

Article

Research on Ultra-Fast Transient Overvoltage Characteristics of Electric Locomotive

Yike Guo, Fuqiang Tian *, Hongqi Liu and Yufeng Yin

School of Electrical Engineering, Beijing Jiaotong University, Beijing 100044, China; 22121450@bjtu.edu.cn (Y.G.); a221261982024@163.com (H.L.); 22126249@bjtu.edu.cn (Y.Y.)

* Correspondence: fqtian@bjtu.edu.cn

Abstract: Operating overvoltage occurs when the pantograph or main breaker of an electric locomotive is operated, which is prone to causing insulation failure of high-voltage equipment. The HXD1 electric locomotive is taken as the research object in this paper to explore the characteristics and influencing factors of operating overvoltage. Under pantograph lifting, main breaker closing, main breaker opening, and pantograph dropping, operating overvoltage waveform in the high-voltage system is recorded by a high-speed oscilloscope and resistance–capacitance voltage divider to analyze the overvoltage characteristics and distribution law. Tested data show that the amplitude of operating overvoltage is in the range of 80 to 330 kV with ultra-high steepness, which is similar to the Very Fast Transient Overvoltage (VFTO) in power systems. The maximum overvoltage during the entire test occurred during the main breaker closing and its amplitude is 328.60 kV with a steepness of 4.21×10^4 kV/ μ s. The max overvoltage of the other operations (pantograph lifting, main breaker opening, and pantograph dropping) are 280.60 kV, 194.73 kV, and 305.56 kV with ultra-high steepness. High-amplitude overvoltage is predominantly located at the pantograph, while the low-amplitude sort is mainly observed around other high-voltage equipment. The result indicates that operating overvoltage belongs to ultra-fast transient overvoltage and its amplitude and steepness are higher than existing research.

Keywords: HXD1 electric locomotive; ultra-fast transient overvoltage; high-frequency signal test; electromagnetic transient process



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1. Introduction

The pantograph–catenary system is the core power of an electric locomotive. Connection or disconnection between the locomotive and the catenary is achieved through the pantograph and the main breaker operation. In this process, relative motion between the pantograph and the catenary contact is accompanied by arc combustion. The pantograph–catenary arc is a kind of discharge phenomenon. High-frequency electromagnetic transients during arc combustion induce operating overvoltage, resulting in serious accidents of high-voltage equipment. On 25 February 2017, a high-voltage transformer on an HXD2B electric locomotive exploded while driving, wherein both of the pantograph carbon contact strips presented the arc traces caused by overcurrent [1]. In 2020, in an electric locomotive that had been in operation for 5 years, it was reported that the catenary voltage exceeded the limit value; the power supply for traction was interrupted and the high-voltage transformer exploded by discharging and its primary winding was seriously damaged (as shown in Figure 1) [2]. Furthermore, the operating overvoltage may lead to abnormal increase in vehicle body potential [3], combustion of discharging gap [4], and so on, which pose a serious threat to the safe and stable operation of high-voltage equipment in electric locomotives. Therefore, it is of great significance to study the operating overvoltage characteristics of electric locomotives to reveal the internal mechanism of high-voltage equipment failure.



Figure 1. Damage and explosion accidents of high-voltage equipment on electric locomotive.

In order to analyze the formation mechanism of the fault of the high-voltage equipment on the roof of the locomotive, and to study whether these accidents are caused by the ultra-fast and high-amplitude transient operating overvoltage, domestic and foreign scholars have tested the operating overvoltage by various methods.

Wu employed a resistance–capacitance voltage divider and data recorder to test the catenary overvoltage of CRH2 EMU during pantograph lifting and dropping, and main breaker opening and closing. The results showed that the amplitude of the operating overvoltage of the catenary was in the range of 40 kV to 70 kV [5]. Ma used voltage divider tape recording equipment and memory oscilloscope to test the overvoltage of pantograph jumping and main breaker closing and opening. The results show that the pantograph jump overvoltage was in the range of 1.24~3.97 p.u., with an oscillation frequency of 1.12 kHz. The overvoltage was not measured during the closing process, the maximum overvoltage generated during the opening process was 7.40 p.u. and its pulse width was 2.32 μ s [6]. Liu used a PCI-5112 data-acquisition card with a real-time sampling rate of 100 MS/s to obtain the overvoltage test signal from the secondary side of the train transformer, and conducted a test on the pantograph dropping overvoltage. The test results show that the pantograph dropping overvoltage can reach more than 60 kV, and its high-frequency components are concentrated between 200 and 400 kHz [7]. Wang used an HS5 data-acquisition card with a sampling rate of 200 MS/s to obtain the overvoltage signal from the transformer installed next to the pantograph of the CRH5 A EMU. The test results show that the maximum value of pantograph overvoltage can reach 67.10 kV, and the maximum amplitude of operating overvoltage of the main circuit breaker is 138.97 kV [8]. Chen used the capacitive divider and the calculus circuit as the sensing unit, and used the Tektronix DPO 7000 series oscilloscope (Tektronix, Basel, Switzerland) with a sampling rate of 5 GSa/s to test the VFTO in GIS. The measured VFTO overvoltage multiple can reach up to 2.70 p.u. and the UHF component in the waveform can reach up to 100 MHz [9].

In the existing research, the test signal was collected from the secondary terminal of the voltage transformer, which led to signal attenuation and distortion. The sampling range of the test system is at the MHz level, which makes it difficult to capture the high-frequency component of the operating overvoltage, but the overvoltage often exists in the high-frequency component, so the test results are not enough to reveal the mechanism of high-voltage equipment failure. It can be seen from ref. [9] that the sampling rate of the measurement system required for the VFTO-type ultra-fast transient overvoltage test is at the GHz level, and it is possible to measure high-frequency components and high-amplitude and high-steep overvoltage signals above 100 MHz. Therefore, on the basis of the existing research, the accuracy of the test results can be improved by changing the sampling rate and signal-collection method of the test system.

In this paper, an operating overvoltage test of the HXD1 electric locomotive is carried out. A resistance–capacitance voltage divider and a high-speed digital-storage oscilloscope with a sampling rate of up to 2 GSa/s are used as the test system to obtain the overvoltage signal directly from the high-voltage equipment of the electric locomotive, and the overvoltage waveforms of four operations are recorded: the pantograph lifting and

dropping, and the opening and closing of the main circuit breaker. The test obtained an operating overvoltage with a maximum value exceeding 10 times the power frequency voltage (27.5 kV 50 Hz) and a steepness exceeding 10,000 kV/ μ s. This is very different from the amplitude and steepness of the existing overvoltage test, and its value is far higher. The formation mechanism of high-amplitude and high-steepness switching overvoltage and its distribution in high-voltage equipment are analyzed and discussed.

