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Publisher's version / Version de l'éditeur:
https://doi.org/10.4224/21273636
Report (National Research Council of Canada. Radio and Electrical Engineering Division : ERA); no. ERA-240, 1952-12

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ERA-240

UNCLASSIFIED

NATIONAL RESEARCH COUNCIL OF CANADA
RADIO AND ELECTRICAL ENGINEERING DIVISION

THE EFFECT OF COMPONENT TOLERANCES ON VOLTAGE STABILIZER DESIGN

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DECEMBER 1952

N.R.C. NO. 2889

ABSTRACT

To make possible the correct adjustment of the output voltage of a stabilizer, certain conditions must be imposed on the resistors used to control this voltage. These conditions are related to the manufacturing tolerances of the resistors themselves, and also to the tolerances of the tube types used in the stabilizer. From the conditions, formulas are derived for determining the correct nominal values of the resistors in terms of their own tolerances, tube tolerances, and the desired output voltage, or range of voltage. Adequate treatments from an analytical or circuitry standpoint are available and are not considered. Rather, the aim is to establish design procedures which ensure that a stabilizer performs adequately within its specified range, and continues to do so without undue ill effects from normal manufacturing variations in the components. The formulas apply directly to one type of circuit only, but they may readily be extended.

Some improvements in stabilizer design, which affect voltage control, meter placement, and circuit location of bleeder resistors, and which arose as by-products of the main investigation, are also included.

FIGURES

CONTENTS

TEXT

THE EFFECT OF COMPONENT TOLERANCES ON VOLTAGE STABILIZER DESIGN

INTRODUCTION

There is an extensive literature* on the theory and performance of voltage stabilizer circuits of the general type shown in Fig. 1. Of the more comprehensive papers (see References 1-5) those of Hogg and Scroggie are particularly noteworthy from the standpoint of design. Nowhere, however, does there appear to be any reference to a procedure for determining the value of the resistors R_1, R_2, and r_v, shown in Fig. 1(a); neither does there appear to be a general appreciation of the effects of the resistors on the characteristics of the stabilizer. The present paper considers such effects and originates methods for proper evaluation of the resistors.

Basically, of course, these resistors, together with the choice of voltage-reference (VR) tube, determine the output voltage — but there are ramifications. Anyone who has used stabilized power supplies has probably, at some time or other, replaced a defective tube or other component with its nominal equivalent only to find, as a consequence, that modification of still further components was necessary to restore normal operation. Perhaps he has found also that a second supply, built "just like the first" failed to perform as expected. Many of these difficulties stem from the use of unsuitable values for the resistors mentioned. However, when these items are correctly chosen (using the methods developed in this report), routine construction becomes possible, and the need for individual selection of parts, and the trial-and-error assembly which so often characterize stabilizer construction, are happily absent.

The circuits of Fig. 1 function to maintain the voltage, V, constant, at least approximately, and the constancy of this voltage is a measure of the merit of the device as a stabilizer. We shall first assume that stabilization is perfect, i.e., that V is absolutely constant, and later consider the effects of this assumption. Computation of the values of the resistors R_1, R_2, and R_v, normally is one of the last phases in the design of a stabilizer. (R_v is the maximum value of the variable, r_v). We assume here that the earlier steps in the design have been completed and, in particular, that the operating grid and plate voltages of the tubes are known. We shall account for effects of variations in tube voltages and characteristics, and it appears that both effects can usually be ignored.

The resistor arrangement shown in Fig. 1(a) has many advantages over that in Fig. 1(b), as will appear. What follows therefore is limited to Fig. 1(a) and the analysis is applicable only to that arrangement. Modifications necessary to adapt the results to circuits other than that in Fig. 1 should be reasonably obvious. This particular circuit was chosen for analysis because of its popularity and not necessarily for its merits.

* The author has compiled a list of some 150 papers relating to these circuits.

FORMULAS FOR RESISTOR VALUES — IDEAL CASE

To determine R_1, R_2, and R_v, we proceed as follows:

The output voltage, E, in Fig. 1(a) is obviously

$$E = \frac{V(R_1 + r_v + R_2)}{R_1} . \tag{1}$$

Usually the output voltage, E, is required to be adjustable over a range, say from a minimum, E_m, to a maximum E_M. (An example with fixed output is given later.) The adjustment is made by altering r_v. If the values $r_v = 0$ and $r_v = R_v$ correspond to the conditions $E = E_m$ and $E = E_M$, respectively, then from Equation (1),

$$E_m = \frac{V(R_1 + R_2)}{R_1} \text{, and} \tag{2}$$

$$E_M = \frac{V(R_1 + R_v + R_2)}{R_1} . \tag{3}$$

Re-arranging (2),

$$\frac{R_2}{R_1} = \frac{(E_m - V)}{V} . \tag{4}$$

By manipulating (3) and combining it with (4),

$$\frac{R_v}{R_1} = \frac{(E_M - E_m)}{V} , \tag{5}$$

or alternatively,

$$\frac{R_v}{R_2} = \frac{(E_M - E_m)}{(E_m - V)} . \tag{5a}$$

The voltage, V, is equal to the known voltage $(V_R + V_{2g})$, and in the two equations (4) and (5) there are then three unknowns R_1, R_2, and R_v. If any one of these three is known then the equations can be solved. Apparently any one of the three can be chosen arbitrarily, but actually there are several restrictions, and these will now be considered.

For stable operation it is practically essential that the variable resistor, r_v, be of wire-wound, rather than carbon-composition construction; the current, i, through the resistors, commonly known as the "bleeder" current, is frequently made as small as is feasible, and therefore maximum resistance is wanted. For variable wire-wound resistors of the common radio type this maximum is 50 kilohms, though 100-kilohm values are available at a slight price premium. Variable resistors above this value are much more expensive, and thus seldom used. For some military applications, limitations on minimum wire size may decide the available maximum. The above considerations usually suffice to determine R_v when maximum resistance, i.e., minimum bleeder current, is wanted.

