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NAVORD REPORT 3595

PRELIMINARY REPORT ON THE MINIMIZATION
OF DRIFT IN MAGNETIC CONTROL AMPLIFIERS

28 JANUARY 1954



U. S. NAVAL ORDNANCE LABORATORY
WHITE OAK, MARYLAND

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PRELIMINARY REPORT ON THE MINIMIZATION
OF DRIFT IN MAGNETIC CONTROL AMPLIFIERS

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ABSTRACT: All magnetic control amplifiers exhibit null drift under temperature, supply voltage, and frequency variations. Many applications specify such a low level of drift that special techniques are demanded in the design and construction of the amplifier. Tests, specifications, and procedures for the practical manufacture of drift insensitive magnetic control amplifiers are given. Conservative estimates of the yields on components are made.

The techniques outlined are applicable to all high performance magnetic control amplifiers and constitute a less complex manufacturing schedule than some practical procedures now used in this field.

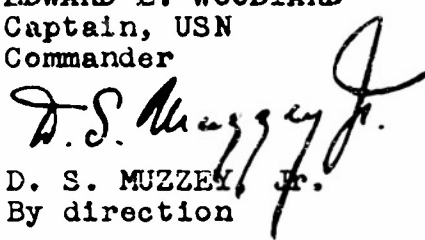
In following these techniques, amplifiers have been consistently produced with drifts below 0.125 microwatt (0.05 volts at 20,000 ohms input impedance) for a temperature range of -55°C to $+71^{\circ}\text{C}$, voltage range of 115 volts $\pm$ 10 volts and frequency range of 400 cps $\pm$ 40 cps.

U. S. NAVAL ORDNANCE LABORATORY
White Oak, Silver Spring, Maryland

28 January 1954

Under Bureau of Ordnance assigned tasks NOL-Re8-1-2-53 and NOL-A8f-1-2-54 for the development of magnetic amplifiers, the problem of null drift in the half-wave magnetic control amplifiers such as those reported in NavOrd Reports No. 2737 and No. 2833 was investigated. As requested verbally by Mr. Ensinger, Re8, the effort was directed toward the minimization of drift in a specific circuit and the development of the tests and procedure necessary for the practical production of this magnetic amplifier.

EDWARD L. WOODYARD
Captain, USN
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By direction

NAVORD Report 3595

CONTENTS

	Page
Introduction	1
System Requirements	2
Outline of Procedure	2
Selection of Rectifiers for Stage I	4
Selection of Cores for Stage I	5
Selection of Rectifiers for Stage II	6
Selection of Cores for Stage II	7
Assembly and Testing of Stage I	9
Assembly and Testing of Stage II	10
Combining Stages I and II	11
Assembly and Testing of Stages III and IV	11
Final Assembly	12
Conclusions	12
Appendix - Outline of Drift Investigation Program	13
References	20

NAVORD Report 3595

ILLUSTRATIONS

	Page
Figure 1. Complete Circuit Diagram	21
Figure 2. Sector Winding Lay-Out	22
Figure 3. Test Circuit for Stage I Components	22
Figure 4. Test Circuit for Measuring E-I Curves	23
Figure 5. Allowable E-I Curve for Stage I Reactors	24
Figure 6. Test Circuit for Stage II Rectifiers	25
Figure 7. Doubler Connected Rectifier Matching	26
Figure 8. Allowable E-I Curves for Stage II Reactors ..	27
Figure 9. Test Circuit for Stage I	28
Figure 10. Gain Curve for First Two Stages	29
Figure 11. Drift of Sample First Stages	30
Figure 12. Test Circuit for Stage II	31
Figure 13. Drift of Sample Second Stages	32
Figure 14. Gain Curve for Last Two Stages	33
Figure 15. Fabrication Procedure	34