2. Test Scheme

Many on-site investigations have found that when the electric locomotive is in operation, the arc phenomenon will occur with abnormal noise, and a huge overvoltage will be generated in a very short time, which results in serious accidents of high-voltage equipment. However, the amplitude of the previous research is relatively low, which is not enough to explain the problem of serious failure of high-voltage equipment. Therefore, starting from the experiment, based on the shortcomings of the existing experiments, this paper improves the means in a targeted manner, eliminates the interference of other electromagnetic signals in the test, the insufficient sampling rate of the equipment and other defects, using the high-speed oscilloscope to directly obtain the signal from the high-voltage equipment. This means that a new measurement system is needed. The following is an introduction of this measurement system.

2.1. Testing System

To record the operating overvoltage of the HXD1 electric locomotive, a testing system is designed in this paper, consisting of high-voltage dividers, a high-speed data-storage oscilloscope and other equipment, as shown in Table 1.

Table 1. Test equipment.

Equipment Name	Specification
Resistance–capacitance voltage divider	ratio 1:1000
Capacitive voltage divider	ratio 1:2016
Attenuating probe	$\times 1/\times 10, \times 10:600$ Vpk
HBM data recorder	20 Msa/s
High-speed digital oscilloscope	2 Gsa/s
Signal line	some

Figure 2 shows the circuit connection of the field test. The voltage divider A is arranged at the pantograph of vehicle A, while the voltage divider B is installed near different high-voltage equipment as the test proceeded. The overvoltage is transmitted from the high-voltage equipment to the voltage divider high-voltage terminal. The signal output from the low-voltage terminal is transmitted to the high-speed oscilloscope. In the testing process, high-frequency signals are directly captured by a high-voltage resistance–capacitance divider rather than the secondary side of the transformer (the standard GB/T 16927.2 [10] states that it is recommended for the measurement system to be connected directly across the ends of the test specimen). Compared with the traditional recorder with a low sampling rate, a high-speed digital-storage oscilloscope with a high sampling rate can avoid the lack of high-frequency data. Therefore, this testing system can restore the actual waveform of operating overvoltage to the greatest extent.

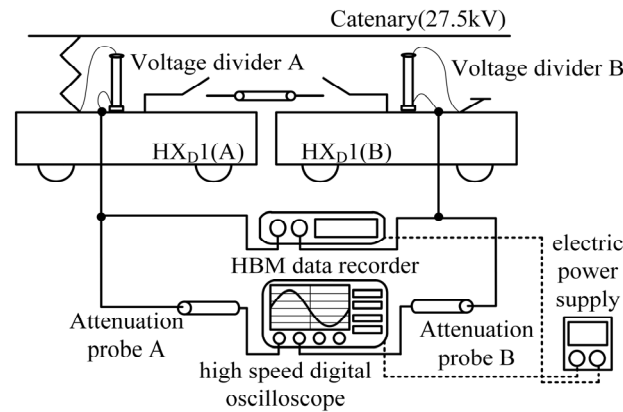


Figure 2. Structure of operating overvoltage-measurement system on electric locomotive.

2.2. Testing Contents

The test includes four kinds of operation processes of HXD1 electric locomotive: pantograph lifting, main breaker closing and opening, and pantograph dropping. In addition to testing the overvoltage of the pantograph, the overvoltage waveforms of the other high-voltage equipment items on the roof of the electric locomotive are recorded at the same time to study the distribution law of overvoltage of the high-voltage equipment. The test points included pantograph, main breaker, and high-voltage insulation sleeving (test points are shown in Figure 3).

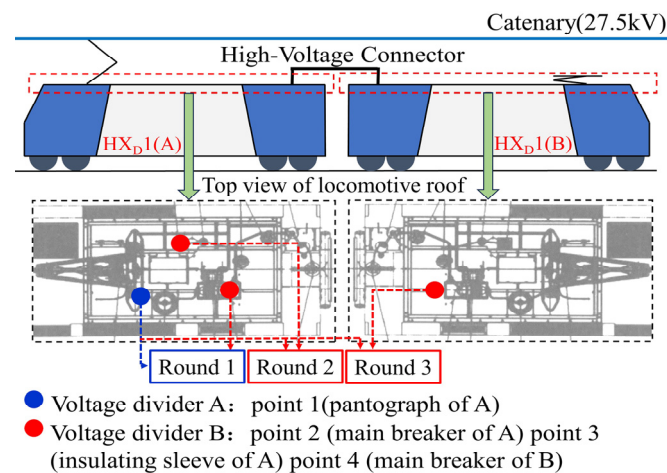


Figure 3. Setting of measurement points on the roof of electric locomotive for operating overvoltage test.

The specific steps of the test are as follows: Firstly, two voltage dividers are installed at the setting test points, respectively. Divider A is set near the pantograph of vehicle A and divider B is arranged at points 2, 3, 4 in sequence. During each operation, the oscilloscope synchronously collected the output waveforms of two voltage dividers at different points. Each round of test is repeated three times according to the operation sequence as shown in Figure 4. At the end of a test round, divider B is moved to the new point for the next round.

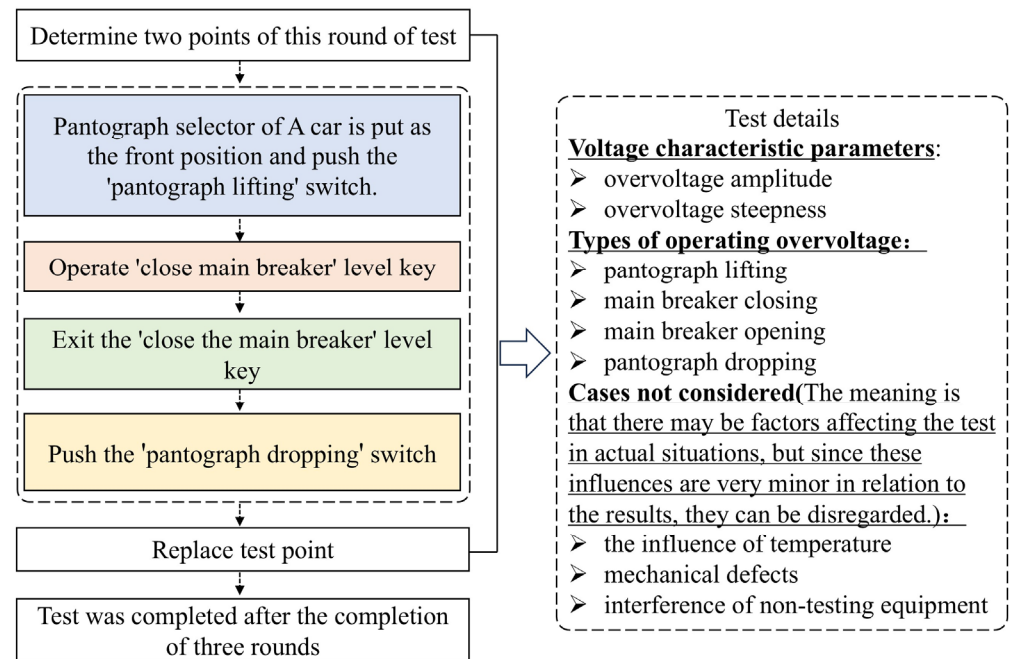


Figure 4. Test flow and details.

