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# CHARGE VIBRATION BEHAVIOUR IN POLYIMIDE UNDER THE PULSE VOLTAGE WITH DIFFERENT RISE AND FALL TIMES

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**Abstract:** High-voltage electronic equipment is widely used in power systems, which normally operate under the pulse voltage condition. However, compared to DC or AC stress, the electrical insulation suffers a more severe ageing process under a pulse voltage with steep edges and so may cause electrical equipments to fail early. The charge behaviour in polyimide under the pulse voltage with different edge times was investigated in this study. The experimental results show that charges vibrate at the pulse edge, while the amplitude of charge vibration increases with decreasing edge times. Furthermore, the detected vibration signal is strong within the nanosecond edge times, while being negligible in the microsecond range. Notably, the amplitude of charge vibration at the falling edge is larger than that at the rising edge in the presence of the column-plate electrode. It is believed that the resultant force acting on the charge increases drastically at the pulse edges, leading to the charge movement and the generation of ultrasonic waves, with the resultant force becoming larger when the edge times decrease. Charge vibration behaviour is harmful to the microstructure of insulation materials, and so it may be concluded that the rise and fall times of the pulse voltage play an important role in insulation failure.

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## 1. Introduction

With the development of high-voltage direct current transmission projects and the large-scale application of new energy power generation and grid connection, the high-voltage (HV) electronic technology plays an increasingly important role in the transmission and distribution network. HV power electronic equipment can realise flexible control and free conversion of electric energy. It can also reduce the volume of power transmission and transformation equipment, which improves the transmission capacity and stability of the system [1, 2].

Power electronic equipment is generally operated under high-frequency pulse voltages for long periods. On the one hand, the power electronic technology, such as pulse width modulation (PWM), is applied to realise flexible control of electronic equipment by subjecting to a high-frequency pulse voltage [3, 4]. For example, the power electronic transformer is a new type of transformer that combines the power electronic technology with a high frequency transformer. Its core component, the high frequency transformer, works under the high-frequency pulse voltage because of rectifying and inverter circuits. On the other hand, the power electronic devices generate the pulse voltage and current with steep rise time at the time of turn-on and turn-off [5]. The polyimide (PI) film is widely used for insulation in different kinds of HV power electronic equipments, such as the inverter-fed motor, power electronic transformer and HV insulated gate bipolar transistor (IGBT) [6, 7]. Thus, the stability and electrical strength of PI under the pulsed voltage is important for the safe operation of such HV power electronic equipments.

However, electrical insulation is more prone to failure under the pulse voltage than under DC and AC voltages. It is a very important feature that the pulse voltage at the rising and falling edges has a very rapid change in the amplitude compared with AC or DC voltages, and the rise and fall times can reflect this characteristic clearly. Here, the rise generally means the time interval that a pulse rises from 10% to 90% of its peak amplitude while the fall time is inverse. P. Facinelli compared the initiation voltage of an electric tree under sinusoidal and pulse voltages, and the result showed that the initiation voltage of the electrical tree is lower under the pulse voltage [8]. Peng Wang investigated the partial discharge (PD) characteristics under a pulse voltage. The results showed that the PD magnitude and insulation endurance under repetitive square wave voltages are around 10 times and one-third times of those under sinusoidal voltages (the frequency of both is 50 Hz) [9]. Furthermore, the PD magnitude and high frequency energy of PD pulses increases with increasing slew rates (from 200 to 400 ns), which leads to a decrease in the average lifetime of insulation [10, 11]. Shin

Nakamura studied the electrical treeing in silicone gel under the pulse voltage with the rise time from 10 ns to 10  $\mu$ s and the results show that the treeing length is longer when the rise time is shorter [12]. It indicates that the pulse voltage causes more damage to insulation and that the rise time of the pulse voltage has an important effect on the insulation lifetime, which puts forward higher requirements for PI films [13–15]. Thus, it is necessary to clarify the mechanism of insulation failure under the pulse voltage with different rise and fall times, in order to improve the reliability of power electronic equipment.

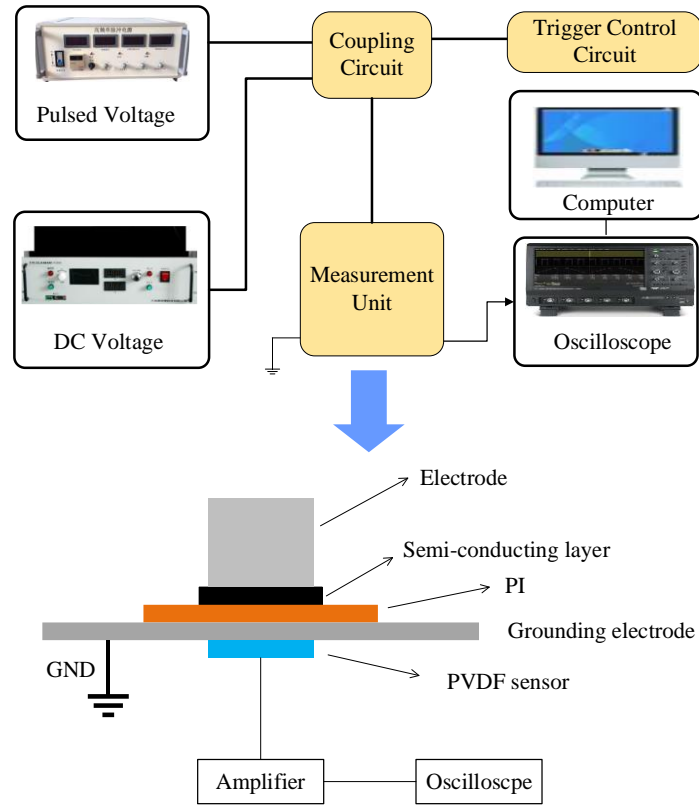
Charge accumulation is a very important factor in the acceleration of insulation deterioration [16–18], which distorts the electric field, causing flashover [19–22] and promoting the initiation and growth of the electrical tree [23]. Previous research has illustrated that the charges may accelerate under the pulsed voltage (100–300 Hz) and collide with the molecular chain, breaking the microstructure of the insulation material and resulting in the increase of the fractal dimension of the electrical tree [24]. Ying Liu studied the characteristics of electrical tree initiation under the DC and pulse voltage (with a maximum amplitude of 30 kV and the edge time adjustable from ns to  $\mu$ s). The results showed that the electrical tree can hardly be generated and that the tree initiation voltage is very high under the DC voltage, while the electrical tree grows faster and has a lower initiation voltage under the pulse voltage [25]. It is believed that the steep pulse rising edge can stimulate charge detrapping, releasing a large quantity of electro-mechanical energy quickly, which will break the molecular chains and induce the electrical tree [26]. Kai Zhou investigated the relationship between the space charge and PD characteristics under the pulse voltage and the results illustrated that the decrease in pulse rise time (from 10 to 1  $\mu$ s) enhances the memory effect of the space charge leading to more intense PD activities [27]. M. Fukuma reported on an increase of the space charge density with the decrease in the rise time ( $|dV/dt|$  from 3040 to 434 kV/s) and it is believed that a larger slope may enhance the efficiency of charge provision or leave less time for charge recombination [28].

