Experimental Study on Secondary Arc Physics with Half wavelength Power Transmission Lines

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- **Half wavelength transmission lines --- the concept in China**

Fig.1 Energy distribution and power transmission concept in China

1. Introduction

Development of half wavelength transmission in China

1

In 1993: half wavelength application prospect began to draw close attention in China power sector.

2

In 2008, further ideas on half wavelength was put forward by an Academician, Prof Zheng Jianchao.

3

In 2009, the State Grid of China set up the first strategic research topics on half wavelength technology.

4

In 2011, the Chinese Society of electrical engineering short-listed Half Wavelength Technology in the special area for future development.

Advantages of the half wavelength transmission technology

1. Without reactive power compensation
2. Extremely good voltage stability
3. Large transmission power capacity
4. Excellent features in economy
5. High reliability and so on

- **Challenges in realizing the half wavelength transmission technology**

1. **Fault-induced or switching over-voltages**
2. **Power dispatch along transmission lines**
3. **Power relay and protection schemes**
4. **Secondary arc extinction and auto-reclosure**

Generation of secondary arc

Single-phase ground fault

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Short circuit arc discharge

↓

Fault phase switch off

↓

Electromagnetic coupling

↓

Secondary arc continues

Fig.2 Short circuit arc

Fig.3 Secondary arc

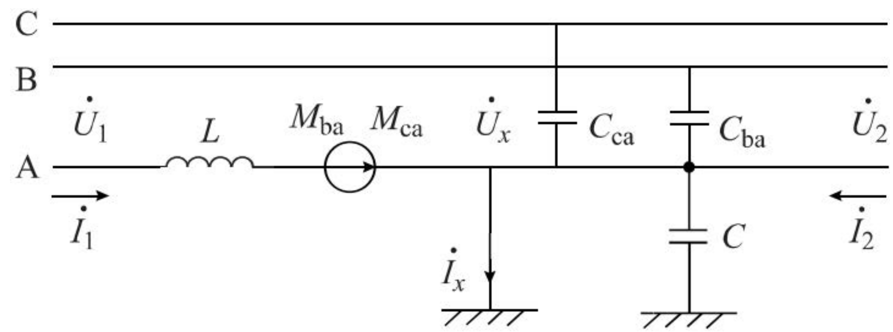


Fig.4 Electromagnetic coupling model for half wavelength transmission lines

1. Introduction

Potential impacts of the secondary arcs

Single-phase reclosing failure

Endanger power equipments

1. Introduction

- **Unique secondary arc characteristics with half wavelength transmission lines**

- Extremely long length of the transmission lines

- Complicated coupling between transmission line phases

- Existence of the series compensation network

1. Introduction

1. Large secondary arc current and recovery voltage. Special suppression are required.

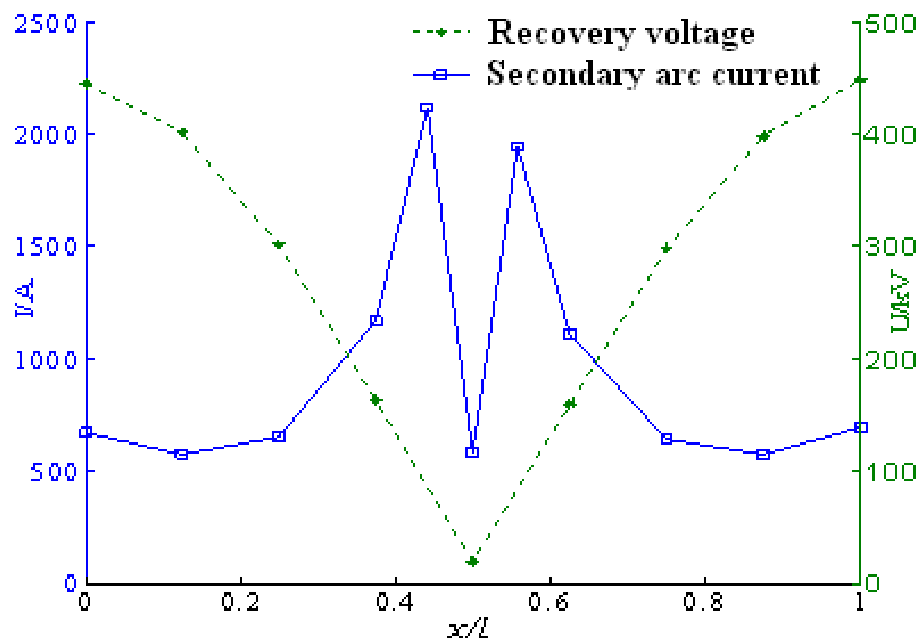


Fig.5 Secondary arc current and recovery voltage along the transmission lines

1. Introduction

2. With large short circuit current, and the impact of which on secondary arcs is not yet clear.
3. Unique electrostatic induction component.
4. Electromagnetic transient interaction process with the power system and the arcing characteristics.
5. The traditional secondary arc suppression method is no longer applicable.

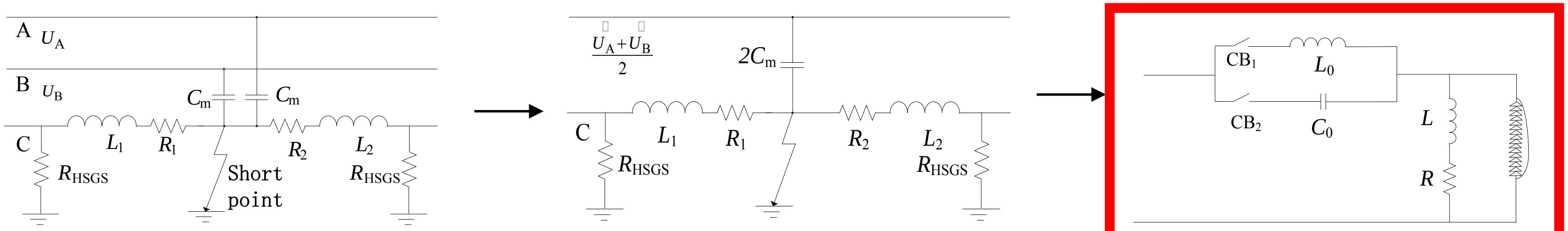
1. Introduction

- **The unique secondary arc behaviors present a challenge for developing half wavelength transmission technology.**

- **Further study on secondary arcs is necessary with a view to clarifying the physical mechanism as well as proposing effective suppressing measures.**

Contents

Equivalent transform of the three-phase transmission lines



(a) Thee phase circuit (b) Two phase circuit (c) Single phase circuit

Fig.6 Equivalent transform of the transmission lines

- The three-phase circuit of the half-wavelength transmission lines with single-phase earth fault can be simplified as a single-phase topology, as shown above.

2. Experimental study on secondary arc physics

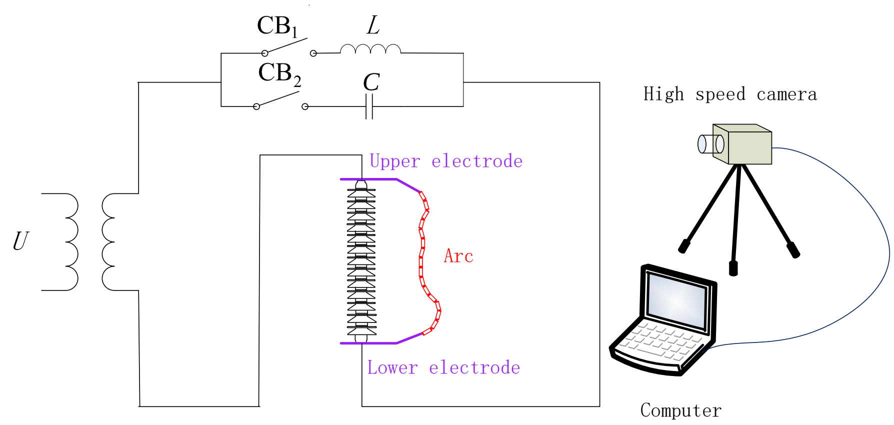


Fig.7 The established experimental circuit

•The platform is mainly composed of a test circuit together with corresponding measurement system, including a 10 kV AC power supply, group capacitors, copper electrodes, HV insulators, fuses to ignite the arc discharge, etc.

•The arc trajectories are recoded with a high speed video camera, while the voltage and current of the secondary arc are measured through voltage dividers, CTs and digital oscilloscopes.

Fig.8 Physical simulation field.

2. Experimental study on secondary arc physics

❖ Experimental instruments and equipments

Equipments	Specifications
Capacitors	BFM19-250-1W
Reactors	CKSG-216/35-6
Insulators	LXP-240
Circuit breaker	ZN63A-12、SPV-12/630、ZN12-40.5kV
Oscilloscope	Yokogawa-DL850
Arc striking material	Nichrome wire，diameter 0.15mm
Wind speed meter	Tesco 405-V1
High speed camera	Lens: Nikon ED AF Nikkor 80-200mm, 1:2.8D Camera System: Motion Pro X3 Plus, 500fps Distinguishability: 1280*1024

2. Experimental study on secondary arc physics

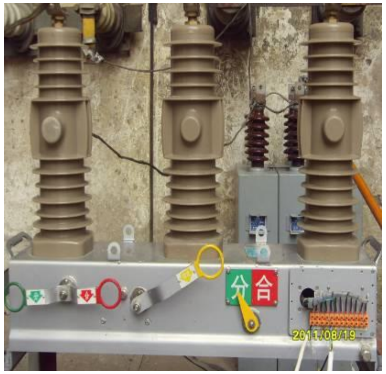
❖ Experimental instruments and equipments

Experiment site

Experiment circuit

Capacitor bank

Circuit breaker



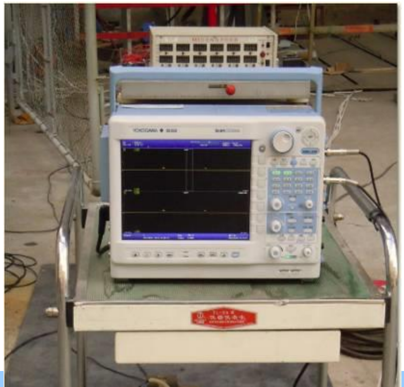
Fans

Nichrome wire

Voltage divider

Hall coil

Oscilloscope



High speed camera

2.1 Differences between short arc and secondary arc

Images of short arc and secondary arc

The short arc current is bigger and the arc movement speed is faster, also, the movement direction of each part is different and severely changeable.