3. Testing Results

Tables 2–4 list the overvoltage amplitude in different rounds. For divider A, the trigger level of the high-speed oscilloscope is set as 51.60 kV, and it turns out to be 5.10 kV for divider B. ‘/’ indicates that the oscilloscope is not triggered, or the tested overvoltage on the high-voltage terminal is lower than the trigger level.

Table 2. Results of the first round of test (unit: kV).

Operation	Pantograph Lifting		Main Breaker Closing		Main Breaker Opening		Pantograph Dropping	
Test Point	1	2	1	2	1	2	1	2
1	155.72	7.41	112.43	7.39	155.09	50.15	222.46	8.03
2	176.16	7.41	328.60	46.22	132.72	49.28	210.13	8.75
3	146.63	6.75	315.10	40.02	194.73	50.12	209.54	8.75

Table 3. Results of the second round of test (unit: kV).

Operation	Pantograph Lifting		Main Breaker Closing		Main Breaker Opening		Pantograph Dropping	
Test Point	1	3	1	3	1	3	1	3
4	237.52	8.72	/	/	/	/	273.89	10.00
5	169.85	7.40	99.14	40.31	/	/	181.00	7.39
6	280.60	11.45	94.99	35.03	85.62	32.85	206.49	9.41

Table 4. Results of the third round of test (unit: kV).

Operation	Pantograph Lifting		Main Breaker Closing		Main Breaker Opening		Pantograph Dropping	
Test Point	1	5	1	5	1	5	1	5
7	193.47	11.60	/	/	/	/	253.70	15.97
8	185.23	10.74	90.78	40.54	/	/	236.33	13.40
9	184.63	10.17	103.40	43.90	/	/	305.60	18.16

According to the field test results, the operating overvoltage amplitude of point 1 is between 112.40 kV and 328.60 kV, while test points 2, 3, 4 are relatively low, only in the

range of 46.80 kV to 50.20 kV. To further study the relationship between the operational conditions and the overvoltage amplitude, Table 5 summarizes the peak overvoltage and steepness of the four operations in all test rounds.

Table 5. Peak amplitude and steepness of the four operating overvoltages.

Operation	Point 1		Point Number	Synchronous Point	
	Voltage (kV)	Steepness (kV/ μ s)		Voltage (kV)	Steepness (kV/ μ s)
Pantograph lifting	280.60	2.31×10^4	3	11.45	9.39×10^2
Main breaker closing	328.60	4.21×10^4	2	46.22	3.02×10^1
Main breaker opening	194.73	1.57×10^4	2	50.12	6.60×10^{-1}
Pantograph dropping	305.60	5.79×10^4	3	18.16	2.58×10^2

It shows that the peak overvoltage occurs during the main breaker closing process, where the amplitude is up to 328.60 kV and the corresponding steepness is 39,470.00 kV/ μ s. During the pantograph lifting and main breaker closing operation, the overvoltage steepness range is 25,000.00~40,000.00 kV/ μ s, which is much higher than that of the main breaker opening and pantograph dropping operation (5000.00~22,000.00 kV/ μ s). The field test results of the overvoltage are 2~3 times higher than existing research results, and the steepness is about 10^6 times higher than current studies. Such high-amplitude and high-steepness operating overvoltage poses a serious threat to the insulation of high-voltage equipment of electric locomotives.

In the standard GB/T 24837-2009 [11], the operating overvoltage is defined as a voltage with a wavefront time of 250 μ s and a half-peak time of 2500 μ s. In the standard IEC 60071-4 [12], VFTO is defined as the time to rise to the first peak in the range of 3 ns to 100 ns, the frequency of the fast oscillation part in the range of 0.3 MHz to 100 MHz, and the amplitude as high as 300.00 kV. In this paper, the characteristics of the test data are closer to the high-amplitude and high-steepness characteristics expressed by VFTO, so it can be considered that the measured overvoltage is a very fast transient overvoltage existing in the high-voltage system of the electric locomotive.

Figure 5 shows the corresponding overvoltage waveforms based on data in Table 5. Since there is a main breaker among test points 2, 3, 4 and test point 1, the equivalent capacitance of the vacuum gap between the breaker contacts is small, and the equivalent impedance is large. Thereby, the overvoltage transmission is effectively blocked, resulting in a much smaller overvoltage amplitude of test points 2, 3, 4 than test point 1.

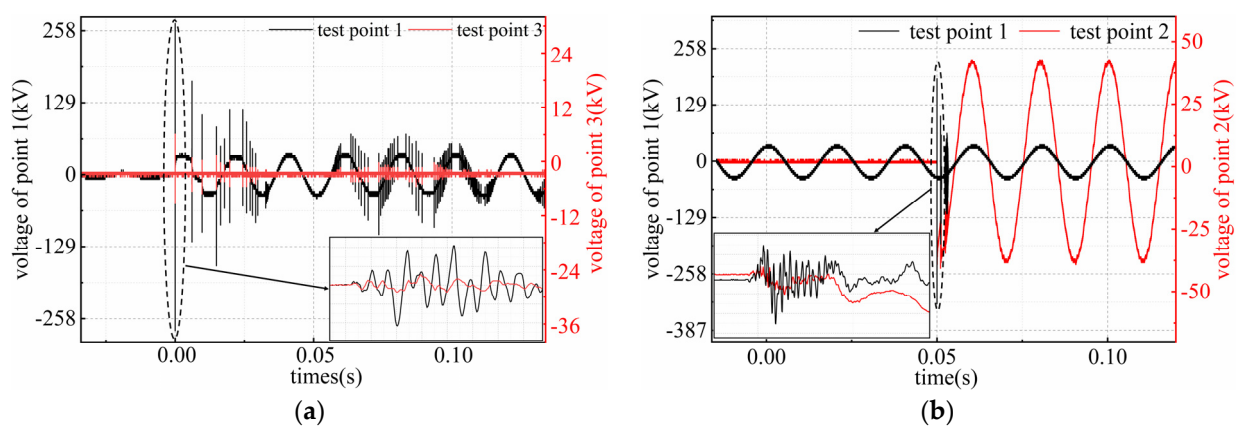


Figure 5. Cont.

