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TOPICAL REVIEW

Ion Electric Propulsion System Electric Breakdown Problems: Causes, Impacts and Protection Strategies

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ABSTRACT Ion electric propulsion systems have been widely used in satellite station keeping, attitude control, and orbit transfer due to their advantages of high specific impulse, good flexibility, and high reliability. The electric breakdown might happen at grids or across isolators due to the disturbing effects of the power source or environment. The electric breakdown can induce spurious effects in the power processing unit (PPU) circuit from the return currents and voltage drops, which could be several orders of magnitude higher than the impulses at normal working conditions. When the electric breakdown happens, it might result in serious electromagnetic interference and damage to the electric and electronic equipment in the spacecraft. This paper provides a comprehensive summary of the various factors that can cause electric breakdown in an ion electric propulsion system, such as environmental factors, manufacturing considerations, and operational conditions of the thruster. Furthermore, a comprehensive analysis of the impact of electric breakdown on the ion thruster, electric propulsion system, and spacecraft mission is explored. The effectiveness of different grounding configurations in safeguarding against ion thruster electric breakdown has also been evaluated. Based on the analysis and discussion, the control and protection strategies are proposed for the ion electric propulsion system electric breakdown problems.

INDEX TERMS Ion electric propulsion system, electric breakdown, ion thrusters, power processing units.

I. INTRODUCTION

With the fast development of aerospace technology in the past decades [1], [2], [3], the space missions require reliable and high-performance propulsion systems, especially electric propulsion systems [4], [5], [6]. Although the traditional chemical thruster can produce high thrust, the electric thruster can generate a much larger exhaust velocity of the propellant than that of the chemical thruster by heating or ionizing the propellant and forming a high speed jet [7], [8]. It means the electric thruster can change the velocity of the aerospace with a much smaller propellant mass, which is suitable and has been widely used in spacecraft and satellite power systems [9], [10]. Therefore, as a low propellant consumption engine, the electric thrusters receive much attention and have been widely studied in the last decade, which include Resistojet, Vacuum arc, Electrospray, Ion thrusters, Hall thrusters, Arcjets, etc [11], [12], [13], [14] Among the various electric thruster designs, Hall thruster and ion thruster (also called gridded-ion thruster) are the most developed and popular electric thrusters [15]. Compared with Hall thrusters, ion thrusters have a higher specific impulse, a higher power ratio and moderate-thrust, and are widely used in spacecraft attitude control, orbit keeping, orbital transfer and orientation of spacecraft [16], [17].

Ion thruster is mainly composed of a discharge chamber, grids, and a neutralizer. The low temperature plasma is produced in the discharge chamber with the applied high voltage between electrodes, and the ions in plasma are extracted and accelerated by DC biased grids. The extracted ions are

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neutralized by the neutralizer, which provides electrons, and then are ejected into the downstream space. Usually, the potential of the ion thruster shell is grounded at 0 V, the anode and screen grid operate at high voltages over 1000 V to generate high ion density, and the acceleration grid has a negative potential of a few hundred V [18], [19]. The physical structure of an ion thruster is very tight. The spacing among screen grid, acceleration grid, and anode is just a few mm [17], [18], [20]. Therefore, the characteristics of high potential and small spacing of the ion thruster physical structure and working conditions cause a strong electric field inside. When there is an instantaneous electric field distortion in the ion thruster caused by the disturbing effects from the power sources or outer environment, it could cause a sudden increase in current and then trigger the protection unit, resulting in an instantaneous breakdown (also known as beam sparkle) and loading of the beam frequently [21], [22], [23], [24]. In a three-grid ion thruster, an additional third grid is placed near the neutralizer to reduce the ion bombardment effect, and the instantaneous breakdown and loading of the beam occurs even more frequently, which would result in the electric propulsion system being unexpected suspended, the service life being greatly reduced, the serious damage to the thruster electrode and grids, and even the failure of the spacecraft mission [25], [26], [27]. It is worth to notice that besides the positive ion thruster, there is a kind of negative ion thruster without the need for additional current and space charge neutralization [28], [29], [30].

To minimize the likelihood of the electric breakdown in the ion thruster, it is important to investigate the main causes of the unexpected breakdowns, the impact of the breakdowns on the electric propulsion system, and the protection methods [31], [32]. It is the primary purpose of this work to summarize the formation of the ion thruster electric breakdown from the environment, manufacture, and operation conditions, the impacts of the electric breakdown on the ion thruster itself, electric propulsion system, and spacecraft mission, and the control and protection strategies of the electric breakdown. This work aims to serve as a solid foundation for guiding future efforts to minimize the probability of ion thruster electric breakdown, protecting the electric propulsion system and spacecraft devices, and improving the utilization efficiencies and performance characteristics of ion thrusters.

II. BASIC WORKING PRINCIPLE

Ion electric propulsion systems are one of the mainstream electric propulsion technologies in the world, and belong to electrostatic acceleration [33], [34], [35], [36]. The input power of the ion electric propulsion system is usually solar energy converted into electricity by photo-electric conversion device, which ensures long-term spacecraft power [37]. Then, in ion electric propulsion system, the electricity would convert into electromagnetic field energy at the discharge chamber to ionize propellant (usually Xe) and generate low temperature plasma with abundant electrons and ions [38], [39], [40]. Finally, under the electrostatic field of the DC biased grids, the ions in discharge chamber are extracted and accelerated, forming an ion beam in the downstream space, thereby realizing the conversion of electricity to kinetic energy.

