CONTROL OF AN ARC DISCHARGE BY MEANS OF A GRID

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The problem of controlling arcs has been under investigation in the research laboratory for many years. Before describing the results of these investigations it may be well to call attention to the difference between this problem and that of controlling a pure electron discharge.

The mechanism by which a grid controls the space charge in a pure electron tube is well known. It is also well known that the grid ceases to influence the space charge as soon as there is appreciable gas ionization. The reason for this failure, however, though often pointed out, is still sufficiently new and of sufficient importance to require restatement.

Figure 1 shows graphically the condition that exists in such a tube containing mercury vapor. The space between filament and plate is filled with a mixture of electrons and positive ions, in nearly equal numbers, to which has been given the name plasma. A wire immersed in the plasma, at zero potential with respect to it, will absorb every ion and electron that strikes it. Since the electrons move about 600 times as fast as the ions, 600 times as many electrons will strike the wire as ions. If the wire is insulated it must assume such a negative potential that it repels equal numbers of electrons and ions, that is, such a potential that it repels all but 1 in 600 of the electrons headed for it.

Suppose that this wire, which we may take to be part of a grid, is made still more negative with a view to controlling the current through the tube. It will now repel all the electrons headed for it, but will receive all the positive ions that fly toward it. There will thus be a region around the wire which contains positive ions and no electrons, as shown diagrammati-
cally in figure 1. The ions are accelerated as they approach the negative wire, and there will exist a potential gradient in this sheath, as we may call it, of positive ions, such that the potential is less and less negative as we recede from the wire, and at a certain distance is equal to the potential of the plasma. This distance we define as the boundary of the sheath. Beyond this distance there is no effect due to the potential of the wire.

The same space charge equations apply to this positive-ion sheath as to electron space-charge, except that the mass of the electron is replaced by that of the ion. These equations are well known. Hence it is possible, knowing the positive-ion current, to calculate the thickness of the sheath for any given potential difference between the wire and the surrounding space. Take, for example, a wire 1 mm. in diameter and a positive-ion current density of 10 m. a. per sq. cm., which corresponds to a very weak arc discharge. The thickness is found to be 0.0035 cm. with the wire at \(-10\) volts, and only 0.02 cm. at \(-100\) volts. This sheath contains the whole potential difference between the space and the wire, so that beyond the sheath boundary there is no potential gradient due to the wire and nothing to indicate the existence of the wire. And since the thickness of the sheath is in general very small compared to the distance between wires, its only effect is to slightly decrease the cross-section available for the arc. This agrees with the experimental evidence that changing the potential of the grid has not the slightest effect on the current.
It should be pointed out that it is possible, by using closely-spaced grid wires and not too great currents, to make the positive-ion sheaths of adjacent wires touch or overlap. Under these conditions the potential of the grid does control the arc current. This kind of control, though restricted, has many interesting features, and will be reported upon at a future time.

The control to be described in this communication is of a different kind. Although it is not possible in general to stop an arc current or to modify its value by varying the grid potential, it is possible to prevent it from starting. For before current starts there are no ions. The electrostatic fields are the same as in a high vacuum tube, and the criterion for no current is the same, viz., that the grid voltage shall be more negative than a definite value. In figure 2 let the solid curve represent the current as a function of grid voltage of a high vacuum tube, for a constant plate voltage of 100. This tube is shown as having an amplification factor 10, which means that each volt of grid potential is equivalent to 10 volts plate potential, so that 10 volts negative grid potential just neutralizes the effect of 100 volts positive plate potential and reduces the plate current to zero. For all values of grid voltage more negative than 10 the electric field around the cathode is negative and no electrons escape.

The same condition must exist when there is gas in the tube, so long as the grid is maintained continuously below 10 volts. As soon as the grid potential is raised to $-9.9$ volts, however, the small electron current, which would flow in the absence of gas, now produces ions which form a sheath around the grid wires as illustrated in figure 1, and the current instantly rises to a value limited only by the emission of the filament or the circuit resistance. The characteristic of the gas-filled tube, for increasing grid voltages, is therefore that given by the broken line in figure 2. It is the characteristic of an exceedingly sensitive current or voltage relay. For example, it is possible by this means to measure the voltage of single transients of only a fraction of a volt and less than a microsecond duration.

The characteristic shown in figure 2 is not reversible. Upon decreasing the grid voltage below $-10$ the current does not fall to zero, but remains at its full value. Hence this characteristic represents only a one-way control, which is capable of turning on a current, but not turning it off. It should be noted, however, that the currents which can thus be turned
on may be very large. Hundreds and even thousands of amperes may be turned on by a fraction of a volt applied to the grid.

The next step in grid control is represented by figure 3. Although the current cannot be stopped by varying the grid voltage, it can be stopped by removing the anode voltage, or reducing it below the ionizing potential. There are many ways of accomplishing this, of which two will be discussed.

The first is to use alternating anode voltage, as shown in figure 3. The current then stops at the end of each positive half-cycle of anode voltage.

![Figure 3](image.com)

**Figure 3**
Plate current as function of grid voltage in gas tube with alternating anode voltage. If the grid voltage rises above the critical value in any cycle, plate current starts and flows for the rest of the cycle.

![Figure 4](image.com)

**Figure 4**
Alternating grid voltage 180 degrees out of phase with anode voltage. No plate current.

![Figure 5](image.com)

**Figure 5**
Phase of grid voltage advanced. Current starts just before end of cycle.

![Figure 6](image.com)

**Figure 6**
Phase of grid voltage further advanced. Current starts earlier in each cycle.

The positive ions have ample time to diffuse to the walls, so that at the beginning of the next positive half-cycle the starting process can be repeated. If the grid is constantly more negative than the critical or cutoff value during any cycle, the current will not start in that cycle, if less negative current will start. The grid potential thus determines during how many of the voltage cycles in a second current will flow, and hence controls the average current. By increasing the frequency of the alternating voltage this average may obviously be made to approximate a continuous...
current to any desired degree. In figure 3 the critical grid voltage, which is a function of anode voltage, is represented by the broken line, and the voltage applied to the grid by an arbitrary curve marked grid voltage.