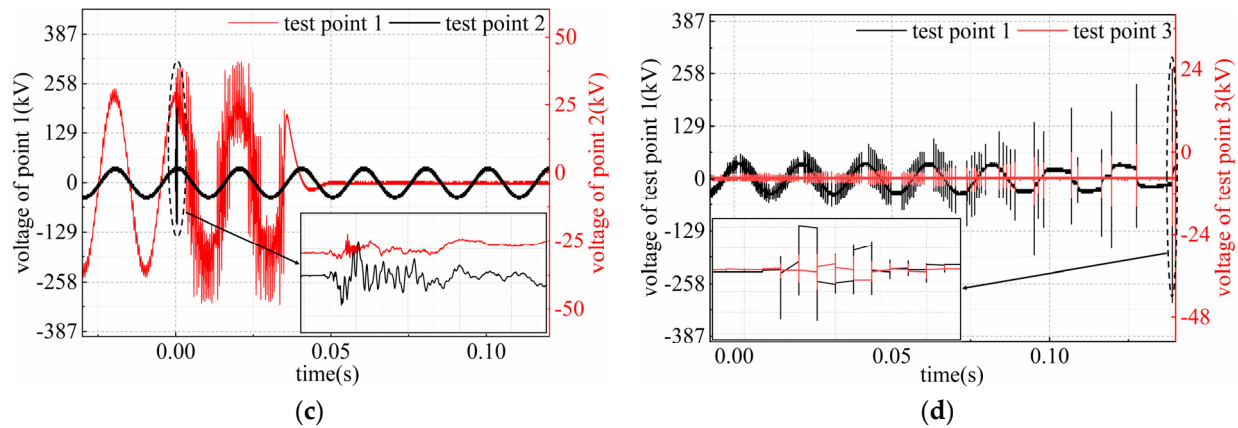


Figure 5. The global graph and fractionated gain figure of the four operating overvoltages. (a) Pantograph lifting. (b) Main breaker closing. (c) Main breaker opening. (d) Pantograph dropping.

In Figure 5a,d, there are multiple arc reignition phenomena in the overvoltage waveform during the pantograph lifting and dropping process. During the pantograph lifting, the peak overvoltage usually appears in the first arc stage and the overvoltage amplitude of arc reignition decreases along with time. During the pantograph dropping, the overvoltage amplitude gradually increases with the development of the arc, reaching the peak at the last arc reignition.

As shown in Figure 5b,c, the operating overvoltage occurs when the catenary phase is near 90° . Due to the short operation time of the main breaker contacts, the arc has not been able to develop fully, and the arc multiple reignition is avoided. Therefore, the multiple overvoltage oscillation caused by the arc reignition cannot be observed in the waveform of the main breaker.

4. Analysis and Discussion

4.1. Formation Mechanism of High-Amplitude and High-Steepness Operating Overvoltage

Very fast transient overvoltage (VFTO) refers to the transient overvoltage phenomenon with a very short wavefront time (about 3~20 ns) caused by disconnector operation in the power system, whose amplitude can exceed 2.50 p.u. [13]. As shown in Figure 6, the detailed waveform of VFTO is similar to the operation overvoltage in Section 2, both of which are ultra-fast transient overvoltage in the power system.

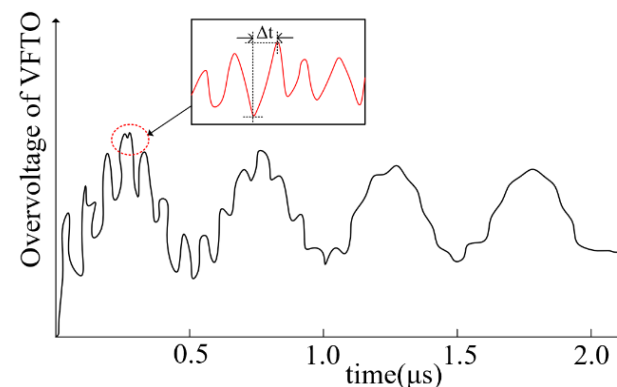


Figure 6. Typical VFTO waveform caused by disconnector closing.

The formation mechanism of VFTO is equipment in GIS (Gas Insulated Switchgear) and works in a slightly inhomogeneous electric field. When the disconnector or main breaker is in operation, the electric field of the air gap changes accordingly. Once the gap breakdown condition is satisfied, equipment will undergo multiple pre-breakdowns and re-breakdowns in SF_6 gas, resulting in very fast transient overvoltage. The overvoltage

transmits along the electric wires on both sides of breaker, thus affecting the internal equipment of GIS. The formation mechanism of operating overvoltage in electric locomotives is similar to VFTO. It is found that the overvoltage waveform is also equipped with the characteristics of high amplitude and high steepness. Because it can be found in the test results that the operating overvoltage has the same high-amplitude and high-steepness characteristics as VFTO, it should be regarded as the ultra-fast transient overvoltage of the high-voltage system of the electric locomotive and the electromagnetic transient process should be fully considered instead of only considering the arc between the pantograph and the catenary.

(1) Arc theory

The locomotive operating overvoltage is often accompanied by the arc phenomenon, and the corresponding formation condition is that the gap electric field is stronger than that of the air breakdown. The formation and development process of the arc is depicted in Figure 7. In the initial stage, the atoms in the gas are ionized by the electric field. As the field strength continues to increase, free electrons accelerate and collide continuously, resulting in more atoms ionizing and forming an electron avalanche. In this process, the energy is gradually accumulated, leading to the partial heating and expansion of the air gap and the formation of a plasma [14]. Finally, the arc is formed when the plasma region penetrates the pantograph–catenary poles.

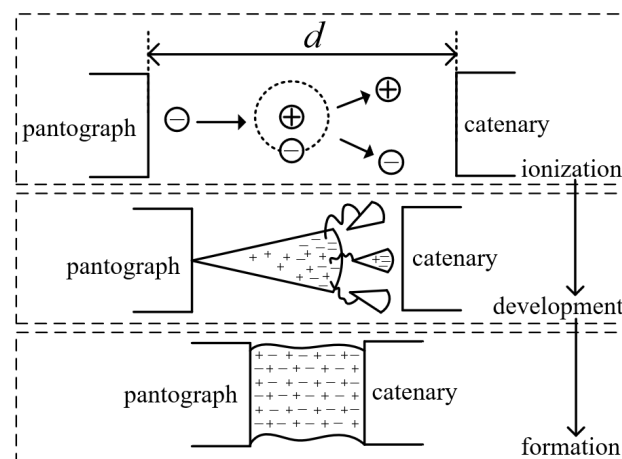


Figure 7. Development process of pantograph–catenary arc.

The expression of arc resistance R_{arc} is:

$$R_{arc} = R_0 e^{-1/T} + r \quad (1)$$

It is illustrated that R_{arc} varies with time T ($3 \text{ ns} \leq T \leq 20 \text{ ns}$), where the arc resistance value is reduced from R_0 (a few megaohms) to r (0.5Ω).

The arc will extinguish after the arc current crosses zero, and there is no conductance between the contacts. Therefore, the voltage-recovery process and the dielectric strength-recovery process are individual in the arc gap. If the arc gap voltage recovery speed is larger than the dielectric strength recovery speed, re-breakdown will occur and the arc reignites. Therefore, the AC arc-reignition condition is the voltage-recovery speed and is larger than the dielectric strength-recovery speed after the first arc extinguishing. As shown in Figure 8, u_3 represents the arc gap voltage, and the strength of the arc gap changes according to u_2 . Then, after point A, $u_3 > u_2$, the gap will be reignited due to the breakdown, and the voltage between the contacts will be converted to the arc voltage u_4 [15].