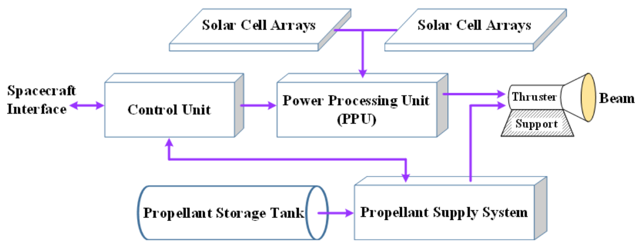

FIGURE 1. Typical schematic diagram of ion electric propulsion system.

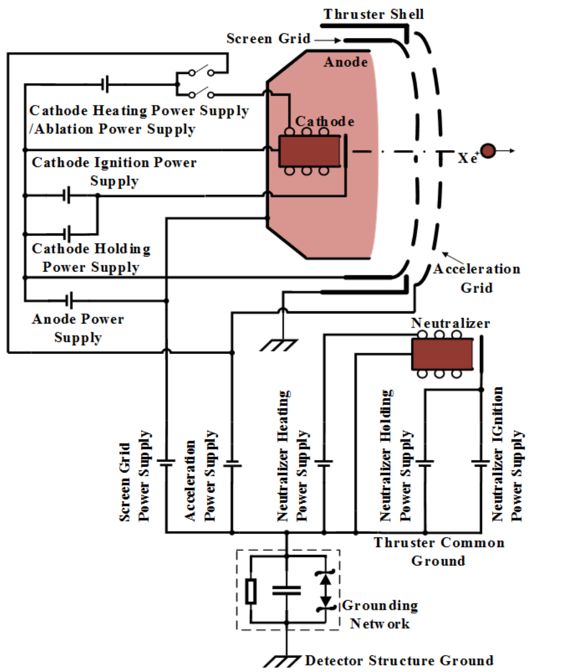

FIGURE 2. Schematic diagram of the connection between the ion thruster and PPU.

Figure 1 is the schematic diagram of a typical ion electric propulsion system, which mainly includes an ion thruster, a power processing unit (PPU), a propellant storage unit (including a propellant storage tank and a propellant supply system), and a control unit. Among them, the ion thruster and PPU are the core parts of the electric propulsion system. Figure 2 shows the detailed schematic diagram of the connection between the ion thruster and PPU. It can be seen that the ion thruster is composed of discharge chamber with an anode and a cathode to ionize Xe and produce plasma, screen grid and acceleration grid to extract and accelerate ions from chamber, and the neutralizer to feed electrons and neutralize ions. The spacing among screen grid, acceleration grid, and anode is very tight but the insulation layer is durable for normal working conditions to avoid ion thruster breakdown and electric propulsion system interruption. However, with the disturbing effects from the devices or coupling effects from outer environment, the unexpected breakdowns in ion thruster cannot be avoided and still occur frequently.

III. CAUSES OF UNEXPECTED BREAKDOWNS

The causes of the unexpected electric breakdowns in ion thrusters are mainly divided into three categories: environment, manufacturing process, and operation parameters. The environment refers to space environment, which is the real working conditions, and ground environment, which is for experiments and tests. The biggest difference between the two environments is the presence of gases and particles in space. The manufacturing process can affect the grade of surface finish of ion thruster grids. The mutual coupling effects of the operation parameters are very complex and also affect the ionic thruster electric breakdown significantly [41].

A. INFLUENCES OF ENVIRONMENT

Before an ion thruster is used on orbit, it experiences ground storage, transportation, and launch three stages. In the three stages, the surfaces of ion thruster grids could absorb gases and particles, resulting in micro-protrusion on the surfaces and frequent breakdown in the early stage of the thruster on orbit. However, due to the limited amount of gases and particles adsorbed on the surfaces of grids, the gases and particles on the surfaces of ion thruster grids would gradually desorb with a high temperature [42]. Thus, the frequency of breakdown caused by the absorbed gases and particles will decrease with the increasing working time of the ion thruster.

When the ion thruster performs the ground long-life test, the frequency of electric breakdown is high at the beginning [43]. The reason is similar to the ion thruster on orbit for the absorption of gases and particles. With the ground test lasting, the frequency of electric breakdown gradually decreases. However, due to the limited space of the vacuum chamber on ground, the diffusion movement of vacuum bulkhead and sputtering material particles in the vacuum chamber has become a unique influencing factor leading to breakdown in ground tests. It is manifested by the fact that the frequency of electric breakdown of ion thruster during the working test on ground is obvious higher than that of ion thruster on orbit.

According to the data of the NASA solar electric propulsion technology applications readiness (NSTAR) thruster space and ground experiments in the United States as shown in Table 1, the electric breakdown caused by different environments is further verified, among which the ground test data are from the life demonstration experiment (LDT) above 8000 h and the extended life experiment (ELT) above 30000 h, and the space application data are from the ‘‘Deep Space 1’’ (DS-1) and ‘‘Dawn’’ spacecraft.

The data in Table 1 shows that the average breakdown frequency will decrease with the increase of the accumulated working time, regardless of ground or space experiments, indicating that the electric breakdown of the ion thruster induced by gases and particles will be reduced for the longer the working time. The breakdown frequency during ground tests is about two orders of magnitude more than that in space environment, indicating that there are more gases and particles in the ground tests, resulting in higher breakdown frequency, many of which are affected by bulkheads and the diffusion of sputtering material particles [49].

TABLE 1. Comparison of NSTAR ion thruster electric breakdown data under space and ground environments.