**Example of control of current by phase of grid voltage. Phase is determined by rate of charging of condenser C by photoelectric current.**

**Method of stopping current with direct current power supply.** Closing switch makes plate negative for an instant, thus allowing grid to gain control.

**Example of control of current by phase of grid voltage. Phase is determined by rate of charging of condenser C by photoelectric current.**

**Time required for deionization of space around grid, as function of pressure.**

Current begins in each cycle when the applied grid voltage becomes more positive than the critical value, and the total amount of current flowing in each cycle is represented by the shaded area. The total current per second is the sum of these areas.
There is another and better method of controlling the average current when alternating plate voltage is used, which consists in allowing some current to flow in each cycle, and predetermining, by means of grid voltage, exactly how much current shall flow in each cycle. This is accomplished by using alternating grid voltage and controlling its phase with respect to the anode voltage. It is illustrated in figures 4 to 6. In figure 4 an alternating voltage is applied to the grid which is 180° out of phase with the anode voltage and of sufficient magnitude to be always greater than the critical voltage. No current flows during the cycle. If the phase of the grid voltage is advanced a few degrees, as in figure 5, current will start just before the end of each positive half-cycle, and flow for the remainder, as shown by the shaded areas. If the grid voltage is further advanced, as in figure 6, the current will start earlier in the cycle and the average current, represented by the sum of the shaded areas, will be proportionately greater.

There are many well-known ways of controlling voltage phase. A single example is shown in figure 7, in which the phase is determined by the rate of charging of the grid condenser $C$ by current through a photo cell. In this way the average current through the tube is made to increase continuously and uniformly as the illumination is increased.

When a direct current source of power is used, it is necessary to employ special means to reduce the plate voltage instantaneously to zero, or to such a value that ionization will cease, and to maintain it below this value for a time sufficient for the ions to diffuse to the electrodes. This may be accomplished by means of a condenser, as shown in figure 8. In order to make the process clear, let us assume a line voltage of 250. When the tube is carrying current the voltage at its anode, and hence at the condenser terminal, is about 15. The other condenser terminal is charged through the resistance $R_1$ to line voltage, 250. If now this terminal is grounded by the switch its voltage will fall to zero, a drop of 250 volts. The terminal connected to the plate must also suffer instantaneously the same fall, which will bring it to −235 volts, from which it will rise gradually to +250 as the condenser is charged through the resistance $R_2$. If the rate of charging is such that there is time for complete de-ionization of the space before the anode voltage reaches zero, we have the same condition as with alter-
nating anode voltage, and the grid, being now negative, will prevent re-starting of the current.

The time required for de-ionization is thus an important factor. This time depends upon the distance between electrodes, the pressure, the current density, and the voltage. Figures 9–11 show the values of this time for a typical tube. The time is directly proportional to the pressure, inversely proportional to the \( \frac{3}{2} \) power of the voltage of the grid with respect to the space, and directly proportional to the 0.7 power of the current. The semi-empirical equation, \( t = 0.0012 \frac{p^{1.7}}{E_{g}^{0.7}} \), appears to fit the observations. This equation is plotted in figure 11 as full lines, with the experimental data as points. The grid voltages in figure 11 are measured from the cathode, which is 23 volts negative with respect to the space around the grid.

Instead of using a switch to ground the condenser and produce instantaneous negative plate voltage, one may use a second tube, as shown in figure 12. The anodes of the tube are connected by a condenser, and the current to each is limited by a series resistance. Assuming tube 1 to be carrying current and 2 idle, the voltage at the anode of 1 is about 15, while that at anode 2 is the full line voltage, 250, for example. If now the grid voltage of 2 is raised above the critical value its current will start abruptly and its anode voltage will fall suddenly from 250 to 15, a fall of 235 volts. The voltage at anode 1 must suffer instantaneously a similar fall, since the two are tied together by a condenser which cannot instantaneously dis-

**FIGURE 11**

De-ionization time as function of current. Solid lines represent empirical equation.
charge. This brings the voltage of anode 1 to −220, which momentarily stops the current and the production of ions. If the condenser is large enough so that the ions in the space between grid and anode have time to diffuse to the walls before the anode voltage again becomes positive, the grid, now negative, can prevent the current from restarting. The current is thus shifted from tube 1 to tube 2. Similarly, by making grid 2 negative and grid 1 positive, it may be shifted back to tube 1. By impressing voltage surges, of any kind, first upon one grid and then upon the other, the current can be shifted from one tube to the other at will. The grid volt-

![Figure 12](image1)

**FIGURE 12**
Method of stopping current through tube with d. c. supply, by means of another tube.

![Figure 13](image2)

**FIGURE 13**
Method of shifting current from one tube to another. This method may be used to change direct current into alternating.

age may be impressed by a transformer, as shown in figure 12, either in the form of individual surges or continuous sine waves, or in any other manner.

It is obvious that an inductance may be used in place of resistance to limit the rate of discharge of the condenser, as shown in figure 13, provided the grid impulses are properly timed. And a secondary winding coupled to this inductance will receive alternating current.

This method of controlling the arc current through a tube has many applications. An obvious one is the transformation of direct current into alternating current, to which the circuit arrangement shown in figure 13 is directly applicable. There are many scientific problems for which it may be used, such as the timing of events and the measurement of short time intervals.