

June 10, 1941.

R. H. VARIAN ET AL

2,244,747

THERMIONIC VACUUM TUBE AND CIRCUITS

Filed May 24, 1938

2 Sheets-Sheet 1

FIG 1

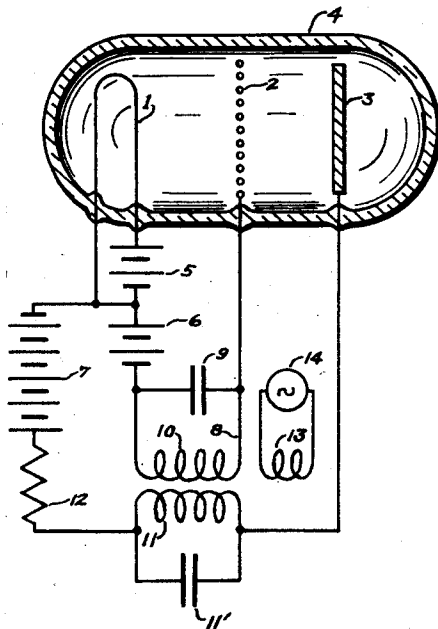


FIG 2

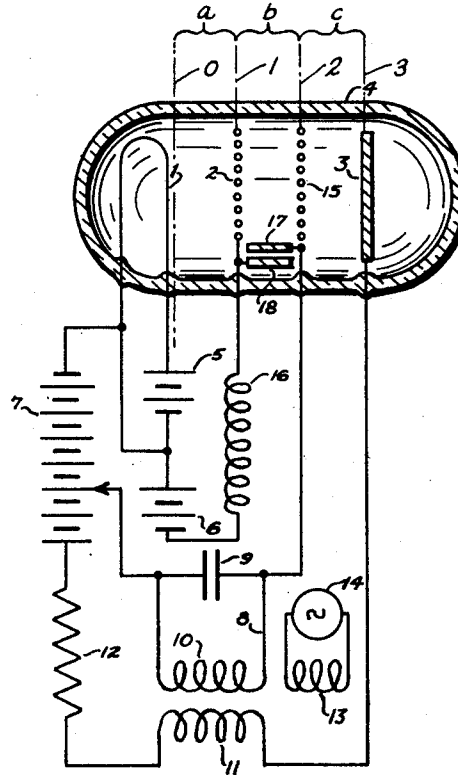
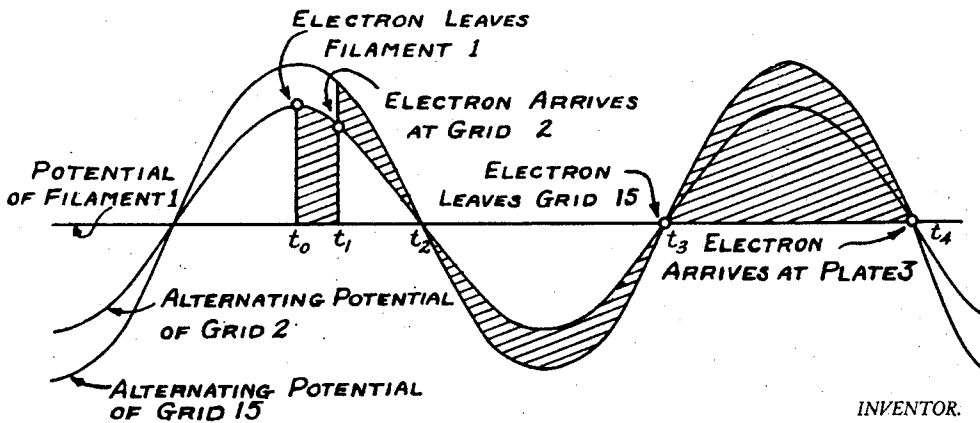


FIG 3



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FIG 4

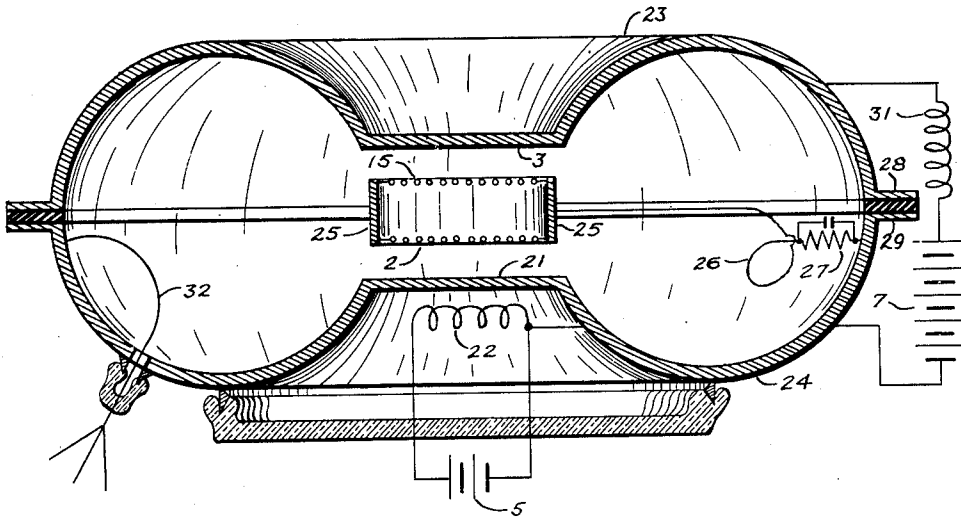
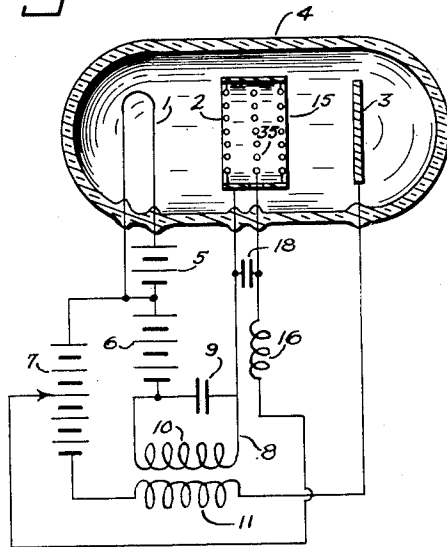