It may happen that a specific bleeder current is desired, rather than minimum bleeder current as assumed above. Procedure is then as follows:

From Fig. 1(a),

$$i = \frac{E}{R_1 + r_v + R_2} .$$

Substituting for E its value from Equation (1), there results

$$i = \frac{V}{R_1} . \qquad (6)$$

(This perhaps surprising result, a bleeder current independent of output voltage, is one notable advantage of the circuit in Fig. 1(a); more will be said of it later). Inserting the given value of i in Equation (6), R_1, is obtained, and Equations (4) and (5a) are then solved for R_2 and R_v.

The value of R_v resulting from the above procedure will not usually be a standard value, and generally it is not feasible to specify non-standard values of variable resistors. Some latitude may be obtained, either by selecting the nearest standard value above the computed value and using only part of the rotation to cover the range, or by shunting this nearest higher standard value with a fixed resistance. There are disadvantages to both methods. The first procedure, by cramping the mechanical range, makes voltage adjustment difficult; it also increases instability effects arising from the sliding contact.

The second procedure destroys the linear relation which exists between shaft rotation of R_v and output voltage, E, in virtue of Equation (1). The effects may not always be important, but they should be considered.

Assuming that a value for R_v has been obtained, insert that value in Equation (5) and obtain R_1; then, substituting this value of R_1 in Equation (4), find R_2. Alternatively, if the bleeder current, i, is given, use Equations (6), (5), and (4), in turn, to obtain R_1, R_v, and R_2, respectively.

FORMULAS FOR RESISTOR VALUES — TOLERANCES CONSIDERED

Now, the procedure up to this point, while correct, suffers from a serious deficiency: no account has been taken of the manufacturing tolerances of the various components, and the neglect of these tolerances is the basic factor underlying many unsatisfactory stabilizer designs.

As given, R_1 and R_2 are nominal values, and the resistors actually may have any value in the range $R_1(1 \pm k)$, $R_2(1 \pm k)$, where k is the specified resistor tolerance in "per unit", not per cent, of value. (It is assumed that R_1 and R_2 have the same tolerances). The variable resistance, r_v, is assumed to have a maximum value of at least R_v. If this variable R_v, has the nominal value R'_v and tolerances $\pm k_v$, then obviously $R_v \leqq R'_v(1 - k_v)$, for we must not assume the variable to have a resistance greater than the manufacturer's lower limit. For example, for a nominal 50k variable resistor with tolerances of $\pm$ 10%, $R_v \leqq 50k(1 - 0.1) = 45k$. Note that R_v need have nothing to do with the actual total value of the variable resistor.

Account must also be taken of the voltage regulator tube tolerances. Since $V = V_r + V_{2g}$, if V_{nr} and V_{NR} are the lower and upper limits for V_r,

then $V_n = V_{nr} + V_{2g}$ and $V_N = V_{NR} + V_{2g}$.

Now recalculate Equations (2) and (3), using the two extreme combinations of tolerances for the components. Simple algebra shows that

$$E_m = \frac{V_N\ [(1 - k)R\ \ + (1 + k)R_2]}{(1 - k)R_1}\text{, and} \qquad (7)"$$

$$E_M = \frac{V_n \left[(1 + k)R_1 + R_v + (1 - k)R_2 \right]}{(1 + k)R_1} ; \qquad (8)''$$

or, more simply,

$$E_m = V_N \left[1 + \frac{(1 + k)\ R_2}{(1 - k)\ R_1} \right] , \text{ and} \qquad (7)'$$

$$E_M = V_n \left[1 + \frac{(1 - k)\,R_2}{(1 + k)\,R_1} + \frac{R_v}{(1 + k)\ R_1} \right] . \qquad (8)'$$

Equation (7)' may be rearranged to give

$$\frac{R_2}{R_1} = \frac{(1 - k)(E_m - V_N)}{(1 + k)V_N} . \qquad (7)$$

By manipulating (8)' and combining with (7)' ,

$$\frac{R_v}{R_1} = \frac{(1 + k)}{1} \cdot \frac{(E_M - V_n)}{V_n} - \frac{(1 - k)^2}{(1 + k)} \cdot \frac{(E_m - V_N)}{V_N} , \qquad (8)$$

or alternatively,

$$\frac{R_v}{R_2} = \frac{(1 + k)^2}{(1 - k)} \cdot \frac{(E_M - V_n)}{(E_m - V_N)} \cdot \frac{V_N}{V_n} - (1 - k) . \qquad (8a)$$

Equations (7) and (8) correspond to Equations (4) and (5), but with the effects of component tolerances included.

The development of Equations (7) and (8) has been one of the main purposes of the present report. Some practical examples demonstrating the use of the equations are given below. The examples serve not only to clarify the paper, but should give a better understanding of the uses to which the equations can be put.

Example 1

Assume the following data:

Maximum required output voltage, $E_M = 300$
Minimum required output voltage, $E_m = 180$
Regulator tube, Type 5651, for which $V_R = 87$ and $V_{nr} = 82$, $V_{NR} = 92$. (For simplicity put $V_{2g} = 0$. In practice, the known value would be used). Then $V_n = 82$, $V_N = 92$. Minimum bleeder current is desired and it has been decided to use a 50 kilohm variable resistor, with tolerance of ±10%. The resistors, R_1 and R_2, are to have ±1% tolerance.

Inserting the above data in Equation (8),

$$\frac{45k}{R_1} = \frac{(1 + 0.01)(300 - 82)}{82} \cdot \frac{(1 - 0.01)^2}{(1 + 0.01)} \cdot \frac{(180 - 92)}{92}$$

$R_1 = 25.6$ kilohms.

