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VOLTAGE-DROP COMPENSATORS FOR DC-MICROAMMETERS

N6-ori-07140
TECHNICAL REPORT NO. 3

ELECTRICAL ENGINEERING RESEARCH LABORATORY
ENGINEERING EXPERIMENT STATION
UNIVERSITY OF ILLINOIS
URBANA, ILLINOIS

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Technical Report No. 3

Project No. NR 072 161
N6-ori-07140

Date:
September 1954

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ACKNOWLEDGMENTS

The author would like to express his appreciation to Professor John Bardeen, Professor W. L. Emery and Professor T. A. Murrell for the interest which they have shown in this problem.

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VOLTAGE - DROP COMPENSATORS FOR DC-MICROAMMETERS

1. ADVANTAGES OF A COMPENSATING DEVICE

The voltage-drop across ammeters having a full-scale deflection of approximately one hundred microamperes is generally of the order of a few tenths of a volt (internal resistance $\sim 2\ K\Omega$) and in several applications it seems desirable to reduce this voltage-drop by a factor of ten or more. This, of course, can be done by replacing the meter by the input resistance of a DC-amplifier, the output of which drives the meter: One method of realization is a transistor in grounded-base connection (having thus an input resistance of the order of 100Ω), the collector circuit being closed by the meter.

The fact that the meter is driven across an amplifying network imposes upon the linearity of this network conditions which often cannot be met easily. In this case, a set-up as shown in Fig. 1 is desirable. The DC-amplifier is used only to create a voltage-drop in a

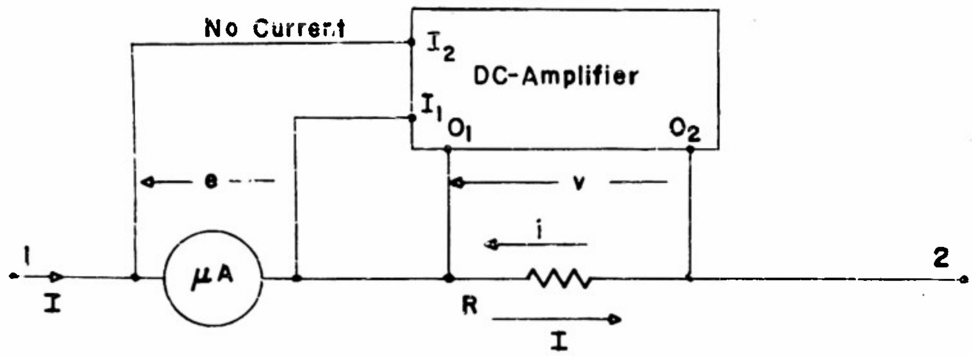

FIGURE 1

resistor, connected in series with the meter, which compensates the meter-drop. If the control of the amplifier needs no current, (a condition easy to realize with tubes but not with transistors), the meter indicates the current flowing into terminal 1 and out of terminal 2.

Three conditions are imposed upon the amplifier:

(1) One input and one output terminal (I_1 and 0_1 in Fig. 1) must be common,

(2) The quiescent voltage-drop across the output resistor, R, must be zero for zero current in the ammeter,

(3) The current increment, i, produced by a current, I, through the ammeter must oppose I.

Let us call e the meter voltage-drop, g the transconductance of the amplifier (supposed constant and independent of R) and k the internal resistance of the meter. Then

$$i = eg = kIg \qquad (1.1)$$

and the apparent resistance R^* of the whole device between terminals 1 and 2 is

$$R^* = \frac{e + v}{I} = \frac{kI + (I - i) R}{I}$$

$$= (k + R) - kRg = R^+ - R^- , \qquad (1.2)$$

where we call positive resistance, R^+, the first term, and negative resistance, R^-, the term kRg. We shall distinguish two types of devices: (1) those which always give $R^- < R^+$ and which therefore are short-circuit stable, and (2) those which can give $R^- > R^+$ and which are likely to go into oscillation if connected to low-resistance exterior circuits.