NAVORD Report 3595

PRELIMINARY REPORT ON THE MINIMIZATION OF DRIFT IN MAGNETIC CONTROL AMPLIFIERS

INTRODUCTION

1. Drift is herein defined as output from the magnetic control amplifier for zero input due to the influence of changes in ambient temperature, voltage and frequency. In a closed loop position control system where the output of the controller tends to remain zero, drift in the magnetic control amplifier results in a null error being present on the input terminals. Both open and closed loop methods of measuring drift are employed in this report and will be justified in each case.
2. The magnitude of drift considered also should be stated at this point. Experience seems to indicate that by employing completely unmatched rectifiers and unmatched Orthanol tape cores selected at random, drift may be encountered equivalent to a signal input of a volt or greater at an input impedance of 10,000 ohms. With nominal selection of components, drift for a temperature range of approximately -55°C to $+71^{\circ}\text{C}$, line voltage of 115 volts ± 10 volts, and frequency of 400 cps ± 40 cps can be reduced to the order of 0.2 volts. This report deals with the matching techniques useful in reducing the drift to below the 0.125 microwatt level (0.05 volt at 20,000 ohm input impedance).
3. In investigating this drift problem and seeking a practical solution a specific magnetic amplifier circuit was selected. This was done in order to indicate the manufacturing problem and its solution through various tests and procedures, and to estimate probable yields on components. A high performance magnetic control amplifier circuit was selected in which the effects of drift were more readily apparent. In addition, part of the circuit comprised an integrator in which it was necessary to maintain essentially unity gain under all conditions. This placed tight restrictions on the slope and linearity of the gain curve.
4. The techniques described in this report were designed to provide a practical manufacturing procedure which would be simple and also give a high yield on all components. These techniques are applicable to all high performance magnetic control amplifiers. In instances where the gain is not required to remain constant, the specifications can be loosened considerably.

NAVORD Report 3595

SYSTEM REQUIREMENTS

5. The specific magnetic control amplifier circuit investigated is shown in figure 1 along with the closed servo loop. The amplifier consists of four half-wave type stages.¹ Positive integral feedback is placed around the first two, forming an integrator for unity loop gain around the two stages.² The system is designed for use with Bureau of Ordnance Servo Motors Mark 12 and Mark 16. Speed proportional voltage from the tachometer generator is fed back to the input of the third stage supplying damping for the system. The synchro error detection system produces 1 volt per degree error.

6. In the closed loop servo system the integrator provides a near-zero velocity error with infinite static accuracy, exclusive of synchro error and drift error. The static error was required to be less than 0.05 volts and the velocity error, including static error was not to exceed 0.1 volts for rotational speeds at the synchro control transformer of up to 20 degrees per second. The maintenance of a low velocity error requires a constant and linear gain in Stages I and II that is unaffected by variations in temperature, voltage and frequency. In many respects this is a more difficult part of the problem than the actual drift and is considered here because it is a requirement frequently placed on high performance amplifiers, both electronic and magnetic. Solution of this portion of the problem causes the drift problem solution to be even more general and useful.

6. The system was required to operate over the temperature range of -55°C to $+71^{\circ}\text{C}$ and from a line voltage of 115 volts ± 10 volts at a frequency of 400 cps ± 40 cps. For the purposes of this investigation it was assumed that line frequency variations could be simulated by additional line voltage variations. Subsequent spot checks supported this assumption. Consequently the line voltage was varied from 100 to 130 volts to simulate both voltage and frequency variations. Under all combinations of conditions the drift was consistently held below the 0.05 volt level and the gain was stabilized so as to allow no more than 0.1 volts velocity error (including drift error) for the input velocities indicated.

OUTLINE OF PROCEDURE

7. In brief outline the technique for the minimization of drift in magnetic control amplifiers is as follows:

(A) Select Stage I rectifiers. This requires the construction of a simple test circuit whereby the rectifiers are

NAVORD Report 3595

are evaluated by two meter readings. The yield in this test is estimated to be approximately 30% and all rejects will be utilized elsewhere in the circuit.

(B) Select Stage I reactors by using the test circuit of (A). The reactors are paired on the basis of two meter readings. Specified E-I curves for all Stage I reactors must fall within a certain range of values. These curves are obtainable with nominally good core material and should be specified in purchasing. When cores are obtained in this manner there should be no rejects.

By use of the above selected components with some additional precautions the drift in Stage I can be reduced to the order of less than 0.1 volt.

(C) Select Stage II rectifiers. This is accomplished in a test circuit which permits rapid measurement and sorting as to characteristics. From these sorted rectifiers matched pairs can be chosen. From large quantities of rectifiers yields in the order of 80% or higher can be obtained with all rejects being utilized in the third stage.

(D) Select Stage II reactors. These should be matched by weight to the third significant figure and have E-I curves that fall in a certain range of values. These properties are obtainable with nominal Orthonol tape cores and if some restrictions are placed on purchasing should result in yields in the order of 95%. All rejects excepting total failures can be utilized in Stage IV.

The above selected components can be used to reduce the drift in Stage II to below the 0.1 volt level.