Next using Equation (7),

$$\frac{R_2}{25.6k} = \frac{(1 - 0.01)}{(1 + 0.01)} \cdot \frac{(180 - 92)}{92},$$

$R_2 = 24.0$ kilohms.

In contrast, the values calculated from Equations (5) and (4), in which tolerances are neglected, are $R_1 = 36.3$ kilohms and $R_2 = 38.8$ kilohms (see Fig. 2(a)).

The values 25.6k and 24.0k, for R_1 and R_2, ensure that the required settings of the variable, r_v, for E_M and E_m, fall within the range of that variable. In particular, if the combination of tolerances is that in Equation (7)', then E_m will occur at $r_v = 0$, and if the combination is that in Equation (8)', then E_M will occur at $r_v = 45k$.

It should be emphasized that the tolerance combinations of Equations (7)' and (8)' cannot occur simultaneously; the equations represent two extreme cases. Solution of these equations with tolerances interchanged (i.e., optimistic instead of pessimistic) gives two further values for r_v:

$$r'_v = 7.14k,$$

$$r''_v = 33.1k.$$

These are the minimum and maximum settings corresponding to the pessimistic maximum and minimum settings, respectively. Thus, for one extreme combination, the voltage range from 180 to 300 volts is covered by variable resistor settings from 0 to 33.1 kilohms, and, for the other extreme, by settings from 7.14 to 45 kilohms. In the worst case, when the variable has its maximum limit of 55 kilohms, the above ranges correspond to 60% and 68% of total resistance variation, and hence of total mechanical rotation; for average resistors the value is about 70%. With our present procedure this result is unavoidable, since uncontrollable variations in components have been accommodated by providing an excess of range in r_v. Adjustable shaft stops can be used to keep r_v within range, thus preventing overstressing of any component.

If the above compression of the voltage range into 70% of shaft rotation is unacceptable, considerable improvement can be effected as follows:

In series with r_v provide an auxiliary variable resistor, r_c (see Fig. 2(b)). Basically, this resistor provides adjustment for variations in components, leaving r_v to its prime purpose of altering the output voltage. Once set, r_c will be altered only when components are altered, and is often referred to as a "semi-fixed" adjustment. Use of the auxiliary resistor, r_c, requires alterations in the values of R_1 and R_2. The determination of the new values, and also that of r_c itself, is done as follows:

Without r_c, maximum <u>variation</u> for r_v was (45 - 7.1) = 37.9 kilohms. We are now going to increase this to 45k, and therefore R_1 and R_2 must be increased proportionately giving

$$R_1 = 25.6 \times \frac{45}{37.9} = 30.4k,$$

$$R_2 = 24.0 \times \frac{45}{37.9} = 28.5k.$$

The largest minimum setting of r_v was 7.1k, and this will now be provided by r_c; its value also must be increased proportionately. We find

$$r_c = 7.1 \times \frac{45}{37.9} = 8.4k\,.$$

A 10-kilohm variable resistor would be used. In use, r_c is adjusted to make E_m coincide with $r_v = 0$. The former maximum settings of r_v, 33.1k and 45k, are now 39.3k and 45k and the scale "spread" is now between 71% and 82%. For average resistors the spread is about 90%. Thus the use of the auxiliary variable, r_c, enables the voltage range to be spread over about 90% of the dial, rather than 70%. The setting for E_M, of course, will vary slightly, depending on the particular combination of components. By adding one more variable this setting, too, could be fixed exactly, but this is seldom worthwhile.

Example 2

In this example the required output voltage is not variable, but fixed at 250 volts. Economy dictates that a Type 991 voltage regulator tube be used, and also that the fixed resistors, R_1 and R_2, be the usual radio type with tolerances of ±10%, and that they be chosen from so-called "standard values", i.e., from the series 10, 12, 15, 18, 22, - - - up to 20 megohms. This series is designed to provide resistors at approximate 20% increments.

Minimum bleeder current is desired and it has been decided to use a 50-kilohm variable resistor, with tolerances ±10% for r_v.

For the Type 991 tube (again assuming $V_{2g} = 0$), $V_n = 53$ and $V_N = 65 + 3$.

These values are for an assumed tube current of 1.5 ma. (If the tube current varies over the full rating from 0.4 to 2.0 ma, $V_n = 48$ and $V_N = 67 + 3$). The value $V_N = 65 + 3$ includes an allowance of 3 volts for increase of voltage during tube life. The above values for the Type 991 tube are all taken from the JAN Specification.

Since nominal resistor values occur in 20% steps, there will always be a nominal value within 10% of any calculated value. Therefore, if, to the manufacturer's tolerance, there is added a further 10%, the computed value can be altered by as much as 10% to reach a standard nominal value and still be satisfactory. Thus in Equations (7) and (8), for the present example, k will be 0.2, of which 0.1 is manufacturing tolerance, and 0.1 is provision for adjustment of the computed value to the nearest nominal value.

Using the above data and Equation (8),

$$\frac{45k}{R_1} = \frac{(1 + 0.2)(250 - 53)}{53} - \frac{(1 - 0.2)^2(250 - 68)}{(1 + 0.2)\ 68},$$

$$R_1 = 21.3k;$$

and from Equation (7),

$$\frac{R_2}{21.3} = \frac{(1 - 0.2)(250 - 68)}{(1 + 0.2)\ 68},$$

$$R_2 = 38.0k$$

For R_1 and R_2, the commercial values 22 kilohms and 39 kilohms ±10% would be used. In this example, as it happens, the computed values are not far from available commercial values and a 10% allowance for adjustment was needlessly large.