FIG 5



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UNITED STATES PATENT OFFICE

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THERMIONIC VACUUM TUBE AND CIRCUITS

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Application May 24, 1938, Serial No. 209,678

4 Claims. (Cl. 250—36)

The present invention relates generally to means and methods for converting direct or low frequency current into alternating current, and particularly to alternating currents of frequencies of 10^8 cycles or more per second. Especially this invention has reference to electrical converters, including oscillators, amplifiers, and detectors employing control grids in connection with cathodes and anodes connected to resonant circuits.

The principal object of the present invention is to overcome a limitation inherent in the known types of thermionic three-electrode tubes, namely, the limitation dependent on "active grid loss," and thus to circumvent to a considerable degree the limitations of the known types of tubes as to the frequencies attainable in their operation. Another object is to provide a control grid arrangement in the class of tubes generally included in the classification "three-electrode," including triodes, pentodes, and other conventional forms, which permits the grid impedance to be, as may be desired, positive, negative or effectively nearly infinite. Still another object is to make it feasible to make three-electrode vacuum tubes for operation at high frequencies without extremely small spacings between the electrodes, thus also facilitating the manufacture of vacuum tubes for high frequency and large power rating.

Other objects and advantages will become apparent from the specification, taken in connection with the accompanying drawings wherein the invention is embodied in concrete form.

In the drawings,

Fig. 1 is a diagrammatic representation of a three-electrode tube circuit as known in the prior art shown for use in explaining the present invention.

Fig. 2 is a representation of a three-electrode tube circuit embodying the present invention.

Fig. 3 is a graph explaining certain features of the invention.

Fig. 4 is a detail showing a modification applicable to Fig. 2.

Fig. 5 shows an alternative form of grid structure.

Similar characters of reference are used in all of the above figures to indicate corresponding parts.

Referring now to Fig. 1, which shows a conventional three-electrode circuit, the phenomena of active grid loss which the present invention overcomes will be explained. In Fig. 1 there is an electron emitting filament 1, a control grid 2,

and a plate 3 in an evacuated container 4. The filament 1 is heated by a battery 5, the grid 2 is biased by a battery 6, and the plate 3 is energized by a battery 7. A resonant circuit 8 comprising a condenser 9 and an inductance 10 impresses an alternating difference of potential on the grid 2 with respect to the cathode 1. An inductance 11 in series with the plate circuit is inductively coupled to inductance 10 for feedback control. A resistor 12 represents the load to which the system delivers energy, and an inductance 13 connected to a generator 14 and inductively coupled to inductance 10 represents the source of alternating current excitation for the system. The system as shown is capable of operating as an oscillator, as an amplifier or as a detector depending on factors of design and adjustment. The general theory of operation is well known in the prior art and will in the following be assumed without explanation except insofar as the effect of active grid loss is concerned.

In the operation of Fig. 1 at low frequencies the time required for an electron to travel from the filament 1 to the plate 3 is small compared with the period, that is, the time corresponding to a cycle of operation. The grid 2 has its potential varied with respect to the filament 1 potential at the frequency of the system, and the impedance of the filament 1 to plate 3 space is varied in accordance with the grid 2 potential. The result is that the grid acts as a valve or gate permitting the electrons to pass through in varying numbers. Each electron permitted to pass the grid 2 jumps from the filament 1 to the plate 3 in a very short time so that any electron passing through grid 2 is subjected to a substantially constant grid 2 potential during the time the electron is passing from filament 1 to plate 3. Under these conditions energy is not transferred between the grid 2 and the electrons which pass through the grid. This statement should not be confused with the fact that a positively charged grid carries current. To avoid possible confusion, however, the subject of grid loss will be explained with reference to a grid which is negative with respect to the filament at all times, and thus does not collect electrons from the surrounding space.

It is well known in the art that so long as grid 2 remains at a constant potential, it may control the number of electrons passing from electron emitter 1 to plate 3, but it cannot influence the energy with which electrons strike plate 3. This follows because whatever the potential of grid

2 may be, the electrons in passing the grid are merely passing a potential valley or hill as the case may be, and the energy lost by the electrons in ascending the hill is all regained in going down the other side. If the grid represents a potential valley, the same is true with the signs reversed. The same is true also if the potential of the grid is changing slowly, and it is easily seen that it will remain true as long as the grid does not change its potential appreciably while the electron is in transit between filament 1 and plate 3.

