

June 8, 1948.

D. V. EDWARDS

2,443,100

ELECTRONIC DEVICE

Filed March 13, 1945

2 Sheets-Sheet 1

FIG. 1

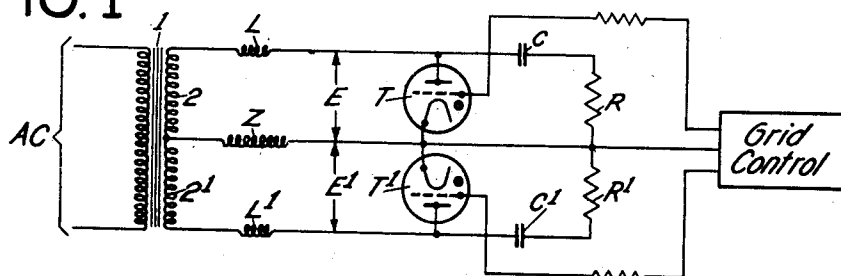


FIG. 2A

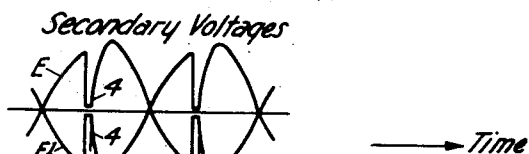


FIG. 2B

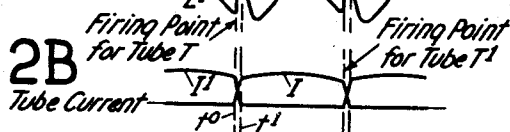


FIG. 2C

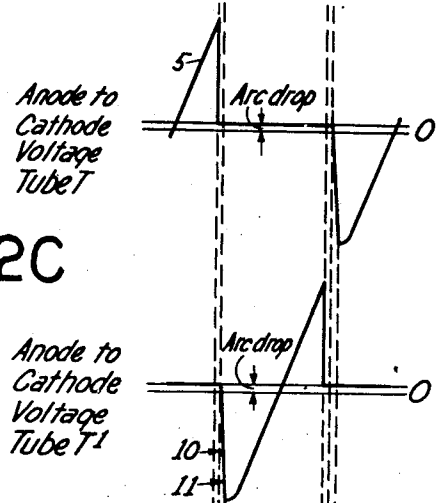
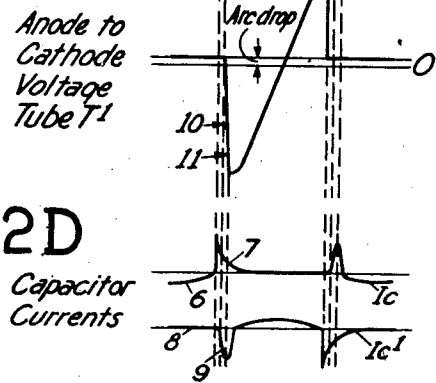


FIG. 2D



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June 8, 1948.

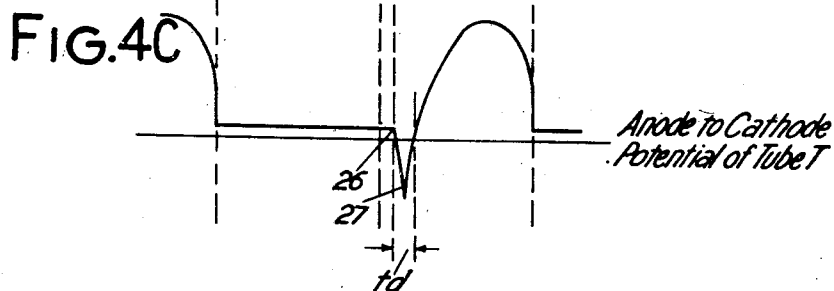
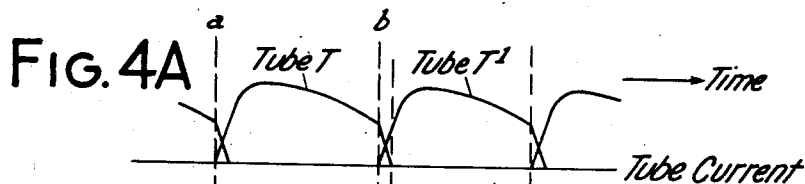
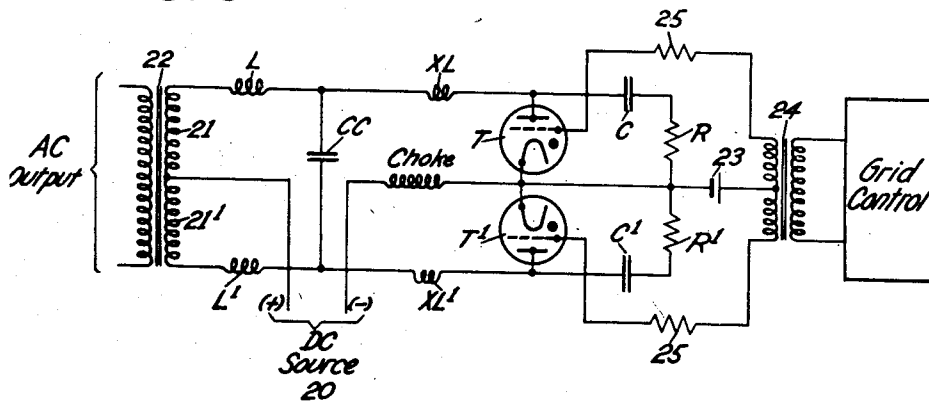
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2 Sheets-Sheet 2

FIG. 3



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2,443,100

ELECTRONIC DEVICE

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Application March 13, 1945, Serial No. 582,487

14 Claims. (Cl. 315-246)

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This invention relates to electronic devices of the gaseous discharge type, and more particularly to methods and apparatus for improving the life and performance of gas discharge rectifiers and grid-control rectifier tubes in circuit organizations where a high inverse voltage is applied immediately after conduction through the tube ceases.

