Electrical Discharge Imaging

By

NIELS JACOB NIELSEN
B.S. (University of California, Davis) 1975

THESIS

Submitted in partial satisfaction of the requirements for the degree of

MASTER OF SCIENCE

in

Engineering

in the

GRADUATE DIVISION

of the

UNIVERSITY OF CALIFORNIA

DAVIS

Approved:

James F. Shackelford
J. K. Mackenzie Jr.

Committee in Charge

Deposited in the University Library .... Date .... Librarian

Acknowledgments

I wish to thank my thesis committee chairman, Professor James F. Shackelford, for all the guidance, encouragement and *optimism* he supplied during this research project.

I also wish to thank Professor Amiya K. Mukherjee and Professor Jerald M. Henderson for their support and advice during the course of my graduate studies and my employment as a teaching assistant for the Mechanical Engineering Department.

Thanks are also due to Bill Blumenthal for the fine S.E.M. photos of the crack sample, and to all the office staff for their patience and helpfulness.

Abstract

The voltage, frequency and air gap width dependence of electrical breakdown in the so-called Kirlian electrophotography apparatus was measured. Test voltages varied from 600 to 1,000 volts peak (425 to 700 volts R.M.S.) over a range of frequencies from 60 to 1,000 hertz. Air gap values ranged from a low of 0.00075 inch to a high of 0.003 inch. The system exhibited two discharge modes which were recorded on Polaroid type 57 sheet film. The first discharge mode was a simple Townsend breakdown-triggered glow mechanism. The second was an edge-enhanced corona discharge in regions of field asymmetry.

The Townsend breakdown followed a modified Paschen curve for applied voltage versus air gap width, in good agreement with theory. The presence of corona was also in keeping with literature predictions. The relative dielectric constant of the Polaroid sheet film was estimated to be 5.2 @ 60 hertz, and was suspected to be a function of frequency in the test range studied.

The usefulness of these electrical discharge mechanisms as non-destructive test methods for surface characterization and flaw detection was demonstrated on several nearly flat metallic test specimens. The Paschen dependence of Townsend breakdown was used to map out flatness deviations in the specimens, while the corona mechanism was used to pinpoint surface cracks.

TABLE OF CONTENTS

Introduction

In papers published during the late nineteen fifties and early nineteen sixties, Russian researchers Semyon and Valentina Kirlian first revealed to the western scientific community their pioneering work in the field of high voltage photography.[1] They discovered that applying a high voltage AC signal to an object would result in the formation of an electrical discharge on the object's surface corresponding to the object's topology and dielectric structure. This glow discharge was found to be a slow, stable, and generally uniform process. Of particular interest to me is the Kirlian device shown in figure 1. This early device consists of a high voltage AC source connected to a metal plate. A sheet of ordinary photographic film in intimate contact with the supply plate dielectrically isolates the plate from the planar test object. The test object is then grounded, and upon application of power, electrical discharges occur in the 0.1 to 1.0 mm air gap present between the film and the object, exposing the film. The "emission image" thus obtained upon subsequent development of the film is a record of where the many local discharges were positioned across the sample's surface.[1]

Coins, plant leaves (living or cut) and human fingertips were typical test objects studied by the Kirlians with their flat plate apparatus, and the later work done by American researchers such as Thelma Moss also centered upon flat plate film dielectric photography of living or once-living things. Moss investigated the use of corona discharge or "Kirlian" photography as a psychological testing tool. This generated much American interest in the so-called Kirlian effect during the early nineteen seventies. Moss reported many qualitative changes in the appearance of fingertip coronas recorded by her apparatus (figure 2) depending on the emotional or physiological state of the test subject.[2] Moss and her co-worker, Kendall Johnson, have maintained that these changes in the corona pattern around the fingertip were independent of such purely physiological effects as galvanic skin response and perspiration. That their test results tended to be difficult to reproduce is understandable, since no precautions were taken to control fingertip pressure on the film or fingertip cleanliness during their tests. Atmospheric humidity might also have had an effect on corona formation around transpiring or otherwise moist objects such as fingertips and leaves. Hence, without careful control over test conditions and careful monitoring of physiological processes in the biological test object, confirmation of the so-called "psychoenergetic effects" in corona discharge photography postulated by Moss and such Russian researchers as Adamenko[2] is not easily made. Further research in the field by Pethek, Faust and Kyler[3] indicates the absence of any photographic image information in the Kirlian photographs they produced in their own lab that could not be attributed to the well-known modes of ordinary corona discharge. These corona formation processes have already been extensively studied by physicists and electrical engineers. An annotated bibliography of some of the standard reference texts on the topic is given in Appendix I.

