Article

Pulse Current of Multi-needle Negative Corona Discharge and its Electromagnetic Radiation Characteristics

Chuang Wang, Xi Chen*, Jiting Ouyang and Jialu Fu

State Key Laboratory of Mechatronics Engineering and Control, Beijing Institute of Technology, Beijing 100081, China; cunghens@163.com (C.W.); jtouyang@bit.edu.cn (J.O); luvivid@163.com (J.F.);

* Correspondence: chenxi@bit.edu.cn (X.C.); Tel.: +86-010-6891-8017

Featured Application: Authors are encouraged to provide a concise description of the specific application or a potential application of the work. This section is not mandatory.

Abstract: Negative corona discharges occur widely in high voltage transmission lines and charged aircraft, which can cause strong electromagnetic interference. Negative corona discharge is typically performed simultaneously at multiple discharge points. In this study, the current and its EM radiation characteristics of single-needle and multi-needle negative corona discharge in different conditions were tested. The current and electromagnetic radiation characteristics of the two discharge structures were compared. The dipole radiation model was established to analyze the EM radiation characteristics of the negative corona discharge.The results show that, It is only when the voltage reaches a certain threshold that the current and electromagnetic radiation fields of the multi-needle discharge structure will be superimposed and their amplitudes will increase significantly. The frequency of electromagnetic radiation signal does not change with the number of needles, cathode geometry and applied voltage, but only depends on ambient pressure. It provides a basis for detecting corona discharge sources under different conditions.

Keywords: corona discharge; Trichel pulse; multi-needle; EM radiation

1. Introduction

Corona discharge is a relatively low-energy discharge process that occurs only in a strong electric field near a small radius of curvature electrode[1,2]. Corona discharge is a common discharge phenomenon, which occurs in plasma generator, ozone generator, electrostatic precipitator, electrostatic printing, electrostatic charge of aerosol particles, high voltage transmission lines and charged aircraft[3–10]. Corona discharge is usually performed simultaneously in a multi-needle (multi-point) format[6,8,11]. Corona discharge is divided into positive corona discharge and negative corona discharge according to the difference of the electrode polarity of the small curvature radius in the discharge structure. Negative corona discharge currents exhibit a regular pulse form, called Trichel pulse[12], which can cause strong EM interference. On the one hand, multi-needle negative corona discharge can cause the loss of power high voltage equipment, radio interference and television interference[13]. On the other hand, multi-needle negative corona discharge electromagnetic radiation signals can be used as target signals for high-voltage transmission line detection and high-altitude aircraft target recognition[14].

Corona discharge and its EM radiation characteristics have always been the focus of research. Juette [15] tested the EM interference near 75 high-voltage lines under different weather conditions. On this basis, S.K Nayak[16] and others in India established a preliminary calculation model for

 doi:10.20944/preprints201810.0471.v1

corona current pulses and calculated the corona radiation interference in high-voltage transmission lines. However, these studies did not rule out the effects of partial discharges such as spark discharges, so the test results were not accurate enough. Yasuyuki T et al[17]. experimentally studied the spectrum of the negative corona discharge radiation signal under the needle-plate discharge structure and compared it with the spark discharge EM radiation signal. Although they obtained the spectrum of the negative corona radiation signal, they did not analyze the mechanism of the radiation signal. Zhang Yu[18] et al. studied the relationship between the spectrum of the single-needle negative corona radiation signal and the discharge parameters and believed that the spectrum of the discharge EM radiation signal is only related to the rising time of the Trichel pulse current. But the study did not analyze the discharge EM radiation process. In addition, the above studies did not pay attention to the EM radiation characteristics of multi-needle discharge. The corona discharge on the high-voltage transmission line is often multi-point simultaneous discharge, and the EM radiation characteristics of multi-point and single-point corona discharge are significantly different. At present, researches on multi-needle (multi-point) discharge mainly focus on the volt-ampere characteristics of discharge and the interaction analysis of discharge process. Researches on the superposition of the multi-needle negative corona discha0rge Trichel pulse current and the interference of the discharge EM radiation signal are rare.

In this paper, the current characteristics of multi-needle negative corona discharge and its EM radiation characteristics were studied. A test system for negative corona discharge radiation characteristic was set up. The effects of discharge parameters on the single-needle negative corona discharge Trichel pulse current and its EM radiation field were tested. The current superposition of multi-needle negative corona discharge and the interference of the EM radiation field were studied. The EM radiation model of dipole negative corona discharge was established, and the relationship between the EM radiation characteristics of negative corona discharge and the parameters of the discharge system was analyzed. This study can provide a reference for corona discharge detection of high-voltage transmission lines.

2. Experimental Setup

The experimental system is shown in Figure 1, which consists of a high voltage generating module, a discharging module, a signal detection module and a shielding module. The high voltage generating module includes the high voltage power supply and the high voltage capacitor. During the experiment, the high voltage power supply first charges the high voltage capacitor. The high voltage power supply is turned off when the voltage reaches a predetermined value. The use of the high voltage capacitor to supply the discharge needle can eliminate the EM radiation interference generated by the high voltage power supply. The capacitance is 20 μf and the withstand voltage is 20 kV. The discharging module includes a discharge needle, a grounding plate, a displacement platform and a vacuum box. Discharge experiments of discharge needles of different tip radius can be carried out through the change of the discharge needle, and multi-needle simultaneous discharge experiments can also be performed. The displacement platform can be used to precisely control the gap of the electrodes. The vacuum box can control the air pressure of the discharge environment. The grounding plate is grounded through a 1 kΩ sampling resistor.