Experience has shown that the life of gas discharge rectifying tubes, and more particularly tubes of the hot cathode type with an inert gas filling, is materially dependent upon the conditions under which an inverse voltage is applied, as well as the magnitude of such inverse voltage. Among other things, it is found that tube life is adversely affected by a sudden application of an excessive inverse voltage immediately after conduction ceases, such adverse effect being dependent to a large degree upon the amount of current being conducted, and the magnitude of the inverse voltage. This deleterious effect upon tube life is ordinarily manifested by a reduction in the normal gas pressure, insufficient electron emission and a definite increase in the arc drop, with the result that the tube fails much sooner than its normal life under other different operating conditions. This characteristic of gas discharge rectifying tubes is generally recognized as imposing a limitation upon their rating for certain applications and uses.

My investigations have indicated that the adverse effect of the application of a high inverse voltage to a tube immediately after conduction ceases is primarily due to the sputtering of anode material caused by the bombardment of the anode with positive ions as they are accelerated by the electric field of the inverse voltage. It is believed that such sputtering of the anode material tends to trap the molecules of the gas filling on the walls of the tube, thereby reducing the normal gas pressure; and it may be this sputtering of anode material adversely affects the electron emission of the cathode by what may be termed a poisoning action. In any event, sputtering of anode material causes in time an increase in the resistance of the arc drop, and the tube fails to conduct properly.

This injurious sputtering of the anode material may be explained on the theory that, during the time the tube is conducting current, ionized atoms of the gaseous filling of the tube are present throughout the conducting path, the density or concentration of these ions varying somewhat with the magnitude of current being conducted, but being relatively dense for all practical cur-

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rents. In the ordinary gas discharge tube, the time of natural deionization for dissipating these gas ions after conduction ceases, either by the process of diffusion, by recombination on the walls of the tube and electrodes, or by other effects, is relatively long, in the order of 1000 microseconds. This time of deionization is shortened by the electric field of an inverse voltage applied to the anode; but the sudden application of a high inverse voltage before the deionization is substantially complete has the effect of attracting the existing positive ions in the gas filling toward the now negatively charged anode, so that if there are enough positive ions present and the voltage accelerating them is high enough, there is an excessive ionic bombardment of the anode which sputters off the anode material.

In view of these considerations, the primary purpose and object of this invention is to devise a method and means for obviating this deleterious sputtering of anode material by the sudden application of a high inverse voltage to a gas discharge rectifying tube immediately after conduction ceases.

A further object of the invention is to attain this end in a simple and efficient manner so as not to interfere materially with the efficiency and performance of gas discharge rectifying tubes, and permit such tubes to be employed effectively in various circuit organizations and for various uses with a normal life expectancy and without the limitations and disadvantages heretofore encountered.

Various other objects of the invention, its characteristic features, attributes, and advantages will be in part apparent and in part pointed out as the description progresses.

Generally speaking, and without attempting to define the exact nature and scope of the present invention, it is proposed to regulate or control the rate of rise of the potential difference between the anode and cathode of a gas discharge tube when an inverse voltage is applied, in such a way as to deionize the gas filling effectively without causing injurious sputtering of anode material. More specifically, it is proposed to employ a cushioning or softening means in connection with the tube which limits the rise of potential between the anode and cathode upon the application of an inverse voltage to a degree sufficient to avoid the objectionable sputtering of anode material that would otherwise result from the direct application of inverse voltage to the tube. In one specific embodiment of the invention, this moderating or cushioning means takes the form of a capacitor

of suitable capacity and a series resistor connected directly across the anode and cathode of the tube.

The accompanying drawings illustrate in a diagrammatic and conventional manner certain specific forms of apparatus for practicing this invention, together with graphs of current and voltage for explanatory purposes, the parts and circuits being shown more with a view of facilitating an explanation and understanding of the nature of the invention, rather than to show in detail the physical embodiments that would be preferably employed in practice.

In these drawings, Fig. 1 illustrates the invention applied to a circuit organization employing full-wave grid controlled rectifiers for supplying current to a highly inductive load;

Figs. 2A to 2D inclusive, illustrate explanatory curves or graphs of certain current and voltage changes for this circuit organization of Fig. 1;

Fig. 3 illustrates the invention applied to a typical inverter of the parallel type;

Figs. 4A to 4C show current and voltage graphs relating to the parallel type inverter organization of Fig. 3.

The cushioning or softening principles of this invention may be applied to gas discharge rectifying tubes in any one of their various applications and uses where a high inverse voltage is suddenly applied immediately after conduction; but an explanation of the characteristic features and functions of the invention as applied to certain typical circuit organizations using gas discharge tubes will serve to make clear the nature and utility of the invention, and indicate how the same principles and practices may be advantageously adopted for other rectifying circuit organizations.

Fig. 1 illustrates one such typical application of the invention to a full-wave grid controlled rectifier organization used for supplying current to a highly inductive load, such as an electromagnetic device, field coils of the generator or motor, or the like. In the circuit organization of Fig. 1, which is illustrated diagrammatically and conventionally, the usual anode transformer 1 has its two secondary windings 2 and 2' connected in the usual conventional manner to the cathodes and anodes of two grid controlled gaseous discharge tubes, so as to supply current through a highly inductive load Z to the midtap of these secondary windings. The grids of the two tubes T and T' may be controlled by any suitable phase control device, or some equivalent arrangement, so that the firing point of the tubes may be regulated to provide the desired load current. The inherent leakage inductance of the anode transformer is a factor to be considered in the analysis of the circuit, and for convenience the effective leakage inductance of the two secondary windings 2 and 2' is shown schematically in Fig. 1 as equivalent lumped inductances L and L'.

The cushioning means of this invention as shown applied to the circuit organization in Fig. 1 comprises a capacitor C and a resistor R connected in series directly across the anode and cathode of the tube T, and a similar capacitor C' and resistor R' connected across the other tube T'. These capacitors and resistors may be of any one of the well known types and constructions, having of course the appropriate insulating and radiating qualities requisite for the voltages and currents involved. The factors determining the values of capacitance and resistance to be

preferably employed are more conveniently considered later after discussing their functions and operating characteristics.

