Zinc oxide (ZnO)-based varistors are widely used in ground fault circuit interrupters for power surge protection. These metal-oxide varistor materials possess a unique diode-like, polarity independent, nonlinear voltage(V)–current(I) response which can restrict voltage rise or divert unintended high voltage to the ground at their switching field, thereby neutralizing the threat to sensitive solid-state electronics and aerospace vehicles. The nonlinear response comes from the unique microstructure of varistors, exhibiting a transition from an ohmic state to a conducting state. The microstructure of ZnO-based varistors possesses highly conductive ZnO grains separated by a thin, glassy, insulating, oxide grain boundary layer. During normal operation, this insulating barrier inhibits grain-to-grain conduction and limits current passing through the varistor. If a surged voltage exceeds its switching field, grain-to-grain conduction begins operating and high current will pass through the varistor and restrict the voltage rise to a magnitude near its switching field. Further, Joule heating from a high switching field and high current density in the conducting state may cause transient or permanent damages to the component. Evidence indicates under extreme conditions in the intrinsic breakdown region, these high density, solid ZnO components can be permanently damaged by fracture or puncture breakdowns, marked by reduced metal on the exit of the breakdown trace. Such a vulnerability can be mitigated by replacing the solid ZnO with a ZnO granule-filled air gap. The uniqueness of using varistor over other dielectric granules in an air gap for surge protection is identified and discussed.

### Abstract

The electric discharge across a varistor granule filled air gap under a fast-rising voltage pulse was investigated for surge protection applications. The effects of temperature and pressure on the arc and the electrical conduction were analyzed by the characteristic changes in voltage waveforms triggered by a fast-rising high voltage pulse. In addition to the gap size, experimental results show that competing mechanisms among arc conduction, conduction through the varistor granule network, thermionic emission from Joule heating at grain-to-grain contact points, and the magnitude of the switching voltage dictate the maximum surge protection voltage for the filled air gap. Experimental evidence indicated that accumulated degradation was created at small contact points between varistor granules by repetitive assaults from longer duration, high voltage pulses. The uniqueness of using varistor over other dielectric granules in an air gap for surge protection is identified and discussed.

### Keywords

dc flash, breakdown, gas discharge, surge protection, varistor

### 1 | INTRODUCTION

Zinc oxide (ZnO)-based varistors are widely used in ground fault circuit interrupters for power surge protection. These metal-oxide varistor materials possess a unique diode-like, polarity independent, nonlinear voltage(V)–current(I) response which can restrict voltage rise or divert unintended high voltage to the ground at their switching field (E_s on Figure 1), thereby neutralizing the threat to sensitive solid-state electronics and aerospace vehicles. The nonlinear response comes from the unique microstructure of varistors, exhibiting a transition from an ohmic state to a conducting state. The microstructure of ZnO-based varistors possesses highly conductive ZnO grains separated by a thin, glassy, insulating, oxide grain boundary layer. During normal operation, this insulating barrier inhibits grain-to-grain conduction and limits current passing through the varistor. If a surged voltage exceeds its switching field, grain-to-grain conduction begins operating and high current will pass through the varistor and restrict the voltage rise to a magnitude near its switching field. Further, Joule heating from a high switching field and high current density in the conducting state may cause transient or permanent damages to the component. Evidence indicates under extreme conditions in the intrinsic breakdown region, these high density, solid ZnO components can be permanently damaged by fracture or puncture breakdowns, marked by reduced metal on the exit of the breakdown trace. Such a vulnerability can be mitigated by replacing the solid ZnO with a ZnO granule-filled air gap. Self-healing arc conduction across air pockets between the
varistor granule network can also help divert surge current to ground during consecutive strikes, thereby protecting critical assets.\textsuperscript{11} The introduction of dielectric granules perturbs the uniform electric field across the air gap and further enhances the local voltage gradient in the air pockets, thereby reducing the gas breakdown voltage—a key concept behind “dielectric stimulated arcing”\textsuperscript{12,13} for high-power surge protection. Furthermore, the intrinsic nonlinear conduction of the varistor materials may further narrow the maximum surge protection voltage distribution and provide additional engineering control to extend its use for high-current power switching tube and fault spark gas protection applications. Therefore, a few mechanisms can operate for a varistor-filled air gap, including conduction current through a percolated path in the varistor granule network and/or dielectric stimulated arcing to divert high current from the unintended voltage surge to the ground. Either mechanism will establish a maximum voltage limit for surge protection. For convenience, “the maximum surge protection voltage” is used in this work to describe the maximum voltage where electric discharge across the air gap occurs.

