Paschen breakdown in dielectric and varistor granule filled spark gaps

UNM, Undergraduate Honors Thesis

Josef Sorenson

May 2021

SAND2021-4938 T

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

ABSTRACT

Dielectric granule filled spark gaps and varistor granule filled spark gaps are used to alleviate high current and high voltage strain on critical systems from lightning strikes. The dielectric granules cause high field concentration points that enable gas ionization at lower voltages. Varistor granules become conducting at their switching field, enabling granule conduction. Here, I report the pressure dependence of voltage mitigation in these dielectric and varistor granule filled spark gaps. I provide a mechanistic interpretation of the observed pressure dependence using gas breakdown, varistor conduction, and thermionic induced emission. The Paschen minimum shifts downward from 1.5(7) cm * Torr to 0.6(3) cm * Torr due to filling with dielectric granules and the magnitude of the breakdown decreases by about 3 fold. The varistor granule filled spark gap shows immunity to pressure variation near ambient conditions due to its granule conduction and thermionic induced breakdown mechanisms. These findings will help inform surge protection under different pressure conditions in both varistor and dielectric granule filled spark gaps.

ACKNOWLEDGEMENTS

A warm thank you to Pin Yang, Mia Blea, and Will Bachmann for enthusiastic mentorship at Sandia. Also, to Paul Schwoebel for supervising my progression and excellent feedback.

Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525. Programmatic support from Bill C. Moffatt on the basic breakdown phenomenon is greatly appreciated.

CONTENTS

1. INTRODUCTION

Research on breakdown mechanisms is usually done with intent to prevent breakdown at higher voltages. Dielectric and varistor stimulated spark gaps take advantage of the often unfavorable breakdown of gas in order to divert high voltage and high current pulses caused by lightning strikes from signal pins to a ground [1]. The signal pins must allow low voltage to pass so that information or power can be transmitted. Gas breakdown acts as a switch when the voltage becomes too high. Gas molecules are continuously rearranging. This makes permanent damage, a problem with solid state surge protectors, impossible in gas filled spark gaps. Spark gaps are left intact after a high voltage pulse so they are available for repeated use which makes them superior in situations where repeated high voltage pulses are possible, and immediate use of the system is necessary (i.e. no time to change a fuse). Such is the case for many critical systems in aerospace vehicles.

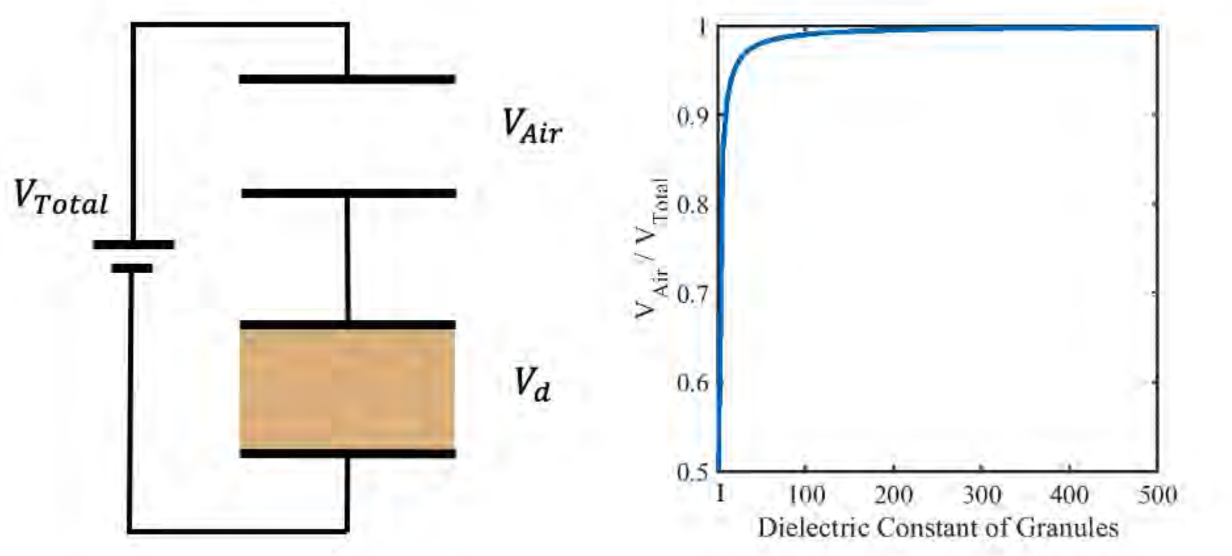

Figure 1-1. Dielectric and air filled capacitors in series (left). The fraction of the total potential across the air filled capacitor is plotted as a function of the dielectric constant of the dielectric filled capacitor (right). For increasing dielectric constant, more of the total potential is across the air filled capacitor.

Introducing high dielectric granules to the gap reduces the breakdown voltage by creating high electric field concentration points [2]. Higher dielectric granules cause higher field concentration across the gas. For a simplistic view of how this works, consider two equal geometry capacitors in series. One capacitor's dielectric is air ($\varepsilon = 1$) and the other if filled with a dielectric with a dielectric constant of ε_d. A potential (V_{tot}) is applied across the two capacitors. This circuit is depicted in Figure 1-1 (left). The potential across the air filled capacitor as a function of the dielectric constant is

$$\frac{V_{air}}{V_{tot}} = \frac{1}{1 + (\varepsilon_d)^{-1}}$$

This is plotted in Figure 1-1 (right). As the dielectric constant of the second capacitor increases, a larger ratio of the total voltage is put across the air gap. In a gas filled spark gap, adding high dielectric granules reduces the volume of gas while keeping the potential across the gas constant. Thus, without increasing the voltage, the electric field across the air increases and a lower than normal voltage is required to reach the breakdown electric field strength of air.

