the isolating switch operation, the

simulation model is built in the ATP-EMTP electromagnetic transient simulation program. The main circuit of the simulation model is shown in the Figure 6.

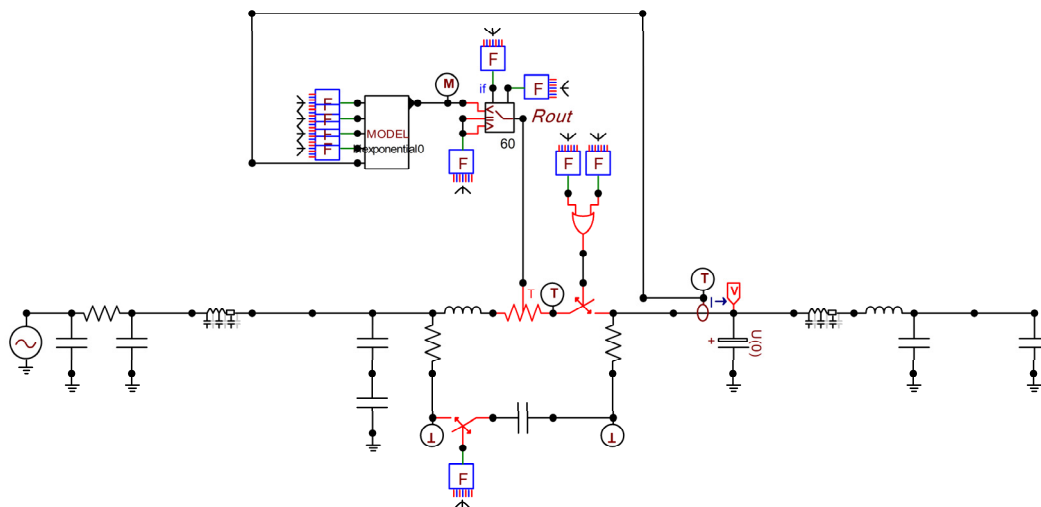


Figure 6. Simulation of the main circuit model.

The arc resistance control module and switch control module are located in the main circuit, which includes operating power supply, overhead line distribution parameters, switch-to-ground capacitor, arc-to-ground capacitor, arc combustion resistance, disconnecting switch, transformer collector capacitor, and load capacitor, so as to simulate the actual line operation. A Models module is designed within the arc resistance control module to program the hyperbola and Mayr arc resistance model and to connect the rekindled arc module, arc extinguishing module, and switch control module to control the resistance value of the arc resistance at different stages. Rout is the dynamic arc resistance value of the whole process of the disconnecting switch operation. The switch control module realizes control of the whole circuit by receiving the arc ignition or arc extinguishing signal from the reignition arc module and the arc extinguishing module. ST is the switch state. The arc channel inductance and clearance capacitor adopt the variable inductance and capacitor components combined with the programming module, and the logic control module is executed according to the time step control program and model.

Through the above model parameter settings, the VFTO waveforms of the transient process during the isolating switch closing operation are shown in Figure 7. The transient voltage waveform is presented in a step-like form, with each step representing a breakdown. The maximum overvoltage amplitude in the simulation results is 114.67 kV.

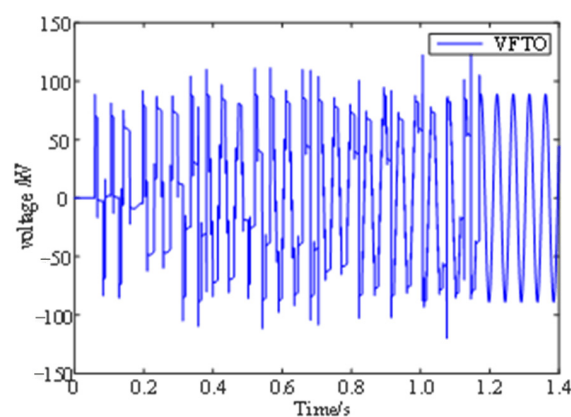


Figure 7. VFTO waveforms of the transient process during the isolating switch closing operation.