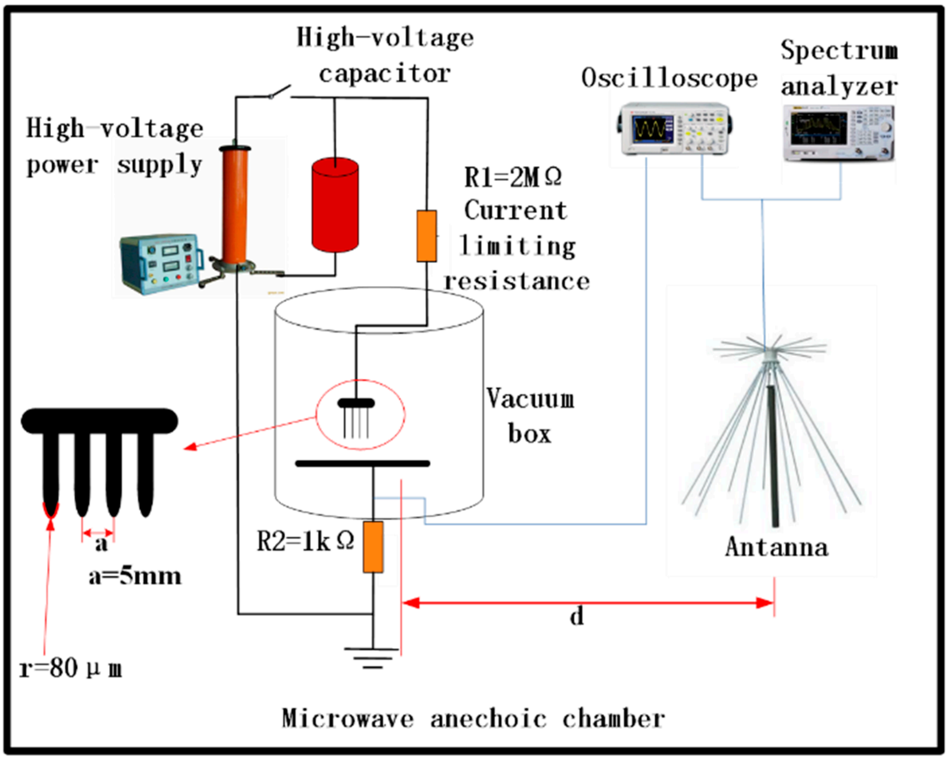

Figure 1. Experimental setup

The signal detection module includes an oscilloscope (Tektronix MDO3104), a spectrum analyzer (Agilent E4447A), and a receiving antenna (Discone Antenna OX-08-02, 20 MHz to 1000 MHz). The oscilloscope measures the voltage waveform on the sampling resistor to calculate the discharge current. The corona discharge EM radiation signal is received by the wide-band diskcone antenna, and the distance d between the antenna and the discharge device can be adjusted. The signal received by the antenna is analyzed by the spectrum analyzer, and the signal is collected by the oscilloscope. In order to eliminate the influence of external electromagnetic interference on the test results, all experiments were carried out in a microwave anechoic chamber.

3. Experimental Results and Analysis

3.1. Single-Needle Negative Corona Discharge Trichel Pulse Current and Ite Radiation Characteristics

The initial stage of negative corona discharge is the Townsend discharge stage, and the discharge current is usually within 1 μA and relatively stable. As the applied voltage increases, the discharge enters the Trichel pulse stage. Figure 2 shows the Trichel pulse current and its radiated signal waveform. Trichel pulses have a short rising time, which is typically tens of ns. The falling time is typically a few hundred ns, much larger than the rising time. Trichel pulses have a stable repetition rate. In the Trichel pulse stage, it will radiate electromagnetic waves to the surroundings. The waveform of the discharge radiation signal received by the antenna corresponds to the Trichel pulse current waveform. The repetition frequency of it is the same as the repetition frequency of the Trichel pulse current. Therefore, it is believed that the discharge radiation signal is generated by the Trichel pulse process. The spectrum of the discharge EM radiation signal under atmospheric pressure is shown in Figure 3. It can be seen from the figure that the spectrum of the single-needle discharge radiation signal is mainly within 200 MHz. The energy distribution near 70MHz is large (the fundamental frequency of the EM radiation signal), and there is also a certain energy distribution near 132 MHz. (second-harmonic generation of the EM radiation signal).

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 22 October 2018 doi:10.20944/preprints201810.0471.v1

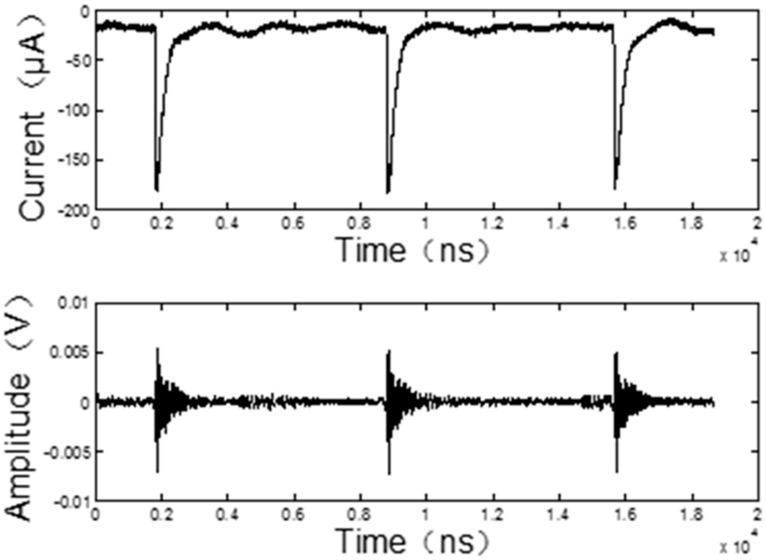

Figure 2. Trichel pulse current and its EM radiation signal

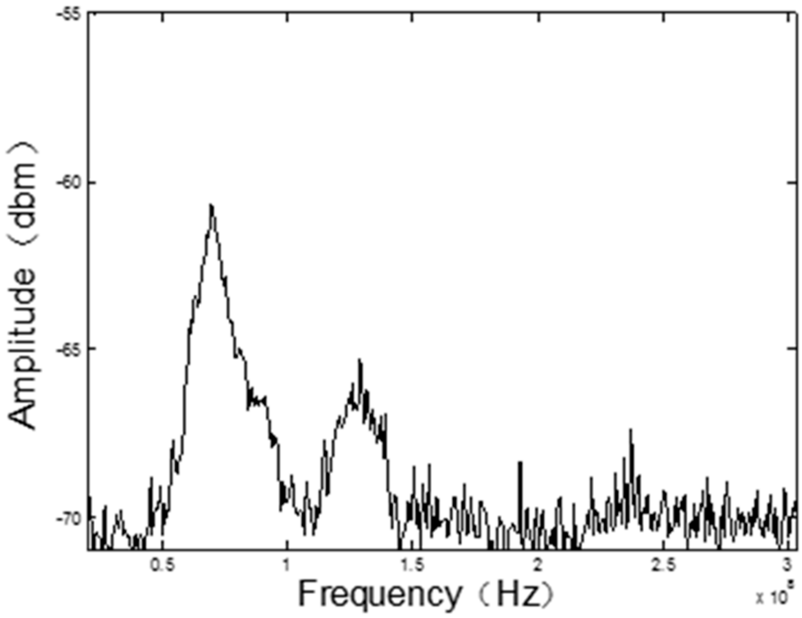

Figure 3. The spectrum of negative corona discharge EM radiation signal

The Trichel pulse generated by negative corona discharge is related to factors such as the applied voltage, the air pressure, and the tip radius of the discharge needle. Figure 4 shows the relationship between the repetition frequency of the Trichel pulse and the applied voltage. As the applied voltage increases, the repetition frequency of Trichel pulse increases, and the amplitude of a single pulse decreases slightly. This is consistent with the research results of Leob [19]. The spectrum of the discharge radiation signal at different pulse repetition frequencies is shown in Figure 5. The intensity of the discharge EM radiation signal decreases slightly, the frequency of the EM radiation signal does not change, the spectral lines become denser, and the average power of the discharge radiation signal increases as the increase of the repetition frequency of Trichel pulse current generated by the negative corona discharge. It is also found that changes in gap distance of electrode do not affect the intensity and frequency of the radiation signal.