For a more realistic view, consider both the dielectric medium and gas in the same capacitor. Figure 1-2 shows the electrodes of the spark gap in a two dimensional plane, with a centered dielectric sleeve. Equipotential lines (black) were found by numerically solving the Poisson's equation using a finite difference method in MATLAB. The electric field corresponds to the density of equipotential lines. Inside the low dielectric sleeve (left), the density of equipotential lines is lower than in the gas. The "squeezing" of the equipotential lines is the sought after characteristic that lowers the breakdown voltage of the gap. For the higher dielectric sleeve (right), the equipotential lines in the gas gap are very dense. Note that the total number of equipotential lines is the same in both cases. The difference in equipotential line density is due to the higher induced surface charge on the sleeve with the larger dielectric constant.

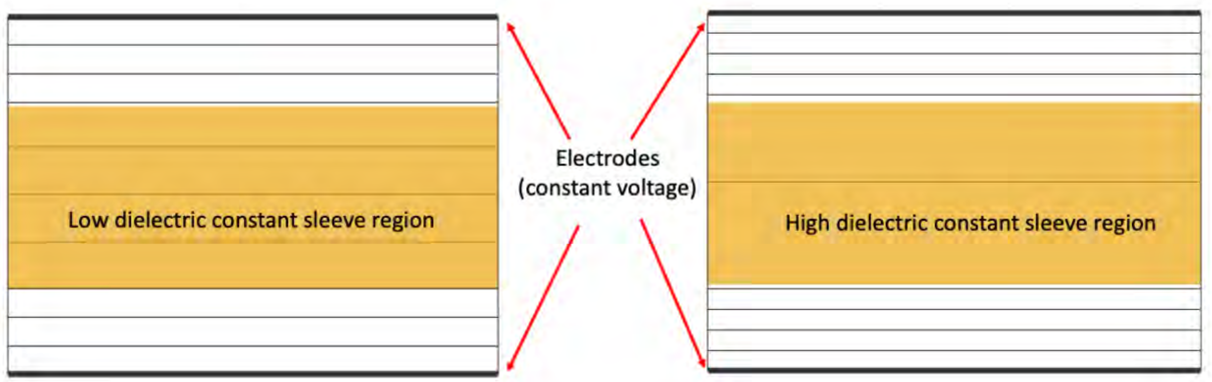

Figure 1-2. Numerical solutions to the Poisson equation for equal geometry low (left) and high (right) dielectric sleeves inside capacitors with the same potential. The higher dielectric sleeve causes greater squeezing of the equipotential lines which means a higher electric field.

Dielectric sleeves were found to be less effective than filling the gap with dielectric [3]. Figure 1-3 shows that the dielectric granule causes extreme squeezing of the equipotential lines near where the dielectric granule makes contact with the electrode plates (red arrow). This reduces the voltage necessary to reach the electric field strength required for gas breakdown. Again, the higher dielectric constant granule (bottom) causes greater squeezing of the equipotential lines than the lower dielectric constant granule (top).

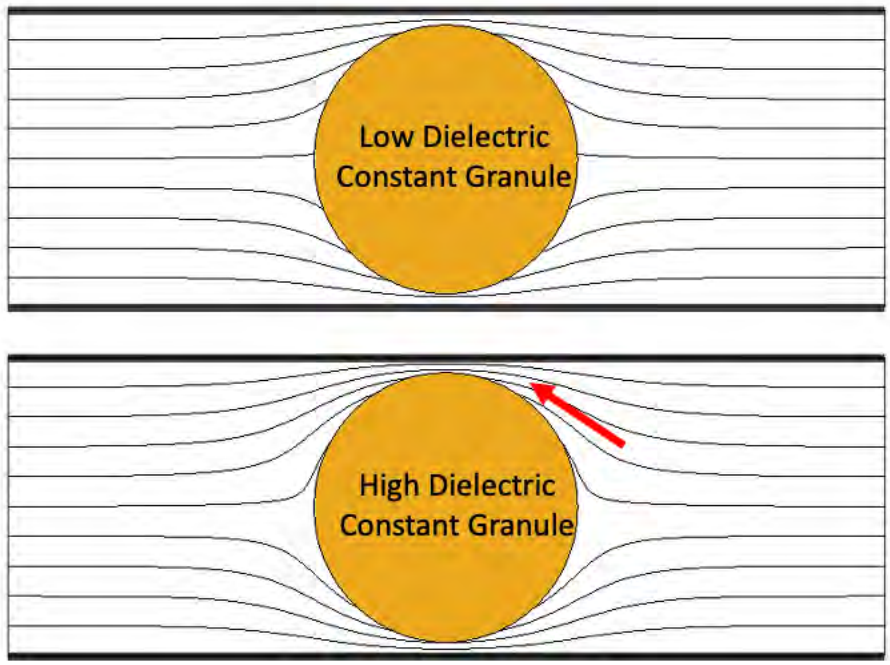

Figure 1-3. Numerical solutions to the Poisson equation for equal geometry low (top) and high (bottom) dielectric granules inside capacitors with the same potential. Near the granule-electrode contact points, the electric field is enhanced (red arrow).

Varistors are a class of material whose resistance is a function of the applied electric field. As the electric field increases, varistor granules become conductive and therefore provide an alternate mechanism for current to be diverted to ground. Varistors have very high resistance when subject to small electric fields, so signal pins will not cross talk with ground, or other signal pins identically grounded. The switching field of a varistor is shown in Figure 1-4. There is a small, linearly increasing current density until the switching field of the varistor is exceeded. At the switching field, there is a sharp rise in current density and the granules "clamp" the voltage. If the switching field is exceeded, varistors can start to experience intrinsic breakdown.

Paschen's law states that the breakdown voltage of gas is just a function of the product of pressure and gap length [4]. In this experiment, all measurements are performed with a constant gap length, so for the rest of the paper Paschen's law will only refer to changes in pressure. The mechanism behind gas breakdown is electron avalanching, where electrons are accelerated by the electric field and cause more electrons to be emitted. In order for the electrons to gain enough energy for their collision to free more electrons, they must have a sufficient mean free path (average distance between collisions). If the pressure is too high, the mean free path is too short and gas breakdown is inhibited. Conversely, if the pressure is too low, there are not enough collisions to establish breakdown. The need for sufficient collisions and ionization multiplication, and kinetic inhibition by too short of a mean free path means there is a pressure where the breakdown voltage has a minimum. Change in the breakdown voltage distribution due to change in pressure near ambient conditions will inform the design of the spark gaps based of the range of pressures the device will be exposed to. This is the most important parameter for device design, but the entire Paschen curve is of scientific interest.