Data source	Environment	Segment duration/kh	Average breakdown frequency/h^{-1}	References
LDT	Ground	8.192	762.7×10^{-3}	[44, 45]
ELT		30.352	488.0×10^{-3}	[44, 46]
DS-1	Space	16.265	12.2×10^{-3}	[47]
Dawn		17.130	3.4×10^{-3}	[48]

TABLE 2. Voltage holding by 10 × 10 cm^2 electrodes over a vacuum gap of 11 mm under high stored energy breakdowns. (V_{max} is the maximum voltage holding reached and V_{final} is the maximum voltage holding after 10000 seconds of operation and about 1000 accumulated breakdowns) [50].

Material	Surface finish	V_{max}	V_{final}
Stainless 304L	Machined	171 kV	160 kV
Stainless 304L	Baked 800 ºC, polished	156 kV	146 kV
Titanium TA6V	Machined	158 kV	154 kV
molybdenum	Machined	147 kV	144 kV
copper	Polished	141 kV	141 kV

B. INFLUENCES OF MANUFACTURING PROCESS

In the processing and manufacturing porous thin grid electrode, usually the electrochemical deburring process is taken to effectively eliminate the burr on the grid surface. However, there are still micro-protrusions, which is one of the important causes for ionic thruster electric breakdown. Esch et al. performed breakdown tests on electrodes made of stainless steel, copper, titanium and molybdenum materials with different surface finish conditions, as shown in Table 2 [50]. From the results of stainless 304L, it can be concluded that the different surface finish conditions can affects the breakdown voltage obviously, and the frequent breakdowns would result in the damage of the electrodes.

The influences of the manufacturing process are analyzed by different types of thrusters and different thrusters of the same type as shown in Table 3. The data are from NASA's evolutionary xenon thruster (NEXT), the DS-1 and Dawn FT series thrusters under NSTAR project.

From the data in Table 3, it can be seen that the average breakdown frequency of the NEXT thruster is about 1.6 times of that of the NSTAR thruster in ground test, which used

TABLE 3. Comparison of breakdown data of NEXT and NSTAR.

Thrusters	Grid	Environment		Segment duration/kh	Average breakdown frequency/h^{-1}	References
NEXT	Double molybdenum grid	Ground		51.100	766.3×10^{-3}	[51]
NSTAR	Double molybdenum grid	Ground		30.352	488.0×10^{-3}	[46]
		Space	DS-1	16.265	12.2×10^{-3}	[47]
			Dawn (FT1)	9.468	7.1×10^{-3}	[52]
			Dawn (FT2)	22.772	1.9×10^{-3}	
			Dawn (FT3)	19.141	3.3×10^{-3}	

the same kind of thrusters. The difference in the breakdown frequency mainly results from the manufacturing processes. For the same type of NSTAR thrusters in space, the difference of the average breakdown frequency can be 6.4 times, which also results from the different manufacturing processes [53].

C. INFLUENCES OF OPERATION PARAMETERS

In addition to the environment and manufacturing process, the operation parameters of ion thruster are also important causes for the electric breakdown, such as beam current density, electric field strength between grids, the kind of grid material, etc. [54], [55] And there are many operation parameters, which can be coupled and cause the ionic thruster electric breakdown more complex. Therefore, it is important to compare the influences of each operation parameter on the frequency of ion thruster electric breakdown individually [56].

Table 4 shows the breakdown frequency data for different beam current densities. In ion thruster, ion beam current density can be accelerated using a gridded ion source and is limited by the space charge effect, which is typically measured in mA/cm^2 and is controlled by discharge current. The data are from two ion thrusters, NEXT (on ground test) and NSTAR (in space). The beam current density is different with other operation parameters same or similar.

From the comparison of the data in Table 4, it can be seen that the beam current density of the NEXT thruster at throttle level TL40 is about 2.9 times higher than that of the NEXT thruster at throttle level TL12, and the breakdown frequency is 3.7 times higher. For the NEXT thruster, the beam current density at throttle level ML111 is about 1.1 times higher than that at throttle level ML90 and ML97, and the breakdown frequency is 5.7 times higher. Therefore, it can be seen that the higher beam current density brings a higher breakdown frequency. But the mechanism of the influence of the beam current density on the breakdown frequency is complex and unclear. The higher breakdown frequency might result from the inaccurate focus, exchange charge ion collisions, etc. Some other researches [23], [58], [59] suggest that the higher charge transferred from breakdown arcs might result in more serious damage on grids and electrodes, which would increase the breakdown possibility.

TABLE 4. Comparison of breakdown frequency under different beam densities.

Thrusters	NEXT (ground)		NSTAR (space)		
Working conditions	TL12	TL40	ML90	ML97	ML111
Grid material	molybdenum	molybdenum	molybdenum	molybdenum	molybdenum
Total voltage/V	2010	2010	1280	1280	1280
Average beam current density/(mA·cm^{-2})	0.95	2.80	2.33	2.48	2.76
Segment duration/kh	3.1	21.9	1.118	1.599	3.213
Number of breakdowns /kh^{-1}	505	13218	2	3	35
Average breakdown frequency/h^{-1}	162.9×10^{-3}	603.5×10^{-3}	1.8×10^{-3}	1.9×10^{-3}	10.9×10^{-3}
References	[44]		[57], [24]		

Table 5 is the breakdown frequency data under different electric field strengths. In electrostatic ion thruster, ions are accelerated by the Coulomb force along the electric field direction. The electric field strength is important for ion beam generation and affects the electric breakdown in ion thruster. Because different countries have different standards, only the ion thrusters of U.S. and China are selected and compared.