As previously indicated, the deleterious sputtering of anode material adversely affecting the life of a gas discharge rectifying tube is dependent upon the magnitude of the inverse voltage suddenly applied and the amount of current being conducted just before the application of such voltage. Generally speaking, where the current conducted varies due to the change in firing point of the tubes, as in the typical application shown in Fig. 1, or due to ordinary variations in load, it is contemplated that the cushioning or softening means of this invention will be designed to satisfy the worst conditions in this regard, although it should be understood that a cushioning or softening action of a lesser degree will be effective in prolonging the life of the tube, and may be adopted, particularly where the extreme conditions of inverse voltage and current conduction are likely to exist only during a small part of the time in the actual performance of the circuit organization.

In describing the principles and functions of this invention, and the theory of operation which is believed to explain the results obtained, it becomes necessary to consider the probable occurrences under transitory conditions existing during extremely short time intervals; and since the phenomena under consideration are not readily measured, certain theoretical premises and deductions are assumed for the purpose of explaining the results. On the basis of such assumptions, Figs. 2A to 2D show graphs or curves of voltage and current changes for certain elements of the circuit organization of Fig. 1; but it should be understood that these curves are presented for explanatory purposes, and are not intended to illustrate the quantitative relations existing in practice. More particularly, the time dimensions for certain changes as illustrated in these graphs of Figs. 2A to 2D have been greatly distorted in order that changes occurring in microseconds may be shown.

In describing the functions and purposes of the invention, and the theory of operation attributed to observed phenomena, it is convenient to analyze separately the transitory conditions existing during different half-cycles of the impressed voltage, the complete performance representing a repetition of such transitory conditions.

In the typical circuit organization illustrated in Fig. 1, it is assumed that the inductance Z of the load will serve to maintain current conduction through each tube until the next tube is fired, particularly where the tubes are fired near the peak of the positive half-cycle of the supply voltage as shown. After a few cycles following the closure of the circuit, the load current may be considered as assuming a steady state condition with a slight ripple; and the current curves I and I' for the tubes T and T' as shown in Fig. 2B are illustrative of the conduction currents through these tubes under such conditions.

Taking the firing of the tube T at the time indicated at t^0 as a convenient starting point for the discussion, at that instant the current being conducted by the other tube T' is decaying at a rate determined by the characteristics of the load circuit, but has a substantial magnitude, even though the phase voltage E^1 applied to this tube T' is in the reverse direction and has risen during the negative half-cycle nearly to its peak value. In this connection, it may be considered that the

decay of current through the inductance Z of the load and the leakage inductance L^1 of the secondary 2^1 of the transformer supplying voltage to the tube T^1 maintains by self-induction an anode potential for the tube T^1 sufficient to maintain ionization and conduction in spite of the reverse voltage of this transformer secondary.

Since the arc drop through the tube T^1 still conducting at the time t^0 under consideration is relatively insignificant with respect to the phase voltages contemplated, being in the order of some ten volts for the typical gas discharge tube, it can be seen that the cathode of the tube T^1 , and likewise by direct connection the cathode of the other tube T , has supplied thereto the negative potential of the phase voltage E^1 less the voltage drop across the arc of the tube T^1 and the leakage inductance L^1 of the transformer, so that at the time t^0 under consideration the voltage across the other tube T has risen to approximately the sum of the two phase voltages as indicated by the voltage curve 5 in Fig. 2C.

Considering now the conditions at the critical time t^0 when the tube T fires, the firing of this tube causes the voltage between its anode and cathode to drop quickly to the relatively insignificant value of the arc drop through this tube. At this instant, since the other tube T^1 is also conducting, and the cathodes of the two tubes are directly connected together, the anode of the other tube T^1 is at approximately the same potential. In other words, at the particular time t^0 under consideration, and for a few microseconds until the tube T^1 previously fired has stopped conducting, the anodes of the two tubes are at substantially the same potential, and the output voltage at the terminals of the secondaries of the anode transformer 1 is zero, the same as if the transformer were effectively short-circuited. This condition is represented by the abrupt changes to zero in the voltage waves indicated at 4 in Fig. 2A. In this connection, the leakage inductances L and L^1 of the transformer control rate of change in current during this very brief interval; and it may be considered that each phase voltage of the transformer is during this interval matched within it by an equal and opposite voltage across its leakage inductances.

The abrupt changes to zero in the phase voltages of the transformer just described is not particularly material to the conditions calling for the application of the principles of this invention, but this is an attribute of the organization and is mentioned here because, among other things, it is involved in the procedure later described for ascertaining the desired values for the cushioning capacitors and resistors.

The occurrences following the firing of the tube T at the time t^0 occurs so fast with respect to variations of the supply voltage that, although the explanatory graphs in Figs. 2A to 2D suggest that there is time for a change in such supply voltage, it may be considered that the supply voltage is constant during the time interval of commutation under consideration.

Still referring to the time indicated at t^0 when the tube T is fired, the firing of this tube T affords a conducting path for load current, in addition to the conducting path through the other tube T^1 ; but since the large inductance of the load tends to prevent any marked change in total current, it may be considered that as the conduction current through the tube T rises, there is an accompanying decrease in the current being conducted by the other tube T^1 , as indicated in

Fig. 2B, until after a very brief interval of commutation, in the order of some 30 microseconds, conduction through the tube T^1 previously fired has completely ceased. Current through the tube T now conducting rises under the influence of the positive half-cycle of its phase voltage E for a time, and then after this phase voltage reverses, starts to decay, as indicated by the current curve I in Fig. 2B, until the other tube T^1 is again fired, whereupon the same commutation phenomena are repeated.