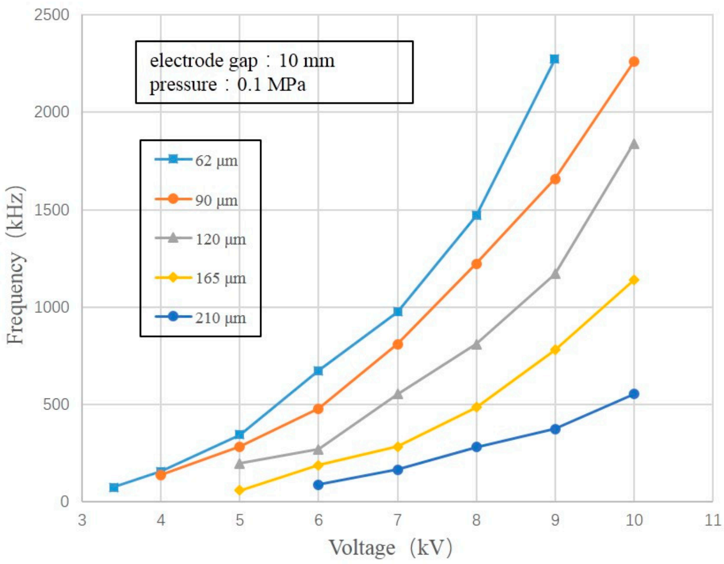

Figure 4. The relationship between Trichel pulse repetition frequency and applied voltage

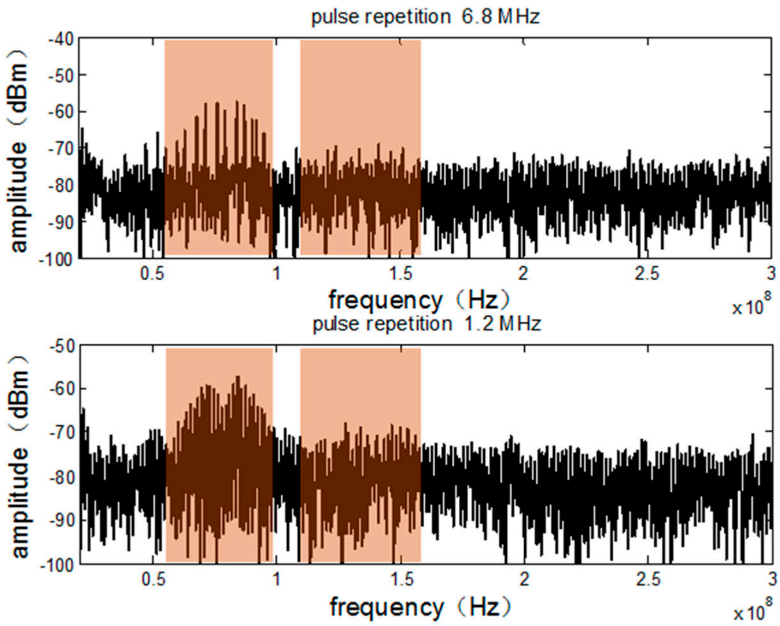

Figure 5. Spectrum of discharge radiation signal at different pulse repetition frequencies

As shown in Table 1, when the air pressure is reduced from 0.1 MPa to 0.04 MPa, the rising time of the Trichel pulse increases from 52 ns to 265 ns, while the pulse amplitude remains unchanged. Studies show that the discharge EM radiation signal spectrum is only related to the rising time of Trichel pulse[19]. The main frequency position of the EM radiation signal generated by the negative corona discharge shifts from 70 MHz to 45 MHz and the power of the discharge EM radiation signal decreases from 1.926 nW to 0.185 nW.

As the tip radius of the discharge needle increases from 62 μm to 210 μm, the amplitude of the Trichel pulse increases from 240 μA to 550 μA. And the rising and falling time of the pulse remains unchanged. This result is consistent with that of Lama[20] and Dordizadeh[21]. The frequency of the negative corona discharge electromagnetic radiation signal remains unchanged and the power of the radiation signal increases from 1.926 nW to 8.581 nW.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 22 October 2018 doi:10.20944/preprints201810.0471.v1

Table 1. Negative corona discharge Trichel pulse current and its radiation characteristics under different tip radius and different air pressures.

Tip radius (μm)	Air pressure (MPa)	Pules amplitude (μA)	Rising time (ns)	Tip radius (μm)	Air pressure (MPa)
94	0.04	241	264	0.185	45,84
94	0.06	245	118	0.752	52,102
94	0.08	243	78	1.19	65,125
94	0.1	240	52	1.926	70,132
120	0.1	290	52	2.395	70,132
165	0.1	410	53	4.796	70,132

Therefore, the frequency of the single-needle negative corona discharge EM radiation signal will be determined when the air pressure is determined. The intensity of the EM radiation signal of the negative corona discharge is affected by the air pressure and the tip radius of cathode. The applied voltage and the gap distance of electrode have no effect on the EM radiation signal frequency, which only affect the intensity and the average power of the discharge radiation signal.

3.2. Multi-needle Negative Corona Discharge Characteristics

In practical applications, corona discharge often has a multi-needle (multi-point) structure. The waveform of a multi-needle discharge is significantly different from that of a single-needle discharge. We first tested the double-needle discharge Trichel pulse current. To distinguish the Trichel pulse currents generated by different discharge needles, we chose two discharge needles with tip radius of 168 μm and 94 μm respectively for experiments (the larger the tip radius is, the larger the amplitude of the Trichel pulse current is). The discharge condition is: applied voltage of 7.4 kV, the gap distance of 10 mm, the ambient pressure of 0.1 MHz, and the relative humidity of 42%. The discharge current is shown in Figure 6a. It can be clearly seen from the figure that the amplitude of the Trichel pulse current generated by the discharge needle with a smaller radius is about 270 μA, and the pulse interval time is 1.32 μs. The amplitude of the Trichel pulse current generated by the large radius needle is about 440 μA, and the pulse interval time is 6.08 μs. Under this voltage, the Trichel pulse currents generated by the two discharge needles appear separately. Through further increasing the applied voltage, the discharge current waveform is shown in Figure 6 b. It can be seen from the figure that as the applied voltage increases, the amplitude of the Trichel pulse current generated by the smaller radius tip decreases from about 270 μA to about 245 μA, and the pulse interval time decreases to 0.69 μs. At the same time, it can be seen that when the applied voltage rises to a certain value, the Trichel pulses generated by the discharge needle with larger tip radius and smaller tip radius superimpose with each other. The maximum amplitude of the superimposed pulse current can reach 535 μA. The minimum amplitude can also reach 490 μA, which is significantly larger than the unsuperimposed pulse. We also tested the discharge current of the multi-needle discharge structure. The test result is similar to the double-needle discharge. As the applied voltage increases, the smaller tip radius needle begins to discharge first. When the applied voltage is further increased, the other needles also begin to discharge. The Trichel pulse current between the needles occurs separately in a certain voltage range. However, as the applied voltage continues to increase, the Trichel pulse current generated by the different discharge needles will be superimposed, and the amplitude of the superimposed pulse will increase significantly.