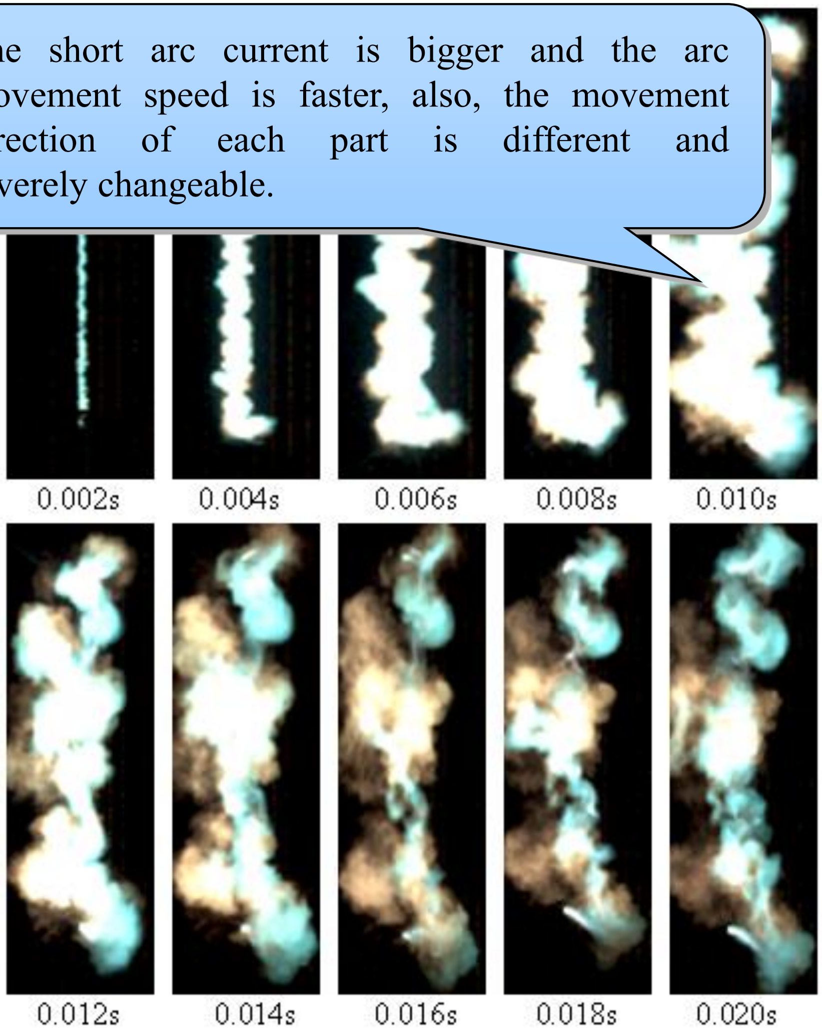


Fig.9 Motion morphology of Short arcs

The secondary arc deflection or deformation occurs continuously, the arc root has a polarity impact. It has a obvious tendency to move up. It is moving back and forth at one location.

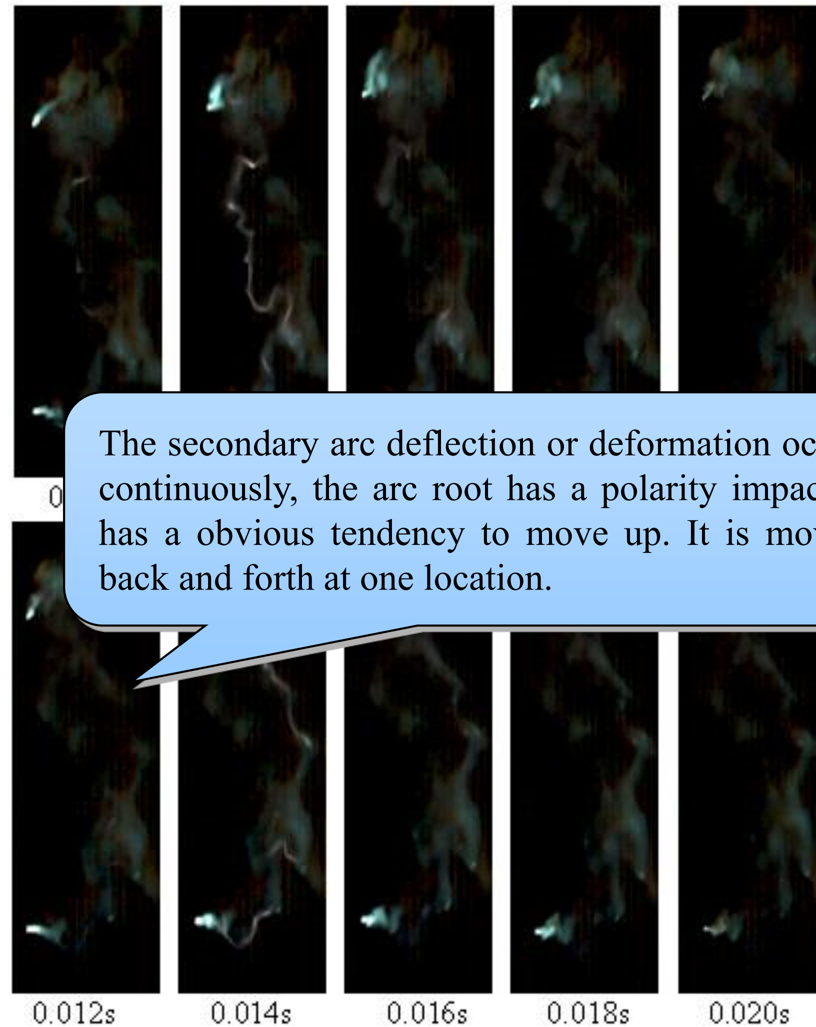


Fig.10 Motion morphology of Secondary arcs

2.1 Differences between short arc and secondary arc

Current and voltage waveforms of short arc and secondary arc

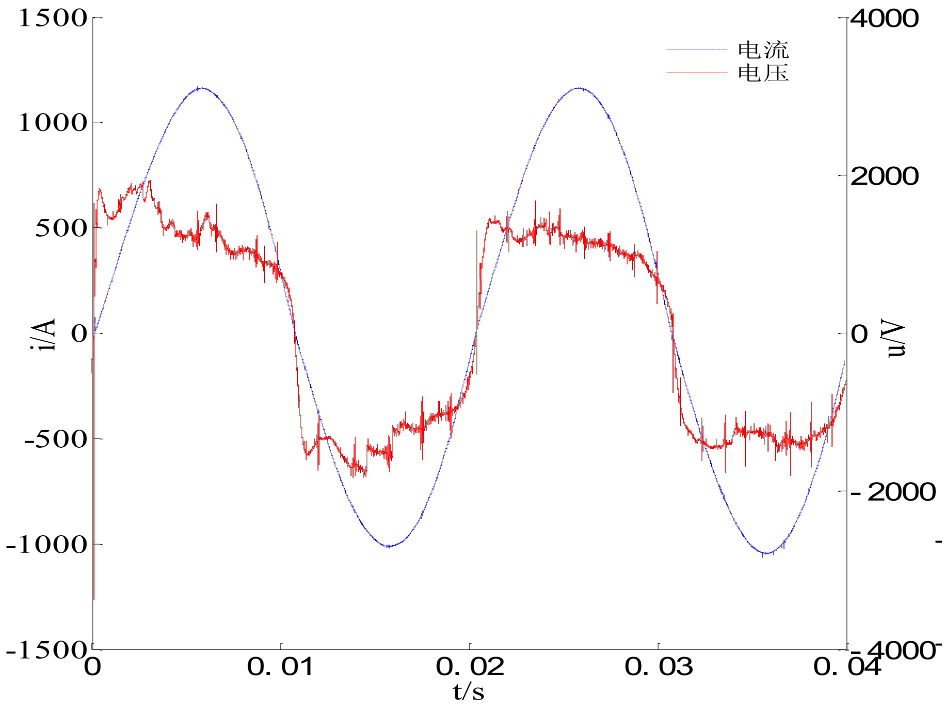


Fig.11 Waveforms of the short arc

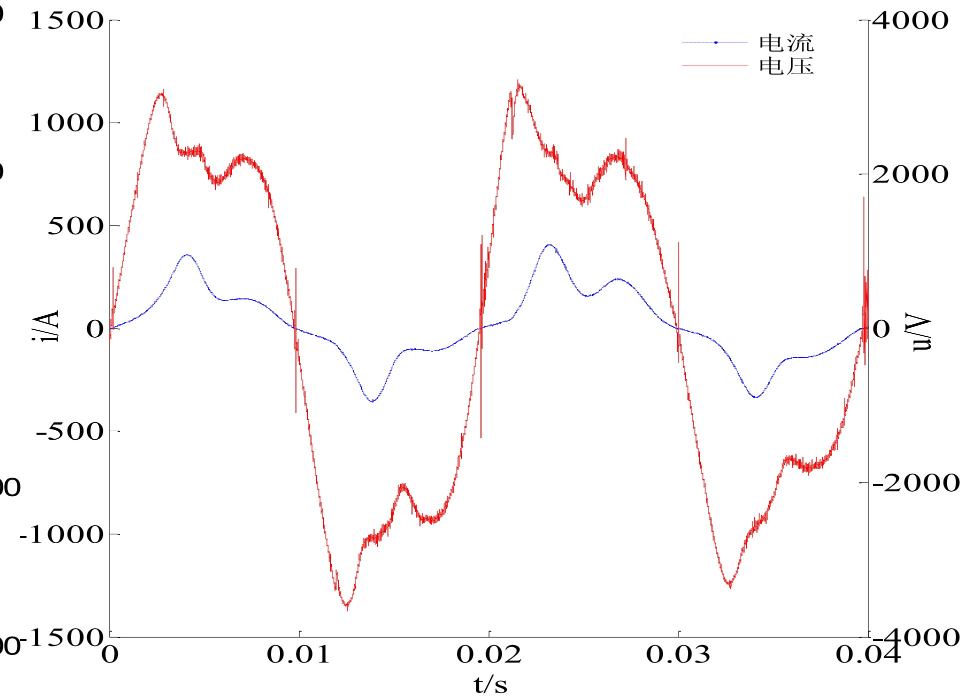


Fig.12 Waveforms of the secondary arc

The short circuit current is big with small distortion on wave, approximately the sine wave. The voltage distortion is serious, similar to a square form.

The secondary arc current is much smaller and the waveform distortion is severe. It has an obvious “zero phenomenon”. The voltage waveform is similar to an saddle. Due to the electric arc thermal inertia, the current peak often lags behind the voltage peak.