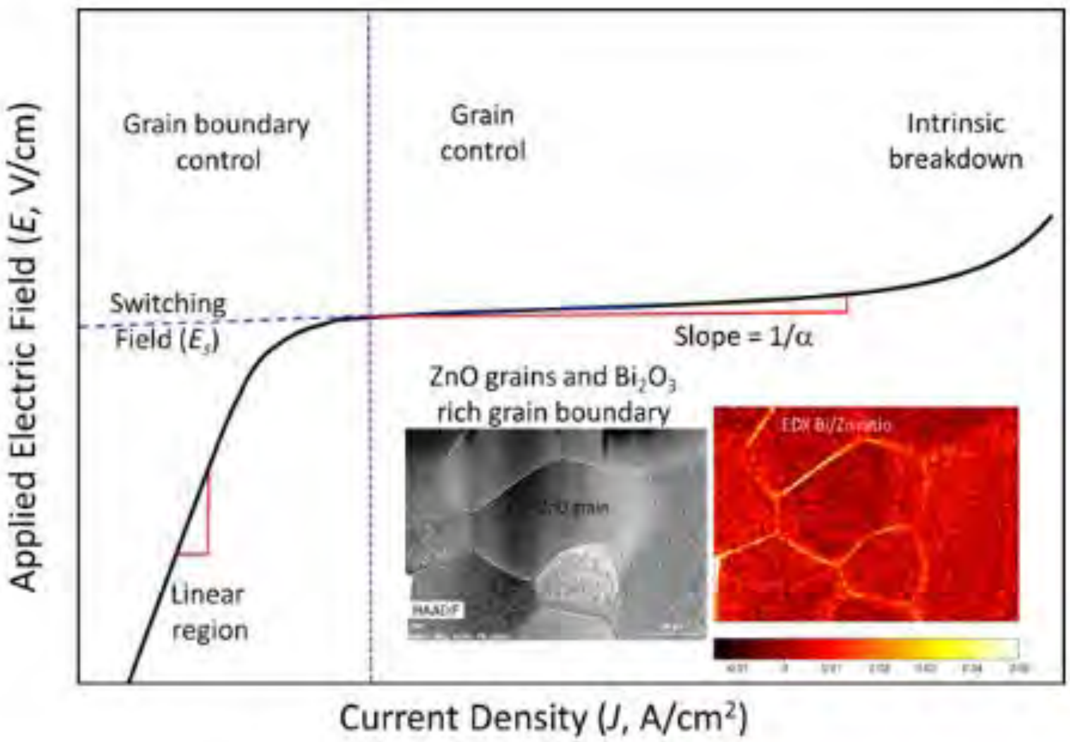

Figure 1-4. Qualitative current density of ZnO varistor versus applied electric field. For low electric fields, the current density is linear with increasing electric field. Once the switching field is reached, the current density rapidly increases with a slope of $(1/\alpha)$. If the switching field is exceeded, the ZnO will experience intrinsic breakdown.

2. EXPERIMENTAL PROCEDURE

A single pin testing fixture was used for all measurements. The fixture consists of a pin held concentrically in a hollow cylinder by Vespel (polyamide) cones, shown schematically in Figure 2-1. The gap between the signal pin and grounded shell is 300 μm. A Kiethley power supply supplies a driving voltage signal to a Trek 609D-6 high voltage amplifier. The DC high voltage from the TREK is gated by a pulse generator (DEI PVX-4140) according to signal from a waveform generator (Keysight 33600A). The positive (high) terminal is connected to the pin and the negative (low) terminal is connected to the grounding shell. A BNC splitter sends the waveform generator signal to an oscilloscope for live verification of the pulse duration. Two high voltage probes connected to an oscilloscope (Agilent, InfiniVision DSO6054A, 500 MHz, 4Gs/s) are attached to the high terminal before the pin and record the entire voltage waveform and optionally a scoped in voltage waveform. A Pearson Wideband Current Monitor 41000 around the high terminal is used to record the current waveform. The high voltage probes and current view transformer connection points are shown in Figure 2-1.

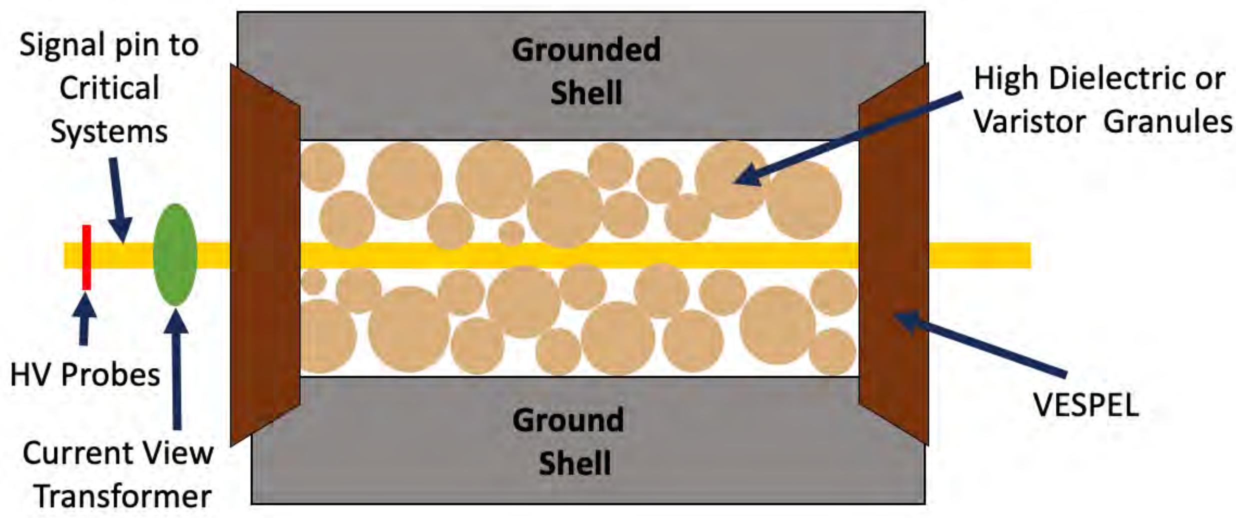

Figure 2-1. A signal pin in used to communicate with protected critical systems. The signal pin is held concentrically in a grounded shell by VESPEL cones. The gap between the signal pin and grounded shell is filled by high dielectric or varistor granules. The HV probes and current view transformer read the voltage and current immediately outside of the single pin tester.

