

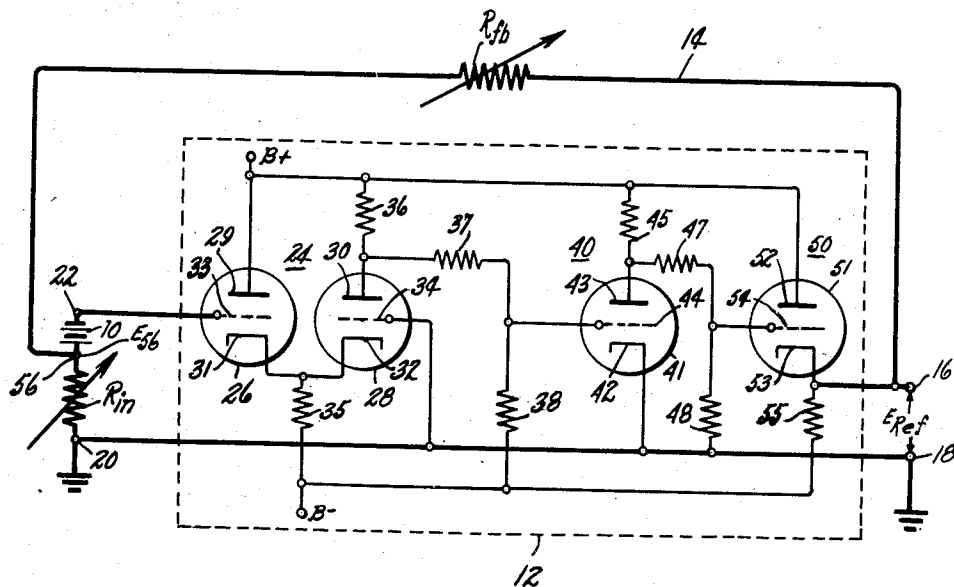
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REFERENCE VOLTAGE SOURCE

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REFERENCE VOLTAGE SOURCE

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This invention relates to a highly stable reference voltage source. More particularly, this invention is directed to such a source which may be used for precision power supplies.

The particular reference voltage source disclosed has been developed for use in precision power supplies for electronic computers and is therefore described in connection with this application. However, it is to be understood that the use of the reference voltage source is not so limited and it is to be particularly understood that the reference voltage source may itself be used as a precision unidirectional voltage source where it is only necessary to supply low output currents (on the order of 20 milliamperes maximum).

High voltage power supplies are used in electronic computers to provide positive plate voltages and negative biasing voltages for the electron tubes used therein and also to provide positive and negative supplies for computing voltages utilized in the actual computations. It is necessary that these power supplies provide precise constant output voltages if the computer with which they are utilized is to give precision results. The main problems encountered in this connection are that variations in the supply voltage of the high gain direct current amplifiers commonly used in electronic computers causes the output of the amplifiers to change or drift and that such voltage variations cause the output incremental impedance of the power supply (i. e., the ratio of corresponding voltage and current changes) to change. These problems are actually problems of computer amplifier design and are not discussed in great detail in this description. However, they are brought out here in order to illustrate an application of the reference voltage source of the present invention. It should suffice to say that if the output of the high voltage power supply varies even over a small range the direct current amplifiers used for the computing operation, usually called operational amplifiers, will have a varying output voltage and this cannot be tolerated if the computations are to be accurate. The problem of the power supply output incremental impedance change is just as important as controlling the voltage output within narrow limits since any variation in output incremental impedance or at least any variation which is greater than a specified minimum value (determined by the particular application) causes feedback effects in the amplifiers due to coupling which results in errors in the computations and even to uncontrolled circuit oscillation in some instances.

The power supplies normally are energized from available 60 cycle alternating current power lines. Such power lines supply a voltage which may vary over a large range in both frequency and amplitude. The power supplies themselves are usually of conventional design, for example, such a rectifier is illustrated in Figure 7.22 on page 13 of the book entitled *Electronic Analog Computers* by Korn and Korn, published by McGraw-Hill Book Company, 1952, and other suitable types of power supplies are illustrated and discussed in Chapter 11 of

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the book entitled *Principles of Electron Tubes* by H. J. Reich, published by McGraw-Hill Book Company. However, in view of the facts stated above it is apparent that some means must be provided to regulate the output of such supplies if they are to be reliable enough for use in computers. The reliability of such power supplies is limited by the degree of regulation which can be obtained.

