



A constant-current generator in the audio-frequency range
by William D Sherwood

A THESIS Submitted to the Graduate Faculty In partial fulfillment of the requirements for the degree
of Master of Science In Electrical Engineering
Montana State University
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Abstract:

The purpose of this thesis is to describe the design and operation characteristics of a constant-current generator. The generator was designed to have a constant load current as the load resistance changes.

The circuit was designed to have a signal voltage gain that varies in a linear manner as the load resistance is changed. The output signal voltage changes in a direct relationship with the load resistance, maintaining a constant proportionality between the two. This ratio of proportionality is the desired constant current.

The design method used was to take an amplifier circuit with desirable characteristics and improve upon its gain characteristic. Good gain, large power capacity, and being capable of handling large signal input without distortion are the desired characteristics. A 6L6 beam-power tube with an unby-passed cathode resistor was selected for the amplifier circuit, A second 6L6 beam tube was placed in the plate circuit of the amplifier to act as a constant d-c current device. This improves the gain characteristic of the amplifier at the higher values of load resistance by making the amplifier plate voltage more-or-less independent of its plate current. The gain characteristic of the amplifier was then made linear by providing a positive feedback to the grid. It was necessary to provide a nonlinear feedback voltage which increased exponentially with the load resistance. This was accomplished by using the inverse current characteristics of two matched germanium diodes. A signal voltage from this diode circuit was amplified by a 6J5 triode tube. The feedback signal was obtained from the plate circuit of this amplifier with the proper phasing for positive feed back.

The constant-current generator works very well for a large range of load resistance variation for small values of load current, but the range is somewhat limited for load currents over 4 ma. The frequency response is very good in the range from 500 to 5,000 cps. The 3-db. loss levels are outside the desired frequency range of 100 to 10,000 cps except on the low-frequency side at high values of load resistance. The low-frequency response could have been improved by proper design of the R-C circuits, Two examples of uses that may be made of this device are discussed at the end of the paper.

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WILLIAM D. SHEPWOOD

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at

Montana State College

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ABSTRACT

The purpose of this thesis is to describe the design and operation characteristics of a constant-current generator. The generator was designed to have a constant load current as the load resistance changes. The circuit was designed to have a signal voltage gain that varies in a linear manner as the load resistance is changed. The output signal voltage changes in a direct relationship with the load resistance, maintaining a constant proportionality between the two. This ratio of proportionality is the desired constant current.

The design method used was to take an amplifier circuit with desirable characteristics and improve upon its gain characteristic. Good gain, large power capacity, and being capable of handling large signal input without distortion are the desired characteristics. A 6L6 beam-power tube with an unby-passed cathode resistor was selected for the amplifier circuit. A second 6L6 beam tube was placed in the plate circuit of the amplifier to act as a constant d-c current device. This improves the gain characteristic of the amplifier at the higher values of load resistance by making the amplifier plate voltage more-or-less independent of its plate current. The gain characteristic of the amplifier was then made linear by providing a positive feedback to the grid. It was necessary to provide a nonlinear feedback voltage which increased exponentially with the load resistance. This was accomplished by using the inverse current characteristics of two matched germanium diodes. A signal voltage from this diode circuit was amplified by a 6J5 triode tube. The feedback signal was obtained from the plate circuit of this amplifier with the proper phasing for positive feedback.

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Two examples of uses that may be made of this device are discussed at the end of the paper.

INTRODUCTION

The problem selected was to design and construct a constant-current generator to operate in the audio-frequency range from 100 to 10,000 cycles per second. The problem can be divided into two types:

(a) The constant-current device which produces a constant-current output when the input varies.

(b) The constant-current device which gives a constant-current output as the output load impedance varies.

The second type is the one developed and discussed in this paper.

Considerable research has been done and a large number of papers have been written on constant-current devices using direct-current, but, to the author's knowledge, no work comparative to this thesis has been done with the alternating-currents over the frequency range used here.

Due to the increasing trend toward the use of electronic computing and control devices, this investigation was thought to be worthwhile. Although the author knows of no particular circuit where a device of this type is used at the present time, its future possibilities should not be overlooked in connection with the aforementioned types of electronic circuits.

The abbreviations and technical terms used in this paper are the common and accepted terms as used in the radio engineering literature.

The experimental data was obtained from amplifiers built by the author. A commercial type of signal generator was used for the input signal.

PROBLEM ANALYSIS

Several types of amplifier circuits were considered and the first one selected was a double-cathode-follower circuit which, when analyzed mathematically, seemed to present the proper characteristics. When tests were run on this circuit it did not operate as expected. Further analysis showed that the transconductance and amplification factor of the tube varied in a nonlinear fashion as the load resistance was increased. There was not a linear correlation between the output voltage and load resistance as desired and the circuit was discarded.

The first attempt to produce a constant-current generator using the cathode-follower circuit gave the writer a better insight into the problem by showing the way to the final circuit and the method by which to approach it. The problem was one of developing an amplifier circuit with a gain that increased in direct proportion to the load resistance. The method of approach was to do the experimental work prior to the analytical work.

It is well known that the gain of an amplifier increases as the load resistance is increased. This gain-characteristic is approximately linear over a very small range of load resistance variation. The improvement of this gain-characteristic was the basic problem to be considered.

To improve the gain-characteristic of the amplifier a constant d-c current device was placed in the plate circuit as shown in Fig. 1. The addition of this circuit improved the gain-characteristic but it was still far from the desired linear gain-load relationship.

The circuit gain-characteristic could be further improved by a non-

linear positive feedback. It was necessary to have more gain at the higher values of load resistance while the gain at the lower values of load resistance remained unchanged. Diode vacuum tubes have plate current-plate voltage characteristics such that the plate current increases as an exponential function of the plate voltage. The possibility of using this type of characteristic curve was investigated. It was determined that the amount of resistance needed in series with the diodes was at least 100,000 ohms. This amount of resistance caused the diode characteristic to flatten out until it was no longer the desired current-voltage relationship.

A Thyrite type of varistor was known to have a high resistance and the desired symmetrical current-voltage characteristic. The unsuccessful effort that was made to obtain this type of varistor led to the consideration of the inverse characteristics of germanium crystal diodes. The inverse current-voltage relationship of germanium diodes exhibits high resistance and approximately the desired exponential variation needed for the feedback circuit. To get a symmetrical characteristic from the germanium diode for alternating voltages, a matched pair of germanium diodes were connected cathode-to-cathode. These diodes, paralleled by a resistor, and resistance, were placed in parallel with the load as shown in Fig. 1. That portion of the output signal voltage appearing across R_4 is applied to the grid of a triode amplifier. The signal output from the plate circuit of this amplifier is fed back to the grid of the beam-tube amplifier as positive feedback.

When the experimental run was made on this complete circuit it was found to be a very good approximation to the desired linear relation between output voltage and output load resistance. The deviations from linearity can be controlled with good accuracy by controlling the amount of resistance in series with the diodes. This resistance controls the characteristic and the amount of feedback voltage.

The amount of current in the output load can be varied by changing the amount of input signal.