This study investigates the effects of temperature, pressure, and repetitive high voltage pulses on the change in conduction behavior of a varistor-filled air gap for surge protection applications. Several distinct voltage waveforms associated with the dielectric stimulated arcing, the conduction through the varistor granules, and a combination of both processes have been observed. The voltage waveform progressively changes with the variation of temperature or pressure, indicating a transition of conduction mechanisms. Breakdown mechanisms associated with each unique condition, as well as performance degradation, are analyzed by the changes observed in the voltage waveforms based on the nonlinear V–I response of varistors and electric arc conduction across the air gap. Understanding the changes in conduction mechanisms under these conditions is sought from intrinsic change in resistance and switching field of the varistor material. The mechanism for degradation due to accumulated damages\textsuperscript{7,14-16} from high voltage pulses is discussed with experimental evidence. A collection of these fundamental understandings helps identify the uniqueness of varistor over other dielectrics\textsuperscript{13} in surge protection design and applications.

\section{Experimental Procedure}
Zinc oxide varistor powder with aluminum, barium, cobalt, sodium, and a trace of other elements was made from reagent grades of ZnO (98 mol\%), CoO (1 mol\%), and BaO (1 mol\%) by a mixed oxides method. The powder was isostatically pressed, crushed, sieved, and made into granules about 200 microns in diameter. These granules were loaded into an alumina crucible and sintered at above 700°C for 1 hour. The densified granules possess submicron grains separated by a barium oxide rich phase at the grain boundary, giving rise to the unique nonlinear V–I response for a varistor material. A single pin tester constructed of stainless steel and thermally stable polymer-based insulating parts was used in a fast-rise voltage pulse (FRVP) measurement. Two conically shaped insulating parts held and centered the stainless-steel pin inside its cylindrical shell from both ends with a 290 µm air gap filled with sintered ZnO granules. The single pin tester was mounted on a fixture in a sealed, fused quartz tube and placed in an environmental chamber with thermocouple, electrical, and gas feedthroughs. The temperature dependence of the FRVP was investigated from room temperature to 350°C at 25°C increments. The effect of air pressure was studied at
room temperature from $10^{-2}$ torr to 1200 torr at 50 torr per step (with more data collected using smaller pressure steps at the lower pressure range). In light of a previous investigation, the air gap was fully filled with varistor granules because an underfilled air gap could affect measurement consistency on the maximum surge protection voltage. To rule out the possibility of degradation or damage due to repetitive FRVPs, fresh granules were used at the beginning of each set of measurements. These procedures were strictly followed to avoid masquerading data with the effects of granule filling and granule degradation.

The FRVP measurement system consists of electric power supplies, a high voltage pulse generator, a pulse shaping network (PSN), and a trigger pulse with controlled signal delays from a function generator (Appendix A, Figure A1). An amplified square trigger pulse of 1,200 V with 300 ns to 1 µs duration was used. The voltage ramp rate was adjusted by the PSN to be as close as possible to 10 kV/µs at ambient conditions to simulate a fast-rising surge condition. Traces of the trigger pulse and voltage waveform across the varistor-filled air gap were digitally recorded by an oscilloscope (Agilent, InfiniVision DSO6054A, 500 MHz, 4Gs/s) with a delay of ~200 ns through a data acquisition system. Prior to data collection, the FRVP tests were performed with and without ZnO granules three times a day for two consecutive days to establish a baseline and ensure testing consistency at ambient conditions. The collected FRVP waveforms were analyzed by a MATLAB program, which sorted the 21 shots (or strokes) based on their breakdown behavior under different testing conditions. The program calculated the maximum surge voltage and the voltage ramp rate from each waveform, as well as the average values and standard deviations of these parameters from 21 consecutive strikes under the same testing condition.

The temperature dependence of DC electrical resistance was measured across the varistor granule filled single pin tester from room temperature to 325°C by a picoammeter (Keithley 6487) at 1-volt DC bias in the environmental test chamber.

