HIGH CURRENT VACUUM GAP DEVICES WITH SLOTTED ELECTRODE VANES

Filed May 19, 1967



Fig. 1.

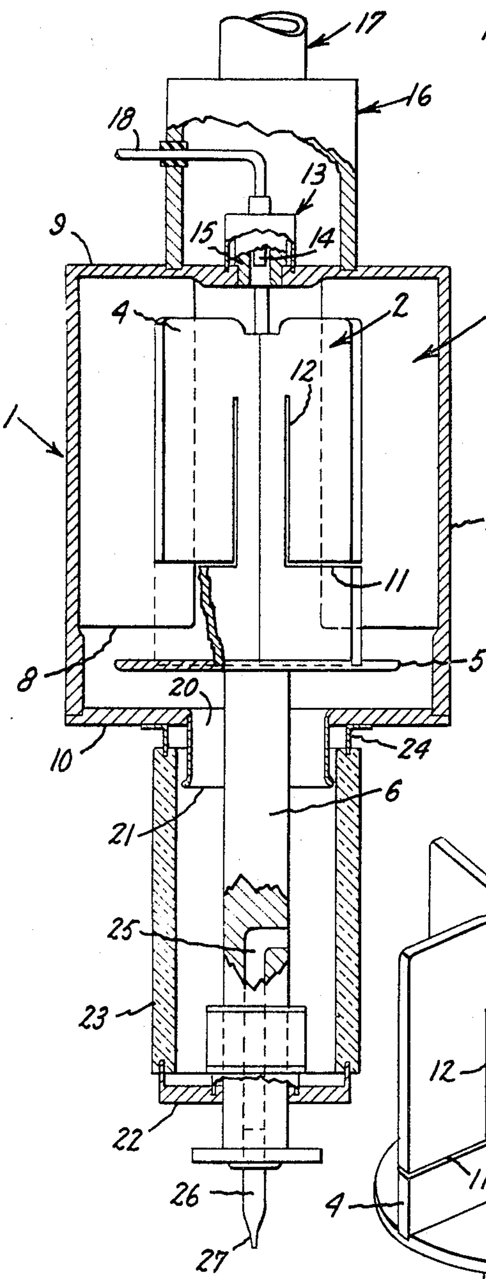



Fig. 3.

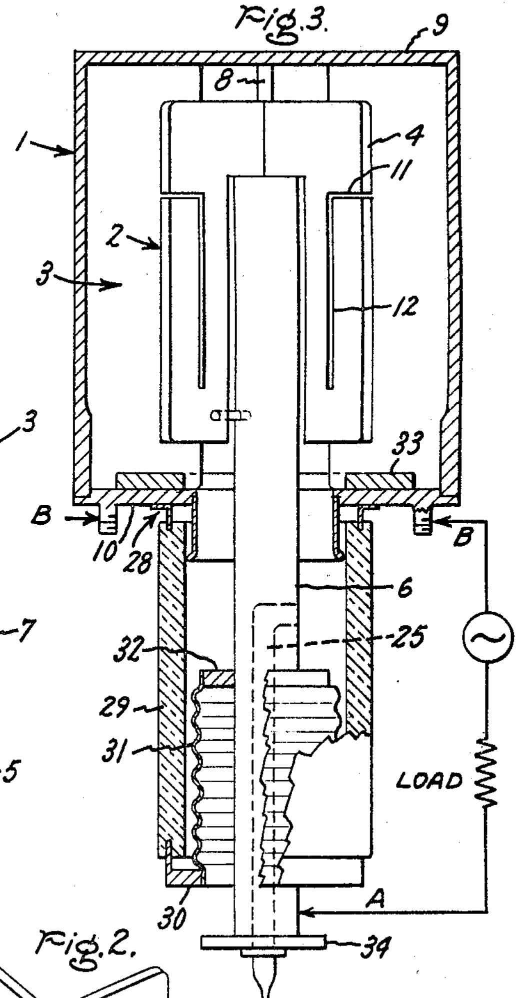
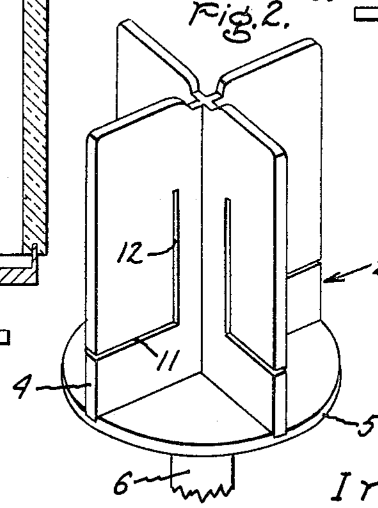



Fig. 2.

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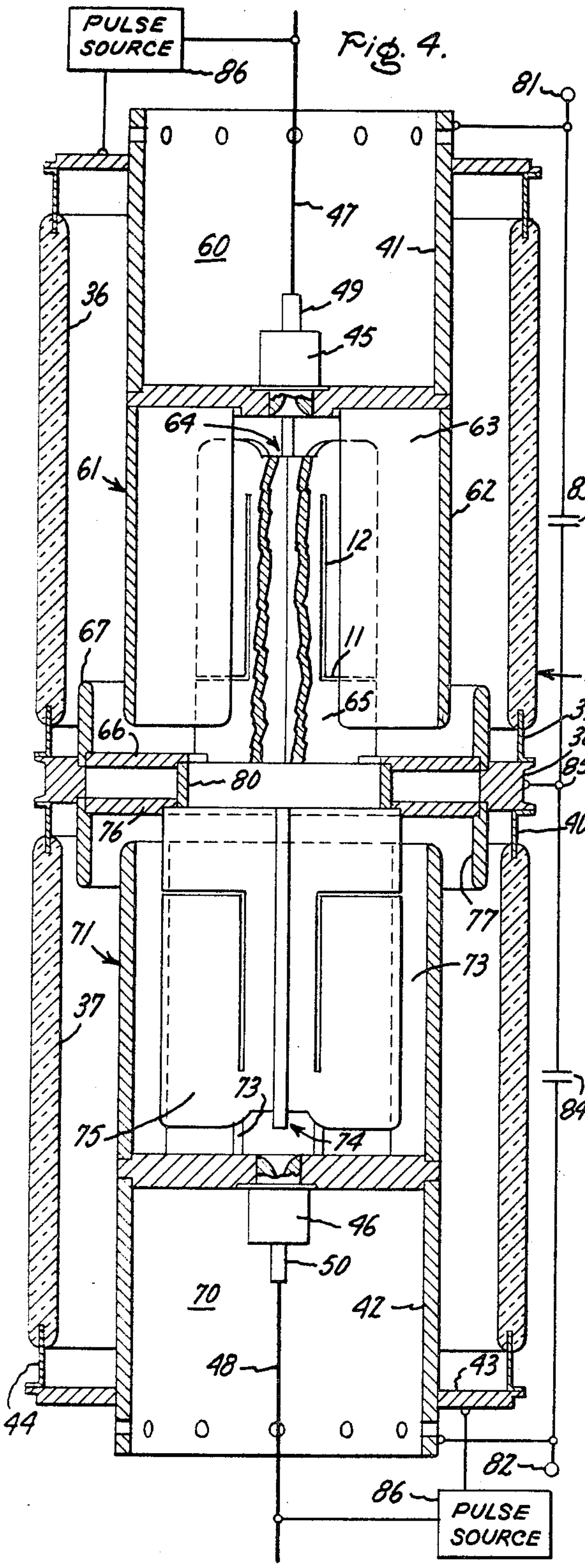


Fig. 4.