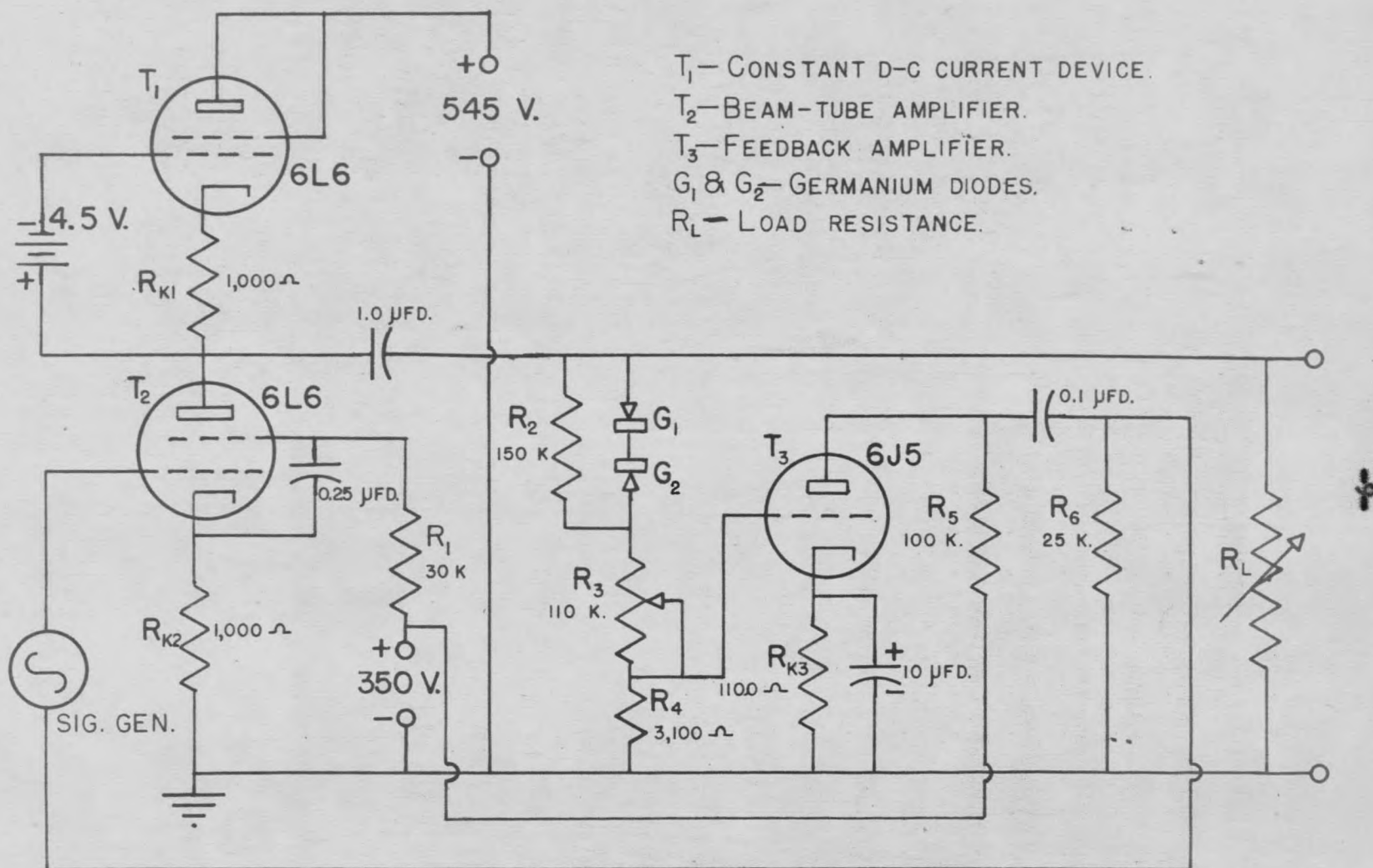


FIG. 1. CONSTANT-CURRENT GENERATOR CIRCUIT.

CIRCUIT ANALYSIS

This constant-current generator is a device which has a directly increasing output voltage as the output resistance is increased resulting in a constant current. The input signal voltage must remain constant in amplitude. The method by which the linear output is obtained is, essentially, one of combining nonlinear devices in such a fashion as to result in a linear output. A mathematical analysis of such a combination is extremely difficult because of the nonlinear characteristics of certain components of the circuit.

When the load resistance is varied the transconductance and plate resistance of the beam tube changes in a nonlinear fashion¹. It may be seen from Fig. 1 that the load impedance of the beam-tube amplifier consists of the load resistance in parallel with the constant d-c current device and the feedback amplifier input circuit. A change in the load resistance, R_L , also affects the constant d-c current device causing its characteristics to change in a nonlinear manner. The germanium diodes in the feedback input circuit were used because of their desirable nonlinear characteristics. Therefore, rather than attempt a rigorous mathematical analysis, which is impracticable because of the nonlinear circuit elements used, a nonmathematical approach will be used in explaining the function of the various parts.

1. Schade, O. H., 1949, ELECTRON TUBES, Vol. 1, p. 360, RCA Review, Radio Corporation of America, Princeton, New Jersey.

The circuit shown in Fig. 1 is the complete circuit. The beam-power tubes were used for their desirable plate current-plate voltage characteristics and to obtain as high power output as possible. The function of the unbypassed cathode resistor, R_{k2} , is to feedback a degenerative component of signal to the control grid. When the load resistance, R_L , is zero, or very small, the entire signal voltage is developed across R_{k2} , which is the only load to a-c voltage in the circuit. This voltage is fed back to the grid and almost entirely degenerates the grid signal voltage. As R_L increases a greater proportion of the signal is developed across the load resistor, R_L , and the constant d-c current device, which are in parallel. The constant d-c current device has a very high impedance to the a-c load voltage, thus R_L is the controlling impedance over the range to be used. As the signal developed across R_L increases the amount of signal voltage across the cathode resistor, R_{k2} , decreases. This effect allows the gain of the stage to increase producing more output voltage across R_L , thus tending to keep the current through R_L constant.

The signal generator used in the grid circuit has a low impedance output. The reason for using this signal generator is to prevent any appreciable loss in feedback signal voltage which is fed back to the beam-tube amplifier grid through the signal generator.

The screen grid has a 30,000 ohm dropping resistor with a 0.25 microfarad bypass capacitor connected directly to the cathode. These components isolate the screen grid from signal voltage changes with

respect to the cathode. This high resistance also prevents the screen grid from drawing excessive current on negative plate signal voltage peaks and allows the screen grid power supply voltage to be quite high. The feedback amplifier plate voltage may also be obtained from the same power source that supplies the screen grid power.

In the plate circuit of the amplifier the constant d-c current device eliminates the effect of plate current variations on the plate voltage while presenting a high impedance to any a-c signal output. This increases the gain at the higher values of load resistance. The effect of this circuit may be seen from a comparison of the graphs plotted in Fig. 2 with those of Fig. 3. Figure 2 is a plot of the output voltage versus load resistance for the beam-tube amplifier alone without the modification of the constant d-c current device. Figure 3 is a plot of the output characteristics for the amplifier with the constant d-c current device in the plate circuit. A comparison of the graphs shows the increased gain at the higher values of load resistance produced by the constant-current device.