As previously explained, it has been found that the life of gas discharge rectifying tubes is adversely affected by the sudden application of a high inverse voltage immediately following conduction; and considering the nature of the inverse voltage applied to the tube T^1 at the instant it stops conducting indicated as the time t^1 , it can be seen that the phase voltages E and E^1 of the anode transformer secondaries are across the tubes T and T^1 . Since the tube T is now conducting, and its arc drop is relatively small, its cathode has applied thereto a potential of approximately $+E$ volts; and since the cathode of the other tube T^1 is at the same potential due to the direct connection, the inverse voltage which is suddenly applied across the tube T^1 when this tube stops conducting at the instant indicated at t^1 , is substantially equal to $E+E^1$, or approximately twice the phase voltage of the anode transformer. Further, this high inverse voltage follows immediately within some 30 microseconds after the time when the tube T^1 is conducting approximately full load current, as indicated by the curve I^1 at the time t^0 .

Having discussed in some detail in the interests of clarity the operating conditions in the circuit organization of Fig. 1 which cause the sudden application of a high inverse voltage immediately after conduction of substantial current, consideration may now be given to the principles and practices characterizing the method and apparatus of this invention for obviating the adverse effect upon tube life which such conditions have heretofore imposed.

As previously pointed out, I have found that the life of the gas discharge rectifying tube is adversely effected under the conditions of excessive inverse voltage under consideration by reason of the sputtering of anode material by the ionic bombardment of the anode. Accordingly, the primary purpose and objective achieved by this invention is to minimize the sputtering of anode material under these conditions to a degree at least where it is no longer a factor in fixing the normal life expectancy of the tube. In other words, if the ionic bombardment of the anode can be regulated or controlled to the appropriate degree in accordance with this invention, the result will be that the tube will fail from other causes characteristic of tubes of this type, rather than due to the damaging sputtering of anode material, thereby enabling the tube to be employed in circuit organizations heretofore considered unsuitable for obtaining satisfactory tube life.

Briefly considering the theoretical considerations apparently involved in this matter of sputtering of anode material, the gas filling of a gas discharge tube is ionized during the period of conduction, and when conduction ceases, an appreciable time is required for deionization of the existing gas ions representative of the immediately preceding flow of current through the tube. Such deionization will occur in time naturally by

a recombination of positive gas ions with free electrons where they may exist at the walls of the tube or the like; but this natural period of deionization may be substantially shortened by the electric field of an inverse voltage applied to the tube. The application of such inverse voltage, however, in addition to facilitating deionization by repelling free electrons toward cathode and other effects, also acts to attract the existing positive gas ions toward the anode, which is now negatively charged by this inverse voltage. Theoretical considerations suggest that all of the gas ions existing at the time an inverse voltage is applied are not necessarily attracted to the negatively charged anode, apparently because some of the ions are so close to the walls of the tube that they are not sufficiently affected by the electric field of the inverse voltage to be carried to the anode, and because other ions become deionized for various reasons before reaching the anode. Also, it is probable that the damaging sputtering action of ionic bombardment of the anode is dependent upon the energy acquired by the positive gas ions striking the anode, which is variable dependent upon the accelerating inverse voltage, as well as the ion density and number of ions reaching the anode.

In this connection, investigations indicate for typical tube structures with gas fillings that inverse voltages in the order of 200 to 300 volts do not ordinarily cause sufficient sputtering to be a controlling factor in shortening the life of the tube, as compared with other causes of tube failure. It should be understood that these suggested values of an acceptable inverse voltage are merely illustrative, and are materially effected by the structure and capacity of the tube, nature of the gas filling, and other factors. It is found, however, that higher voltages cause an ionic bombardment for ordinary density of gas ions, which is materially damaging in the sputtering of anode material and definitely affects adversely the normal life expectancy of the tube.

On the basis of this analysis of the causes and conditions of the damaging effect of suddenly applied inverse voltages, it is proposed in accordance with this invention to regulate or control automatically the rise of the actual potential between the anode and cathode of a tube as the inverse voltage is applied thereto, dependent upon and in accordance with the rate of effective ionization of the gas filling of the tube under the existing conditions, in order that, during the process of deionization under the influence of the inverse voltage, the relative density of the positive ions, in association with the rising potential accelerating these ions, will not result in an accumulated effect of ionic bombardment of the anode in a sufficient degree to adversely affect the life of the tube.

In practicing the invention, a suitable agency or means is employed to retard, cushion or soften the rate of rise of the actual potential between the cathode and anode of the tube as the high inverse voltage is applied; and for this purpose I preferably employ a suitable capacitor and resistor in series, or equivalent electrical elements to absorb temporarily the applied inverse voltage, so to speak, and restrain the rise in the actual potential across the electrodes of the tubes to the desired rate.

Referring to the typical application of the invention shown in Fig. 1, the cushioning capacitors C and C¹ and their associated resistors R and R¹ are directly connected across the cathode and

anode of the respective tubes T and T¹, and perform the desired purpose of retarding the rise of potential across the electrodes of these tubes upon application of the inverse voltage in the manner now to be explained.

Considering the action of the softening capacitors C and C¹ more in detail, and referring to the period prior to the firing of the tube T at the time t⁰, while the anode potential for the tube T is rising to approximately the value of E+E¹ as indicated by the curve 5 in Fig. 2C, this tube T is non-conducting; and this rise in voltage results in charging the capacitor C as indicated at 6 in Fig. 2D. When the tube T fires at the time t⁰, the capacitor C discharges through the tube T in series with its resistor R, as indicated at 7 in Fig. 2D. The initial value of this discharge current is represented by the voltage of approximately E+E¹ on the capacitor C, divided by the resistance of the resistor R; and one function of the resistor R is to limit the intensity of this discharge current through the tube T when it fires, because without the resistor R such discharge current though momentary might be so large as to be injurious to the tube. The discharge current of the capacitor C dies out according to the usual exponential function determined by the time constant of the circuit afforded by the capacitor C and resistor R, so that while the tube T is firing, the capacitor C is substantially discharged.