(E) With the stages assembled the drift curve of each over the temperature range is plotted. A Stage I and a Stage II whose drifts are in the same order of magnitude are connected so that the drifts oppose each other. This insures a drift in the first two stages of below the 0.05 volt level. The yield in stages should be 95% or higher when large numbers of stages are built.

8. The drift associated with the third and fourth stages has been found to be negligible when nominal care is taken in obtaining components. Thus the 0.05 volt drift associated with the first two stages represents the maximum drift in this four stage magnetic control amplifier.

NAVORD Report 3595

SELECTION OF RECTIFIERS FOR STAGE I

9. It was found that for very accurate matching of rectifiers the exact operating conditions in the circuit must be duplicated in the testing circuit. Also the sensitivity of the testing circuit had to be of a very high order to detect sufficiently small differences in the rectifiers. For these reasons a comparison type rectifier matching circuit was constructed in which pairs of rectifiers are checked against each other. The reactors used in the test circuit are of the same type as those used in the completed amplifier stage.

10. The construction of the rectifier testing circuit is as follows:

(1) Select a pair of 4-79 molybdenum permennol cores, matched by weight to the third significant figure.

Specifications: 1-1/2" O.D. 1-1/8" I.D. 8 mil laminations, insulated by 1 mil paper, total 12 laminations.

(2) Sector wind with the following windings:

800 turns #35 (Winding A)

800 turns #29 (Winding B)

800 turns #29 (Winding C)

800 turns #35 (Winding D)

The distribution of windings is shown in figure 2.

(3) Connect in differential circuit as shown in figure 3. Note that no balancing is used. Components should be chosen such that without desensitizing the meter, meter A does not read off scale.

(4) Calibrate meter A by placing 0.05 volts d.c. on the signal input terminals. If meter A has an internal impedance of approximately 550 ohms the change in output current should be in the order of 8 microamperes.

(5) With the rectifiers under test in positions #1 and #2 note the unbalance reading on meter A.

(6) Interchange rectifiers #1 and #2 and again read unbalance on meter A.

NAVORD Report 3595

(7) The algebraic difference in the readings of step (5) and step (6) must not exceed four times the magnitude of the calibrated change in output current noted in step (4) for the rectifiers to be sufficiently matched.

11. The circuit rectifiers in Stage I are 5/8" square 6 plate half-wave connected selenium rectifiers. Radio Receptor Company rectifiers, which were immediately available in quantity, were used in the study of the drift problem and gave the desired results. Other rectifiers may be substituted so long as amplifier performance (gain and time delay) are unimpaired. In general, the highest reverse to forward impedance possible at 400 cps power frequency is preferred.

12. Before matching, the rectifiers must be temperature cycled ten times from -60°C to +75°C and afterwards formed for 24 hours at rated current and voltage. Care must be exercised in soldering connections to these rectifiers after they have been matched because undue local heating of this type may change their characteristics.

SELECTION OF CORES FOR STAGE I

13. Laminated core material was chosen for the cores of Stage I to minimize the sensitivity to strains over the temperature range. The material is 4-79 molybdenum permennol. The cores are constructed of 8 mil laminations insulated by 1 mil paper having inside diameter of 1-1/8 inches and outside diameter of 1-1/2 inches. A total of 12 laminations are used. The cores to be matched should come from the same heat treating anneal and be matched by weight to the third significant figure. Sufficient paper should be inserted in the core box to prevent excessive movement of the laminations, although binding of the laminations in the box is to be avoided.

14. The cores are then sector wound with

800 turns #35 (Winding A)

800 turns #29 (Winding B)

800 turns #29 (Winding C)

800 turns #35 (Winding D)

as shown in figure 2. After winding, the reactor is vacuum impregnated in medium weight oil of fairly constant viscosity such as hydraulic oil. It is not necessary to temperature cycle these cores.

15. The wound reactor when checked on the test set-up of figure 4 using 800 turns should have an E-I curve in the range shown in figure 5. This measurement is not sufficiently sensitive to be used as a matching test but rather is used to insure the necessary gain in the first stage. Consequently, the E-I curve of the reactor must be as good as the range indicated.