The curves of Fig. 3 are plotted for different biasing arrangements on the two 6L6 tubes showing how the gain characteristics may be controlled to obtain the necessary final output characteristic. The 1000 ohm resistors, R_{k1} and R_{k2} , used in the cathode circuits produced the most nearly linear curves and the optimum bias for proper operation of the tubes. A 4.5-volt biasing battery is necessary in the grid circuit of the constant-current device to control the current through the tube and cause

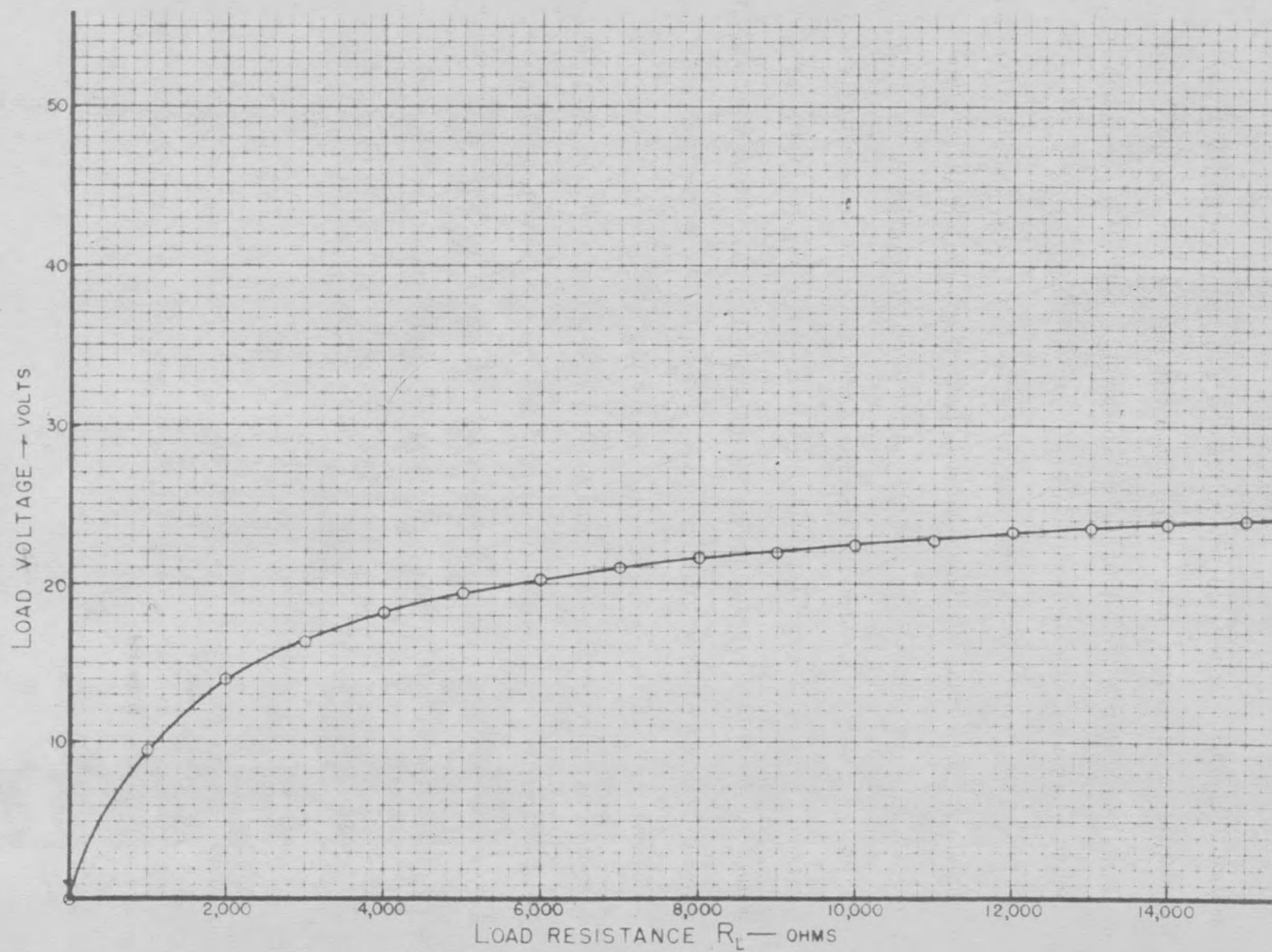


FIG. 2. OUTPUT CHARACTERISTIC OF BEAM-TUBE AMPLIFIER.

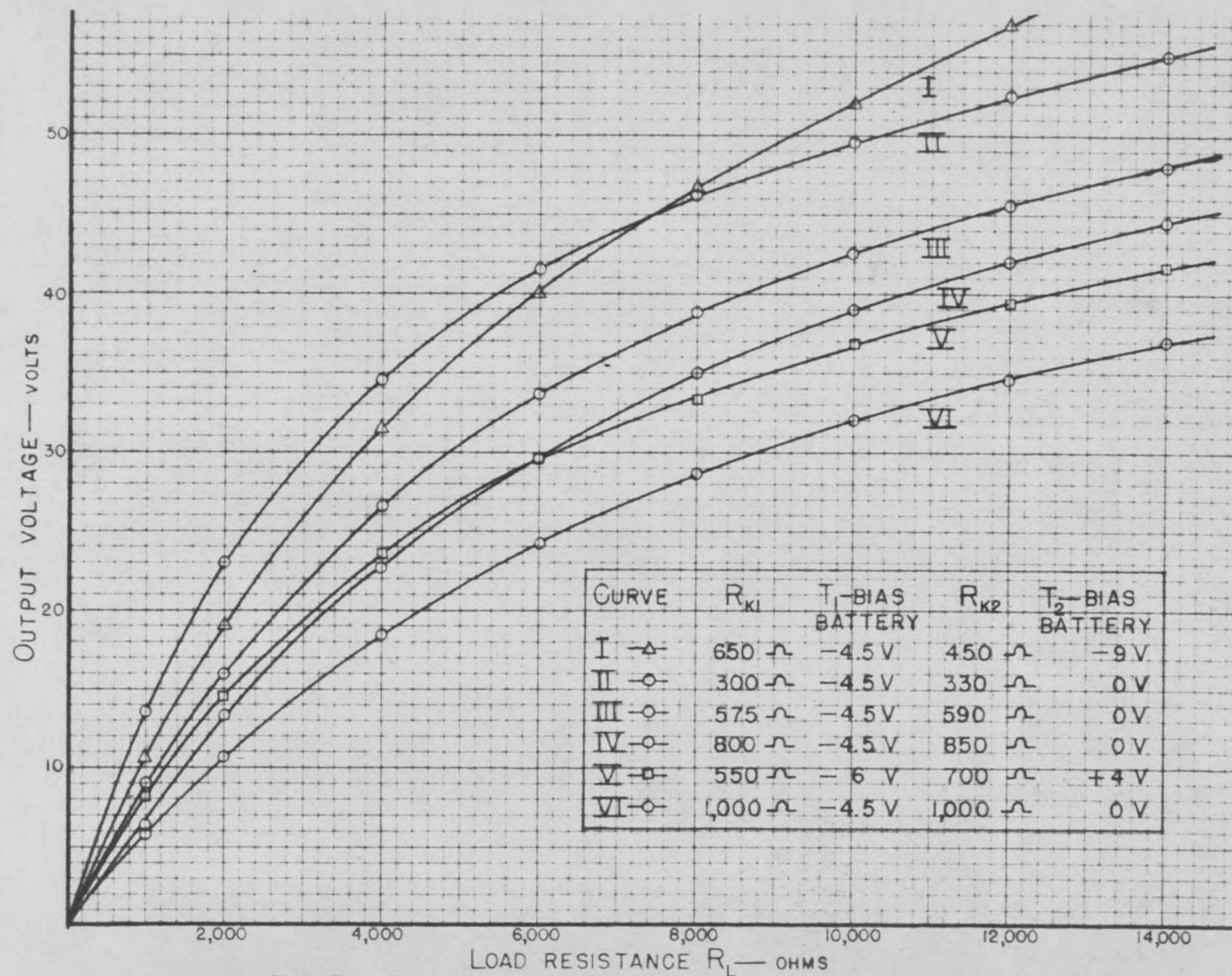


FIG. 3. OUTPUT CHARACTERISTICS OF MODIFIED AMPLIFIER.

the power supply voltage to divide equally across the two tubes giving 250 volts of plate to cathode voltage on each tube. The circuit will not operate as a constant current device without this biasing battery.¹ It produces a constant increment of bias which is necessary especially at large values of load resistance where there is considerable signal voltage developed across the unbypassed cathode resistor, R_{k1} . The unbypassed cathode resistor, R_{k1} , produces the high impedance to the a-c component of signal output voltage presented by the constant-current device. This reduces the shunting effect of the constant-current stage at the higher values of load resistance.

