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AMPLIFIER FOR SMALL DIRECT CURRENTS

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Fig. 1.

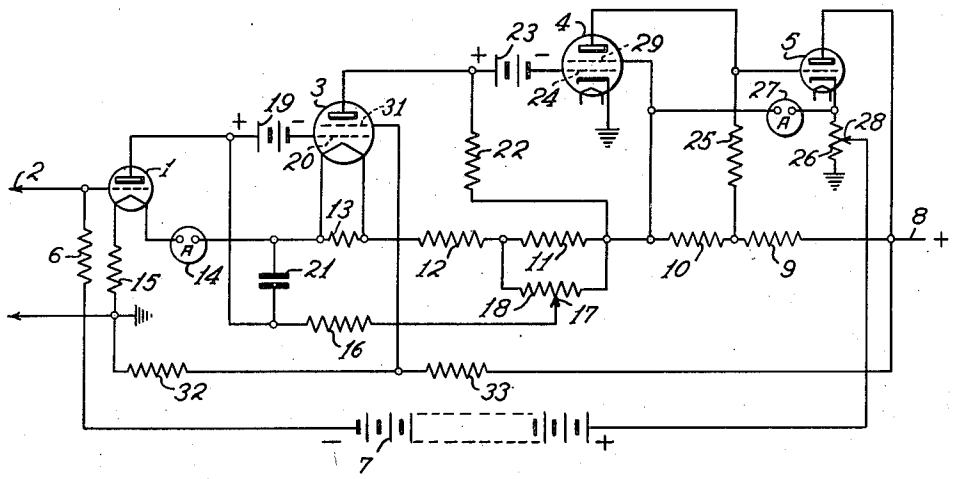
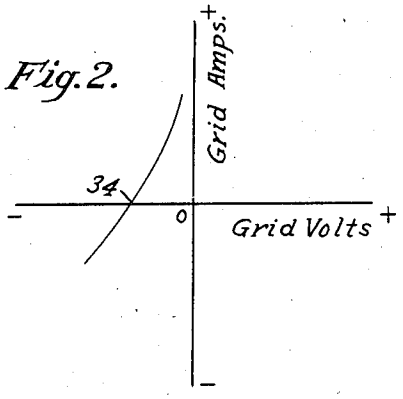


Fig. 2.



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AMPLIFIER FOR SMALL DIRECT CURRENTS

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Our invention relates to amplifiers and, in particular, relates to amplifiers for extremely small direct currents.

Where it is desired to amplify extremely small direct currents such, for example, as those with magnitudes covering a range between 10^{-15} amperes and 10^{-12} amperes which are found in the output circuit of a mass spectrometer such as described in Hipple Patent 2,331,189, issued October 5, 1943, and assigned to the assignee of this application, difficulty arises from the fact that variations in the grid current of the first amplifier tube must be kept to a value which is small compared with the current being measured if they are not to result in serious impairment of the fidelity with which the output current of the amplifier follows variations in the current being measured. While it is possible to obtain amplifier tubes having grid currents which vary so slightly with changes of voltage impressed on their control electrodes that satisfactory operation of the amplifier is obtainable, such tubes are of very special construction which renders them much more expensive and less rugged than ordinary amplifier tubes now on the market. The latter tubes, however, have too rapid a variation of grid current with grid voltage to be satisfactory for measurement of the extremely small currents above mentioned.

In accordance with our invention, we have discovered that by employing an amplifier circuit in which there is a negative feedback of energy from the output stage to the input of the first amplifier tube, such negative feedback being great enough so that the net voltage amplification between the input and output terminals of the cascade is of the order of unity, and by adjusting the grid bias of the first amplifier tube so that, when the current to be measured is zero, the first amplifier tube draws no grid current, it is possible to obtain satisfactory operation while using a first amplifier tube of the less expensive type above mentioned in which the grid current varies at a substantial rate with changes in grid voltage.

One object of our invention is accordingly to provide an amplifier of minute current, for example ranging from the order of 10^{-15} amperes to 10^{-12} amperes, which shall utilize only amplifier tubes having a relatively rapid variation of grid current with grid voltage.

Another object of our invention is to provide an amplifier in which the grid current drawn by the first amplifier tube undergoes an extremely small variation with variation of current in the input circuit to said amplifier.

Still another object of our invention is to provide an amplifier using a first tube in which the variation of grid current with grid voltage is substantial, but which operates over a substantial

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range of variation of current in its input circuit with an extremely minute variation in grid current.

A further object of our invention is to provide an amplifier for small direct currents in which only relatively inexpensive and standard electronic amplifier tubes are employed.