Hence, what biological test data already exists is of limited utility for the engineer. More important is whether or not a corona discharge probe, based upon the well-understood physics of electrical discharge in gases, can be used to characterize material features such as surface topography, surface cracks, or other flaws in metallic samples. Any data derived from an engineering test of this type should correlate with data in the high voltage electrical engineering literature. The purpose of my work in this field was to design such a probe, verify its operation by comparison with literature and handbook data, and demonstrate some of its capabilities.

Theory

At this point I will summarize the fundamental electrical processes which are the basis of corona discharge photography. The key to the process is that air stops being a good insulator and instead becomes a fairly good conductor. When this occurs, light can be produced, as will be shown later.

Air can conduct electricity only if mobile ions are present in it. Positively charged ions can be created spontaneously in air by occasional cosmic rays or ultraviolet photons, both of which are capable of knocking an electron free of a gas molecule or atom. This process occurs so seldom under ordinary conditions that very few electron/ion pairs are available at any given time to transport charge through air. The electron/ion pairs also quickly recombine, further reducing the effect. Hence, air is a common insulator. Now, consider two metallic electrodes separated by a small air gap. If a voltage V_a is applied across them, an electric field will be established in the insulating gap. This field will apply a force to any charged object in the gap, tending to accelerate it. A few electron/ion pairs in the gap will move under the influence of the field, accepting energy from it as they are accelerated. As the lighter and hence more mobile electrons move towards the positively charged electrode, they collide with and ionize more gas molecules, creating a growing avalanche of free electrons which are drawn towards the positively charged anode. When they strike it, a burst of ultraviolet photons is released and causes still more ionization in the air gap. The positively charged gas molecule ions, being more massive than their electron counterparts, move much more slowly towards the negatively charged cathode. When one of these positive ions strikes the cathode surface, it knocks loose a host of free electrons, some of which recombine with and hence neutralize the ion. A light photon is released during recombination. Visible light is produced, usually deep blue or violet in color, since the most frequently excited radiation in this whole process is from the second band group of highly energized N_2 molecules. Whatever "surplus" electrons are left over after the colliding ion is neutralized are free to be accelerated towards the cathode, and in turn create more ion pairs by collision. This avalanche process is what turns insulating air into a conductive yet electrically neutral plasma.

Allow the number of surplus ejected electrons released by ion impingements on the cathode to be γ. Allow each ejected electron to experience η ionization event collisions per unit voltage increment as it traverses the gap from cathode to anode. Then one electron from the cathode will cause an avalanche containing $\exp(\eta V_a)$ electrons, where V_a is the voltage across the gap. This will also result in the formation of $\exp(\eta V_a)-1$ positive ions. If one positive ion ejects γ surplus electrons at the cathode surface upon striking it, the $\exp(\eta V_a)-1$ positive ions will produce $\gamma=\gamma(\exp(\eta V_a)-1)$ electrons.[4]

A critical condition will exist when each electron leaving the cathode involves itself in collision and ionization processes in the air gap by which means it is eventually replaced by a new electron leaving the cathode.[5] When this happens, the discharge is said to be "self-sustaining." Mathematically, this can be solved for by fixing $g=1$ and solving for V_a in the equation for g previously given: $\gamma(\exp(\eta V_B)-1)=1$. V_a has been replaced by V_B, the voltage at which the criticality condition is met. This voltage is called the Townsend breakdown voltage after Sir John Townsend, the physicist who first derived the breakdown criticality condition. It is also referred to as V_s or the "sparking potential," because it is at this voltage level that the current flowing through the air between the electrodes increases discontinuously. This discontinuous current jump is sometimes accompanied by a spark jumping the gap between the electrodes. Any voltage across the gap which is less than V_B will not result in breakdown. The weak current flow resulting from these lower voltages is called Townsend or "dark" discharge.