It is common in regulator units for such power supplies to provide some means to compare a portion of the regulated output voltage with the voltage of a highly stable reference voltage source, such as a battery or the voltage drop across a gas discharge tube, and provide some means to correct any error in the regulated output voltage.

The regulation obtained cannot be better than the quality of the reference voltage source used. Therefore, the quality of the available reference voltage source is a major limitation on the accuracy of the power supply itself.

Examples of two comparison circuits which may be used in voltage regulators are illustrated in Figure 7.24 of *Electronic Analog Computers* on page 319. One of these circuits is illustrated with a gas discharge tube providing the reference voltage and the other circuit is illustrated as using a battery for this purpose. Figure 7.27 of this same book, on page 321, illustrates a power supply which utilizes a reference element (shown as a battery) to obtain a regulated output from an unregulated unidirectional voltage source. One source of error of such systems results from the fact that a portion of the output of the regulated power supply must be obtained by some means such as by a precision voltage divider in order to make a comparison with a low voltage reference source such as a standard cell. Accuracy is sacrificed in such schemes. Another problem presented by systems which utilize batteries, such as standard cells, as the reference voltage source is that damaging current may be drawn from the standard cell or cells under certain conditions.

A method which has been utilized to overcome the problem of obtaining only a portion of the regulated output of the voltage supply in order to compare it with the lower reference voltage is to amplify the voltage of a low voltage source, such as a standard cell, to obtain a relatively high voltage reference source and compare this reference voltage with at least a portion of the regulated output voltage. Major disadvantages of such systems are that the output voltage of direct current amplifiers tend to drift and damaging currents are likely to be drawn from the standard cell. In order to overcome the drift problem, various mechanical arrangements have been used. For example, mechanical choppers are used to compare the amplifier output voltage with that of the standard cell and a feedback circuit is utilized to correct the amplifier output in accordance with any error between the compared voltages. This problem and the apparatus described above is discussed in detail in an article by Williams, Tarpley, and Clark which appears in *Transactions of the American Institute of Electrical Engineers*, 67:47, 1948, and also in the article entitled "Stabilization of D-C Amplifiers" by E. A. Goldberg in *RCA Review*, 11:296, 1950.

The mechanical arrangements used to overcome the difficulties discussed above give rise to other problems. For example, vibrations and temperature changes may render them unstable and, further, mechanical choppers have short life and are sources of noise. Other disadvantages are their high output impedance and the possibility of drawing damaging current from the cell or cells used.

Accordingly, it is an object of this invention to provide a highly stable reference voltage source which does not require moving parts.

Another object of this invention is to provide a reliable reference voltage source which has a relatively long life and is highly stable.

Briefly stated in accordance with the preferred embodiment of this invention, a highly stable reference voltage source is obtained using a stable unidirectional voltage source such as a standard cell or cells and a high gain direct current amplifier. The problems of drawing a damaging current from the battery is eliminated by connecting the battery directly to the input control grid circuit of the amplifier and a stable reference voltage output is obtained from the amplifier by connecting one impedance in series with the battery and the grid circuit of the amplifier and connecting a feedback circuit from the output of the amplifier to a point between the battery and said one impedance. The feedback circuit is also provided with an impedance.

The novel features which are believed to be characteristic of this invention are set forth with particularity in the appended claims. The invention itself, however, both as to its organization and method of operation together with further objects and advantages thereof, may best be understood by reference to the following description taken in connection with the accompanying drawing in which the circuit and apparatus utilized in a preferred embodiment of this invention is schematically shown.