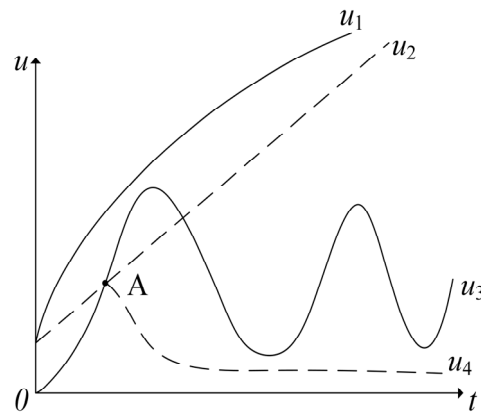


Figure 8. Reignition and extinction condition of arc.

(2) Formation Mechanism of Overvoltage induced by Arc

Burning, extinguishing, and reignition of the arc changes the circuit structure and circuit parameters. The rapid exchange of electromagnetic energy between the capacitance and inductance components induces complex electromagnetic oscillation. This oscillation will produce a transient overvoltage which is much higher than the normal operating voltage. It is impulsive and strong damping, usually decaying within a few milliseconds to tens of milliseconds [14].

The higher the system-rated voltage, the higher the amplitude of operating overvoltage. For 220 kV and below systems, considering the cost of equipment and the probability of high-voltage accidents, the insulation of electrical equipment is designed according to 3~4 times the rated voltage. When the ultra-fast transient overvoltage with high amplitude and high steepness happens frequently, serious accidents on high-voltage equipment are hard to avoid.

(3) Formation Mechanism of Ultra-Fast Transient Overvoltage Caused by Pantograph Lifting and Main Breaker Closing

The process of pantograph lifting and main breaker closing involves contact connection, which can be classified as a closing operation. Figure 9a shows the equivalent circuit of the pantograph lifting process. The amplitude of operating overvoltage can be calculated by establishing an equivalent circuit [16]. Taking the pantograph lifting process as an example. The closing operation of the switch is used to represent the closing process between the pantograph and the catenary. L_0 and R_0 represent the equivalent inductance and resistance of the catenary. $u(t)$ is the catenary voltage. L_m is the equivalent excitation inductance of the high-voltage transformer and C_0 is the equivalent ground capacitance of the post-stage circuit. For simplicity, the catenary resistance and transformer inductance are ignored, as shown in Figure 9b.

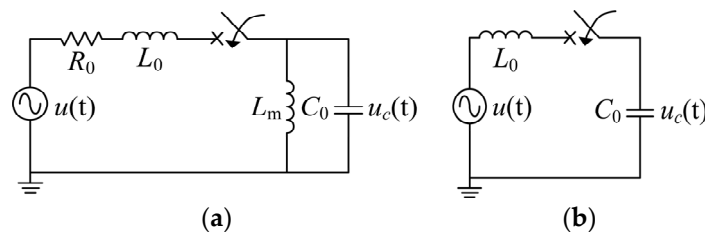


Figure 9. Pantograph lifting equivalent circuit. (a) Equivalent circuit; (b) simplified circuit.

The circuit equation of pantograph lifting is:

$$L_0 C_0 \frac{d^2 u_c}{dt^2} + u_c = U_m \sin(\omega t + \varphi) \quad (2)$$

By solving (2):

$$u_c(t) = \frac{\frac{1}{\omega C_0} \cdot U_m \sin(\omega t + \varphi)}{\frac{1}{\omega C_0} - \omega L_0} + A \cos(\omega_0 t) + B \sin(\omega_0 t) \quad (3)$$

In (3), U_m is the amplitude of the power supply voltage, φ is the initial phase angle, A and B are the integral constants. Among them, $\omega_0 = 1/(L_0 C_0)^{1/2}$ and $\omega L_0 \ll 1/(\omega C_0)$. Suppose that the initial conditions are as follows:

- (1) Before the pantograph lifting, the voltage of the residual charge on the catenary is U_0 .
 $u_c(0) = U_0$ when $t = 0$.
- (2) The current does not mutate due to inductance in the circuit, when $t = 0$, $i_c(0) = 0$.

Substituting the initial conditions into (3), the capacitor voltage $u_c(t)$ is derived as:

$$u_c(t) = U_m \sin(\omega t + \varphi) + (U_0 - U_m \sin \varphi) \cos \omega_0 t - \frac{\omega U_m \cos \varphi}{\omega_0} \sin \omega_0 t \quad (4)$$

If $\omega_0 \gg \omega$, the maximum capacitance voltage U_{cmax} occurs at $\omega t = 0$. Based on (4), it is obtained that:

$$U_{cmax} = U_m \sin \varphi - (U_0 - U_m \sin \varphi) = 2U_m \sin \varphi - U_0 \quad (5)$$

When the initial value of $u_c(0)$ is $-U_m$, the maximum operating overvoltage of pantograph lifting can reach $3U_m$. Considering the thermal and charge-accumulation effect of the arc, the pantograph–catenary gap is equivalent to the RC circuit shown in Figure 10a. $R(t)$ represents the arc resistance while $C(t)$ represents the arc capacitance. The expressions of $R(t)$ and $C(t)$ are deduced as [17]:

$$\begin{cases} R(t) = R_1 e^{-\frac{t}{\tau_1}} + R_2 e^{\frac{t}{\tau_2}} \\ C(t) = 24.72 t^{0.32} \end{cases} \quad (6)$$

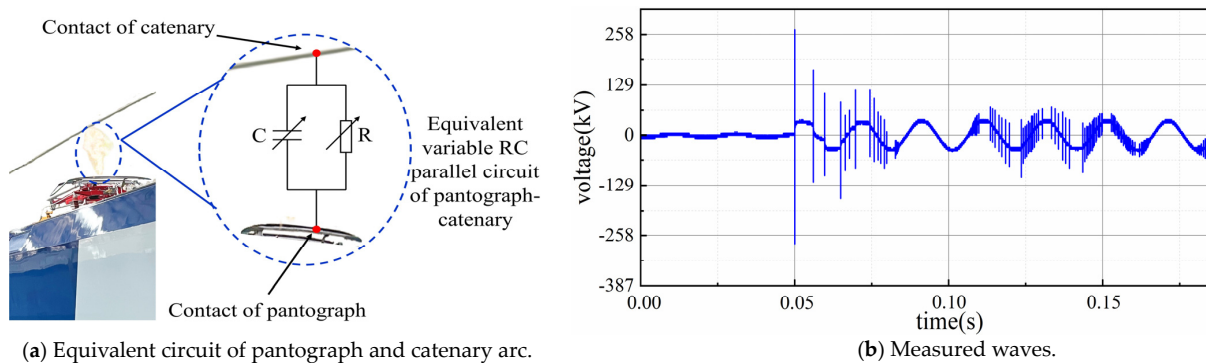


Figure 10. Equivalent circuit and actual condition.