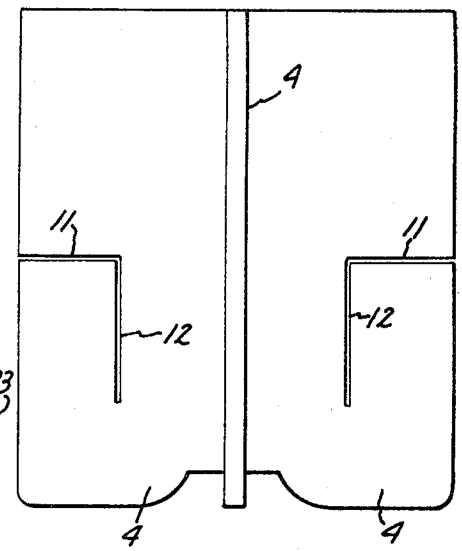


Fig. 5.

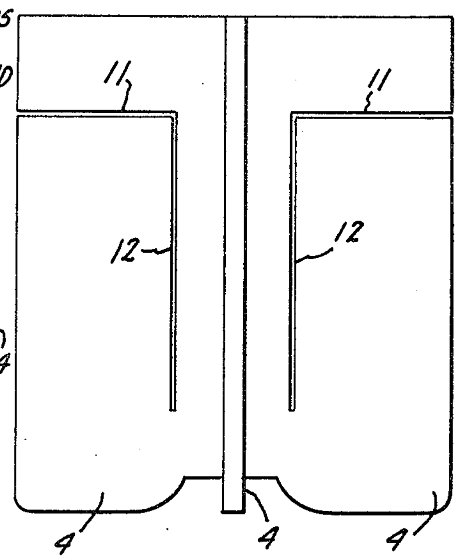


Fig. 6.

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Fig. 7.

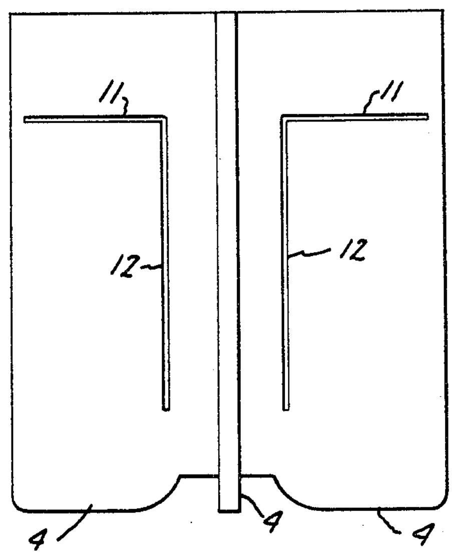



Fig. 9.

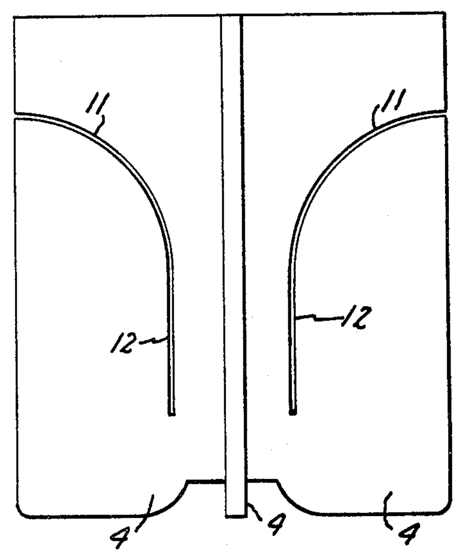



Fig. 8.

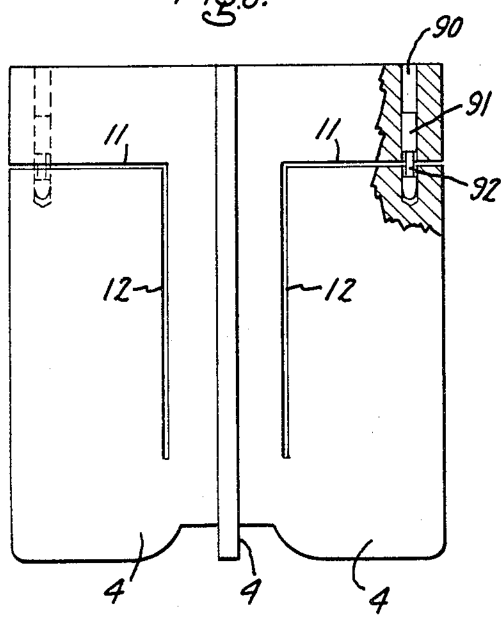
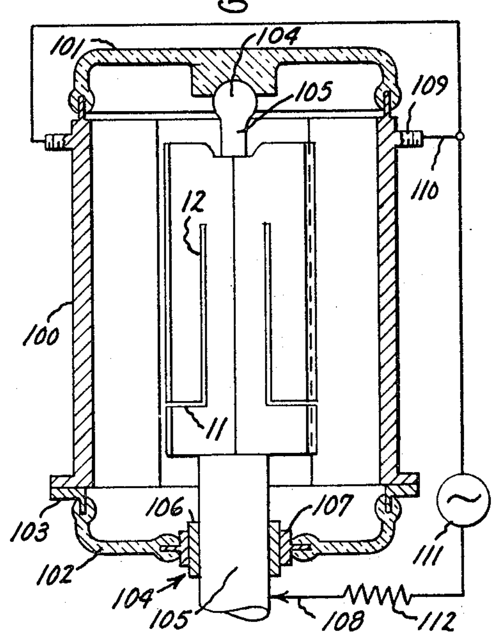



Fig. 10.

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United States Patent Office

3,432,713
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3,432,713

# HIGH CURRENT VACUUM GAP DEVICES WITH SLOTTED ELECTRODE VANES

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Continuation-in-part of application Ser. No. 586,751, Oct. 14, 1966. This application May 19, 1967, Ser. No. 639,844
U.S. Cl. 313—231 12 Claims
Int. Cl. H01j *17/26, 61/28*

## ABSTRACT OF THE DISCLOSURE

Vacuum gap devices adapted for very high current usage include a first inner electrode having outwardly disposed thin vanes and a second outer electrode having inwardly disposed thin vanes. Vanes of inner electrode are slotted to define a "folded-back" path of current conduction therein. Folded-back current path causes flux lines caused thereby to move arcing paths within interelectrode gaps to large mating vane area and permit high currents to pass between electrodes without high current density at any given point, thus avoiding anode spot formation.

This application is a continuation-in-part of my copending application Ser. No. 586,751, filed Oct. 14, 1966, now Patent No. 3,356,894 which is a continuation-in-part of my copending application Ser. No. 535,948, filed Mar. 21, 1966, now Patent No. 3,356,893, both of which are assigned to the assignee of the present invention, the complete specifications of both of which are incorporated herein by reference thereto.