Referring specifically to the single drawing, it may be seen that the reference voltage source of this invention employs a stable unidirectional voltage source 10, such as a standard cell or cells, a conventional high gain direct current amplifier 12, and a feedback circuit 14 which interconnects the amplifier output and input. The high gain direct current amplifier 12 is provided to amplify the voltage of the standard cell 10 and provide a highly stable reference voltage E_{ref} across its output terminals 16 and 18. The feedback circuit 14 is employed and the forward gain of the amplifier 12 is made as high as possible (e. g., a gain on the order of 500 to 50 million may be used) in order to render the reference voltage E_{ref} between the output terminals 16 and 18 of the amplifier substantially independent of amplifier drift. The amplifier 12 may be of any variety but is preferably one of the conventional high gain, low drift, direct current amplifiers commonly used in computer applications.

The amplifier circuit illustrated is a conventional three-stage direct current amplifier sometimes referred to as the University of Michigan Amplifier (Figure 5.31, page 193 of *Electronic Analog Computers*).

The function of the amplifier 12 in its present application is to amplify any unidirectional voltage applied between input terminals 20 and 22. A conventional difference or differential amplifier is used as the first amplifier stage 24 in order to reduce drift. This difference amplifier incorporates two three-element, or triode, electronic vacuum tubes 26 and 28. The two tubes 26 and 28 are provided with anodes 29 and 30, cathodes 31 and 32, and control grids 33 and 34 respectively. The cathodes 26 and 28 of both tubes are connected to a source of negative potential B— through a cathode resistor 35. The anode 29 of the input tube 26 is connected directly to a source of positive potential B+ while the plate of the second tube 28 is connected to the same source of positive potential through a plate resistor 36. The control grid 33 of the first or input tube 26 is connected to one input terminal 22 and the control grid of the second tube 28 is connected to the input terminal 20 which is at ground or reference potential. The output of this stage is developed across first stage load resistors 37 and 38 which are connected in series with each other and between the anode 30 of the second tube 28 and the source of negative potential B—.

The second amplifier stage 40 is simply a higher level regulating amplifier. This stage utilizes a single triode vacuum tube 41 which has a cathode 42, an anode 43, and a control grid 44. This circuit, which is conven-

tional, has the anode 43 connected to the source of positive potential B+ through a plate resistor 45 and the cathode 42 connected to ground or reference potential. The control grid 44 is connected to receive the voltage developed across load resistor 38 of the first amplifier stage. The output voltage of this stage is developed across the second stage load resistors 47 and 48 which are connected between the anode 43 of the third vacuum tube 41 and the negative potential source B—. In order to minimize the output impedance of the amplifier 12, the output stage 50 utilizes a conventional cathode follower. This stage also incorporates a vacuum tube 51 having an anode 52, a cathode 53, and a control grid 54. In this stage the anode 52 of the vacuum tube 51 is connected directly to the source of positive potential B+, its cathode 53 is connected to the negative potential source B— through a cathode resistor 55 which also serves as the amplifier load resistor, and the control grid 54 is connected to receive the voltage developed across the second stage load resistor 48. The output voltage from the third amplifier stage 50 and the output voltage of the direct current amplifier 12 is developed between one amplifier output terminal 16, which is connected directly to the cathode 53 of the output tube 51 and the other terminal 18 which may be connected to ground or other reference potential.

Each stage of the amplifier is conventional and is analyzed in detail in numerous elementary texts. In view of this fact and in view of the fact that the particular amplifier employed is not critical to the present invention, the operation of the amplifier 12 is not analyzed in detail in the present description. However, it is noted that the first stage difference amplifier 24 is analyzed on pages 116 and 117 of *Electron Tube Circuits* by Samuel Seely, published by McGraw-Hill Book Company, Inc., 1950, the second amplifier stage 40 is a simple triode amplifier discussed and fully analyzed in Chapter 3, pp. 39-51, inclusive, of this book, and the output (cathode follower) stage 50 is analyzed in detail on pages 102-108, inclusive, of this text. In addition, the coupling problems involved when using direct coupled amplifiers of the type illustrated and described here are discussed on pages 111-117, inclusive, of this book.

