THE CORONA MECHANISM
IN THE PRESENCE OF A MAGNETIC FIELD

by

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THE CORONA MECHANISM
IN THE PRESENCE OF A MAGNETIC FIELD

INTRODUCTION

The influence of a magnetic field on the corona mechanism is the subject of investigation presented in this thesis. The classifications and terminology listed by Churchill (1, p. 23) will be utilized in this presentation. The influence of the magnetic field on the onset voltage, pulse repetition rate, pulse amplitude, radio noise, and type of point were of interest.

The study was conducted with a modified point-to-plane configuration. The point projected from a cylindrical bar. This geometry simulates a point projecting from a high voltage conductor. This bar formed the current path for establishing the magnetic field. The point was coupled directly to a cathode follower whose output was displayed on an oscilloscope.

THE AC CORONA GENERATOR

The corona generator is shown in Figure 1-a. The plane electrode is a 14-inch diameter cast aluminum disc with an edge radius of 0.875 inches. It is mounted horizontally with its axis twenty-one inches above a large aluminum ground sheet. It is connected directly to the high voltage transformer by means of an aluminum shaft. To this shaft is also fastened a 200 megohm resistor which serves as part of the resistive voltage divider.
Figure 1 Equipment used in the investigation. Shown are the high voltage transformer, plane electrode, bar, cathode follower, induction regulator and voltmeters, magnetic breaker, and the Variacs used in the phase shifting network.
The high voltage transformer control circuit is shown in Figure 2. The water rheostat was used in the circuit when crest voltages below 40 kilovolts were desired. This allowed the regulator to operate at a higher voltage which minimized the harmonic distortion. It also made it easier to set a desired gap voltage.

The high voltage transformer was calibrated in conjunction with two voltmeters and 6.25 cm. and 20 mm. sphere gaps. For gap spacings less than 1 cm, the gap was irradiated with an ultra-violet lamp.

The data was corrected to 760 mm. and 25°C. or a relative air density of unity. Figure 3 shows the high voltage waveform taken from the resistive divider at 40, 60, and 100 kilovolts crest.

The current circuit is also shown in Figure 2. The aluminum bar was located 21 inches above the ground plane, parallel to the face of the plane electrode and 8 inches distant from it.

The point projected through the bar as shown in Figure 4-a. Figure 4-b shows a cross-sectional view of the bar. From this illustration, the limitation on point diameter can be seen. The bar sizes available were 1, 7/8, 3/4, 5/3, and 1/2 inch in diameter.

The waveforms of the voltage across the bar and \( \frac{dv}{dt} \) for 250, 500, and 1000 amperes are shown in Figure 5. Examination of these waveforms show that for all practical
Figure 2 Current and High Voltage control circuit.

Current Control Circuit

High Voltage Control Circuit
Figure 3  High voltage waveform obtained from the resistive divider. Gap voltages are 40, 80, and 100 kilovolts from top to bottom. Horizontal scale, 5 milliseconds per centimeter. (In all oscilloscope pictures, the distance between major scale divisions represents one centimeter.)
Figure 4-a Point projecting through the bar

Figure 4-b Bar cross section at point hole
Figure 5-a di/dt obtained with an air-core coil. Current is 250, 500, and 1000 amperes from top to bottom. Vertical scale, 0.05 volts/centimeter. Horizontal scale, 5 milliseconds/centimeter.

Figure 5-b Voltage across the bar. Current-250, 500, and 1000 amperes from top to bottom. Vertical scale, 0.5 volts/centimeter. Horizontal scale, 5 milliseconds/centimeter.
purposes, they are sinusoidal. The derivative of current with respect to time was obtained by the use of an air core coil attached to the bar. The output of this coil was integrated and compared with the voltage developed across the bar. The phase difference between the integrated output of the coil and the voltage across the bar was not measurable. The voltage across the bar was then used as a reference to obtain the phase relationship between current in the bar and gap voltage. A Tektronix type 551 Dual Beam Oscilloscope was used for phase measurements.