The present invention relates to improved high power, high current vacuum gap devices, particularly those of the triggered vacuum gap and vacuum switch types, suitable for the attainment of very high power and current ratings without the development of anode spots and the attendant destructive erosion thereof.

Vacuum gap devices, in particlar vacuum switches and fixed vacuum gaps of the triggered vacuum gap type, have recently been the subject of intense technological and commercial interest. After nearly 40 years of developmental evolution, commercial vacuum switches at high power ratings are presently being manufactured. Similarly, since the advent of the triggered vacuum gap disclosed and claimed in my U.S. Patent No. 3,087,092, issued Apr. 29, 1963, and entitled "Gas Generating Switching Tube," gaps of this type which avoid the previously existing problems of instabilities and nonuniform breakdown voltages have been adapted for a number of commercial applications. Both vacuum switches and triggered vacuum gaps are often limited in their ability to operate at high power levels and, particularly, to carry currents of the hundreds of thousands of ampere range for more than one half cycle, by the inability of conventional anodes to withstand destructive melting caused by the formation of intense anode spots which are the anode footpoints of individual electric arcs existing between cathode and anode. In gaps with closely spaced electrodes, the destructive melting also occurs at the cathode electrode, because of intense radiation and heating from the anode spots.

In my copending applications, Ser. No. 535,948, and 586,751, I disclose a novel arrangement of arc-electrodes for vacuum gap and vacuum switch devices wherein the primary arc-electrodes include a first primary, central arc-electrode having a plurality of thin outwardly-depending vanes which are interleaved with the inwardly-depending vanes of a second primary, outer arc-electrode which is generally disposed outwardly of said first electrode surrounding the same. By virtue of this arrangement, a plurality of arcing paths is provided and a high current capacity is attained without the attainment of a high current density at any given spot.



Although the devices claimed in the aforementioned copending applications are very greatly improved in current carrying capacity under most circumstances, I have found that under certain circumstances, at extremely high currents, the arcs may tend to concentrate at a particular portion of each arc-electrode pair and, although a plurality of arcing paths are provided, a plurality of anode spots may be formed which may tend to limit the operating current of the devices under such circumstances.

Accordingly, it is an object of the present invention to provide improved vacuum gap devices by provision of a unique adaptation of the thin-vane, interleaved arc-electrode configuration which avoids the formation of anode spots altogether.

A further object of the present invention is to provide vacuum gap devices, including vacuum switches and fixed gap devices which are adapted to operate at high current and power levels for long duty cycles without the formation of anode spots and thereby exhibit long-lifetime characteristics.

A further object of the present invention is to provide improved triggerable vacuum gap devices suitable for operation at higher currents and higher voltage levels than heretofore obtainable, without the incidence of anode spots.

Yet another obejct of the present invention is to provide improved high current, high power vacuum switches which may be utilized for a greater number of circuit interruptions than heretofore obtainable without the occurrence of anode spots therein and the ultimate destruction of the electrodes thereof.

In accord with one feature of the present invention, I provide a vacuum gap device including, as essential elements thereof, a pair of primary electrodes which may define therebetween a plurality of parallel vacuum gaps. More specifically, in accord with the present invention the electrodes of the primary gap are interleaved between one another and contained within an evacuable envelope which, during arcing is substantially filled with an electron-ion plasma, which provides an infinite number of current carrying paths, none of which has sufficient current density to cause destructive melting of either anode or cathode electrodes and, specifically, of the anode electrode. In the embodiment of the invention one primary electrode constitutes a plurality of outwardly depending radial fins attached at the center thereof to a centerpost and the other primary arc-electrode comprises a plurality of inwardly depending radial fins interleaved between the outwardly depending radial fins and connected to the outward edges thereof together so as to form an electrically unitary electrode structure.

In all embodiments of the present invention, improved current carrying characteristics are obtained and anode spot formation is completely eliminated by providing, in either the outwardly depending vanes of the inner primary arc-electrodes, or the inwardly-depending vanes of the outer arc-electrode, a pattern of slots which separate adjacent portions of each vane so as to provide a "folded-back" path of current therein under current carrying conditions. The folded-back current path causes flux lines resulting from the current existing within each vane to interact with electric current flow in the interelectrode gap to spread the paths of current flow over a large electrode surface and inhibit any tendency of the current carrying paths therebetween to bunch up at any given spot to cause a high current density and a resultant anode spot.

In one general class of embodiments of my invention the electrode structure, as described hereinbefore, is permanently juxtaposed so as to define a plurality of fixed gaps and current is initiated between the two primary electrode structures by the pulsing of a trigger apparatus associated therewith to cause the injection into the primary gap of a charged electron-ion plasma to cause the breakdown thereof.

In accord with yet another general class of devices constructed in accord with the present invention, the electrode structure, as described hereinbefore, has one movable with respect to the other so that the central electrode apparatus, for example, may be moved with respect to the outer electrode apparatus, either by a longitudinal motion or by rotation thereof. In this case, plasma to form a conduction path between the primary arc-electrode is produced by the arc struck upon circuit interrupting and the vaporizing and ionization of electrode material. The initial arc is struck upon a separation of the two electrode apparatus and the arc rapidly diffuses over the many parallel surfaces of the electrode structures so that the evacuated volume containing the electrode is rapidly filled with an electron-ion plasma which conducts high currents at high power levels until the occurrence of a current zero, at which time the discharge is extinguished.

The novel features believed characteristic of the present invention are set forth in the appended claims. The invention itself, however, together with further objects and advantages thereof may be more readily understood by reference to the appended drawing in which:

FIGURE 1 is a vertical cross sectional view with parts broken away of a fixed gap triggerable vacuum device constructed in accord with the present invention,

FIGURE 2 is a perspective view of the inner electrode assembly of the device of FIGURE 1,

FIGURE 3 is a vertical cross sectional view with parts broken away of a variable gap vacuum switch constructed in accord with another embodiment of the present invention,

FIGURE 4 is a vertical cross sectional view, with parts broken away, of yet another device constructed in accord with a further embodiment of the present invention,

FIGURES 5, 6, 7, 8, and 9 represent alternative structures to the lower central electrode assembly of the device illustrated in FIGURE 2 of the drawing, and

FIGURE 10 is a vertical cross sectional view, with parts broken away, of a device constructed in still another alternative embodiment of the present invention.

A triggered vacuum gap constructed in accord with one embodiment of the invention and illustrated in FIGURE 1 of the drawing comprises an evacuable envelope **1** containing therein a pair of primary electrode assemblies including a central electrode assembly **2** and an outer electrode assembly **3**. Central electrode assembly **2**, comprises a plurality of outwardly-depending radial vanes **4**, each of which is thin, having a small thickness dimension as compared with its length and width dimensions, and is substantially perpendicular to a transverse plane, and which are fastened at the lowest ends to a plate or disc **5** which is connected to and supported upon an electrode support member **6**.

Electrode assembly **2** is also illustrated in FIGURE 2 of the drawing in perspective, showing the inter-relationship of vanes **4**, plate **5**, and support member **6**.