The fixture is inside of a sealed quartz tube as part of a pressure tight system. The pressure system allows switching between house compressed air, nitrogen, and argon gas. A vacuum pump is used to reduce the pressure. Pressure is measured with an MSK 901P transducers. After changing the granule or gas type, the system was purged (pumped to 0.07 Torr and refilled with test gas) over 7 times to ensure reasonable gas purity.

All Paschen curves started at the systems lowest pressure (0.08 Torr) with increasing pressures up to 1200 Torr (~2 times ambient pressure). The vespel was deliberately loosened to allow gas leakage into the fixture gap. Measurements were not taken for at least a minute after the systems pressure was set to allow the gap the come to equilibrium pressure. All measurements consisted of 20 shots (HV pulses) separated by 5 seconds. Error is reported as the standard deviation of the 20 shots.

Data was recorded from the oscilloscope by NI LabVIEW software and transferred to MATLAB for analysis.

Two types of granules are used in this experiment. The first is Lead Magnesium Niobate – Lead Titanate (PMN-PT). PMN-PT has a dielectric constant of ~1000 near ambient conditions which makes it a preferred granule for dielectric stimulated breakdown. Granules are made by solid-state reaction between submicron PMN (50 mol.%, Tamtron) and PT (50 mol %, Ferro) powders at 750 C for four hours. The resulting powder is isostatically pressed at 30 kpsi into pellets. The pellets are crushed, and sieved between 210 μm and 149 μm sieves to control the granule size. The granules are fired at 1050°C for 90 minutes and PMN-PT phase is verified with X-Ray Diffraction.

The second type of granule was Zinc Oxide (ZnO2) varistor material. Granules are made by combining ZnO (98 mol. %), CoO (1 mol. %) and BaO (1 mol.%) via a mixed oxides method. The resulting powder was pressed, crushed, and sieved into granules. The granules were sintered at above 700°C for 1 hour. The densified granules have submicron grains separated by a barium oxide rich phase at the grain boundaries which gives rise to the unique nonlinear I-V response for varistor materials. Normally ZnO has a dielectric constant of ~10, but the barium oxide rich grain boundary raises the dielectric constant to be on the order of 1000. Therefore, these ZnO varistor granules are can exploiting the same field concentration effects that the PMN-PT granules use.

3. RESULTS AND DISCUSSION

3.1. Gas Filled Spark Gap

Figure 3-1 shows a typical spark gap gas breakdown waveform. At 0.2 µs the pulse is applied and the voltage across the spark gap rapidly increases. At 2500 V, the gas breaks down and the voltage quickly falls below the 0 V line. Oscillation after breakdown, which is observed in all breakdown waveforms, is due to the inductance and capacitance of the pulse shaping network and the testing fixture. Different testing fixtures cause vastly different oscillations, but do not change the breakdown voltage. The breakdown voltage is dependent on the slope of the rising pulse, so the slope (or "rise-time") is recorded and used to verify good testing conditions.

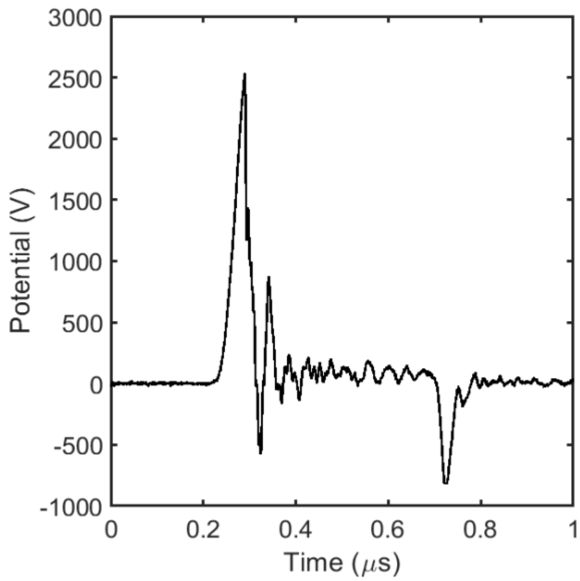

Figure 3-1. Breakdown waveform showing typical gas breakdown characteristic of a spark gap with no granules. The fast rise in voltage after 0.2 µs shows the high voltage pulse is turned on. The voltage where there is a sharp drop is the breakdown voltage. Oscillation after breakdown is due to the inductance and capacitance of the pulse shaping network and the test fixture.

Figure 3-2 shows box plots of the breakdown voltage in a nitrogen filled spark gap with no granules. The input pulse height is 3 kV. The red dashed line marks where no breakdown is observed due to the breakdown voltage exceeding the pulse height. The box plot marks the median (red line), 25th and 75th percentiles (blue lines), and the most extreme non-outlier breakdown voltages (vertical black dashed line). Outliers are marked by red crosses. At pressures lower than 3 Torr and greater than 500 Torr the breakdown voltage exceeded the pulse amplitude so the stochastic nature of breakdown is not represented in these regions. Between 3 and 500 Torr, the breakdown voltages stochastic nature is captured and manifests as a large range of breakdown voltages. In particular, near the Paschen minimum (50 Torr) the average breakdown voltage is 1670 V with a standard deviation of 192 V. Near ambient pressure (600 Torr) the breakdown voltage exceeds the 3kV pulse amplitude. An apparent second minima is observed at 0.3 torr. This is due to the sporadic nature of gas breakdown and is was not reproduced in any other measurements.