4. Experimental Validation and Comparison

4.1. Test Verification

To verify the accuracy of the proposed simulation model for the entire disconnecter operation process, this study adopts a combined approach of experimental testing and simulation. Based on actual line parameters, a capacitive low-current test circuit for the disconnecter was constructed, as shown in Figure 8, to simulate the electromagnetic interference generated during disconnecter operation and to obtain VFTO waveform data. The measured results were compared and analyzed against the simulation data to validate the accuracy of the developed model.

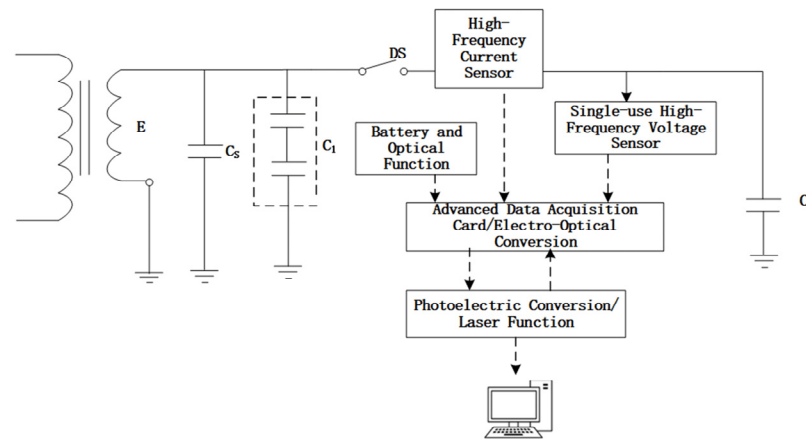


Figure 8. A 110 kV disconnecter operation test system.

E represents the operating power supply voltage of 220 V; C_s denotes the power supply side capacitance; capacitor voltage divider C_1 is used to monitor the voltage in the test circuit. DS is the isolation switch, and C_L represents the load capacitance, which is used to simulate the ground capacitance of the no-load short bus during actual operation. A high-frequency voltage and high-frequency current sensor, a high-speed acquisition card, and other devices are used to measure and collect the voltage and current signals during the test. In order to ensure the stability and reliability of data transmission and ensure the safety of operation, photoelectric isolation is adopted between the high-speed acquisition card and the computer.

As shown in Figure 9, due to the relatively slow speed of the disconnecter contact movement during the entire closing process, the contact gap experiences tens or even hundreds of breakdowns, leading to the presence of many transient single-pulse waveforms with decaying oscillation characteristics in the VFTO macro waveform. The waveform generally transitions from sparse to dense, and the amplitude decreases. This is because, at the initial stage of closing, the large gap distance requires a higher voltage to initiate breakdown, which makes it more difficult for breakdown to occur. whereas in the opening process, the situation is the opposite.

The test system operates at a voltage level of 110 kV, and the base value is selected for calculation:

$$1pu = 110 \times \frac{\sqrt{2}}{\sqrt{3}} = 89.81 \text{ kV} \quad (8)$$

The maximum amplitude of VFTO is 118.67 kV (about 1.32 p.u.).

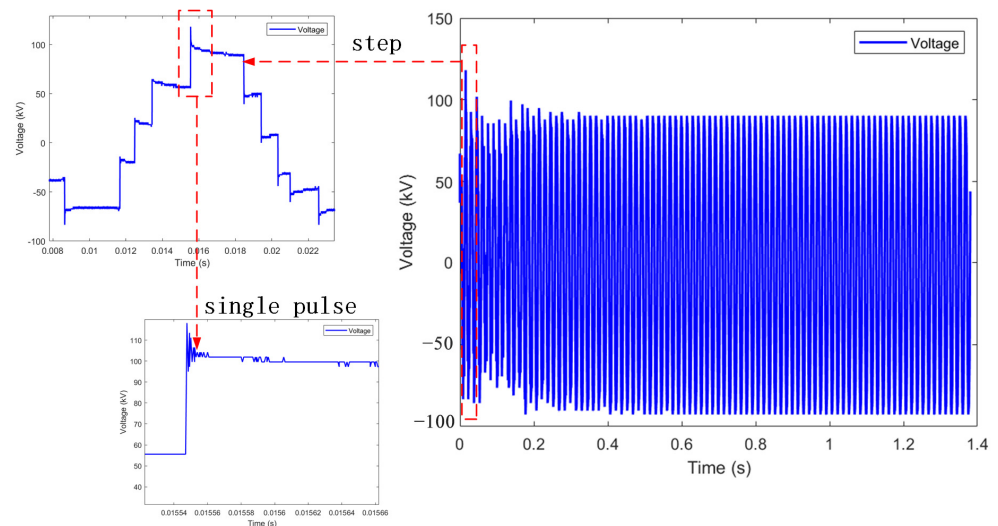


Figure 9. The test waveform of the entire VFTO process.