In (6), R_1 and R_2 correspond to the steady-state value and the arcing resistance value in the double exponential arc-resistance model, respectively. τ_1 and τ_2 are the decay time constants of the exponential function, which represent the time of arc combustion and extinguishing during one arc process. The equivalent variable RC parallel circuit between the pantograph and the catenary is adopted to simulate the high-frequency electromagnetic oscillation at closing, which may induce the overvoltage over $3U_m$. Figure 10b is shown as the waveform diagram of a pantograph lifting test. It can be clearly seen that the overvoltage generated at the moment of pantograph lifting is the largest with the amplitude exceeding 10 times the power frequency voltage. This phenomenon can be explained by the equivalent circuit method on the left side of Figure 10a.

(4) Formation Mechanism of Ultra-fast Transient Overvoltage Caused by Pantograph Dropping and Main Breaker Opening

The process of pantograph dropping and main breaker opening involves a contact-separation operation, which can be classified as an opening operation. When the pantograph is not completely separated from the catenary, the distance between them is short, so the electric field strength is large, which can easily lead to gap breakdown. The equivalent circuit of pantograph dropping is illustrated in Figure 11a. Figure 11b is a simplified circuit without considerations of catenary resistance and transformer inductance. It is assumed that the amplitude of the catenary voltage is U_m .

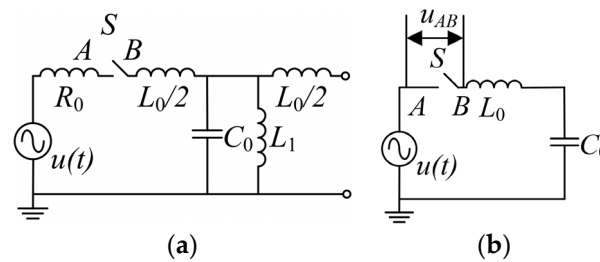


Figure 11. Pantograph dropping equivalent circuit. (a) Equivalent circuit. (b) Simplified circuit.

In the equivalent circuit shown in Figure 11, the A side represents the catenary and the B side represents the pantograph. The catenary is connected to the 27.5 kV traction power supply system, and the power supply potential is set as:

$$e(t) = U_m \cos \omega t \quad (7)$$

Then the current is:

$$i(t) = \frac{U_m}{X_c - X_L} \cos(\omega t + 90^\circ) \quad (8)$$

In the formula, X_c and X_L are $1/2\pi f C_0$ and $2\pi f L_0$ respectively. For the no-load line, the current through the breaker is the capacitive current of the circuit, so the current is ahead of the voltage. Ignoring the influence of line capacitance effect, the line voltage is equal to the power supply voltage before the switch 'S' is off.

(1) The first arc-extinguishing process

Before pantograph dropping, the capacitor voltage is approximated to the power supply voltage due to $\omega L_0 \ll 1/(\omega C_0)$, and the current is ahead of the voltage by 90° . Supposing the power supply voltage $u(t) = U_m \cos \omega t$, the power supply current $i(t) = -U_m \omega C_0 \sin \omega t$. In Figure 11b, point A represents the catenary, while point B represents the pantograph. If the pantograph drops at t_1 , the voltage of point B is kept at $+U_m$ due to the capacitive elements in the circuit. The voltage at point A is consistent with the power supply voltage, which changes according to the cosine law. The recovery voltage u_{AB} between the contacts of the breaker is [18]:

$$u_{AB} = e(t) - (-U_m) = U_m(1 + \cos \omega t) \quad (9)$$

When $t = t_1$, $u_{AB} = 0$, then the recovery voltage u_{AB} becomes higher and higher. After t_1 , if the deionization effect between the main breaker contact is strong, the contact between the insulating strength recovery exceeds the recovery voltage rise speed, the arc will be extinguished, and the circuit will be truly disconnected [19]. At this time, no matter the pantograph or the catenary side, there will be no overvoltage. On the contrary, arc reignition may occur between pantograph and catenary.

(2) The first arc-reignition process

Considering the most serious case, it is assumed that the arc is reignited when the recovery voltage u_{AB} reaches the maximum, at time t_2 in Figure 12a. Then $e(t) = U_m$, $u_{AB} = 2U_m$. At the moment of arc reignition, the catenary voltage U_m is suddenly added to

the oscillation loop composed of the line inductance L_0 and the capacitance C_0 with the initial value of $-U_m$, as shown in Figure 11b. The loop voltage equation for the oscillation process is (considering the circuit with an equivalent load, that is, a small resistance R):

$$Ri_c + L \frac{di_c}{dt} + u_c = U_m \sin(\omega t + \varphi) \quad (10)$$

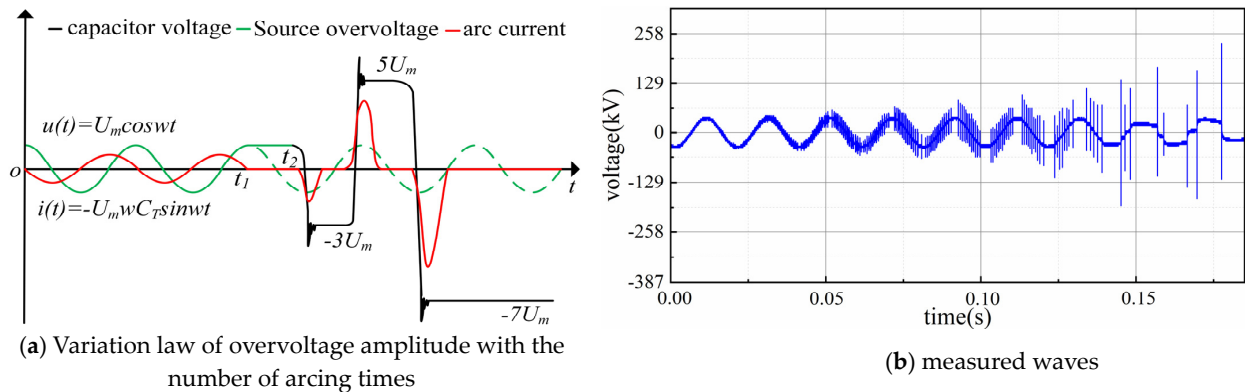


Figure 12. Variation law and actual condition.

Since the transient recovery voltage exists for a short time, the power frequency power supply voltage changes little in a short time. At this time, setting condition $U_0 = U_m \sin \varphi$:

$$Ri_c + L \frac{di_c}{dt} + u_c = U_0 \quad (11)$$

due to

$$\begin{cases} i_c = C \frac{du_c}{dt} \\ \frac{di_c}{dt} = C \frac{d^2 u_c}{dt^2} \end{cases} \quad (12)$$

Then

$$LC \frac{d^2 u_c}{dt^2} + RC \frac{du_c}{dt} + u_c = U_0 \quad (13)$$

Ignoring the resistance R , the expression of u_c is:

$$u_c = U_0 [1 - e^{-\delta t} (A \cos \omega t + B \sin \omega t)] \quad (14)$$

After the arc reignition, the oscillation process will occur, and overvoltage will be generated during the oscillation process. The natural frequency of the oscillation circuit is:

$$f_0 = \frac{1}{2\pi \sqrt{L_0 C_0}} \quad (15)$$

This frequency is much larger than the power frequency of 50 Hz, so the cycle is much smaller than the power frequency cycle of 0.02 s. At this time, it can be considered that the power supply voltage keeps U_m unchanged during the transient high-frequency oscillation. The capacitance voltage during the transition process can be calculated as follows:

$$\text{Overvoltage amplitude} = \text{Steady state value} + (\text{Steady state value} - \text{initialization value}) = U_m + (U_m - (-U_m)) = 3U_m \quad (16)$$

And the arc develops according to this law: there will be multiple reignition overvoltage of $-5U_m, 7U_m, -9U_m$ [20]. If the development of the overvoltage is not influenced by external factors, it will continue to develop, and theoretically, it can reach more than 10 times of power frequency overvoltage (27.5 kV 50 Hz). The same development law can

be clearly seen in Figure 12b. As the number of arc reignitions increases, the overvoltage amplitude increases, and the maximum overvoltage occurs at the last arc reignition.