If on the other hand the grid 2 does appreciably change its potential while an electron is in transit between filament 1 and plate 3, the electron may strike the plate with either increased or diminished energy, for if the height of the potential hill, or the depth of the potential valley, at grid 2 changes while the electron is in transit, the energy lost on the ascent side will in general not equal the energy gained on the descent side. The matter of whether the electron gains or loses energy as a result of the change in the potential hill or valley at grid 2 depends on the phase of the change when the electron passed through the field of grid 2.

If a stream of electrons uniformly distributed in time crosses the cyclically varying potential hill or valley at grid 2 there will be as many electrons gain energy as lose energy, and if the gain or loss is small compared with total energy, the cyclic variations in the barrier, that is, the potential of grid 2, will not increase or decrease the average energy with which the electrons strike the plate 3. However, in a three-electrode tube the electron stream is not uniformly distributed in time, and it therefore becomes necessary to investigate the phase relations existing between the maximum electron emission and the grid potentials to determine whether the electron stream on an average gains energy from, or loses energy to, the grid circuit. The greatest number of electrons will leave the filament 1 when the grid 2 is most positive, and these electrons will gain energy from the grid circuit in traveling from the filament 1 to the grid 2, and since the grid 2 will be more negative while the electrons complete their journey from the grid 2 to the plate 3, these electrons will not lose all the energy they gained in traveling from the filament 1 to the grid 2 or may even acquire more energy from the grid in their flight to the plate. Hence the grid 2 will lose energy to the electron stream. This is known as active grid loss.

In the tube as shown in Fig. 1, at high frequencies, the time required for an electron to travel from the filament 1 to the plate 3 may become comparable with a period of oscillation of the system. In tubes of ordinary dimensions the transit time in the tube becomes comparable with the period at frequencies of the order of 10^8 cycles per second or less, the larger the tube in general the lower the frequency where transit time becomes appreciable. When the transit time of the electron traveling from filament 1 to plate 3 is an appreciable fraction of the oscillation period the potential of grid 2 with respect to filament 1 changes materially during the time of transit of the electron from the filament 1 to plate 3, and the tube is thus subject to active grid loss.

The active grid loss is understood in the prior art. Some attempts to overcome this loss have been made, in particular attempts to reduce the

transit time of electrons in the tube by reducing the spacing between the electrodes, but none of the attempts known prior to the present invention did more than reduce the effect by dimensional design.

In the present invention the factors which determine active grid loss are controlled in a definite way so the active grid loss may be eliminated entirely or made negative so that the grid 2 can receive energy from the electrons in their transit from the filament 1 to the plate 3. This is accomplished by shifting the phase of electron departure from the grid 2 with respect to the phase of electron entrance to the grid 2. This can be done in at least two ways.

A general way of controlling active grid loss is accomplished in the arrangement shown in Fig. 2 in which all the elements shown in Fig. 1 are present with the addition of a second grid or grid section 15, a choke 16, and capacitance elements 17 and 18. In the operation of the system shown in Fig. 2, the oscillations are produced in exactly the same way, in general, as in Fig. 1. This potential is communicated from tuned circuit 8 to grid 15. Grid 15 is held at a direct current potential which is positive, with respect to the cathode 1, by connection to the plate battery 7. The difference in direct current potential between grids 2 and 15 is required in order to avoid excessive grid impedance. If it were not for this, grids 2 and 15 would be connected together, an arrangement desirable in some instances but not applicable in general.

The capacitance between grids 2 and 15 as especially provided by plates 17 and 18 is used to transmit alternating voltages from grid 15 to grid 2. Since the coupling of grid 2 to other elements of the tube is mainly capacitive, the alternating voltage on grid 2 will be in approximately the same phase as that on grid 15. The choke 16 is used to avoid the bypassing of alternating current from grid 2 to filament 1.

Grid section 2 acts as the control grid, as usual, and by varying the space charge in front of the cathode regulates the departure of electrons from the filament 1. The electrons in traveling from filament 1 to plate 3 transfer energy to or from grid 2, as explained before. If the electrons leaving filament 1 are, for example, approaching grid 2 during the time when grid 2 is positive and becoming more negative they would in an ordinary tube as shown in Fig. 1 recede from grid 2 during a time when grid 2 is more negative than when the electron is approaching the grid. But if the electron were delayed at grid 2 for a suitable fraction of a cycle, it could traverse the remainder of the distance to plate 3 in a phase relation to the grid swing that would cause the electron receding from grid 2 to do a maximum amount of work on grid 2.

Obviously it is inconvenient to stop and start electrons at grid 2, but the same effect can be had by making grid 2 in effect occupy enough space between the filament 1 and the plate 3 to permit the electron to enter grid 2, remain in effect on the grid for a suitable time and then leave the grid and proceed toward the plate 3. This is accomplished as shown in Fig. 2. The electron enters grid 2 from the filament 1, and proceeds from grid 2 to grid 15 in a time which is approximately three-fourths of a cycle minus the flight time from filament 1 to grid 2. It then leaves grid 15 and proceeds to plate 3. Grids 2 and 15 in the special case now being considered

are approximately at the same alternating potential although at different direct potentials. The direct difference of potential in the case under consideration makes no difference in the theory because it is the variation in alternating potential of the grid that is responsible for the active grid loss. The effect of the difference of direct potential between grids 2 and 15 is merely to impart a constant acceleration to the electrons between grid 2 and grid 15 which is independent of the alternating potentials of the grids.