Townsend's work has shown that the breakdown avalanche phenomenon is caused by the quantity η, the ionization coefficient, and the quantity γ, the secondary emission coefficient. For greatly reduced air gap (or for greatly reduced gas pressures in larger gaps), the electrons flowing across the gap encounter fewer gas molecules, resulting in less ionization; therefore, η will go down. Under these conditions, ionization can be increased by increasing the applied voltage V_a. For much wider gaps (or much higher gas pressures in smaller gaps), the electrons flowing across the gap lose so much of their energy by frequent elastic collisions with gas molecules that they cannot ionize the molecules. Again, η goes down. Similarly, ionization can be increased only by increasing the applied voltage V_a in this regime. In between these two extremes, η goes through a maximum, which in turn causes V_B to go through a minimum.[4] So, η is some inverse function of the gap width d and the gas pressure p (or, more correctly, the density of the gas), and a direct function of applied voltage. It also varies from gas to gas. On the other hand, γ is dependent both on the type of gas in the gap and in the composition and cleanliness of the cathode surface. Data on γ for different materials are typically quoted for vacuum conditions. Experimentally, V_B is primarily a function of η and is not as strongly dependent upon γ. Also, for most conditions, $\exp(\eta V_B)$ is much greater than 1, so we can now rewrite our earlier expression for V_B this way: $V_B \cong (-\ln\gamma)/\eta$. The $(\ln\gamma)$ term is less than zero because γ is typically much less than one. If γ is not a strong function of gap width, gas density or applied voltage, then neither is $\ln(\gamma)$, so we conclude that V_B is approximately proportional to $1/\eta$ and that η is hence proportional to $1/V_B$. We know from before that η is equal to some function of (V_a/pd). If we now allow $V_a=V_B$, we conclude that $1/V_B$ is a function of (V_B/pd), or that V_B is some function of the non-independent product of gas density and gap spacing. This was originally derived by Paschen in 1889.[4] A plot of experimentally measured V_B values versus the pd products for a given gas is called a Paschen curve and allows the prediction of Townsend (spark) breakdown if gap spacing and gas pressure are known. A Paschen curve for ordinary air is given in figure 3. Paschen curves are usually plotted for direct current voltages, but for low frequency AC (power or audio frequency) voltages, V_B values will vary only by a few per cent from the DC V_B values.[8] To interpret the curve, remember that for all operating points on or above the curve, breakdown will occur, and for all points below the line, no breakdown is possible. Note also that for an operating voltage of 0.4 V (peak), breakdown is possible in a wide range of pd product combinations ranging from slightly less than 4×10^{-3} to just under 2×10^{-2} BAR-mm. If pressure is constant, this represents a range of gap widths in which discharge can occur at the prescribed voltage. At gap spacings falling outside this range, the discharge will be extinguished.

Since the mass of the positive ions is so great, they will tend to accumulate in the gap with the passage of time, rather than being easily swept up by the cathode. This is especially true in the case of AC excitation, where the anode and cathode switch position at each half-cycle. This cloud of positive ions represents a space charge which distorts the electrostatic field in the gap. Its effect is to make the positive anode "appear" closer to the negative cathode than it actually is. In its most extreme form, the accumulated space charge can "squeeze" the field to the point where it exists only in a narrow region next to the cathode, with the rest of the gap being at one potential because of the accumulated charge in the gap. This will cause deviation from the ideal picture presented in the Paschen curve, but the general form of the curve is still followed. For practical applications where space charge accumulation may be present, theoretically derived Paschen curves are somewhat less important than actual experimental results when attempting to predict breakdown in a given gap geometry.[5] Space charge effects are usually demonstrated in gaps several centimeters wide. They are virtually impossible to measure in millimeter-sized gaps. In my experiments, gap spacing was on the order of hundredths of a millimeter. Therefore, the influence of space charging cannot be known in my experiments and will not be treated further here. The interested reader is directed to Penning's excellent treatment of the topic.[4]

