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Cite as: AIP Advances 10, 015002 (2020); https://doi.org/10.1063/1.5128773
Submitted: 22 September 2019 . Accepted: 12 December 2019 . Published Online: 02 January 2020

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ABSTRACT
The breakdown characteristics of a trigatron spark gap triggered by a plasma jet are studied in this paper; the development of a plasma jet and the influence of the gap distance, working coefficient, and plasma jet ejection properties on breakdown characteristics are compared. The results show that the plasma jet ejecting process can be divided into expanding, steady, and dissipating phases. The electric field distortion induced by the plasma jet is different during the expanding and dissipating phase, in which the plasma jet length increases and the radius of the curvature of the plasma jet front decreases, respectively. As the two processes have different variation rates, a faster increasing rate of the breakdown delay can be obtained during the dissipating phase. A detailed physical mode that explains the effects on the triggered breakdown process is presented. The shape of a plasma jet induced by polyethylene and ceramic surface discharge changes to a great extent during the dissipating phase; a more stable plasma jet can be obtained when induced only by polyethylene, resulting in a smaller breakdown delay under a low working coefficient. The ultraviolet radiation (UV) generated by the plasma jet is effective in reducing the critical breakdown electric field, while the electric field distortion induced by the plasma jet is the main reason behind the triggered breakdown under different working coefficients; the UV could play a limited role in the triggered breakdown process.

I. INTRODUCTION
Gas-insulated trigatron spark gaps could be used in a wide range of applications as high voltage switches in high-voltage pulse forming networks, as Marx generators and particle accelerators due to their voltage and current handling capabilities, and in simple constructions and applications in high voltage engineering. In order to increase the operating reliability, the working coefficient of a spark gap needs to be lower than 60%. A working coefficient is defined as the ratio of the charging voltage to the self-breakdown voltage of the spark gap. However, the reliable working coefficient of the conventional triggering technology for trigatron switches and field distortion switches is generally above 70%. Hence, it is of great significance to investigate new, reliable triggering technology for spark gaps operated under very low working coefficients.

Based on recent research, it is indicated that plasma jet triggered gas switches can achieve a reliable breakdown probability under low working coefficients. By injecting a plasma jet, the electric field distortion is enhanced gradually with the development of plasma ejection, and the reliable triggering performance of gas switches is obtained. According to the generating methods of plasma jets, plasma jet triggered gas switches can be divided into laser plasma, spark plasma, and ablation plasma triggered switches. By comparison, the ablation plasma generated by a surface or capillary discharge has the characteristics of high velocity, high temperature, high pressure, and high density. Moreover, the properties of an ablation plasma jet can be regulated by adjusting the discharge energy and parameters directly. Therefore, ablation plasma jets can meet the need of a spark gap ignition under low working coefficients.
In this paper, the discharge characteristics of a trigatron spark gap triggered by a plasma jet will be discussed. The physical development and the main influence factors of the breakdown delay time and jitter are analyzed with high-speed multiframe camera photos.

The key determining factors of a trigatron spark breakdown triggered by a plasma jet are discussed. The effect of the gap distance, working coefficient, plasma shape, and plasma ejection properties on discharge characteristics is compared. As the breakdown delay time and jitter are the most crucial parameters of the discharge characteristics of a spark gap, this paper mainly focuses on the change in trend of the breakdown delay time and jitter of the trigatron spark gap, and gives reasonable explanations of the breakdown delay time and jitter formation under the surface ablation plasma jet triggered breakdown process.

II. CONFIGURATION AND TEST SETUP

The experimental setup of trigatron spark gap discharge is shown in Fig. 1. The length of the plasma jet can be controlled by adjusting the RLC discharge parameters to form different amplitude current pulses; a pulse transformer ST is used to generate a nanosecond voltage pulse to breakdown the trigger gap; then, a microsecond current pulse generated by C2 pass through the trigger gap, resulting in the plasma being injected into the main gap. The combined use of C1 and D2 can isolate the voltage pulse and the current pulse, eliminating their interaction. Surface discharge of polyethylene and the ceramic tube are used to generate different shapes of the plasma jet to study the effects on the trigger breakdown process. The development of the polyethylene surface ablation plasma with a low current pulse (charging voltage on capacitor C2 = 200 V) and high current pulse (charging voltage on capacitor C2 = 1200 V) under 0 kV of charging voltage applied on the spark gap is carried out by using an HSFC-Pro four-frame optical camera, which with a minimum exposure of 3 ns/frame, allows images of a load in the visible range at desired points of time; the results are as shown in Figs. 2(a) and 2(b). The breakdown delay time $t_\tau$ is defined as the time interval between the trigger gap breakdown and the main gap breakdown, as shown in Fig. 1(b); the jitter $\sigma_\tau$ is the standard deviation of $t_\tau$ of 50 discharges.