It can be inferred from the above studies that the rising and falling edges of the pulse voltage have a triggering effect on insulation failure, and this impact is related to special charge behaviours occurring at the pulse edges, due to the rapid change in the voltage amplitude. The rise and fall times depend on the performance of switching devices and the external circuit structure. The inductance and capacitance of the external circuit make the rising and falling edges slow and its degree of influence depends on the time constant of the circuit. With the development and application of the wide-bandgap semiconductor silicon carbon (SiC) and gallium nitride (GaN), the power and switching frequency become much higher than in conventional Si semiconductor devices [29] and can generate a pulse voltage with shorter rising and falling times [30, 31]. The shorter rise time helps to increase the frequency of the switching devices and thus improves the efficiency of the power electronic equipment. But this requires higher insulation strength. Thus, charge behaviours at the nanosecond rising and falling edges need to be investigated for further understanding of the mechanism of insulation degradation under the pulse voltage. However, the current research mainly focusses on the accumulation and decay characteristics of the charge under the pulse voltage, while the dynamic charge characteristics at the rising and falling edges are still not clear. Thus, it is important to clarify the motion mechanism of the space charge at the pulse edge.

In this study, an experimental set up has been built to probe the electro-mechanical response under the pulsed voltage with different rise and fall times. The experimental results show that there exists a special charge behaviour at the pulse edges, which has a close relationship with the rise and fall time. The mechanism of charge behaviour at the pulse edges is analysed from the perspective of the resultant force acting on the charge.

## 2. Experiment Setup

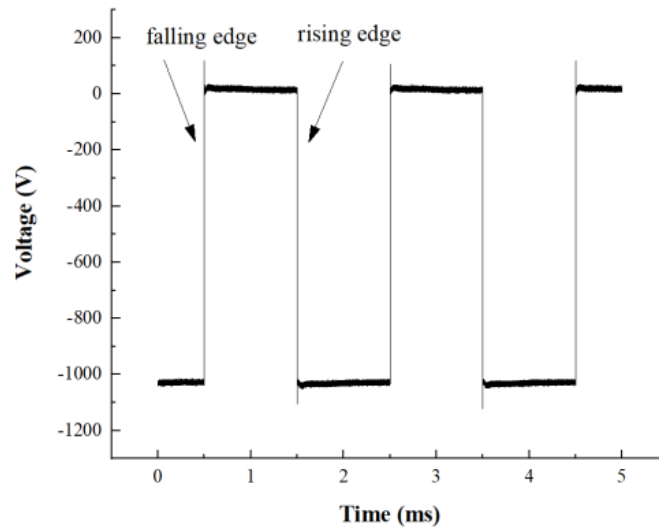
In this study, a method to investigate the electro-acoustic response at the pulse edge is proposed. The structure of the charge measurement unit is shown in Figure 1. The experimental system is composed of a high-voltage pulse source, a DC power supply, a coupling circuit, a trigger control circuit, a charge measurement unit, an oscilloscope and a computer. The high-voltage pulse source can generate a pulse voltage with rise and fall times from the nanosecond to the microsecond level. The trigger control circuit can achieve a space charge measurement at the rising and falling edges and the DC and pulse voltages are superimposed of the coupling circuit. The measurement unit is mainly composed of an upper electrode (applying a high voltage), a semi-conducting layer, PI insulation, a grounding electrode, a PVDF sensor, and an amplifier, in which the upper electrode is a copper cylindrical electrode with a diameter of 15 mm and the grounding electrode is a flat aluminium electrode with a diameter of 100 mm. In addition, the whole electrode system is put in a confined coaxial space to avoid interference.



**Figure 1. The illustration of experimental system**

If the pulse rising and falling edges have an effect on charge behaviour, it may lead to space charge vibration and generate an ultrasonic waveform. The ultrasonic waveform passes through a grounding electrode and acts on the polyvinylidene fluoride (PVDF) piezoelectric sensor, converting acoustic signals to electrical signals. In this way, the charge dynamic behaviours at the rising and falling edges can be studied.

In this experiment, a square-wave pulse voltage with a frequency of 500 Hz, an amplitude of  $\pm 1$  kV and a duty cycle of 50% was applied to the PI film (Kapton 500 HN, a standard series without nano-particles and coating) with a size of 5×5 cm and thickness of 125 $\mu$ m. The waveform of the negative pulse voltage is shown in Fig. 2. In this study, the 'rising edge' denotes the increase in the voltage amplitude and the 'falling edge' represents the decreasing amplitude of the pulse voltage. For example, the rising edge of negative pulse voltage is the voltage from 0 kV to -1 kV and the falling edge is the voltage from -1 kV to 0 kV. The rise and fall times were set to 100 ns, 200 ns, 400 ns, 1  $\mu$ s, 2  $\mu$ s, 4  $\mu$ s, 10  $\mu$ s, 20  $\mu$ s, 50  $\mu$ s, 80  $\mu$ s, 100  $\mu$ s, 150  $\mu$ s and 200  $\mu$ s.