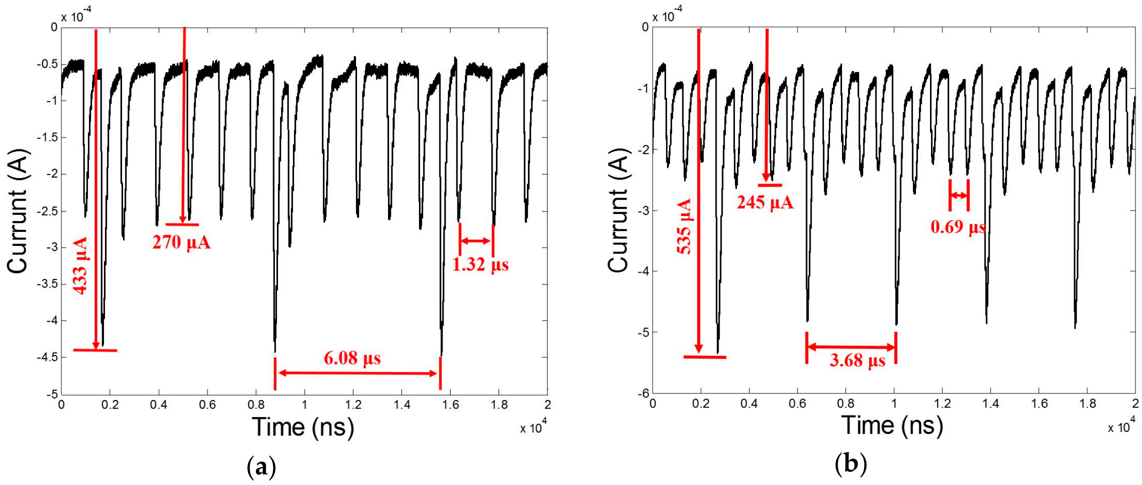

Figure 6. Negative corona discharge current waveform under double-needle discharge structure: (**a**) Applied voltage of 7.4 kV; (**b**) Applied voltage of 8.7 kV

When the applied voltage is lower, the Trichel pulse processes of the two needles will not happen at the same time. The EM radiation signal generated by the negative corona discharge corresponds to the Trichel pulse current, so the EM radiation signal is determined by the Trichel pulse current generated by each needle. When the applied voltage rises to an appropriate value, the Trichel pulse processes of the two needles will occur simultaneously. The Trichel pulse current waveform and the EM field signal generated during the simultaneous discharge of the two needles are shown in Fig. 7. The pulse pointed by the arrow 1 and the arrow 2 is the Trichel pulse generated by the two different discharge needles respectively, and the larger pulse pointed by the arrow 0 is the superimposed pulse generated by the simultaneous discharge of the two discharge needles. It can be seen that the discharge radiation signal generated by the non-superimposed Trichel pulse current has an amplitude of about 4.5 mV, and for the superimposed pulse current, the amplitude of the generated EM radiation signal can reach 7.5 mV. Therefore, when the double-needle simultaneous discharge pulse currents superimpose, the generated EM radiation field will also be superimposed, and the EM radiation signal intensity will increase significantly.

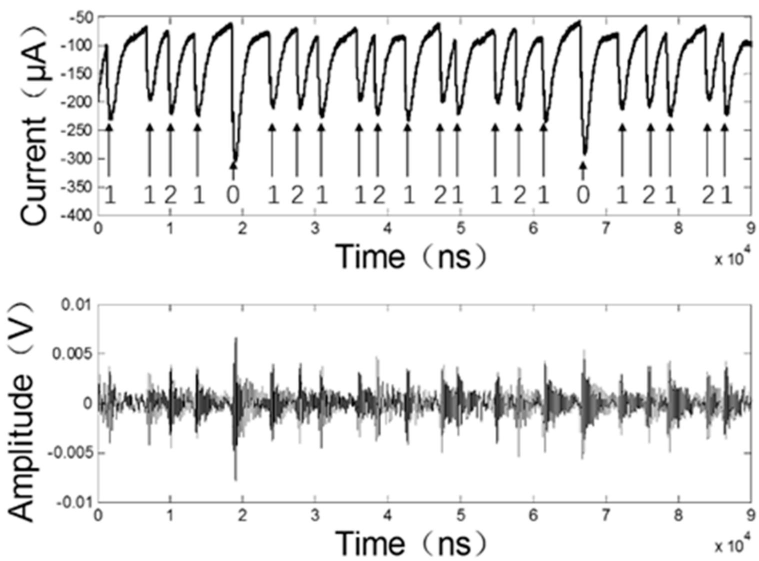

Figure 7. Trichel pulse current and radiation signal of the double-needle discharge structure

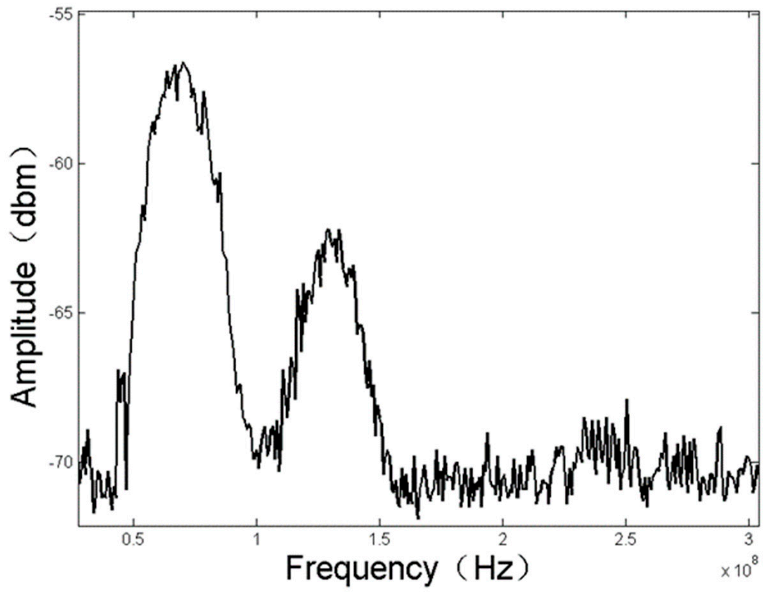

Figure 8. Spectrum of discharge radiation signal of the double-needle discharge structure

The double-needle discharge radiation spectrum is shown in Figure 8. The air pressure is 0.1 MPa, and the tip radius of both discharge needles is 60 μm. It can be seen that the spectrum of the EM radiation signal of the double-needle negative corona discharge is mainly distributed within 200 MHz, the signal intensity is large in the frequency band around 70 MHz, and there is also a certain spectrum distribution in the frequency band around 140 MHz. Under the same discharge condition, the double-needle negative corona discharge has the same frequency as the single-needle negative corona discharge. However, when the Trichel pulse processes of two discharge needles occur simultaneously, the spectral intensity of the generated EM radiation signal increases significantly when the pulse process is superimposed, and the spectral intensity of the radiation signal near 70 MHz is increased from -60 dBm of the single-needle discharge structure to -57 dBm of the double-needle discharge structure.