Suppose an electron leaves filament 1 at the instant when grid 2 is at the least negative part of its cycle, and that it reaches grid 2 one quarter of a period later. The electron will have been acted upon by an alternating component of potential in the region from maximum positive alternating value to zero alternating value. Now suppose the electron takes one-half period to reach grid 15. It will then leave grid 15 at the time when the alternating component of potential is again at zero and is starting toward its maximum positive value. If the tube is designed so that the electron requires either one-half or one-quarter cycle to reach plate 3 from grid 15 it will be subjected to an alternating grid potential, in its course from grid 15 to plate 3, of the same value as that to which it was subjected in traveling from filament 1 to grid 2. Under these conditions no energy will have been transferred to or from the tuned circuit 8 by the group of electrons considered and there will be no active grid loss due to this group of electrons.

In the tube shown in Fig. 2 it is possible by correctly proportioning the inter-electrode spaces to regulate the exchange of energy from the electrons to the grids 2 and 15 so the electrons deliver energy to the grid circuit 8 through grids 2 and 15. This in effect establishes an "active grid gain" analogous to the active grid loss described before. If the grids 2 and 15 gain energy every cycle the system can be maintained in oscillation without resorting to feedback of energy from the plate circuit coupling coil 11 to the grid circuit inductance 10. This, of course, has advantages of reducing circuit equipment and the losses thereof. In such an arrangement coil 11, inductance 13 and generator 14 are eliminated and energy may be taken from circuit 8. For operation with active grid gain, either the interelectrode spacings are made so that comparatively little energy is taken from the grids 2 and 15 by the electrons in their travel from filament 1 to grid 2, and more energy is given to the grids 2 and 15 in the travel of the electrons from grid 15 to plate 3, or the energy lost by the grids to the electrons in traveling from filament 1 to grid 2 is allowed to be what it may, and steps are taken to cause the grids to gain an abnormally large amount of energy from the electrons as they travel from grid 15 to plate 3.

Either of the alternatives mentioned may be accomplished with the apparatus shown in Fig. 2. To accomplish the first alternative it is necessary that the flight time between cathode 1 and grid 2 be approximately $\frac{1}{2}$ -cycle so that the electrons when they reach grid 2 have not on an average derived energy from the grid. In this case grid 15 may have the same alternating potential as grid 2, as will be the case if capacity 17-18 is made large. To achieve the second alternative, grid 15 is caused to have a larger A. C. potential than grid 2, but of the same phase.

This may be accomplished by reducing the size of capacity 17-18, so that grid 15 has a considerably higher A. C. potential resulting in the electrons doing work on grid 15 in their passage to plate 3, as will further appear. In this way it is possible to increase the energy gained by the grids from the electrons in their flight from grid 15 to plate 3, and at the same time to gain some energy from the electrons while they are in the interspace between grid 2 and grid 15. Because of the increased energy acquired by the grid structure from the electrons in the second alternative it is possible to place grid 2 much less than $\frac{1}{2}$ -cycle from cathode 1, as is indicated in the flight times shown in Fig. 3, because the initial loss of energy by grid 2 can be more than made up in the remainder of the electron flight time.

The operation of this second alternative arrangement may be explained, with reference to Fig. 3, by considering an electron starting from filament 1 at the time t_0 when grid 2 is at the most positive part of its cycle. The electron arrives at grid 2 at time t_1 while grid 2 is still positive with respect to filament 1, and thus absorbs energy from grid 2. This is represented by the shaded area under the curve representing the alternating potential of grid 2. This area represents the integrated product of force on the electron multiplied by the distance it travels. Passing through grid 2, the electron travels between grids 2 and 15 for nearly three-fourths of a period. The electron absorbs a small amount of energy from the grid structure due to the difference of potential during the remainder of the quarter cycle in which it started from filament 1 i. e., between t_1 and t_2 . This is shown by the shaded area extending partially between the grid 2 and grid 15 and between the potential curves above the axis of the curves. During the next half cycle i. e., between t_2 and t_3 , the electron transfers energy to the grids as shown by the shaded area between the grid potential curves below the curve axis. The electron leaves grid 15 just as the potential of the grids 2 and 15 with respect to the filament reverses and becomes positive again. In moving from grid 15 to plate 3 during the interval between t_3 and t_4 , the electron is attracted and retarded by the positive grid and thus energy is transferred from the electron to the grid. The energy transferred is represented by the shaded area between the curve axis and the potential curve extending between grid 15 and plate 3. The net transfer of energy between the electron and the grids in this instance is from the electron to the grids and is the maximum possible under the assigned conditions. Any other electron leaving earlier or later in the cycle than the particular electron discussed would transfer less energy to the grids, or would receive energy from the grids. It should be kept in mind in considering Fig. 3 that the potential differences concerned are related to the alternating grid potentials and that they should not be confused with the unvarying voltages, such as grid bias, which are not shown in the diagram. The unvarying voltages have no cyclic variation and thus take no direct part in the active grid loss or gain under consideration.