4.2. Comparison of Test and Simulation Waveforms

In order to compare the improvement effect of the model presented in this paper, the dynamic resistance model proposed by article [21] is integrated into the main circuit of this study. The VFTO waveforms obtained using the same parameter settings are shown in Figure 10, and the maximum overvoltage amplitude is 130.36 kV (about 1.45 p.u.).

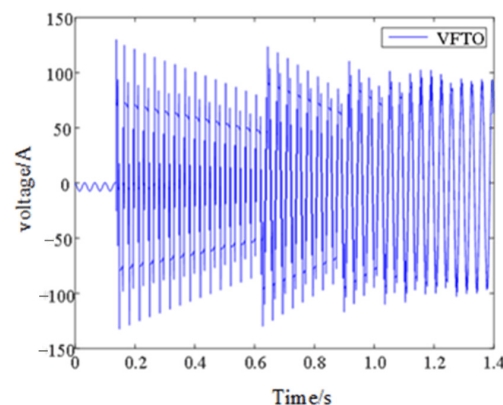


Figure 10. The VFTO simulation waveform when considering only the dynamic resistance model.

The VFTO maximum amplitude obtained from the test is 118.67 kV (about 1.32 p.u.), while the VFTO maximum amplitude from the model proposed in this paper is 114.67 kV (about 1.27 p.u.), with an error rate of 3.49%. The VFTO maximum amplitude obtained by considering only the dynamic resistance is 130.36 kV (about 1.45 p.u.). From this, it can be concluded that the simulation model proposed in this paper is closer to the experimental results in terms of both maximum amplitude and macro waveform trends. Additionally, the simulation waveforms in this paper better reflect the randomness of the disconnector operation. In comparison, the dynamic resistance model's simulation waveform deviates significantly from the experimentally obtained waveform.

The simulation and measured waveforms at the VFTO peak during the isolating switch closing operation are shown in Figure 11. It can be observed that the VFTO simulation waveform is in good agreement with the experimental waveform, with the variation patterns of the simulation and experimental waveforms being roughly the same.

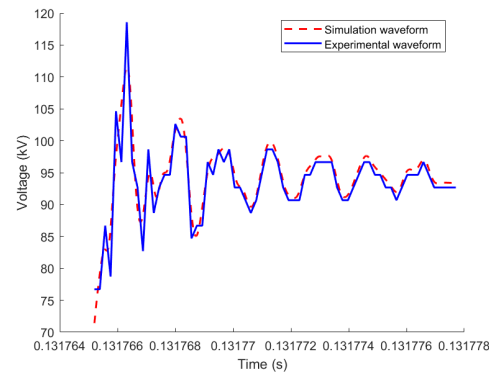


Figure 11. Comparison of the VFTO simulation and the experimental maximum peak single pulse.

The frequency spectrum analysis of the VFTO full waveform data from the isolation switch operation simulation model is shown in Figure 12a,b. It can be observed that the frequency band of the VFTO waveform is primarily distributed within 15 MHz, with the main frequency distributions of both the VFTO experimental and simulation waveforms being very similar. The main frequency distribution occurs in the following ranges: 1.49 MHz, 2.26 MHz, 6.2 MHz, 7.09 MHz, 8.26 MHz, 9.16 MHz, and 11.23 MHz. The difference lies in the fact that the simulation data also shows additional main frequencies at 2.99 MHz, 6.67 MHz, and 12.09 MHz. This discrepancy is mainly due to the presence of high-frequency noise in the transient overvoltage during the experimental process. To enhance the reliability of the data, noise reduction was applied to the experimental data, which led to the filtering out of shorter pulse signals. In contrast, the simulation data did not undergo noise reduction, allowing it to capture the shorter pulse processes and thus resulting in a richer main frequency distribution.