The point is coupled directly to a cathode follower. The schematic diagram is shown in Figure 6. The cathode follower is a totally enclosed, air cooled unit. The point terminating resistor can be changed quite easily by sliding the device out of its aluminum case. As shown by Churchill (1, p. 13-17), the corona generator has an internal impedance almost infinite. This makes it essentially a constant charge generator. The terminating resistor, $R_L$, influences only the magnitude of the output voltage but not the total charge transfer (1, p. 16).

The points used were 0.010 inch and 0.020 inch diameter steel points, and a 0.020 inch diameter dielectric coated steel point. These points were measured with a 50 power stereo microscope.
Point Terminating Resistors

10,000 ohms
3000 ohms
1000 ohms
300 ohms
100 ohms
15 ohms

+150 volts dc
0.2 microfarads

5718

10 feet
RG 114/U
185 ohms

#6 volts dc

To oscilloscope

Figure 6 Cathode follower circuit diagram.
To facilitate accurate measurement of point projection, the cathode follower unit was equipped with a 32 thread per inch lead screw. This enabled point advancements of 1/64 of an inch to be made quite easily.

The equivalent measuring circuit is shown in Figure 7. The shunt capacitance to ground was measured with the point projecting through the bar. This value, 14 picofarads, includes the interelectrode capacitances of the tube in the cathode follower.

The risetime of the signal appearing at the grid of the cathode follower is distorted by the parallel RC combination of \( R_L \) and \( C_S \). This distorted signal is further modified by the RC combination \( R_0C_0 \) and the risetime of the preamplifier and oscilloscope vertical amplifier. The coaxial cable can be considered as a lossless line which would only introduce delay into the system.

The output of the cathode follower was displayed on a Tektronix Type 545A oscilloscope. Several different types of plug-in preamplifiers were used. These included the fast rise time, wide band, and dual trace units. Occasionally it was necessary to use a Tektronix Type 551 Dual Beam oscilloscope equipped with the fast rise time units.

The oscilloscope display was photographed with an Allen B. DuMont Oscillographic Camera equipped with an f 1.9 lens.
Figure 7-a Actual measuring circuit.

- $C_s$ - Input shunt capacitance to ground
- $R_L$ - Point terminating resistor
- $g_m$ - Tube transconductance
- $C_T$ - Tube output capacitance
- $r_p$ - Tube dynamic plate resistance
- $\mu$ - Tube amplification factor
- $R_T$ - Coaxial cable terminating resistor
- $C_I$ - Oscilloscope preamplifier input capacitance
- $R_I$ - Oscilloscope preamplifier input resistance

Figure 7-b Equivalent measuring circuit.

$$R_C = R_T || \frac{r_p R_L}{1 + \mu}$$

$$G_C = C_I + C_T$$
Radio noise measurements were made with a Stoddart Field Intensity meter, type NM20B (5). For these measurements, the output of the cathode follower was coupled to the noise meter with a 10 picofarad capacitor. The point terminating resistor used while making the radio noise measurements was 1000 ohms.
THE CORONA MECHANISM

Definition of Terms

In order to proceed with the discussion of the corona mechanism and the experimental results, the following definitions used by Churchill (1, p. 23) are given.

Onset -- Upon raising the gap voltage, the value of this voltage at which corona first appears.

Extinction -- Upon lowering the gap voltage, the value of this voltage at which corona disappears.

Initial Pulse -- The first corona pulse appearing on the ascending waveform of each half cycle in an a-c system.

Terminal Pulse -- The last corona pulse appearing on the descending waveform of each half cycle of an a-c system.

Positive Mechanism

An electron entering the gap where the positive electrode is producing a diverging field gains enough energy to cause ionization and excitation by collision. This results in an electron avalanche which progresses to the anode. The positive ion column left behind effectively extends the anode potential into the gap. This effective extension of the anode into the gap cause the gradient at the head of the column to increase. New avalanches formed by electrons
created by photo ionization from photons liberated during the initial avalanche advance toward the head of the positive column. This is due to the head of the positive ion column being at the highest potential in the gap. As these avalanches proceed toward the head, more columns of positive ions are formed. These new positive ions tend to increase the diameter of the head of the positive column and extend it further into the gap. The formation of new positive ions ceases when the field at the head of the column is weakened by the expansion and extension, to the point that new photo-electrons cannot gain sufficient energy to cause ionization. The mechanism ceases, leaving behind a large positive ion space charge.