Referring now to the critical time t⁰ when the tube T fires, the other capacitor C¹ associated with the other tube T¹ is substantially discharged, as indicated at 8 in Fig. 2D, because this other tube T has been conducting for some time and has afforded a discharge path of low resistance for its capacitor C¹. Consequently, at the critical time t¹ when conduction through the tube T¹ ceases, and the excessive inverse voltage of E+E¹ is applied thereto, its associated cushioning capacitor C¹ is in a discharged state. This capacitor C¹ and its associated resistor R¹ are directly connected to the anode and cathode of the tube T¹; and it can be readily seen that, regardless of the magnitude of the inverse voltage E+E¹, the actual potential across the anode and cathode of the tube T¹ cannot exceed the voltage drop across the capacitor C¹ and its resistor R¹. In other words, the rate of rise of potential applied to the electrodes of tube T¹ is dependent upon the growth of the charging current to the cushioning or softening capacitor C¹, because it is the growth of this current which increases the voltage drop across the resistor R¹ and accumulates a charge on the plates of the capacitor C¹ to provide the potential across these electrodes.

For these reasons, when the softening means of the invention is employed, the potential across the cathode and anode of the tube T¹ when it stops conducting at the time t¹, instead of jumping abruptly to the full inverse voltage of approximately E+E¹, as indicated by a dash vertical line at 10 in Fig. 2C, is controlled or restrained by the cushioning action of the capacitor C¹ and resistor R¹ to rise at a slower retarded rate, such as indicated by the line 11 in Fig. 2C.

It can be readily appreciated that the growth of charging current to the cushioning capacitors C and C¹ may be made as gradual as desired to provide such rate of increase in potential applied across tube elements as is necessary for normal life expectancy of the particular tube employed and circuit organization involved. In this con-

nection, the circuit path for charging the capacitor C^1 at the time t^1 when the tube T^1 stops conducting may be traced from the upper terminal of the secondary 2 of the anode transformer, leakage inductance L , through the arc drop of the tube T now conducting, resistor R^1 , capacitor C^1 and leakage inductance L^1 to the lower terminal of the other secondary 2^1 of the anode transformer. It can thus be seen that the rate of increase in the charging current for the capacitor C^1 is dependent upon the resistor R^1 , as well as the inherent leakage inductances L and L^1 of the anode transformer. Thus, the resistor R^1 , in addition to limiting the rate of discharge of capacitor C^1 when the tube T^1 fires, also performs the function of controlling the rate of charging of the capacitor C^1 , and hence the rate of potential rise between the cathode and anode of this tube T^1 .

The quantitative values of the cushioning capacitors C and C^1 and the resistors R and R^1 preferably employed in practice are dependent upon a number of factors, including the structural characteristics of the tube, and kind of gas filling, as well as the voltages and currents involved in the particular circuit organization in which the tube is used. The acceptable rate of potential rise between anode and cathode of a given tube immediately following conduction of substantially full load current may be estimated by calculation for different tubes when certain factors for the type of tube are known from observation and test; and life tests or any other desired procedure, may be employed to check the acceptable rate of potential rise between anode and cathode for a given tube structure. Generally speaking, it is found that rates less than about 10,000,000 volts per second are acceptable for the types of gas discharge tubes which I have investigated; but it should be of course understood that conditions may well exist where either higher or lower rates of rise of inverse voltages are suitable for adequate tube life.

Once the tolerable rate of inverse voltage rise has been determined for a given tube structure in some suitable manner, a desirable value of the cushioning capacitors and resistors for any given application of this tube in a circuit organization may be determined by calculation, or preferably by direct observation of the anode voltage trace with an oscilloscope. In this connection, it has been previously noted that, during the commutation period between t^0 and t^1 in Figs. 2A to 2D, the phase voltages of the anode transformer drop to zero, as indicated at 4 in Fig. 2A, and then recover. If the vertical deflection plates of an oscilloscope are connected directly across the anodes of tubes T and T^1 in the organization of Fig. 1, there can be seen on the voltage trace a similar sudden drop and recovery of the potential during the period of commutation; and if the time scale is suitably expanded by operating the sweep circuit of the oscilloscope at a frequency which is a large multiple of the supply frequency, this change in the trace of the anode voltage may be enlarged sufficiently to permit measurement, after due calibration, of the rate of rise of the anode potential relative to the cathode. In other words, by utilizing the appropriate oscilloscope technique, the actual rate of rise of the cathode to anode potential with a given value of cushioning capacitor C and resistor R may be observed, and appropriate changes made in the values of this capacitor and resistor to bring such observed rate of potential rise within the toler-

able limits prescribed for the tube in question. In this connection, as typical or representative of the general order of acceptable values of cushioning capacitors and resistors, it has been found that a capacitance of one microfarad with a resistance of 200 ohms is suitable for one type of gas discharge tube employed in the circuit organization shown in Fig. 1.

With regard to the preferred values of the resistors R and R^1 , it can be seen that the addition of a capacitor C in a circuit organization in the manner contemplated in accordance with this invention may cause the circuit to approach an oscillatory condition; and the values of the resistors R and R^1 should be chosen to avoid oscillation, which can be readily detected by watching for any over-shoot in the trace of anode voltage on an oscilloscope. In the interest of efficiency and avoiding useless losses in the resistors R and R^1 , I consider it preferable to employ a resistance for these resistors comparable with the value for critical damping; and generally speaking, it is considered preferable to use resistors R and R^1 corresponding in value to the square root of 4 times the sum of the leakage inductances L and L^1 in henries, divided by the capacitance of the capacitors C or C^1 in farads.

It should be understood that the theoretical considerations and quantitative relationships explained in the foregoing discussion of the invention are presented merely to facilitate an understanding of the nature of the invention and how to practice the invention, and that the method and apparatus of this invention are in nowise limited by this explanation, and may be practiced in various other ways in various degrees to prolong the life of gas discharge tubes in various circuit organizations, to any extent desired.

Fig. 3 illustrates the invention applied to a circuit organization for a typical parallel type inverter for converting direct current to alternating current; and Figs. 4A-4C illustrate certain curves or graphs of voltage and current relations for explanatory purposes. In the circuit organization of Fig. 3, the grids of the gas discharge tubes T and T^1 are controlled in a suitable manner so as to be fired alternately at the desired frequency to cause current from a suitable source of direct current indicated conventionally at 20 to flow alternately through the primaries 21 and 21^1 of an output transformer 22, and thereby provide an output of alternating current in the secondary of this transformer. As conventionally illustrated, the grids of the tubes T and T^1 are assumed to be biased by a suitable source 23 to prevent firing of these tubes until this bias is removed by an impulse voltage from the secondaries of a grid control transformer 24, which is governed by a suitable grid control means shown diagrammatically. The usual protective resistances 25 are preferably included in the grid circuit.