It should suffice to say that any potential difference between the control grids 33 and 34 of the difference amplifier input stage 24 results in an amplified output voltage at the plate 30 at the second tube 28 which voltage is developed across the output resistors 37 and 38 of this stage. A portion of this voltage is applied to the control grid 44 of the second amplifier stage 40 which further amplifies the difference voltage applied between the grids 33 and 34 of the input stage. This output voltage is developed across second stage output resistors 47 and 48. The control grid 54 of the cathode follower stage 50 is connected to receive at least a portion of the voltage developed by the second amplifier stage 40 and amplifies this voltage so that a voltage appears between the amplifier output terminals 16 and 18 which is a function of the potential difference between the input control grids 33 and 34.

The particular feedback circuit arrangement is more important to the operation of the apparatus as a highly stable reference voltage source than the particular type of amplifier used. From an inspection of the single drawing it is seen that the feedback circuitry employed includes the circuitry commonly used in direct current analog computers for multiplying a direct current voltage by a constant.

For the algebraic operation of multiplying, an input impedance R_{in} is normally connected directly to the input of a direct current amplifier 12 and a feedback impedance R_{fb} is connected from the output of the amplifier back to a point 56 between the amplifier input and the input impedance R_{in} . Any voltage E_c to be multi-

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plied is then connected to the amplifier input through the input impedance R_{in} and the output voltage supplied by the amplifier E_{ref} is equal to the product of the voltage E_c applied to the circuit times the ratio of the magnitude of the feedback impedance R_{fb} to the magnitude of the input impedance R_{in} ; i. e.,

$$E_{out} = \frac{R_{fb}}{R_{in}} E_c \quad (1)$$

Thus, by varying the ratio of the two impedances, the system gain is varied. This operation is described in detail in Electronic Analog Computers on pages 10, 12, and 13 and illustrated in Figure 1.7(b) on page 11.

The reference voltage supply of the present invention differs from the usual scaling amplifier just described in two notable respects. First, the input impedance R_{in} is connected to the input terminal 20 which is at ground or reference potential instead of being connected to a computing voltage source and secondly, a voltage source, illustrated as standard cells 10, is connected between the input impedance R_{in} and the input terminal 22 of the direct current amplifier 12 which input terminal is connected to the control grid 33 of the first tube 26 in the amplifier input stage 24. Input terminal 22 is referred to as the amplifier input since the opposite input terminal is connected to ground or other reference potential. Ignoring the voltage provided by the standard voltage source 10 and utilizing Equation 1 above, it is seen that the computing voltage applied to input terminal 22, is illustrated as being ground potential (zero voltage), therefore the output voltage using this arrangement would also be zero. However, the introduction of the standard voltage source 10 between the amplifier input terminals 20 and 22 (along with the input impedance R_{in}) provides a constant error voltage in the input circuit of the amplifier 12. This error voltage is amplified by amplifier 12 and results in an amplified potential difference which appears between the output terminals 16 and 18.

As illustrated and as preferred, the source of standard voltage 10 is poled so that it applies a negative potential to the input terminal 22 of the amplifier 12 and a positive potential to the junction 56 between the input and feedback resistors R_{in} and R_{fb} .

It is common practice to assume that a high gain direct current amplifier of the type contemplated here does not draw grid current and this assumption is essentially correct. Thus, when the standard voltage source is connected in series with the input of the amplifier, as illustrated here, damaging current cannot be drawn from the standard cell. A stable reference voltage source is provided if the polarity of the standard cell is reversed but it has been found that some current may be drawn from the standard source under certain biasing conditions.

With the circuit connections as illustrated and described above, the reference voltage which appears between the output terminals 16 and 18 is equal to the voltage from the standard voltage source multiplied times the factor (1 plus the ratio of the value of the feedback resistor to the value of the input resistor). In other words,

$$E_{ref} = E_{std} \left(1 + \frac{R_{fb}}{R_{in}} \right) \quad (2)$$

where E_{std} is the voltage of the standard cells 10, R_{fb} is the magnitude of feedback resistor and R_{in} is the magnitude of the input resistor. This relationship is mathematically derived below. First assume that there is no grid current drawn by amplifier 12. Then using a Kirchoff loop it may be seen that:

$$\frac{E_{56} - E_{ref}}{R_{fb}} + \frac{E_{56}}{R_{in}} = 0 \quad (3)$$

where E_{56} is the voltage at the junction 56 between the input resistor R_{in} and the standard cells 10. The other

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symbols have been explained previously. An inspection of the circuit shows that:

$$E_{ref} = A (E_{56} + E_{std}) \quad (4)$$

5 where A is the forward gain of amplifier 12.