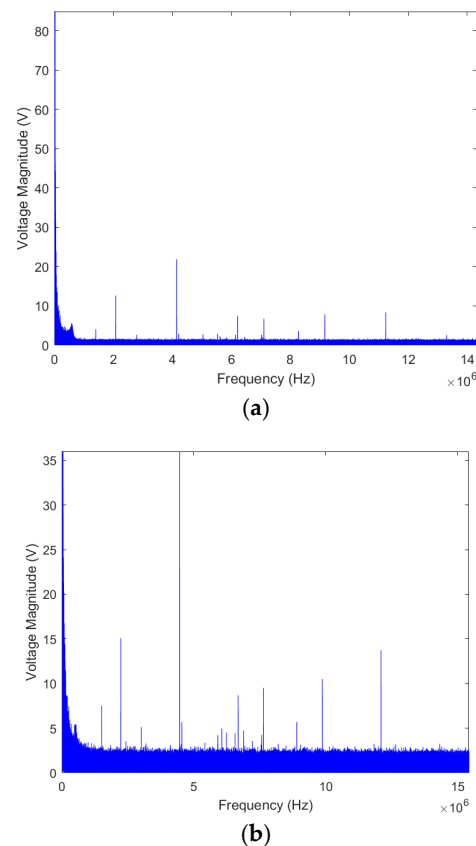


Figure 12. Main frequency distribution of VFTO from the experiment and simulation. (a) Main frequency distribution of VFTO from the experiment. (b) Main frequency distribution of VFTO from the simulation.

In summary, compared with the experimental waveform, the VFTO waveform obtained through simulation shows a similar trend in terms of both the macro waveform and the individual pulse waveform. This indicates that the simulation results in this study accurately reflect the VFTO waveform during the operation of the disconnecter. Therefore, this validates the effectiveness of the proposed simulation model for the disconnecter operation process.

5. Statistical Analysis of Single-Pulse Special Parameters

The disconnecter has a large dispersion during operation, and it is difficult to describe the distribution law of VFTO single-pulse waveform characteristic parameters using a standard distribution model. In contrast, kernel density estimation (KDE) can obtain the probability density distribution according to the characteristics of the sample data and does not need to make any assumptions about the distribution of the sample data [22–24]. In conclusion, the kernel density estimation method is used to estimate the distribution of single-pulse characteristic parameters, providing the frequency distribution of each parameter, the estimated optimal kernel probability density distribution, and the evaluation results.

$$f_h(x) = \frac{1}{nh} \sum_{i=1}^n K\left(\frac{x - X_i}{h}\right) \quad (9)$$

where X_i is a given sample data point, h is the window width and a non-negative constant; $K(\cdot)$ is a kernel function.

There are many kinds of kernel functions. In view of the fact that the data generally obey the Gaussian distribution, the more commonly used Gaussian (Gaussian) kernel density function is used, and the probability density function is expressed as follows:

$$K(\cdot) = \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{x^2}{2}\right) \quad (10)$$

The selection of the bandwidth h is crucial for the accuracy of kernel density estimation. Whether the kernel density estimation can estimate the sample well depends on the value of the window width h . If the value of h is too small, the result will be unstable; if the value of h is too large, the discrimination rate of the result will be very low. As for the selection of window width, the algorithms for calculating the optimal window width based on different error formulas are different [25]. Mean integrated squared error (MISE) is used to obtain the optimal window width. Among them, MISE is based on the principle of minimum square difference to measure the difference between the estimated density and the true density to obtain the window width. The specific expression is as follows:

$$\text{MISE}(f_h(x)) = E\left[\int \{f_h(x) - f(x)\}^2 dx\right] = \int [E f_h(x) - f(x)]^2 dx + \int \text{var} f_h(x) dx \quad (11)$$

In the formula, $E(\cdot)$ is the expectation, $f_h(x)$ is the true probability density function of the sample data, and $\text{var}(\cdot)$ is the variance.

By solving the equation, the optimal window width can be obtained when $\text{MISE}(f_h(x))$ takes the minimum value.

This subsection makes a statistical analysis of the duration, rise time, time interval, and the number of single pulses.