From Table 5, it can be seen that for NEXT and NSTAR thrusters in the U.S., the former electric field strength is only 1.6 times that of the latter, but the breakdown frequency is 11.4 times higher than the latter. For LIPS-300 and LIPS-200 thrusters of China, the former electric field strength is 1.5 times that of the latter, but the breakdown frequency is about 50 times higher than the latter. It is because LIPS-300 is a three-grid structure and excluding the 30% breakdown frequency caused by the accelerator grid and the decelerator grid, the breakdown frequency of LIPS-300 is still 30 times higher than that of LIPS-200, which is a two-grid structure. Therefore, the electric field strength has a great influence on the breakdown frequency, and it is also one of the key factors that determine the breakdown frequency.

Table 6 is the data of the comparison of breakdown frequency under different grid materials. In electrostatic gridded designs, charge-exchange ions produced by the beam ions with the neutral gas flow can be accelerated towards the negatively biased accelerator grid and cause grid erosion. Grid erosion cannot be avoided and is the major factor

TABLE 5. Comparison of breakdown frequency under different electric field strengths.

Thrusters	United States		China	
	NSTAR	NEXT	LIPS-200	LIPS-300
Grid material	molybdenum	molybdenum	molybdenum	molybdenum
Total voltage/V	1289	2010	1185	1635
Electric field strength/(V·mm^{-1})	1953	3045	1185	1817
Segment duration/h	2031	2038	2000	2100
Number of breakdowns	393	4400	40	2162
Average breakdown frequency/h^{-1}	0.19	2.16	0.02	1.03
References	[60]	[61]	[62]	

TABLE 6. Comparison of breakdown frequency under different grid materials.

Thrusters	U.S. NSTAR		Japan IES-14	
Grid material	molybdenum	C/C	molybdenum	C/C
Segment duration/h	2031	1029	1859	3815
Number of breakdowns	393	2043	—	—
Average breakdown frequency/h^{-1}	0.19	2	0.5	High frequency times or even continuous
References	[60]	[63]	[64]	[65]

limiting grid lifetime. With the optimal design and material selection, the lifetime of grid could be 20,000 hours or more. The molybdenum and carbon-carbon composite materials (C/C) are the most common used materials. Among of them, molybdenum is a standard electrode material due to its low sputter erosion rate, good structural and thermal properties, and ability to be chemically etched to form the aperture array. Carbon is also a desirable material for ion thruster grid electrodes for its low sputtering yield under ion bombardment as compared with molybdenum. The surfaces of these materials should be carefully prepared to withstand high electric fields required to produce the highest thrust density. The breakdown events usually impact the subsequent voltage hold-off capability of the grid surfaces, which affects the long-term performance of the thruster. From Table 6, it can be seen that the breakdown frequency of the C/C grid of the NSTAR thruster of U.S. is 10.5 times that of the molybdenum grid. The C/C gate thruster of IES-14 of Japan even failed to load due to the high pressure caused by high-frequency continuous breakdown [66]. This is because the breakdown resistance of the C/C grid itself is worse than that of the molybdenum grid [67]. Therefore, the C/C grid has a high breakdown frequency, which leads to the limited usage of the C/C material as thruster grid material even it has a better stability and sputter resistance capability than molybdenum. Martinez et al. investigated the electric field breakdown characteristics of molybdenum and carbon-based electrodes and found molybdenum had a much higher breakdown electric field than that of graphite [68]. Goebel et al. performed threshold voltage com-parison for field emission and for arc initiation of molybdenum, pyrolytic graphite, C/C, CVD coated C/C, and CVD coated C/C grid and the results showed that the breakdown threshold voltage of molybdenum was highest [58].

With the development of new materials and new fabrication technologies applied in spacecraft, the grid erosion problem can be mitigated and the breakdown frequency can be reduced [67]. For example, superconductor has a set of physical properties such as electrical resistance vanishes and magnetic fields are expelled from the material. It has applications in electric power transmission, transformers, electric motors, power storage devices. Right now, superconductors have already been adopted for spacecraft missions [69]. The 3D printing technology can construct a three-dimensional object in a variety of processes in which material is deposited, joined or solidified under computer program. From 1980s, 3D printing techniques were considered suitable only for the production of functional prototypes. With the development of technology, the precision, repeatability and material range of 3D printing have increased for various industrial products. The carbon-based 3D printing technology is expected to applying for grids manufacturing [70]. It is worth mentioning that plasma surface modification is also an important technology, which can change materials' surface chemical and physical characteristics and improve surface properties without changing bulk properties [71], [72]. The plasma material treatment technology would also have potential to enhance the properties of the electrodes and grids in ion thruster.

D. EFFECT OF ELECTRIC BREAKDOWN ON SPACECRAFT

1) For the ion thruster itself, the electric breakdown will cause instantaneous changes of voltage and current, destroy the continuous stable operating conditions, and cause the extinguishing of the neutralizer and the discharge chamber. And for the long-term electric breakdown, the accumulated energy would induce a high temperature on the surface of the electrodes or grids, which results in the evaporation of part of the electrode and grid materials and the damage of the electrode and grid. The evaporated electrode materials might deposit on the grids, and for the short screen-accelerator grid gap, the deposited particles might result in short circuit of the screen and accelerator grids and prevent the thruster

TABLE 7. Main impacts of the bream breakdowns.