Returning to FIGURE 1, outer electrode assembly **3** comprises a hollow, cylindrical member **7** and a plurality of inwardly depending radial vanes **8** physically and electrically connected thereto. Vanes **8** are also thin, having a small thickness dimension as compared with their length and width dimensions and substantially perpendicular to the same traverse plane. Electrode assemblies **2** and **3** are juxtaposed so that the individual, inwardly-depending vanes **8** and the individual, outwardly-depending vanes **4** define a plurality of electrically parallel breakdown gaps therebetween. Each of the electrically parallel gaps is substantially of equal dimension to the others. Vanes **8** of arc-electrode assembly **3** extend for substantially the entire length of the discharge space within envelope **1**. The vanes **4** of arc-electrode assembly



**2** are somewhat shorter as is consistent with the necessity of maintaining the space between arc-electrodes **2** and apertured end wall members **9** and **10** of such length to prevent a spurious arcing, since members **9** and **10** are of the same electrical potential as arc-electrode **3**. As a practical matter, however, vanes **4** are at least one-half of the length of vanes **8**. The thinness of vanes **4** and **8** is such that essentially no appreciable increase in electrical resistivity is incurred, but due to the thinness, a large number of parallel primary breakdown gaps, none of which is overloaded by extreme current densities, may be formed in a relatively small volume.

In further accord with the invention, each of vanes **4** of arc-electrode assembly **2** is slotted, horizontally at slot **11** at a distance that is at least approximately two-thirds of the length of the vanes **4** from the end thereof at which breakdown first occurs. Vertical slot **12** intersects horizontal slot **11** and is located at a region at least approximately two-thirds of the width of vane **4** to the center post. The function of slots **11** and **12** in vane **4** of arc-electrode assembly **2** is to provide a folded-back path for current flow within vane **4**. Thus, for example, any path of current conduction from vanes **8** of electrode assembly **3** to a portion of vane **4** of arc-electrode assembly **4** causes a current path which passes upwardly over the upper tip of slot **12** and downwardly along the center post causing a folded-back current conduction path. This folded-back current conduction path causes the flux lines of the magnetic field caused thereby to reinforce the magnetic field caused by current paths within the external arc-electrode **3**, to force the paths of current conduction radially outwardly from the point of initial breakdown adjacent the source of electron-ion plasma injected into the interelectrode space and upwardly along the large areas of vanes **4** and **8**. This precludes the "bunching up" of conduction paths at the corner of thin vanes **4** of arc-electrode **2** and the establishment of high density anode spots thereat, which can cause erosion, damage and subsequent failure of the device **1**.

Envelope **1** of the device of FIGURE 1 contains a metallic, substantially cylindrical sidewall member **7** and a pair of oppositely disposed end caps **9** and **10**, respectively. Both sidewall and end wall members are composed of a suitable conductive material, as for example high purity cooper, or the equivalent. The cylindrical sidewall member may be the cylindrical portion **7** of exterior electrode assembly, as illustrated, or, alternatively the electrode assembly may be firmly mechanically and electrically connected to the interior thereof. The aperture in upper end wall member **9** is hermetically closed with a suitable trigger electrode assembly **13** having a trigger anode **14**, a trigger cathode **15**, and a trigger gap therein (not shown) for supplying a pulse of gaseous ion-electron plasma or vaporized and ionized electrode material to cause breakdown between primary electrode assemblies **2** and **3** upon the initiation of a suitable electrical signal to trigger electrode assembly **13**. Electrode assembly **13** is suitably brazed to end plate **9**. Suitable trigger electrode assemblies are illustrated, disclosed and claimed in my aforementioned U.S. Patent and in my copending applications, Ser. No. 516,914, Ser. No. 516,942; and Ser. No. 516,943, all filed Dec. 28, 1965 and assigned to the assignee of the present invention.

The trigger electrode assembly **13** is surrounded by a conductive cylindrical member **16** which is brazed to end plate **9** and which may be an intermediate electrical connection therebetween and electrical terminal conductor **17**. An insulated trigger electrode lead **18** passes through cylinder **16** to allow for connection of trigger electrode assembly **13** to a suitable source of pulsed voltage (not shown).

Central electrode support rod **6** passes down through aperture **20** in end wall member **10**, through a ferruled breakdown shield **21** and is supported by a closure disc **22** which is hermetically sealed to a ceramic insulator bushing **23**, which in turn is hermetically sealed to end closure **10** by means of a suitable annular chrome-iron or equivalent alloy sealing flange **24**. A central tubulation **25** in support rod **6** permits the evacuation of envelope **1** and is sealed into an exterior tubulation **26** which extends through the end of support rod **6** and is pinched off at **27** to complete the evacuation and sealing of envelope **1**.

FIGURE 3 of the drawing illustrates in vertical cross section with parts broken away, another embodiment of the invention. In FIG. 3, which has many similar structural features common to the embodiment of FIGURE 1, like numerals are utilized to identify like members. In FIGURE 3, an evacuable envelope **1** comprises a general cylindrical metallic sidewall member and a pair of upper and lower end wall members **9** and **10**, respectively. The aperture in end plate **10** is closed by an hermetic seal between an annular sealing flange member **28** of a suitable Fe-Ni-Co alloy, or equivalent, and a ceramic insulating bushing **29**. Ceramic insulating bushing **29** is closed by an annular apertured end plate **30** which is hermetically sealed by ceramic-to-metal sealing techniques thereto and welded, brazed, or otherwise suitably fastened to a longitudinally flexible bellows **31** which is capped by an annular end piece **32** which is sealed around and, by an hermetic seal, sealed to electrode support member **6** to complete a vacuum-tight envelope. Within the envelope of FIGURE 3, a first central primary electrode assembly **2** comprising a plurality of slotted outwardly-depending, radial vanes **4** is interdigitated between the inwardly-depending radial vanes **8** of an outer electrode assembly **3** which is substantially the same as that illustrated in the embodiment of FIGURE 1 of the drawing and which is electrically and mechanically a portion of the outer electrode assembly **3**. Vanes **4** and **8** are thin, as described hereinbefore, define a plurality of electrically-parallel gaps and are substantially perpendicular to the same transverse plane. As mentioned hereinbefore, vanes **4** are slotted with horizontal and vertical slots **11** and **12**, as in the embodiment of FIGURE 1 and illustrated more particularly in FIGURE 2 of the drawing, in order to cause current conduction therethrough to be folded-back to cause the interaction of the magnetic fields with the conduction current paths to force conduction current paths outwardly from the center of envelope **1**, downwardly along the surface of vanes **4** and **8** in order to prevent the concentration of conduction paths at any given point, primarily the corner of vanes **4** by electromagnetic bunching and the establishment of a destructive anode spot upon the periphery of vane **4** to cause erosion and melting thereof. Additionally, due to the method of initiating herein, vanes **4** are attached to support member **6** only at the upper portion thereof to provide a doubly folded-back current path.

A metallic contact ring **33** rests in electrical and mechanical contact with the inner surface of the lower metallic end plate **10**, and is also, electrically, a portion of electrode assembly **3**.