The usual commutating or control condenser CC , characteristic of this type of inverter, is shown connected across the primaries 21 , 21^1 of the output transformer 22; and to permit the cushioning means of this invention to function to the best advantage, additional inductances XL and XL^1 are preferably included in the circuit connections between this condenser CC and the anodes of the tubes T and T^1 . If desired, the commutating condenser may be connected across the secondaries of the output transformer 22; and then the leakage inductances L and L^1 of the transformer itself will function in the same

way previously described in connection with the cushioning operation, and the additional inductances XL and XL^1 may be omitted.

In applying the principles and practices of this invention to the circuit organization of Fig. 3, cushioning capacitors C and C^1 and associated resistors R and R^1 are connected directly across the cathode and anode of the respective tubes T and T^1 in the same way and for the same purpose as described in connection with Fig. 1.

Since the theories and mode of operation relating to the parallel type inverter are generally familiar to those skilled in the art, it is not necessary to discuss this operation in detail, but merely point out the conditions under which the cushioning means of this invention acts to prolong the life of the tubes. Starting with the time indicated at a in Figs. 4A-4C, when the tube T fires, this tube becomes conducting and allows current to flow from the direct current source 20 through the corresponding primary 21 of the output transformer 22, as indicated by the current curve in Fig. 4A, this current rising at a limited rate due to the leakage inductance L of the transformer and the additional inductance XL , and also decreasing from a peak value under ordinary operating conditions, primarily due to the influence of the load. The particular shape of the curve of conduction current through a tube when it fires varies with the character of the load on the output circuit and other factors, and the curves shown in Figs. 4A-4C are merely representative of the character of current flow ordinarily found with conventional loads of a non-inductive character.

When the tube T starts to conduct at the time a , the potential between its anode and cathode drops to the relatively low voltage of its arc drop, as indicated in Fig. 4C. Also, when the tube T fires, a charging current flows through the other primary 21¹ of the output transformer 22 to the commutating condenser CC , as indicated in Fig. 4B.

Considering now the critical time indicated at b in Figs. 4A-4C when the other tube T^1 fires, the commutating condenser CC performs its function of stopping conduction through the tube T previously fired by causing its anode to suddenly assume a negative potential with respect to its cathode, as indicated in the curve of Fig. 4B. In the operation of this type of parallel inverter, the condenser CC is arranged to maintain the anode of the tube T last fired at a negative potential long enough for effective deionization to permit the grid of this tube to regain control; and in many applications and under the various load conditions, the negative potential provided by the commutating condenser CC is relatively high. In other words, an inverse voltage provided by the commutating condenser CC is suddenly applied to the tube T last fired, while it is still conducting approximately full load current; and this sudden application of a high inverse voltage adversely affects the life of the tube for the same reasons previously explained.

When the cushioning means of this invention is employed, however, when the inverse voltage is applied to the tube T by the commutating condenser CC at the time b , the cushioning capacitor C associated with this tube T is substantially discharged through the relatively low resistance of the arc drop of this tube; and consequently the actual potential between the anode and cathode of the tube T , instead of rising abruptly to the full voltage provided by the control

condenser CC as indicated at 26 in Fig. 4C, is restrained by the action of the cushioning capacitor C to rise at a controlled rate, as indicated at 27 in Fig. 4C. In this connection, the additional inductance XL retards the growth of charging current to the cushioning capacitor C ; and although this cushioning capacitor C retards the rate of increase in the negative potential on the anode of the tube T , this potential is still effective to cause deionization of the tube T and permit its grid to regain control. The capacity of the cushioning capacitor C is relatively small as compared with that of the control condenser CC , and the time interval indicated as td in Fig. 4C during which the anode of the tube T is negative is not materially effected by the use of the cushioning capacitor C .

Thus, the principles of softening or cushioning the application of inverse voltage to gas discharge tubes in accordance with this invention are applicable to circuit organizations, such as shown in Fig. 3, where the inverse voltage is artificially applied to produce operations characteristic of the organization, rather than from a supply source.

The same cushioning means characteristic of the present invention may be advantageously employed in various other applications of gas discharge tubes to rectifying organizations. In view of the foregoing explanation, it is apparent that deleterious sputtering of anode material and the need for some form of cushioning means arises whenever the firing time of the tube, inductive character of the load, or other conditions in the circuit organization, result in the application of a high inverse voltage when conduction ceases; and it can be appreciated that the cushioning means of this invention may be advantageously employed in any situation where these conditions exist. In the case of a high voltage high-power polyphase rectifier, for example, even though the firing time of the tubes may not be delayed by grid control, the period of commutation, corresponding to the time t^0 to t^1 in Figs. 2A to 2D, may be approximately 20 to 30 electrical degrees, due to the relatively high leakage reactance load of the associated transformer, together with the reactance of the load or other parts of the circuit organization; and during this commutation time the voltages between phases will have time to increase from zero and apply an inverse voltage to the tube last conducting in excess of the tolerable inverse voltage, and thereby causing damaging sputtering of anode material. For instance, in a three-phase rectifier organization for a 3000-voltage system, the voltage between the phases during a commutation period of twenty electrical degrees will increase from 0 to some 2000 volts, so that without the use of a cushioning means in accordance with this invention, the inverse voltage applied when conduction ceases is high enough to cause deleterious ionic bombardment of the anode. Even though the gas filling is mercury vapor and the gas disappearance is not a factor in the life of the tube, such excessive ionic bombardment of the anode materially affects the ability of the tube to withstand inverse voltage; and it is found that the use of the cushioning means of this invention serves to raise the tolerable inverse voltage rating for rectifiers of the mercury-vapor type.