2.1 Differences between short arc and secondary arc

Harmonic characteristics

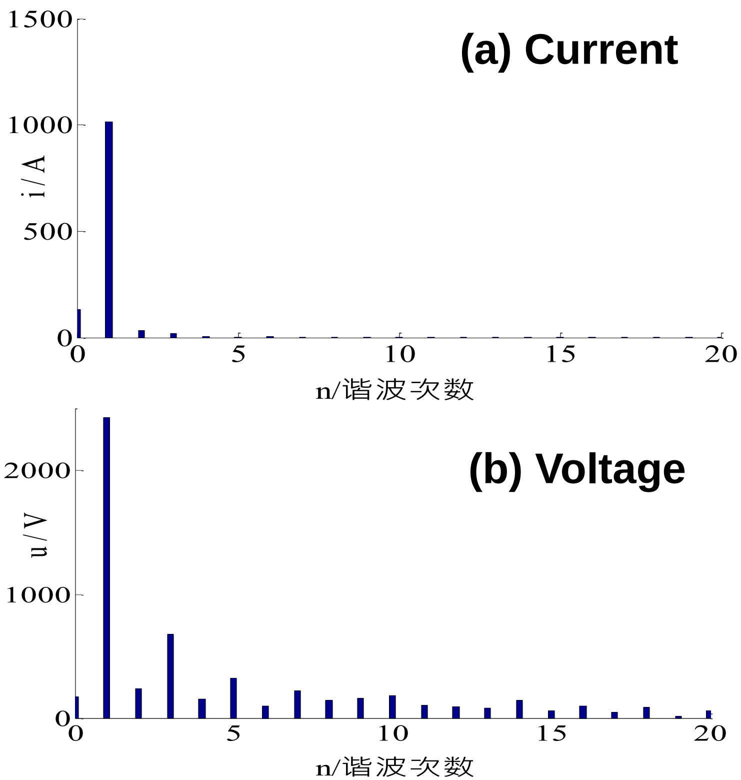


Fig.13 Harmonic contents of the short arc

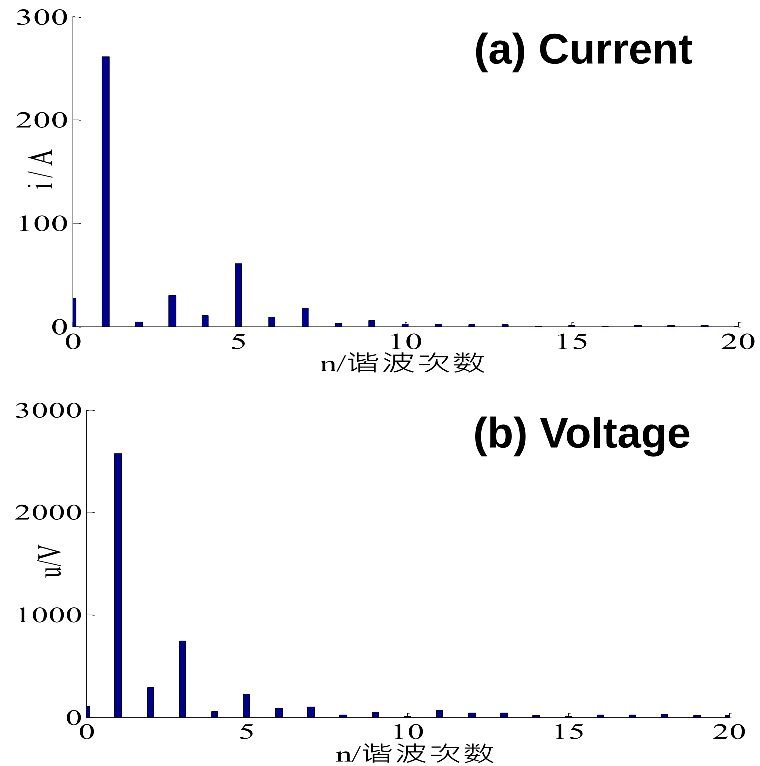


Fig.14 Harmonic contents of the secondary arc

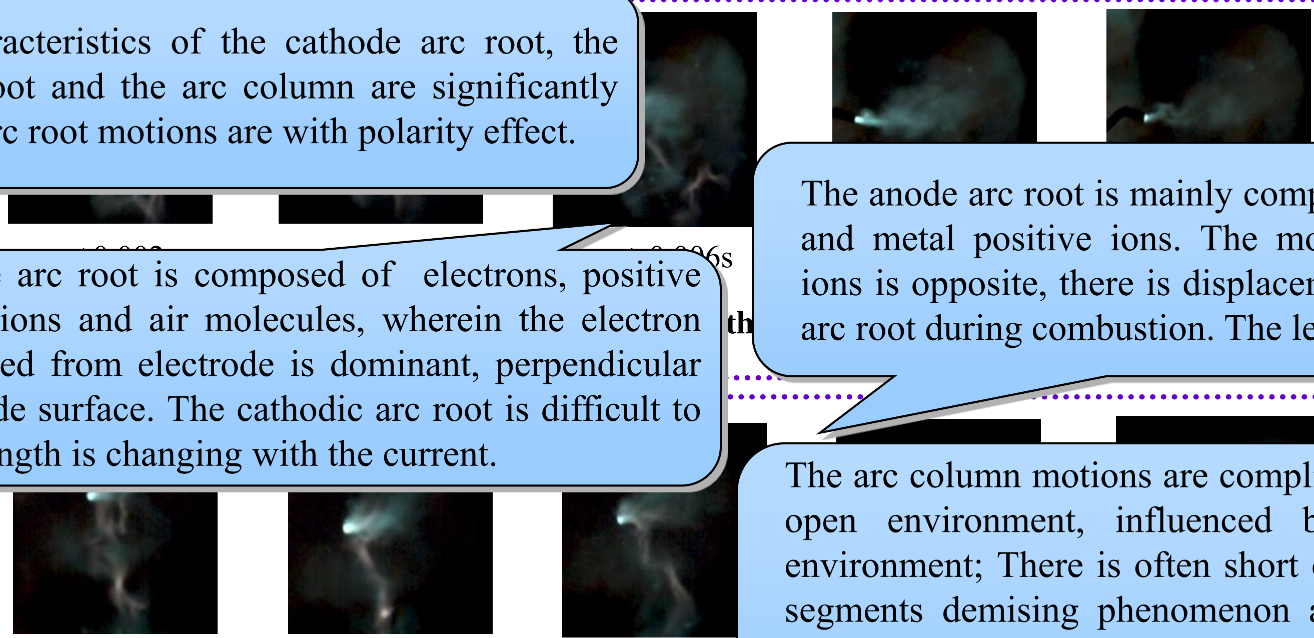
2.2 Typical motion characteristics of secondary arc

Motion characteristics of the cathode arc root, the anode arc root and the arc column are significantly different . Arc root motions are with polarity effect.

The cathode arc root is composed of electrons, positive ions, metal ions and air molecules, wherein the electron beams emitted from electrode is dominant, perpendicular to the cathode surface. The cathodic arc root is difficult to move, the length is changing with the current.

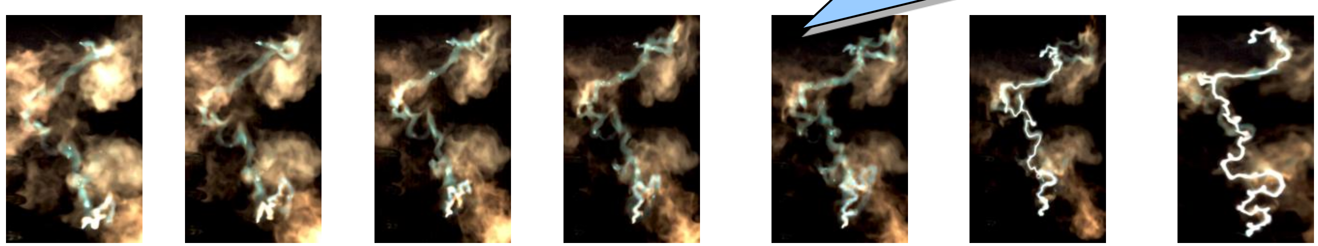
The anode arc root is mainly composed of electrons and metal positive ions. The motion direction of ions is opposite, there is displacement of the anode arc root during combustion. The length is short.

The arc column motions are complicated. It is in an open environment, influenced by the external environment; There is often short circuit and some segments demising phenomenon appears; easy to break down with the anode, forming arc root jump phenomenon; it shows upward motion trend.



t_0+0.002s t_0+0.004s t_0+ 0.006s

Fig. 2 Motion of the a



t_0 t_0+0.01s t_0+ 0.02s t_0+0.03s t_0+0.04s t_0+0.05s t_0+0.06s

Fig. 3 Motion of the arc column

2.2 Typical motion characteristics of secondary arc

2.2.1 Motion mechanism of the secondary arcs

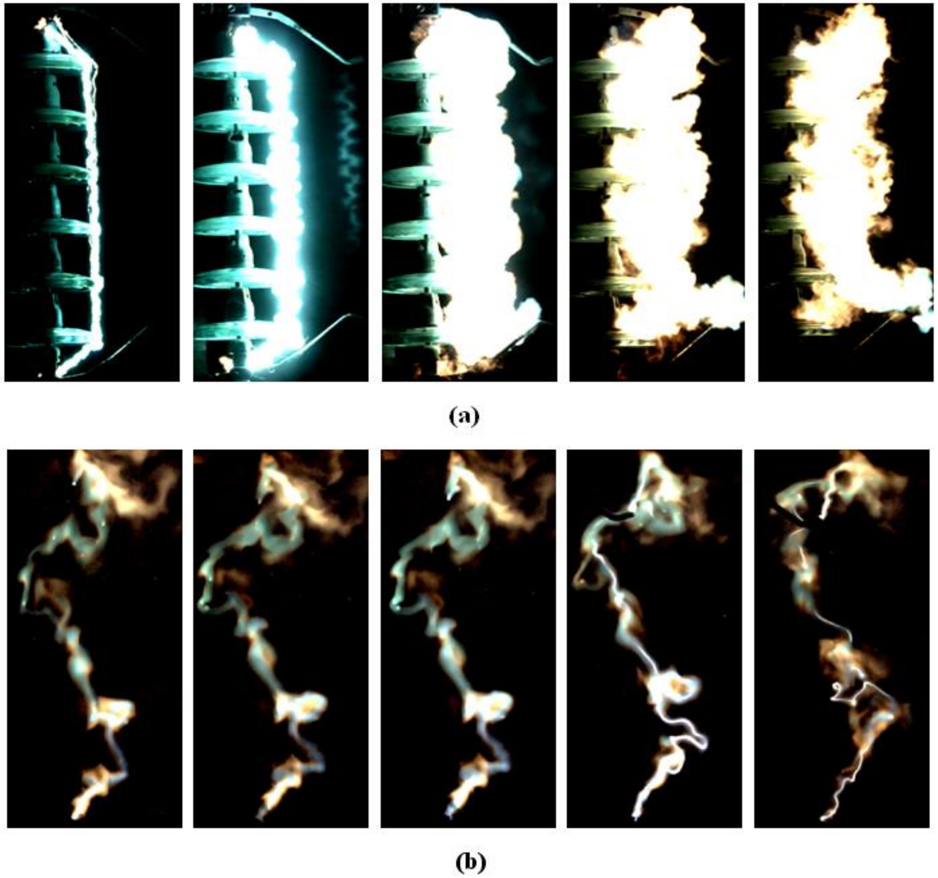


Fig.18 Images of the secondary arc column: (a) for a moving arc root and (b) for a fixed arc root.