**Figure 2. Waveform of pulse voltage applied to the polyimide**

### 3. Experiment Results

#### 3.1. Acoustic response at pulse edges

Figure 3 shows the experimental results under the square-wave pulse voltage. The red curve in Figure 3 is the electro-acoustic signal measured from the PVDF sensor that reflects charge vibration. It can be seen from the picture that there exist vibration signals at the pulse edge. However, no signal is detected during the constant voltage stage. Figure 4 shows the electroacoustic waveform measured by the PVDF sensor at the rising and the falling edge, shown inside the rectangular box in Figure 3. As shown in Figure 4, the electro-acoustic waveform can be divided into three parts. This phenomenon indicates that the rising and falling edges of the pulse voltage indeed have a special effect on the space charge.

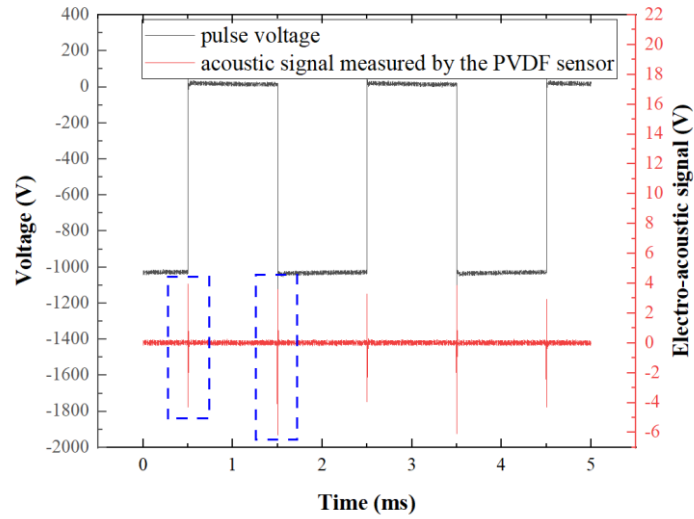


Figure 3. Electro-acoustic signals measured by the polyvinylidene fluoride sensor

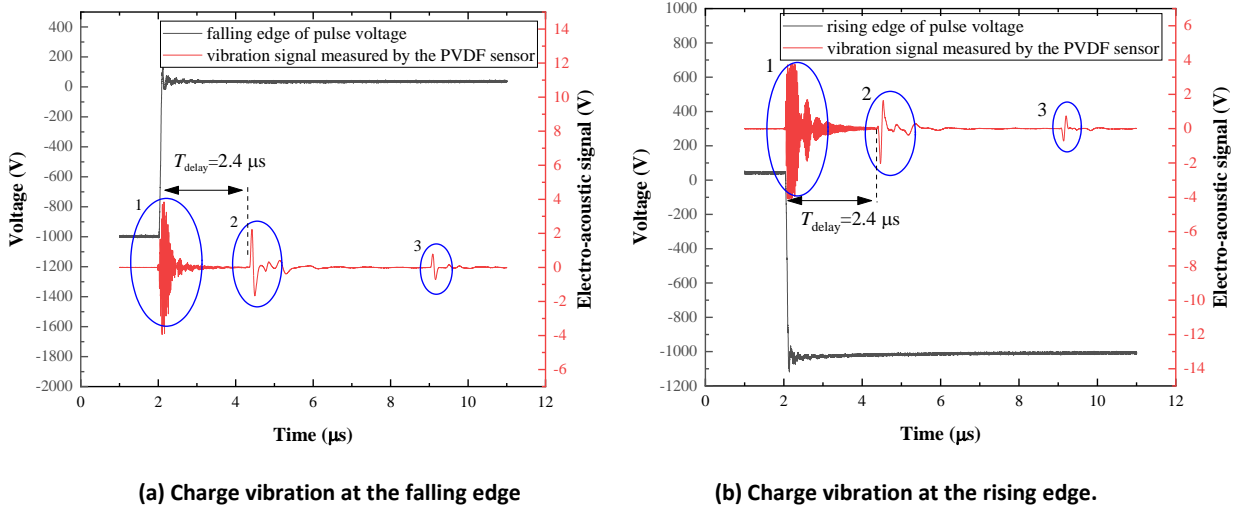


Figure 4. Waveform measured from the polyvinylidene fluoride sensor under -1 kV pulse voltage with 100 ns rise and fall time.

Part 1 of the waveform corresponds to the electromagnetic noise caused by the step of the electric field at the pulse edge. The starting position of the electromagnetic oscillation is at the same position as the inflection point of the rising edge because the speed of the electromagnetic wave is very fast, and is close to the speed of light.

Part 2 may be the ultrasonic signal generated by the charge because some delay time is needed for the PVDF sensor to measure the ultrasonic signal. The theoretical delay time can be calculated and compared with the delay time measured by the oscilloscope to determine whether it is generated by the charge. The signal generated by the charge near the grounding electrode first propagates to the sensor and the schematic of the propagation path is shown in Figure 5.

In Figure 5,  $x$  is the propagation distance of the ultrasonic wave, which is the thickness of the grounding aluminium electrode (15 mm). The speed  $v$  of the ultrasonic wave in aluminium is approximately 6300 m/s. The delay time  $T_{delay}$  can be calculated using the following equation:

$$T_{delay} = \frac{x}{v} \quad (1)$$

The theoretical delay time is approximately 2.4  $\mu$ s, which is consistent with the actual value of the signal measured using the oscilloscope. Thus, it can be determined that the second part of the waveform is generated by charge vibration. The shape of the third part is the same as that of the second part and the delay time between parts 2 and three is about 4.8  $\mu$ s, that is twice the propagation time of sound waves in the aluminium plate. Therefore, it can be deduced that part 3 is the catadioptric waveform of part 2 in the aluminium electrode.

Since there is an electro-acoustic response that reflects the charge vibration at the rising and falling edges, it can be used to probe the changes in the charge behaviour with the variation of rising and falling edges of the pulsed voltage, which can help clarify the mechanism of insulation failure under the pulsed electric field.

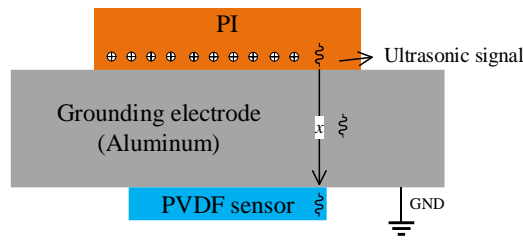


Figure 5. Schematic of the propagation path of the ultrasonic waveform generated by the charge

### 3.2. Charge vibration laws with different rise and fall times

The electro-acoustic signal amplitude measured from the piezoelectric sensor reflects the vibration level of the space charge. Under the same condition of the voltage amplitude, the higher the voltage measured, the stronger will be the force charge generated and the more will be the damage caused to the microstructure of insulation materials.