The symmetry of the construction of Fig. 3 makes it evident that an electron which leaves filament 1 half a cycle before or after the one described will absorb the same amount of energy from the grids as the one described gave to the grids. Further, if electrons left the fila-

ment 1 at the same rate throughout successive cycles, the net total transfer of energy between the electrons and the grids would be zero. Actually, the electrons leave the filament at a greater rate when the grids are positive than when they are negative and thus an unsymmetrical factor is introduced into the mechanism of energy transfer between grids and electrons.

In the foregoing description, the energy interchange between the electron stream and the grid structure is illustrated on a curve representing the potentials of grids 2 and 15 and further, in the drawings, the distance the electron travels is represented as the same for equal successive intervals of time. To do this simplifies the drawings, but it must be pointed out that this renders it qualitative only, since it is the integral of potential gradient with respect to distance which gives the energy interchange and not the integral of the potential on the grids with respect to time. To make the curve quantitatively correct it is only necessary to use a relation of gradient to potential taking into account the effects of tube dimensions and the changes of electron velocity in the tube.

In some arrangements the grids 2 and 15 can be connected together, forming in effect a thick grid. One such arrangement is shown in Fig. 4 in which a thick grid is used in an oscillator utilizing the enclosed resonator type of circuit described in copending patent application of W. W. Hansen, filed July 27, 1936, Ser. No. 92,787.

In Fig. 4 the emitter is a heated surface 21 instead of a simple filament. Surface 21 is heated by an element 22. Surface 3 is a portion of the wall of a resonator opposite the emitting face 21 and constituting the plate of the circuit. Between the emitter 21 and plate 3 there are the two grids 2 and 15 connected together by the conductors 25. The grids 2 and 15 are excited by a loop 26 in the resonator field. A grid leak is provided and connected to the resonator wall so as to be at the potential of the emitter 21. The two halves 23 and 24 of the resonator have capacitive flanges 28 and 29. The usual plate battery 7 is connected to the plate 3 and emitter 21 as usual, and a choke 31 is shown in the positive battery 7 lead. A loop 32 in the resonator field provides for removing energy from the system.

In the operation of the arrangement shown in Fig. 4, the ordinary principles of grid control are employed, with the control of transit time between grids 2 and 15 as described before. The operation similar to an ordinary tuned plate-untuned grid oscillator. The field of the resonator constitutes the tuned plate circuit and the loop 26 in the resonator field the untuned grid circuit.

The distance between the grids 2 and 15, as indicated, depends upon the frequency of the system, and also on the voltage and other characteristics of the system.

An alternative form of grid arrangement is shown in Fig. 5. Its operation is substantially the same as explained for Fig. 2, but a structural change in grids is provided. In this arrangement grids 2 and 15 are connected together and a third grid 35 maintained at a positive potential is placed between them.

For quantitative consideration of the operation of the present invention the mathematical analysis following is applicable. This analysis has reference to Fig. 2 regarding which, for purposes of computation, special assumptions are

made and special notations are adopted. These are: The electrons are assumed to start from a plane, designated as 0, between filament 1 and grid 2 and parallel to grids 2 and 15 and plate 3 all of which are assumed to be sections of infinite parallel planes. The plane 0 is, of course, recognized as a virtual cathode, a convention already in common use. The electrons are assumed to move from the virtual cathode plane 0 through grids 2 and 15 and to stop at plate 3 without the possibility of any secondary emission. It is assumed also that grids 2 and 15 do not collect any of the electrons but that they have only pure valve action on the electrons in transit. A further assumption regarding plate 3 is that the voltage on it is constant. This condition can be attained in effect by putting a screen around plate 3 at the plate potential. The screen is placed at the distance from grid 15 assumed for plate 3 and plate 3 is put farther away. In this arrangement the screen grid becomes a virtual plate. Inasmuch as the virtual plate effect of a screen grid is well known in the art and its introduction here is solely for convenience in assuming a constant plate voltage, it has not been shown in the drawings, nor is the nomenclature complicated by its addition. Reference to plate 3 will in all instances imply the conditions stated for constant plate voltage. For convenience in the mathematical nomenclature the plane of the virtual cathode is said to be at 0, the planes of grids 2 and 15 are said to be at a and b respectively, and the plate 3 at c . The distance between the virtual cathode 0 and the grid 2 is a , that between grids 2 and 15 is b , and between grids 15 and plate 3 is c . The distance to any plane in the tube from the virtual cathode 0 is x . In the analysis the power lost or gained by the grids 2 and 15 is calculated disregarding the effect of velocity grouping of electrons.

In the spaces a , b , and c the electric fields are given by:

$$\text{Field in space } a: E_a^0 + E_a^1 \cos \omega t$$

$$\text{Field in space } b: E_b^0$$

$$\text{Field in space } c: E_c^0 + E_c^1 \cos \omega t$$

where ω is $2\pi f$ and f is the frequency of operation of the tube and E^0 stands for a constant field, and the subscripts "a," "b," and "c" designate the spaces in which the respective constant fields E^0 exist. Also, E^1 stands for the peak A. C. field, and the subscripts "a" and "c" designate the spaces in which the A. C. fields exist, just as in the case of the D. C. potentials.