The minimum breakdown is at 50(25) Torr, and the gap width is 300 µm. Therefore the Paschen minimum is at 1.5(7) cm * Torr. This is in agreement with the usually observed Paschen minimum in nitrogen of 1 cm * Torr.

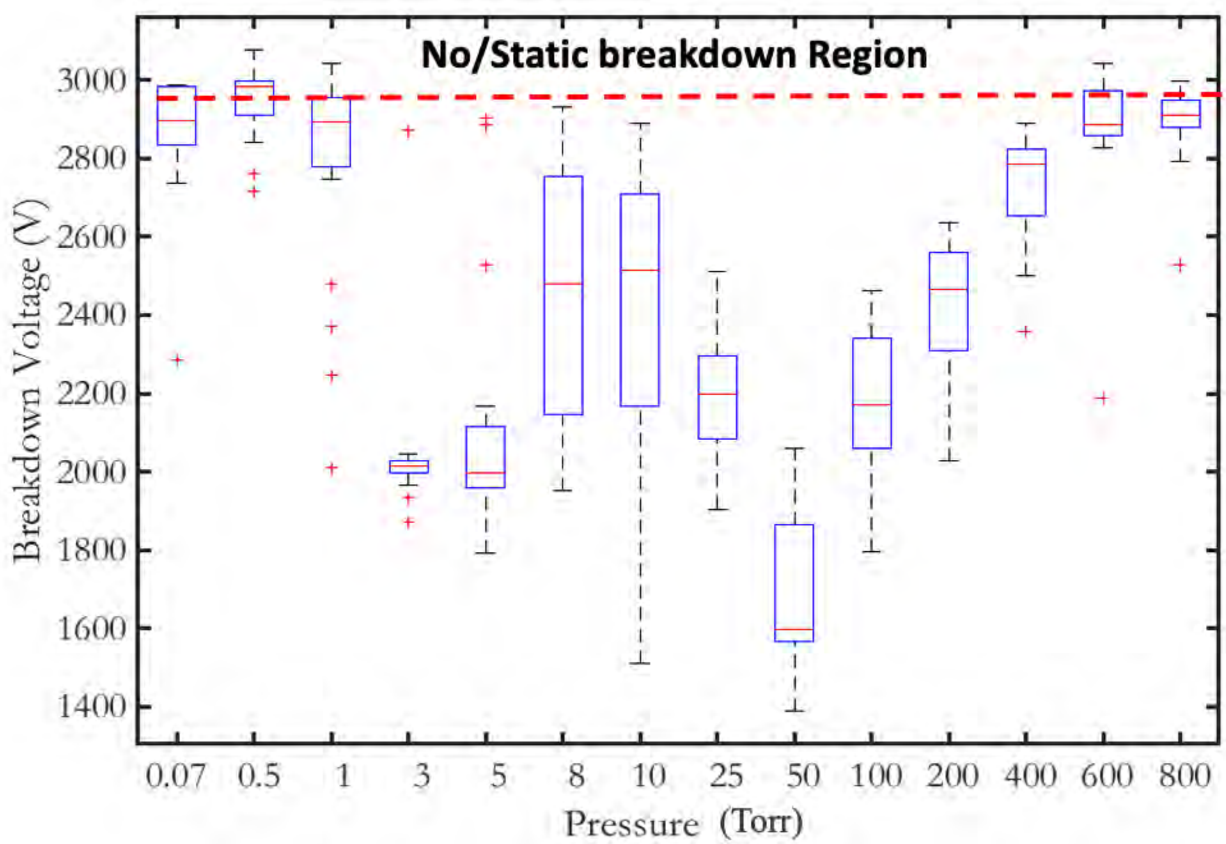

Figure 3-2. Box and whisker plots showing the distribution of breakdown voltages at different pressures in nitrogen without granules present. The red dashed line represents the voltage where the pulse height exceeds the breakdown voltage and the measurement is no longer capturing stochastic breakdown.

This measurement serves two purposes. First, it verifies that the single pin tester shows a well behaved Paschen response before adding granules since a clear minimum exists at 1.5(7) cm * Torr. Second, it demonstrates the severe drop in breakdown voltage when introducing dielectric granules to the gap, which will be discussed in the next section.

3.2. PMN-PT Granule Filled Spark Gap

The next measured Paschen curve was of a dielectric (PMN-PT) granule filled spark gap in air with 1200 V pulses in the single pin tester. This curve is plotted in Figure 3-3. For most of the measurement, breakdown is observed far below the system limit of 1200 V. The breakdown's stochastic nature is therefore not subject to systematic error and the data is plotted with error bars. The points represent the mean and the length of the error bars represents the standard deviation of the 20 shots. A breakdown voltage of 1200 V was exceeded after the pressure went above 800 Torr and below 0.5 Torr, at which point the measurement is subjected to systematic error.

The lowest observed average breakdown voltage in air is 630 V with a standard deviation of 82 V at 20 Torr. Near ambient pressure (600 Torr), the breakdown voltage is 1060 V with a standard deviation of 23 VThe Paschen minimum is at 20(10) Torr for this 300 µm dielectric filled spark gap so the Paschen minimum is at 0.6(3) Torr * cm.