3 | RESULTS AND DISCUSSION

3.1 | Microstructure of varistor granules and baseline measurements

Backscattering electron images obtained by a scanning electron microscope show that these sintered granules possess a round shape with submicron grains (Figure 2A,B). The average diameter of these granules is about 200 µm; therefore, there are no more than two to three granules spanning the air gap, minimizing tortuous arcing paths. These granules were taken out of the single pin tester after multiple FRVP measurements at different temperatures. Some intergranular microcracks are observed on the surface, presumably due to thermal shock induced by the drastic change in temperature generated by high power density electric arcs. The chemical mapping, using energy dispersive x-ray spectroscopy,
provides images of element distribution on the surface of one of the granules (Figure 2C-F) taken out from the air gap. In addition to the major constituents (i.e., Zn, Co, and Ba), it is found that a trace of sodium, silicon, and nickel are evenly distributed (not shown) on the granule surface. Heavy elements such as barium separate from zinc and form small islands (Figure 2D) with cobalt (Figure 2E) and aluminum (Figure 2F). Because of the high Z (atomic number) contrast, these barium rich regions show as bright spots on the backscattering image (Figure 2B). The excess barium oxide at grain boundaries (similar to Figure 1) provides a unique nonlinear V–I response and switching behavior, which will be seen and discussed in the later sections.

### 3.2 Dielectric stimulated arcing and voltage regulation

Prior to temperature and pressure dependence of FRVP measurements, a baseline measurement was performed on an empty single pin tester from room temperature up to 350°C at 50°C increments at ambient pressure with a peak pulse voltage of 1200 V. These FRVP waveforms exhibit a typical gas breakdown behavior (similar to Figure 3D, but at higher voltage). The results indicate both the average breakdown voltage and the voltage ramp rate are insensitive to temperature. The average breakdown voltage is $860 \pm 39$ V and the average ramp rate is $8.2 \pm 0.2$ kV/µs across the entire temperature range (not shown). Depending on humidity and other factors, air breakdown generally happens between 25 kV/cm and 35 kV/cm between two parallel plates. For a 290 µm air gap, the air breakdown voltage should be around 870 V, which is when applied electric field exceeds 30 kV/cm. Therefore, the measured average breakdown voltage for the single pin tester is within the expected air breakdown range. These results indicate that the single pin tester used in this experiment is well-behaved; therefore, any significant disparities or deviation from the baseline measurement can be attributed to the introduction of ZnO varistor granules in the air gap.

**Figure 3** Waveforms produced by a fast-rise square trigger pulse (0.7 µs pulse width) (A) no breakdown, (B) "voltage clamping" (with a shorter 0.4 µs pulse width under 1200 torr), (C) "thermionic-induced air breakdown", and (D) "dielectric stimulated arcing" or air breakdown. The blue and red traces are the voltage and the current waveforms, respectively.
The capacitance across the air gap between 1 kHz and 100 kHz before and after filling with varistor granules is 17.6 pF and 20.4 pF, respectively. The voltage (blue trace) and current (red trace) waveforms driven by a 5 V, 700 ns fast-rise square trigger pulse with voltage output greater than 500 V are given in Figure 3 to illustrate different conduction mechanisms across the varistor granule filled air gap. The current waveforms are digitally recorded through a wideband current view transformer (Pearson Electronics Inc., Model 4100).

The first kind of waveform is associated with no air breakdown across the varistor granule filled air gap, which can be the result of a low voltage stimulus pulse or a voltage clamping condition. When the single pin tester is subjected to a voltage pulse (Figure 3A) below the varistor switching voltage, both voltage and current traces rise simultaneously, then voltage stays almost constant at the applied stimulus voltage (i.e., 500 V in this illustration) while the small displacement current quickly drops back to zero until the trigger pulse is turned off. In this case, no current is crossing the air gap. The oscillating signals observed in the current and the voltage waveforms after the trigger pulse is turned off are attributed to the specific circuit design used in the PSN, which includes several inductors, capacitors, resistors, and rectifiers. Note, when the voltage pulse is turned off before breakdown, the voltage trace falls off gracefully without crossing the Y axis. The current trace, on the other hand, exhibits a significant swing and oscillates in sync with the voltage trace with an additional capacitive response from the voltage swing across the air gap. These are typical voltage and current responses when there is no arc or breakdown across the air gap. Similarly, if current is conducted through the varistor granule network (Figure 3B, but with a shorter 0.4 µs pulse), the maximum surge voltage across the filled air gap will be limited or clamped by the switching voltage of the varistor (~720 volts) while current stays almost constant then slightly increases, as illustrated in Figure 3B for the duration of the applied pulse. The condition is only permitted when the pulse voltage is greater than switching field of the varistor without causing air breakdown. The slope observed in the current in Figure 3B after voltage is clamped at the switching voltage could be a result of joule heating which changes the “stationary” behavior of the I–V curve.5 This type of FRVP response can be categorized as “voltage clamping.” As in the “no breakdown” condition, the voltage trace falls off gracefully without crossing the Y axis when the voltage pulse is turned off (after 0.4 µs).