The high gradient in the vicinity of the point must be restored before the mechanism can start again. This requires removing the accumulated space charge in the gap. The time required to remove the space charge governs the pulse repetition rate of the positive corona.

Characteristics of positive point-to-plane corona are described very well by Mesecar (3, p. 8-15).

Negative Mechanism

The negative mechanism is initiated by an electron leaving the vicinity close to the cathode surface. This forms an avalanche which is short in both length and time. Photons from this initial avalanche strike the cathode and
produce secondary electrons. These electrons form more new avalanches. The result of these avalanches is a space charge of positive ions near the cathode. As the positive space charge increases, electrons from the avalanches slow down due to a weakened field farther out in the gap. They attach themselves to oxygen molecules by "dissociative attachment" (2, p. 940), forming negative ions (O⁻). The negative ions form another space charge beyond the positive ion space charge. The growth of these space charges will continue until there is not sufficient energy available for secondary electron production.

The positive space charge is then swept into the cathode where the positive ions are neutralized. The resulting pulse of current is shown in Figure 8. This is the output of the cathode follower as observed on an oscilloscope.

After the positive ion space charge has been neutralized and the negative ions have proceeded farther into the gap, a new pulse may start. With microdimensional points, less than 0.2 inches in diameter, these pulses occur at regular intervals. These pulses are termed "Trichel" pulses after G. W. Trichel who investigated them (6). With an a-c gap voltage, the interval between pulses decreases as the instantaneous voltage increases. The increase in pulse repetition rate is also accompanied by a decrease in pulse height. This is in agreement with the investigations
Figure 8 Output of the cathode follower in response to a corona impulse input. Vertical scale, 0.02 volts/centimeter. Horizontal scale, 0.5 microseconds/centimeter.
of d-c point-to-plane corona conducted by Mesecar (3, p. 18-29).

Figure 9 shows the relationship between the instantaneous gap voltage and the corona pulses. The variation in pulse height with instantaneous gap voltage is readily shown. The change in repetition rate from these photographs is not apparent, however.
Figure 9  Corona pulse relation to the high voltage waveform.  (a) 0.010 inch diameter point. Top picture; horizontal scale, 1 millisecond/centimeter; bottom picture; horizontal scale, 2 milliseconds/centimeter.  (b) 0.020 inch diameter point. Top picture; horizontal scale, 1 millisecond/centimeter; bottom picture; horizontal scale, 2 milliseconds/centimeter.
Geometrical Effects on Corona Parameters

The modification of the basic point-to-plane geometry with the bar has a marked effect on the onset voltage. The onset voltage is increased by as much as twenty times the value for the same gap spacing with the point-to-plane geometry. Figure 10 shows the influence of bar diameter with a fixed point projection on the onset voltage. As the point projection from the bar increases, the values of onset voltage for different diameter bars becomes more nearly the same. This is due to the reduced shielding of the point by the bar as the point projection increases. The curves of Figure 11 show more clearly the effect of reduced shielding.

Within the limits of the point projections investigated, the onset voltage varied inversely as the distance from the surface of the bar. This is illustrated in Figure 12. Due to the limit on the voltage available, and geometrical limits, it was not practical to investigate shorter or longer point projections.

The variation of repetition rate with point projection is shown in Figure 13 for a constant gap voltage. The repetition rate was obtained by measuring the average period between the initial pulse and the next pulse. The measurement was made from the oscilloscope display.
Figure 10 Variation of onset voltage with bar diameter for a constant point projection. Point diameter, 0.020 inches.

Relative air density, 0.98

A - 3/32" point projection
B - 1/8" point projection
C - 5/32" point projection
D - 3/16" point projection
E - 1/4" point projection
F - 5/16" point projection
Figure 11 Point projection influence on onset voltage with a constant bar diameter.
Relative air density, 0.98. O - 0.020" diameter point. △ - 0.010" diameter point.
A - 1" diameter bar  
B - 3/4" diameter bar  
C - 1/2" diameter bar  
D - 1" diameter bar  
E - 3/4" diameter bar  
F - 1/2" diameter bar
Figure 12 Variation in onset voltage with $l/d$, where $d$ is the projection from the surface of the bar.