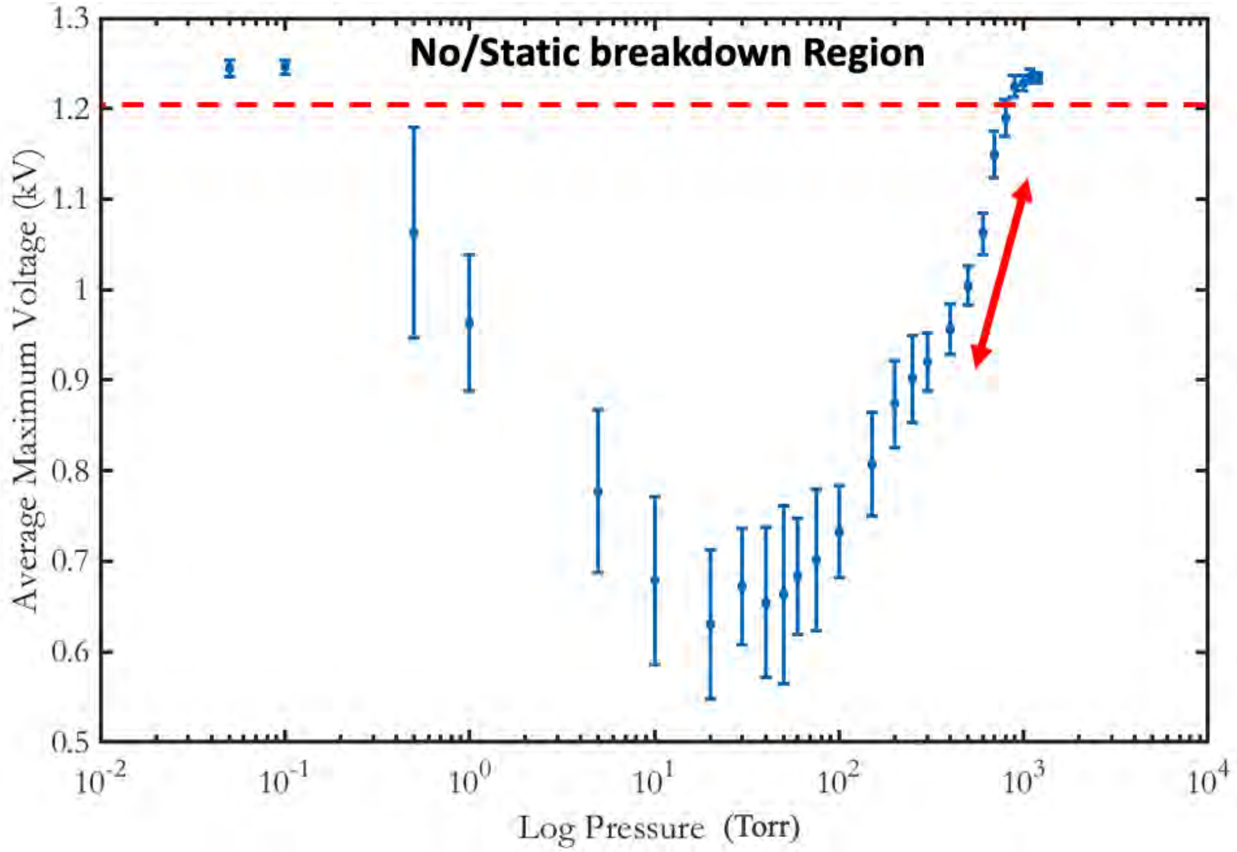

Figure 3-3. Average breakdown voltage of dielectric filled air spark gap. The error bars correspond to the standard deviation of the 20 shots. The red dashed line marks the pulse amplitude of 1200V, past which the breakdown is no longer measured. The red double arrow draws attention to the variability of the breakdown voltage near ambient pressures.

Figure 3-4 shows the Paschen response of a dielectric filled spark gap filled with nitrogen gas. The same trends are apparent as the PMN-PT filled spark gap in air. A minimum near 20 Torr with an average breakdown voltage of 595 V and standard deviation of 75 V. At 600 Torr, the average breakdown voltage is 1060 V with a standard deviation of 35 V. Again, the Paschen minimum is at 0.6(3) cm * Torr. . It is immediately apparent that for the entire range of the measurement, the breakdown voltage of a dielectric granule filled spark gap in nitrogen is only about one third the breakdown voltage of a nitrogen filled spark gap without granules. The same trend is observed when using air instead of nitrogen (not shown).

Nitrogen and air's similarity is easily explained since air is 80 % nitrogen. For further discussion, I will refer to nitrogen, but the arguments can be applied to either gas.

The objective for implementing dielectric stimulated spark gaps is mitigating high voltage and high current. Therefore the rapid change in breakdown voltage due to small changes in pressure near ambient conditions is of great interest. This region is indicated by the red double arrow in Figure 3-3. Linear fitting of the average breakdown voltages between 200 and 900 Torr suggests 0.53 V /

Torr ($R^2 = 0.98$) slope in a dielectric stimulated spark gap in nitrogen. This creates concern in situations where the spark gap needs to function with fluctuations in pressure. As an example, if the spark gap needs to operate 200 Torr above its normal operating pressure then the system will need to survive ~ 100 V more before gas breakdown alleviates the voltage.