- In the beginning of the arcing process, the original arc root at one electrode and the arc column are accelerated forward and outwards by the Lorentz force at the same time. As the arc root bears a larger Lorentz force than the arc column, it moves faster than the latter. Driven by the arc root, the arc column is accelerated and the air surrounding the arc column is gasified quickly, as is shown in Fig.18 (a). It is also found that the secondary arc column mainly experiences a horizontal motion at the earlier stage.

2.2 Typical motion characteristics of secondary arc

2.2.1 Motion mechanism of the secondary arcs

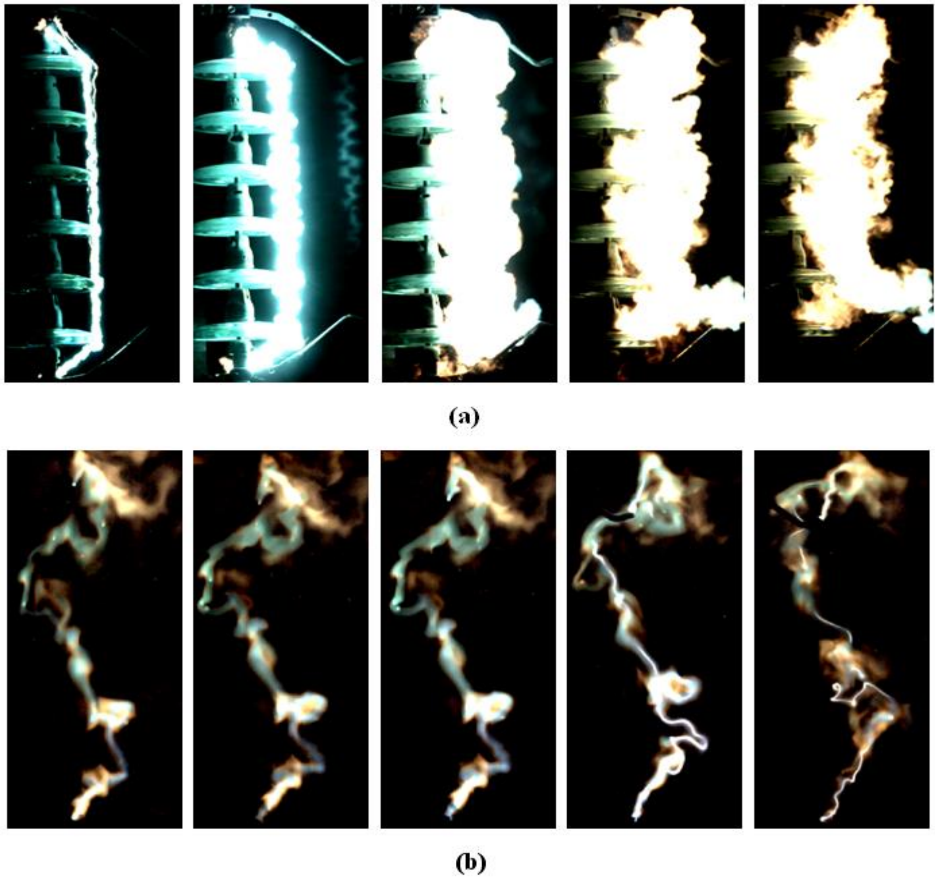


Fig. Images of the secondary arc column: (a) for a moving arc root and (b) for a fixed arc root.

- When the arc root moves to the end of the electrode and its position is approximately fixed, The horizontal displacement of the arc column becomes small. The surrounding air continues to be heated and vaporized with a sudden rise in temperature, and the convection between the heated hot air and the surrounding cold air is strengthened immediately. Driven by the hot air convection, the arc column mainly performs a vertical motion, as is shown in Fig.18 (b).

2.2 Typical motion characteristics of secondary arc

2.2.1 Motion mechanism of the secondary arcs

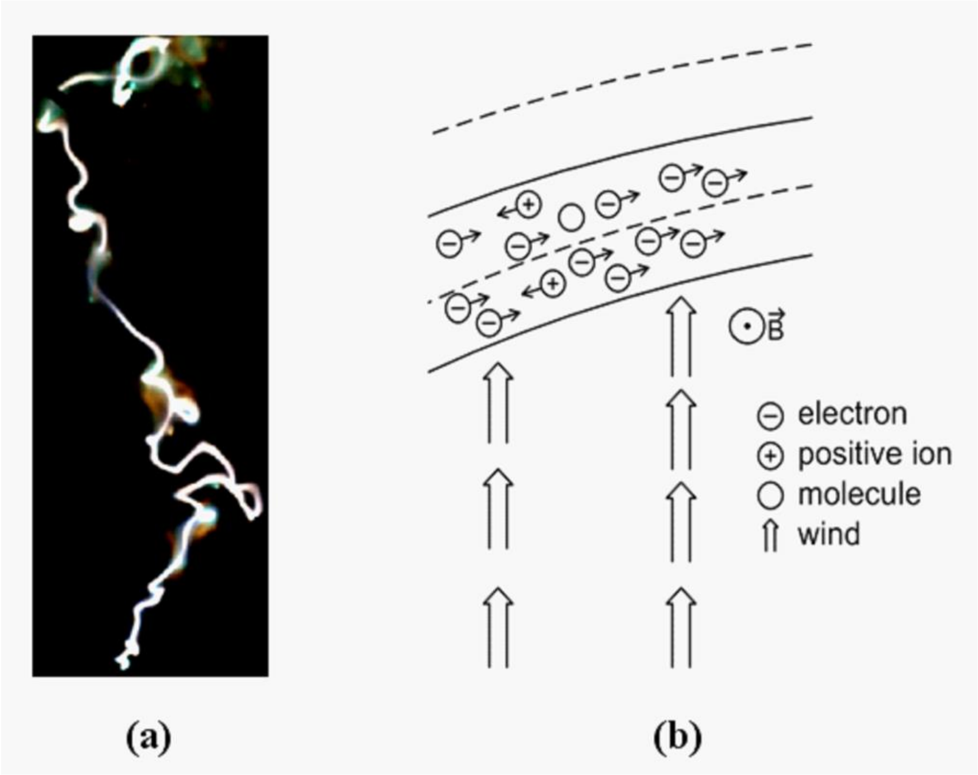


Fig.19 The secondary arc column: (a) for typical image and (b) for motion mechanisms

A typical image of the secondary arc column is given in Fig.19 (a). The arc column plasma of the secondary arcs contains electrons, positive ions, neutral molecules, atoms, etc. Due to the difference in mass, the moving speed of the ions are much less than that of the electrons, and thereby the current inside the arc column plasma is mainly formed by the movement of the free electrons, as shown in Figure (b).

2.2 Typical motion characteristics of secondary arc

2.2.2 Short-circuit phenomenon of secondary arc during motion process

•The secondary arc column is several meters long, and it is often found that short-circuit phenomenon typically happens during the motion process. This phenomenon can be normally manifested in two aspects: one is short-circuit between the arc column and the electrodes as shown in Fig.20 (a), the other is short-circuit between the arc sections themselves as shown in Fig.20 (b).

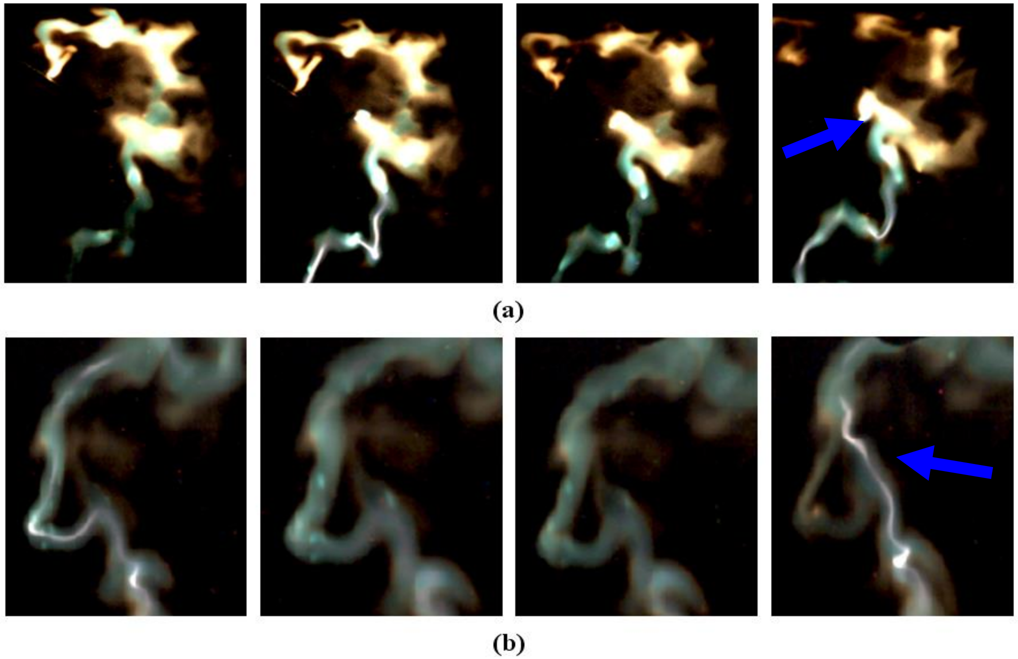
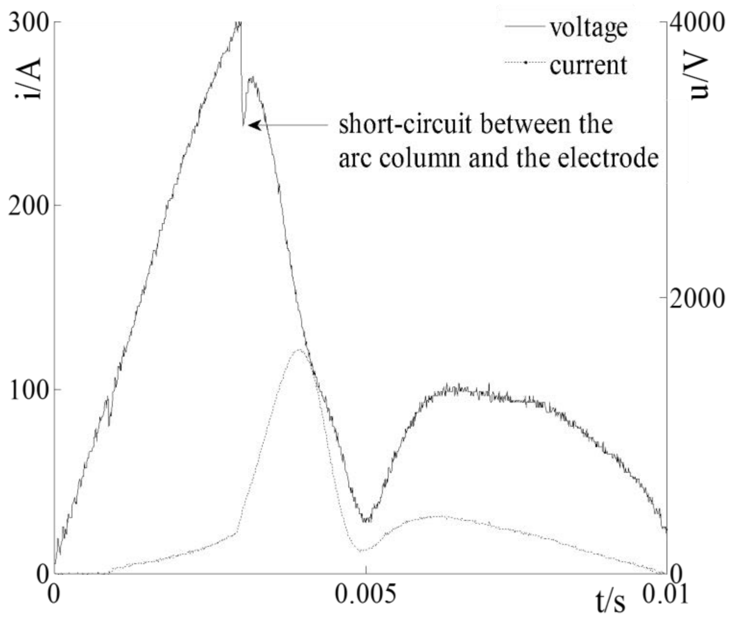


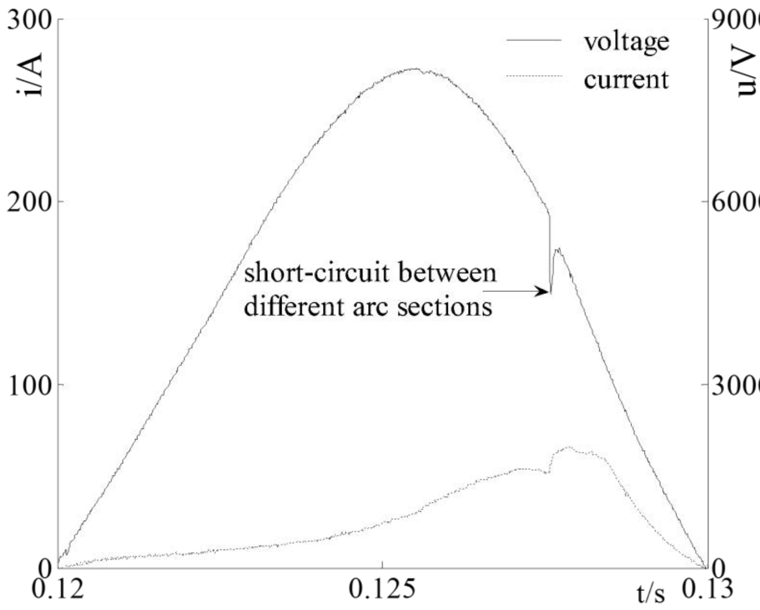
Fig.20 Short circuit phenomenon of the secondary arc column: (a) for short circuit between the arc column and the electrode and (b) for short circuit between the arc sections.