2. DEVICES EXHIBITING NEGATIVE APPARENT RESISTANCE AND DEVICES OF THE CATHODE-FOLLOWER TYPE

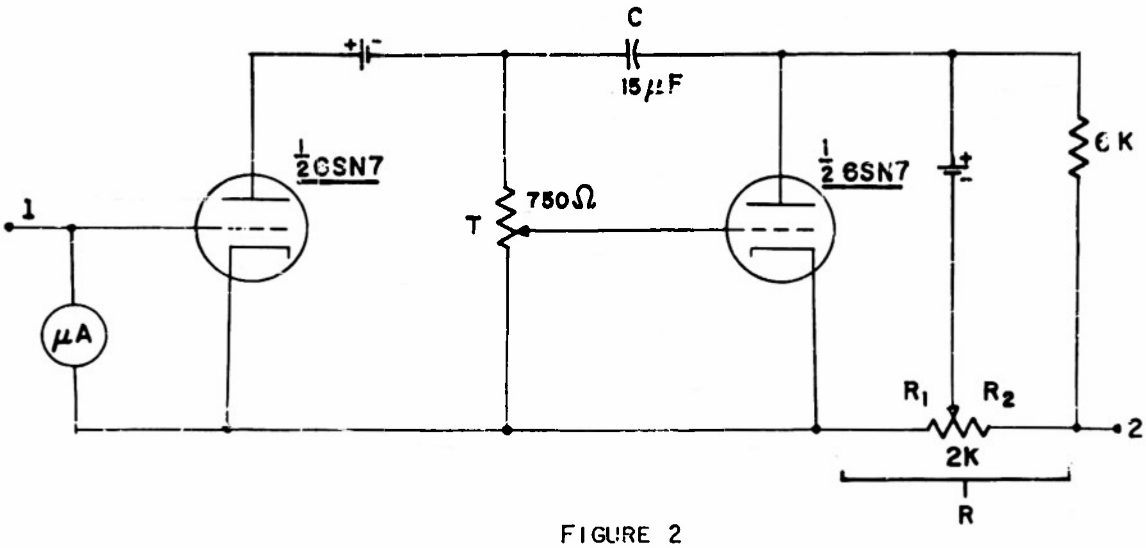

FIGURE 2

A set-up as in Fig. 2 satisfies the requirements enunciated in the last paragraph. After having set the gain at the required value by adjusting r, one has only to balance out the quiescent voltage-drop created by the second tube in R_1, for example by short-circuiting terminals 1 and 2 and bringing the meter to zero with the potentiometer R. As soon as the apparent resistance R^* approaches zero, oscillations set in on the slightest provocation. This tendency can be reduced by connecting a capacitor between the grid and the plate of the last tube, viz., by using a Miller-network to stabilize the device.

It is easy to see that for slowly varying voltages

$$R^+ = k + R_1 + R_2$$

$$R^- = kr\ R_1\ (g_m)^2 \tag{2.1}$$

where g_m is the transconductance of either of the tubes and r the grid resistance in the second stage. For rapidly varying voltages, the impedance of C drops to a low value and the feedback thus obtained decreases R^-.

This set-up is usable, but suffers from several shortcomings: interdependence of the gain and compensating controls, big drift due to the fact that the drop created by the tube current in R_1 is compensated by a tube-independent drop in R_2 (resistor network), and, near zero apparent resistance R^*, variation of the sign of R^* with temperature-dependent tube parameters.

The appearance of $R^* < 0$ when $R^- > R^+$, is clearly a result of the fact that the voltage-drop in the meter is overcompensated. If the voltage injected in series were always slightly smaller than this drop, great stability could be obtained. This slightly smaller voltage is a natural feature of the circuit of Fig. 3 (cathode-follower), i.e., for sufficiently large values of R_1 the voltage-drop between 1 and 2 is negligible as fas as variational values are concerned. The quiescent voltage-drop in R_1 can be eliminated by the balanced circuit design of Fig. 4, which overcomes the drift problem at the same time. The resist-

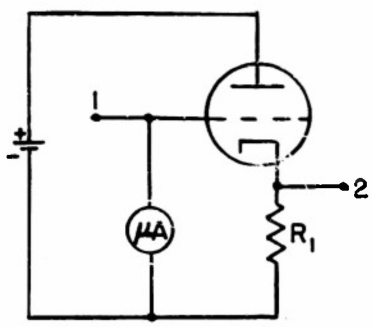

FIGURE 3

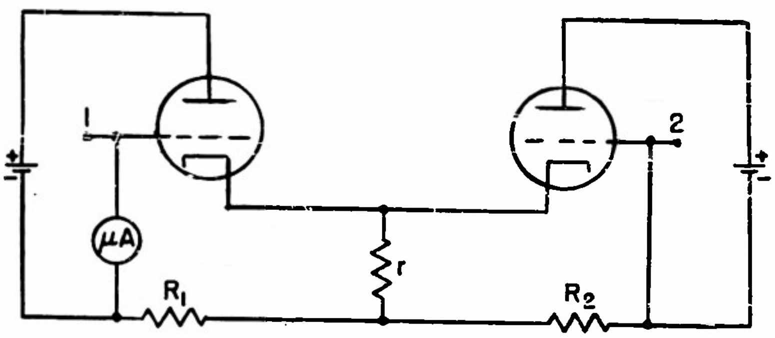

FIGURE 4

ance, r, common to the two cathode-circuits, can be left out, but practically it reduces the drift of the device appreciably.