In Fig. 2, we can see that at the initial stage, the length and density of the injected plasma increased due to the push power driven by high temperature, and the pressure gradient induced by the surface arc discharge also increased. Then, with a decrease in...
the current pulse, the energy input and the density of the injected plasma decreased, while the length of the injected plasma was constant for a relatively long time. With the current further decreasing, the length of the injected plasma decreased, and the shape of the plasma changed and began to dissipate. This phenomenon could be achieved due to the energy balance between the deposited energy on the polyethylene by arc joule heating and the radiation and conduction by the plasma jet. A higher deposited energy can induce more plasma injection, leading to an increase in the length and density of the plasma. When the deposited energy became lower, the density and the temperature of the injected plasma began to decrease, dissipating the injected plasma. The shape of the plasma jet was unchanged as the pressure gradient had no obvious change. When the density and the temperature further decreased, the plasma jet began to shrink due to the recombination process, leading to a change in the shape of the plasma jet. Hence, from this analysis, the plasma ejecting process can be divided into the expanding phase, steady phase, and dissipating phase.

Figure 3 shows the development of the length of the plasma jet under different trigger current amplitudes; it can be seen that there is an obvious difference in the growing trend of the length of the plasma jet under different phases. The fastest increasing rate is achieved due to the energy balance between the deposited energy on the polyethylene by arc joule heating and the radiation and conduction by the plasma jet. A higher deposited energy can induce more plasma injection, leading to an increase in the length and density of the plasma. When the deposited energy became lower, the density and the temperature of the injected plasma began to decrease, dissipating the injected plasma. The shape of the plasma jet was unchanged as the pressure gradient had no obvious change. When the density and the temperature further decreased, the plasma jet began to shrink due to the recombination process, leading to a change in the shape of the plasma jet. Hence, from this analysis, the plasma ejecting process can be divided into the expanding phase, steady phase, and dissipating phase.

III. RESULTS AND DISCUSSION

A. Breakdown characteristics under low working coefficients

Setting the high-current plasma ejected from the ground electrode to the high voltage electrode, the experiment of the spark gap breakdown is conducted. The gap distance varies from 5.0 mm to 12.0 mm, and the discharge voltage is fixed to 5.0 kV. According to the measured self-breakdown voltage, the working coefficient of the spark gap ranges from 13.9% to 33.3%. The change tendency of the breakdown delay time \( t_1 \) and jitter \( \sigma_t \) with the gap distance is shown in Fig. 4. The point is the mean value of the breakdown delay time \( t_1 \), and the error bar represents the breakdown delay time jitter \( \sigma_t \). It can be seen that the breakdown delay time \( t_1 \) and jitter \( \sigma_t \) increase with the gap distance; when the gap distance increases to greater than 7.0 mm, the delay time \( t_1 \) and jitter \( \sigma_t \) increase sharply.

The development of the spark gap breakdown is shown in Fig. 5. Because of the higher conductivity of the plasma jet, the working voltage is mainly applied at the gap between the plasma jet front and the high voltage electrode, which can be treated as the ground electrode, because of which the original gap distance is significantly shortened. From Fig. 5(a), we can see that a discharge channel can be formed when a protrusion arises in the front of the plasma jet, while breakdown cannot happen when the plasma jet is more regular. These results indicate that the shape of the plasma jet greatly affects the electric field distribution; the smaller the radius of the curvature of the plasma jet front, the higher is the electric field distortion degree and the easier it is to breakdown.

From Fig. 5(b), we can see that the streamer can formed near the anode surface within 40.0 ns, once the electric field induced by plasma jet is high enough. With the help of the plasma jet, the discharge channel is finally set up. Thus, the breakdown delay time \( t_1 \) is mainly composed of three parts: the plasma jet formation and development delay time \( t_2 \), the gap between the high voltage electrode and the plasma jet front breakdown delay \( t_3 \), and the conductive channel commutation delay \( t_5 \). As \( t_2 \) and \( t_3 \) are usually in the order of nanoseconds and microseconds, respectively, of \( t_1 \), the discharge delay \( t_1 \) is dominated by \( t_1 \).