As in the embodiment of FIGURE 1, the device of FIGURE 3 may be evacuated to a central tubulation in electrode support member **6** which terminates in a tubulation which, after evacuation, is sealed to vacuum by a pinch. The device of FIGURE 3 constitutes a vacuum switch or circuit interrupter. In operation, the two primary electrode assemblies **2** and **3** are brought into electrical circuit-making position by a downward thrust upon annular flange **34** surrounding the lower end of electrode support member **6** or an equivalent force supplied by means not illustrated. At the end of the downward stroke, the lower end edges of the outwardly depending radial vanes **4** of central electrode apparatus **2** impinge upon, and make electrical contact with, annular contact ring **33**. While any number of contact vanes may be used, contact at all points between vanes **4** and ring **33** is facilitated if only three vanes extend from the central post. A circuit to be switched is connected through the switch in series circuit relationship therewith by making one device terminal to the lower end of electrode support member **6**, as represented by arrow A. The other terminal may be made at suitable connecting studs attached to the outward portion of lower end plate **10**, contact studs being represented by arrows B. Between these terminals, a source of alternating voltage may be connected in series circuit relationship with an electric load to be switched.



To interrupt the flow of current through the switch, the electrode support member **6** is moved longitudinally upward, as permitted by bellows **31**, separating the lower portions of vanes **4** of electrode assembly **2** from the upper surface of contact ring **33**. A plurality of arcs are thereby struck between each of the vanes and the contact ring. Since the path of current through support member **6**, electrode assembly **2**, the arc, contact ring **33**, lower end plate **10**, and a plurality of peripheral terminal lugs at B constitutes a loop, magnetic forces cause a concentration of flux at the center of the loop which urges the arc upwardly between the vanes of the inwardly depending outer electrode assembly and the outwardly depending, inward electrode assembly, thus tending to render the entire surface of the vanes available as contact surfaces on the electric arc. To reinforce this force tending to cause the entire surface of vanes **4** and **8** of arc-electrode assemblies **2** and **3** to be active arcing surfaces in operation, slots **11** and **12** cause the path of current within vanes **4** of arc-electrode assembly **2** to be folded-back upon itself. This causes a further reinforcement of the magnetic field to act in conjunction with the current paths across the interelectrode gap, to cause any tendency of the current paths to bunch at the corners of the vanes **4** of arc-electrode **2** to eliminated and forces the conduction paths upwardly along the entire surface of vanes **4** of arc-electrode assembly **2**.

The location of electrical terminals for current connection as shown in FIGURE 3 is extremely important. While it has long been recognized that dispersal of high current carrying arcs into a plurality of segments, both in series and parallel, is desired in arcing devices, the achievement of such dispersal has not heretofore been effectively obtained. Any system in which the initial arc is struck between one pair of electrodes and transferred to another pair is difficult to achieve because the arc always seeks the lowest energy position. Herein, magnetic forces generated by the arc itself are utilized in a novel fashion to force the arc into the space between the interleaved radial vanes and, by virtue of slots **11** and **12**, to force the conduction paths between the vanes of the two arc-electrode assemblies to spread upwardly along the entire surface of vanes **4** and **8**. If, on the other hand, terminals were placed longitudinally along the axis of the device of FIGURE 1 and attempts were made to utilize the vanes, the balanced magnetic fields established by the initial arcs struck between vanes **4** and ring **33** would prevent the original arc or arcs from ever being transferred by magnetic or other propulsion uniformly over the area of the gaps between vanes **4** and **8**.

Similarly, if slots **11** and **12** were not cut in vanes **4** of inner electrode assembly **2**, the outwardly disposed force acting upon the current conduction paths would tend only to move the arc paths outwardly to the corner edges of vanes **4** of arc-electrode assembly **2** and the arc would stay there, causing a destructive anode spot at high currents rather than migrate upwardly to cover the entire surface of vanes **4**. Once the discharge is dispersed between electrode apparatus **2** and **4**, as described above, no high current density electrode spots, particularly destructive anode spots, are formed, and the entire interior surface of the envelope within the arcing area is filled with a gaseous plasma conducting electrically between the outwardly and inwardly disposed electrode assemblies. Current continues to flow until the occurrence of a first current zero, at which time the existing arcs are extinguished and the vaporized metals, which constitute conduction carriers of the discharge evaporate to the cold walls where they condense, so that the high dielectric strength of the vacuum is returned, holding off further high, but permissible voltages.

FIGURE 4 of the drawing illustrates, in vertical cross sectional view, a multiple-stage, cascaded, triggered vacuum gap device constructed in accord with the present invention. The device of FIGURE 4 is an improvement upon the multiple stage trigger vacuum gap device disclosed and claimed in my aforementioned copending application, Ser. No. 586,751, filed Oct. 14, 1966 and includes an evacuable envelope indicated generally as **35**, including a pair of insulating cylindrical sidewall envelope members **36** and **37** disposed along a common axis and connected by an annular ring electrode support member **38** by a pair of annular flange ceramic-to-metal seals **39** and **40**. The ends of evacuable envelope **35** are closed by a pair of apertured cup members **41** and **42**, each of which is fastened to the respective juxtaposed cylindrical insulating body by an annular collar **43** and an annular metallic-to-ceramic sealing flange **44**. A trigger electrode assembly **45** is disposed within the aperture in cup member **41** and hermetically sealed thereto. A trigger electrode assembly **46** is disposed within the aperture in end cup **42** and hermetically sealed thereto. A trigger electrode lead wire **47** is used to supply an electrical signal to trigger electrode assembly **45** and a similar trigger electrode lead **48** supplies a signal to trigger electrode assembly **46**. Each of trigger electrode leads **47** and **48** is passed in insulating relationship through trigger electrode assembly **45** or **46** through respective insulating bushings **49** and **40**.

The members enclosed within that portion of envelope **35** generally encompassed by cylindrical insulating member **36** constitutes a first triggerable gap stage represented generally by **60** and the members enclosed within that portion of evacuable envelope **35** including the volume encompassed by cylindrical insulating member **37** constitutes a second triggerable gap assembly represented generally by **70**. First triggerable gap stage **60** includes an outer electrode assembly **61** including a cylindrical outer member **62** and a plurality of relatively thin extended area inwardly-dependent radial fins **63** which are parallel with the longitudinal axis of the device of FIGURE 4, which axis may be described as a line passing through the central portions of trigger electrode assemblies **45** and **46**, about which the cylindrical insulating members **36** and **37** are concentric. A second electrode assembly **64** within triggerable gap stage **60** includes a plurality of outwardly-depending thin, relatively large area, radial vanes **65**. Vanes **65** are disposed so as to be interposed between adjacent vanes **63** of electrode assembly **61** and are equidistant from adjacent ones thereof. The length thereof is slightly less than the length of the inwardly dependent vanes **63** of outer electrode assembly **61**. The vanes **65** are each supplied with slots **11** and **12**, as is the device of FIGURE 1, for insuring that the electric discharge paths within stage **60** are evenly dispersed over the entire surface of the vanes, as in the device of FIGURE 1. Electrode assembly **64** is mechanically and electrically connected to an annular support member **66** at the lower portions thereof, which annular support member is, in turn, electrically and mechanically connected to and supported by annular member **38**, which constitutes a portion of the evacuable envelope **35**. At the same point that annular support member **66** joins support member **38**, support member **38** also is joined by a short cylindrical annular shield member **67**, the prime purpose of which is to prevent the passage of metallic particles out from the interelectrode space so as to short-circuit the insulating cylinder **36** by causing the coating thereof with metallic particles. Although this shield member is shown as being relatively short, it may be of any desired length and configuration sufficient to shield insulator **36** and to prevent an electric field from occurring in the area where **35** and **39** join.