3. THEORY OF THE BALANCED CATHODE-FOLLOWER CIRCUIT

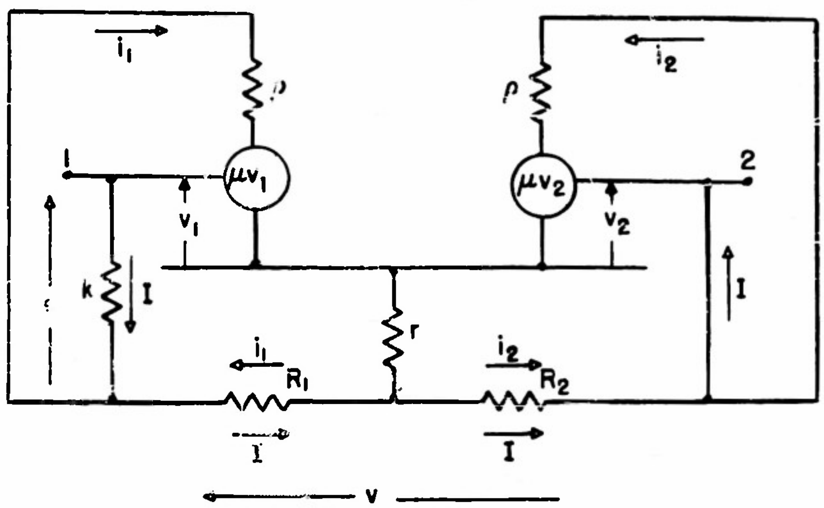

FIGURE 5

Let us call ρ the plate resistance of the two (identical) tubes, μ their amplification factor and g_m their transconductance, v_1 and v_2 the grid voltages, i_1 and i_2 the plate currents, k the meter resistance, $R_1 = R_0$ and $R_2 = R_0$ the cathode resistances, and r the resistance in the common cathode lead.

The network equations are then

$$v_1 = -r(i_1 + i_2) - R_0 i_1 + (k + R)\, I \quad (3.1)$$
$$v_2 = -r(i_1 + i_2) - R_0 i_2 - RI \quad (3.2)$$
$$\mu v_1 = (\rho + R_0 + r)\, i_1 - R_0 I + r i_2 \quad (3.3)$$
$$\mu v_2 = (\rho + R_0 + r)\, i_2 + R_0 I + r i_1 \quad (3.4)$$
$$e + v = (k + 2R_0)\, I - R_0\, (i_1 - i_2) \quad (3.5)$$

Subtracting Eq. 3.2 from 3.1 and 3.4 from 3.3 and substituting,

$$(i_1 - i_2) = \frac{(\mu k + 2\mu R_0 + 2R_0)}{\rho + R_0 + \mu R_0} I \tag{3.6}$$

i.e., by Eq. 3.5,

$$R^* = \frac{e + v}{I} = (k + 2R_0) - \frac{R_0 (\mu k + 2\mu R_0 + 2R_0)}{\rho + R_0 + \mu R_0} . \tag{3.7}$$

Let us introduce the notation of the first paragraph:

$$R^+ = k + 2R_0 \tag{3.8}$$

$$R^- = \frac{R_0 (\mu k + 2\mu R_0 + 2R_0)}{\rho + R_0 + \mu R_0} . \tag{3.9}$$

It is easy to see that if

$$Q = \frac{R^-}{R^+} = \frac{1 + \frac{2R_0}{\mu R^+}}{1 + \frac{\rho + R_0}{\mu R_0}} , \tag{3.10}$$

one has for sufficiently large values of μ

$$S = 1 - Q \cong \frac{1}{\mu} \left[\frac{\rho + R_0}{R_0} - \frac{2R_0}{R^+} \right] \tag{3.11}$$

i.e., for $k << R_0 << \rho$,

$$S \cong \frac{1}{\mu} \cdot \frac{\rho}{R_0} \tag{3.12}$$

and

$$R^* = R^+ (1 - Q) = R^+ S$$

$$= \frac{\rho}{\mu} (2 + \frac{k}{R_0}) = \frac{1}{g_m} (2 + \frac{k}{R_0}) . \tag{3.13}$$