A - 1" diameter bar; B - 3/4" diameter bar; C - 1/2" diameter bar; D - 1" diameter bar; E - 3/4" diameter bar; F - 1/2" diameter bar.

○ - 0.020 inch diameter point
△ - 0.010 inch diameter point
Figure 13 Influence of point projection on pulse repetition rate with a constant bar diameter.
This measurement also substantiates the premise that the bar shields the point. Increased repetition rate for a fixed gap voltage must be due to higher gradients in the region of the point. Higher gradients in this region could only be due to decreased shielding by the bar.

The circuit configuration limits the measurement of ion currents to the discharges which occur from the point only. This eliminates any measurements of the phenomena which might occur on the bar. Due to the increase in the onset voltage, this investigation was restricted to negative corona. The maximum crest voltage available from the high voltage transformer was 103 kilovolts. The voltage required for positive streamer onset for a 0.01 inch diameter point with a 7.5 inch gap in the classical point-to-plane geometry is approximately 60 kilovolts crest. The shielding due to the bar will raise the streamer onset voltage also. The exact increase is not known, for with the point projections investigated, positive streamers were never observed.

**Characteristics of the Magnetic Field**

The magnetic field produced by a known current flowing in the bar can be calculated by using Ampere's Law. The bar can be considered a long, straight conductor for the point projections under investigation. Ampere's Law is stated in equation form below.
\[ \oint \mathbf{H} \cdot d\mathbf{l} = I \text{ amperes} \quad (1) \]

This equation states that the line integral of \( \mathbf{H} \), the magnetizing force, around a closed path is equal to the current enclosed. The magnetic field at a fixed radius \( r_1 \), from the center of the bar is the same due to the cylindrical shape of the bar. The average magnetizing force is equal to

\[ \bar{H} = \frac{I}{2\pi r_1} a_e \frac{\text{amperes}}{\text{meter}} \quad (2) \]

The magnetic flux density, \( B \), is obtained by the following relationship.

\[ \bar{B} = \frac{\mu_0}{4\pi} \frac{\text{Webers}}{\text{meter}^2} \quad (3) \]

\[ \bar{B} = \frac{\mu_0 r_1 I}{2\pi r_1} a_e \frac{\text{Webers}}{\text{meter}^2} \quad (4) \]

The symbol \( \mu_0 \) is the permeability of free space. Its value is \( 4\pi \times 10^{-7} \) Webers/ampere meter. The relative permeability, \( \mu_r \), for air is unity.

The current, \( I \), varies sinusoidally with time as shown earlier. Replacing \( I \) in equation (4) we obtain equation (5).

\[ \bar{B} = \frac{\mu_0 I_{\text{max}}}{2\pi r_1} \sin \omega t a_e \quad (5) \]

With a current of 1000 amperes RMS flowing through a 1 inch diameter bar, the maximum magnetic flux density at the surface of the bar would be \( 1.79 \times 10^{-2} \) Webers/meter\(^2\).
At a distance of 0.5 inches from the surface of the bar, the maximum flux density would be $0.895 \times 10^{-2}$ webers/meter$^2$. These values of flux density are within the same range as those encountered on high voltage transmission lines.

The equation for the force on a charged particle in time varying magnetic field could be introduced here. However, it would be of no significant value to the discussion. A rigorous mathematical analysis of the force on the charged particles in the region of the point is beyond the scope of this investigation. The mathematical analysis of the electron avalanche and the associated space charge, and the resultant distortion of the electric field has not been sufficiently refined to be of any practical value to this investigation.

The range of the phase angle between current and voltage on a transmission line in the field would most likely be $90^\circ$ lag to $90^\circ$ lead. With the laboratory equipment, any phase angle from $0^\circ$ to $360^\circ$ was available. To insure that the investigation was complete, phase angles throughout the entire range were used.