Defining the main gap distance as \( L \) and the maximum length of the plasma jet as \( L_e \), the breakdown delay time \( t_1 \) and jitter \( \sigma_t \) increase with the ratio of \( L \) to \( L_e \), as shown in Fig. 6. Under very low working coefficients, the breakdown happens at the moment when the plasma jet is close to the high voltage electrode; when the gap distance increases, the required length of the plasma jet that...
the spark gap discharge demands also increases. Thus, the breakdown delay time \( t_1 \) and jitter \( \sigma_1 \) derived from the development of the plasma jet formation and ejection increase correspondingly. When the required length of the plasma jet that the spark gap breakdown demands is less than \( L_e \), the breakdown takes place during the plasma jet expanding phase. In this phase, the delay time \( t_1 \) and jitter \( \sigma_1 \) derived from the plasma formation and ejection can be controlled in a relatively small range. The breakdown delay time \( t_1 \) is no more than 22 \( \mu s \), and the jitter \( \sigma_1 \) is less than 2.5 \( \mu s \), which was measured from the fitting curve. When the required length of the plasma jet is more than \( L_e \), the spark gap breakdown \( \sigma_1 \) in the plasma jet is in the steady and dissipating phase. As the randomness of the plasma ejection grows and the plasma jet shape is changing very slowly with the effects of plasma density and temperature gradient, the breakdown delay time \( t_1 \) and jitter \( \sigma_1 \) could increase greatly.

FIG. 6. Change in trend of \( L/L_e \) under a working coefficient of 0.25.
FIG. 7. Change in trend of delay time $t_\tau$ and jitter $\sigma_\tau$ under different working coefficients and gap distances.

B. Effect of working coefficients on breakdown characteristics

Figure 7 shows the comparison of the breakdown delay time $t_\tau$ and jitter $\sigma_\tau$ under different working coefficients. The gap distance varies from 5.0 mm to 12.0 mm, and the working coefficient increases from 10% to 75%. With the increase in the working coefficient, both the breakdown delay time $t_\tau$ and jitter $\sigma_\tau$ reduced. When the working coefficient is 35% and the gap distance increases from 5.0 mm to 12.0 mm, the differential range of the breakdown delay time $t_\tau$ and jitter $\sigma_\tau$ is 9.8 $\mu$s and 1.5 $\mu$s, respectively. When the working coefficient increases to 75%, the differential range of the breakdown delay time $t_\tau$ and jitter $\sigma_\tau$ decreases to 0.96 $\mu$s and 0.13 $\mu$s, respectively. When the working coefficient is more than 75%, the maximum value jitter $\sigma_\tau$ is no more than 0.1 $\mu$s when the working coefficient is more than 75%. With the increase in the working coefficient, the electric field in the spark gap is enhanced, leading to the diminishing demand of the electric field distortion. Hence, the required length of the plasma jet that the spark gap breakdown needs decreases by many degrees.

The images taken at the breakdown moment captured by the high-speed multi-frame camera under different working coefficients are shown in Fig. 8. With the working coefficient increasing from 20% to 75%, the ratio of $L$ to $L_e$ increases by 1.51–3.21. When $L_e$ stops increasing, the breakdown moments change from the plasma jet expanding phase to the steady and dissipating phase. The breakdown delay $t_1$ increased with the decreasing working coefficients, and the shape of the plasma jet changes greatly during the plasma jet development, which can affect the breakdown moments under the same working coefficient, leading to an increase in the breakdown jitter $\sigma_1$.

C. Effect of the plasma shape on discharge characteristics

When introducing the plasma jet to trigger the spark gap breakdown, the discharge characteristics is mainly dominated by the properties of plasma ejection. Therefore, the basic method to reduce the delay time $t_\tau$ and jitter $\sigma_\tau$ of the trigatron spark gap is to optimize the properties of plasma ejection. The breakdown moment triggered by different shapes of the injected plasma is shown in Fig. 9. It can be seen that the shape of the plasma jet changed greatly even under the same discharge parameters. A higher trigger current can form a more regular and stable plasma jet, ensuring the breakdown happens only with a lower breakdown jitter $\sigma_\tau$. Meanwhile, due to the enhancement of the strongest electric field on the protrusion of the plasma jet front, the discharge channel is usually formed in this location, which is circled in red in Fig. 9. While there exists randomness of the protrusion formation on the plasma jet, the breakdown jitter triggered by the plasma jet is usually larger than that triggered by electric field distortion.