The waveform in Figure 3C indicates a combination of voltage clamping and a fast arc breakdown before the voltage pulse is turned off. This is when the fast-rising voltage is clamped by the varistor switching voltage while current (red trace) stabilizes for a short period then rapidly increases before an arc breakdown indicated by a large current spike across the air gap followed by oscillation. The first short period (~20 ns) after the nonlinear response on the current trace corresponds to a high grain-to-grain conduction when a transient current passing through the varistor granule network as illustrated in the high current region of Figure 1. The following fast-rise high current before air breakdown is in the varistor intrinsic breakdown region (Figure 1). Together with a high switching voltage and a high current density, it can cause significant Joule heating5,17 at these small varistor–varistor contact points, creating local hot spots within the percolation granule network,7 which in turn can cause thermionic emission and accumulated damages12 at these contact points. Typical breakdowns in ceramics lead to permanent damage with a low impedance path,7 but this phenomenon has not been observed during consecutive pulse measurements in this study. Therefore, the observed up-rising current could be a transient, recoverable thermal runaway18,19 event where additional ionized species are generated by thermionic emission. Such an event will ultimately trigger arc discharge across the air gap and produce a large current spike, if the switching voltage is high. Since a gas discharge is self-healing, air breakdown induced by this transient arc event can be consistently observed during repeated strikes. Therefore, the observed response can be attributed to a “thermionic-induced air breakdown.” Without thermionic induced ionization amplification, arc breakdown would not occur, as current is already flowing through the varistor granule network. Contradictory to a voltage clamping condition (Figure 3B), the arc breakdown voltage trace does not drop gracefully, rather the voltage exhibits a fast swing across the zero-voltage line followed by oscillation before the voltage pulse is turned off (Figure 3C).

The last type of waveform (Figure 3D) indicates a dielectric stimulated arcing, a behavior commonly observed under low-pressure conditions (Section 3.3). This is when the pulse voltage is increased to a sufficient level (>1000 volts) for an immediate air breakdown to be observed. The sudden breakdown causes a large current spike, which directly indicates an arc discharge across the air gap. Sometimes, ultraviolet emission from the arcing can introduce an extra small voltage signal by photoionization20 on the collected waveforms before the voltage signal falls across the zero-voltage line. Unlike thermionic induced breakdown (Figure 3C) where there is a regulated fast-rising current trace, on the verge of arc discharge the rising current trace suddenly exhibits a short nonlinear transition (less than 40 ns) before current spikes. This behavior prior to the arc breakdown is similar, if not identical, to the voltage waveform observed in a lead magnesium niobate-lead titanate granule filled air gap13 where dielectric stimulated arcing is the only breakdown mechanism.

The absence of Townsend and glow discharge characteristics on the voltage and current waveforms immediately before breakdown suggests these mechanisms may have been suppressed by the fast-rising voltage due to their longer incubation period. Consequently, the buildup of electrical potential
is released solely through arcing in the small air gap from a localized ionization event.

These waveforms show characteristics of three different mechanisms commonly observed in a varistor-filled air gap. These mechanisms are able to restrict the voltage rise of an applied pulse, either by the conduction through granules, the thermionic-induced arc breakdown, or the dielectric stimulated arcing across the air gap.

3.3 Pressure effect on fast-rising pulse measurement

Since most breakdowns are observed in the first 200 to 300 ns under a fast-rise high voltage pulse, the effects of pressure and temperature on FRVP are studied based on a shorter 500 ns pulse for surge protection evaluation. Current traces presented in the previous section will be omitted. The voltage waveforms collected under different pressure conditions at ambient temperature are summarized in Figure 4. These waveforms are representative of most FRVP behaviors selected from one of the 21 strokes under each pressure condition. Note, not all the waveforms collected under the same pressure are exactly the same, but in general the difference is trivial. Sometimes, near the transition range or under high pressure (>800 torr), mixed responses can be observed. Nevertheless, waveforms on Figure 4 can be used to depict the evolution of FRVP response as pressure increases.

Data indicate below 0.146 torr, and particularly below 0.08 torr, air breakdown can be suppressed—a phenomenon similar to the Paschen curve behavior at low pressure, where there are insufficient gas molecules to be ionized. Therefore, mixed breakdown responses, including air breakdown and voltage clamping, can be observed in the lowest pressure range.