In order to prevent changing the air density in the vicinity of the point, the current through the bar was not maintained long enough to cause appreciable heating. A limited duty cycle was also imposed to prevent damage to the current transformers used to generate the current.
obtain currents in excess of 1000 amperes, it was necessary to exceed the normal limit of 5 amperes on the secondary of each current transformer.

Onset Voltage

The value of onset voltage was determined by increasing the gap voltage until a corona pulse appeared on each negative half cycle on a multiple cycle oscilloscope display. Figure 14-a shows onset voltage as a function of current in the bar. From this curve, it is apparent that current magnitude has no effect on the onset voltage. The phase angle between current and voltage produces no significant change in onset as shown in Figure 14-b. The small variations of the onset voltage are less than 0.2%, which are well within the limits of experimental error.

The values of onset voltage were obtained by first adjusting the current flow through the bar and then increasing the gap voltage. Setting the gap voltage first and then increasing the current in the bar was also tried. There was no difference noticed between the two methods.

Electrical Position of Initial and Terminal Pulses

The position of the initial and terminal pulses on the high voltage waveform is shown in Figure 15. The electrical position of these pulses showed no variation due to the magnetic field.
Figure 14-a Uniformity of onset voltage with increasing current magnitude. 0.020" diameter point. 1" diameter bar. Relative air density, 0.99
- 3/32" point projection - 3/16" point projection

Figure 14-b Uniformity of onset voltage with phase angle variation. 0.020" diameter point. 1" diameter bar. Relative air density, 0.99
○ - 3/32" point projection △ - 3/16" point projection
Figure 15 Initial and terminal pulse electrical position on the high voltage waveform with increasing gap voltage. The separation of curves B and C show the phenomenon of "termination lead". 0.020" diameter point, 1/4" point projection. Relative air density, 0.98. △ - Curve A-initial pulse locus. □ - Curve B-terminal pulse locus. ◊ - Curve C-constant 51,3 kilovolt intercept on the high voltage waveform.
The distortion of the high voltage waveform is apparent from the fact that the negative and positive crests occur at 100 degrees lagging wave zero instead of 90 degrees. Curve A of Figure 15 is the locus of a 51.3 kilovolt intercept on the high voltage waveform as the crest voltage is increased.

The phenomenon of "termination lead" as described by Churchill is evident in Figure 15 (1, p. 25-27). "Termination lead" is the difference between the electrical positions of the initial and terminal pulses with respect to the electrical position of the crest of the wave for a fixed crest voltage. This indicates that for a fixed crest voltage greater than the minimum onset voltage, the terminal pulse occurs at a voltage of higher magnitude than the initial pulse. This phenomenon should not be confused with difference between RMS values of onset and extinction voltage with a changing gap voltage. In the case of the changing gap voltage, the extinction voltage will be lower than the onset voltage.

The amount of termination lead was not affected by the magnitude or phase angle of the current through the bar.

Repetition Rate

The average pulse repetition rate showed no variation due to the applied magnetic field. Figure 16 shows photographs of the cathode follower output as displayed on a
Figure 16 Cathode follower output. 76 kilovolts crest, 0.010 inch diameter point, 1/16 inch projection, relative air density, 0.99. Top trace, no current; middle trace, 500 amperes; bottom trace, 1000 amperes. Vertical scale, 20 millivolts/centimeter. Horizontal scale, 20 microseconds/centimeter.
Tektronix type 545A oscilloscope. Currents of 0, 500, and 1000 amperes were used at phase angles of 0°, +90°, -90°, and 180°. There is a variation in the distribution of the pulses in these pictures. However, comparing the distributions for no current in each of the four photographs shows that there is a definite difference in distribution. This is primarily due to small fluctuations in line voltage. Line voltage regulation was a continual problem. In most cases, its magnitude was very small and did not affect the results. However, its influence on the distribution of the pulses was quite visible on the oscilloscope. Figure 17-a shows consecutive photographs taken 1 minute apart. The gap voltage was maintained at 90 Kv for these exposures. During the period when these pictures were taken, small line voltage fluctuations were noticed on the voltmeter. Figure 17-b shows the cathode follower output for the same conditions with an increased sweep speed.