The construction of the second triggerable vacuum gap stage of the device of FIGURE 4 represented generally by **70** is substantially identical with that of the first stage **60** and like elements thereof are indicated by the corresponding numerals of the "70" series to those elements indicated in the "60" series in first triggerable gap stage **60** of FIGURE 4. In first stage **60** of FIGURE 4, the inwardly-depending, outer radial vanes are shown in full and the outwardly-depending, inner radial vanes are shown in partial section. In stage **70**, on the other hand, the inner outwardly-depending electrode vanes are shown in full view and the outer inwardly-depending vanes are shown in partial section. A plasma transfer tube **80**, which is a cylindrical member, is connected between the inner electrode support members **66** and **76** and is electrically connected to the inner electrode assemblies **64** and **74**. It presents an open, unimpeded path for the conduction of electron-ion plasma between the interaction spaces of stages **60** and **70** during operation.

Means are provided by contacts **81** and **82** to provide connection with an electrical load circuit to be protected, switched, or otherwise controlled by the operation of the triggerable vacuum gap device of FIGURE 4. A pair of capacitors **83** and **84** constituting a voltage divider network having a center tap at **85**, connected to electrode support member **38**, is connected between the load connectors **81** and **82**. Means for applying a triggering pulse to trigger electrode assemblies **45** and **46** are provided by a pair of separate, but simultaneously controlled, pulse sources **86** which are connected to the associated trigger electrode lead **49** or **50** and to cup members **41** and **42**.

In FIGURE 4 the preferred structural materials of the various illustrated constituents are substantially the same as the materials set forth with respect to the device of FIGURE 1. For example, members **36** and **37** are a high voltage insulator, as for example, a fosterite ceramic, Pyrex glass, or high density alumina. Electrode assemblies **61**, **64** and **71** and members **66**, **67** and **76** and **77** and **74** are made of extremely high purity, preferably zone-refined material, as for example copper having less than 1 part $10^6$ of gas, or gas-forming impurities, particularly oxygen or oxygen-containing impurities. Such material may, for example, be prepared in accord with the method set forth in U.S. Patent No. 3,234,351, issued Feb. 8, 1966 to M. H. Hebb. The other metallic members, as for example, end cap members **43** and **44** and support member **38** should be constructed of high purity metals, as for example, copper, stainless steel, or nickel which are out-gassed to preclude the presence of concentrations of gas or gas-forming materials, but need not have the extremely high purity of the electrode materials themselves. Before operation, the device is evacuated to a pressure of $10^{-5}$ mm. of mercury or less to obtain the high hold-off and rapid recovery characteristics of vacuum.

In operation, it should be assumed that the device is to be used to switch from a nonconducting to a conducing condition between a high voltage applied between terminals **81** and **82**. With the voltage supplied between terminals **81** and **82**, the voltage divider comprising capacitors **83** and **84** causes a division of the applied voltage between the two series interelectrode gaps of stages **60** and **70**. Thus, for example, approximately half the applied voltage is across the capacitor **83** and similarly, is applied across the vanes of electrode assemblies **61** and **64**. The remaining half of the applied voltage is across the capacitor **84** and, similarly, is applied across the vanes of electrode assemblies **71** and **74**.

When it is desired to fire the device and to cause the voltage between terminals **81** an **82** to be short-circuited or switched, a predetermined control causes a positive pulse of from 50 to 5,000 volts, for example, depending upon the magnitude of the voltage being held off and the dimensions of the interelectrode gaps between the primary electrode assemblies, to be applied to the trigger electrode leads **47** and **48** respectively. If the applied line voltage is a unidirectional voltage, only one of the primary arc-electrodes **61** or **71** is associated with the two trigger assemblies **45** and **46** and will be negative. A positive trigger voltage applied to the trigger associated with the negative electrode cause a trigger breakdown between that electrode assembly and the trigger anode of the associated trigger assembly. If, on the other hand, the voltage applied to terminals **81** and **82** is an alternating voltage, one of the two primary electrode assemblies **61** and **71** is more negative than the other and the associated trigger assembly, either **45** or **46**, will break down, causing the injection of an electron-ion plasma into the interelectrode space between the associated primary electrodes. Assuming the initial breakdown occurs in the interaction gap between the electrode assemblies **61** and **64**, a pulse of ion-electron plasma is injected into the interelectrode spacing between electrodes assemblies **61** and **64**, causing the establishment of a high voltage arc therebetween. Upon the establishment of the arc, the charge from capacitor **83** discharges through the connections to the respective electrodes, thus preventing the extinction of the arc and permitting the establishment of a diffuse arc over the wide area of the narrow vanes **63** and **65** of electrode assemblies **61** and **64**. Upon the establishment of the full arc across the interelectrode gap between electrode assemblies **61** and **64**, the electron-ion plasma generated thereby is propelled through arc transfer tube **80** and into the interelectrode spacing between the vanes of the electrodes of triggered gap sections **70**, namely electrode assemblies **71** and **74**. With the establishment of the arc between the electrodes **61** and **64**, substantially the entire voltage between the terminals **81** and **82** is transferred across capacitor **84**. With this high voltage applied across the electrodes **71** and **74** in the presence of the electron-ion plasma propelled thereinto from triggered vacuum gap section **60**, an arc is established between electrode assemblies **71** and **74** within a matter of less than a microsecond after the initial breakdown of gap section **60**. Upon the establishment of an arc between electrode assemblies **71** and **74**, the charge uopn capacitor **83** discharges thereacross and the current is complete from terminals **81** through the spacing between electrode assemblies **61** and **64**, then through the arc between electrode assemblies **71** and **74** and finally, out to terminal **82**, with the voltage distributed substantially evenly between the two arcs and the erosion upon any given arc-electrode being no greater than that would be if it were the only arc between the arc terminals. As is mentioned hereinbefore, the erosion upon any given arc electrode is minimized or substantially eliminated by causing the slots in the inner, outwardly-disposed arc-electrode vanes to cause a folding-back of the current conduction path with a resultant magnetic field which causes the arc currents to be diffused uniformly over the surfaces of the respective arc-electrode vanes rather than bunching together at the corners of the vanes and causing the establishment of a destructive and eroding anode footpoint thereat.

Also, in the operation of the device in accord with this embodiment of the present invention and the cascading of the plurality of arc-electrodes and triggered vacuum gap stages, one upon another, it is possible to hold off higher voltages because the ovltage held off is distributed evenly as the number of gaps is increased, all with substantially no anode spot formation and erosion.