In waveforms obtained from 0.146 torr to 494 torr, the voltage traces exhibit an abrupt downswing immediately upon reaching the peak voltage, shown most elegantly by the waveforms collected at 0.146 torr (orange trace) and 101 torr (red trace). This behavior can be identified as “dielectric stimulated arcing” illustrated in Figure 3d, where gas molecules are ionized before the varistor granules have been “switched on” under the FRVP causing arcing across the air gap. The arcing allows the voltage signal to immediately drop below the zero line. This observation indicates that the introduction of dielectric ZnO granules in the air gap can cause stimulated arcing and reduce the maximum breakdown voltage from 860 volts to 720 volts below ambient pressure (i.e., 760 torr) at room temperature. These fast arc breakdowns are generally observed near the minimum breakdown voltage range on the Paschen curve\(^2\) (~50 torr, not shown) which is lower than ambient pressure.

As the pressure increases above 500 torr, the arc conduction is inhibited by shortening the mean free path of charge carriers and ionized molecules, which limits their kinetic energy gain in the electric field, thereby suppressing ionization multiplication and arcing processes. As a result, the nonlinear switching behavior is activated and clamps the peak voltage, which is illustrated by waveforms collected at 499 torr (green trace) and 651 torr (yellow trace). The time which voltage is held at the regulating level to the time of breakdown is relatively short (~150 to 200 ns). The electric breakdown observed in this pressure range matches a transient “thermionic-induced air breakdown” behavior shown in Figure 3C.

As pressure continues increasing above 800 torr, the final time-to-breakdown is further delayed. Even though most of the breakdown waveforms are similar to the “thermionic-induced

\[\text{FIGURE 4} \quad \text{The change of voltage waveform under FRVP as a function of air pressure at room temperature}\]
air breakdown,” more voltage waveforms exhibit a voltage drooping near the end of trigger pulse as illustrated by traces obtained at 950 torr (blue trace) and 1200 torr (purple trace). Sporadically, waveforms will exhibit a voltage clamping response—similar to the waveform given in Figure 3b without gas breakdown. Therefore, a mixed pattern of waveforms can be observed in this pressure range. The delay in air breakdown, particularly under a high clamping voltage, incurs more Joule heating or disruptive damage\textsuperscript{22} through the varistor granule network that contributes to localized damages at granule-to-granule contact points and causes a voltage decline\textsuperscript{23} near the end of the voltage trace. It is observed that at over 1200 torr the voltage waveforms show no sign of air breakdown as the voltage trace, after declining, reduces to zero when the applied voltage is turned off, indicating gas ionization is completely inhibited (not shown, but similar to Figure 3B). This response belongs to “voltage clamping,” where surge voltage has been restricted at the switching voltage by conduction current through the varistor granule network until some local degradation at contact points is incurred. The delay in breakdown under high pressure is intriguing and has important implication in practical applications because the protective effect, that is, the integral of voltage up to the time of breakdown, of a device depends on the time that the mitigated voltage stresses the protected system.\textsuperscript{22}

These results indicate at ambient conditions the breakdown across a varistor-filled air gap is controlled by the transient “thermionic-assisted air breakdown” mechanism. Two important features are also immediately recognized, including: (1) the standard deviation of the regulating voltage at each pressure condition from ambient pressure to 1200 torr is below 6.6 V (not shown) which is significantly narrower than the standard deviation observed in an empty (\textsim 40 V) or a high permittivity granule filled air gap (> 35 V),\textsuperscript{13} and (2) although breakdown mechanism may change with pressure, the maximum surge protection voltage remains the same. The former is manifested by the superior low intrinsic variations in switching voltage of varistor materials in comparison to a stochastic gas discharge mechanism.\textsuperscript{11,12} The latter indicates that the maximum surge protection voltage for a varistor-filled air gap is immune to the pressure change for surge protection applications near and above ambient pressure. Details about the pressure effect on the FRVP breakdown for a dielectric filled air gap will be published in a separate paper.