It is assumed here that:

(1) all the E 's are constants and that

(2) $E_a^1 \ll E_a^0$ and $E_c^1 \ll E_c^0$

The assumption (1) is valid only when the cathode 0 is a virtual cathode at the plane of maximum space charge. The assumption (2) means that the signal is comparatively weak so the alternating components of voltage in the tube are much smaller than the unidirectional components. The electrons are assumed to leave the virtual cathode 0 with zero velocity.

The energy gained by an electron of charge e starting at 0 at the time $t=t_0$ is given by

$$W = e \int_0^1 (E_a^0 + E_a^1 \cos \omega t) dx + e \int_1^2 E_b^0 dx + e \int_2^3 (E_c^0 + E_c^1 \cos \omega t) dx$$

In this equation the integral subscripts and superscripts indicate the integration from the re-

spective planes indicated. The first is from the virtual cathode 0 to the grid 2, the second that from grid 2 to grid 15 and the third from grid 15 to plate 3.

This energy can be divided into two parts:

$$(2) \quad W_0 = e \int_0^1 E_0^2 dx + e \int_1^2 E_2^2 dx + e \int_2^3 E_3^2 dx \\ = e(E_0^2 a + E_2^2 b + E_3^2 c)$$

and

$$(3) \quad \Delta W = e \int_0^1 E_1' \cos \omega t dx + e \int_2^3 E_3' \cos \omega t dx$$

The first part W_0 is the energy obtained from the unidirectional plate 3 potential. The second part ΔW is the energy gained from the alternating components of the interspace fields due to the effects of the control grids. It will be noticed here that there is no alternating component of field in space b between grids 2 and 15, inasmuch as condenser plates 17 and 18 in Fig. 2 provide a low impedance path for the alternating grid currents.

To calculate the power loss of the control grids, ΔW is multiplied by the number of electrons leaving the virtual cathode 0, during the time between $t=t_0$ and $t=t_0+dt_0$, that is, $i+\Delta i \cos \omega t_0$ and to integrate over one period. This is accurate providing the operation of the tube is in the linear part of its characteristic in which i and Δi are constants.

The power loss is then

$$(4) \quad \Delta \epsilon = \frac{1}{T} \int_0^T \Delta W (i + \Delta i \cos \omega t_0) dt_0 \\ = \frac{1}{2\pi} \int_0^{2\pi} \Delta W (i + \Delta i \cos \delta_0) d\delta_0$$

where

$$T = \frac{2\pi}{\omega} = \frac{1}{f}$$

f =frequency, and $\delta_0 = \omega t_0$.

From elementary considerations,

$$\cos \omega t = \cos [\omega t_0 + \omega(t-t_0)] \\ = \cos \delta_0 \cos \omega(t-t_0) - \sin \delta_0 \sin \omega(t-t_0)$$

This is substituted in Equation 3.

$$(3) \quad W = \int_0^1 E_1' [\cos \delta_0 \cos \omega(t-t_0) - \sin \delta_0 \sin \omega(t-t_0)] dx + \\ e \int_2^3 E_3' [\cos \delta_0 \cos \omega(t-t_0) - \sin \delta_0 \sin \omega(t-t_0)] dx$$

Equation 3 as now written is substituted into Equation 4 as follows:

$$(5) \quad \Delta \epsilon = \frac{1}{2\pi} \int_0^{2\pi} \left\{ e \int_0^1 E_1' [\cos \delta_0 \cos \omega(t-t_0) - \sin \delta_0 \sin \omega(t-t_0)] dx + \right. \\ \left. e \int_2^3 E_3' [\cos \delta_0 \cos \omega(t-t_0) - \sin \delta_0 \sin \omega(t-t_0)] dx \right\} (i + \Delta i \cos \delta_0) d\delta_0$$

Since

$$\int_0^{2\pi} \sin \delta_0 d\delta_0 = \int_0^{2\pi} \cos \delta_0 d\delta_0 = 0$$

the unidirectional component i of the current does not contribute to the power loss. Further, since

$$\int_0^{2\pi} \sin \delta_0 \cos \delta_0 d\delta_0 = 0$$

none of the terms containing $\sin \delta_0$ contribute. Therefore, using

$$\frac{1}{2\pi} \int_0^{2\pi} \cos^2 \delta_0 d\delta_0 = \frac{1}{2}$$

$$(7) \quad \Delta \epsilon = \frac{e \Delta i}{2} \left\{ \int_0^1 E_1' \cos \omega(t-t_0) dx + \int_2^3 E_3' \cos \omega(t-t_0) dx \right\}$$

This equation can directly evaluated quantitatively for small values of $t-t_0$, a restriction not ordinarily desired in practice, but for more general cases quantitative evaluation is better accomplished by an indirect method. For this the mean value theorem is applicable.

The mean value theorem states that for any function $f(x)$ continuous in the interval $a \leq x \leq b$

$$\int_a^b f(x) dx = f(x)(b-a)$$

with $a < x < b$. For approximate solution x does not have to be evaluated.

Therefore,

$$(8) \quad \Delta \epsilon = \frac{e \Delta i}{2} \left\{ E_0' a \cos \omega(t_a - t_0) + E_3' c \cos \omega(t_c - t_0) \right\}$$

where t_a denotes a moment of time which although definite is not evaluated more precisely than to say that at time t_a an electron that started from the vertical cathode 0 at time t_0 is in the region a between filament 1 and grid 2. In this equation the locations of specified electrons in the regions a and c are not ascertained more closely than the limits of the regions themselves to which the instants of time t_a and t_c refer because of the approximation involved in the use of the mean value theorem for obtaining a solution of the problem. Consequently the location of an electron at time t_a is not stated more closely than to say it is somewhere between the virtual cathode 0 and the grid 2, and likewise that at time t_c the electron is stated to be somewhere between grid 15 and plate 3.