The frequency of the EM radiation signal generated by the double-needle negative corona discharge is only related to the ambient pressure. When the air pressure is determined, the frequency of the radiation signal generated by the double-needle discharge will remain unchanged. The intensity of the EM radiation signal is related to the air pressure, the tip radius of cathode and applied voltage.

It is found through the experimental test that the multi-needle simultaneous discharge current characteristics and EM radiation characteristics are basically consistent with those of the double-needle discharge structure. When the applied voltage is low, the pulse processes of the discharge needles do not occur at the same time, and the radiation signals are generated by the discharge pulse process of each discharge needle alone. As the applied voltage rises, different discharge needle pulse processes may occur simultaneously, and the pulse currents will be linearly superimposed, resulting in an increase in the discharge radiation field intensity. If the applied voltage is increased continuously, the corona discharge will enter the glow stage, the discharge current will be in a DC state, and the radiation signal will disappear. The frequency of the EM radiation signal of the multi-needle negative corona discharge is only related to the air pressure. The number of discharge needles, the tip radius of cathode, the gap distance of electrode and the applied voltage only affect the intensity of the discharge radiation signal. Therefore, when the air pressure is determined, the frequency of the EM radiation signal will also be determined, and the detection of the negative corona discharge can be realized by detecting the characteristic spectrum of the negative corona discharge radiation signal.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 22 October 2018 doi:10.20944/preprints201810.0471.v1

4. Discussion

4.1. Mechanism Analysis of EM Radiation Generated by Negative Corona Discharge

The space between the two electrodes of negative corona discharge can be divided into a ionization zone, a plasma zone and a drift zone[22]. As shown in Figure 9. The ionization region is near the tip of the discharge needle. At the beginning of the discharge, the seed electrons near the electrode collide with the neutral air molecules under the action of a strong electric field. The neutral molecules are ionized into positive ions and electrons, the positive ions move toward the negative electrode under the action of the electric field, and the electrons continue to ionize other neutral molecules under the action of the electric field. In a very short period of time, the number of electrons increases sharply, forming an ionosphere near the tip of the discharge needle, and the external circuit current increases sharply. This process is called electronic avalanche. The thickness of the ionization region of the negative corona discharge is usually about 1.5 mm[1]. Since the electric field is relatively strong and the charge-to-mass ratio of the electron is relatively large in this region, the velocity of electrons in this region can reach 0.01 times the speed of light[23,24]. After leaving the ionization region, the electrons will enter the plasma region. The electric field in the plasma region cannot provide sufficient energy for the electrons to complete the impact ionization. Therefore, the electrons combine with the neutral air molecules to form negative ions in the plasma region, and then enter into the drift region and move towards the anode under the action of the electric field. Since the charge-to-mass ratio of positive ions and negative ions is much larger than that of electrons, the velocity of positive ions and negative ions is negligible compared to electrons moving at high speed in the ionization region. Therefore, it can be considered that for each pulse process in the entire discharge region, the discharge EM radiation field is generated due to the exponential growth and rapid movement of electrons in the process of the electron avalanche in the ionization region and the plasma region.

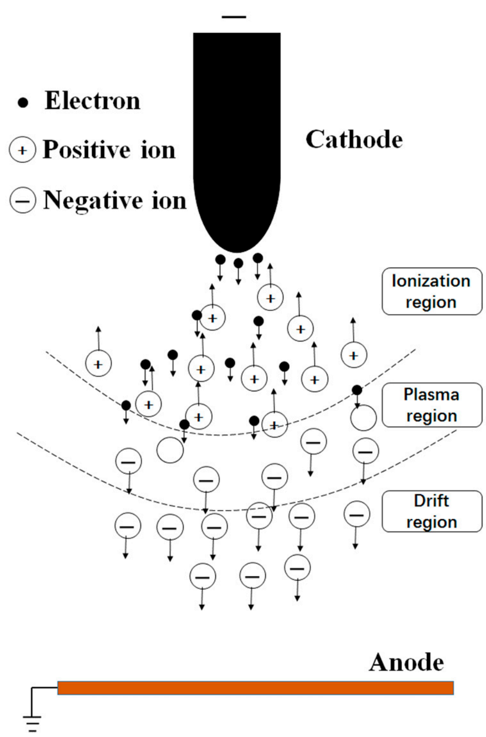

Figure 9. Negative corona discharge region division

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 22 October 2018 doi:10.20944/preprints201810.0471.v1

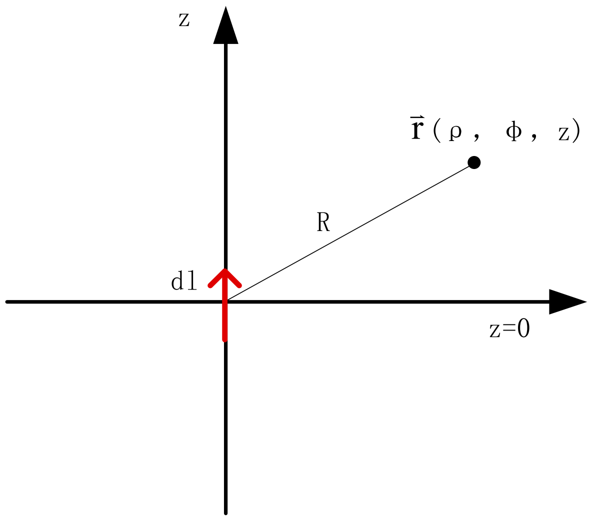

Figure 10. Negative corona discharge dipole radiation model

We equate the EM radiation field generated by negative corona discharge to the dipole radiation model, as shown in Figure 10. The dipole length dl=1.5mm (thickness of the ionization region), the direction is along the z-axis of the cylindrical coordinates, and the center of the dipole is the coordinate origin. For this configuration, the fields are found to be:

$$\begin{aligned}
&\bar{E}(\bar{\mathrm{r}},t)=\bar{a}_{\rho}dl\frac{\eta_0}{2\pi}\frac{\rho z}{R^2}\left\{\frac{3i(\mathrm{u})}{R^2}+\frac{1}{cR}\frac{\partial i(\mathrm{u})}{\partial u}\right\}+\bar{a}_{z}dl\frac{\eta_0}{2\pi}\left\{\left[\frac{3z^2}{R^2}-1\right]\frac{i(\mathrm{u})}{R^2}+\left[\frac{z^2}{R^2}-1\right]\frac{1}{cR}\frac{\partial i(\mathrm{u})}{\partial u}\right\}\\
&H(\bar{\mathrm{r}},t)=\bar{a}_{\phi}dl\frac{1}{2\pi}\frac{\rho}{R}\left\{\frac{i(\mathrm{u})}{R^2}+\frac{1}{cR}\frac{\partial i(\mathrm{u})}{\partial u}\right\}
\end{aligned} \tag{1}$$

Where R the distance from the discharge point to the observation point $\bar{\mathrm{r}}$ (ϱ, φ, z), η_0 the free space wave impedance, $i(\mathrm{u})$ the discharge current time-dependent waveform evaluated at time u, where u = t-R/c indicates the time lag when the radiation signal propagates to point P.