2.2 Typical motion characteristics of secondary arc

2.2.2 Short-circuit phenomenon of secondary arc during motion process



(a)

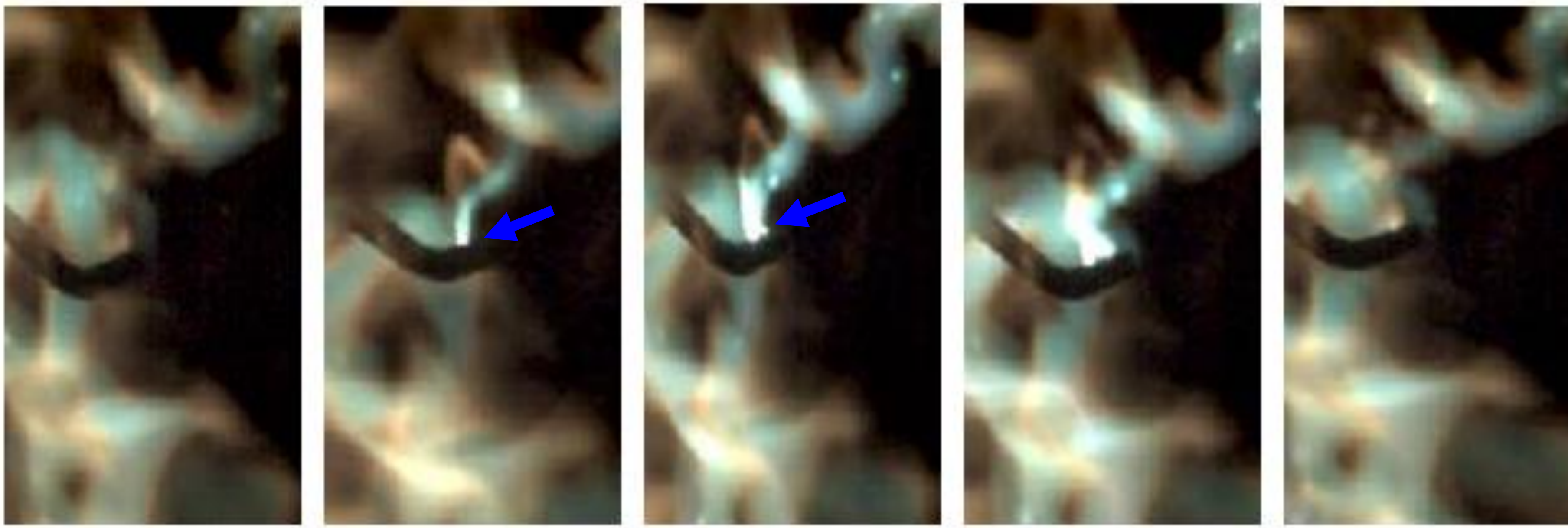


(b)

Fig.21 The secondary arc current and voltage: (a) for short circuit between the arc column and the electrode and (b) for short circuit between the arc sections

2.2 Typical motion characteristics of secondary arc

2.2.3 Induced phenomenon of the cathode arc root



$t_0+0.002$ $t_0+0.004s$ $t_0+ 0.006s$ $t_0+0.008s$ $t_0+0.01s$

- There is induced phenomenon of the cathode arc root occasionally appearing in the process of arc motion. There exist two cathode arc root and the spatial distance between the two is usually very short.

2.3 Wind effects on the arc trajectory

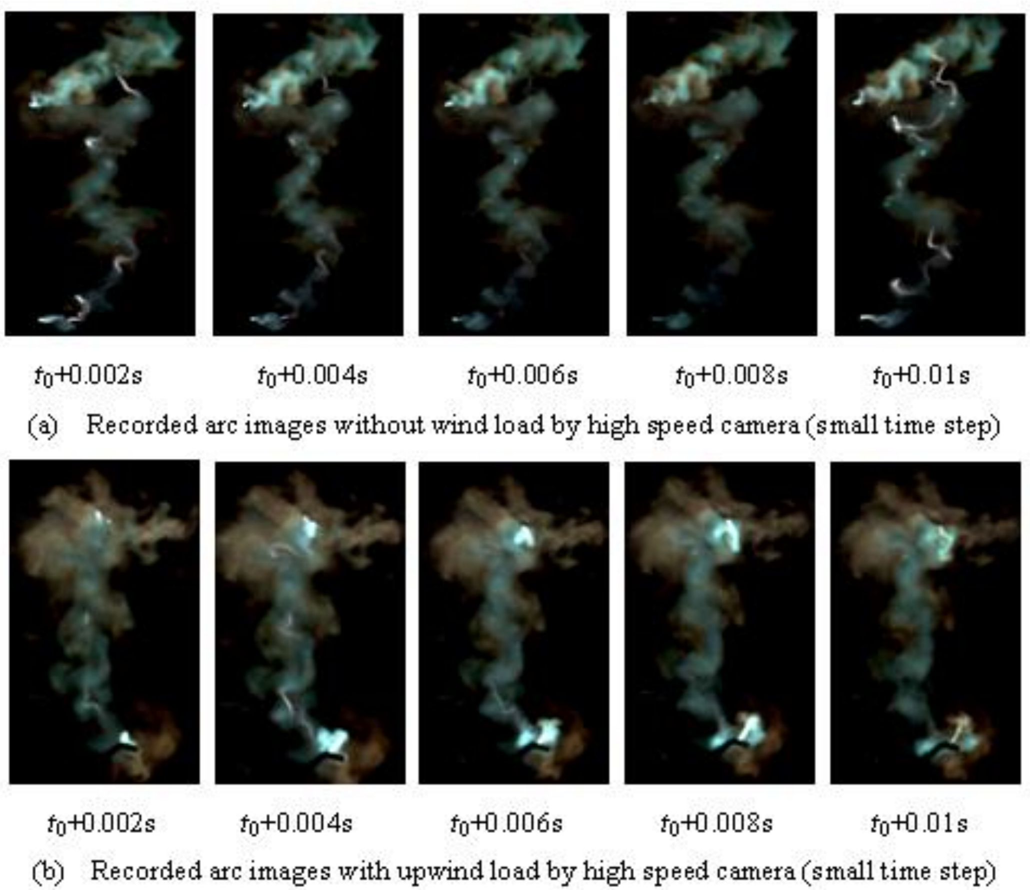
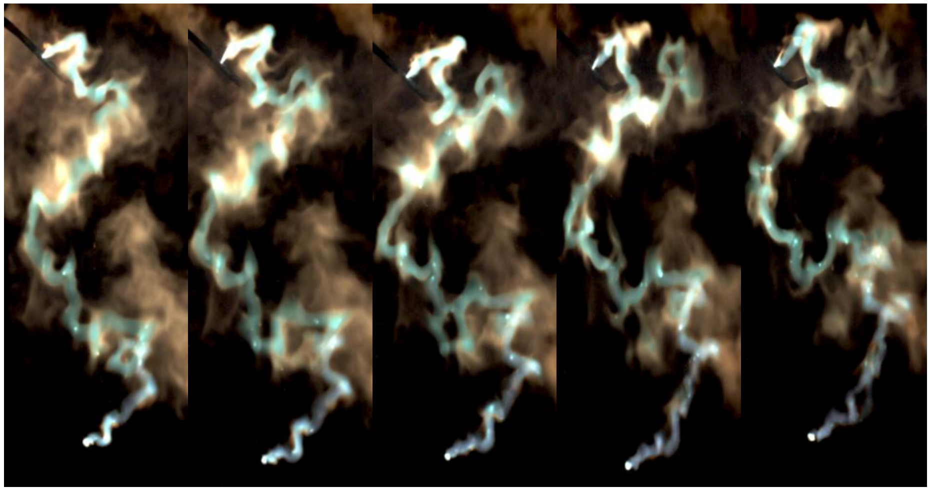


Fig.22 Recorded images of the secondary arc motion trials for without wind (a) and with wind (b).

•It is also found that, the secondary arc burning in the free space is much easy to be influenced by the wind loads. The moving trajectories of the secondary arc under stress of the wind forces are shown in the figure, wherein the wind direction is perpendicular to the arc channel with a typical wind speed of 1.5 m/s.

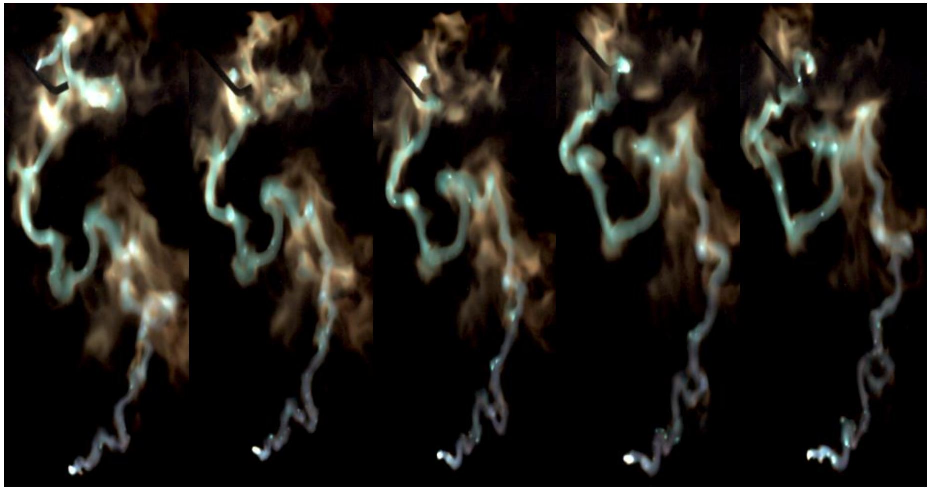
2.3 Wind effects on the arc trajectory

Wind in the same direction with arc motion



t_0 +0.18s t_0 +0.19s t_0 +0.20s t_0 +0.21s t_0 +0.22s

Wind is an important factor to the motion and extinction of the secondary arc. It accelerates the dissipation of the plasma in arc tract and enhancing the arc energy exchange with the outside world, speeding up the arc extinction.