VARIATIONS IN TUBE CHARACTERISTICS

Joint Army-Navy (JAN) Specification 1A for Radio Electron Tubes gives much useful information on the permissible manufacturing limits of vacuum tubes. Though tubes in general are not required to comply with this specification, actually it forms a very good guide to what variation may be expected in a given tube type.

For the Type 6SL7 high-mu triode, which is often used in the V_2 position of Fig. 1, the JAN Specification requires that the plate current be within the limits 1.4 and 3.2 ma (i.e., 2.3 ±0.9) for plate and grid voltages of 250 and -2.0 volts. The tube has an average transconductance of 1600 micromhos, and we assume the specification can be interpreted as equivalent to the requirement that the grid voltage be in the range -1.44 to -2.56 volts (-2 ± 0.56) for plate current and voltage of 2.3 ma and 250 volts. Similarly, for the Type 6SH7 tube which is often used in the V_2 position when a pentode rather than a triode is desired, the JAN Specification permits a plate current range of 10.8 ± 2.6 ma with plate, screen and control-grid voltages of 250, 150, and -1.0 volts. The equivalent grid-voltage interpretation is -1.0 ± 0.53 volts for plate parameters of 250 volts and 10 ma, and 150 volts on the screen.

Normally, of course, a tube is not used under the conditions given in the JAN Specification, but there is no reason to suppose that the results will differ greatly with changed conditions. Based on the results for Types 6SL7 and 6SH7, a range of ± 0.5 volts at the grid of V_2 would seem a reasonable allowance for compensating for differences occurring in any tube type used in the V_2 position.

The Type 6B4 tube is typical of triodes used in the V_1 position. For this tube the JAN Specification permits a plate current of 42 to 82 ma (62 ± 20) at plate and grid voltages of 250 and -45 volts. Using the nominal transconductance of 5250 micromhos, we interpret the permissible plate-current range as equivalent to a grid-voltage range of 8 volts (45 ± 4). Dividing this change in the grid voltage of V_1 (it is also the change in the plate voltage of V_2) by the amplification factor of V_2, gives us the equivalent change in V, i.e., the change in grid voltage of V_2. With a Type 6SL7 tube, for which the amplification factor is 70, ±0.055 volts is the equivalent change at the grid. Seldom would a tube with a lower amplification factor be used, so that ±0.055 volts constitutes an upper limit.

Proceeding in the same way for the Type 6Y6 tube, a pentode common in the V_1 position, we find that compensation for its range of characteristics (43-79 ma at plate, screen, and grid, voltages of 200, 135, and -14, respectively) can be obtained with a variation in V of ±0.043 volts (again assuming a Type 6SL7 tube for V_2).

Obviously these voltages, ±0.055 and ±0.043, which arise from variations in V_1, are quite negligible by comparison with the ±0.56 or ±0.53 volts which arise from variations in V_2. Before showing how these tube variations affect the design, it is necessary to consider the deficiencies of the circuit in Fig. 1.

DEFICIENCY OF CIRCUIT (FIG. 1)

The stabilizer circuit of Fig. 1 was assumed perfect, and by this was meant that with perfect components, the voltage, V, would be absolutely constant. In truth, the voltage, V, would vary slightly, even with perfect components, owing to the finite gain in the feedback loop. A complete description of this effect may be found in any of the References (1-5). Here we will calculate simply the result of this effect in a typical case.

Example

Assume a stabilizer using a Type 6SL7 tube for V_2 and paralleled Type 6B4 tubes for V_1. We wish to know the effects on the voltage, V, of changes in the input voltage, E_i, and of adjustments to the output voltage, E_o. The difference between these voltages is the plate voltage of V_1; thus any change in either voltage is also a change in the plate voltage of V_1. Assume that maximum and minimum output voltage and current are 300 and 180 volts, and 120 and 20 ma (100 to 0 ma available current, 20 ma bleeder). Finally, assume that E_i will increase 25 volts with the change in current from 120 to 20 ma and may increase a further 35 volts owing to external causes such as line voltage, transformer and filter tolerances. The maximum change in the plate voltage of V_1 arising from a combination of these factors is (300-180) + 25 + 35 = 180 volts.

To carry 120 ma requires two Type 6B4 tubes in parallel. Assume that, at maximum current, one tube carries 80 ma, the other 40 ma (this large a difference is permitted by the JAN Specification), and, at minimum current, each tube carries 10 ma. From the characteristic curves of the Type 6B4 tube, we find that for the two extreme conditions, 80 ma and 10 ma, the operating potentials will be 80 plate volts at zero grid volts, and 260 plate volts at -60 grid volts. To effect the change from 0 to -60 volts at the grid of V_1, and also at the plate of V_2, will obviously require a change of 60/40 = 1.5 volts (± 0.75) at the grid of the Type 6SL7 tube, assuming a gain of 40 for this stage. (The stage gain was assumed infinite in the perfect stabilizer.) Obviously, the higher the gain of V_2, the lower the corresponding change in V, for changes in E_i or E. The value ±0.75 volts is larger than is usual, since our sample stabilizer, with its rather low over-all gain from two triodes, would be barely acceptable as a practical stabilizer.

EXACT VALUES OF V_m AND V_M

In earlier examples, approximate values were used for V_m and V_M. From the last example, there is now sufficient information to enable the exact values to be computed.

Assume that in the stabilizer a Type 5651 voltage-reference tube is used. Recall that for this tube V_R = 87 ± 5 volts. The nominal grid voltage on the Type 6SL7 tube is assumed as -1.0 volts.