With the plasma jet in the steady phase, the length of the plasma jet stops increasing, whereas the plasma density decreased; under this condition, the diffusion induced by plasma density and temperature gradient can increase the length of the plasma jet very slowly; hence, the breakdown can happen with a longer delay time. With the
energy undergoing further reduction, the plasma jet began to dissipate and shrink, which could result in breakdown because of the change in the plasma jet shape, which is shown in Fig. 10. It can be seen that the density of the plasma jet at the breakdown moment is lower than that at an earlier time, but the shape becomes subtriangular, which means that the radius of curvature decreased largely. As the electron ionization coefficient $a$ is mainly dependent on the maximum electric field $E_{tr}$ and pressure $p$ of the filled gas, the decrease in the radius of curvature can increase $E_{tr}$, resulting in the increase in $a$, indicating that the breakdown can happen under a lower applied voltage. While the shape of the plasma jet is changing throughout the dissipating phase and its effects on electric field distortion varied with the shape of the plasma jet, a sharp increase in the breakdown jitter $\sigma_t$ is obtained when triggered breakdown happened during the dissipating phase.

In order to obtain the effects of the change in the plasma jet shape on the breakdown delay and jitter during the dissipating phase, the properties of the plasma jet generated by polyethylene and ceramic surface discharge are captured, which are shown in Fig. 11, and the breakdown delay time $t_\tau$ and jitter $\sigma_t$ are shown in Table I. The results show that the shape of the plasma jet generated by polyethylene surface discharge is more regular and stable during the whole development process, while different shapes such as the square and triangle can be found during the dissipating phase when induced by ceramic surface discharge, indicating that the shape of the plasma jet induced by ceramic surface discharge is variable. The breakdown delay time $t_\tau$ and jitter $\sigma_t$ triggered by polyethylene surface discharge are always lower than those triggered by ceramic surface discharge, and the difference increased with decreasing applied voltage, which means that the breakdown that happened during the

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**FIG. 9.** Breakdown moment triggered by different density plasma jets: (a) the breakdown moment triggered by the high-density plasma under different working coefficients and (b) the breakdown moment triggered by the low density plasma under different working coefficients.

**FIG. 10.** Breakdown process during the plasma jet dissipating phase.
plasma jet dissipating phase showed a great difference. This result is consistent with the plasma jet shape changing characteristic during the dissipating phase. The reason could be because polyethylene is a type of gassing material, which can break down into CH₄, C₂H₄, and H₂ under a high temperature environment. More mass is heated up to the ionization state and ejected into the discharge gap, which is helpful for stabilizing the plasma jet. While the ceramic surface discharge cannot produce vaporized material into the plasma jet and the plasma stabilizing the plasma jet. While the ceramic surface discharge can -  tive space charge is of the order of the external field, breakdown mechanism. Its physical meaning is that when the field of a posi- tive space charge is of the order of the external field, breakdown can happen, while the multiplication of the positive space charge in the spark gap. When the electron avalanche χ increased to a critical value where the number of the positive space charge reaches 10²⁰, breakdown can happen, and the distance χ of the electrons moving from the avalanche to the streamer can be calculated by Raether’s breakdown criterion, which is described as follows:

\[
a_χ = 17.7 + \ln χ.
\]

When the electron ionization coefficient a is dependent on the electric field E₀ and pressure p of the filled gas,

\[
a = Ap \exp \left(- \frac{Bp}{E₀}\right),
\]

where A and B are the two constants related with the gas type; for common air, A = 8.5(cm 133 Pa)^{-1} and B = 250 V/(cm 133 Pa)^{-1} when the ratio of the field and pressure (E/P) is within 20–150 V/(cm 133 Pa). The enhanced electric field near the front of the injected plasma E₀ can be rewritten as

\[
E₀ = λE_m.
\]

E_m is the mean electric field between the front of the injected plasma and the opposite electrode and can be given as E_m = U_m/d_m, where U_m is the applied operating voltage, and d_m is the distance between the front of the injected plasma and the opposite electrode. It can be seen that a is mainly determined by E₀, and the increase in a can make the distance χ shorter to reach the breakdown criterion.