16. In order to facilitate purchase of these cores, the d-c data is given. Sufficient correlation has not been obtained to guarantee that duplication of the d-c data will necessarily produce the E-I curve required. However the d-c data should be of the following order:

Maximum permeability = μ max = 700,000 to 800,000

Coercive force (H_c) = .0045 oersteds

Maximum flux density = 7800 - 7900 gauss

Residual flux density = 5100 - 5300 gauss

17. The wound reactors are matched in pairs in the test set-up of figure 3. A set of fairly well-matched rectifiers are required from the rectifier matching test. Provision must be made for the insertion of the reactors into the circuit and for interchanging them. With the reactors in the circuit the unbalance is noted on meter A. Then the reactors are interchanged and the unbalance reading again noted. The algebraic difference of these two unbalances must not exceed twice the magnitude of the calibrated output for 0.05 volts d.c. input.

SELECTION OF RECTIFIERS FOR STAGE II

18. The selenium rectifiers for Stage II are composed of 8 plates one inch square, doubler connected with plates in intimate contact. Before testing they are temperature cycled ten times between -60°C and +75°C and then formed for 24 hours at rated current and voltage. Care must be exercised in soldering connections to these rectifiers after they have been tested as undue local heating of this type may change their characteristics.

19. The rectifier characteristics are measured in the circuit of figure 6. An rms voltage of 15 volts is applied and the half-wave average current is regulated, by the variable resistance, R, to 30 ma. This simulates to some extent actual circuit conditions. The circuit in series with the rectifier under test gives a measure of reverse leakage current while the circuit in parallel with the rectifier under test gives a

NAVORD Report 3595

measure of the forward voltage drop. The germanium diodes used are General Electric type IN92, selected to have less than 45 microamperes leakage current with 45 volts d.c. applied in the reverse direction. The microammeters and milliammeter are adjusted to read on scale (preferable mid-scale) whereupon the test circuit is ready to indicate relative values of the rectifiers to be tested. More elaborate calibration could be made so as to indicate actual values of current and voltage but this is not necessary. If desired, the error due to leakage currents in the germanium diodes can be reduced by placing the germanium diodes in dry ice. However again this is not necessary. Each four plate section of the doubler connected rectifier is now tested. Figure 7 shows a pair of doubler connected rectifiers and the sections that must be matched. Two sections are considered matched if the microammeter readings (proportional to reverse current) agree within 4 microamperes, and the milliammeter readings (proportional to forward voltage drop) agree within 0.04 milliamperes. If the sensitivity of the two meters is increased better matching can be obtained but this will probably not be necessary unless the temperature sensitivity of the rectifiers used is greater than those so far encountered.

SELECTION OF CORES FOR STAGE II

20. If commercially selected cores are available in which the coercive forces and remanences are matched, these should be obtained. In general however unmatched cores will be purchased in which case the selected set should be matched in weight to the third significant figure. The real test as to their acceptability is that an E-I curve taken on the test set-up shown in figure 4 using 2200 turns must fall in the range of values indicated in figure 8. This specifies the gain properties of the core as well as relative matching.

21. In order to simplify the production and selection of cores that will have the above specified E-I curves when wound and tested the following heat treatment is indicated. This heat treatment is used successfully on a laboratory scale at the Naval Ordnance Laboratory and will serve as a guide to producing the desired cores.

22. An alloy of 50% nickel, 50% iron is cold reduced approximately 99% to .002" tape. While being wound into a toroidal tape core it is insulated in a mixture consisting of 200 grams of magnesium hydroxide, 5.25 grams of Lomar PW and 2 liters of water passed through a colloid mill. Then it is rapidly heated to 975°C (requiring approximately 15 minutes) in a pure hydrogen atmosphere. After being held at this temperature of

NAVORD Report 3595

975° for two hours it is rapidly cooled by being withdrawn from the furnace heat zone. The core temperature should fall below 200°C in approximately 20 minutes.

23. The heat treatment will vary slightly with different amounts of impurities in the alloy and with different amounts of cold reduction. In general the d-c properties obtained in the cores will be as follows:

Maximum permeability (μ_m) = 85,000

Coercive force (H_c) = 0.15 oersteds

Ratio of residual flux density to maximum flux density ($\frac{B_r}{B_m}$) $\approx$.93

24. Again it should be noted that the above properties can not be used as a guarantee that the wound reactor will possess the specified E-I curves since complete correlation has not yet been obtained between the above d-c properties and the dynamic performance of the cores in a magnetic amplifier circuit. The above procedure and values will however serve as a help to the manufacturer in producing the desired cores.

25. It should be made clear that the properties demanded of the cores in the second, third and fourth stages are those possessed by nominally good square loop core material manufactured commercially under the names of Orthonol, Orthonik, Deltamax, etc. No difficulty should be experienced in purchasing these cores. They are usually obtainable in phenolic core boxes with some packing such as silicone grease to prevent excessive movement.