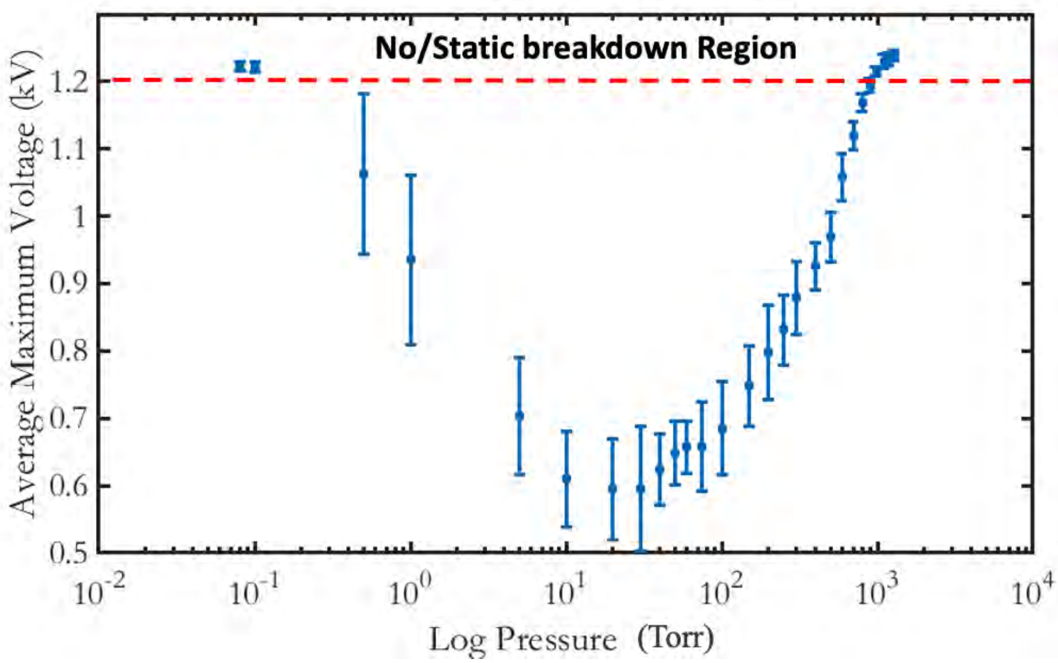

Figure 3-4. Average breakdown voltage of dielectric filled nitrogen spark gap. Error is the standard deviation of the measurement. The red dashed line marks the pulse amplitude of 1200V, past which the breakdown no longer measured.

3.3. Varistor Granule Filled Spark Gap

The final measurement is of the varistor granule filled spark gap in nitrogen and is shown in Figure 3-5. A 1200 V pulse was used. In the extreme high and low pressure regions, the empty and dielectric filled spark gaps (Figures 3-2, 3-3, 3-4) showed breakdown voltage exceeding the pulse height (3 kV and 1.2 kV respectively). In the varistor stimulated spark gap, the maximum voltage mitigation does not exceed 650 V. The lowest observed breakdown voltage is at 30(10) Torr.

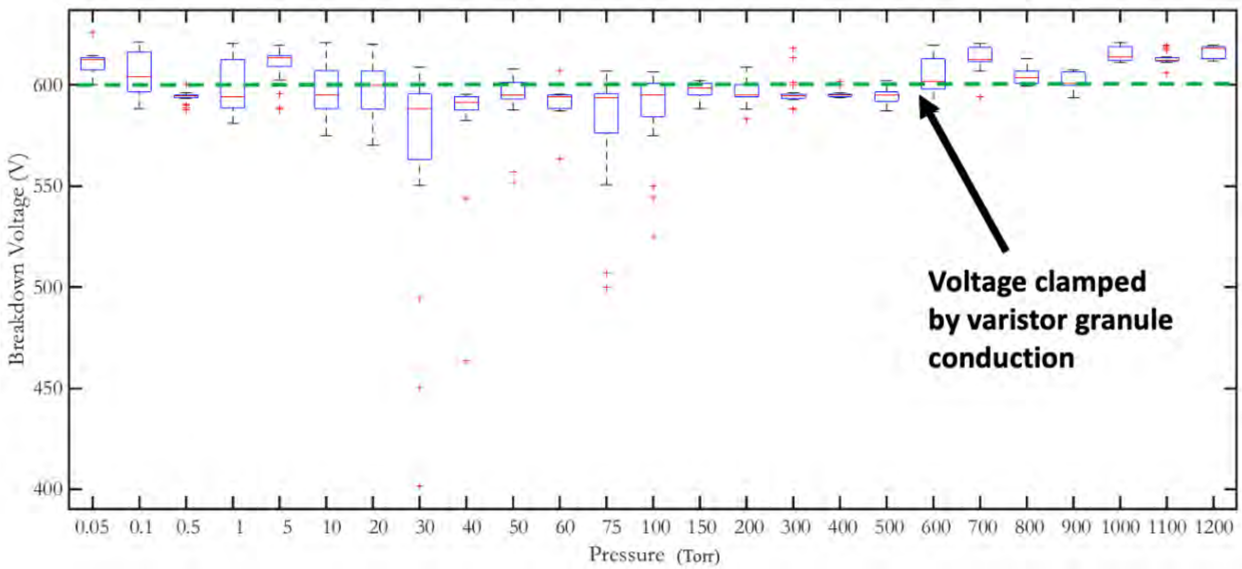

Figure 3-5. Pressure dependence of voltage mitigation in varistor filled spark gap in nitrogen. The dashed green line approximately indicates where the switching field of the varistors is exceeded and granule conduction becomes the dominant voltage mitigation mechanism.

Two additional voltage switching mechanisms are responsible for varistor granules mitigating high voltage in the low and high pressure regions. First is granule conduction. After ~ 600V the switching field of the varistor is exceeded and any additional voltage is mitigated by conduction through the granules to the ground. A typical granule conduction waveform is shown in Figure 3-6. The pulse is turned on at 0.2 μs and the voltage is allowed to quickly rise until 600 V, at which point the granules become conductive and the voltage is no longer allowed to rise.

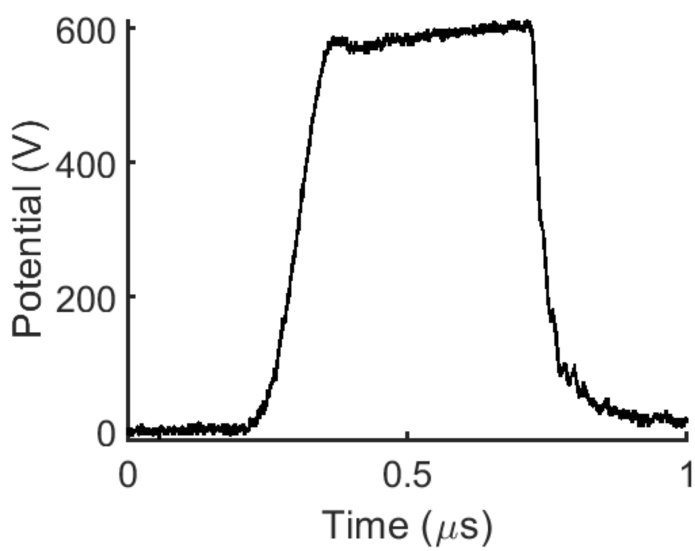

Figure 3-6. Granule conduction waveform. The voltage pulse is turned on at 0.2 μs and rises quickly to 600 V. At 600 V, the granule switching field is exceeded and the voltage is clamped by granule conduction to ground. The voltage remains clamped until the pulse is turned off 0.5 μs later.