Another effect which can cause considerable scatter in deriving a Paschen curve from experiments is initiatory time lag. Because the process of initial ion pair production in the air gap by cosmic rays or ultraviolet light is a random one, a delay sometimes occurs before Townsend breakdown is observed at the start of a breakdown experiment. This time lag can be 0.01 second long.[7] If the duration of the breakdown test is on the order of the time lag, many of the experiments will not show breakdown as predicted by theory. Reliable data collection for Paschen curve assembly is always performed with at least one of the electrodes illuminated with a short wave ultraviolet source. This causes photoelectrons to be ejected from the electrode(s). These are available for conduction the instant that voltage is applied across the gap, and the statistical initiatory time lag is hence eliminated. For small air gap spacings, illumination becomes difficult. Ultraviolet triggering of this sort cannot be used when running breakdown experiments with the Kirlian apparatus because photographic film is present in the gap. It would be completely fogged by the ultraviolet triggering illumination, rendering the test useless. Therefore, tests which are based upon the use of photographic film to record the presence and location of Townsend breakdown in a small air gap must be of such a duration as to render test nonuniformity due to time lags negligible. As will be seen in the materials and methods section, this effect made early experiments difficult to reproduce.

Further deviation from ideal Paschen curve breakdown behavior has been observed at very high fields (10^5-10^7 volts/cm), because of the onset of field emission.[6] This phenomenon occurs when the magnitude of the applied electrostatic field in the gap is so great that electrons are extracted from the metal electrode surface despite the work function barrier present there. Ion pair production and subsequent air ionization in the gap do not enter in. This phenomenon is usually studied in vacuo, and hence its effects on experiments conducted at atmospheric pressure are hard to identify and will be neglected here. Comparison of my results with literature data has shown this to be permissible. All effects observed in my experiments can be explained without the need to invoke the field emission mechanism, which involves the statistical "tunneling" of electrons through the work function potential barrier under the influence of a very strong field.[8]

At this point it is instructive to present a somewhat idealized mapping of current and voltage for breakdown phenomena in uniform fields (which, for instance, would exist in the air gap separating two identical flat metal electrodes carrying opposite charges). Cobine[5] offers the graph reproduced here as figure 4. It shows the low current pre-breakdown Townsend discharge region, terminating in unstable transition at the Townsend breakdown voltage V_S. At breakdown, light production begins, and a drop in the voltage required to maintain conduction is observed. This drop is sometimes absent. In any event, a plateau follows. In this region, visible discharge spreads over the electrode surfaces as the current through the now-conductive air gap is permitted to increase. The amount of visible discharge present is hence related to the current supply capability of the power source. Once Townsend breakdown has occurred, the system current will jump up until the power supply's limit as a current source is attained. In this way, an operating point for the system will be established on the curve where the power available from the supply equals that dissipated by the discharge. This power dissipation is expressed as predominately ultraviolet light emission from the ionized air in the gap. Some visible light from the same source is also produced, giving the discharge its characteristic faint blue color. Ozone is also produced by the ionization processes and, at high power levels, can be given off in amounts sufficient to produce physiological damage to an experimentor. Heating due to current flow through the resistance of the conductive air also can happen, particularly at the higher power levels.

Increases in current flow through the air gap are attended by increases in ionization processes in the gap. This gives rise to the accumulation of positive ions in the gap, causing space charge effects as explained previously. These space charge effects become progressively more severe as the plateau in the characteristic curve is traversed. At the right-hand end of the plateau, where the visible discharge has completely covered the electrode surfaces facing the gap, increased current flow can be had only by increasing the magnitude of the applied voltage. The curve slopes upward towards another unstable transition as the voltage gradient (field) is progressively squeezed down into a smaller and smaller space next to the electrodes by the accumulating space charge.[4] Eventually the glow discharge degenerates into an intense arc, which may pass hundreds of amperes at ten to twenty volts potential difference between the electrodes.