5.1. Maximum Peak Value of Single Pulse

When analyzing VFTO, special attention should be paid to its high-amplitude characteristics. Therefore, the maximum peak voltage of VFTO can be considered a key character-

istic parameter. The statistical results of the single-pulse maximum peak under simulation and experimental conditions during switching operations are shown in Table 2.

Table 2. Statistical results of single-pulse maximum peak values.

Item	Simulated Single-Pulse Maximum Peak	Experimental Single-Pulse Maximum Peak
Amplitude/kV	[9.97, 114.69]	[9.49, 120.47]
Average Value/kV	66.93	59.68

As shown in Table 2, the distribution range of the single-pulse maximum peak voltage obtained from the simulation during switching operations is [9.97, 114.69] kV, with an average peak value of 66.93 kV. In comparison, the experimental results show a distribution range of [9.49, 120.47] kV, with an average maximum peak of 59.68 kV. Further statistical analysis of the single-pulse peak values of VFTO generated during disconnecter closing operations reveals that the frequency distribution and KDE of the maximum peaks under optimal bandwidth settings are illustrated in Figure 13a,b, respectively. The optimal bandwidths for the KDE models of the single-pulse rise time are 9.629 and 7.958. Both the simulation and experimental results indicate that the distribution of the single-pulse maximum peaks does not follow a normal distribution or a unimodal distribution; instead, it exhibits a bimodal distribution pattern. Moreover, the distribution ranges of the maximum peaks obtained from the simulation and experiment are generally consistent, with the majority of values concentrated within the range [9.49, 79.78] kV, accounting for 84.35%.

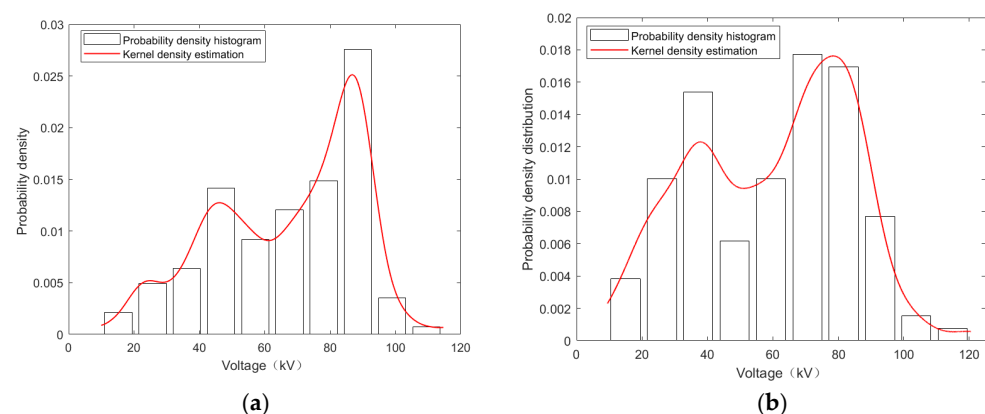


Figure 13. Comparison of maximum peak value of single-pulse and optimal kernel density distribution during closing. (a) Maximum peak and kernel density distribution of single pulses from simulation during closing operation. (b) Maximum peak and kernel density distribution of single pulses from the experiment during closing operation.

5.2. Duration

The duration of a single pulse refers to the time from the beginning of the pulse waveform to the end of the oscillation. The statistical results of single-pulse durations under simulation and experimental conditions during switching operations are shown in Table 3.

Table 3. Statistical results of single-pulse duration.

Item	Simulated Single-Pulse Duration	Experimental Single-Pulse Duration
Duration/ μ s	[0.12, 20.87]	[0.05, 19.4]
Average Value/ μ s	1.61	2.52

As shown in Table 3, the distribution range of single-pulse durations obtained from the simulation during switching operations is $[0.12, 20.87] \mu\text{s}$, with an average duration of $1.61 \mu\text{s}$. In contrast, the experimental results show a distribution range of $[0.05, 19.4] \mu\text{s}$, with an average duration of $2.52 \mu\text{s}$. Further statistical analysis of the single-pulse durations of VFTO generated during disconnecter closing operations reveals that the frequency distribution and kernel density estimation (KDE) under optimal bandwidths, as shown in Figure 14a,b, respectively. The optimal bandwidths for the KDE models of single-pulse duration are 0.774 and 0.854. Both the simulation and experimental results indicate that the single-pulse durations mainly exhibit a unimodal distribution, with most durations concentrated in the range of $[0.09, 0.23] \mu\text{s}$, accounting for 92.24% and 85.82%, respectively.

