MULTISTABLE SERIES CONNECTED GASEOUS DISCHARGE DEVICES

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ABSTRACT OF THE DISCLOSURE

Voltage regulator includes a series connected longitudinal stack of separate gaseous discharge devices wherein spaced members define separate compartments and are cathode of one separate device and anode of abutting separate device. Intermediate member is apertured to allow separate arcs or a single arc for entire device, thus attaining bistable voltage characteristic.

The present invention relates to gaseous electric discharge devices of the voltage-regulator type. More particularly, the invention relates to improved voltage-regulator tubes uniquely adapted for multistable operation.

Voltage regulator tubes are two-element cold-cathode gas discharge devices which are ionized to become conductive at a voltage denominated as "breakdown voltage," and sustain a glow discharge having a constant potential difference between the electrodes thereof over a substantial range of current. The present invention is directed to an improved voltage regulator tube which is stable at any of a plurality of levels, the particular level being dependent on the magnitude of the applied current. The regulator tube of the present invention is adaptable for use as a generator of a staircase waveform and may, due to the presence of a region where the voltage decreases with increasing current or negative resistance region, be used as an oscillator. Such a device may also be used as a switch or may, for example, function as a safety device to reduce the voltage drop across another circuit element to successively lower levels, should the current increase accidentally.

Accordingly, it is an object of the present invention to provide an improved multi-stable voltage regulator device.

It is another object of the present invention to provide an improved voltage regulator device for switching between various levels of stability.

In accord with the present invention, I provide a multi-stable voltage regulator comprising a plurality of interconnected monostable inert gas filled voltage regulators, each of which comprises an anode and cathode having plane parallel symmetry. The anode and cathode of each monostable unit are joined together by a ceramic member providing a thin disc-like tube. Each successive pair of monostable units includes, as a common electrode, a single disc which functions as the cathode of one unit and the anode of the next unit. Interconnection is provided by means of the common electrode and by an aperture through the common electrode. The aperture is located within the discharge region of the device, preferably in the center thereof, and provides for the combination of the independent discharges in each pair of successive units into a single discharge when the current exceeds a predetermined level.

The novel features believed characteristic of the invention are set forth in the appended claims. The invention itself, together with further objects and advantages thereof, may best be understood by reference to the following description taken in connection with the appended drawings in which:

FIGURE 1 is a cut-away perspective view, partially broken away, of a multi-stable voltage regulator device constructed in accord with the present invention;

FIGURE 2 is a graph showing the voltage-current characteristic of a bistable voltage regulator as shown in FIGURE 1; and

FIGURE 3 is a cut-away perspective view of a multi-stable voltage regulator device having three levels of stability.

In FIGURE 1, a bistable voltage regulator unit 1 is shown comprising a pair of interconnected monostable voltage regulator units 2 and 3. The units 2 and 3 are preferably of the type described and claimed in my prior U.S. Patent No. 2,887,614, issued May 19, 1959, and reference is made thereto for further description of the structure and particular advantages of these devices. The term "monostable" is used herein to indicate that the normal operation of each such unit is to regulate the voltage at one stable level. Specifically the unit 2 includes disc-shaped cathode and anode electrodes comprising respectively cathode member 4 and electrode member 5. An annular insulating member 6, hermetically sealed to electrodes 4 and 5, holds them in plane parallel spaced relation. The member 6 is provided with a counterebore 7 at one longitudinal end thereof and annular groove 8 is formed in the surface of the counterebore 7. Counterebore 7 and groove 8 form a shielded space 9 which is not in direct line with the main volume 10 of unit 2. Similarly unit 3 comprises disc 5, which form a cathode for unit 3, an anode disc 11, and an annular insulating member 12 having a counterebore 13 and groove 14 therein. An aperture 15 interconnects the interiors of units 2 and 3. The aperture must be located within the region of the device where the discharge takes place to enable operation of the device, and it is preferably centered in the discharge region to insure consistency of operation. Thus, the device 1 includes end members, comprising cathode disc 4 and anode disc 11, and an interposed electrode 5 which functions as an anode in unit 2 and as a cathode in unit 3.