In FIGURE 5 of the drawing, an alternative arrangement for the slotting of lower, inner, outwardly-depending arc-electrode vanes **75** of arc-assembly **74** of section **70** of the device of FIGURE 4 of the drawing is illustrated. As will be noted from a comparison of FIGURE 5 with FIGURE 6, which is a vertical cross sectional view of the arc-electrode assembly **74** illustrated in FIGURE 4 of the drawing, it may be seen that the slots **11** are herein not disposed as close to the top of the vane illustrated in FIGURE 5 as they are in the vane of arc-electrode assembly **74** of FIGURE 6, wherein the horizontal slot **11** is at least two-thirds of the distance from the bottom of the vane **75**. Although the folding-back of the current path described with respect to the devices of FIGURES 1, 3 and 4 which is accomplished by the configuration illustrated in FIGURE 6, is also achieved by the configuration illustrated in FIGURE 5, in practice, on some devices which I have tested, it turns out that some erosion does occur when the vertical slotting is as in FIGURE 5. This is because the juxtaposition of the inwardly depending vanes **8** of arc-electrode **4** of FIGURE 1 terminates substantially evenly with vertical slot **12** in FIGURE 5, so that there is a tendency for an anode spot to form at the point where vertical slot **12** is cut. Accordingly, it has been determined experimentally, in devices constructed in accord with the present invention which I have made, that the slotting should be such that the vertical slot **12** does not intersect the plane of vane **4** in a region that is closely disposed to the inward edge of inwardly disposed vane **8** of arc-electrode assembly **4**. Although in devices in accord with the invention which I have constructed, this is achieved by slotting as in FIGURE 6, it is conceivable that in some other dimensional relationships the vertical slot **12** in FIGURE 6 may, in another configuration, be the one to be avoided. It suffices to say that the vertical slot should be cut in the outwardly disposed vane so that it does not intersect the vane surface at a point that is closely disposed to the inward edge of inwardly disposed vanes **8** of arc-electrode assembly **4**.



The slotting of the vanes illustrated heretofor is entirely suitable to avoid the formation of anode spots in accord with the present invention. This is particularly so, irrespective of the material from which the arc-electrodes are fabricated. In particular, no further measures need be taken if the arc-electrodes are fabricated from an alloy that has a particularly high strength, as for example copper with minor additions of beryllium, nickel, tin or lead. It should be appreciated, however, that the same magnetic forces that cause the arcing paths to be moved around the corner of the inner, outwardly-disposed vanes, to avoid the formation of an anode spot upon the outer corner of the vane, also cause enormous forces to be exerted upon the vanes themselves. Although the aforementioned copper alloys and other high strength materials are sufficiently rigid and resilient to withstand this force, particularly if the slotting does not extend too deeply or too highly into the vane, as for example as illustrated in FIGURE 5, no deleterious effect is noted, If, however, the electrodes are fabricated of high purity copper or high purity tin or any such element which is relatively soft and is in a relatively pure state, or any alloy which is relatively soft, and if the slotting is such as to substantially weaken the mechanical strength of the vane, the mechanical forces caused by the magnetic fields, due to the folding-back of the current path through the vanes, may tend to cause the portion of the vane which is surrounded by the horizontal and vertical slots to warp outwardly, away from the main body of the vane. It is desirable that such warping be avoided if such a ductile material is utilized and the slotting is such as to substantially weaken it.

In FIGURE 7 of the drawing a central electrode assembly is illustrated which overcomes the aforementioned difficulty. In FIGURE 7, it may be noted that horizontal slot **11** does not extend to the edge of the vane **4** but, rather, extends to within approximately $\frac{1}{16}''$ thereof. In other respects, the configuration of the slots in the vane **4** of FIGURE 7 is substantially the same as that illustrated in FIGURE 6. It has been found that the main path of current utilizing the vane slot configuration illustrated in FIGURE 7 does not substantially differ from that utilizing the vane slot configuration of FIGURE 5. This is because the conduction path from the lower to the upper portion of the vane through the narrow region that is unslotted between the end of horizontal slot **11** and the edge of the vane is so small that substantially no current, as compared with the current path in the folded-back pattern, exist, so as to adversely affect the magnetic control of the current paths in accord with the present invention.

FIGURE 8 illustrates an alternative vane slot configuration to that illustrated in FIGURE 7 which accomplishes the same purpose. In cases where it has been determined that passage of current through the uncut portion of the vanes is excessive or, for fabrication purposes when it is desired that it is most expedient and economical from the manufacturing point of view to cut the slot with a device such as a band-saw, the slots are cut as in FIGURE 5 and a hole **90** is bored through the upper end of the plate **5** downwardly through vane **4** and through the slot. A small stainless steel pin **91** having a reduced area portion **92** therein is placed into the hole with the reduced area portion **92** adjacent the slot and not in contact with the vane thereat. Because stainless steel is exceedingly strong and a very poor conductor of electric currents, the illustrated stainless steel pin in FIGURE 8 of the drawing is sufficient to withstand the magnetic forces tending to move the slotted portion of the vane outwardly under magnetic stress, and yet is not such as to cause any change in the electric current path within the vane, so that the vane operates substantially as that illustrated in FIGURE 6 of the drawing, but without any distortion due to the magnetic field and its effect upon the vane. Instead of stainless steel, any poor conductor or insulator which has sufficient strength may be used.

FIGURE 9 of the drawing illustrates an alternative slotting, wherein the slot is cut in the form of a gentle curve which may be advisable from a manufacturing standpoint since a single cut with a band-saw may accomplish this fabrication. Functionally, the slot pattern illustrated in FIGURE 9 of the drawing is the substantial equivalent of that shown in FIGURES 5 and 6. Since, however, the same forces which operate on these vanes may tend to force the remote portion of the vane outwardly during arcing if the material is soft, it may be advisable to utilize the same technique in FIGURE 9 as is illustrated in FIGURE 8, drilling a hole through plate **5** into vane **4** and inserting a suitable stainless steel or other high-strength, poorly electrical conductive material to keep the vane from being distorted.

FIGURE 10 of the drawing illustrates yet another alternative embodiment of the invention. In FIGURE 10, a vacuum switch embodying the invention operates to move from a circuit-making to a circuit-breaking position in response to a rotational motion of the central electrode assembly. The envelope of the device of FIGURE 10 is composed of a substantially cylindrical, metallic side wall member **100**, an upper closed end plate **101** and a lower, dished, or upwardly flanged, apertured end plate **102**. Member **100** is composed of a highly conductive material, as for example, copper. Members **101** and **102** are composed of a suitable gas impervious insulating dielectric material as for example, an alumina ceramic. Apertured end wall member **102** is fastened hermetically to cylindrical side wall member **100** by means of an annular sealing flange **103**, preferably of a fernico alloy. A vacuum-tight sleeve bearing **104** permitting limited rotation of the central electrode assembly is connected and hermetically sealed with central electrode support rod **105** and comprises a sleeve member **106** which is hermetically sealed to ceramic end wall member **102** by means of an annular ceramic-to-metal sealing flange member **107**. Electrical contact is made to the respective primary electrode apparatus by making contacts to electrode support member **105**, as represented schematically by arrow **108**, and by making contact to cylindrical side wall member **100** at terminal lug **109**, as represented schematically by arrow **110**. An alternating current source **111** and a suitable load impedance **112** may be disposed in series or parallel circuit relationship between these points, as indicated schematically.