Other objects of our invention will become apparent from reading the following description taken in connection with the drawings, in which:

Figure 1 is a diagrammatic showing of the circuit of an amplifier in accordance with our invention; and

Fig. 2 is a diagram illustrating the relationship between grid voltage and grid current in an electronic tube of a type which may be used as a first tube in an amplifier circuit in accordance with our invention.

Referring in detail to Fig. 1, reference numeral 1 indicates the first tube of an amplifier for direct currents of very small magnitudes such as 10^{-15} amperes to 10^{-12} amperes. Such an amplifier may be referred to as an electrometer. The positive terminal from the source of such currents is connected to the point 2, while the negative terminal of said source is connected to ground. The tube 1 is supplemented by any desired number of cascade amplifier tubes such as 3, 4, and 5, the particular number shown being, of course, merely illustrative, but the total number of tubes in the amplifier should be an even number. To give a specific illustration, the line connected to the terminal 2 may be the output terminal of a mass spectrometer such as is shown and described in the Hipple patent above mentioned, the negative terminal of the mass spectrometer output circuit being grounded. The control electrode of the tube 1 is connected to the output circuit of some suitable tube in the amplifier such, for example, as tube 5, through a resistor 6 and a suitable bias battery 7 in a way which will be described in more detail below.

It will be evident to those skilled in the art that the circuit containing the resistor 6 and source 7 constitutes a negative feedback to the control electrode of the tube 1. Were this negative feedback connection omitted, it would be necessary to use for the first tube 1 an amplifier tube in which the rate of variation of the current drawn by the control electrode of tube 1 over the range of variation of the current flowing into terminal 2 from the source to be measured would be small compared with the inflowing current. To take an example, where the current to be measured flowing into the terminal 2 is of the order of 10^{-12} amperes, and the grid resistor connecting the terminal 2 to the output of the measured source is of the order of 10^{11} ohms, the variation in voltage impressed on the control electrode of tube 1 would be of the order of 0.1 volt. Under such cir-

cumstances, maintenance of constancy in the ratio of changes in output current of tube 5 to change of input current to terminal 2 requires that the variation of control electrode current of tube 1 should be only of the order of 10^{-15} amperes over the range of control electrode voltage just mentioned. It is possible to obtain an electron amplifier tube, for example the FP-54 tube manufactured by the General Electric Company, which has a grid current variation of the order just mentioned. However, such tubes are extremely delicate and expensive.

By employing the feedback circuit through the resistor 6 and biasing source 7 already mentioned as characterizing our invention, it is possible to substitute a radio amplifier tube having a much greater variation of grid current with grid voltage than 10^{-15} amperes when the grid voltage varies by 0.1 volt; for example, the tube RH-507, manufactured by the Westinghouse Electric & Manufacturing Company of East Pittsburgh, Pennsylvania, may be used.

In accordance with our invention, the cathode of the tube 1 may be a directly heated one supplied with heating current from a direct-current voltage source of the order of 220 volts having its positive terminal at the point 8 and its negative terminal grounded. Current for heating the cathode of tubes 1 and 3 flows from the terminal 8 through resistors 9, 10, 11 and 12, thence through a resistor 13 in multiple with the cathode of tube 3, then through a suitable ampere meter 14 to the cathode of tube 1 and thence through a resistor 15 to ground.

The anode of tube 1 is connected through a resistor 16 to a movable tap 17 on a potentiometer 18 which shunts resistor 11 and likewise through a suitable bias battery 19 to control electrode 20 in tube 3. The anode of tube 1 is also connected through a capacitor 21 to the negative terminal of resistor 13. The anode of tube 3 is connected through a suitable resistor 22 to the positive terminal of resistor 11. The anode of tube 3 is also connected through a suitable bias battery 23 to the control electrode 24 of tube 4. The anode of tube 4 is connected through a suitable resistor 25 to the positive terminal of resistor 10, and is likewise connected to the control electrode of tube 5. The anode of tube 5 is connected to the positive terminal 8 of the voltage source already mentioned.

The cathode of tube 4 is preferably of the indirectly heated type and is connected to ground. The cathode of the tube 5 is preferably likewise of the indirectly heated type and is connected to ground through a resistor 26. It is likewise connected through a suitable ammeter 27 to the positive terminal of resistor 11. A sliding tap 28 on the resistor 26 is connected to the positive terminal of voltage source 7, and thus acts to impress a negative feedback, already mentioned, through the resistor 6 on the control electrode of tube 1. A screen grid electrode 29 in tube 4 is preferably connected to the positive terminal of resistor 11. A screen electrode 31 in tube 3 is likewise connected to the common junction of a pair of serially connected resistors 32, 33, which in it form a path shunted between the positive terminal 8 already mentioned and ground.