The plate and screen grid are connected directly to the power supply. Without a load resistor in the plate circuit the plate and screen grid will both be at 250 volts positive with respect to the cathode. With this connection the tube acts as a regular beam power tube which has the desired constant-current characteristics. The power supply voltage is 545 volts, of which, 45 volts is dropped across the biasing resistors, R_{k1} and R_{k2} and the remaining voltage divides equally across the two 616 tubes.

The output is taken directly from the plate of T_2 , the beam-tube. The d-c voltage of the plate circuit is blocked by the 1 microfarad condenser.

1. Valley, G. E. and Wallman, H., 1948, VACUUM TUBE AMPLIFIERS, p. 440
McGraw-Hill Book Company, Inc., New York and London

The large capacitance is necessary to give good low frequency response at small values of R_1 . The load resistance, R_1 , consists of two noninductive, 10,000 ohm, decade resistance units in series. This load could represent any variable resistive load.

The output voltage is also applied across the feedback input circuit. This circuit, as shown in Fig. 1, consists of the two germanium crystal diodes, G_1 and G_2 , and the resistors R_2 , R_3 , and R_4 . The two diodes were matched for inverse characteristics by applying a d-c voltage across each diode in series with 100,000 ohms of resistance. The voltage polarity was directed to make the cathode positive. In this manner, each of the six germanium diodes available were tested and the pair most nearly matched were selected. By placing a resistance in parallel with the diodes the overall characteristic impedance of the diodes can be made more suitable for this circuit. The optimum value for the resistance, R_2 , was found to be 150,000 ohms. This resistor reduced the impedance offered by the diodes from 250,000 ohms to 100,000 ohms at 30 volts. At 60 volts the total impedance of the combination is 40,000 ohms. This impedance in series with R_3 and R_4 is large enough that the shunting effect on the load, R_1 , is not serious over the range of values used for load resistance.

The variable resistor, R_3 , serves a dual purpose. It controls the amount of the output signal voltage that appears across R_4 . This signal voltage is the input to the triode feedback amplifier. Thus, R_3 controls the amount of feedback to the beam-tube amplifier. It also controls the diode characteristic by varying the portion of the output signal voltage

drop across the diodes. This controlling action can be seen in Fig. 4. Figure 4 is a plot of the voltage developed across R_4 against the total voltage applied across the diode circuit. Increasing the resistance of R_3 decreases the signal voltage across R_4 and also decreases the slope of the curve at the higher values of resistance. The action of the slope can be seen by drawing tangent lines to the curves at corresponding applied voltage points. The angle between the tangents increases as the applied voltage increases. This type of controlling action by R_3 was found to be desirable to extend the range of load resistance variations for different load currents without causing an undue amount of distortion in the wave shape of the output voltage.

The optimum size of R_4 was determined to be 3100 ohms to apply the proper amount of signal voltage to the grid of the feedback amplifier. This value of R_4 allows R_3 to be varied over the range from 50,000 to 80,000 ohms. This range of values is necessary to select the proper operating conditions for different values of load current.

The 6J5 triode tube was selected for the feedback amplifier. This tube has good operating characteristics for the power supply available and still maintains a fairly high gain. The feedback amplifier circuit was designed to have a gain of 12, which is more than ample. With this gain the beam tube can easily be overdriven. The output of the feedback amplifier is taken from the plate circuit. This gives the proper phasing for positive feedback. The 100,000 ohm plate load resistor, R_5 , provides high resistance in the plate circuit to maintain a high gain for the