3.4 Temperature effect on fast-rising pulse measurement

The changes in FRVP response as the temperature increases are illustrated in Figure 5. Data are collected from room temperature to 350°C at 50°C increments without changing out granules in the air gap. Therefore, results may be affected by the accumulated damages from repetitive FRVPs. As aforementioned, not all the waveforms (21 shots) collected at the same temperature are identical, but generally the difference is small, indicating the progressive changes observed from these waveforms are mechanistically controlled. Similar to the changes in pressure measurement, near a transition range (i.e., 100°C and 200°C, Figure 6), mixed responses can be observed. The results show that from room temperature to 100°C, the waveforms (represented by blue (50°C) and green (100°C) traces) exhibit a typical “thermionic-induced air breakdown.” At 150°C (orange trace), the waveform indicates the breakdown remains in the “thermionic-induced air breakdown” mode but exhibits a typical nonlinear varistor
behavior above the switching voltage with a slower voltage ramp rate. In comparison of the waveforms at 150°C (orange) and lower temperatures, these overshoots observed on the 50°C (blue) and 100°C (green) curves during the first 50 ns before leveling off at the switching voltage indicate an inability to respond to a fast-rise pulse when the intrinsic resistance of the varistor is greater (section 3.5, Figure 7). The nonlinear V–I response creates high current density passing through small contact points between the varistor granule network which can induce thermionic emission at these hot spots, and ultimately triggers the arc breakdown before the applied voltage is turned off. Between 200°C (red trace) and 350°C (purple trace), the FRVP waveforms show a distinct “voltage clamping” response. Under these conditions, the maximum switching voltage drops below 400 V where the electric field across the air gap is too low to cause ionization amplification or arcing. Consequently, arcing across the air gap is inhibited, and voltage is clamped until the applied voltage is turned off. However, under a longer pulse and a higher switching voltage (> 400 V), a few “thermionic-induced air breakdowns” can still be observed due to accumulated heating resulting in thermionic emission at hot spots between ZnO granules.

The results of these waveform analyses are summarized in Figure 6, which shows the average of the maximum surge protection voltage (blue) and the average voltage ramp rate (red) from 21 shots as a function of temperature. The average
maximum surge protection voltage decreases monotonically from room temperature to 250°C, then suddenly drops below 100 V at temperatures above 300°C. Note, the low switching voltage at these temperatures can still divert current from unintended high voltage events to the ground, but also may raise concerns of crosstalk between signal lines in the same surge protector, particularly when the design maximum surge protection voltage is higher than the switching voltage of the varistor.

The progressive change from one breakdown behavior to another and the underlying mechanism governing these changes as a function of temperature is intriguing and will be discussed in the next section with the support of experimental evidence.

3.5 Changes in resistance and regulating voltage

As described in the Introduction, at a constant temperature, the resistance of a varistor changes from an ohmic response to a highly conductive state and eventually to an intrinsic break-through region under a high voltage condition (Figure 1). The switching voltage of a varistor during the nonlinear transition is known to be less sensitive to temperature near room temperature, an important attribute for use in ground fault circuit interrupters. Information about the changes in ohmic and nonlinear ranges for varistors at elevated temperatures (>100°C) is quite scarce. Because the electric resistance of a varistor is dictated by the glassy oxide layer at the grain boundary, the change in resistance plays an important role on the switching voltage and the maximum surge protection voltage. The following sections will be devoted to how the change in resistance across a varistor granule filled air gap as a function of temperature affects the FRVP response.

Figure 7 shows the resistance change as a function of temperature. The resistance, as measured at 1 V, drops six orders of magnitude from room temperature (5 \times 10^{10} Ohms) to 320°C (4 \times 10^{4} Ohms). At temperatures below 100°C, the resistance remains almost constant, consistent with observations reported in the literature. The resistance decreases monotonically as temperature increases up to 320°C, at which point the leakage current caused the picoammeter to go over range. Therefore, it is expected that resistance will continue to decrease as the temperature increases above 320°C, as reported in the literature.

Above 150°C, the resistance decreases following an Arrhenius relationship (not shown). This intrinsic decrease in resistance at high temperatures suggests that more charge carriers could be thermally activated and overcome the Schottky barrier at the ZnO grain boundary, resulting in the decrease in resistance across the air gap. The trend observed in this measurement is consistent with data reported, but not consistent with absolute resistance values which could be attributed to chemical composition, packing factor in the granule assembly, or the size of the air gap used in these measurements.

Assuming the capacitance (C) of the varistor granules will not change significantly with temperature, a reasonable assumption as varistor is a linear dielectric, the change of resistance (R) at the grain boundary can significantly affect the time constant (RC) during the FRVP test, particularly when the resistance value drops a few orders of magnitude when above 100°C. A high resistance grain boundary phase at lower temperatures will lead to a greater time constant; therefore, the varistor cannot respond to the fast-rising voltage pulse immediately which gives an overshoot at temperatures below 100°C (Figures 4 and 5) and favors arc breakdown under low pressure when gas discharge is more favorable.