Clearly the minimum of R^* is obtained for R_0 as big as possible, but generally the choice of the tube determines the value of R_0. The minimum apparent resistance

$$R^*\text{min} = \frac{2}{g_m} \tag{3.14}$$

depends only on the tubes used, i.e., even for zero meter impedance, the impedance of the device cannot be lower than R^*min. The same result holds for pentodes. Table I gives R^* min and R^* for a meter of 2 KΩ internal resistance for some common tubes. The resistances R_0 are equal to 10 KΩ except for the 6SF5, where we took 60 KΩ.

Table I

Tube	R^* min	R^* for a 2 KΩ-meter
6SF5	1600 Ω	1630 Ω
6SN7	660 Ω	800 Ω
6AC7	220 Ω	260 Ω
6AG7	180 Ω	220 Ω

4. PERFORMANCE OF THE BALANCED CATHODE-FOLLOWER CIRCUIT

The ripple of plate and screen voltages having no effect on the performance of a balanced circuit, a very crude power-supply as shown in Fig. 6 is sufficient. The potential divider between the cathodes and screen grids gives to the cathodes a negative polarization which offsets the negative grid voltage due to the fact that the grids are tied to the negative side of the plate-circuit resistors.

To zero the instrument, one only has to short-circuit IN and OUT and adjust the 2 KΩ potentiometer. There is no gain control.

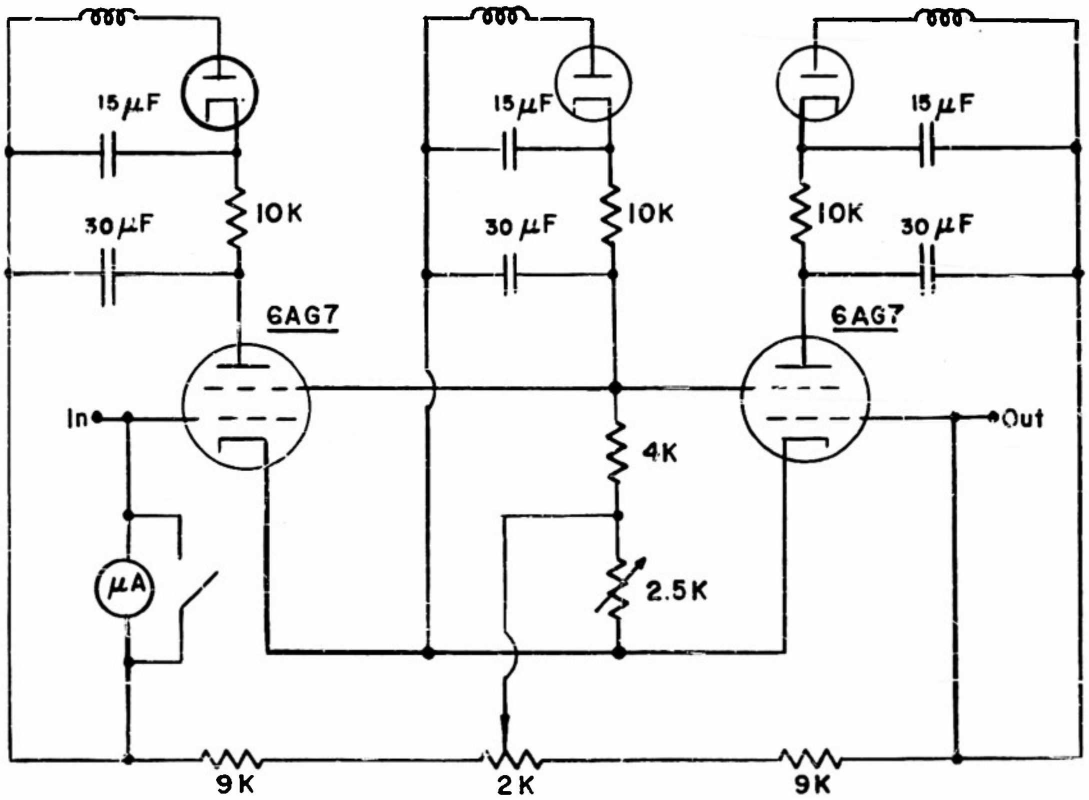

FIGURE 6

As long as the device is connected to a high resistance circuit, there is no drift because an unbalanced voltage in the plate circuits then causes a negligible additional current. The meter indicates, of course, the exact value of the current and in certain applications the additional injected voltage may be of little consequence. For a circuit resistance of 10 KΩ and properly matched tubes, drift is less than 2μA/hour once the device is properly warmed up, i.e., after 15 minutes. During this operation, it is useful to short-circuit the meter because of transient grid currents.