4.2. Distribution Law of Ultra-Fast Transient Overvoltage on High-Voltage Equipment

The amplitude and steepness of operating overvoltage are maldistribution on the high-voltage equipment of locomotive. As shown in Figure 13, the amplitudes of ultra-fast transient overvoltage at test points 2, 3, 4 are much lower than that at test point 1. At the same time, the voltage changes faster at point 1, resulting in a much higher-voltage steepness ($3400.00 \text{ kV}/\mu\text{s} \sim 42,100.00 \text{ kV}/\mu\text{s}$) compared to other test points ($0.20 \text{ kV}/\mu\text{s} \sim 939.00 \text{ kV}/\mu\text{s}$).

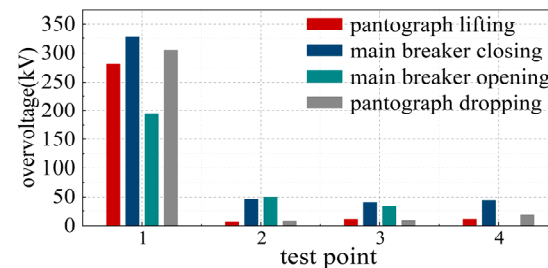


Figure 13. Distribution law of ultra-fast transient overvoltage on high-voltage equipment.

The analysis of the distribution characteristics of overvoltage on the high-voltage equipment of electric locomotive is as follows: As shown in Figure 14, it is a schematic diagram of the distributed parameter circuit structure of the high-voltage equipment of an electric locomotive. It can be found that point 1 is near the pantograph, and the electrical distance from the pantograph–catenary contact where the arc occurs is very small. The overvoltage can easily spread to point 1 and the high-voltage transformer. For points 2, 3, and 4, because the circuit breaker is in the breaking state during the experiment, it exists in the form of a large resistance of $1 \text{ M}\Omega$ in the circuit. Such a large electrical distance makes the operating overvoltage unable to continue to propagate backward, and the circuit breaker has strong insulation and arc-extinguishing performance, so the overvoltage with high steepness can hardly be seen at points 2, 3, and 4.

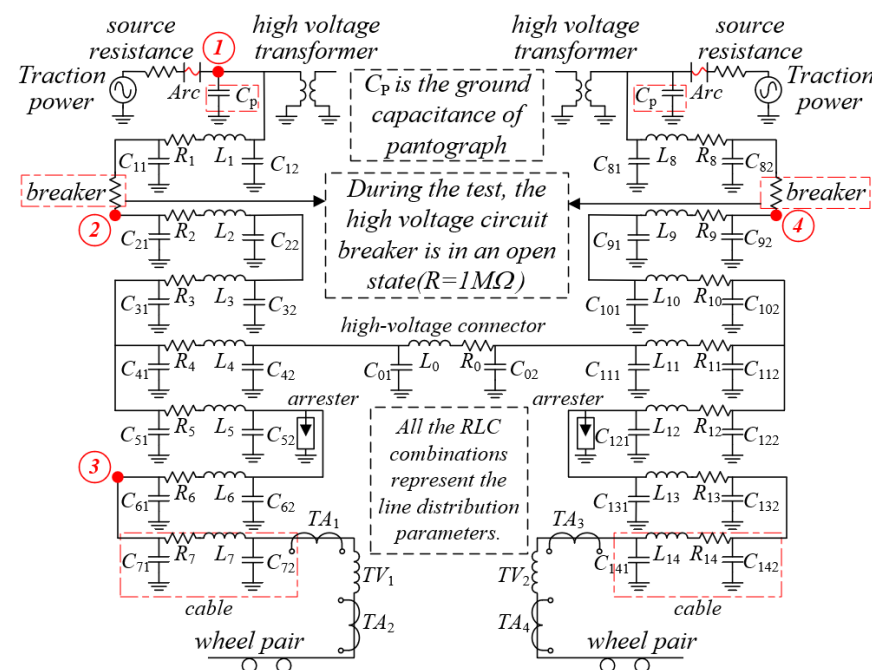


Figure 14. Equivalent distributed parameter circuit of high-voltage system of electric locomotive.

Figure 15 shows the overvoltage waveforms generated by the measured points 2, 3, 4 under a certain operation. It can be seen that the overvoltage with high amplitude and high steepness does not propagate to these three points, and their amplitudes are below 15 kV.

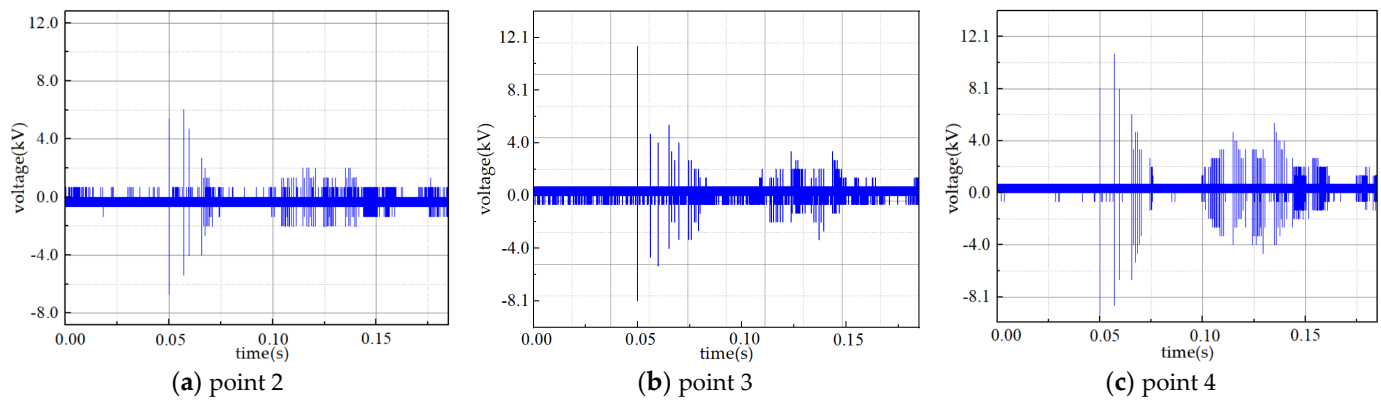


Figure 15. Overvoltage waveform of point 2, 3, and 4 under a certain operation.