Figure 6 shows the electro-acoustic waveform under the  $-1$  kV pulse voltage with the rise times of 100 ns, 400 ns, 1  $\mu$ s and 10  $\mu$ s. The first peak is the space charge near the grounding electrode (closest to the PVDF sensor) which demonstrates that its attenuation of amplitude is the smallest. It can therefore be used to reflect the change of the charge characteristics. It is apparent from the figure that there is a dramatic decline of the charge vibration amplitude: the vibration amplitude is 1.9 V at the 100 ns rising edge while it decreases to 0.067 V at the 10  $\mu$ s rising edge. Different rise and fall times were applied to clarify the decreasing trend of the charge vibration amplitude and the results are shown in Figure 7.

Figure 7 shows the variation of the electro-acoustic signal amplitude with different rise and fall times under the negative and positive pulse voltage, respectively. A logarithmic X-scale is adopted to show the effect of changes in rise and fall times over several orders of magnitude. It can be seen from the graph that the amplitude of charge vibration decreases with the increase in rise and fall times. In particular, the vibration amplitude is much higher at the nanosecond rise and fall times. Then, the response drops sharply when the rise and fall times change from the nanosecond to the microsecond range, and the vibration signal is very weak at the microsecond level, meaning that it is almost undetectable. The transition zone is approximately between 1 and 5  $\mu$ s, and the vibration amplitude is nearly zero when the pulse edge time is longer than 50  $\mu$ s.

The characteristic of pulse edges is sudden changes in the voltage amplitude and this can be accounted for by the absolute of the slope,  $\alpha = |dV/dt|$ . Thus, it is necessary to study the change law of the slope under different pulse edge times. Figure 8 shows the 200 ns falling edge of the negative pulse. The voltage variation is not linear: the slope first increases, arrives at a maximum point, then decreases gradually. The place where  $\alpha$  is the highest may have the greatest impact on charge behaviour.

To clarify the relationship between the pulse edge time and charge vibration, the maximum value of the absolute slope under different rise and fall times was calculated and the results are shown in Figure 9. It is apparent that the change law of the slope with the pulse edge time is similar to that of the charge vibration amplitude. The maximum slope is very large at the nanosecond rise and fall time, while it decreases rapidly with the increase in pulse edge time. When the rise and fall times increase to microsecond levels, the slope is small and the rate of decline slows down. This reveals that the vibration amplitude of the charge may be determined by the maximum value of the absolute slope of the pulse edge.

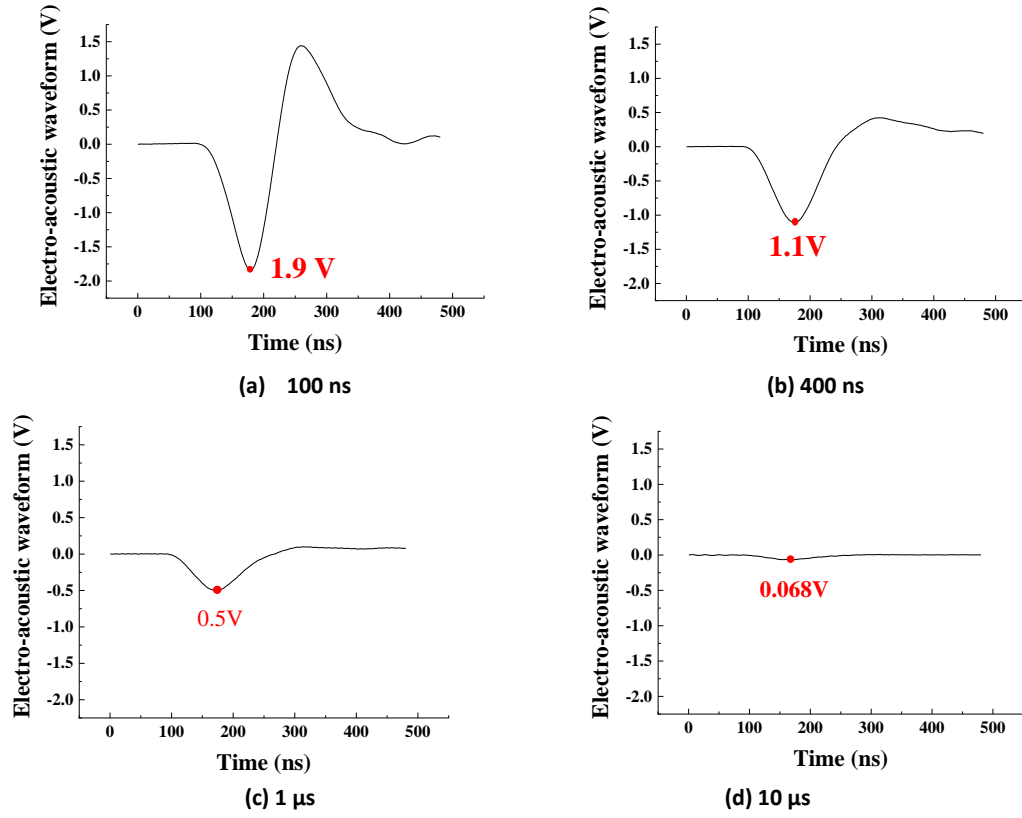


Figure 6. Electro-acoustic waveform under -1 kV pulse voltage with different rise times.

It can be seen from Figure 7 that the amplitude of the acoustic signal at the falling edge is larger than that at the rising edge, regardless of whether the polarity of the pulse voltage is negative or positive. However, the maximum value of the absolute slope is the same at the rising and falling edges. These features tend to show that the response is not only that due to capacitive charges.

There exists a period of high level to reach the falling edge and more charges are injected to the PI film during the high-voltage level stage. The charge density at the falling edge is larger than that at the rising edge, because the constant stage before the falling edge is in a high-voltage level stage while in a low-voltage level stage before the rising edge. Thus, the reason leading to the difference in the acoustic signal amplitude at the rising and falling edges may be that more charge accumulation enhances the overall effect of charge vibration. It can be concluded that the falling edge of the pulse voltage may cause more damage to the insulation material than the rising edge.