Solving Equation 4 for E_{56} we get:

$$E_{56} = E_{ref} \left(\frac{1}{A} \right) - E_{std} \quad (5)$$

10 If we assume the forward gain, A, is very large, e. g., 50 million, then the term

$$\frac{1}{A}$$

15 approaches zero and therefore Equation 5 reduces to:

$$E_{56} = -E_{std} \quad (6)$$

In other words, if the gain of amplifier 12 is made very high, the output voltage E_{ref} is independent of the gain. 20 Thus we may substitute $(-E_{std})$ in Equation 3 for E_{56} as follows:

$$\frac{(-E_{std}) - E_{ref}}{R_{fb}} + \frac{-E_{std}}{R_{in}} = 0 \quad (7)$$

25 Solving this equation to get an expression for the reference (output) voltage E_{ref} we get:

$$E_{ref} = -E_{std} \left(1 + \frac{R_{fb}}{R_{in}} \right) \quad (2)$$

30 which again is Equation 2 above.

From the relationship of Equation 2 above, it is seen that the output voltage E_{ref} may be varied by varying the value of either or both of the input resistor and feedback resistor. Thus, the voltage of the reference source may be made adjustable by making either or both of these resistors adjustable.

While a particular embodiment of this invention has been shown it will, of course, be understood that the invention is not limited thereto since modifications both in the circuit arrangement and in the instrumentalities employed may be made. It is contemplated that the appended claims will cover such modifications as fall within the true spirit and scope of this invention.

45 What we claim as new and desire to secure by Letters Patent of the United States is:

1. A reference voltage source including direct current amplifying means having a pair of input terminals for receiving a control voltage and a pair of output terminals for supplying the reference voltage, said amplifying means having at least one amplifying current conducting device with a control element for controlling the conduction of said amplifying device connected to one input terminal, input impedance means and a standard source of unidirectional voltage connected between the input terminals in such a manner that said standard source is connected to said control element, and a feedback impedance connected from the junction point between said input impedance and said standard source to one of said output terminals.

2. A reference voltage source including the combination of a direct current amplifier having at least one current conducting amplifying device with a control element for controlling the conduction of said device, said amplifying device having a pair of input terminals adapted to receive a control voltage for supplying the reference voltage and a pair of output terminals, one of said input terminals and one of said output terminals being connected to a common potential, the opposite one of said input terminals being connected to said control element, an input impedance means and a standard unidirectional voltage source connected between said input terminals in such a manner that said standard source is connected to said control element, and a feedback impedance connected from the remaining output terminal to the junction

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tion point between said input impedance and said standard voltage source.

3. A reference voltage source comprising a direct current amplifier having an input and an output, an input impedance and a standard source of unidirectional potential connected in series circuit relationship with each other, said standard source being connected directly to said input, and a feedback impedance connected between the output of said amplifier and the junction between said standard source and said input impedance. 10

4. In a reference voltage source, amplifying means having a pair of input terminals for receiving a control voltage and a pair of output terminals for applying the reference voltage to a load device, control means for determining the output of said amplifying means connected to one of said input terminals to receive a control voltage applied thereto, an input impedance means, a standard source of unidirectional voltage, said input impedance means and said standard source being connected in series with each other and between said input terminals in such a manner that said standard voltage source is connected to said control means and applies a negative potential thereto, and feedback imped-

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ance means connected from the junction point between said standard source and input impedance means to one of said output terminals.

5. In a reference voltage source, amplifying means having an input and an output, input impedance means, means for supplying a unidirectional potential, said input impedance means and said potential supplying means being connected in series circuit relationship with each other and to said amplifier input in such a manner that said potential source is connected directly to said input and applies a negative potential thereto, and feedback impedance means connected between the output of said amplifying means and the junction between said potential source and said input impedance means.

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