Pulse Height

Within the resolution power of the oscilloscope, no variation in pulse height could be detected as the magnetic field was applied. Figure 18 shows the output pulse of the cathode follower for three different values of current and four phase angles. If the repetition rate is unaffected, the pulse height would also be unaffected (3, p. 26-29).
Figure 17 Variation in pulse distribution with time. One minute between exposures. Gap voltage, 90 kilovolts crest. 0.020 inch diameter point. 3/16 inch point projection.
Figure 18 Pulse output of cathode follower. 90 kilovolts crest, 0.010 inch diameter point, 1/16 inch projection, relative air density, 0.99. Top trace, no current; middle trace, 500 amperes; bottom trace, 1000 amperes. Vertical scale, 0.02 volts/centimeter. Horizontal scale, 0.5 microseconds/centimeter.
Radio Noise Characteristics

Radio noise measurements were made with two types of points. One point was the standard 0.010 inch diameter steel point and the other was a 0.010 inch diameter steel point coated with General Cement No. 47-2 Corona Dope. The diameter of the coated point was 0.020 inches. This formed an insulating layer over the surface of the point. The point terminating resistor was 1000 ohms for all tests. The output of the cathode follower was coupled to the radio noise meter by a 10 picofarad capacitor.

The RIV curves for the steel point are shown in Figures 19 and 20. There is no noticeable influence of the magnetic field on the Radio Influence Voltage, FI or QP. Currents of 250, 500, and 1300 amperes were also used. The 1300 ampere checks were made only at 0° and 180°. At other phase angles in the region of 90° lead or lag, 1000 amperes was the maximum available current. The data taken at these points shows so little deviation from the 1000 ampere curves that it could not be plotted without many points falling on top of one another.

The radio noise characteristics of the coated point are illustrated in Figures 21 and 22. With this point, both positive and negative discharges occurred. This simulated a dielectric point on a transmission line. Again, there was no apparent influence on the radio noise by the
Figure 19 Radio influence voltage characteristics of a steel point with changes in current magnitude and phase angle. 1" diameter bar, 0.010" diameter point, 1/16" point projection. Relative air density, 0.99

- No current
- 1000 amperes Phase angle = 0°
- 1000 amperes Phase angle = 90° Lead
- 1000 amperes Phase angle = 90° Lag
Figure 20 Radio influence voltage characteristics of a steel point with changes in current magnitude and phase angle. 1" diameter bar, 0.010" diameter point, 1/16" point projection. Relative air density, 0.99

- No current
- 1000 amperes Phase angle - 90° Lead
- 1000 amperes Phase angle - 90° Lag
Figure 21 Radio influence voltage characteristics of a steel point coated with dielectric material. 1" diameter bar, 0.070" diameter point, 1/16" point projection. Relative air density, 0.99.

- No current
- 500 amperes Phase angle - 0°
- 500 amperes Phase angle - 90° Lead
- 500 amperes Phase angle - 90° Lag
Figure 22 Radio influence voltage characteristics of a steel point coated with dielectric material. 1" diameter bar, 0.020" diameter point, 1/16" point projection. Relative air density, 0.99.

- No current
- 500 amperes Phase angle = 0°
- 500 amperes Phase angle = 90° Lead
- 500 amperes Phase angle = 90° Lag
magnetic field. The FI and QP were also checked at each voltage with 250 and 1000 amperes. The points were so close together that it would be very difficult to distinguish between them if they were all plotted on one curve.
CONCLUSIONS

1. The point projection from the bar influences the corona onset voltage.

2. The bar diameter for a fixed point projection influences the corona onset voltage.

3. The phenomenon of "termination lead" is also present with this geometry.

4. Magnetic fields of the magnitude encountered on high voltage transmission lines where corona is present have no measurable influence on the onset voltage, pulse repetition rate, pulse height, or radio noise characteristics of negative corona, from a steel point, regardless of phase angle with respect to the high voltage waveform.

5. Any influence of the magnetic field on the onset voltages, both positive and negative, and the radio noise characteristics of a dielectric point is not detectable.
BIBLIOGRAPHY