5. NUMBER OF BALANCED TWO-TUBE CIRCUITS USABLE AS COMPENSATORS

We can obtain this number in the following way: we can draw two general DC single-tube equivalent circuits each having a cathode resistor and a divided plate resistor ($r_1 \ldots r_{3'}$). Let r_p and $r_{p'}$ be the equivalent plate resistances, (see Fig. 7).

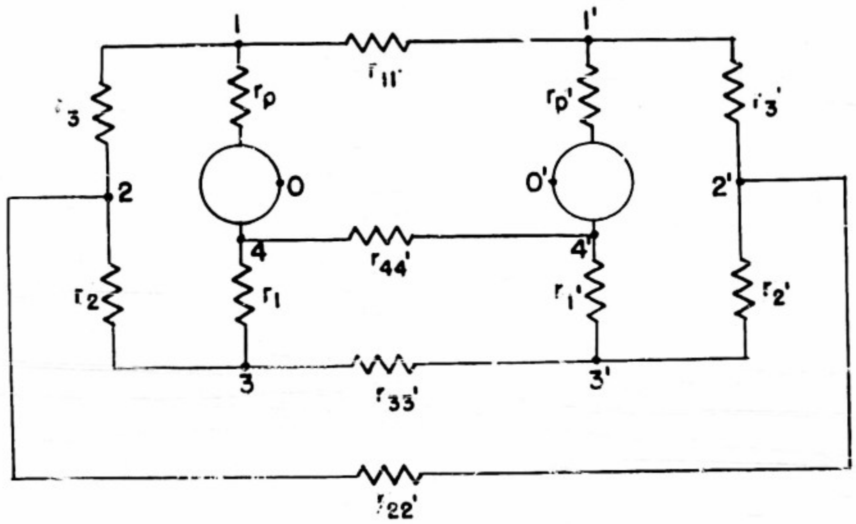

FIGURE 7

This gives in either circuit four points of interest - 1, 2, 3, 4, 1′, 2′, 3′, 4′ - which can be connected in a symmetrical manner (balanced circuit) by four feedback resistors, $r_{11'} \ldots r_{44'}$. The two grids, 0 and 0′, can then be tied through a resistor either to the circuit of the same tube ("straight-coupled") or to that of the other tube ("cross-coupled"). There are then the following possibilities:

$$\begin{pmatrix} 0 & 1 \\ 0' & 1' \end{pmatrix} \quad \begin{pmatrix} 0 & 2 \\ 0' & 2' \end{pmatrix} \quad \begin{pmatrix} 0 & 3 \\ 0' & 3' \end{pmatrix} \longrightarrow \text{"straight-coupled"}$$

$$\begin{pmatrix} 0 & 1' \\ 0' & 1 \end{pmatrix} \quad \begin{pmatrix} 0 & 2' \\ 0' & 2 \end{pmatrix} \quad \begin{pmatrix} 0 & 3' \\ 0' & 3 \end{pmatrix} \longrightarrow \text{"cross-coupled"}$$

It is easy to see that the "cross-coupled" circuits are unstable (multivibrators) for if the potential of 0 rises, that of 1, 2 and 3 drops; then the potential of 1′, 2′ and 3′ drops too, i.e., that of 0 rises further still.

We thus only have to examine the three "straight-coupled" circuits. Now the meter has to be connected to 0 (or 0′) to guarantee that its indications are correct. On the other hand there is no fundamental difference between the cases where the other end of the meter, i.e., the grid, is tied to points 1, 2, and 3, (4 is excluded, because the meter must be in series with one of the resistors on the tube circuit). It is also clear that the condition that the IN-OUT-circuit must include resistors in the tube plate circuits forces us to take 0 as "IN" and, by symmetry, 0′ as "OUT". Further, the direction of the plate current increments produced by a meter-drop imposes the closing of the circuit by a fairly small resistance in position $r_{22'}$, $r_{33'}$, or $r_{44'}$. All circuits satisfying the above requirements are thus fundamentally the same as the one discussed in this paper.

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