Other specific instances of the application and utility of the cushioning means of this invention might be discussed; but it is believed that the foregoing will indicate the general scope of use and application of the invention.

The specific circuit organizations and method of cushioning illustrated and described as characteristic of the invention, together with the various explanatory graphs and theoretical discussion of the phenomena assumed to be involved in connection with the purpose of the invention and the results desired, are merely typical or illustrative of the nature and character of the invention; and I desire to have it understood that my invention is in no sense limited to the specific arrangements of parts and circuits shown and described, or to the particular procedures and processes discussed, and in particular is not to be assumed as necessarily involving the particular theories and assumptions herein given in explanation of tube performance, mode of operation, and results obtained by practicing the invention.

What I claim is:

1. In a rectifying circuit organization of the character described, in combination with a plurality of gas discharge rectifying tubes having a gas filling adversely affected by excessive ionic bombardment of the anode, a full-wave rectifying circuit organization including a source of alternating current and an inductive direct current circuit connected to the anode circuits of said tubes, said circuit organization acting at times to subject said tubes to a relatively high inverse voltage immediately after conduction ceases, of a capacitor and a resistor connected in series across the anode and cathode of each tube and acting to control the rate of rise of potential difference between the cathode and the anode caused by the application of such inverse voltage, said capacitors and resistors having values to avoid an oscillatory condition, whereby the damaging sputtering of anode material by ionic bombardment of the anode resulting from such difference of potential is kept within controlled limits.

2. A rectifying organization comprising in combination, a plurality of grid controlled gas discharge rectifying tubes connected to a highly inductive load, means for governing the firing of said tubes for controllable intervals and acting to provide commutation periods of simultaneous conduction by two tubes, transformer windings providing energization of the anodes of said tubes with alternating potentials of opposite instantaneous polarities and acting to apply across each tube at times a relatively high inverse voltage as soon as conduction ceases, and a capacitor and a resistor connected in series across the anode and cathode of each of said tubes to retard the rate of rise in potential between the cathode and the anode of that tube as the inverse voltage is applied thereto, said resistors having a value to provide a damped non-oscillatory circuit through the tubes, whereby the damaging sputtering of the anode material is limited.

3. In power conversion apparatus of the character described employing grid controlled gas tubes, the combination with a tube having an inert gas filling subject to clean-up by excessive ionic bombardment of the anode, a circuit organization including said tube and a source of alternating voltage, said circuit organization including a relatively large inductance in the anode circuit of said tube and acting at times to apply across the anode and cathode of said tube immediately after conduction of full load current an inverse voltage much higher than said alternating voltage and of an intensity capable of causing damaging sputtering of anode mate-

rial to reduce the life of the tube, and non-oscillatory circuit means including a capacitor and a resistor in series associated with the cathode and anode of said tube for controlling the rate of rise of the actual potential between the cathode and the anode as said inverse voltage is applied.

4. Power conversion apparatus of the character described comprising in combination, a plurality of grid control gaseous discharge tubes having inert gas fillings and subject to gas clean-up by excessive ionic bombardment of the anodes of said tubes, a circuit organization providing full-wave rectifying connections between an alternating current circuit and an inductive direct current circuit, said circuit organization rendering said tubes conductive alternately and acting at times to cause commutation of current in said direct current circuit from one tube to another tube at a time when the anodes of these tubes have a high difference in potential, and thereby apply across the anode and cathode of a tube immediately following conduction of full load current a high inverse voltage exceeding the maximum instantaneous value of the voltage in said alternating current circuit, cushioning means including in series a capacitor and resistor for automatically limiting the rate of rise in potential between said anode and cathode of each tube upon application of an inverse voltage in conformity with the characteristics of the tube and the intensity of the current conducted, and thereby cause a rate of deionization as compared with the increase in the voltage accelerating the positive gas ions toward the cathode which will obviate excessive sputtering of the anode material by ionic bombardment, said cushioning means including damping means for avoiding an oscillatory condition in the circuit through said tube.

5. A circuit organization for electron discharge tubes comprising, two grid controlled gas discharge tubes each having a thermionic emissive cathode and a gas filling, the pressure of said gas filling being adversely affected by excessive ionic bombardment of the anode, a full-wave rectifying circuit organization including a relatively large inductance in a direct current circuit and other inductance in the anode circuit of each tube, grid control means for rendering said tubes conductive to supply current to said inductance at different intervals with a commutation period of concurrent conduction, said circuit organization under certain conditions of said grid control means retarding the firing of said tubes for a substantial angle acting to subject the anodes of said tubes to a relatively high inverse voltage immediately after full conduction ceases, and circuit means including a capacitor and resistor in series associated with each tube for artificially and automatically retarding the rate of rise of the potential difference between its anode and cathode as the inverse voltage is applied thereto.

6. In a rectifying organization, the combination with a pair of grid control gas tubes having a gas filling adversely affected by excessive ionic bombardment of the anode, a rectifying circuit organization including said tubes and a highly inductive load, said circuit organization applying to the anodes of said tubes alternating potentials of opposite instantaneous polarity and sometimes acting to commutate the load current between said tubes at a time when said alternating potentials are near their maximum instantaneous values, thereby subjecting each tube to a high inverse voltage immediately after con-

duction ceases, of a capacitor and resistor connected in series across said cathode and anode to retard the rate of rise in potential difference between said cathode and anode, and thereby control the amount of sputtering of anode material by the impact of positive gas ions remaining from the immediately preceding conduction under the influence of said potential difference, said capacitor and resistor having values to prevent oscillatory conditions in the circuit through the tube.

7. In a rectifying organization of the character described, the combination with a gas discharge tube having a gas filled envelope including a heated electron emissive cathode and an anode, a circuit organization including a source of alternating current and an inductive load associated with said tube to act at times to subject said tube to a high inverse voltage immediately after conduction ceases, and a capacitor and a resistor connected directly in series across the anode and cathode of said tube, said capacitor acting to retard the rate of rise of the potential between the anode and cathode caused by the application of the inverse voltage and thereby limit the sputtering of anode material by the application of such inverse voltage, said resistor limiting the magnitude of current through the tube in its conducting direction upon discharge of said capacitor and also providing damping to prevent an oscillatory condition in the circuit through the tube.