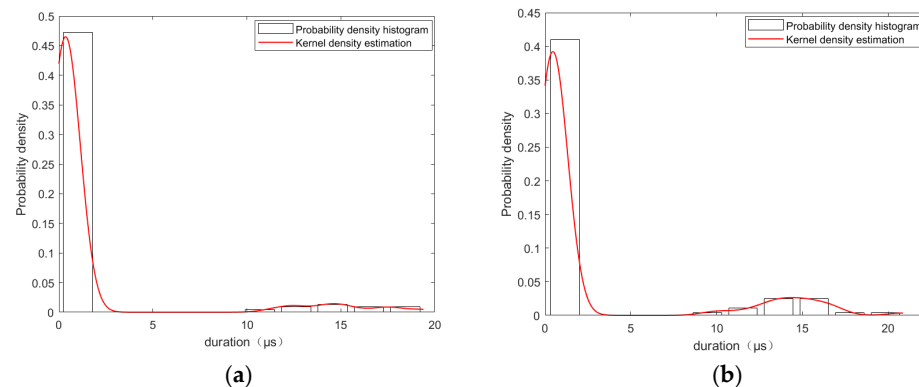


Figure 14. Comparison of single-pulse durations and optimal kernel density distributions during closing operation. (a) Duration and kernel density distribution of single pulses from simulation during closing operation. (b) Duration and kernel density distribution of single pulses from the experiment during closing operation.

5.3. Up Time

The VFTO single-pulse waveform generally exhibits a decaying oscillation characteristic, and the amplitude typically does not appear within the first oscillation cycle. To facilitate statistical analysis, the rise time of a single pulse is defined as the time required for the waveform amplitude to rise from 10% to 90% of its peak value. The distribution range of the single-pulse rise times, as obtained from the statistical analysis, is shown in Table 4.

Table 4. Statistical results of single-pulse up time.

Item	Simulated Single-Pulse Up Time	Experimental Single-Pulse Up Time
Up Time/ μs	$[0.54, 8.70]$	$[0.43, 8.64]$
Average Value/ μs	1.72	1.55

As shown in Table 4, the distribution range of single-pulse rise times obtained from the simulation during switching operations is $[0.54, 8.70] \mu\text{s}$, with an average rise time of $1.72 \mu\text{s}$. The experimental results show a distribution range of $[0.43, 8.64] \mu\text{s}$, with an average rise time of $1.55 \mu\text{s}$. Further statistical analysis of the single-pulse rise times of VFTO generated during disconnecter closing operations reveals the frequency distribution and kernel density estimation (KDE) under optimal bandwidths, as shown in Figure 15a,b. The optimal bandwidths for the KDE models of the single-pulse rise time are 0.275 and 0.254, respectively. Moreover, the rise time distribution ranges obtained from the simulation and experiment are generally consistent, with the majority of rise times concentrated in the range of $[0.36, 5.26] \mu\text{s}$, accounting for 94.88% and 93.02%, respectively.

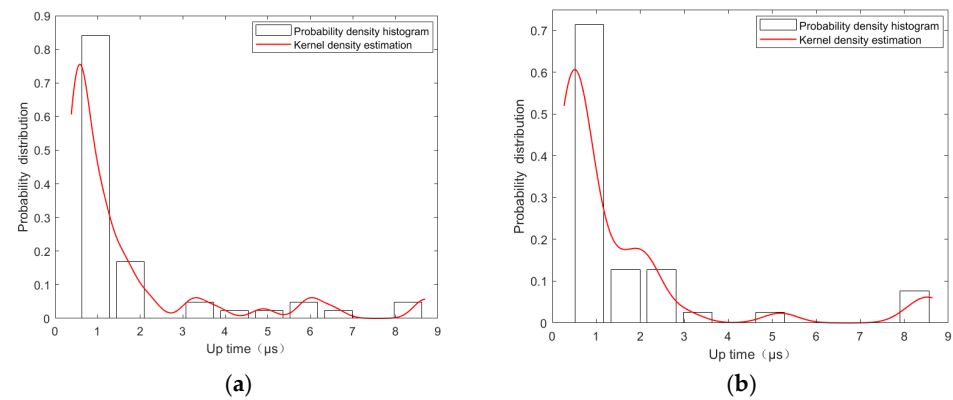


Figure 15. Comparison of single-pulse up time and optimal kernel density up time during closing operation. (a) Up time and kernel density distribution of single pulses from simulation during closing operation. (b) Up time and kernel density distribution of single pulses from the experiment during closing operation.