The potential difference between plate 3 and the virtual cathode 0 has been stated to be constant so

$$E_1' a + E_3' c = 0$$

If, for convenience, $E_1' a$ is represented by V_1' , Equation 8 can be written

$$(9) \quad \Delta \epsilon = \frac{e \Delta i V_1'}{2} \left\{ \cos \omega(t_a - t_0) - \cos \omega(t_c - t_0) \right\}$$

as the active grid power loss.

A complete understanding and interpretation of this equation indicates the dimensional characteristics of the embodiments of the present invention shown in Figs. 2, 4 and 5 which have already been explained in a qualitative way, and in addition indicates how the ordinary three-electrode tube shown in Fig. 1 can be modified for the partial or complete elimination of active grid loss. It also indicates how the tube of Fig. 1 can be made to oscillate without the grid 2.

In the ordinary three-electrode vacuum tube as shown in Fig. 1 the time $(t_c - t_0)$ for an electron to get into the region between grid 2 and plate 3 is a small portion of a period of oscillation. That is $(t_a - t_0) \omega \ll 1$ and $(t_c - t_0) \omega \ll 1$, and accordingly the cosines of these angles are both close to 1. In this region of the cosines, $\cos x \cong 1 - x^2/2$. Using this approximation for the cosines, Equation 9 is approximated by

$$(10) \quad \Delta \epsilon = \frac{e \Delta i V_1'}{2} \left\{ 1 - \frac{\omega^2}{2} (t_a - t_0)^2 - 1 + \frac{\omega^2}{2} (t_c - t_0)^2 \right\}$$

which simplifies to

$$(11) \quad \Delta \epsilon = \frac{e \Delta i V_1'}{2} \left\{ \frac{\omega^2}{2} [(t_c - t_0)^2 - (t_a - t_0)^2] \right\}$$

This equation indicates that within the ordinary ranges of frequencies encountered in triode practice the active grid loss increases as the square of the frequency. This equation represents the operation of triodes inasmuch as $(t_c - t_0)$ is always greater than $(t_a - t_0)$ as long as $(t_c - t_0)$ is

one-half period or less as has been the practice in the prior art.

Returning now to Equation 9

$$\Delta\epsilon = \frac{e\Delta V_s}{2} \left\{ \cos \omega(t_a - t_0) - \cos \omega(t_c - t_0) \right\}$$

it may be seen that if, for instance, $\omega(t_a - t_0)$ and $\omega(t_c - t_0)$ are both in the region between zero and π the quantity in the brackets will always be positive because the difference between the cosines will always be positive since $(t_a - t_0)$ is necessarily less than $(t_c - t_0)$. But if $(t_a - t_0)$ and $(t_c - t_0)$ are increased by increasing the distances inside the tube until $\omega(t_c - t_0)$ is increased to a value between π and 2π , the cosine of the angle will begin to increase again.

This can be accomplished by increasing the spacings between the virtual cathode 0 and the grid 2, and between the grid 2 and the plate 3 sufficiently so that $\omega(t_c - t_0)$ is of the order of 2π . This is in direct contradiction to the practice of the prior art in which triodes for high frequency have been made with interelectrode spacings as small as possible. By suitably spacing the electrodes of the tube with reference to the frequency and voltage of the system the grid loss thus can be made either positive, negative, or zero. If it is made negative, the grid 2 will gain energy from the electrons, accomplishing thereby the conversion of direct to alternating current directly within the grid circuit.

Further examination of Equation 9 indicates that if the grid 2 is removed entirely only one cosine term will remain. This is $\cos \omega(t_a - t_0)$ and the plate then has the mathematical meaning formerly given to grid 2. As is evident from Equation 9 it is only necessary to make this term negative to accomplish active grid gain instead of active grid loss. Accordingly it is only necessary to restrict the term $\omega(t_a - t_0)$ to the region between $\pi/2$ and $3\pi/2$ in order that its cosine will be negative. Under these conditions the electrons leaving the virtual cathode 0 at $t=t_0$ will leave there in varying numbers per unit of time as usual in response to the alternating component of voltage between the cathode and anode. The greater number per unit time will leave the cathode when the alternating component is a maximum. These electrons will arrive at a plane in the region *a* through which the electrons pass at time t_a about $1/2$ period after they leave the virtual cathode 0. It should perhaps be noted again that this plane is not the plane of the physical plate, for in using the mean value theorem we merely showed that such a definite plane existed, and did not define its position more precisely than to say that it lay somewhere in the region *a*. Under these conditions $\cos \omega(t_a - t_0)$ has a minimum value and is negative, and hence the electrons passing across the space between cathode and plate will deliver energy to the resonant circuit connected to the plate. This condition can be satisfied if the plate occupies some definite position beyond the plane through which electrons pass at the time t_a , and hence the diode may become self-oscillatory. For this type of oscillator the arrangement shown in Fig. 1, with grid 2 and resonant circuit 8 both omitted and with a plate circuit condenser 11' for use with inductance 11 added, is satisfactory.