In accordance with our invention, it is preferable to operate the tube 1 with its voltages so adjusted that when the current input to terminal 2 is zero, the potential of the control electrode of tube 1 is adjusted to the point where that control electrode draws no current.

Fig. 2 illustrates the relationship between the potential of the control electrode of tube 1 relative to its cathode, and the amount of current drawn by that control electrode from the electron emission of its cathode. In short, it is preferable to operate the tube 1 at the point 34 corresponding to zero grid current in Fig. 2. In order to insure that the tube 1 is so operating, the terminal 2 is disconnected from the current source to be measured, and a short circuit is alternately made and broken across the resistor 6. The position of the tap 28 on resistor 26 is then varied until a point is found in which the reading of ammeter 27 undergoes no variation with the opening and closing of this short circuit. Under such conditions it is obvious that since the only current flow between the cathode and control electrode of tube 1 must go through the resistor 6, and opening and closing a short circuit across that resistor produces no change in the currents flowing through the output circuit of tube 5, the current through resistor 6 must be zero. Hence, the grid current of tube 1 must be zero.

The value of the bias battery 7 and the position of tap 17 are made such that the relative feedback from the tap point 28 reduces the net voltage amplification through the amplifier tubes 1, 3, 4 and 5 to substantially unity. Under such circumstances, the output resistor 26 impresses such a strong negative voltage on the control electrode of tube 1, when a change in the current input to terminal 2 tends to raise or lower the potential of that control electrode, that this tendency is reduced nearly to zero. As a result, the voltage of the control electrode of tube 1 never departs substantially from the point 34 shown in Fig. 2, and there is correspondingly substantially no change in the control electrode current in tube 1 from the zero value indicated by that point 34. There is, consequently, no substantial flow of current from grid to cathode in tube 1 and the entire input current to the terminal 2 flows to ground through the resistor 6. As a result, voltage variation on the resistor 6 is exactly proportional to current variations flowing into the terminal 2 and output current variations through the ammeter 27 follow, with substantial fidelity of proportion, all variations in the input current to the terminal 2.

To give a specific example of the application of the principles of our invention, the tube 1 may be a Westinghouse RH-507, tube 3 an R. C. A. 1S5, tube 4 an R. C. A. type 6S7, and tube 5 an R. C. A. 6F6. The resistors above enumerated may have the following values.

Resistor No.	Megohms
6	105
9	500
10	1,530
11	300
12	1,240
13	150
15	50
16	1
18	200
22	1
25	0.52
26	1,000
32	50
3	200

The bias voltage sources have the following values: 7, 50 volts; 19, 3 volts; 23, 45 volts. Capacitor 21 is 0.1 microfarad.

We claim as our invention:

1. In combination with an amplifier input electrical discharge tube of a grid-controlled type

in which the grid current varies at a comparatively high rate with changes in grid voltage, a negative feedback circuit between the output of said amplifier and the control electrode of said tube adjusted to give an overall voltage amplification of the order of unity for said amplifier, means for impressing on said grid such a bias voltage as makes said grid current zero, and current responsive means in the output circuit of said amplifier.

2. In an amplifier for relatively small direct currents, an input tube having a grid and of a type in which grid current varies at a substantial rate with grid voltage, a negative feed-back between the output circuit of said amplifier and said grid adjusted to produce an overall voltage amplification in said amplifier of substantially unity, means for giving said grid voltage a value which makes said grid current zero, and current responsive means in the output circuit of said amplifier.

3. In combination with a source of relatively small direct current, an amplifier therefor comprising an input tube of the type in which the control electrode current varies at a relatively high rate with the control electrode voltage, a negative feedback connection from the output of said amplifier to said control electrode adjusted to give a voltage amplification of the order of unity in said amplifier, means to make said control electrode current zero when said direct current is zero, and current responsive means in the output circuit of said amplifier.

4. In an amplifier of the electronic type, an input tube of a type in which the control electrode current varies at a substantial rate with changes in control electrode voltage relative to the cathode of said input tube, a feedback connection from

the output circuit of a tube separated from said input tube by an even number of amplifier tubes, a resistor in said feedback connection, and means for varying the amount of voltage impressed through said resistor to make the control electrode current of said input tube zero when the input current to its control electrode circuit is zero.

5. In combination with an amplifier having an input tube having a control electrode in which the current varies at a substantial rate with variations in the control electrode voltage relative to the cathode, a second tube separated from said input tube by an even number of intervening amplifier tubes, a resistor connecting the cathode of the last-mentioned tube to the cathode of said input tube, a feedback connection containing a resistor between the control electrode of said input tube and a tap point on the last-mentioned resistor, and means for giving said control electrode voltage such a value as to make said current zero.

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