The entire interior volume of unit 1 is filled with a suitable gaseous atmosphere, preferably a purified stable inert gas which may comprise helium, neon, argon, krypton, xenon or mixtures thereof. The exact gas or mixture of gases selected to fill the interior of the tube depends upon the desired regulating voltage, since the voltage change may be obtained with a gas mixture having a high proportion of a gas with a high breakdown voltage.

Thus, the device 1 includes end members, comprising cathode disc 4, disc 5 and anode disc 11 may be of any highly conductive metal, such as copper, they are preferably fabricated from titanium. Titanium is used to obtain optimum characteristics from the device because of the unique gettering characteristics thereof. The gaseous atmosphere provided is preferably a high purity inert gas in accord with my prior patent since this is necessary to maintain a substantially uniform potential difference between cathode and anode of the device or a substantially large range of operating currents thereof. If any small quantity of a chemically reactive gas other than the inert gas intended to be utilized is present within the tube, the characteristics change markedly with use. Accordingly, the voltage regulator tubes of the present invention are preferably filled with an atmosphere consisting of a stable inert gas or a mixture of stable inert gases while the device is being sealed in accord with the invention disclosed and claimed in my U.S. Patent No. 2,957,741, issued Oct. 25, 1960. This patent relates to sealing gaseous discharge devices utilizing an inert gas filling by sealing titanium members to a titanium-matching ceramic member or members while the tube is maintained in an atmosphere of the operating gas.
at a suitable pressure. When titanium is heated to the temperatures (of the order of 700° to 1200° C.) at which titanium may be bonded to titanium-matching ceramics and cooled, the metal is an excellent getter for chemically active impurities commonly present in noble gases such as CO₂, H₂, H₂O, N₂, and O₂ and the like. When the devices of the present invention are so formed, the resultant atmosphere comprises highly purified noble gases or a mixture of noble gases.

Annular insulating members 6 and 12 comprise a refractory ceramic insulating material, the coefficient of thermal expansion of which is a close match for that of titanium, and which hence may be suitably bonded at high temperatures to form hermetic seals with titanium cathode disc 4 and disc 5. Such a ceramic is a sintered agglomerate of the oxides of aluminum, magnesium and silicon denominated as Forsterite. One such Forsterite ceramic and the method of preparation thereof is disclosed and claimed in U.S. Patent No. 2,912,340, Piaus, issued Nov. 10, 1959.

An important element in devices of this type is the shape of annular insulating members 6 and 12. Since the device is extremely thin it is necessary that complete insulating member 6 be maintained throughout the life of the device between cathode 4 and anode 5. For this reason, insulating member 6 is, of course, electrically non-conductive. However, during the life of the tube metal is sputtered from the cathode onto the inner side wall of insulating member 6 forming a metallic surface. Such a metallic surface can constitute a leakage path which effectively short-circuits the tube. This is avoided, however, by counterbore 7 and annular groove 8 in insulator 6 which structure effectively forms a surface region which is not in direct contact or within the line of sight of the cathode. Accordingly, the metal which is sputtered on the walls does not form a surface path between cathode 4 and anode 5. As a result, insulator 6 is maintained throughout the life of the device. Similarly, a surface region is provided in member 12 to insulate the electrodes 5 and 11.

Coatings 16 and 17 are provided over at least a portion of the annular insulating members 6 and 12 which terminate at the lip of counterbore 7. The coatings 16 and 17 are connected to the electrodes 4 and 5 so as to define breakdown gaps, respectively, between electrodes 4 and 5 and electrodes 5 and 11. The coatings may be formed in one of the mono-stable units at a time by performing the following steps: After construction of the device as described above the mono-stable unit is subjected to a supply voltage across its electrodes, for example discs 4 and 5, which is approximately 100 volts in excess of its designated regulating voltage. Breakdown then occurs, and a load discharge fills the interior of the unit. A current is then pulsed intermittently at a value of approximately 1 ampere per square centimeter for several hours. This high current glow discharge causes a large amount of metal to be sputtered from the cathode and deposited upon the inner surface of the annular insulating member. The annular gap between the counterbore and the anode disc then constitutes the breakdown gap for the device. In accord with known techniques, the width of the gap is predetermined in accord with Paschen's law to be that distance at which breakdown occurs at the minimum of the Paschen's curve for the gas, gas pressure and cathode material utilized. A more complete discussion and illustration of this determination may be found in my aforementioned Patent No. 2,887,614.