In the preceding discussion of Equation 9 as applied to Fig. 1 it was shown that the active grid loss can be reduced to zero or made negative by making the space from the cathode to the grid

comparatively large. This construction has some disadvantages which are overcome by the construction of Figs. 2, 4, and 5.

In Figs. 2, 4, and 5, $t_a - t_0$ can be made as small as may be desired, that is, grid 2 may be placed as near the filament 1 as is convenient. Then by making the time of flight between grids 2 and 15 sufficient the spacing between grid 15 and plate 3 can be made either large or small. If, for example, grid 2 is very near filament 1, and $t_a - t_0$ is very brief, $\cos \omega(t_a - t_0)$ is approximately 1. If now the space between grids 2 and 15 is made sufficient so that $\omega(t_c - t_0)$ is approximately 2π , the quantity $\cos \omega(t_a - t_0) - \cos \omega(t_c - t_0)$ will approximate $1 - 1 = 0$ and there will be little or no active grid loss. If, as a second example, the space between filament 1 and grid 2 is made considerable so that $\omega(t_a - t_0)$ approximates π , and then the spaces between grids 2 and 15 and between grid 15 and plate 3 are made so that $\omega(t_c - t_0)$ approximates 2π , the quantity $\cos \omega(t_a - t_0) - \cos \omega(t_c - t_0)$ will approximate

$$-1 - (+1) = -2$$

This means that instead of active grid loss there is an active grid gain, and a consequence of this condition is self-oscillation of the system.

In general, for maximum grid gain of power, that is, for maximum transfer of energy from the electrons to grids 2 and 15, the interelectrode spacings and the voltages are adjusted so that $\omega(t_a - t_0) \cong \pi$ or any odd multiples of π , and $\omega(t_c - t_0) \cong 2\pi$ or any even multiples of π . Emphasis is again placed on the fact that t_a and t_c are not the precise instants of time when the electrons reach the planes of grid 2 and plate 3 respectively, but are times prior to the instants of time when the electrons reach these two electrodes.

As many changes could be made in the above construction and many apparently widely different embodiments of this invention could be made without departing from the scope thereof, it is intended that all matter contained in the above description or shown in the accompanying drawings shall be interpreted as illustrative and not in a limiting sense.

What is claimed is:

1. In an electrical converter, a closed hollow conducting body comprising capacity coupled body half sections, means for establishing a direct current potential between opposing inner surfaces of said body half sections, means for causing thermionic emission from one of said opposing surfaces, and a grid structure interposed between said surfaces and comprising a pair of mutually spaced grid sections, a conducting loop within said body connected to said grid sections for exciting the latter, the flow of electrons within said body acting to build up a suitable transient and establish an oscillating electromagnetic field within said body for exciting said loop and effecting space charge control of the electrons, the flight time of the electrons between said grid sections being substantially one-half cycle of oscillation of the field within said body.

2. A thermionic tube constructed for operating at high frequencies so that the grid changes in potential during the transient time of the electrons comprising, a cathode, a control grid acting directly on the cathode and operating on the principle of space charge control of the current leaving the cathode, said control grid having

spaced, mutually coupled grid sections, and a plate, the spacing of said grid sections providing an electron flight time therebetween that is substantially one-half cycle of the operating frequency of the tube, oscillatory circuit means including capacity elements connected with said grid sections for establishing desired alternating potentials thereon while maintaining the interspace between said grid sections substantially free of alternating electric fields, and means for maintaining said grid sections at differing direct current potentials and for maintaining said plate at a higher direct current potential than either of said grid sections.

3. A thermionic tube constructed for operating at high frequencies so that the grid changes in potential during the transient time of the electrons, comprising, a cathode, a control grid acting directly on the cathode and operating on the principle of space charge control of the current leaving the cathode, said control grid having spaced grid sections, and an anode, the spacing of said grid sections providing an electron flight time therebetween that is substantially one-half cycle of the operating frequency of the tube, means for applying alternating control potentials to said grid sections, means for applying a positive potential to said anode with respect to said cathode and grid, said grid sections enclosing a region of space that is substantially free of alternating electric fields and is shielded from the fields existing between the control grid and the cathode and anode, the spacing of said control grid sections from one another and the spac-

ing of the first grid section from the cathode being such that the electrons consume substantially three-fourths of a cycle in transversing the space from the cathode to the second grid section, the majority of the electrons doing work on the varying control grid field during the operation of the tube.

4. An electrical converter comprising, a vacuum electric tube having a cathode, a grid structure acting directly on said cathode, and an anode held at a positive potential with respect to said cathode and grid structure, said grid structure comprising, a pair of mutually spaced end grid sections electrically interconnected so as to provide a space therebetween substantially free of alternating electromagnetic fields and a central grid section maintained at a positive direct current potential, means for exciting said grid structure to effect space charge control of electrons as they leave said cathode thereby alternately varying the density of the electron stream leaving the cathode, the spacing of said grid structure end sections being such that the electrons spend substantially one-half cycle of the control frequency during their passage within said grid structure whereby a phase delay of substantially one-half cycle is produced in the entry of the electrons into the field existing between the control grid structure and the anode so that the electrons are caused to impart a maximum amount of energy to the grid circuit.

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