26. Before they are tested, the wound reactors should be temperature cycled over the required temperature range to be sure the necessary expansion and contraction is obtainable and to produce any permanent strains that will result from normal usage.

27. A recommended procedure is to take the reactors through ten temperature cycles from -60°C to +75°C.

28. Summarizing, the selection of cores for Stage II involves the following:

(1) Select cores in sets of two by matching their weights to the third significant figure.

NAVORD Report 3595

(2) Wind the cores with the prescribed windings and temperature cycle the wound reactor ten times from -60°C to $+75^{\circ}\text{C}$.

(3) Check to see if the E-I curve falls in the prescribed range.

29. The tape wound toroidal core size used is 1-1/8" inside diameter, 1-3/8" outside diameter, 1/4" tape width. The tape thickness is .002". The same core size is used in the third and fourth stages allowing the use of rejects from the second stage with the necessary modification of windings.

ASSEMBLY AND TESTING OF STAGE I

30. After selection of the rectifiers and reactors according to the above procedure, Stage I is assembled. To test Stage I, it is cascaded with a "standard" second stage which is known to be fairly well-balanced. This test connection is shown in figure 9.

31. While connected in this manner Stage I is trimmed for voltage insensitivity. The circuit is first balanced for zero output (with the input terminals shorted) by placing a high resistance across one of the 800 turn windings on one of the reactors. Trial and error will show which reactor must be shunted to zero the output. The line voltage is then varied over the desired range of insensitivity, in this case 100 volts to 130 volts. The variation in the output meter reading is noted. A small capacitance is placed across one of the 800 turn windings on one of the reactors. When rebalanced with resistance, the sensitivity to line voltage variation is again checked. If the variation in the output meter reading is reduced for the swing in line voltage the capacitance is on the right reactor and only the proper value of capacitance remains to be determined. When the proper values of capacitance and resistance are obtained, the output, with zero input, will be insensitive to changes in line voltage over the range from 100 to 130 volts. To prevent the use of reactors that are too greatly mismatched, the values of trimming resistance and capacitance are limited. The capacitance should not exceed .0015 microfarads and the resistance should not be below 100,000 ohms.

32. The gain curve of the two stage connection of figure 9 is now checked and should fall in the range indicated in figure 10.

33. The final test of Stage I is to check its drift (output

for no input) over the temperature range of -55°C to $+71^{\circ}\text{C}$. Again, connected as in figure 9, and with the signal input shorted, Stage I is placed in the temperature chamber. Some provision, such as sealing in a container, must be made to prevent moisture condensation on the components of Stage I. Very large drifts are encountered when this precaution is not taken.

34. The open loop drift vs temperature curve for Stage I is plotted. Two examples are shown in figure 11, where the closed loop drift for Stage I is also given for comparison with the specified open loop drift. It is to be noted that they correlate within a small fraction of the drift specification. This drift will be in the order of 0 - 0.1 volts and will be placed in opposition to a drift of roughly the same magnitude in Stage II to insure drifts below the 0.05 volt level. (Actually 90% of the samples investigated had less than 0.05 volts drift alone when the procedure requirements were followed.)

35. The facility with which these curves can be taken is seen when it is pointed out that these are all open-loop measurements requiring only an output meter in the way of instrumentation. Large numbers of stages can be run simultaneously in one temperature chamber requiring only a meter reading on each at a given temperature.

ASSEMBLY AND TESTING OF STAGE II

36. A similar assembly and testing procedure to that of Stage I is followed for Stage II. Stage II is assembled and cascaded with a "standard" Stage I (assembled from matched components) as shown in figure 12. While connected in this manner the two stage circuit is trimmed for voltage insensitivity in the same manner as that outlined in Assembly and Testing of Stage I. The trimming, it will be noted, is applied to the "standard" Stage I and the same limits to the amount of trimming, namely, less than .0015 microfarads and no less than 100,000 ohms, apply. Trimming in excess of this indicates that the Stage II under test is too greatly mismatched to be used.

37. Again the gain curve of the two stages is obtained and must fall, in the range given in figure 10. The gain curve test ordinarily should not result in any rejects at this point in the assembly process.