In the operation of mono-stable devices as described in my prior patent, No. 2,887,614, a voltage is applied across the anode and counterbore until the breakdown voltage of the device, determined by the gas, pressure, cathode material and breakdown gap distance, is reached. The voltage across the device immediately decreases to the designed regulating voltage and is maintained at that level. A plurality of the devices may be arranged in series to achieve regulation of a voltage equal to the total of the designated regulating voltages of the respective devices. In this form, when the applied voltage reaches the total of the individual breakdown voltages, discharges will initiate in all of the devices and the voltage is regulated as desired.

At a low current level, the devices constructed in accord with the present invention operate in the same fashion; that is, when the applied voltage equals the sum of the individual breakdown voltages of the combined mono-stable units, discharges occur in all of the devices and the series of mono-stable units provide independent discharges. For example, in the device of FIGURE 1, if each of the units 2 and 3 break down at 270 volts and are designed to regulate at a level of 200 volts, the bi-stable device 1 begins to conduct when the applied voltage equals 540 volts and the series total of the regulating voltages 400 volts, is maintained. As the current is increased, the glow discharge expands and eventually completely covers the discharge region of each cell. As the current is increased further, the voltage across the units starts to rise slightly and eventually a point is reached where the energy loss in the two separate discharges is the same as that resulting from a single discharge through the aperture 15, even though losses due to contact of the discharge with the walls of the aperture consume some energy. When this point is reached, the two discharges combine into a single discharge between discs 4 and 11 by virtue of the ions and electrons from each discharge passing through aperture 15 in the discharge region. The potential difference across the device then falls to nearly half its former value, 200 volts in the example stated. The device maintains this level of voltage even with further increases in the applied current. The device is “bi-stable” since it regulates the voltage at either of two stable levels, depending on the applied current.

The voltage regulation curve of such a device is illustrated in FIGURE 2 wherein it can be seen that, after the initial breakdown at 540 volts, the voltage drop across the tube is regulated at a level very close to the nominal value of 400 volts until the current reaches 3 milliamperes at which time the voltage drop decreased to 200 volts where it is maintained even up to a current level of 18 milliamperes. It is noted that once the current is increased above the switching level, 3 milliamperes in the case illustrated, the single discharge continues and the voltage drop is maintained at the lower level until the discharge is terminated and re-started even though the current is reduced below the level at which switching from two discharges to one occurred. This is because the potential difference is held at a low level by the single discharge and the energy necessary to restart the separate discharges cannot be supplied.

As will be understood from the above, the factor which determines the switching current between the double and single discharge situations is the energy lost from the discharge to the walls of aperture 15. Accordingly, two parameters may be varied to suitably adjust the proportionate level of the maximum regulating voltage at which switching occurs. These parameters are the thickness of disc 5 and the diameter of aperture 15. If the aperture is small or if the disc 5 is thick, the energy lost to the walls is high and two separate discharges is the preferred situation. Therefore the current must be increased to a relatively high level before switching occurs. If, on the other hand, the aperture is wide or the disc 5 is thin, the energy loss to the walls is low and the device switches to the single discharge situation at a lower level of applied current. Thus, within the range of voltages permitted by varying the two parameters, the switching level can be regulated above or below half of this value by selecting an appropriate thickness for the disc 5 and appropriate diameter for aperture 15. In the case of the graph shown in FIGURE 2, the specific device used was a 3/4 inch tube filled with xenon to a pres-
sure of 20 mm. of Hg. The disc 5 was 0.015 inch thick and the aperture 15 was 0.030 inch in diameter.