The intrinsic change in resistance of the ZnO varistor can modify the LCR (inductance–capacitance–resistance) response for the test system which in turn will alter output waveforms. Because varistor consists of a high resistance (or high potential barrier) grain boundary phase with a highly conductive grain, such a structure can be simulated by an equivalent circuit with a variable resistor for the grain boundary and a parallel circuit of a capacitor and an inductor for the conductive grain in series. Circuit simulation (Multisim, NI), based on the change of resistance observed in Figure 7, on a circuit equivalent to the present setup qualitatively shows how changes in resistance impact the PSN output, which can subsequently impact the waveform response. This simulation replicates the slowdown of the voltage ramp rate due to the decreasing resistance with rising temperature. The slowdown in voltage ramp rate allows the ZnO varistor to switch to its nonlinear behavior; therefore avoiding an overshoot peak and exhibiting a typical nonlinear V–I behavior.

Another intrinsic change in physical property that can greatly impact the FRVP behavior is the change in switching voltage of the varistor. When the switching voltage is sufficiently high (e.g., >650 V), the probability of inducing gas breakdown or arcing through accelerating and multiplying ionized species increases. Conversely, if the switching field is too low (<400 V as in the 200°C and 350°C traces on Figure 5), ionized species will be unable to gain sufficient kinetic energy in the electric field to trigger ionization multiplication or arcing; therefore, gas breakdown can be completely inhibited and give rise to a voltage clamping situation.

Determining the switching voltage of a varistor-filled air gap as a function of temperature requires holding the varistor switching voltage for a sufficient amount of time before thermionic-induced air breakdown transpires. We have shown that higher pressure conditions will delay the gas breakdown (Section 3.3, Figure 4) and that the switching voltage is an intrinsic property of varistor material that is insensitive to gas pressure. The switching voltage of varistor granules at different temperatures can, therefore, be determined under a high-pressure condition where current passes only through the varistor network in the air gap. Data for the switching voltage at different temperatures were collected at 1200 torr,
and results are given in Figure 8. The switching voltage follows an Arrhenius relationship (Figure 8, insert figure). The progressive decrease in the switching voltage can, thereby, change the surge protection mechanism from a “thermionic-induced air breakdown” to a “voltage clamping” as the testing temperature increases. Under the same applied voltage pulse width, the change solely depends on the magnitude of switching field and the probability of air breakdown. The higher switching voltage can trigger the air breakdown or arcing. Therefore, the maximum surge protection voltage is determined by a competing process among dielectric-stimulated arc breakdown, varistor switching behavior, and thermionic emission at contact points between varistor granules, which differs from other dielectric-filled air gaps that solely rely on the dielectric-stimulated arcing mechanism.11,12

Disparities in the switching field can be observed between Figure 6 and Figure 8. The discrepancies can be attributed to the accumulated damages in these measurements. The temperature dependence of the maximum surge protection voltage was collected continuously from room temperature to 350°C at 50°C to 100°C increment (Figure 6), and there are 21 FRVP measurements at each temperature. In light of the pulse degradation,11 the switching field measurement was determined by 10 pulses at each temperature for a few selected temperatures (Figure 8). The differences due to accumulated damages will be discussed further with experimental verification in the next section (Section 3.6).