5.4. Interval Time

The single-pulse interval time refers to the difference between the occurrence times of two adjacent pulses. The statistical results indicate that the VFTO single-pulse interval time during switching operations mainly falls within the millisecond range. Therefore, it can be assumed that the two VFTO breakdown events are temporally independent and do not overlap. The statistical results are shown in Table 5.

Table 5. Statistical results of single-pulse interval time.

Item	Simulated Single-Pulse Interval Time	Experimental Single-Pulse Interval Time
Interval Time/ms	[0.04, 4.98]	[0.06, 5.10]
Average Value/ms	0.61	0.65

Figure 16 shows the frequency distribution of single-pulse interval times obtained from simulation, along with the kernel density distribution under the optimal bandwidth. The statistical results indicate that the optimal bandwidths for the rise time probability density distribution models obtained from simulation and experiment are 0.256 and 0.219, respectively. Furthermore, the interval times obtained from both simulation and experiment exhibit a unimodal distribution, and the distribution ranges are generally consistent. The majority of interval times are concentrated in the range of [0.06, 1.74] ms, accounting for 94.83% and 93.72%, respectively.

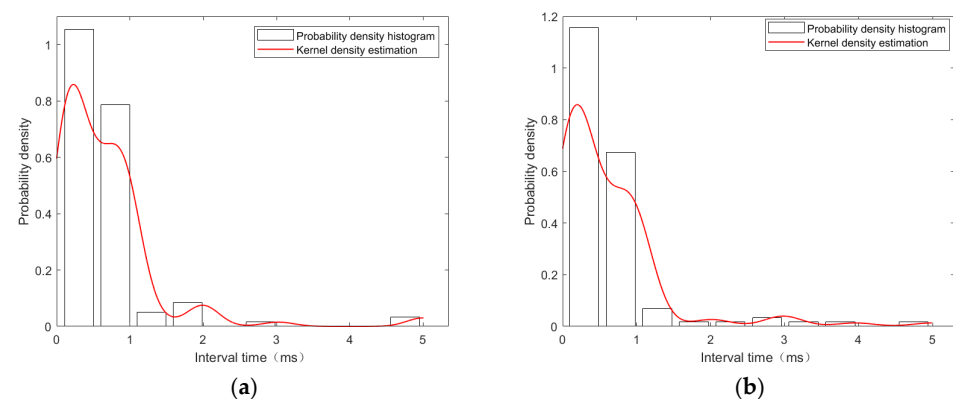


Figure 16. Comparison of single-pulse interval times and optimal kernel density distributions during closing operation. (a) Interval time and kernel density distribution of single pulses from simulation during closing operation. (b) Interval time and kernel density distribution of single pulses from the experiment during closing operation.

6. Conclusions

This paper presents a comprehensive model of disconnecter operation, designed by analyzing the functions of the arc module, arc extinction module, arc resistance control module, and switch control module, along with the calculation logic of each module. Compared to the actual measured transient waveforms, the results show that the simulation results from the proposed model are consistent with the tested characteristics, demonstrating the correctness and accuracy of the proposed simulation model. The results indicate that the proposed model can be applied to transient operation simulations, providing a more accurate model for the study of transient electromagnetic interference. To further validate the model's accuracy, this paper compares and analyzes the transient waveform characteristics of both the experiment and the simulation, extracts key parameters, and constructs probability density functions. The comparison results reaffirm the model's high-precision fitting ability. The statistical distribution pattern of VFTO single-pulse characteristics has been clarified. The research findings offer a more convenient approach for studying the transient processes caused by disconnecter operation, reducing the human and material resources consumed by actual measurements and testing analysis, making the process safer and more economical.

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