In accordance with another embodiment of this invention, a series of mono-stable units may be assembled each successive pair being interconnected by a common electrode having an aperture, so as to provide a stepwise switching arrangement wherein the voltage is reduced to successively lower values as predetermined levels of current are reached. Such a device is illustrated in FIGURE 3 which incorporates three mono-stable units 15, 19 and 20. Like numerals in FIGURES 1 and 3 indicate like elements while the additional units of unit 19, which correspond to elements 11-15 of FIGURE 1, are indicated by the numerals 21-25. The units 18 and 19 are interconnected by common electrode 5 having an aperture 15 while units 19 and 20 are interconnected by a common electrode 21 having an aperture 25 therein.

In FIGURE 3 aperture 15 is illustrated as being slightly larger than aperture 25. Therefore, after establishment of three initial discharges whereby the voltage across the overall device is regulated at the total of the three design regulating voltages, an increase in voltage to a predetermined level causes the discharges in units 18 and 19 to combine, thus causing the voltage thereacross to approximately half its former value and decreasing the total voltage across the device to nearly two-thirds. When the current through the device is increased to a second predetermined level, the discharge in unit 20 combines with that in units 18 and 19, thus reducing the total voltage drop across the device to one-third of the original level. Thus, the device regulates voltage at predetermined levels of current, the maximum level depending on the maximum current applied after initiation of the discharges. Such a device is useful, for example, where it is desired to provide a safety device to protect against a possible surge voltages but where it is also desired to maintain as high a current level as possible. A device in accord with the present invention permits the current to remain at a high level in the event of a low voltage surge while providing adequate protection against a high voltage surge.

FIGURE 4 illustrates an embodiment wherein a plurality of units 26-29 are connected in series. Each of these units is similar to those described above, the difference lying in the fact that the electrode 31 between units 27 and 28 is not aperture. It is also noted that in the illustration, apertures 32, 33 and 34 are of different size. In operation, conduction initiates when the applied voltage equals the total of the breakdown voltages for the five units. As the current increases, the discharges in units 26 and 27 combine first since aperture 32 is largest. As the current increases, the discharges in units 28 and 29 combine and finally the single discharge in units 28 and 29 combines with that in unit 30. Thus, if the regulating voltage of each of the units is the same, for example 200 volts, the device regulates, progressively, at levels of 1000, 800, 600 and 400 volts.

In general, any number of units may be combined into a single device and varying outputs may be obtained by appropriately designing the geometry of the various apertures. For example, in FIGURE 4, two of the apertures 32 and 33 may be made identical so that four discharges combine into two at a predetermined current and the 800 volt regulation level is skipped. It is also noted that the transition current at which two discharges combine is variable either by selecting a particular geometry as described above or by applying a voltage to the aper
tured electrode to increase or reduce the loss by electron flow thereto and thus increase or reduce the current at which transition occurs. Such a voltage may be on the order of the regulating voltage or less and its polarity determines the direction of the shift. In a particular case, a trigger pulse might be supplied to reduce the transition current and switch the device to a lower level of regulation.

Finally, it is noted that the current at which devices in accord with the invention operate may be increased by increasing the area of the device. The regulating voltage of each unit may be varied by changing the gas and the electrode material used. For example, the above described devices which regulate at about 200 volts use argon as the gas and titanium as the electrode material. Providing helium as the gas used increases the regulating potential while adding barium to the electrode decreases it.

While I have shown and described several embodiments of my invention, it will be apparent to those skilled in the art that many changes and modifications may be made without departing from my invention in its broader aspects. I therefore intend the appended claims to cover all such changes and modifications as fall within the true spirit and scope of my invention.

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

1. A multi-stable voltage regulating gaseous discharge device comprising:
   (a) a disc-shaped cathode end member;
   (b) a disc-shaped anode end member;
   (c) at least two disc-shaped electrode members interposed between said cathode and anode end members; (cₐ) said interposed electrode members defining with said cathode and anode end members at least three distinct compartments,
   (cₐ) each of said interposed electrode members having an aperture therein, (cₐₐ) said apertures being of different size so that the electrical discharges in an adjacent pair of said compartments combine into a single discharge through one of said apertures at a first level of current and said single discharge combines with an independent discharge in a third of said compartments at a second level of current through said device.

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