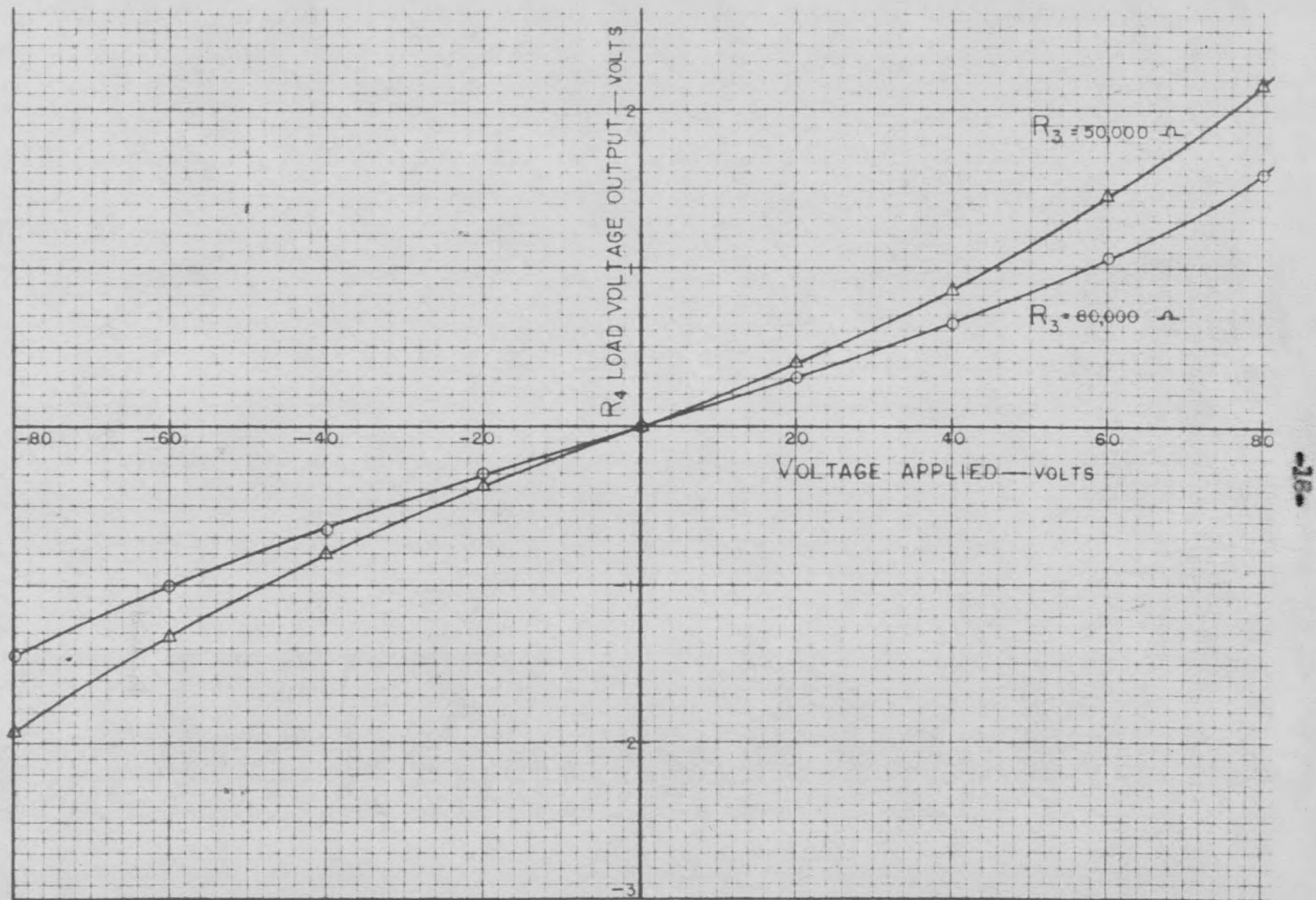


FIG. 4. GERMANIUM DIODE CIRCUIT CHARACTERISTICS.

triode amplifier. The coupling resistor, R_6 , may be designed to control the amount of feedback signal returned to the beam-tube amplifier. A potentiometer was tried for this purpose but experimental runs proved that R_3 was the more desirable and effective control for the feedback voltage.

DISCUSSION OF RESULTS

The results of the experimental tests on the circuit are plotted in Fig. 5. The curves have all been corrected by adjusting the feedback control, R_3 of Fig. 1, to produce the most linear relationship between output voltage and output load resistance. The curves are adjusted to represent the 1, 2, 3, 4, 5, 6, and 7 milliampere values of load current.

The 1 ma. curve was made most linear by adjusting R_3 to 50,000 ohms and the 2 ma. curve is corrected by setting R_3 to 64,000 ohms. Both of these curves are good approximations to linear constant current output beyond the maximum value of 22,000 ohms of load resistance used. The 3 ma. and 4 ma. curves are corrected by setting R_3 to 76,000 and 80,000 ohms respectively. The deviations from linearity in these two curves, at the higher values of load resistance, is positive. To compensate for this deviation more resistance is needed in R_3 than is required for 1 ma. and 2 ma. For the 1 ma. and 2 ma. curves it was necessary to correct for a negative deviation at the higher values of load resistance. The same relative sag of these current curves can be noticed on the 3 ma. and 4 ma. curves at 11,000 ohms of load resistance. At this load resistance the beam-tube amplifier gain is the controlling factor for the 3 ma. and 4 ma. curves and thus the sag cannot be corrected by adjusting the feedback control, R_3 . The 3 ma. and 4 ma. curves are good approximations to linearity up to 20,000 ohms of load resistance. The useful range could probably be extended by placing a variable resistance across the germanium diodes in place of R_2 in Fig. 1. This circuit change was not tried by the

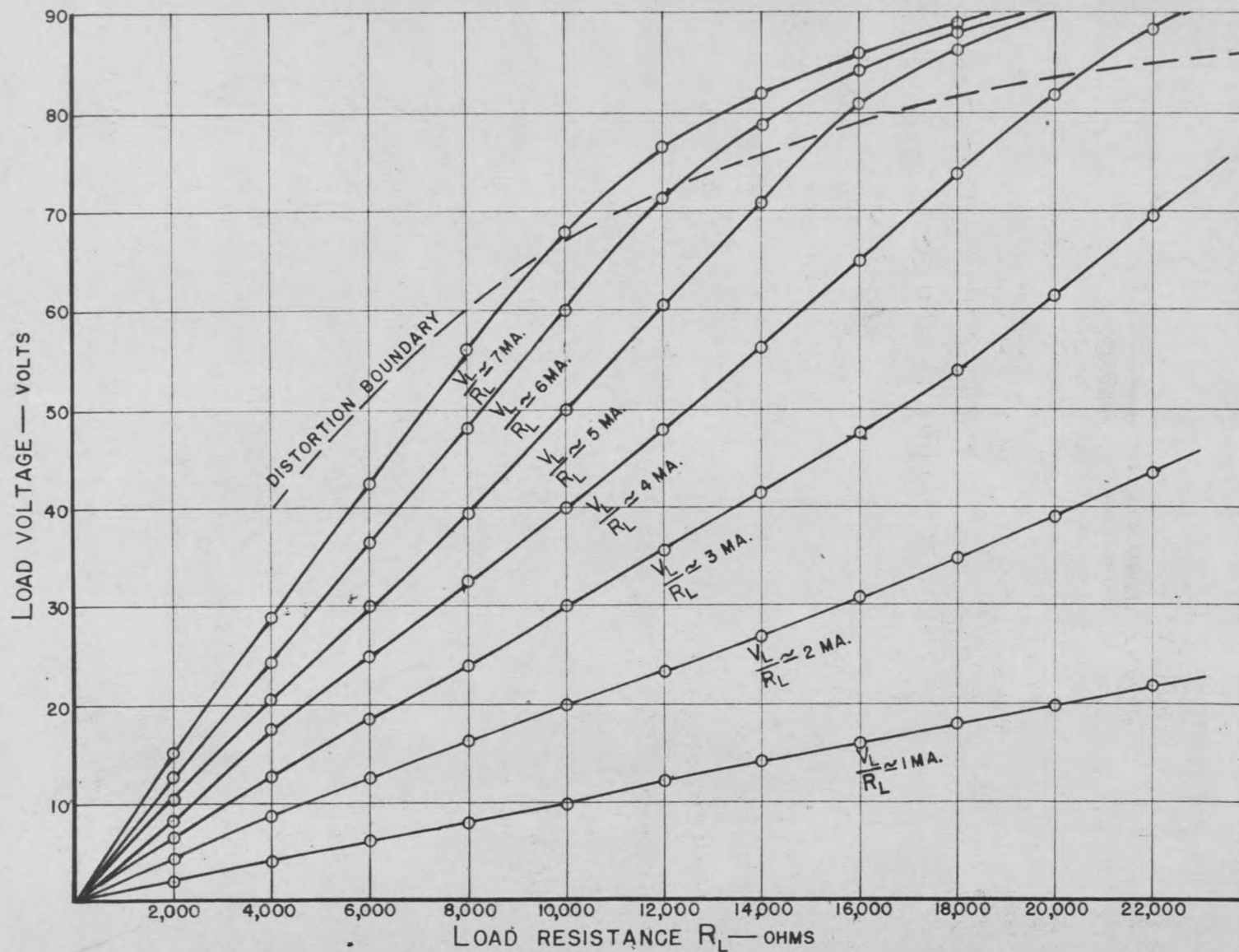


FIG. 5. OUTPUT CHARACTERISTICS OF THE CONSTANT-CURRENT GENERATOR.

author, but experimental data taken on the diode characteristics with and without the paralleling resistor indicated this possibility. It is doubtful that the load resistance range can be extended appreciably for the 4 ma. curve because undesirable waveshape distortion apparently begins at slightly over 22,000 ohms of load resistance. This effect was not verified by experimental data but is indicated by the intersection of the dashed distortion-boundary curve on Fig. 5.

The distortion-boundary curve was determined by observing the output voltage wave form on a cathode-ray oscilloscope. The observations were compared with the current curves and it was found that above this boundary the curves sagged beyond the control of R_3 . This curve indicates the approximate largest load resistance that can be used with each current without noticeably distorting the wave shape. The optimum values of maximum load resistance are determined by the intersection of this boundary curve with the respective current curves.