3.6 | Degradation of performance

In addition to temperature induced intrinsic changes, it is conceivable that extrinsic effects such as hot spots generated by localized heating at contact points between varistor granules may also contribute to the decrease in the maximum surge protection voltage between 250°C and 300°C (Figure 6). This is partially supported by the fact that ZnO varistor ceramics can be thermoelectrically reduced to its metallic form during a puncture breakdown. Additionally, arc flash can easily reach extremely high temperature far beyond 1100°C when ZnO becomes highly unstable indicated by the Ellingham diagram.27 Therefore, thermal reduction at the granule–granule contact points during thermionic-induced breakdowns is not completely insurmountable. Thermal effect can also affect a complex redox and diffusion problem with one of the key additives such as CoO at the grain boundary. Additionally, a reduction of a major oxide to its metallic form at the grain boundary phase in ZnO varistor has been reported under a high current spark plasma sintering process.30,31 Degradation can also be caused by field-induced ionic motions in electrically stressed varistor material.15,32 These issues may have significant implications on the switching behavior. In this study, puncture breakdown with a permanent, irreversible short has never been observed, and these degradation mechanisms at the varistor grain boundary may not be completely applicable to the degradation phenomenon observed in a varistor granule filled air gap. However, it will not negate the possibility of creating localized nonlethal degradations due to accumulated electric and thermal assaults from arc breakdowns, as ZnO-based varistors are known to be susceptible to these physical attacks. This is particularly true for delayed breakdowns in the voltage clamping conditions (Figure 3C) where disruptive effect is much greater than in the case of an abrupt air breakdown (Figure 3D). This hypothesis was evaluated based on additional measurements at room temperature after the series of FRVP measurements were completed at 350°C. If these
contact points are subjected to electric/thermal degradation, re-establishing new contact points by changing the granule configuration in the air gap should restore the breakdown behavior. Therefore, by comparing the voltage waveforms before and after shaking these granules in the air gap followed by repetitive strokes at high temperature, the degradation due to accumulated damages at contact points can be verified.

Waveforms in Figure 9 depict such a comparison based on this hypothesis for data collected from a single pin tester, where the red and the black traces represent the waveforms collected before and after shaking, respectively. Note that the switching voltage after shaking (black trace) is around 690 V which is close to the data collected from the first maximum surge protection voltage measurement at room temperature (Figure 6). Additional tests (not shown) were performed with reduced pulses (i.e., 10 pulses) at each temperature at 25°C, 50°C, 100°C, 150°C, and 350°C to minimize the total accumulated damages. Waveforms collected under these conditions show a much higher surge protection voltage particularly at these temperatures as shown in Figure 8. Based on these observations, it is believed that the electric conductivity at these contact points between varistor granules may have been increased due to accumulated damage from Joule heating by multiple high voltage strokes. These observations support the hypothesis that the physical properties at these contact points can degrade under repeated electric assaults. However, exact damages to these contact points are not clear and further investigation and characterization on these contact points is needed.

4 | SUMMARY

The changes of temperature, pressure, and characteristics in the waveforms are used to identify and understand mechanisms for conducting a fast-rise, high-voltage pulse across a varistor granule filled air gap. The results show that intrinsic properties such as resistance and switching voltage of the varistor are important for controlling the conducting path for surge protection. The competition among dielectric stimulated arcing, conduction through a percolated varistor granule network, and localized heat-induced thermionic emission at granule-to-granule contact points dictates how surging voltage is diverted to ground. The dielectric stimulated arcing is favorable when both resistance and switching voltage of the varistor are high. The high intrinsic resistance delays the non-linear switching response under a FRVP, which favors arc conduction and results in an overshoot in the voltage waveform near room temperature. This leads to a rapid arc breakdown across the air gap at lower pressures near the minimum point on the Paschen Curve. Current will pass through varistor granules when arc conduction is prohibited or when the resistance of the varistor is low. In this situation, if the switching voltage of the varistor is sufficiently high, Joule heating at these small granule-to-granule contact points can induce thermionic emission, and ionization multiplication can ultimately lead to a “thermionic-induced air breakdown” at a later time. At higher temperatures when the switching voltage is low and cannot cause additional ionization, current passes through the granule network and the voltage rise will be clamped by the varistor switching voltage. Under these conditions the maximum surge protection voltage will be determined by the switching voltage of the varistor. Increasing the air pressure will reduce the kinetic energy gain for ionized air molecules in the gap, thereby decreasing the probability of gas breakdown and forcing the current to pass through percolated paths in the varistor granule network.
Evidence shows that accumulated damages due to repetitive high current density assaults at these granule contact points will cause degradation. In summary, the inherent nonlinear response of varistors provides a superior control over the maximum surge protection voltage, narrows the breakdown voltage distribution, and makes the surge protection voltage completely immune to pressure change above ambient pressure. Precautions are needed when designing surge protection for high-temperature applications as the conduction mechanism across the air gap changes. These breakdown mechanisms, particularly the dielectric induced arcing, have important implications for dielectric barrier discharge devices for generating plasma resources.

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APPENDIX A

The fast-rising breakdown measurement system

**FIGURE A1** Schematic diagram of the fast-rising voltage breakdown measurement system. A steel housing for the single pin tester in attached on the bottom left corner, where a steel pin is centered and held by a plastic fixture and ceramic granules are filled between the air gap [Color figure can be viewed at wileyonlinelibrary.com]