Obviously, from Fig. 1(a),

$$V = V_R + V_{2g}.$$

Inserting numerical values,

$$V = 87 - 1.0.$$

Adding the possible variations and allowances,

$$V = 87 \pm 5 - 1.0 \pm 0.75 \pm 0.53 \pm 0.055,$$

$$\text{or, } V_m = 79.7, V_M = 92.3 .$$

In the equation for V:

± 5 is the possible variation in reference-tube voltage,
-1.0 is the grid voltage of the Type 6SL7 tube (affects only the average V),
± 0.75 compensates for the finite voltage gain of 40,
± 0.53 allows for compensation for Type 6SL7 variations,
± 0.055 similarly is an allowance to cover Type 6B4 variations.

An approximation, which includes only the voltage-reference tube variations, is thus seen to be justified, since the probability of the voltage extremes is very small, though unfortunately unknown.

ADVANTAGES OF THE CIRCUIT OF FIG. 1(a)

The circuit of Fig. 1(a) has many advantages over that of Fig. 1(b). These advantages, however, do not appear to be known, since the latter circuit is the one more commonly seen in the literature, probably because it is somewhat the more obvious arrangement. Of the advantages of Fig. 1(a), some hold only for stabilizers in which the output is adjustable over an appreciable range, as in laboratory equipment, but others are true rather generally. A knowledge of these possible advantages is necessary if advantage is to be taken of them in design.

Stability

Use of the Fig. 1(a) circuit results in improved stability. To quote Hogg (2), p. 328 --- "What happens is that although the total resistance of [our] r_v remains constant, the tapping point appears to vary from time to time, usually taking up a different value each time the apparatus is switched on. This is not surprising, considering the absence of current through the tapping point* ---- a better device than the potentiometer is a combination of fixed and variable resistance as shown in [our] Fig. 1(a). In any case the variable resistance should be wire wound".

Linear Control of Output Voltage

Examination of Equation (1) shows that for Fig. 1(a) the output voltage is a linear function of r_v. In particular, if r_v has a linear resistance versus shaft rotation characteristic, then the control dial will have a linear voltage graduation. The advantages of such a relation are obvious. Fig. 1(b), on the other hand, gives a hyperbolic relation between resistance, r_v, and output voltage. It is possible, with Fig. 1(b), by shunting the movable contact of r_v to the negative line with a suitable fixed resistance, to obtain an approximately logarithmic variation of output voltage when r_v follows a linear rotation characteristic. Fig. 3 shows the approximation obtained. Such a procedure may have its uses. Incidentally, it improves stability by causing current to flow through the movable contact. For completeness, it should perhaps be added that a third control arrangement is possible in which r_v forms part of R_1, rather than R_2 in Fig. 1(a). The arrangement was suggested by Hunt and Hickman (3), p. 15, but appears to have no particular advantage, an inverse variation of voltage versus rotation being obtained.

Design and Analytical Simplicity

Another advantage of Fig. 1(a), of some importance to the designer, is the analytical simplicity of the arrangement; this simplicity results from the linear resistance versus output voltage relation mentioned.

Greater Output Current

Several of the advantages of Fig. 1(a) are the result of the relation given by Equation (6). The equation is repeated here for convenience,

$$i = \frac{V}{R_1} .$$

Since R_1 is fixed and V, as will be shown later, normally varies less that 1 per cent, the bleeder current, i, is practically constant.

* For a fuller explanation of this phenomenon see S. Rudeforth, "Contact Resistance and Its Variation with Current", Post Office Engineers' Journal, vol. 42, pt.2, pp. 65-69, July, 1949.

Obviously, on the other hand, in Fig. 1(b),

$$i = \frac{E}{R_1 + R'_V + R_2},$$

and the bleeder current is proportional to output voltage.

Now the type of power source usually used to feed these stabilizers is characterized by a rapid and undesirable rise in voltage if the current output is permitted to fall below a certain value. Therefore a minimum permissible bleeder current is usually specified. Obviously, this bleeder current reduces the useful output or load capacity of the unit and should be no larger than specified. With the circuit of Fig. 1(a) there is no difficulty, but the circuit of Fig. 1(b) must be designed to draw minimum bleeder current at minimum output voltage, and of course at higher voltages the bleeder current increases proportionately and the available output current is reduced. In a typical numerical case, with Fig. 1(a) we might have an output of 100 ma with 20 ma bleeder current. For Fig. 1(b), assuming an output voltage range of two to one (moderate), the 20 ma bleeder current at minimum voltage rises to 40 ma at maximum voltage and the available output current at maximum voltage is reduced from 100 ma to 80 ma. A voltage range of seven to one is not uncommon, and in such a case useful output from the arrangement of Fig. 1(b) would be nil.

It may appear preferable to place the bleeder resistor across the input of the stabilizer rather than across the output, since the range of voltage may be much less at the former position. More constant bleeder current would be obtained, the current through V_1 would be decreased, a reduction in current through the voltage-adjusting resistors would be possible and would reduce temperature effects there. Furthermore, the flow of bleeder current would not depend on V_1, the increased dependability giving added protection to personnel and to the power source. These apparent benefits are mostly illusory, the possible improvement being less than expected for the following reasons. At low currents the characteristics of V_1 become unpredictable, so that proper design control is impossible. There is a large increase in plate resistance, so that performance deteriorates. An appreciable bleeder current must, therefore, flow through V_1 if performance is to be satisfactory when the current to the load is small, as it often is in laboratory applications. An appreciable bleeder current on the load side of V_1 is especially important where small negative load currents may be encountered, particularly transitory ones, since the damping is much improved, V_1 being less likely to cut off. In practice the minimum satisfactory current for V_1 is found to be of the same order as the specified minimum bleeder current. Little is to be gained, therefore, by placing a bleeder across the input.