The 5 ma., 6 ma., and 7 ma. curves were obtained with R_3 set at 72,000 ohms. The distortion limits the range of load resistance for these current values to such an extent that feedback control need not be varied for each individual current curve. The maximum load resistance that can be used with the 5 ma. curve is 16,000 ohms. For the 6 ma. and 7 ma. curves 12,000 and 9,000 ohms respectively are the maximum values of load resistance usable. These values are each limited by the distortion boundary.

No experimental data was taken for curves of 8 ma. or more because

the signal generator was incapable of supplying enough input signal voltage. The distortion-boundary curve indicates that this circuit would have only a small range of usefulness for currents above 8 ma. The distortion curve indicates that good linearity could be approximated up to 6,000 ohms for 8 ma. and only 4,000 ohms for 9 ma. of load current.

The operation for each of the curves was selected first by trial and error and then, after the useful range of operation was found, the optimum adjustments were made as follows:

- (1) The approximate mid-point of the useful load resistance range is determined for the load current desired.
- (2) The load is set at this determined value and the input signal level adjusted to produce the proper output voltage to give the desired load current.
- (3) The load is then set to the range maximum and the feedback adjusted by R_3 until the desired output voltage is reached at this point to produce the proper current through the resistance.

These adjustments are usually sufficient, however, it was found desirable to check the deviation from linearity at the three-quarter point of load resistance range. If the deviation is too large the feedback may be readjusted to reduce it to within a tolerable value.

The curves all have a positive deviation at the lower values of load resistance. This deviation can be reduced if it's effects are undesirable by placing a 1500 ohm variable resistance in the cathode circuit of the beam amplifier in place of R_{k2} of Fig. 1. Increasing this resistance

lowers the gain of the beam amplifier as shown in Fig. 3. If this resistance is increased the power supply voltages must be readjusted to keep the beam-tube plate voltage down and the constant-current tube plate voltage up to where the power supply voltage divides equally. This maintains the desired operating properties of these two tubes. If the operating range of load resistance is small, say 8,000 ohms, the circuit can be adjusted as in (1), (2), and (3) above for this range and the total overall deviation will be insignificant. An experimental verification of this was taken for the 5-ma. curve and found to give good linearity for an 8,000 ohm range of load resistance. The plot of this curve is Fig. 6.

The frequency used for the curves of Fig. 5 was 2,000 cps. This frequency was selected because at 2,000 cps. the circuit has high gain and it is near the center of the logarithmic frequency range.

The frequency responses for the 5-ma. and 2-ma. load currents are shown in Fig. 7. and Fig. 8. respectively. The curves represent the different values of load resistance for these current values. Load resistances for these curves were selected to represent the entire useful range for each of the current values used. It was thought, by the author, to be unnecessary to plot frequency characteristics for each current value, therefore, the 5-ma. and 2-ma. currents were selected as representative of the higher and lower values of load currents respectively

The data for the frequency response curves was taken by making the adjustments, for the current value selected, as stated on page 23. The input signal voltage from the signal generator was measured and maintained

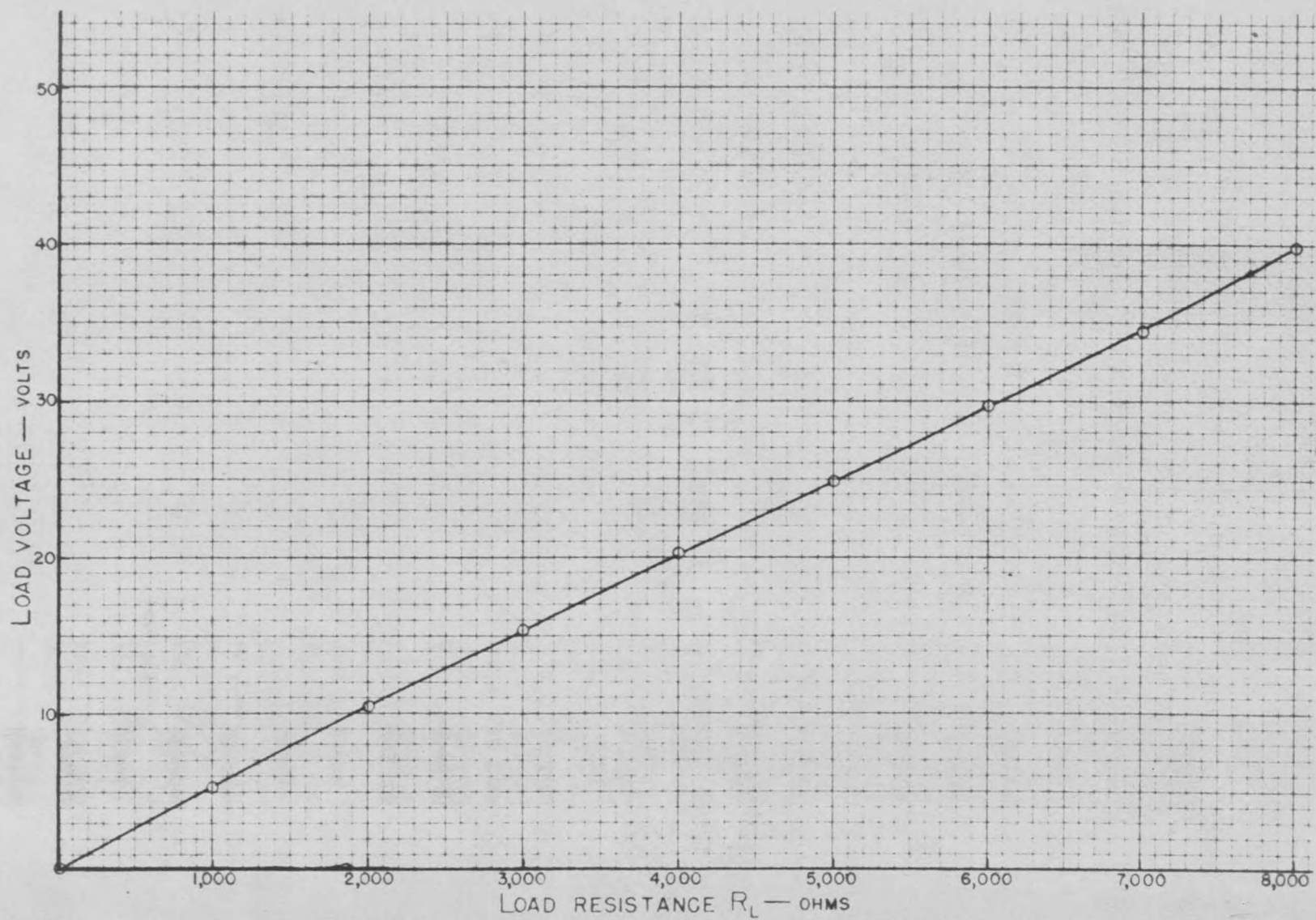


FIG. 6. OUTPUT CHARACTERISTIC OF CONSTANT-CURRENT GENERATOR FOR SMALL LOAD RANGE.