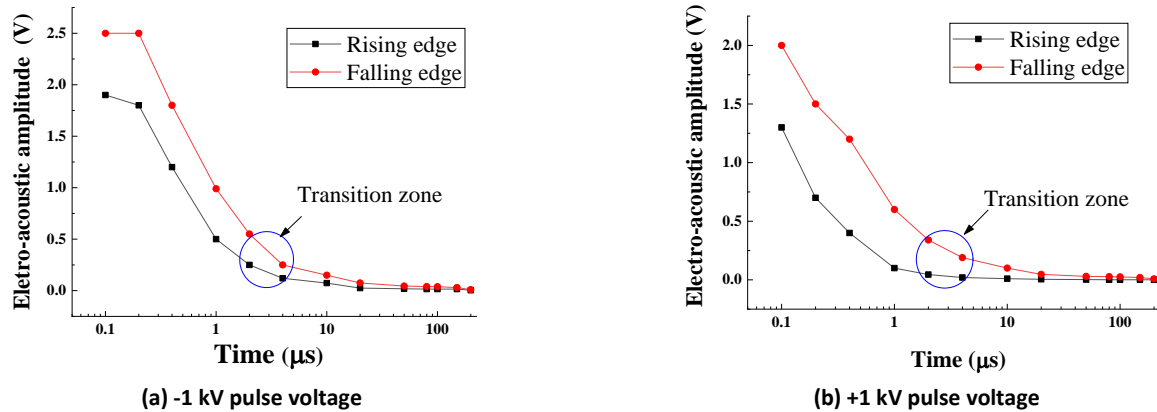


Figure 7. Electro-Acoustic signal amplitude at different rise and fall times under pulsed voltage. (a); (b).

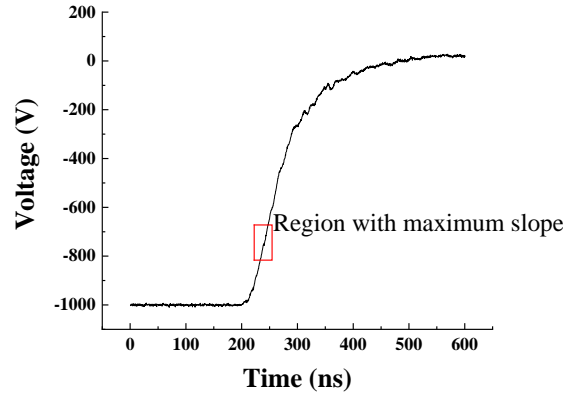


Figure 8. Change law of the absolute of slope at 100 ns negative pulse falling edge

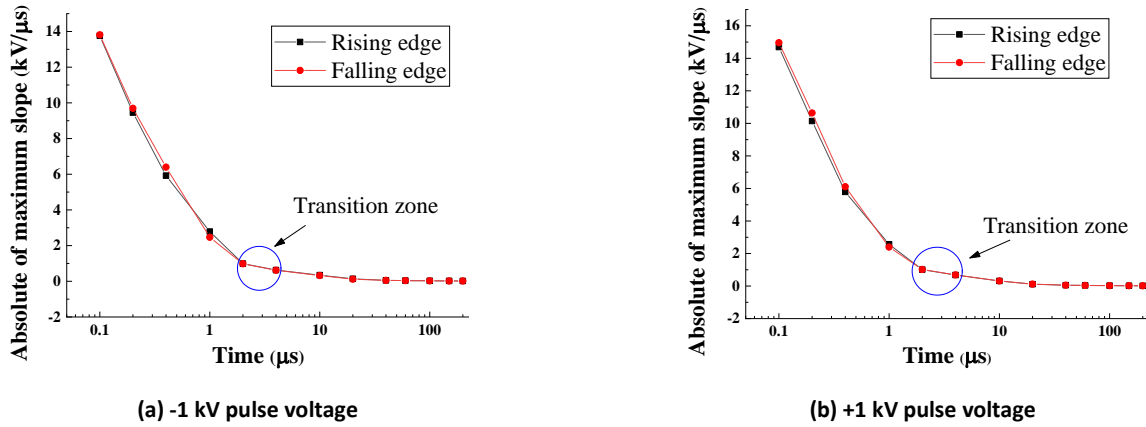


Figure 9. Maximum slope at different rise and fall times.

### 3.3. Charge vibration laws under the pulse superimposed dc voltage

Figure 10 shows the variation of the electro-acoustic signal amplitude with rise and fall times under the condition of the  $-1$  kV pulsed superimposed DC voltage to  $-1$  kV DC voltage and the  $1$  kV pulsed superimposed DC voltage to  $1$  kV DC voltage, respectively. With the superimposed DC voltage, the charge vibration amplitude increases compared with that under the merely pulsed voltage condition in Figure 7. The higher voltage injects more charge to the PI film and increases the total vibration effect.

Although the charge vibration amplitude increases with the superimposed DC voltage, the transition zone does not change showing the same change law as when the vibration amplitude decreases significantly due to change in the pulse edge time from nanosecond to microsecond. The vibration amplitude decreases close to zero when the pulse edge time is longer than  $50 \mu\text{s}$ .

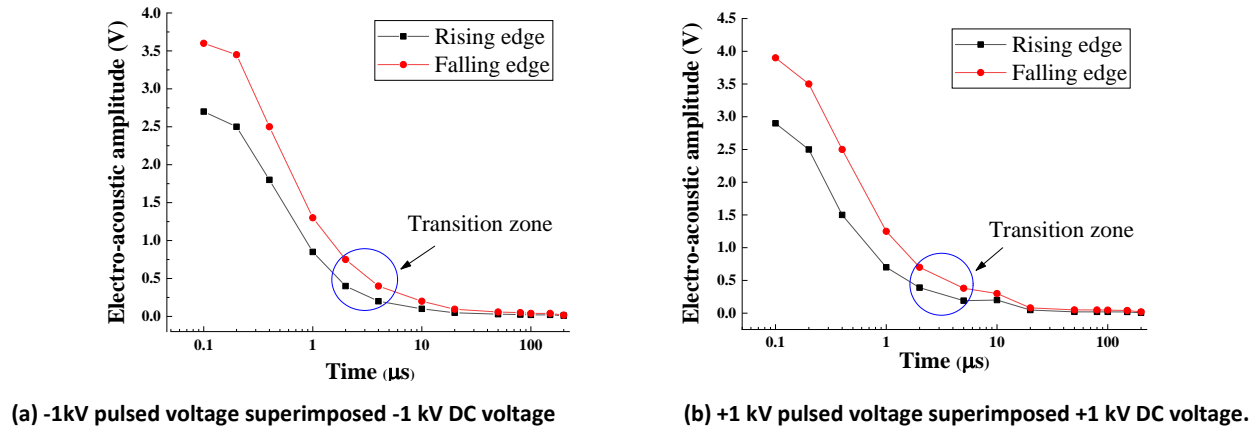


Figure 10. Electro-acoustic signal amplitude under the pulse superimposed DC voltage.