Reduced Temperature Effects

Even for cases in which the bleeder current has negligible effect on the load current, its heating effect on the voltage-adjusting resistors R_1, R_2, and r_v cannot be neglected. Usually, it is not possible to obtain variable resistors wound with low temperature coefficient alloy, at least not in the high resistance values required. Under this limitation it is preferred that the fixed resistors have the same temperature coefficient as the variable one, rather than a low temperature coefficient. Ordinarily, it is not possible to obtain a very good match, neither is it feasible to obtain R_1, R_2, and r_v with equal thermal time constants. With a varying bleeder current, therefore, an undesirable transient, of perhaps a few minutes duration, occurs following each output voltage adjustment. The effect is particularly irritating when measurements are to be made at a series of voltage increments. The circuit of Fig. 1(a) with its constant bleeder current is, of course, practically free from this effect.

Current Measurement

Examination of Figs. 1(a) and 1(b) will reveal that the current meters are not similarly located with respect to the voltage-adjusting resistor group: in Fig. 1(a) the meter is directly in series with V_1, while in Fig. 1(b) it is directly in the output lead. Now a typical meter, such as a 0-100 ma Weston Model 301, has a resistance of 1.0 ohms. In series with V_1, as in Fig. 1(a), this 1 ohm resistance, added to the 500-odd ohms plate resistance of V_1 has no effect. In the location shown in Fig. 1(b), however, the meter resistance adds directly to the stabilizer internal resistance, and since, in a modern stabilizer, the internal resistance is about 1 ohm or so, the meter greatly degrades performance.

From a performance viewpoint, obviously, the meter location of Fig. 1(a) is preferable, but there is one drawback: the meter, thus located, indicates the total bleeder-plus-useful-load current, whereas what is wanted is the useful current alone. Fortunately, since the bleeder current in Fig. 1(a) is constant, all that is necessary is to offset the zero adjustment of the meter so that the meter reads zero with the stabilizer switched on, but with no load connected. Means should be provided for preventing anyone from unwittingly re-zeroing the meter with the stabilizer switched off. Meters with a soldered zero-set screw are advised. With the circuit of Fig. 1(b), the above artifice for subtracting bleeder from load current cannot be used, for the bleeder current varies. The subtraction must be performed analytically, after the bleeder current, at the voltage used, has been determined. This subtraction is both time-consuming and liable to oversight; therefore, when the circuit of Fig. 1(b) is used, the meter is located as shown, and the lowered performance accepted.

When a shunted meter movement, such as the Model 301 mentioned, is used, the resistance varies little with frequency. If, however, an unshunted-type of meter movement should be used, particularly one whose damping is poor, its resonant impedance may be several times the d-c value and the meter location of Fig. 1(b) is then very poor indeed. It is indicative that Warner (6), when using the circuit of Fig. 1(b), by-passes the meters with 100-microfarad electrolytic capacitors.

Stabilized Current Available

In most stabilizers much of the residual instability arises from cathode temperature variations, and though circuit arrangements are available which minimize this effect, a stabilized source for heating the cathodes is much to be desired. If the output voltage is fixed, then the stabilized output voltage itself can be used. On the other hand if the output voltage is adjustable, the solution is not always so simple. Fig. 4, which is a slight modification of Fig. 1(a), shows how such a stable heating current can be obtained, even when the output voltage is adjustable over a wide range. Performance, too, is improved, since the filament-plate transconductance of the tube is now also effectively used to increase gain. The arrangement, of course, is most useful for tubes with directly heated cathodes.

Reduced Requirements for r_v

The circuit of Fig. 1(a) is unaffected by the total resistance value of r_v. The available resistance must be sufficient to cover the range, but any resistor above this value can be used; with Fig. 1(b), on the other hand, the total value of the resistor must be specified. To put it differently, in Fig. 1(a) the voltage is affected by the amount of resistance on one side of the movable contact only, in Fig. 1(b) by the resistance on both sides. In specifying a resistor for Fig. 1(b), therefore, closer tolerances will usually be required.

CONCLUSION

The increasing use of stabilized power supplies, not only as separate units but as inherent parts of many electronic instruments, requires that their design be put upon a sounder basis than has been the case. In this report the aim has been to establish design procedures which ensure that a stabilizer performs adequately within its specified range and continues to do so without undue ill effects from normal manufacturing variations in the components. Freedom from selective assembly (i.e., "cut-and-try") is thus obtained, and replacement of tubes and other components simplified.

As happens, some rather unrelated design improvements have been discovered and these have been included in the paper. While for simplicity the investigation has been done in terms of one particular circuit, the extension of the results to other circuits should not be difficult. It is perhaps unnecessary to add that the requirements laid down here, while necessary, are by no means sufficient to ensure that a stabilizer will perform as desired.

* * * * *

Acknowledgments

The major part of this work was done in the Electrical Engineering Section of the Radio and Electrical Engineering Division of the National Research Council, under Mr. N.L. Kusters, but the author is also grateful to Mr. W.C. Brown, head of the Army Section for permission and time to complete the paper while in his Section, despite the pressure from military commitments.

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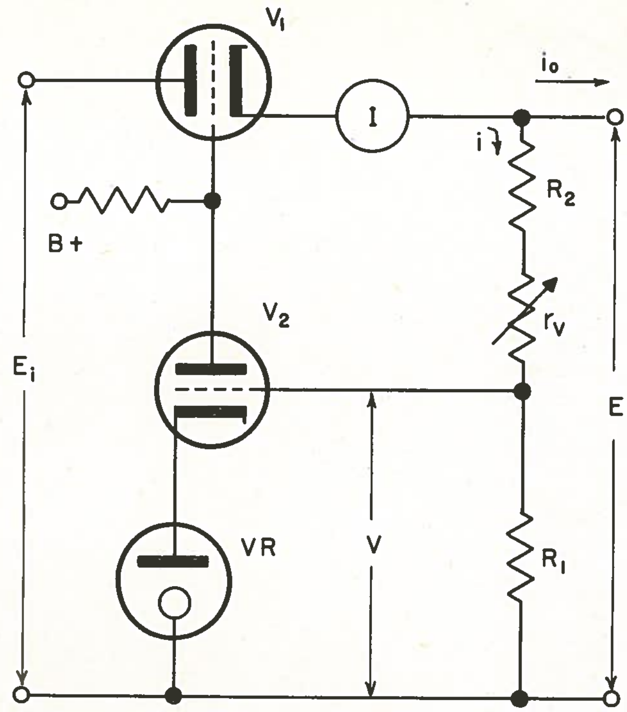