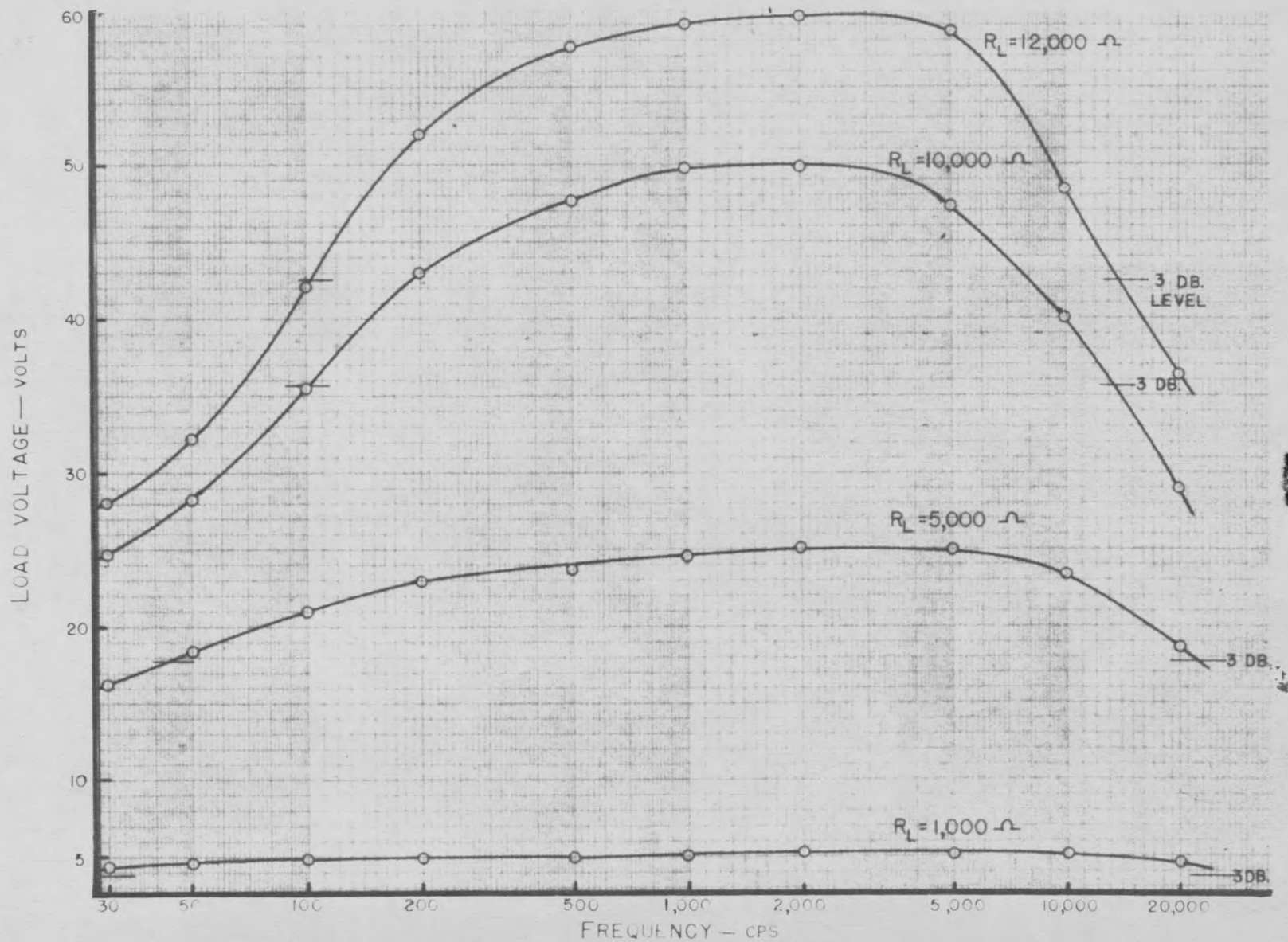


FIG. 7. FREQUENCY CHARACTERISTICS FOR 5 MA. LOAD CURRENT.

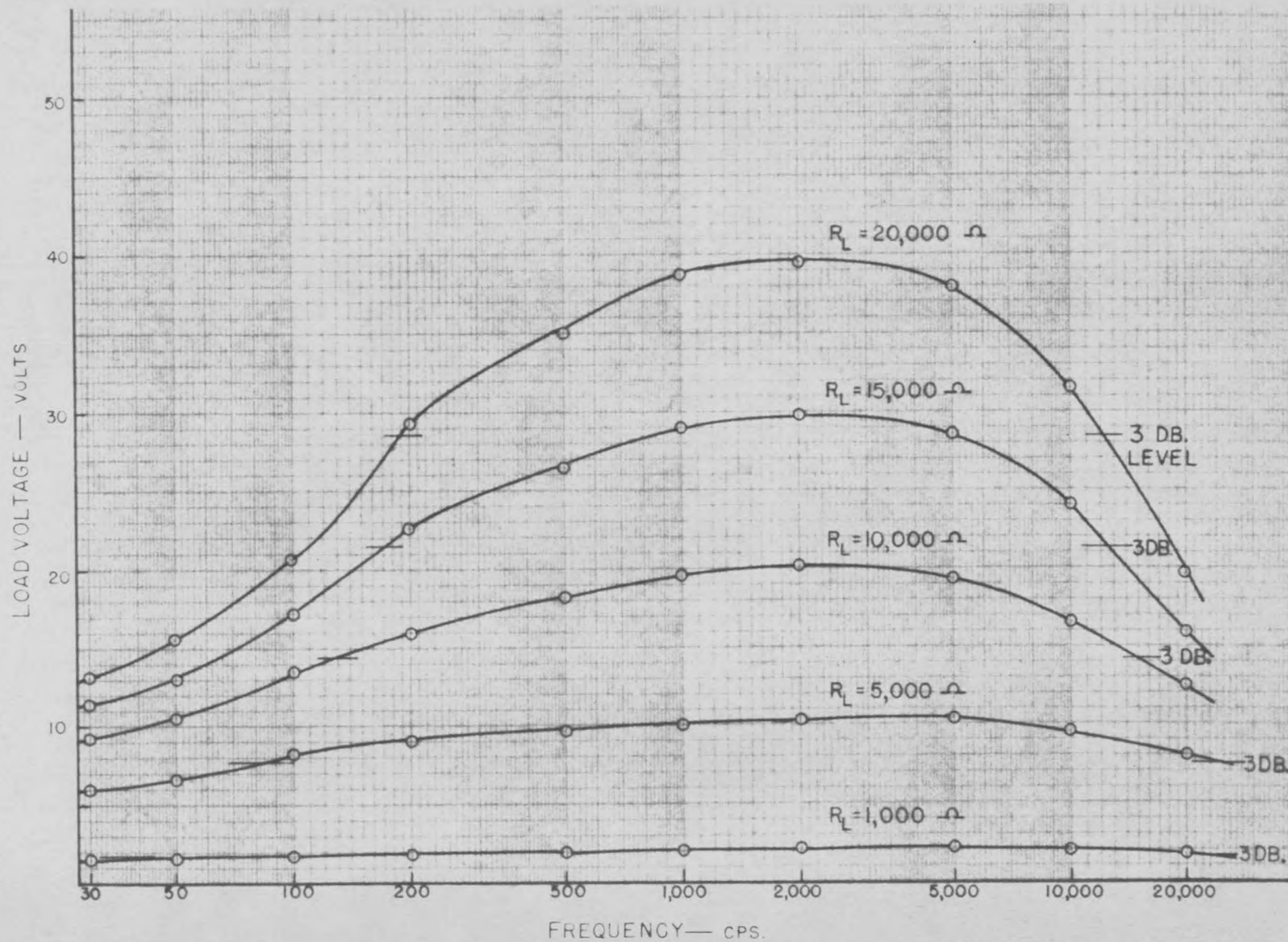


FIG. 8. FREQUENCY CHARACTERISTICS FOR 2 MA. LOAD CURRENT.

constant as the frequency was varied throughout the entire range.