8. In a rectifying organization of the character described, the combination with a source of alternating voltages having different instantaneous values at the same time and a highly inductive direct current circuit, of a plurality of grid controlled gas discharge tubes alternately fired at such points with respect to the alternating voltages as to cause a much higher inverse voltage to be applied to each tube immediately after conduction through that tube ceases, and non-oscillatory cushioning means including a capacitor and resistor in series associated with each of said tubes to retard the rate of rise of the potential between the anode and cathode of that tube upon application of said inverse voltage thereto, whereby sputtering of anode material by ionic bombardment resulting from the inverse potential as between the cathode and anode of the tubes is restricted in spite of the high inverse voltage applied to the tubes.

9. In a rectifying organization, the combination with a source of alternating current and an inductive load, of a circuit organization including a plurality of grid controlled gas discharge tubes for supplying unidirectional current pulses from said source to said load, said circuit organization sometimes acting to retard the conduction through said tubes for a substantial angle and thereby subject each of said tubes to a relatively high inverse voltage immediately following conduction, and non-oscillatory cushioning means associated with each of said tubes for controlling the rate of rise of the potential between the cathode and anode of that tube upon application of the inverse voltage thereto, said cushioning means including a resistor conducting charging current to a capacitor to provide across the tube a potential difference increasing at a restricted rate, whereby the rate of rise of the potential as between the cathode and anode of the tube as compared with the deionization characteristics of the tube is limited to restrict the ionic bombardment of the

cathode and avoid damaging sputtering of the anode material.

10. A circuit organization for grid controlled gas discharge tubes comprising, two grid controlled gas filled tubes having their anodes connected to the opposite terminals of a transformer winding having a mid-tap connected in series with a relatively large inductance to the cathodes of said tubes, means for governing the potential on the grids of said tubes to cause them to be conductive alternately at predetermined intervals with a brief commutation period of simultaneous conduction, said grid control means acting under some operating conditions to retard the firing of said tubes for a substantial angle and thereby cause the anode of each tube to have a relatively high inverse voltage applied thereto immediately after the commutation period and cessation of conduction through that tube, and a capacitor and resistor connected in series directly across the anode and cathode of each tube for limiting the rate of rise of the difference of potential between the anode and cathode of the corresponding tube as the inverse voltage is applied to the anode of that tube, said resistors and capacitors having values to prevent an oscillatory condition in the circuits including said tubes.

11. A circuit organization for supplying rectified alternating current to an inductive load comprising, two grid controlled gas discharge tubes having their anode circuits connected to the two halves of the secondary of a transformer, means for controlling the grids of said tubes to render them conductive alternately to supply current from said two halves of said transformer to an inductive load associated with said transformer, said load acting to maintain conduction through each tube in turn for a time after the voltage applied to its anode from the associated secondary of said transformer has become negative, said circuit organization acting to apply to the anode of each tube a relatively high inverse voltage immediately after conduction through that tube ceases, and a capacitor and a resistor for each tube directly connected in series across the anode and cathode of that tube to limit the rate of rise of potential between the cathode and anode of the tube upon the application of said inverse voltage, and thereby limit the ionic bombardment of the anode, said resistors having a value to damp out oscillations in the circuits including said tubes.

12. A circuit organization of the character described comprising, two grid controlled gas discharge tubes having their anode circuits connected to the two halves of a transformer winding, said transformer winding having substantial leakage reactance, means for governing the potentials on the grids of said tubes to render them conductive alternately at predetermined intervals, a direct current circuit including a relatively large inductance associated with said transformer winding and the anode circuits of said tubes, said inductance and said grid control means cooperating at times to maintain conduction through each tube in turn until the voltages in the two halves of said transformer winding have nearly obtained their maximum instantaneous values of opposite polarities and thereby cause the anode of each tube to have a relatively high inverse voltage applied thereto upon cessation of conduction of that tube, and non-oscillatory cushioning means including a capacitor and resistor directly connected in series across

the anode and cathode of each tube for automatically limiting the rate of rise of potential of the anode of each tube in turn with respect to its cathode as said inverse voltage is applied to said anode.

13. A rectifier circuit organization comprising in combination, a plurality of grid control gas tubes having their operating characteristics adversely affected by excessive ionic bombardment of the anode, a circuit organization including a direct current circuit and an alternating current circuit associated with the anode circuits of said tubes, said organization including means for controlling the firing of said tubes and acting at times to cause the firing of the tubes at times when a relatively high inverse voltage is applied across each tube in turn immediately after that tube has conducted full load current, and circuit means associated with each tube for artificially and automatically controlling the rate of rise of potential between the anode and cathode of that tube upon the application of said relatively high inverse voltage, said circuit means including a capacitor and resistor in series directly connected across the anode and cathode of the tube and having values preventing an oscillatory condition in the circuit through said tube, whereby ionic bombardment of said tubes by such high inverse voltages is kept within tolerable limits.

14. A circuit organization of the character described comprising in combination, a source of alternating voltages out of phase and having different instantaneous values at a given time, a direct current circuit including a relatively large inductance, a plurality of grid control gas filled tubes having anode circuits associated with said direct current circuit and alternating voltages, the operating characteristics of said tubes being

adversely affected by excessive ionic bombardment of their anodes, each of said tubes under certain operating conditions being subjected to an inverse voltage much higher than the maximum instantaneous values of said alternating voltages immediately after conduction of full current by that tube, and a capacitor and resistor in series directly connected across each tube and having values dependent upon the deionization characteristics of the tubes, said capacitor and resistor cooperating to retard the rate of rise of potential between the anode and cathode of the associated tube upon application of said inverse voltage and thereby keep the ionic bombardment of the anode of said tube within tolerable limits, said resistor limiting the magnitude of current through the associated tube in its conducting direction upon discharge of said capacitor and also providing damping to prevent oscillation in the anode circuit of the tube.

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