#### 4. Analysis of Charge Behaviour at Pulse Edges

##### 4.1. Mechanism of charge vibration

The signal measured from the PVDF sensor is caused by charge displacement and the movement of all objects occurs under the drive of the force. Thus, the resultant force acting on the charge can be analysed to clarify the mechanism of charge vibration at the rising and falling edges.

How the resultant force changes with the variations in rise and fall times can be roughly calculated by the kinetic energy theorem. The function of the kinetic energy theorem is described as follows:

$$F\Delta t = mv - mv_0 \quad (2)$$

where  $F$  is the resultant electrostatic force acting on the charge,  $\Delta t$  is the change of time,  $m$  is the quality of charge,  $v$  is the velocity of charge in the terminal state, and  $v_0$  is the velocity of charge in the initial state. The charge velocity can also be reflected from the voltage amplitude measured by the PVDF sensor: a charge with a larger velocity will generate a stronger ultrasonic wave and the higher voltage is measured by the PVDF sensor. In other words, the higher voltage signal represents the larger charge velocity.

Before the rising and falling edges (during the constant voltage stage of pulse),  $v_0$  and  $v$  are all approximately zero because no charge signal was measured. This means that the resultant force acting on the charge is small and the charge is in the equilibrium state. At the rising and falling edges, the charge vibrates and has a certain velocity. With the decreasing rise and fall times, the amplitude of charge vibration increases significantly, which represents that the charge has a larger velocity and the change in kinetic energy increases; while,  $\Delta t$  decreases. Thus, according to Equation (2), it can be calculated that the resultant force is larger with the rise and fall times decreasing.

The reason the resultant force acting on the charges increases with the decrease in pulse edge time is not clear. An analysis method based on the balance of forces acting on the charge has been proposed in a previous study [32]. This theory can also be applied to explain this phenomenon and the forces acting on the charge need to be further analysed to explore the variation of the resultant force with pulse edge time. Figure 11 shows two kinds of forces acting on the charge: the electrical field force and the other forces. The other forces can be summarised as ‘material stress’ and include the bondage of the nucleus and the electrons to the charge, the attraction and repulsion of other charges around etc. These forces depend on the relative distance between charges. Therefore, the magnitude of the material stress is related to the position of the charge: the material stress would remain constant if the charge position does not change.

The change of forces acting on the charge at the rising and falling edges is shown in Figure 12. Under the constant voltage stage of the pulse, the electric field force is balanced with the material stress. The resultant force is close to zero and the charges remain stationary. When the rising or falling edge is met, the electric field force can increase or decrease rapidly. The charge cannot migrate immediately when the rise or fall time is less than the relaxation time of the charge; thus, the material stress cannot change at once. Therefore, the equilibrium of the forces acting on the charge is broken and the resultant force suddenly increases at both the rising and falling edges, causing the charge to gain a large acceleration, move and generate the ultrasonic wave measured by the PVDF sensor.

With the rise and fall times increasing, the change of the electric field force becomes slower and the rise and fall times become closer to the relaxation time of the charge. The position of charges will make an adjustive shift, and change the relative distance from other charges. This allows the material stress to adjust, attempting to balance with the electric field force. Therefore, the resultant force acting on the charge will decrease with the increase in pulse edge time; as a result, the amplitude of charge vibration decreases.

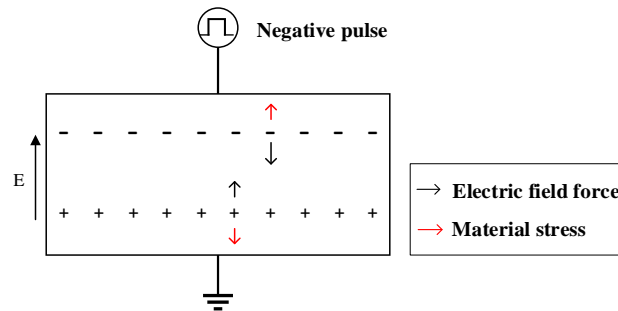


Figure 11. Forces acting on the charge.

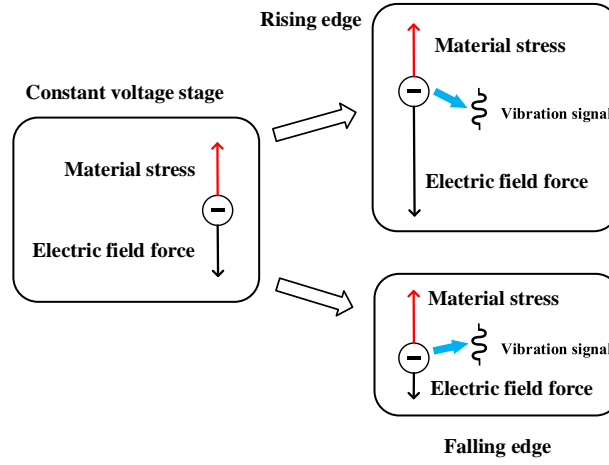


Figure 12. Change of forces acting on the charge at the rising and falling edge.

#### 4.2. Relationship Between Polarity of Charge Waveform and Resultant Direction

Figure 13 shows the electro-acoustic waveform at the 100 ns rising and falling edges of +1 and -1 kV pulse voltages, respectively. Comparing Figure 13a,b (or Figure 13c,d), it can be found that although the polarity of the pulse voltage does not change, the polarity of the voltage measured from the PVDF sensor is opposite to that at the rising and falling edges. Moreover, comparing Figure 13a,c (or Figure 13b,d), the polarity of the charge waveform is the same as that at the rising or falling edge despite the change in the polarity of the pulse voltage. This may be related to the movement direction of the charge.