Main impact	Thrusters	Results	Working conditions/Models	Number of occurrences	References
ion thruster itself	NEXT	Beam extinguishment	TL01	3	[44], [73]
			TL12	10	
			TL12	1	
		Short circuit	TL01	24	
			TL05	111	
			TL12	4	
ion electric propulsion system	Dawn	Beam reboot	FT1	65	[24]
			FT2	26	
			FT3	58	
mission of the spacecraft	PROCYON	Failure of the spacecraft's mission	—	2	[62]

from performing normally. For example, the NEXT thruster and NSTAR thruster had been extinguished in ground-based long-life experiments due to the unexpected electric breakdowns [73], [74].

2) For the ion electric propulsion system, the electric breakdown will cause the interruption of the system, including the interruption caused by the safety control system and the interruption caused by the discharge extinguishing. The large instantaneous current of the electric breakdown will induce transient changes of voltage and current in the PPU circuit and eventually lead to the failure of the PPU unit. When there are multiple ion thrusters working together in the electric propulsion system, the electric breakdown in one thruster would result in the incompatibilities of ion thrusters, and then the inability to coordinate the behavior between PPU and ion thrusters. A high frequency electric breakdown will reduce the life and reliability of the ion thruster significantly. For example, due to the breakdown between grids caused by particle deposition and the coupling fault of the PPU, the service life of multiple XIPS-13 ion thrusters on the BSS-601HP was greatly reduced [75].

3) For the mission of the spacecraft, the electric breakdown causes the ion beam to be interrupted and loaded instantaneously, which will cause the unstable output of the ion thruster. Then, the actual output might be far less than the expected thrust, which may lead to the failure of the spacecraft's mission. For example, the mission of the first Japanese interplanetary micro-spacecraft, PROCYON, was deep space exploration. But due to the deadly short circuit caused by the electric breakdown between the thruster grids, PROCYON had to abandon its mission [57], [76].

IV. IMPACT OF BEAM BREAKDOWN

Even few reports about the failures of spacecraft directly by the electric breakdown issues, the impacts and harms caused by the ion thruster breakdown are multifaceted, which can

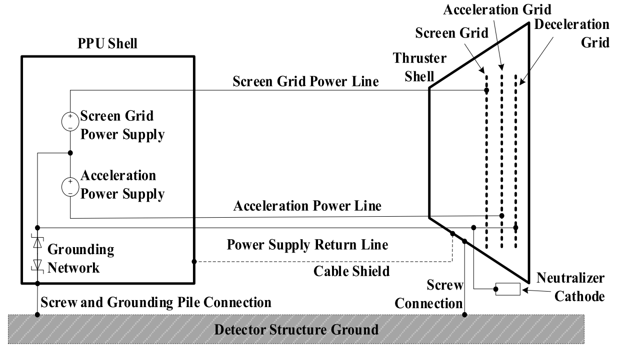

FIGURE 3. Schematic diagram of the connection between the PPU, ion thruster, and ground.

result in the damage to the electrodes and grids of the ion thruster, the reduction of the service life, poor reliability, the erosion of grids, interrupt the normal working state of the ion electric propulsion system, and even lead to the failure of space missions [75]. The formation of an arc from electric breakdown at the cathode electrode (the acceleration grid) and the deposition of a significant amount of energy and heat into the anode electrode (the screen grid) can cause both the grid surfaces to be damaged. The breakdown usually impacts the subsequent voltage hold-off capability of the grid surfaces, which affects the long-term performance of the thruster. The energy delivered to the acceleration grid surface by the arc and the amount of damage to the surface incurred by material removal is independent as long as the current is stable for the breakdown time. The grids have high voltages applied over small grid gaps, leading to breakdown and unreliable thruster operation. If sufficient field emission occurs because of excessive voltage or a modification to the surface that enhances field emission, the gap breaks down. Physical damage to the arced surfaces during the breakdown is attributed to energy deposition and the melting or evaporation of the material.

It should be noted that the beam breakdown has different impacts on the performance of the spacecraft under different grounding methods and different grounding positions of the ion electric propulsion system. The screen grid is close to the thruster shell and the sparks between them would result in a breakdown current loop. The type of the loop depends on the grounding positions, which will affect the design of the PPU and the performance of the ion thruster. Figure 3 shows the schematic diagram of the connection between the PPU, ion thruster, and ground.

A. DIFFERENT GROUNDING METHODS

The thruster grounding methods include the fixed grounding, floating grounding, and grounding network three kinds. Fixed grounding is the direct connection of the thruster power supply ground to the detector structure ground [78]. Floating ground is equivalent to an open circuit in the PPU's internal ground network. For grounding network, it usually contains the bleed resistors, capacitors, and clamping devices, through which the thruster is powered by the network connection to the detector structure ground. The impact of the three grounding methods is mainly manifested in the following aspects [19]:

1) For fixed grounding, it has the advantage of low common mode disturbances. However, a few electrons from the neutralizer are inevitably attracted by the spacecraft structure and the solar panel, which form leakage currents at the level of tens to hundreds of mA. The small leakage current has no obvious effect on PPU operation, but for ion thrusters, a higher electron beam from neutralizer is required. Therefore, in practical applications, the emission current is composed of neutralizer current, ion beam, and spacecraft leakage current. But the neutralizer and spacecraft share the same ground in fixed ground, and the leakage current cannot be accurately determined.

2) For floating grounding, there is a floating voltage relative to the thruster power supply ground to the whole spacecraft structure, which may cause a wide range of voltage potential fluctuations and oscillations under the action of environmental charge and discharge, and the transient electrical stress of the ion thruster. It affects the electric propulsion thrust of ion thruster, and affects the insulation design of the PPU and the ion thruster, so it is a high risk in the completely floating grounding scheme.