According to equation (1), the space around the discharge needle can be divided into a near-field region ($d<\lambda/2\pi$) and a far-field region ($d>\lambda/2\pi$), where is the wavelength of the radiation signal[25]. In the near-field region, the EM radiation signal is mainly determined by $i(\mathrm{u})$. The intensity of the radiation signal is attenuated as R^2. In the far field, the EM radiation signal is mainly determined by $\partial i(\mathrm{u})/\partial t$, and the EM radiation signal intensity is attenuated as R.

Substitute the experimentally measured Trichel pulse current into the dipole radiation model to calculate the EM radiation field generated by the Trichel pulse. Figure 11 shows the Trichel pulse current of the discharge needle with a tip radius of 210μm under 0.1MPa. The current amplitude is 550μA, and the rising time is 53ns.

Substitute the Trichel pulse current into equation (1) to calculate the discharge radiation field intensity waveform at different detection distances. As shown in Figure 12, the calculated EM radiation field intensity forms a pulse form, and the amplitude of the radiation signal is approximately inversely proportional to the detection distance. The electromagnetic wave propagates in the space at the speed of light, and the EM radiation field delay time is different at different positions.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 22 October 2018 doi:10.20944/preprints201810.0471.v1

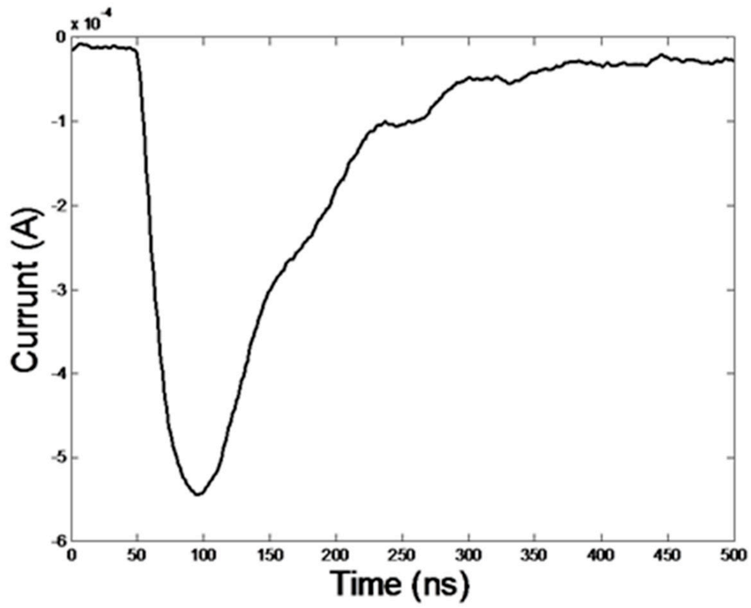

Figure 11. Single Trichel pulse current waveform

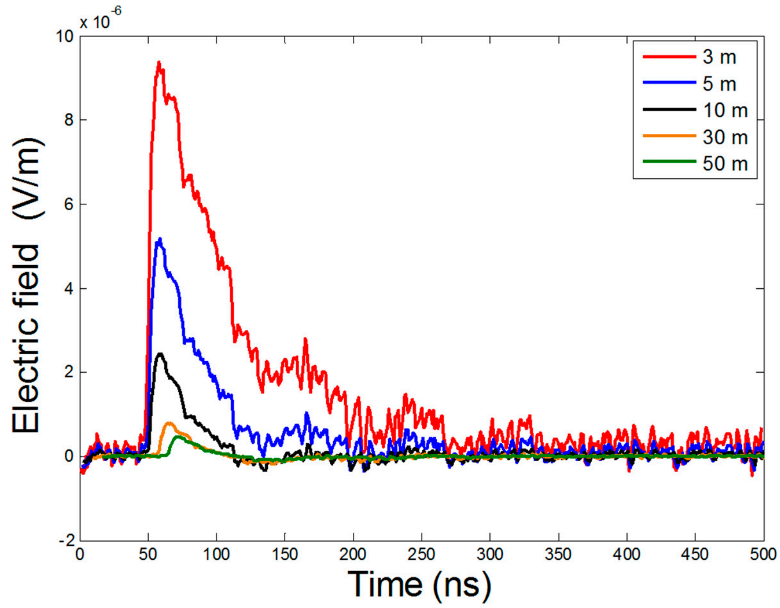

Figure 12. Discharge EM radiation field waveform

4.2. Comparison of Calculation Results of Dipole Radiation Model with Experimental Test Results

Document [18] has studied the effect of Trichel pulse current parameters on the discharge radiation spectrum.This paper mainly analyzes the relationship between the amplitude of discharge EM radiation field and Trichel pulse parameters. When the single Trichel pulse current waveform is the same, as the pulse repetition frequency increases, the average power of the radiation signal will increase, but the repetition frequency of the pulse will not affect the EM radiation signal generated by each pulse current, which is consistent with the experimental results (Figure 5).

 doi:10.20944/preprints201810.0471.v1

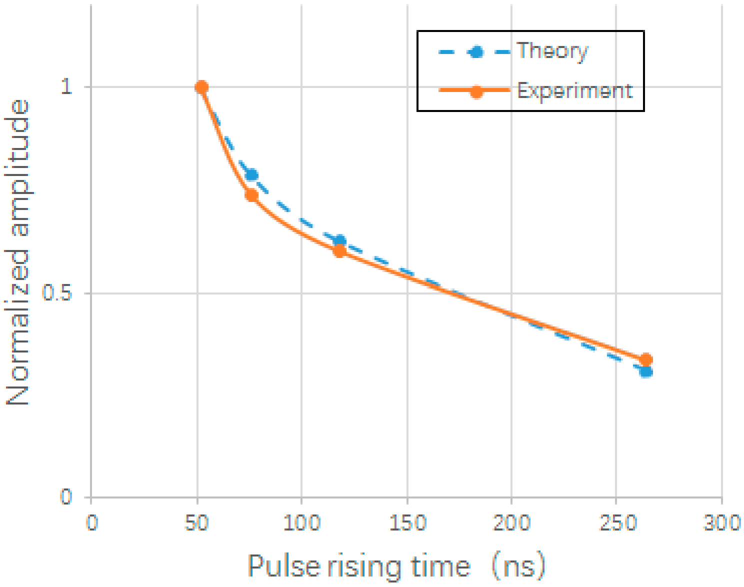

Figure 13. Theoretical calculated and experimentally tested "relationship between Trichel pulse rising edge and radiation signal amplitude"