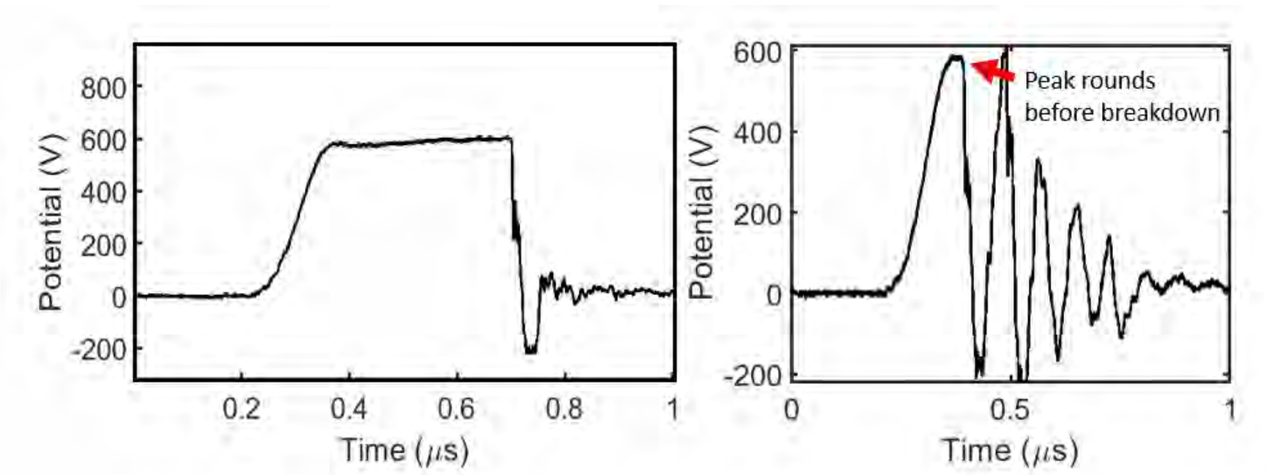

Figure 3-7. Thermionic induced breakdown waveform. Electron emission due to high joule heating at granule contact points can initiate the breakdown. Breakdown can be induced quickly (right) or after several hundred nanoseconds of conduction (left).

The second mechanism is thermionic induced emission. If the cross sectional area of a conducting wire decreases then its resistance increases. Likewise, at the granule contact points there is a small area for the current to flow through so there is higher resistance. When the switching field is exceeded, there is high Joule heating at these contact points from the increased resistance ($P = I^2R$). Electrons can be emitted from the hot contact points and initiate gas breakdown. Two waveforms of this mechanism are shown in Figure 3-7. On the left, there is a fast rising voltage that gets clamped by the varistor switching mechanism. After being clamped, gas breakdown is initiated and the voltage falls below the 0 V line (when there is no breakdown, the voltage does not fall below 0 V, as in Figure 3-6). The right waveform shows the varistor conduction mechanism rounding off of the voltage near 600 V. Shortly after being rounded off, gas breakdown is initiated. Thermionic emission allows breakdown at 600 V at up to 900 Torr which was not observed in the dielectric filled air gap. The thermionic induced breakdown can therefore alleviate the conduction mechanism near ambient pressures to avoid varistor damages from Joule heating.

The three mechanisms that varistor granule stimulated spark gaps employ make them less susceptible to changes in pressure. Applying the same linear fitting to the maximum voltage between 200 and 900 Torr suggest a 0.055 V / Torr slope ($R^2 = 0.6084$). A 200 Torr increase in pressure will result in only a ~10 V increase in maximum mitigated voltage which is less than the standard deviation of any one measurement. Therefore, near ambient conditions varistor granule filled spark gaps are not highly susceptible to changes in pressure.

4. CONCLUSION

Dielectric and varistor stimulated spark gaps both show superior voltage mitigation through gas breakdown in air and nitrogen gas due to both types of granules having a high dielectric constant. This highlighted by the shift of the Paschen curve minimum from 1.5(7) cm * Torr to 0.6(3) cm * Torr, and the reduction of breakdown voltage by ~3 fold for the entire curve in the case of different granules.

The three voltage mitigation mechanisms of varistor stimulated spark gaps (gas breakdown, varistor granule conduction and thermionic induced emission) resolve the variability in pressure that dielectric stimulated spark gaps have. The rise in maximum voltage due to pressure in varistor stimulated spark gaps (0.055 V / Torr) is about 1/10th the rise in dielectric stimulated spark gaps (0.5 V / Torr). Therefore, when spark gaps are expected to reliably perform in systems with a possible extreme drop or rise in pressure, varistor spark gaps should be considered.

REFERENCES

[1] J. P. Brainard and L. A. Andrews. (1980). "Flashover of Resistor and Varistor Materials," 1980 Annual Report, Conference on Electrical Insulation and Dielectric Phenomena, Edited by S. A. Boggs et al., National Academic of Science. Washington DC, 428.

[2] Yang, P., Sorenson, J. D., Gomez, C. A., Blea-Kirby, M. A., and Moffatt, W. C. (2020). "Fast rise breakdown in dielectric filled air gap for surge protection." *Journal of Applied Physics*. doi:10.1063/5.0019478.

[3] J. P. Brainard, L. A. Andrews, and B. A. Anderson. (1981) "Varistor-initiated Arcs in lightning Arrestor Connectors," *IEEE Trans. Components, Hybrids, and Manufacturing Technology*, CH1671, 308.

[4] J. M. Meek and J. D. Craggs. (1978). "Electrical Breakdown of Gasses.*" John Wiley & Sons*. 210-309.