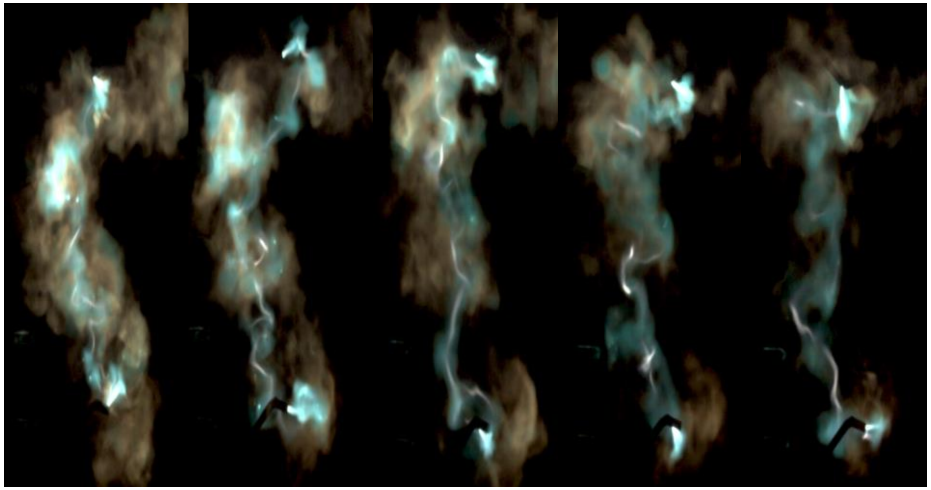


t_0 +0.23s t_0 +0.24s t_0 +0.25s t_0 +0.26s t_0 +0.27s

There is obvious deformation of the secondary arc under the action of wind. The arc column is constantly stretched until the energy provided by the transmission lines are not sufficient for the secondary to burn and ultimately the arc is extinguished.

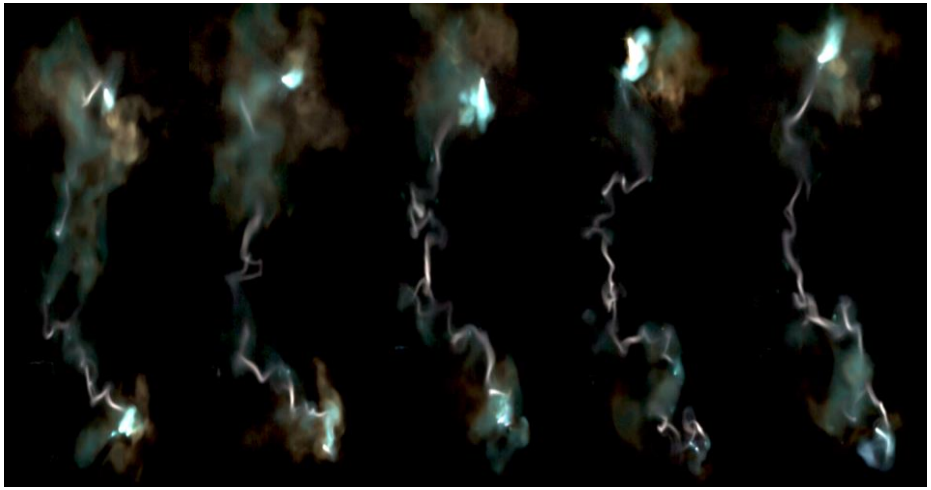
2.3 Wind effects on the arc trajectory

Wind in the opposite direction with arc motion



t_0 +0.102s t_0 +0.122s t_0 +0.142s t_0 +0.162s t_0 +0.182s

Different wind directions have different effects on secondary arcs. When the wind direction is opposite to the arc motion, the development of arc is inhibited. At this moment the arc burning time is also significantly increased.



t_0 +0.202s t_0 +0.222s t_0 +0.242s t_0 +0.262s t_0 +0.282s

As can be seen from the figure, there is arc root jumping phenomenon under the action of wind and thermal buoyancy. The arc column is stretched along the wind direction.

2.4 Extinction of the secondary arcs

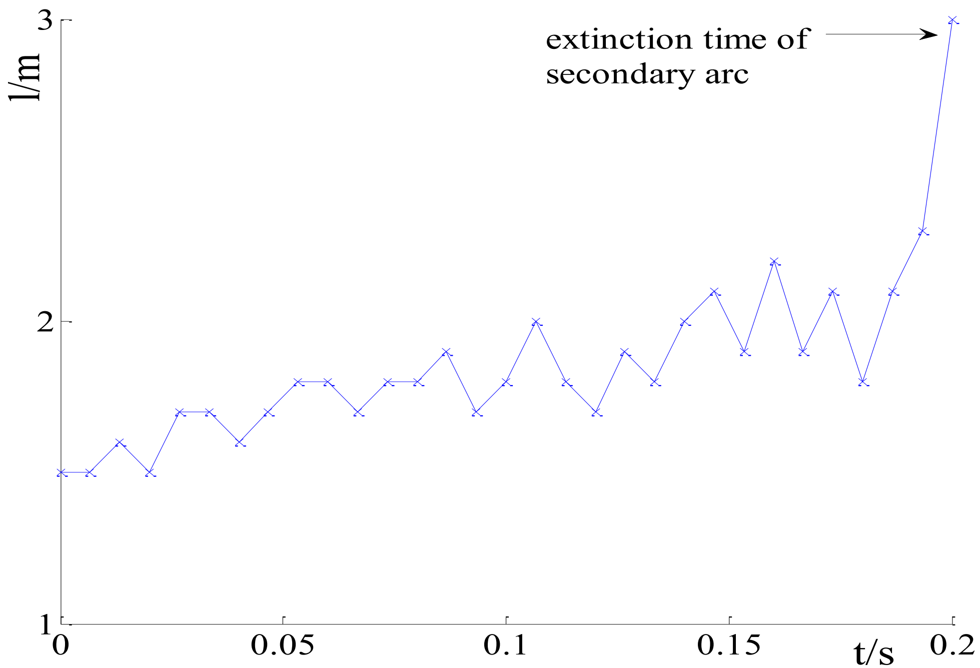


Fig.23 Relationship between the approximate length of the secondary arc column and the arcing time

- As the moving direction of each segment of the arc column is random and different, the overall effects of which result in continuous extending of the arc column length. The relationship between the approximate length of the secondary arc column and the arcing time is shown in the left figure. It can be found that the total length of the secondary arc column increases slowly at the early stage of the arcing process, but it rises steeply before the arc is extinguished.

2.4 Extinction of the secondary arcs

Table 1 Extinction time of secondary arc

Secondary arc current	Recovery voltage gradient	Wind speed	Average extinction time	90% extinction time
45A	1.6kV/m	0-0.5m/s	Quickly extinguished	-
90A	3.0kV/m	0-0.5m/s	Quickly extinguished	-
120A	2.8kV/m	0-0.5m/s	Quickly extinguished	-
	3.9kV/m	0-0.5m/s	Quickly extinguished	-
150A	3.9kV/m	0-0.5m/s	0.045s	0.065s
	5.4kV/m	0-0.5m/s	0.159s	0.243s
180A	3.7kV/m	0-0.5m/s	0.176s	0.245s
	4.7kV/m	0-0.5m/s	0.220s	0.382s
240A	5.4kV/m	0-0.5m/s	0.359s	0.468s
	7.0kV/m	0-0.5m/s	0.479s	0.884s

2.5 Extinction time of the secondary arcs with different compensation schemes

Uncompensated

Secondary arc current	Recovery voltage gradient	Average extinction time	90% extinction time
15A	17.1kV/m	0.112s	0.168s
	21.9kV/m	0.085s	0.136s
	30.5kV/m	0.128s	0.168s
30A	17.1kV/m	0.200s	0.278s
	21.9kV/m	0.232s	0.356s
	30.5kV/m	0.280s	0.318s

Under-compensated

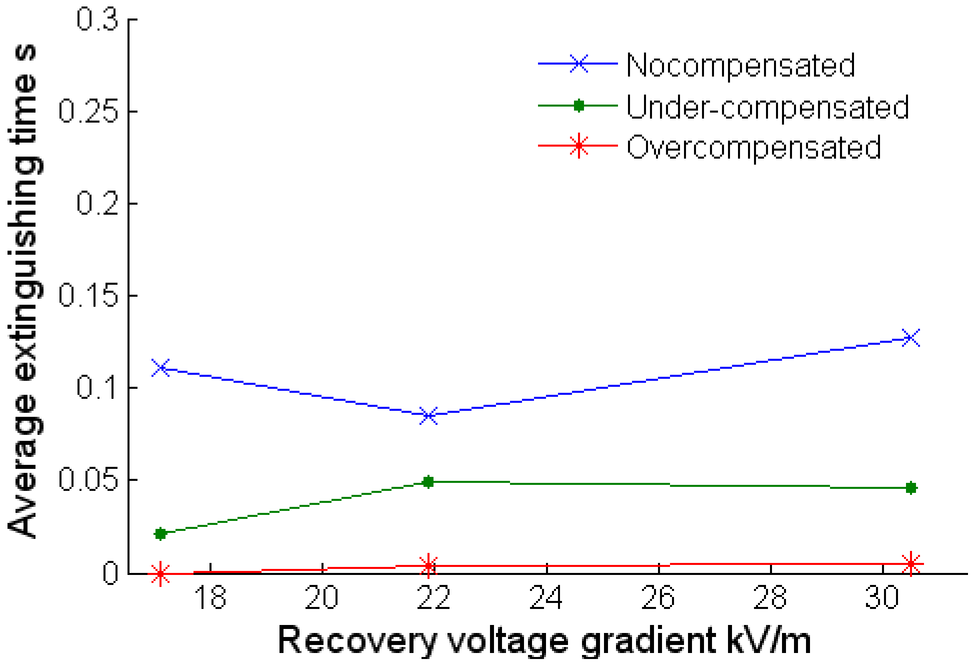
Secondary arc current	Recovery voltage gradient	Average extinction time	90% extinction time
15A	17.1kV/m	0.021s	0.056s
	21.9kV/m	0.049s	0.119s
	30.5kV/m	0.046s	0.097s
30A	17.1kV/m	0.050s	0.078s
	21.9kV/m	0.096s	0.128s
	30.5kV/m	0.110s	0.166s