In operation, the device, once having been fabricated and evacuated to a pressure of less than $10^{-5}$ mm. of mercury, is caused to move from a circuit-making condition in which the electrodes are in substantial mating position to a circuit-breaking position, by a slight rotation of the central electrode apparatus. Contact is made between coupled thin contact vanes each of which is substantially perpendicular to the same transverse plane at the abutting edges thereof. To increase the area of contact, both inner and outer vanes are beveled at the ends to meet flushly with the mating vane. It is along these beveled surfaces that a plurality of parallel arcs are struck upon separation of the electrodes. As the arc current increases the discharge spreads out substantially over the entire surface of the vanes constituting the individual portions of the electrode structure. Since the arc is extinguished at the first occurring current zero, which for 60 cycle alternating current occurs at less than 8 milliseconds, the vanes do not have time to separate far enough so that the arc spreads between the back surface of a movable vane and the back surface of the next adjacent fixed vane. Hence, arcs are established in the switch only between mating vanes which are separated by the circuit breaking rotation. Arcs are not generated at the other gaps due to the simple fact that it is not mechanically feasible to bring the remaining gaps to the gap length required to strike arcs therein less than 8 milliseconds.

As in the devices illustrated in FIGURES 1 through 9, slots **11** and **12** in the outwardly projecting vanes of the inner electrode assembly cause magnetic forces to move the arcs over the entire surfaces of the respective vanes, preventing the formation of destructive anode spots.

From the foregoing it should be readily apparent that, in accord with the present invention, I provide improved vacuum gap devices, such as triggerable vacuum gap and vacuum switch devices, having a pair of arc-electrodes in which a first inner electrode has a plurality of outwardly-disposed electrode vanes and a second outer electrode with inwardly-disposed electrodes vanes which avoid the formation of anode spots. In accord with the present invention, anode spot formation is avoided by causing the vanes of the inner electrode assembly to be appropriately slotted, thus causing currents therein to be folded-back, causing magnetic flux lines to force current conduction paths to diffuse evenly over a large area of the electrode vanes. This diffusion over a large area keeps the current density to a relatively low value and prevents the current from exceeding the threshold for the formation of anode spots. Devices constructed in accord with the present invention may, therefore, carry much higher currents, without destructive erosion thereof, than such devices which do not have this improved geometry.

While the invention has been described hereinbefore with respect to certain embodiments and features thereof, many modifications and changes will readily occur to those skilled in the art. Accordingly, it is intended by the appended claims to cover all such modifications and changes as fall within the true spirit and scope of the invention. Thus for example, although throughout the description the inner electrode assembly has been described as being slotted, advantageous results may be obtained by slotting the outer electrodes, using the same criteria, instead. Alternatively, both electrode assemblies may be slotted. The important criterion is that at least one electrode assembly be slotted to cause a folding-back of current paths and a magnetic field to disperse current paths over the electrode vane area. For ease of fabrication and superior performance, however, I prefer to slot the inner electrode assembly vanes only.

What I claim as new and desire to secure by Letters Patent of the United States is:

1. A vacuum gap discharge device comprising:

(a) an hermetically sealed envelope evacuated to a pressure of $10^{-5}$ mm. of Hg or less and including a portion fabricated from a high voltage dielectric;

(b) a first primary arc-electrode assembly supported within said envelope and including a first plurality of thin substantially planar vanes projecting therefrom and being substantially perpendicular to a transverse plane through said envelope;

(c) a second primary arc-electrode assembly supported within said envelope and including a second plurality of thin substantially planar vanes projecting therefrom and being substantially perpendicular to said transverse plane through said envelope;

(d) the vanes of said first primary arc-electrode assembly and the vanes of said second primary arc-electrode assembly being interleaved alternatively between one another so as to define a plurality of electrically-parallel gaps between said first and second primary arc-electrode assemblies to cause electrical breakdown between said primary arc-electrode assemblies to occur simultaneously at a multiplicity of points whereby the formation of high current density anode spots is avoided;

(d1) the vanes of at least one of said electrode assemblies having slots cut therein from passing radially therein over a substantial portion thereof but requiring current paths from the edges of a major portion of the edges thereof to describe a folded-back path creating magnetic fields which force a diffusion of arcing currents over a large surface portion of said vanes,

(e) means for connecting said primary arc-electrode assemblies in circuit with a high power electric line; and

(f) means for producing at a preselected time a copious quantity of electron-ion plasma within said electrically-parallel gaps to establish a plurality of electrically-parallel current arcs within said envelope whereby said device carries a high power load without destructive formation of anode spots on said electrodes.

**2.** The device of claim **1** wherein said slots in the vanes are cut in said inner electrode assembly.

**3.** The device of claim **1** wherein the slots are cut in both inner and outer electrode assemblies.

**4.** The device of claim **1** wherein said slots comprise a first slot substantially perpendicular to the longitudinal axis of said device and at least approximately two-thirds of the distance from the end of said assembly at which said electron-ion plasma is first produced and a second slot which is substantially parallel with the longitudinal axis of said device and intersects said first slot.

**5.** The device of claim **1** wherein said slots comprise a first slot substantially perpendicular to the longitudinal axis of said device and a second slot substantially parallel to the longitudinal axis of said device, intersecting said first slot, and disposed at a distance of at least approximately two-thirds of the distance from the active edge thereof which is closest to said other electrode assembly.



**6.** The device of claim **1** wherein said slots comprise the slot configuration set forth in claims **4** and **5**.

**7.** The device of claim **1** wherein the device is a fixed gap device with stationary electrode assemblies and the means for supplying said plasma is a trigger electrode assembly which is operative to an external electrical pulse to inititate breakdown.

**8.** The device of claim **1** wherein the device is a vacuum switch with at least one electrode assembly movable in response to an external force to separate the vanes of said electrode assemblies, said separating of said vanes constituting means for establishing an electron-ion plasma between said arc-electrode assemblies.

**9.** The device of claim **2** wherein said slots comprise a first slot substantially perpendicular to the longitudinal axis of said device and at least approximately two-thirds the length of said vanes from the end thereof at which said plasma first appears and said second slot is substantially parallel to the axis of said device and at least approximately two-thirds the width of said vanes from the edge thereof which is closest to said outer arc-electrode assembly and intersects said first slot.

**10.** The device of claim **9** wherein said first slot does not extend entirely to the edge of said vane, but is terminated at a distance therefrom which is sufficient to leave a quantity of said vane between portions thereof on either side of said slot which is mechanically strong enough to prevent deformation of said vane due to concentrated magnetic forces but which is narrow enough so as to have negligible effect upon said folded-back current paths within said vane.

**11.** The device of claim **9** wherein said first slot extends to the edge of said vane and a bore is made through said vane passing through said slot and substantially parallel to the longitudinal axis of said device and a pin having high strength, but poor electrical conductivity is inserted therein bridging said slot and preventing deformation of said vane during operation by magnetic forces.

**12.** The device of claim **11** wherein said pin is stainless steel and said electrode is high purity copper.

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# UNITED STATES PATENT OFFICE
# CERTIFICATE OF CORRECTION

Patent No. 3,432,713 Dated March 11, 1969

Inventor(s) James M. Lafferty

It is certified that error appears in the above-identified patent and that said Letters Patent are hereby corrected as shown below:

Column 13, line 24, after "therein", insert --

-- preventing current paths therein --

SIGNED AND
SEALED
MAR 10 1970

(SEAL)
Attest:

Edward M. Fletcher, Jr.
Attesting Officer

WILLIAM E. SCHUYLER, JR.
Commissioner of Patents