Arcs, however, are not desired. The portion of the characteristic curve which is useful for my purposes lies between the Townsend regime and the high space-charge regime. In this low power region, ozone production is minimized and heating effects are eliminated. Glow production at the left hand end of this operating range can be used as an indicator of Townsend breakdown in the gap. If the applied voltage is known, the width of the gap can be solved for by referring to a Paschen curve. In this manner, the discharge phenomena observed in a small air gap separating two oppositely charged metal electrodes can be used to map the topography of the electrode surfaces. If one surface is known to be flat, the flatness of the other electrode can be tested for in this manner.

Before concluding my treatment of discharge mechanisms, I will introduce one more deviation from the idealized Paschen curve behavior of electrical discharge in air gaps. It is called corona and is frequently encountered in high-voltage power transmission and switching systems. Corona is a form of glow discharge in which the criticality condition for self-sustenance is primarily a function of electrode shape rather than interelectrode air gap width. It is observed when the electrostatic field between two electrodes is strongly asymmetric, as is the case when the opposing electrodes are radically different in shape. Corona would be invited, for instance, by a system consiting of a sharply pointed rod electrode next to a flat metal plate electrode. It also occurs when the spacing between symmetric electrodes is much greater than the physical dimensions of the electrodes themselves. An example of this would be the corona observed on the surfaces of two parallel, oppositely charged overhead power transmission lines. In this latter case, corona is a precursor to Townsend breakdown of the gap between the lines, since the corona inception voltage can be much lower than the Townsend breakdown voltage for the same gap,[6] if the gap is large. For small gaps and symmetric electrodes, the corona inception voltage approaches the Townsend breakdown voltage V_s and for very small gaps the two are identical, i.e., Townsend breakdown occurs first and hence corona discharge is not seen.[6] Determining the criticality condition for establishing a self-sustaining corona discharge is considerably more complex than the Townsend derivation for symmetric electrodes. Corona inception voltages are generally tabulated for various electrode geometries encountered in power transmission design and are derived from experiment rather than from first principles.[9]

Despite this, the phenomenon of corona discharge is useful in the design of a surface inspection probe in this way: imagine once again a symmetric electrode configuration consisting of two circular metal discs facing each other and separated by a small air gap. If a voltage less than V_B is applied across the air gap, Townsend breakdown will not occur. However, the applied voltage may be sufficient to cause the edges of the discs to ignite with corona discharge, if the edges are sharp enough. This is because the electrostatic field, while uniform in the gap between the discs, is highly non-uniform in the region near the edges of the discs.[5] The sharper their edges, the more pronounced the nonuniformity. This nonuniformity is the same as that of a field between two asymmetric electrodes; therefore, corona will be seen in the gap nearest the edges of the discs before Townsend breakdown occurs uniformly throughout the gap. Imagine now that one of the electrode discs has a crack in it which intersects its surface. The edges of the crack will cause local nonuniformity of the field in the gap and hence will cause corona to be visible at a voltage less than V_B for the given gap. This fact can be used to inspect a smooth metal surface for cracks. This would be done by making the metal test surface one electrode in a symmetric electrode system, which is then run at a voltage close to the V_B corresponding to the gap width present. Enhanced discharge will then pinpoint the region of the crack.