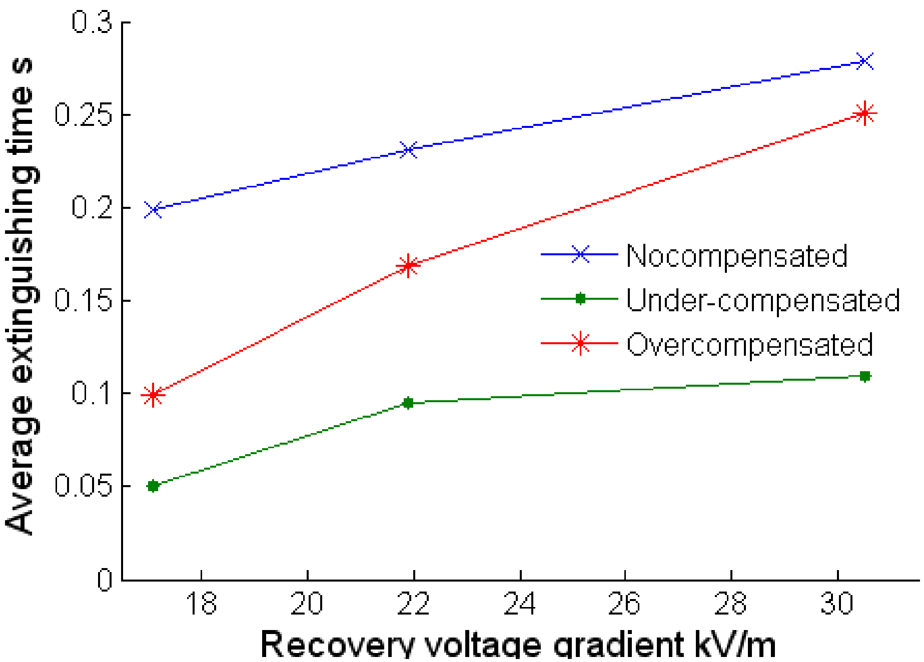
Overcompensated

Secondary arc current	Recovery voltage gradient	Average extinction time	90% extinction time
15A	17.1kV/m	Quickly extinguished	-
	21.9kV/m	Quickly extinguished	-
	30.5kV/m	Quickly extinguished	-
30A	17.1kV/m	0.099s	0.100s
	21.9kV/m	0.169s	0.234s
	30.5kV/m	0.2517s	0.2943s

2.5 Extinction time of the secondary arcs with different compensation schemes

Extinction time of the secondary arcs with different compensation schemes



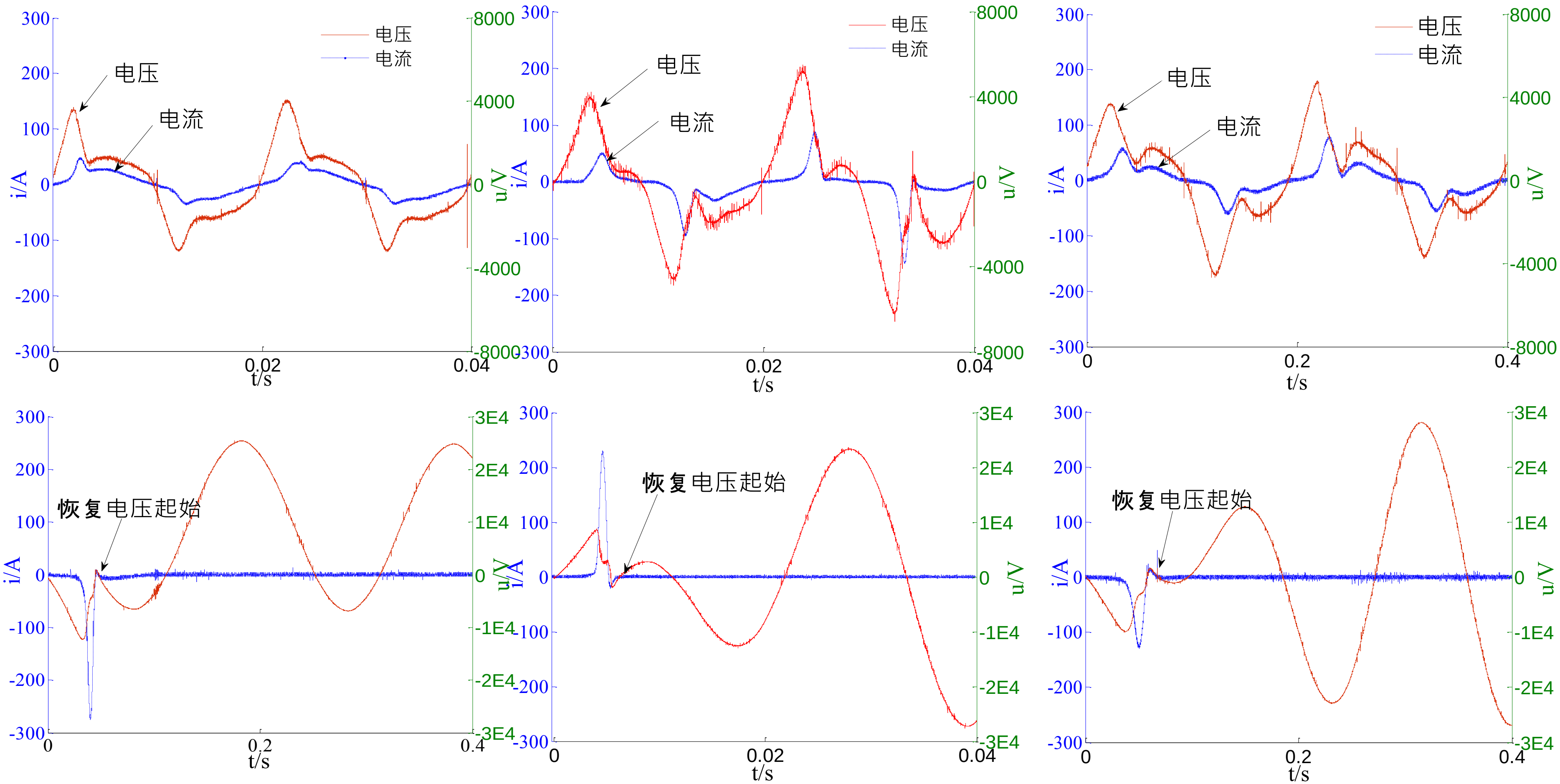


- With the increase of secondary arc current and recovery voltage, the extinction time becomes longer. Without compensation scheme is the longest of all. Under appropriate compensation conditions, the arc extinction time can be greatly shortened. With different degrees of compensation, the difference is sensible.

2.5 Extinction time of the secondary arcs with different compensation schemes

Current and recovery voltage with different compensation schemes

Uncompensated ***Under-compensated*** ***Overcompensated***



2. Experimental study on secondary arc physics

Summary

1. The motion of the anode arc root, cathode arc root and arc column is different. Short-circuit and induced phenomenon often occur during the process.
2. Wind presents an important influence on secondary arcs. When in the same direction, it can speed up the arc extinction.
3. The length of the secondary arc is closely related to arc extinction.
4. With different degrees of compensation, the extinction time differs a lot. With appropriate compensation, the arc extinction time can be greatly shortened.

Contents

3. Dynamic Modeling of the Secondary Arcs

A. Establishment of the mechanical model

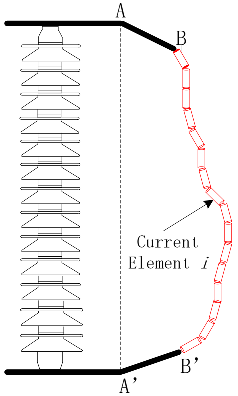


Fig.1 Cascaded chain model for secondary arcs.

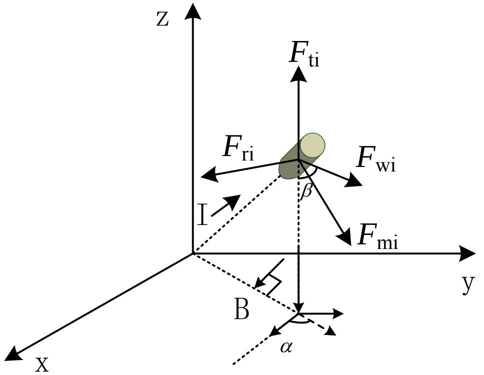


Fig. 2 Mechanical model of a single current element.

- Digital simulation of the secondary arc motions is further carried out based on the dynamic model proposed above, with a view to characterizing the spatial movement and evolving mechanism of the secondary arcs.

3. Dynamic Modeling of the Secondary Arcs

B. Simulation considering thermal buoyancy

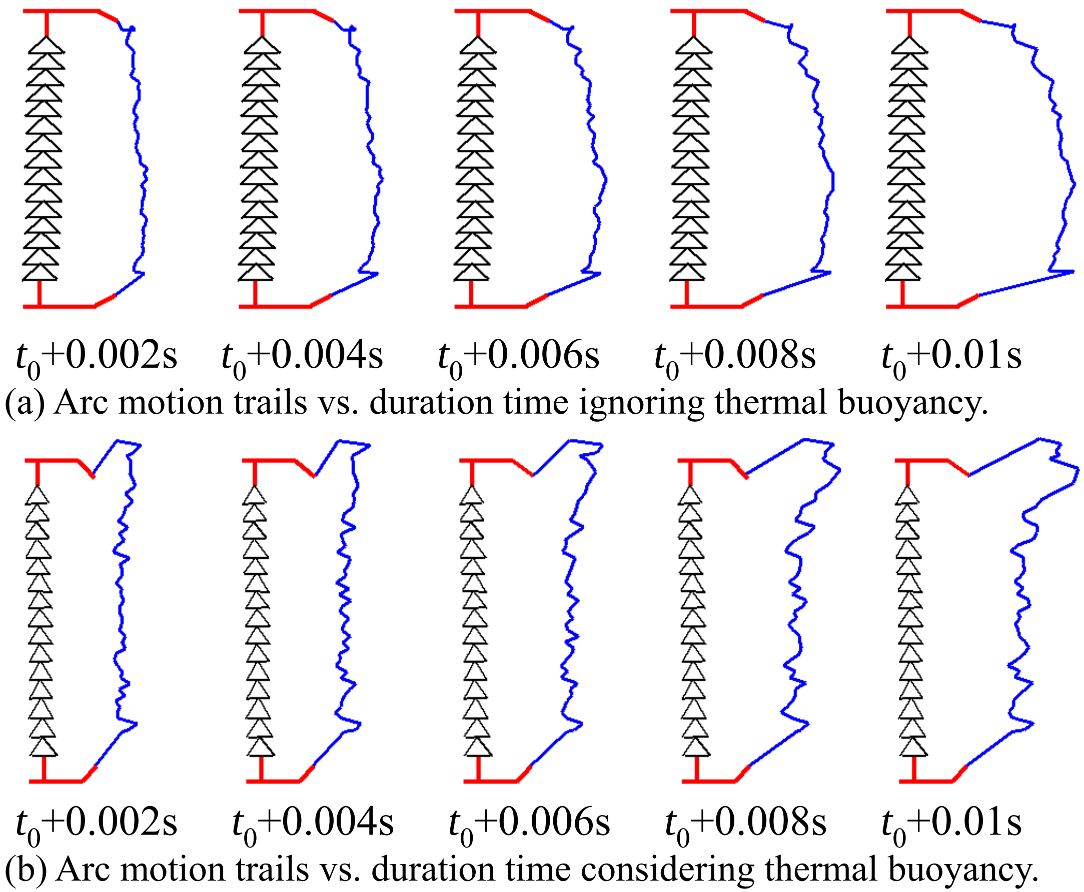


Fig. Simulated motion trails of the secondary arcs for ignoring thermal buoyancy (a) and considering thermal buoyancy (b).