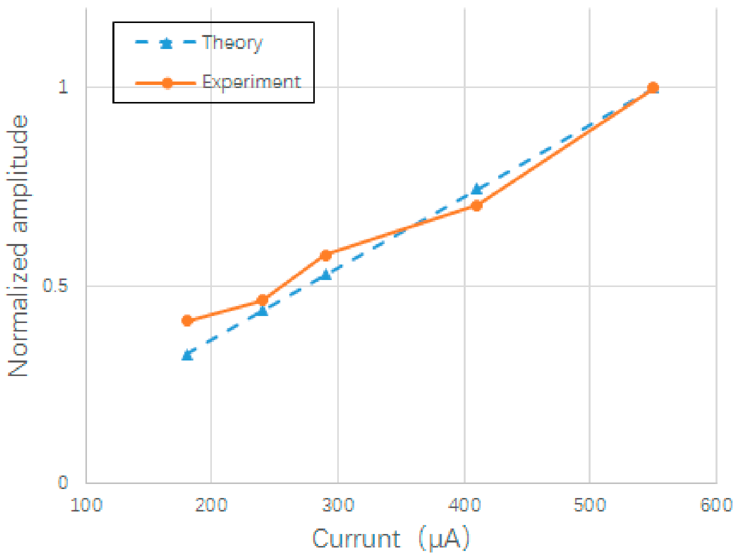

Figure 14. Theoretical calculated and experimentally tested "relationship between Trichel pulse amplitude and radiation signal amplitude"

The band of the antenna used in the experimental test is 20 MHz~1000 MHz. When the antenna was placed at a distance of 3m from the discharge device, the received radiation signal shows far-field characteristics. The discharge EM radiation signal was dominated by $\partial i(\mathrm{u})/\partial t$. If the $\partial i(\mathrm{u})/\partial t$ becomes smaller, the amplitude of the EM radiation signal will be smaller. As the air pressure decreases, the rising time of the Trichel pulse becomes larger, and other parameters of the Trichel pulse remain unchanged. As shown in Figure 13, when the rising time of the pulse increases from 52 ns to 264 ns, the amplitude of the theoretically calculated EM radiation signal decreases by 69%, and the amplitude of the experimentally tested EM radiation signal decreases by about 66%. The theoretical and experimental results were basically consistent. When the tip radius of the cathode increases, the amplitude of the Trichel pulse increases, and other parameters of the Trichel pulse remain unchanged. When the amplitude of the Trichel pulse increases from 180 μA to 550 μA, the $\partial i(\mathrm{u})/\partial t$ increases, the intensity of the EM radiation signal increases, as shown in Figure 14. The theoretically calculated amplitude of the radiation signal increases approximately linearly, and the measured value is consistent with the theoretical value.

4.3. Effects of Multi-Needle Discharge Structure on EM Radiation Characteristics of Negative Corona Discharge

The ionization during negative corona discharge generates a large number of electrons and positive ions in the ionization region. Since the charge-to-mass ratio of electrons is much smaller than that of ions, the ions move slowly in the electric field and form positive ion clouds in the ionization region. The electrons leave the ionization region during the movement to the anode and combine with the neutral particles to form negative ions, forming a negative ion cloud outside the ionization region. The space charge of the positive ion cloud and the negative ion cloud will generate a spatial electric field, which has an effect on the original electric field[26]. In the multi-needle discharge structure, the ion cloud formed by the discharge needle in the pulse phase will affect the electric field around the nearby discharge needle, thereby affecting the Trichel pulse process. As shown in Figure 15, when a discharge needle is subjected to a pulse process, the positive ion cloud formed by it has little effects on the electric field in the ionization direction of the other discharge needle, and the negative ion cloud has a significant weakening effect on the electric field in the ionization direction of the other discharge needle. Therefore, in the case of a small applied voltage, the previous discharge needle pulse process has an inhibitory effect on the other discharge needle pulse process[27]. As the applied voltage increases, the effect of the negative ion cloud is reduced, and the pulse processes of the two discharge needles occur simultaneously.

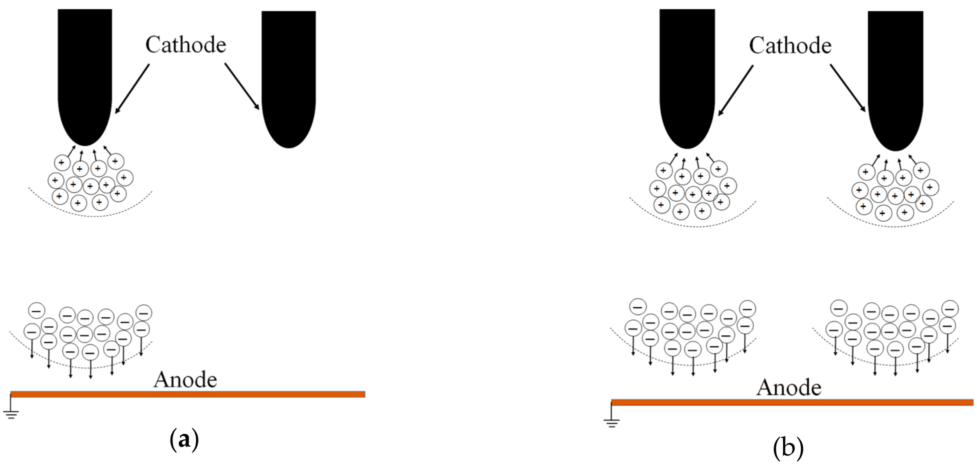

Figure 15. Double-needle Trichel pulse process: (**a**) Trichel pulse process under small applied voltage; (**b**) Trichel pulse process under large applied voltage.

5. Conclusions

In this paper, the pulse current characteristics of multi-needle negative corona discharge and its EM radiation characteristics are studied.

In the multi-needle discharge structure, when the applied voltage is low, the negative corona discharge Trichel pulse processes of the respective discharge needles are mutually suppressed, and the discharge needle pulse processes occur separately. When the applied voltage increases to a certain threshold, the pulse processes of different discharge needles will occur simultaneously, the multi-needle discharge current will be linearly superimposed, and the generated EM radiation field will also be linearly superimposed. The frequency of the radiation signal after multi-needle simultaneous discharge superposition is the same as the frequency of the single-needle discharge EM radiation signal, but the amplitude of the EM radiation signal is increased.

The negative corona discharge radiation process can be equivalent to the dipole antenna radiation model. The dipole length is the sum of the thickness of the ionization region and the plasma region. The radiation field in the near-field region is dominated by $i(\mathrm{u})$, and the discharge radiation

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 22 October 2018 doi:10.20944/preprints201810.0471.v1

field in the far-field region is dominated by $\partial i(\mathrm{u})/\partial t$. The amplitude of the EM radiation signal is related to the tip radius of the cathode and the air pressure. The larger the tip radius, the larger the amplitude of the pulse current, and the larger the intensity of the EM radiation signal. The lower the airt pressure, the larger the rising time of the pulse, the smaller the change of current as time, and the smaller the intensity of the radiation signal. The spectral characteristics of the EM radiation of the multi-needle negative corona discharge are only related to the air pressure. The intensity of the EM radiation signal is related to the tip radius of the cathode, the air pressure, and the number of discharge needles.

The results of this work may provide promising method for evaluation of insulation condition of electric apparatus as well as detection of the charged body.