FIG. I(a)
VOLTAGE STABILIZER CIRCUIT
(PREFERRED FORM)

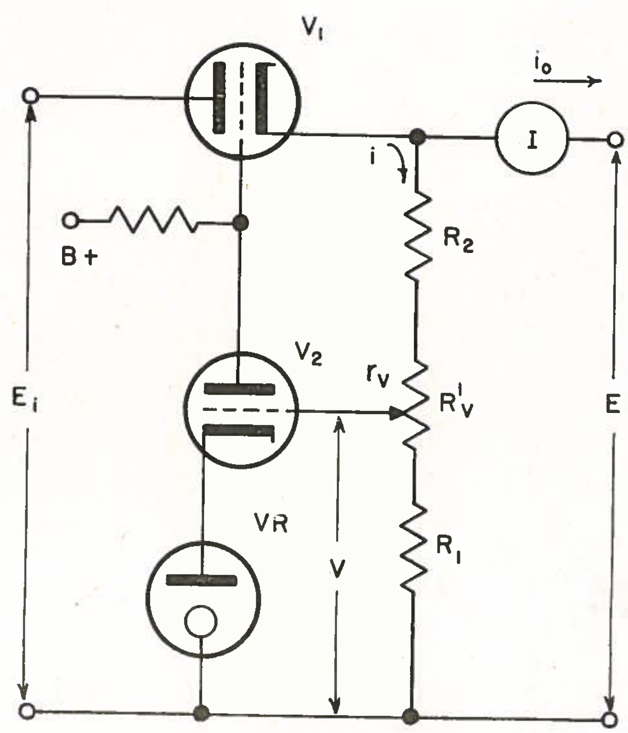

FIG. I(b)
VOLTAGE STABILIZER CIRCUIT
(USUAL FORM)

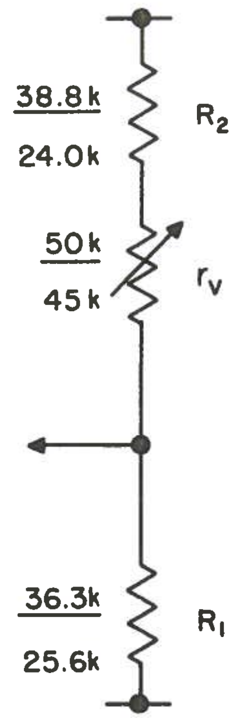

FIG. 2 (a)
COMPARISON OF THEORETICAL (UNDERLINED) AND ACTUAL VALUES OF RESISTORS REQUIRED FOR RANGE OF 180-300 VOLTS

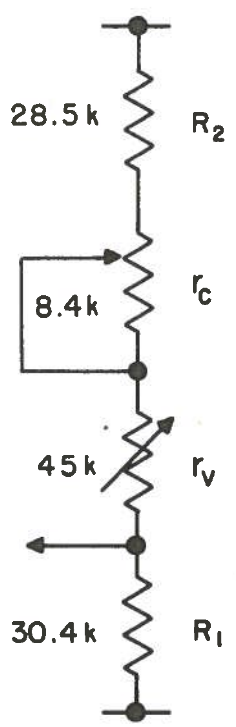

FIG. 2 (b)
FIG. 2 (a) MODIFIED TO INCLUDE AUXILIARY VARIABLE RESISTOR
(CONSEQUENT CHANGES IN OTHER RESISTOR VALUES ARE SHOWN)