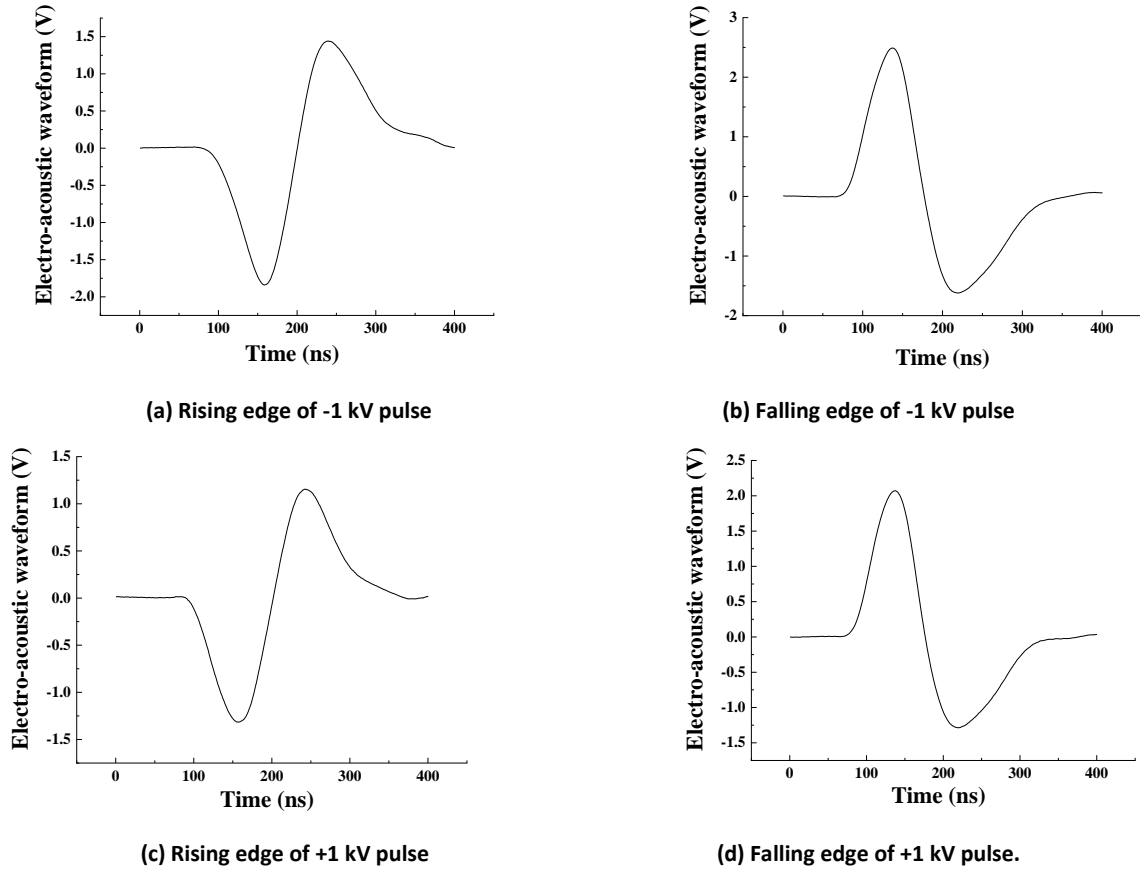


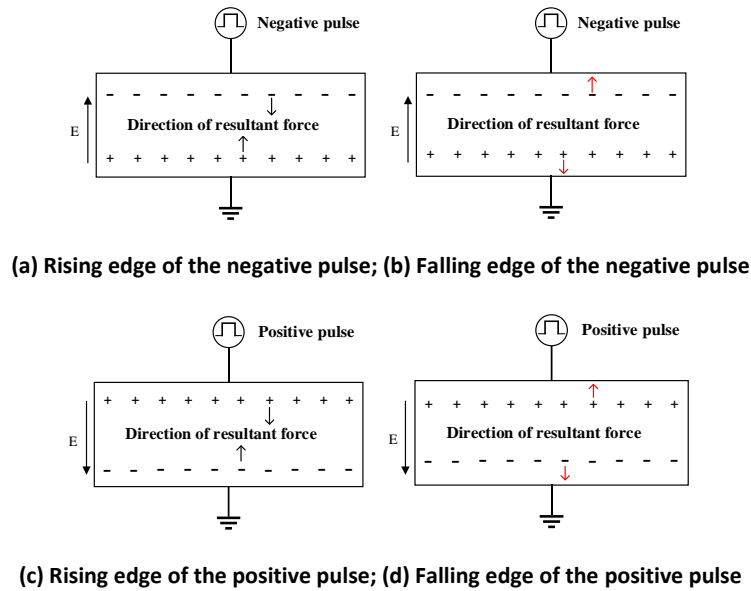
Figure 13. Electro-acoustic waveform measured by the polyvinylidene fluoride sensor at  $\pm 1$  kV pulse voltage at the 100 ns edge.

This phenomenon can also be explained using the force analysis theory. Figure 14 shows the movement direction of the charge. At the rising edge of the negative pulse voltage, the electric field force increases suddenly but the material stress changes slowly. This leads to the electric field force being greater than the material stress and the direction of

the resultant force is the same as that of the electric field force, which in turn will lead to the movement of the charge in the direction of the electric field force, as shown in Figure 14a. The directions of the electric field force acting on the negative charge near the cathode and the positive charge near the anode are reverse. Therefore, two charge peaks with opposite polarity are observed. On the contrary, the material stress is greater than the electric field force at the falling edge of the negative pulse voltage. Thus, the charge will move in the direction of the material stress, as shown in Figure 14b. This can also be used to analyse the charge movement behaviour at the rising and falling edges of the positive pulse. It can be seen that charges have an opposite movement direction at the rising and falling edges under both negative and positive pulses. This is consistent with the charge waveform having opposite polarities at the rising and falling edges (the comparison between Figure 13a,b or 13c,d).

In addition, although the polarity of the charge in the PI film is opposite under the negative and positive pulses, the movement direction of the charge with different polarities is the same at the rising or falling edge, as is shown in Figure 14a,c or 14b,d. This explains why the charge vibration waveform has the same polarity at the rising or falling edge of both negative and positive pulses.