3) When the ion thruster is grounded through the grounding network, the thruster power supply ground is floating within the clamping voltage range, which can prevent a leakage current toward the spacecraft by forming a closed current loop with the neutralizer current and the ion current. At the same time, the clamping circuit limits the potential difference between the thruster power supply ground and the structural ground, ensuring the insulation safety between the PPU and the thruster, and the insulation safety inside the thruster. Therefore, the grounding network scheme for thruster grounding is relatively better than others.

B. DIFFERENT GROUNDING POSITIONS

The grounding network connects the thruster power supply loop and the spacecraft detector structure, and can be selected to ground at the PPU end or the thruster end. The differences between the two options are mainly manifested as:

1) The first difference is that the common mode voltage dV generated on the line acts on the thruster or PPU. Figure 4 shows a schematic of the common-mode voltage generated by the breakdown current passing through the circuit.

If the grounding point is chosen at the thruster, the voltage at the output of the PPU is the clamping voltage of the grounding network V_{CLAMP}+dV, and the voltage at the thruster is V_{CLAMP}. This situation not only puts pressure on the insulation of the PPU, but also interferes with the normal operation of the PPU.

If ground is chosen at the PPU, the voltage at the output of the PPU is the clamping voltage V_{CLAMP} of the ground network, and the voltage at the thruster is V_{CLAMP}+dV. Therefore, the insulation of the PPU becomes less important, and

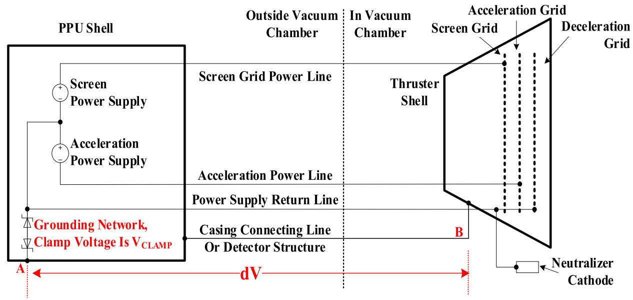

FIGURE 4. The common-mode voltage generated by the flashing current through the wire.

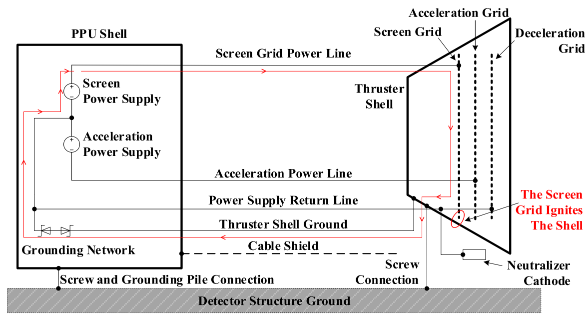

FIGURE 5. Breakdown current loop of the grounding network on the thruster side.

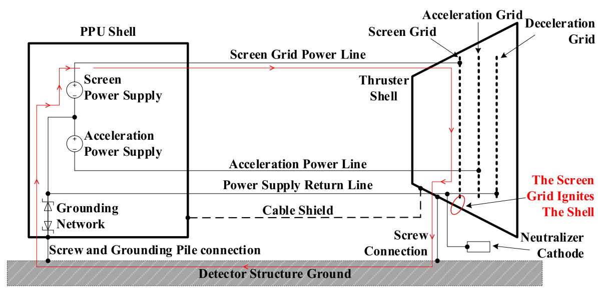

FIGURE 6. Breakdown current loop of the grounding network on the PPU side.

the endurance capacity is mainly depended on the thruster. The common-mode transient at the thruster interface can usually be handled by the internal insulation of the ion thruster, so this grounding scheme is relatively more favorable for the system.

2) The second difference is that the screen grid of the ion thruster has a different breakdown current loop. Placing the grounding point of the grounding network on the thruster side, as shown in Figure 5, PPU internal secondary power output and the thruster shell is insulated. At this time, the breakdown current returns through the wires connecting PPU and thruster structure, which can avoid the breakdown current flowing through the detector structure ground. By placing the grounding point on the PPU side, as shown in Figure 6, the breakdown current returns through the detector structure connecting the PPU and thruster structure, which increases the risk of interference with the control signals of PPU or other equipment.

V. CONTROL AND PROTECTION STRATEGIES OF ELECTRIC BREAKDOWN

A. MITIGATION TECHNOLOGIES OF ELECTRIC BREAKDOWN FOR THE ION THRUSTER

For the ion thruster itself, the mitigation of electric breakdown mainly includes the following three aspects:

1) The selection of the appropriate grid material. Usually, the grid materials should have the properties of high temperature resistance, sputter resistance, good thermal conductivity and for the protection of the ion thruster electric breakdown, the grid materials should have the capability of withstand high voltage. At present, molybdenum and C/C materials are the mostly used grid materials [79], [80], among which molybdenum can withstand higher voltage than C/C composites.

2) The appropriate electric field strength. The electric field strength between grids is one of the important factors affecting ion thruster electric breakdown, but there is a contradiction between the high electric field strength requirement for performance and the reduction of electric breakdown for safety. A smaller electrodes spacing and a larger potential difference would results in higher ion beam efficiency and higher specific impulse. But the frequency of the electric breakdown would be high. Therefore, in engineering, the equation $K = E_{m0}/E_m$ is generally used. K is the safety coefficient of the grid working electric field strength, and E_{m0} is the minimum electric field strength of the electric breakdown in vacuum obtained by experiment, and E_m is the maximum electric field strength of the grid at working conditions. Considering the factors such as electrode edge, non-ideal surface state, thermal deformation of grid spacing, etc., the minimum safety coefficient K is generally set above 6 [66].