As the streamer velocity is usually in the range of 10⁸ cm/s under atmospheric pressure, the time of the streamer propagation is very short, under a centimeter spark gap distance. Thus, the breakdown time is mainly decided by the development of the plasma jet. The plasma jet had two effects on the change in shape of the plasma jet became the main reason for

| TABLE I. Breakdown delay and jitter comparison. |
|-----------------------------------------------|
| **Gap distance** | **Working coefficient (%)** | **Breakdown delay time t_r (μs)** |
|                 |                             | Polyethylene | Ceramic     |
| 10 mm           | 10                          | 25.9         | 85.3        |
|                 | 20                          | 17.5         | 25.4        |
|                 | 30                          | 15.9         | 21.8        |
|                 | 40                          | 14.6         | 18.7        |
|                 | 60                          | 11.8         | 13.5        |

FIG. 11. Change in shape of the plasma jet induced by polyethylene and ceramic surface discharge: (a) polyethylene and (b) ceramic.
increase in $E_{tr}$, for the electric field distortion coefficient increased with the decreasing curvature radius of the plasma jet front. As the plasma jet dissipating process is decided by the pressure and density gradient, the changing of the plasma jet shape could be very slow, leading to a very slow increase in $E_{tr}$. Hence, the time growth characteristics where $E_{tr}$ increased to a critical value for the breakdown are different under different types of plasma jet development, leading to the change in trend of the breakdown delay formation, as shown in Figs. 4 and 7 under different gap distances. As the shape of the plasma jet changed greatly during the dissipating process due to a very low diffusion velocity, the dispersibility of the breakdown delay increased largely, leading to the increase in jitter, as shown in Fig. 6.

Besides the electric field distortion effects by the plasma jet, a strong ultraviolet radiation (UV) is accompanied with the plasma ejection, where the UV illuminates the whole space of the spark gap. A part of the neutral air molecules in the spark gap can absorb the UV to form photo ionization, which can increase the density of the free space charge. Thus, the insulating air is preionized equivalently before breakdown; a longer UV illumination can form more space charges in the spark gap. As the Meek criteria for the spark gap breakdown is usually dependent on the number of the space charge, the critical breakdown electric field can be reduced with the help of UV illumination.

**IV. CONCLUSION**

In this paper, the physical development of a trigatron spark gap breakdown triggered by a plasma jet is analyzed, and the influence of the gap distance, working coefficient, and plasma ejection properties on breakdown characteristics of spark gap is compared. With the increase in the gap distance, the required length of the plasma jet that the spark gap breakdown demands increases, and the breakdown delay time $t_d$ and jitter $\sigma_t$ increase gradually. The breakdown usually happens between the plasma jet front protrusion and the anode surface, where the electric field distortion is the strongest. The irregular shape of the plasma jet can make the discharge type change from sphere-to-plane discharge to rod-to-plane discharge and has the tendency to change to needle-to-plane discharge, making the breakdown criterion easier to reach due to more serious electric field distortion. Even when the plasma jet stops increasing during the dissipating phase, the triangle shaped plasma jet with a low density also can trigger the spark gap breakdown with a long breakdown delay and jitter. When the triggered breakdown happens in the plasma jet expanding phase, the breakdown delay time $t_d$ is mainly decided by the expanding velocity, and the jitter $\tau$ is relatively low. When the breakdown happens in the plasma jet steady and dissipating phase, the slow change in the shape of the plasma jet can result in a range of effects of the plasma jet on electric field distortion increase, leading to an obvious increase in the breakdown jitter $\sigma_t$. This could be the main reason behind a sharp increase in the breakdown delay and jitter that changes with the spark gap distance, pressure, and the energy input to the plasma jet.

The plasma jet generated by polyethylene and ceramic surface discharge shows a great difference in shape during the plasma jet steady and dissipating phases. Due to a lighter molecular weight and the lower mass of the plasma jet generated by ceramic surface discharge, the shape can change easily during the dissipating phase, leading to a wide variation in the effect of the electric field distortion and the increase in the breakdown time jitter $\sigma_t$ when triggered by ceramic surface discharge. The ultraviolet radiation (UV) accompanied with the plasma ejection can illuminate the whole space of the spark gap, leading to more free space charge formation from photo ionization, which is a part of the reason for the trigatron spark gap to reliably trigger breakdown under working coefficients.

**ACKNOWLEDGMENTS**

The authors gratefully acknowledge the support from the China National Natural Science Fund, Grant Nos. 51790523 and 51807157, the National Key Research and Development Program of China, Grant No. 2017YFE0032300, and the Natural Science Foundation of Shaanxi Province, Grant No. 2019JM-335.

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