Through the above discussion, it can be concluded that the polarity of the charge waveform obtained from the force analysis is consistent with that measured by the experiment. This also confirms that it is reasonable to analyse the charge vibration behaviour at the rising and falling edges from the perspective of the resultant force change.

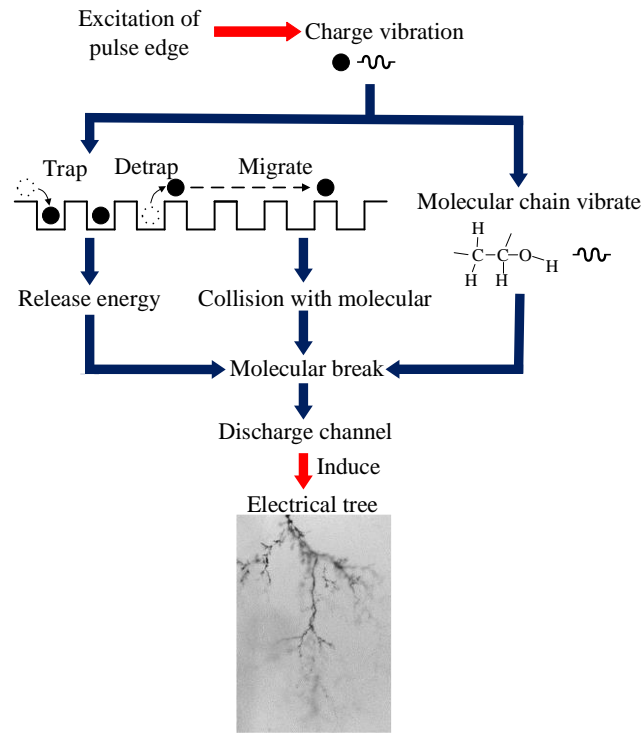


**Figure 14. Movement direction of charge.**

## 5. Discussion

Under the condition of the DC or constant voltage stage of the pulse, space charges injected from the electrode or produced by the ionisation of internal impurities are captured by the trap and the trapped charges are in the equilibrium state. When the rising and falling edge of the pulsed voltage arrives, they can deviate from the steady state due to the disturbing force and return to the equilibrium position after the force is removed [33]. The suddenly increased resultant force at the rising and falling edges acts as the driving force, which compels the charge to move and vibrate.

However, if the resultant force is strong enough or the force acts enough times, the charge may not be able to return to the equilibrium position. This could result in the charge being detrapped, followed by a large amount of energy being released in this process. As a result, the microstructure of the insulation may be broken by the released energy. Then, the detrapped charge will move back and forth under the action of the pulses edge, colliding with the molecular chain. The charges will migrate to another position after being detrapped, which leads to a more uneven electric field. Distortion of the local electric field will change the force distribution inside the insulation materials. The chemical structure of the molecular chain will be deformed under the action of the non-uniform force, resulting in the reduction of mechanical and electrical properties of the insulation material. The influence mechanism of the pulse edge on insulation degradation is shown in Figure 15.



**Figure 15. Influence mechanism of pulse edge on insulation degradation**

The behaviour of charge vibration at the rising and falling edges is harmful to the insulation material, which will accelerate the destruction of the insulating material microstructure. In the process of charge vibration, the charge will drive the molecular chain to vibrate in the same way. The molecular structure of the PI film will be damaged and cracked, resulting in a tiny crevice forming inside the insulation. This will drop the electrical strength and eventually lead to a breakdown. With the rise and fall times decreasing, charge vibration becomes more violent, which will cause more damage to the insulation material. The phenomenon that the charge vibration only exists at the condition of rising and falling edges instead of being at the constant voltage stage of the pulse voltage could be used to explain why the electrical tree has a lower initiation voltage and grows faster under the pulse voltage than that under the DC voltage, and the insulation has a shorter lifetime under the pulse voltage.

The analysis of the resultant force acting on the charges in this study is a preliminary explanation and is not yet mature. In further studies, the intrinsic mechanism of material stress needs to be investigated in a quantitative manner. Additionally, the quantitative descriptive relationship between the charge vibration amplitude and the degree of insulation degradation needs to be clarified, which could help formulate insulation standards under pulse electric fields. Based on the charge behaviour theory, an effective strategy to suppress charge vibration under the pulse voltage can be explored and proposed, in order to enhance the electrical properties and stability of the PI film and other insulation materials operated in high-voltage power electronic equipment.

## 6. Conclusion

Through the measurement of ultrasonic waves generated from the PI material by the piezoelectric transducer, the experimental results reveal that there exists the charge vibration behaviour at the rising and falling edges, and that the rise and fall times have an important effect on charge vibration. The main conclusions are as follows:

- (1) Space charge vibrates under the motivation of the pulse voltage at the rising and falling edges from the nanosecond to microsecond level. The amplitude of charge vibration increases with the decrease in the rise and fall times; and the degree of charge vibration at the nanosecond level of the rise and fall times is more severe than that at the microsecond level. It is believed that the pulsed voltage edge acts as a disturbance source on trapped charges, and breaks the equilibrium of the functional forces on charges. The sudden increased resultant force due to the rapid change of the electric field force results in charge movement and vibration. The resultant force decreases with the increase in rise and fall time, because of the adjustment of material stress. Furthermore, the vibration amplitude at the falling edge is higher than that at the rising edge, due to more charge accumulation.

(2) The charge vibration waveform at the rising edge has an opposite polarity to that at the falling edge and the polarity of the charge waveform is the same at the rising or falling edge despite the change in the polarity of the pulse voltage. The direction of the resultant force determines the movement direction of the charge and the latter determines the waveform polarity of charge vibration. Under the same polarity of the pulse voltage, the movement direction at the rising edge is opposite to that at the falling edge; and the movement direction of the charge is the same at the rising or falling edges with different polarities in the pulse voltage.

(3) Charge vibration is a harmful behaviour for insulation, which will destroy the microstructure of materials and induce the electrical tree initiation. In future studies, the quantitative descriptive relationship between the charge vibration amplitude and the degree of insulation degradation needs to be explored. Lastly, it is important to propose a strategy suppressing charge vibration, which can improve the insulation performance under pulse electric fields.

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