3) The reasonably design for the ion beam distribution uniformity and beam density. The former can be improved by the discharge chamber design and the variable aperture grid design, and the latter can be reasonably optimized by defining the safety factor, that is, the ratio of the limit beam density to the maximum working beam density, which is usually greater than 2 [66].

4) The improvement and optimization of the breakdown resistance characteristics of PPU. When the electric breakdown occurs, the large pulse output current and the transient process will affect the high-voltage power supply such as acceleration and beam current of the PPU, especially the power failure caused by a single severe electric breakdown or the accumulation of multiple electric breakdowns. The improved design of PPU requires not only artificial simulated short-circuit verification between PPU and resistive load, analog short-circuit circuit, short-circuit rod, etc. [81], but also full verification of the actual working conditions of PPU and ion thruster [82].

B. CONTROL AND PROTECTION TECHNOLOGIES OF ELECTRIC BREAKDOWN FOR THE ION ELECTRIC PROPULSION SYSTEM

The ion electric propulsion system covers a wider range than the ion thruster, which includes the following three aspects:

1) The real-time monitor of electric breakdown and fast response. The ion thruster electric breakdown is often accompanied by grid arc discharge, if not monitored and eliminated in time, the deposited energy will lead to grid damage or even burnout, and the damage will be accompanied by a micro-convex or tip formation on the grid surface, thereby causing breakdown again. Therefore, by using the sudden changes in current and voltage accompanied by breakdown, some monitoring measures can be taken on the internal circuit, and beam cycle procedures can be designed, so that the system can obtain real-time monitoring and fast response capabilities.

2) The removal of the deposited energy by the breakdown process on grid surface. If the deposited energy is not removed in time, the grid surface will be damaged further. To control this problem, it is necessary to take the threshold of total charge transfer that does not cause grid surface damage as a premise, which can be determined by grid breakdown and damage experiments [67], [83], and then combined with the ignition cycle program and the matching PPU high-voltage power supply output energy storage limit, so as to alleviate the problem of deposition energy on grid surface.

C. CONTROL AND PROTECTION TECHNOLOGIES OF ELECTRIC BREAKDOWN FOR WORKING ENVIRONMENT

The influence of the working environment of the ion thruster on the electric breakdown is complex, and it is necessary to pay attention to the following three aspects and implement protective measures:

1) Low-pressure-induced electric breakdown dominates both ground long-lived experiments and the early stages of space applications. Low pressure mainly comes from propellant gas, material release gas, thruster external environment, etc. For the propellant gas, it is important to prevent propellant leakage into the vacuum area, which can be enhanced by improving gas tightness and the firmness of the material, and the efficiency of propellant in discharge chamber to reduce the of gas molecules flow to the downstream. For the material release gas and the thruster external environment, the problem can be lower by reducing the use of organic materials, replacing them with metal materials as much as possible, and it is also necessary to use the heating and pumping methods together before the thruster works [84].

2) The plasma environment is one of the most important factors inducing electric breakdown, which includes plasma inside the discharge chamber and grids, plasma outside the neutralizer and downstream outside ion beam, and plasma of the diffusing particles in space application and ground test. For the internal plasma environment, it is necessary to pay more attention to the beam focusing of the grid and reduce the density of charge ions exchanged between the grids, and then improve the mechanical seal property and plasma shielding design by considering the leakage of ions. For the ex-ternal plasma environment, it is mainly to prevent the electrons from the neutralizer entering the grid. On the one hand, the design of the accelerator grid voltage and the safety margin

need to match the aperture of the accelerator grid and the beam density [78]. On the other hand, the control program for the grid's high voltage power supply on and off should be properly designed [85].

3) The contamination can lead to the ion thruster electric breakdown. The contamination mainly comes from the manufacturing process, the experimental and ap-plication processes, and self-products produced by the ion thruster during operation. For the residues of the manufacturing process, such as grid burrs, the electrochemical polishing can be used before the assembly of the grid to reduce burrs [84]. For contamination from experimental and application, such as storage and transportation, the thruster can be covered and the parts can be cleaned and dried. For the contamination introduced by the operation, it is necessary to find the pollution source and take proper method.

D. CONTROL AND PROTECTION TECHNOLOGIES OF ELECTRIC BREAKDOWN IN ENGINEERING APPLICATIONS

In engineering applications, the well-designed on-orbit processing procedures include:

1) The ion thruster undergoes a pre-treatment protection procedure before launching into orbit. Compared with molybdenum and carbon, titanium has a higher breakdown electric field, which would be a better choice [62]. The margins of safety for the maximum working electric field intensity and beam density are also important to avoid electric breakdown [58], [59]. However, it would limit the performance of ion thruster. The high grade of surface finish of grids and electrodes would also reduce the surface sputtering and erosion from surface burrs [62], [80]. From manufacturing to launch, the electrodes of the ion thruster would adsorb ambient gas particles, and the ion sputtering deposits would crack or warp due to thermal expansion and contraction. The pre-treatment procedure can reduce this kind of problem and thus reduce the frequency of electric breakdowns [81], [85], [87]. The pre-treatment procedure is: the pipe-line exhaust to eliminate residual gas impurities in the pipeline and thruster, the cathode ignition to eliminate the surface contamination on electrodes, the discharge chamber ignition to eliminate the gas absorbed by the discharge chamber electrodes and grids, and the ion beam test to eliminate the gas absorbed by grids and the contaminants from outside.