The 5-ma. curves of Fig. 7 show a very good flat frequency response over the entire frequency range for the lower values of load resistance. At the higher values of load resistance the flat portion of the response curve becomes more narrow. The frequency range desired for this circuit was 100 to 10,000 cps. The 3-db. level is well outside these frequency limits except for the higher load resistances. The points at which the output voltage is 3-dbs. below the voltage level at 2000 cps. is indicated on each curve as the 3-db. level. At 10,000 ohms the low-frequency 3-db. level is right at 100 cps. and the low-frequency 3-db. level for 12,000 ohms is at 103 cps. This low-frequency response could be improved by using a larger resistance for R_6 and a larger blocking condenser in the feedback coupling circuit of Fig. 1.

The 2-ma. curves of Fig. 8 show the same general characteristics as the curves for the 5-ma. load current. The low-frequency response could be improved in the same way as for the 5-ma. curves. The curves for the 5,000 ohm intervals are quite equally spaced in the range from 200 to 10,000 cps. This shows that the circuit maintains its constant-current characteristics very well over this range of frequencies. The best frequency range for the 2-ma. curve is 500 to 7000 cps. This is the most nearly flat portion of each curve. The best range for the 5-ma. curve is approximately 300 to 7000 cps.

SUMMARY AND CONCLUSIONS

The problem of developing a constant-current generator was essentially worked out by starting with an amplifier with desirable characteristics and improving its gain - load characteristic to be a constant ratio. This ratio is the load current. The feedback circuit alone improved the constancy of the gain - load ratio but the result deviated positively and negatively about the desired constant value of load current. This effect was reduced by adding the constant d-c current device in the plate circuit of the amplifier. The final results still deviate alternately above and below the desired ratio as the load resistance is increased, but these effects can be limited to small values by use of the feedback characteristic and output control. Using this control and the procedure outlined within the thesis a very good approximation to constant current can be obtained with this circuit.

The load resistance range is small for the larger values of current because of the limited output voltage that can be obtained from an amplifier without distortion. This distortion occurs from over-driving the amplifier tube. The distortion may be reduced by using a larger bias and a higher plate voltage but this would necessitate using another power supply for the plate voltage source. The increase in load resistance range would not be sufficiently large to warrant this in most cases.

The linearity of the output voltage to load resistance is very good considering the resistance range for which this circuit is designed. Improvements in linearity could undoubtedly be made for any particular

current value at some constant input frequency and voltage.

The frequency response of this circuit leaves something to be desired for the low frequencies at high load resistance. This could be corrected by careful design of the resistance-capacitance coupling circuits and the amplifier stages. The frequency response is very good at the midrange of frequencies and a variation of one or two thousand cycles per second would not change the current linearity characteristics a great deal.

A practical use of this circuit could be made as shown in Fig. 9 where a signal voltage of constant amplitude is desired for input for a variable number of other devices. For example, suppose it is desired to have a constant signal voltage output from across R_1 and R_2 as other resistors are added to the circuit. The constant-current generator, as designed, would work very well for this type of operation as long as the total resistance variation was within the range capabilities of the generator. Another possible use of this circuit may be, as an example of Norton's theorem. Norton's theorem states that a network, containing generators and linear impedances, may be represented as a constant-current source generator in parallel with the internal admittance of the generator. An example of Norton's theorem is shown in Fig. 10 where the box contains the original generator which is regarded as a constant current source I in parallel with its internal admittance G_0 . G_L represents a load conductance which may be connected to the network.

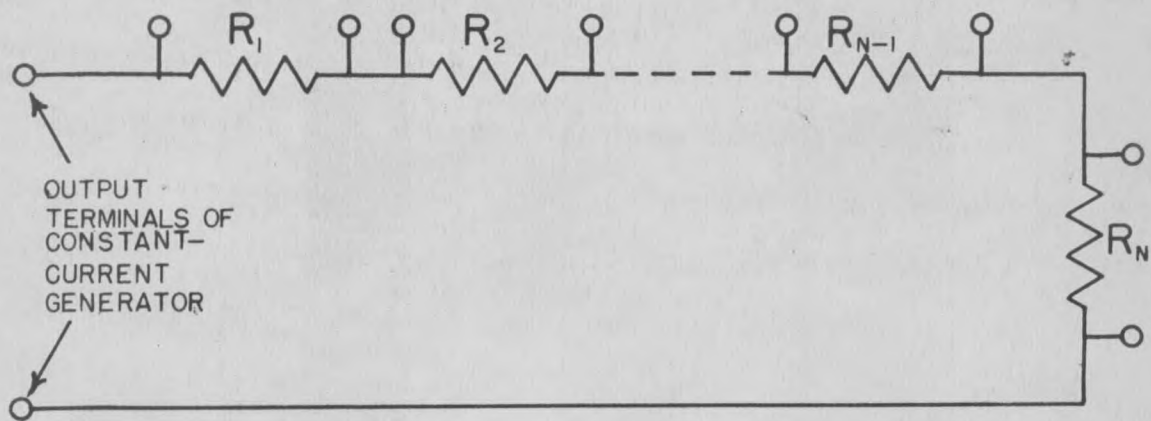


FIG. 9. A TYPE OF LOAD FOR USE WITH THE CONSTANT-CURRENT GENERATOR.

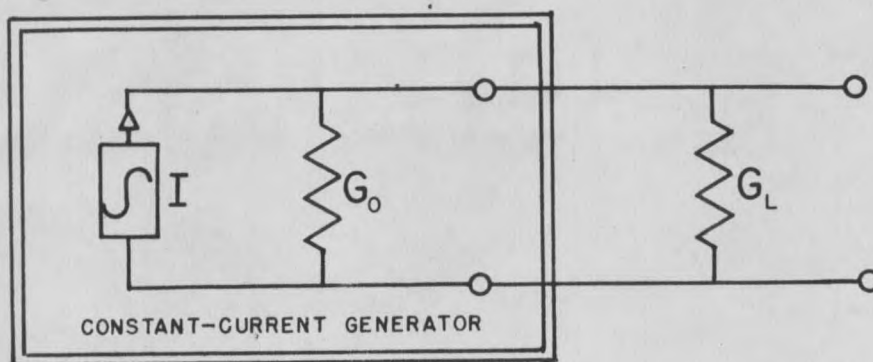


FIG. 10. EXAMPLE OF NORTON'S THEOREM.

LIST OF EQUIPMENT

Audio Oscillator - Hewlett-Packard, Model 200 BR.

Cathode-Ray Oscilloscope - DuMont, Type 208, No. 2836.

D-C Power Supply, 0-600 volt.

Decade Resistance Boxes - General Radio Company,
Type 602J, Nos. 14060 and 14040.

Germanium Diodes - Sylvania Electric Company,
Type 1-N-34, Nos. 4 and 5.

Vacuum Tube Voltmeter - Hewlett-Packard, Model 410-B.

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