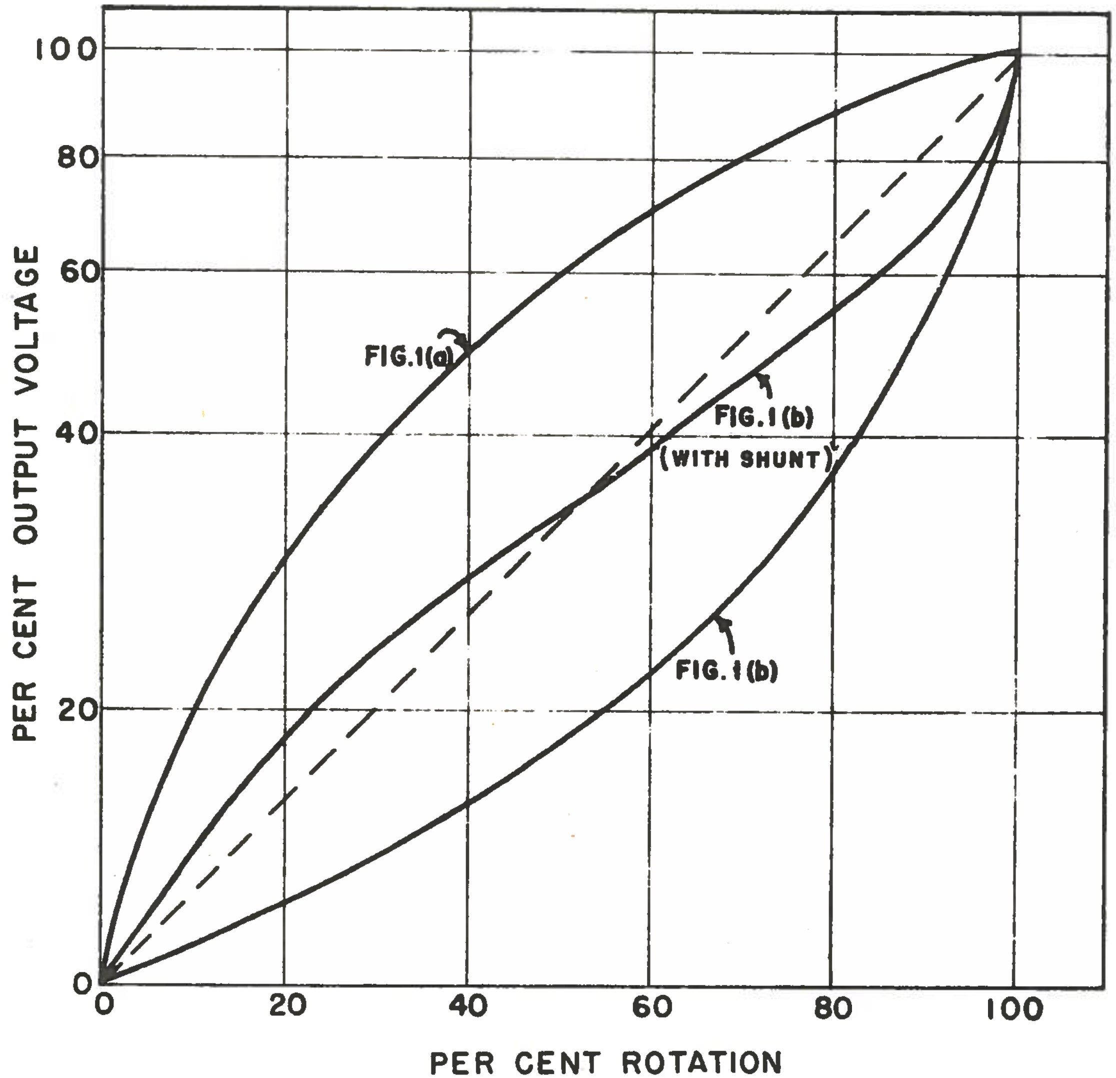

FIG. 3
EFFECT OF SHUNTING MOVABLE CONTACT IN FIG. I (b) TO NEGATIVE LINE TO OBTAIN APPROXIMATE LOGARITHMIC CONTROL

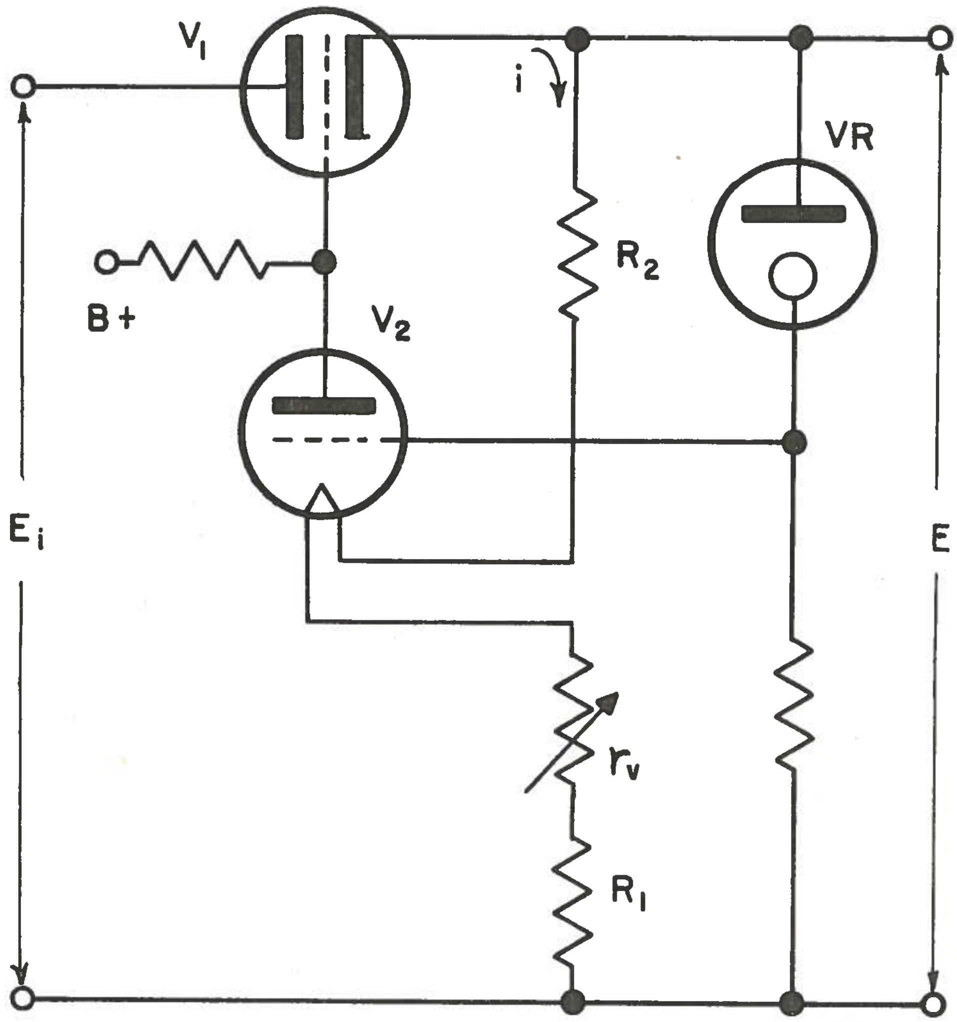

FIG. 4
CIRCUIT SHOWING METHOD OF SUPPLYING STABILIZED HEATING POWER TO TUBE
(HEATING CURRENT IS INDEPENDENT OF THE OUTPUT VOLTAGE, E)