2) Set the program to control the continuous breakdowns. When a breakdown occurs, the propulsion system runs the breakdown control program. If the problem is not solved, the system will enter the cycle program again [88], [89], [90], [91], [92], so the control program can prevent the continuous breakdown from further causing the damage to the power supplies and grids, for example, the control unit monitors 25 times or more beam cur-rent recovery within 90s, then the propulsion system would be shut down and a fault message would be given.

3) Design the operation mode to eliminate the grid short circuit. When the control program shut down the propulsion system by continuous breakdown, it means that the grid is short circuit and it is necessary to recover the system by eliminating the grid short circuit [93], [94], [95], [96]. In this recovery mode, the contamination between the grids would be cleaned and evaporated by heating. However, this method alone is not safe, because if the heating current is too small, the contamination cannot be evaporated. Excessive heating current will damage the grid [97]. Therefore, the thermal cycle method should be preferred, that is, to break or remove the excess through the thermal cycle between grids. If it still cannot be solved, use the above heating method together.

VI. ELECTRIC BREAKDOWN DIAGNOSIS

Advanced diagnostic techniques play a crucial role in identifying and understanding breakdown phenomena in ion thrusters. The electric breakdown is a gas discharge process, which can be diagnosed by optical emission spectroscopy (OES), Langmuir probe, time resolved imaging, electric field probe, Particle-in-Cell (PIC) Simulations, etc. These techniques can help researchers gain insights into the underlying mechanisms causing breakdown and enable them to develop effective solutions.

OES is a non-intrusive diagnostic technique [98], [99], [100] that measures the light emitted by the plasma within the thruster. By analyzing the emission spectra, researchers can determine the composition, temperature, and density of the plasma. OES helps identify the presence of unstable ionization processes or abnormal plasma behavior that may lead to breakdown.

Langmuir probe is typical diagnosis tool for low pressure plasma with small electrodes inserted into the plasma in discharge chamber to measure the local electron density, electron temperature, and plasma potential [101]. These measurements provide valuable information about the plasma characteristics and can help identify regions of instability or abnormal behavior. Langmuir probes are particularly useful in diagnosing instabilities related to ionization and sheath formation.

Time resolved imaging technique involves capturing high-speed images or videos of the plasma discharge [102], [103]. This allows researchers to observe the temporal evolution of the plasma and identify transient phenomena associated with breakdown. High-speed cameras or intensified CCD cameras are commonly used for this purpose.

Electric field probe is used to measure the electric field distribution within plasma [104]. By mapping the electric field, researchers can identify regions of high field strength or field distortions that may contribute to breakdown. Electric field probes are crucial for studying grid-related breakdown phenomena.

In low pressure, PIC simulation is more suitable than fluid model to simulate the behavior of charged particles [7], [105], [106]. These simulations provide a detailed understanding of the plasma dynamics, including particle trajectories, collisions, and interactions with electric fields. PIC simulations help researchers analyze breakdown mechanisms and optimize thruster designs.

VII. CONCLUSION AND OUTLOOKS

This paper has presented a comprehensive overview of the causes, impacts, and control strategies of electric breakdown in ion electric propulsion systems. The sources of electric breakdown have been identified as stemming from environmental factors, manufacturing processes, and operational conditions. The study shows that electric breakdown is less frequent in space applications compared to ground testing, largely due to differences in environmental gases and particles. Additionally, manufacturing processes such as grid surface processing have been found to impact the frequency of electric breakdown.

The effects of electric breakdown on ion thrusters include damage to the grid surface, disruption of the normal operation of the propulsion system, and potential failure of spacecraft missions. The performance of the spacecraft is also impacted by the type of grounding method and position of the ion electric propulsion system.

To reduce the probability of electric breakdown and protect the propulsion system, proper selection of grid materials, electric field strength, and operation conditions are essential. The insulation and breakdown resistance design of ion thrusters and PPU should be optimized, and real-time monitoring of electric breakdown should be employed to minimize its occurrence. The diagnosis methods are also introduced.

The development direction of ion thruster is primarily focused on addressing the breakdown problems and finding solutions to improve their overall performance and reliability: One of the main directions is to developing advanced control algorithms and feedback systems to mitigate these instabilities and ensure stable operation. It can reduce the ionization instability and avoid the fluctuations in thrust and efficiency. The type of grounding method and position of the ion electric propulsion system are important for reducing breakdown problem, which has been discussed in this paper; For a certain amount of breakdown issue is caused by cathode sputtering, to address this problem, it is possible to explore new materials for the cathode that are more resistant to sputtering and developing techniques to enhance its durability; Ion thrusters use grids to accelerate and control the ion beam. However, these grids can experience breakdown due to high voltages and ion bombardment. To overcome this challenge, new grid designs and materials can be explored to improve their electrical insulation and reduce breakdown occurrences; Furthermore, the development of advanced diagnostic techniques is crucial for identifying and understanding breakdown phenomena. These techniques help researchers gain insights into the underlying mechanisms causing breakdown and enable them to develop effective solutions, such as OES, Langmuir probe, electric field probe, and PIC simulation, etc. Through a combination of experimental measurements and computational simulations, researchers can continuously improve the performance, reliability, and lifetime of ion thrusters.

Despite the complex of the field of ion thruster electric breakdown, this review provides a comprehensive understanding of electric breakdown causes, impacts, and control strategies, and can guide the development of more reliable and effective ion electric propulsion systems. Hopefully, this paper provides a foundation for other researchers to investigate this field further.

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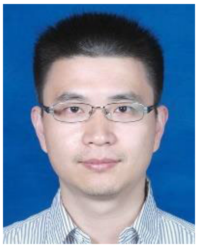

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