4.3. Hazard of Ultra-Fast Transient Overvoltage to Locomotive High-Voltage Equipment

For winding equipment, the inductance and capacitance of the winding form a complex distributed parameter circuit, so the complex electromagnetic oscillations occur with the ultra-fast transient overvoltage. The main insulation and longitudinal insulation will suffer very high overvoltage and potential gradients which can lead to turn-to-turn insulation breakdown [21]. The larger the steepness, the more severe the oscillation. The winding potential gradient is derived as:

$$\left. \frac{du}{dx} \right|_{x=0} = -U_0 \alpha = -\left(\frac{U_0}{l} \right) \alpha l \quad (17)$$

U_0 is the initial voltage on the winding, U_0/l is the initial average potential gradient of the winding and α is the steepness of the invasion wave. When U_0/l is constant, the potential gradient of the winding is proportional to the steepness α of the invasion wave. The tested overvoltage steepness is 10^6 times higher than existing tests while the potential gradient on the winding is greatly increased. For example, the voltage difference on the two-turn winding is greater than the insulation tolerance between the windings, and the inter-turn breakdown phenomenon will occur in the winding, which will aggravate the partial discharge inside the winding, thus accelerating the aging of the equipment and shortening the service life of the equipment.

For insulation-protection equipment, external insulation will flashover under overvoltage while the internal insulation may completely break down. GB/T 11032 [22] stipulates that the power frequency discharge voltage of the arrester is generally 2.5 to 4 times the rated voltage, and the ultra-fast transient overvoltage multiple tested in this paper reaches up to 7.8 times the rated voltage of the arrester, which is much higher than the specified value in the standard. As the crucial protection device for overvoltage, a single flashover or breakdown of the arrester generally does not cause immediate failure. However, repeated flashover or local breakdown will accelerate the aging process of insulating materials and lead to severe faults ultimately. Especially when there are undetectable flaws within the insulator, these flaws will develop under repeated overvoltage, further exacerbating the risk of insulation failure.

When the waveform steepness becomes larger, the residual voltage on the nonlinear resistor of the arrester will increase at the same time. When the front time of the invasion current wave changes from 8 μ s to 0.5 μ s, the residual voltage on the metal oxide nonlinear resistor increases by 0.15~37.93% [23]. As the residual voltage on the arrester increases, the risk of insulation breakdown of high-voltage equipment which is in parallel with the arrester also increases significantly.

4.4. Influence of Installation Position and Quantity of Arresters on Ultra-Fast Transient Overvoltage

Two tests are carried out on the HXD1C electric locomotive to study the effect of arrester installation position and its quantity on ultra-fast transient overvoltage. For the HXD1 electric locomotive, there is only one on-roof arrester that is located near the high-voltage insulation sleeving, while the HXD1C electric locomotive has two arresters on its roof. One is installed near the high-voltage insulation sleeving and the other is located at the pantograph (as shown in Figure 16).

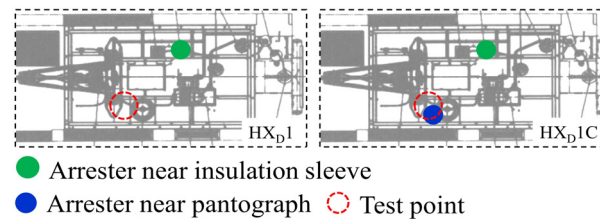


Figure 16. Arrangement of arrester of HXD1 and HXD1C.

It can be seen from Table 6 that for different types of operating overvoltage, increasing the number of arresters can reduce the value of overvoltage to varying degrees. Among them, the most obvious effect of the arrester is the closing overvoltage, which decreases by more than 200 kV. The nonlinear characteristics of the arrester give full play to its function, which can quickly turn on and release a lot of energy. The decrease values of the two closing overvoltages in the table are 225.40 kV and 263.49 kV, respectively. For the rising bow overvoltage, because the value of the voltage is not very high, it is close to the action threshold of the arrester, so the nonlinear response of the arrester is weak, and the resistance drop is small, so the limiting effect of the overvoltage is not obvious. The drop values of the two lifting overvoltages in the table are 49.35 kV and 28.34 kV, respectively.

Table 6. Comparison of operating overvoltage data of HXD1 and HXD1C.

Operation	Operating Overvoltage		
	HXD1 (kV)	HXD1C (kV)	Δu
Pantograph lifting	176.16	126.81	−49.35
Main breaker closing	328.60	103.20	−225.40
Main breaker opening	132.72	86.04	−46.68
Pantograph dropping	253.70	113.91	−139.79
Pantograph lifting	146.63	118.29	−28.34
Main breaker closing	315.09	51.60	−263.49
Main breaker opening	194.73	68.76	−125.97
Pantograph dropping	236.33	116.10	−120.23

The operating overvoltage test process and scheme of HXD1C are consistent with HXD1. After placing the voltage divider, the overvoltage waveform is recorded by a high-speed digital-storage oscilloscope similarly. On the HXD1C electric locomotive, the operation of pantograph lifting, main breaker closing, main breaker opening, and pantograph dropping are tested sequentially two times. The tested data are selected for comparison in Table 6. The peak operating overvoltage of HXD1C is 126.81 kV, which is significantly lower than the peak value of 328.60 kV of HXD1. The results show that a reasonable arrangement of the arrester can effectively reduce the amplitude of the ultra-fast transient overvoltage and provide better protection for the pantograph and other high-voltage equipment on the roof.

5. Conclusions

In this paper, the operating overvoltage induced by the pantograph lifting, main breaker closing, main breaker opening, and pantograph dropping in HXD1 electric locomotive is analyzed. The formation mechanism, the distribution law, the hazard as well as the influence of arresters on overvoltage is discussed in detail. The conclusions are summarized as follows:

- (1) The tested amplitude and steepness of operating overvoltage is higher than in existing reports. The peak operating overvoltage of HXD1 is 328.60 kV and its steepness is 4.21×10^4 kV/ μ s, exhibiting characteristics similar to VFTO. The phenomenon of multiple arc reignition is obvious in the pantograph lifting and dropping process, whereas it is not apparent in the main breaker closing and opening operations.
- (2) The amplitude of overvoltage during the pantograph lifting and breaker closing exceeds $3U_m$ of rated voltage considering the equivalent variable capacitance between the pantograph and the catenary. In addition, for pantograph dropping and main breaker opening overvoltage, the amplitude tends to increase in a pattern of 3, 5, 7, 9, and 11 times the rated voltage as the arc reignition.
- (3) Ultra-fast transient overvoltage is unevenly distributed at high-voltage equipment of the electric locomotive. The overvoltage with high amplitude and high steepness mainly concentrates at the pantograph while other test points are relatively low.
- (4) Operating overvoltage poses a serious threat to high-voltage equipment, and reasonable layout of the arrester can effectively reduce the overvoltage amplitude and decrease the likelihood of damage to the high-voltage equipment.

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