Author Contributions: Conceptualization, C.W. and X.C.; Methodology, C.W. and J.O; Software, C.W. and J.F.; Validation, C.W , J.O. and X.C. ; formal analysis, C.W. and J.F ; Investigation, J.O.; Resources, C.W. and X.C.; Data curation, C.W. and X.C.; Writing—original draft preparation, C.W. and X.C.; Writing—review and editing, C.W.; Visualization, C.W.; Supervision, X.C.; Project administration, X.C.; Funding acquisition, C.W , X.C. and J.O.;"

Funding: This work was financially supported by grants from National Natural Science Foundation of China (#U1630130, #51777010, #51707008, #51407009).

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Rycroft, M. J. Gas discharge physics. *J. Atmos. Terr. Phys.* **1993**, *55*, 1487, doi:10.1016/0021-9169(93)90114-E.
2. Sigmond, R. S. *Corona Discharges*; 1978;
3. Bussiahn, R.; Brandenburg, R.; Gerling, T.; Kindel, E.; Lange, H.; Lembke, N.; Weltmann, K. D.; Von Woedtke, T.; Kocher, T. The hairline plasma: An intermittent negative dc-corona discharge at atmospheric pressure for plasma medical applications. *Appl. Phys. Lett.* **2010**, *96*, doi:10.1063/1.3380811.
4. Kanazawa, S.; Chang, J. S.; Round, G. F.; Sheng, G.; Ohkubo, T.; Nomoto, Y.; Adachi, T. Removal of NOx from flue gas by corona discharge activated methane radical showers. *J. Electrostat.* **1997**, *40–41*, 651–656, doi:10.1016/S0304-3886(97)00072-7.
5. Pongrác, B.; Kim, H. H.; Janda, M.; Martišovitš, V.; Machala, Z. Fast imaging of intermittent electrospraying of water with positive corona discharge. *J. Phys. D. Appl. Phys.* **2014**, *47*, doi:10.1088/0022-3727/47/31/315202.
6. Jaworek, A.; Krupa, A. Electrical characteristics of a corona discharge reactor of multipoint-to-plane geometry. *Czechoslov. J. Phys.* **1995**, *45*, 1035–1047, doi:10.1007/BF01691996.
7. Huang, S.; Liu, Y.; Chen, S.; Zhou, G.; Zhuang, W. Corona Onset Characteristics of Bundle Conductors in UHV AC Power Lines at 2200 m Altitude. *Energies* **2018**, doi:10.3390/en11051047.
8. Abdel-Salam, M.; Hashem, A.; Sidique, E. Characteristics of negative corona discharge in single-needle- and multi-needle-to-plane configurations. *Int. J. Plasma Environ. Sci. Technol.* **2013**, *7*, 121–135.
9. Tanner, R. L.; Nanevicz, J. E. An Analysis of Corona-Generated Interference in Aircraft. *Proc. IEEE* **1964**, *52*, 44–52, doi:10.1109/PROC.1964.2741.
10. El-Khabiry, S.; Colver, G. M. Drag reduction by dc corona discharge along an electrically conductive flat plate for small Reynolds number flow. *Phys. Fluids* **1997**, *9*, 587–599, doi:10.1063/1.869219.
11. Thanh, L. C. Negative Corona in a Multiple Interacting Point-to-Plane Gap in Air. *IEEE Trans. Ind. Appl.* **1985**, *IA-21*, 518–522, doi:10.1109/TIA.1985.349697.
12. Trichel, G. W. The mechanism of the negative point to plane corona near onset. *Phys. Rev.* **1938**, *54*, 1078–1084, doi:10.1103/PhysRev.54.1078.
13. Fernando, S. C. Electromagnetic Radiation due to Partial Discharge and Fault Detection Method for Overhead Distribution Lines Electromagnetic Radiation due to Partial Discharge and Fault Detection Method for Overhead Distribution Lines. **2012**, 1–118.
14. Zhang, L.; Han, X.; Li, J. Partial discharge detection and analysis of needle-plane defect in SF6 under negative oscillating lightning impulse voltage based on UHF method. *IEEE Trans. Dielectr. Electr. Insul.* **2017**, *24*, 296–303, doi:10.1109/TDEI.2016.005979.
15. Juette G W, Charbonneau H, Dobson H I, et al. CIGRE/IEEE survey on extra high voltage transmission line radio noise. *IEEE Trans. Power Appar. Syst.* **1973**, *PAS-92*, 1019–1028, doi:10.1109/TPAS.1973.293668.
16. Nayak, S. K.; Thomas, M. J. A Novel Technique for the Computation of Radiated EM1 due to Corona on HV Transmission Lines. 738–742.
17. Tsutsumi Yasuyuki et al. Electromagnetic noise spectra of corona discharge at point-to-plane electrodes in air. *IEEJ Trans. Fundam. Mater.* **2008**, *111*, 733–740.
18. Zhang, Y.; Liu, L. J.; Miao, J. S.; Peng, Z. L.; Ouyang, J. T. Trichel pulse in negative DC corona discharge and its electromagnetic radiations. *J. Electr. Eng. Technol.* **2015**, *10*, 1174–1180, doi:10.5370/JEET.2015.10.3.1174.

19. Loeb, L. B.; Kip, A. F.; Hudson, G. G.; Bennett, W. H. Pulses in negative point-to-plane corona. *Phys. Rev.* **1941**, *60*, 714–722, doi:10.1103/PhysRev.60.714.
20. Lama, W. L.; Gallo, C. F. Systematic study of the electrical characteristics of the “trichel” current pulses from negative needle-to-plane coronas. *J. Appl. Phys.* **1974**, *45*, 103–113, doi:10.1063/1.1662943.
21. Dordizadeh, P.; Adamiak, K.; Castle, G. S. P. Experimental study of the characteristics of Trichel pulses in the needle-plane negative corona discharge in atmospheric air. *J. Electrostat.* **2017**, *88*, 49–54, doi:10.1016/j.elstat.2016.12.013.
22. Chen, J.; Davidson, J. H. Model of the Negative DC Corona Plasma: Comparison to the Positive DC Corona Plasma. *Plasma Chem. Plasma Process.* **2003**, *23*, 83–102, doi:10.1023/A:1022468803203.
23. Nath, D.; Kumar, U. Total electric field due to an isolated electron avalanche. *IEEE Trans. Dielectr. Electr. Insul.* **2016**, *23*, 2562–2571, doi:10.1109/TDEI.2016.005593.
24. Cooray, V.; Cooray, G. Electromagnetic radiation field of an electron avalanche. *Atmos. Res.* **2012**, *117*, 18–27, doi:10.1016/j.atmosres.2011.06.004.
25. Wilson, P. F.; Ma, M. T. Fields Radiated by Electrostatic Discharges. *IEEE Trans. Electromagn. Compat.* **1991**, *33*, 10–18, doi:10.1109/15.68245.
26. Colver, G. M.; El-Khabiry, S. Modeling of DC corona discharge along an electrically conductive flat plate with gas flow. *IEEE Trans. Ind. Appl.* **1999**, *35*, 387–394, doi:10.1109/28.753633.
27. Lama, W. L.; Gallo, C. F. Interaction of the “trichel” current pulses of a pair of negative coronas. *J. Phys. D. Appl. Phys.* **1973**, *6*, 1963–1972, doi:10.1088/0022-3727/6/16/317.