The preceding discussion of breakdown and discharge phenomena suggests the potential usefulness of Kirlian electrophotography -- which I more precisely refer to as electrical discharge imaging -- as a non-destructive surface inspection probe. The earliest rigidly controlled experiments in this area were performed by W. A. Tiller and D. G. Boyers.[10] Their intent was to characterize the dischage patterns occurring in the air gap between flat, polished metal disc electrodes. Photographic film inserted in the gap was used to record the discharges. Their work permitted the first detailed explanation of the various colors observed when color film is used in the gap. They based their explanation on the interaction between the myriad local discharges and the various filtering and emulsion layers in the film. They cited much the same breakdown and discharge mechanism as previously described in the Townsend derivation, and obtained repeatable photographs of randomly positioned, localized "streamers" of discharge happening all across the electrode surfaces facing the gap. They used single and repeated 100 to 500 μsec pulses of 1 megahertz sine waves applied across the electrode faces, at an applied potential of 20 kilovolts. A new network of discharge points occurred with each successive pulse since ion recombination in the air gap -- causing the locally conductive streamer channels to be extinguished -- could occur during the "off" portion of the duty cycle. Long exposure times at lower, non-pulsed excitation frequencies might then be the cause of the more non-localized, diffuse discharge illumination usually observed under such conditions.[10] Superposition of discharge points from each successive half-cycle of excitation would cause this averaging. With these facts established, further research into engineering applications of electrical discharge imaging could follow.

The first major attempt at applying Boyer's and Tiller's findings to the study of engineering materials was undertaken by D. Lord and R. Petrini at Lawrence Livermore Laboratories in the mid nineteen seventies.[11] Using a flat plate Kirlian apparatus similar to those previously described, they obtained many interesting results. For example, a metal block with a fly-cut milled surface was used as one of the electrodes in the device, after first having had the milled surface obliterated by bead-blasting. Despite this, the circular milling cutter marks were clearly visible in the resulting photograph, even though neither a Talysurf profileometer nor ordinary visual inspection could resolve any milling marks on the bead-blasted electrode surface.

In another test, hardness test indentations, made on one side of a flat, metallic tensile test specimen, apparently showed through as "shadows" on its opposite, unmarked side when it was similarly tested. No visual evidence of the indents could be found on the unmarred side before or after the test. Furthermore, an electrical discharge image of a cycled (and failed) fatigue toughness specimen exhibited light and dark fringes in those regions of the specimen where yielding and residual strains were believed to be present.[11] The discharge photograph bore a tantalizing resemblance to the familiar light-and-dark fringe patterns ordinarily seen in plastic models of plates under polarized light illumination (the photoelastic stress method).

It is unnecessary to conclude from this that electrical discharge imaging can be used to photograph residual stresses in a failed machine part. The Paschen dependence of discharge location in an air gap of varying thickness is sufficient to explain the fringe effects seen in the Lord and Petrini fracture toughness specimen photograph, if one assumes the specimen contained residual strains in the form of slight deviations from perfect flatness. This deviation-from-flatness hypothesis seems all the more plausible when one realizes that none of the three test specimens described above was gound absolutely flat prior to testing in the discharge device. While residual strains in a metal test object necessarily involve physical distortion of that object (buckled plates and necked tensile test specimens being two obvious examples), using what is really a very sensitive surface flatness test to photographically record residual strains could be misleading. As an extreme example, a curved surface sample could be deformed into perfect flatness before testing, giving no "stress pattern." Deviations from flatness brought on by cracking or porosity, however, might well be detectable with such a test.

Lord and Petrini's most advanced apparatus[12] represents a significant deviation from the original simple flat plate device used years ago by the Kirlians. It consists of a bell jar which can be evacuated, hence allowing the second electrode to be located several centimeters distant from the object under test. This is because the Paschen curve abcissa is classically scaled in terms of a pressure and gap spacing product pd, as shown before. Therefore, discharge at a certain voltage can be observed in a large interelectrode gap if the gas pressure in the gap is reduced. Nonplanar objects may then be inspected (at rather high power input) inside the bell jar, causing corona discharge to appear all over the test object's surface. Lord and Petrini also made provision for leaking controlled atmospheres of helium or neon, for example, into the jar during a test to investigate what effects these may have on discharge production. A major effect is different characteristic discharge colors. Figure 5 illustrates this device.

Despite Lord and Petrini's work, the exact dependence of ignition onset upon gap width, applied voltage and source frequency still remained to be determined. My specific intent was to experimentally determine this dependence, check it against electrical engineering literature predictions and show that the combined phenomena of Townsend and corona discharge can be used to locate surface imperfections and warpage in flat metallic test samples.