- **As can be seen from the figures, the imposed magnetic force on the secondary arc is not a strong one due to small arc current, and the secondary arc shape changes little in a short time. If without thermal buoyancy, there is no obvious upward arc moving except a little displacement caused by the magnetic force, but with stress by thermal buoyancy, the secondary arc is driven upward with extended tendency.**

3. Dynamic Modeling of the Secondary Arcs

C. Simulation considering wind force

- **The motion trails of the secondary arc under wind force are shown in the Figure below, in which the wind speed is set as 1.5m/s while the direction is opposite to the secondary arc motion direction.**

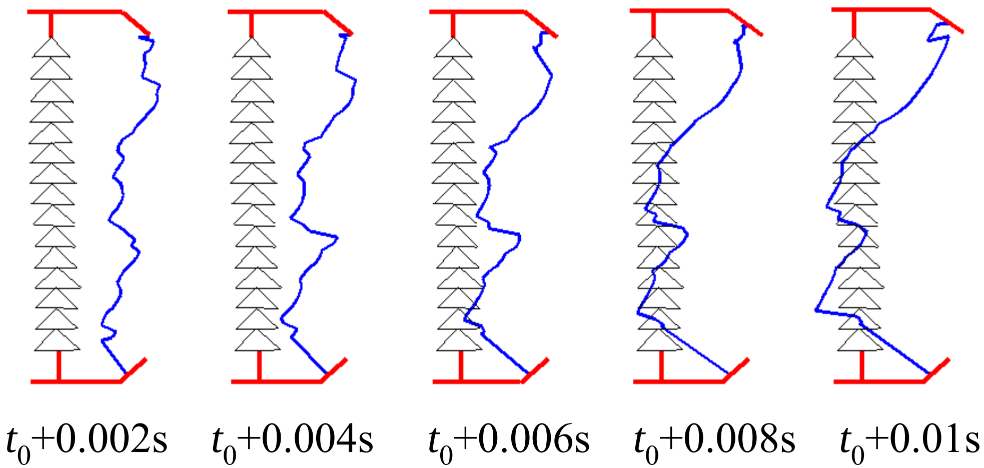


Fig. Simulated motion trails of the secondary arc under stress of wind load.

- **Under wind force, the motion trail of the secondary arc experiences large variations, and the middle of the arc column is evidently inflected along the wind direction while the secondary arc length is elongated quickly.**

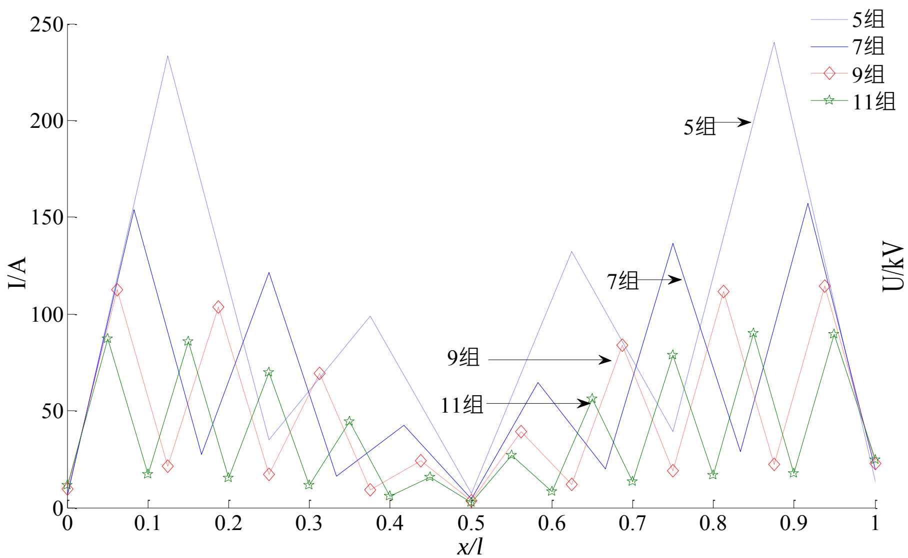
Summary

1. A dynamic model is established and digital simulation of the secondary arc motions is further carried out.
2. Simulation with thermal buoyancy and wind force are compared and it shows quite good coincidence with the experiments.

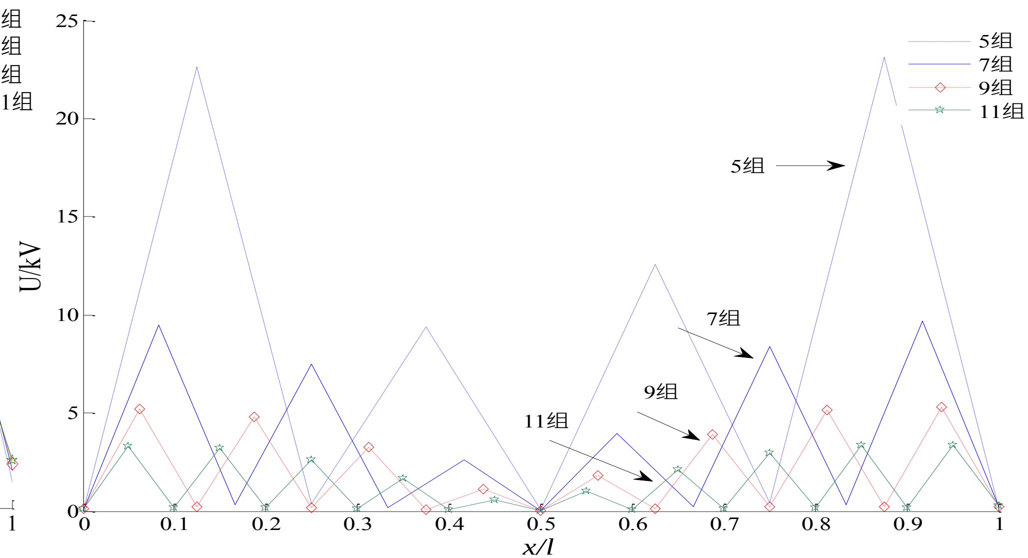
Contents

4. Suppressing methodology of secondary arc

4.1 Suppressing methodology with high speed grounding switches



(a) Secondary arc current



(b) Recovery voltage

- With multiple sets of high speed grounding switches, the secondary arc current and recovery voltage can be greatly reduced.

4. Suppressing methodology of secondary arc

4.2 Suppressing methodology based on an impedance paralleled to line circuit breaker

- A novel method for suppressing secondary arc based on an impedance paralleled to line circuit breaker is proposed.

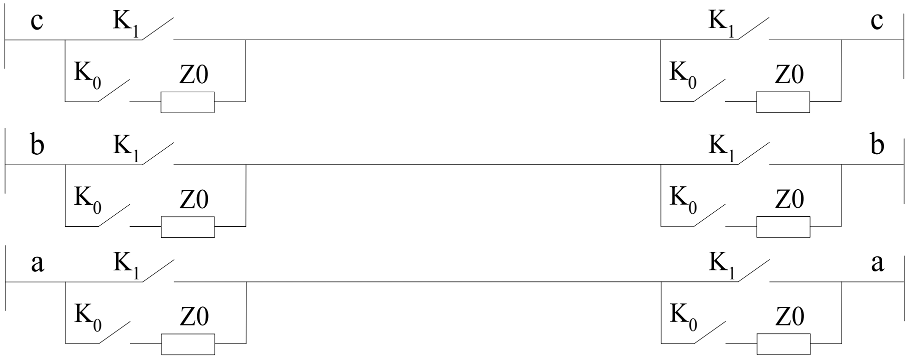


Fig. Schematic diagram of the novel suppressing topology.

- For normal operations, K_1 is closed and K_0 is open, while for fault conditions, the line circuit breakers K_1 on both sides of the faulty phase will trip and then K_0 immediately closes to insert the parallel impedance into the fault phase.

4. Suppressing methodology of secondary arc

4.2 Suppressing methodology based on an impedance paralleled to line circuit breaker

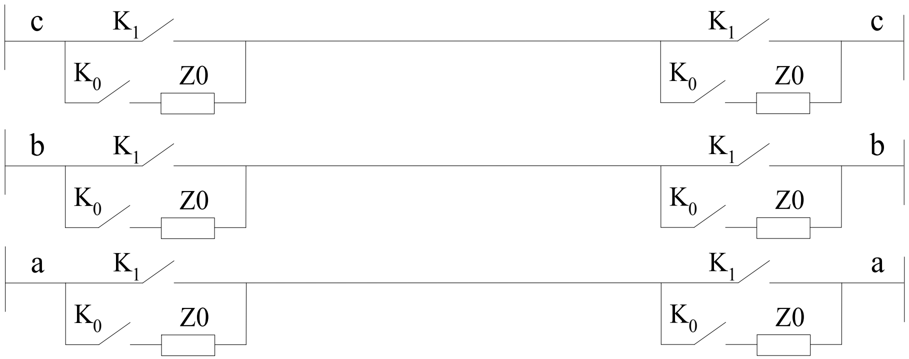


Fig. Schematic diagram of the novel suppressing topology.

- With proper setting of the parallel impedance Z_0, the formed current by electromagnetic coupling from the healthy phases and the injected current from the faulty phase may possess equal amplitude but with inverse phase angle, as a result, the aggregate secondary arc current will approach zero so as to accelerate extinction of the secondary arcs.

4. Suppressing methodology of secondary arc

Summary

1. With multiple sets of high speed grounding switches, the secondary arc current and recovery voltage can be greatly reduced.
2. A novel method for suppressing secondary arc based on an impedance paralleled to line circuit breaker is proposed, but awaiting further experimental verifications

Contents

5. Conclusion

- The Secondary arcs of the half wavelength transmission lines is different from the ordinary transmission lines and need detailed study.
- Experiments are carried out focusing on the secondary arc physics, Unique motion characteristics are discovered.
- Spatial Dynamics Modeling is adopted to study the motion mechanism of the secondary arcs and it shows good coincidence with the experiments.
- Suppressing methodology of the secondary arc with high speed grounding switches is proved to be effective, and a novel method based on an impedance paralleled to the line circuit breaker is proposed.

Thank You !