38. An open loop drift (output for no input) curve for the temperature range of -55°C to $+71^{\circ}\text{C}$ is now taken with the

NAVORD Report 3595

Stage II in the temperature chamber. Again precaution must be taken to prevent moisture condensation on the components. This curve will be similar to the sample curve of a Stage II given in figure 13 where the closed loop drift for the Stage II is also given for comparison. The maximum drift will be in the order of 0-0.1 volts and will be opposed to the drift of a Stage I to produce drifts below the 0.05 volt level.

39. Again it should be pointed out that in a production set-up, large numbers of stages can be run simultaneously in a temperature chamber requiring only a meter reading on each at the desired temperatures.

COMBINING STAGES I AND II

40. The testing of Stages I and II yields a drift curve for each stage. The two stages which are to be used together are selected on the basis of the magnitude of their drift curves. Stages are chosen with drift curves that when subtracted from each other fall well below the 0.05 volt level. This is relatively easy since all the drift curves should be below the 0.1 volt level. If the curves run on the test circuits of figures 9 and 12 have drifts opposite in polarity, then the output terminal A of Stage I is connected to input terminal A' of Stage II and B is connected to B'. This results in subtraction of the drifts. If the curves run on the test circuits of figures 9 and 12 have drifts of the same polarity then the output terminal A of Stage I is connected to the input terminal B' of Stage II and the output terminal B of Stage I is connected to input terminal A' of Stage II. This again results in subtraction of the drifts.

41. The two stages are wired together at this point and remain together when inserted in the completed unit. Again it is advisable as a production check to take a gain curve of the two stage amplifier.

ASSEMBLY AND TESTING OF STAGES III AND IV

42. The selection of components and the assembling of Stages III and IV requires no special technique. The Orthonol tape cores should have gain properties as good as those described in Stage II for satisfactory performance. As stated previously although Radio Receptor Company rectifiers gave the desired results, other rectifiers may be substituted so long as amplifier performance (gain and time delay) are unimpaired.

43. It may be advisable to temperature cycle the rectifiers and reactors as done for Stage II to stabilize them as far as possible. The rectifiers should afterwards be formed for 24 hours at

rated current and voltage.

44. With the input to Stage III shorted through its 1000 ohm input resistance, any unbalance in Stages III and IV can be removed by shunting a winding on a reactor of Stage III with a high resistance. The gain of these two stages should be checked and should be approximately that of the gain curve in figure 14 or higher.

FINAL ASSEMBLY

45. The combined first and second stages are now assembled with stages III and IV. The final adjustments are made after the servo loop is closed. There are two adjustments to be made which interact somewhat. The feedback around Stages I and II must be set by means of the voltage divider on the output of Stage II. This is adjusted until the running error is below 0.1 volts for both directions of rotation and for all speeds up to 20 degrees per second at the control transformer shaft. If a static error is present, allowance must be made for this error while measuring the running error. The adjustment of the voltage divider may have a slight effect on the static null error. When the divider is set the final balancing is accomplished by means of resistance and capacitance shunt on a reactor of Stage I. It will be recalled that such a balancing and voltage insensitizing procedure was carried out in the assembly and testing of Stage I. The capacitance and resistance shunts if still present on Stage I may have to be adjusted in this final balancing and voltage insensitizing check.

46. The amplifier is now completed. A block diagram of the construction schedule is shown in figure 15 which will summarize the steps taken.

CONCLUSIONS

47. Input stage circuit components operate in such a non-linear manner and require such sensitive matching that they must be selected by comparison under actual circuit conditions.

48. The remaining stages can be drift insensitized by nominal selection of components.

49. This procedure though moderately complicated is of such a nature as to make possible the practical manufacture of drift insensitive, high performance, magnetic amplifiers.

50. Though outlined for one specific circuit this procedure with slight modifications is applicable to all high performance magnetic amplifiers.

APPENDIX

OUTLINE OF DRIFT INVESTIGATION PROGRAM

1. When the study of drift in magnetic amplifiers was undertaken, preliminary tests indicated that the three main sources of drift were (1) disturbances causing unbalanced operation of rectifiers, (2) disturbances causing unbalanced operation of reactors, and (3) disturbances causing a change in level of operation of the rectifiers which changed the level of operation of the reactors, causing unbalanced operation. This latter source of drift is difficult to detect because reactor unbalance occurs when the rectifiers only are in the temperature chamber.
2. The disturbances, causing drift, that are considered in this drift study are temperature, voltage and frequency. To simplify the investigation the assumption was made that frequency variations could be roughly simulated by voltage variations. Consequently the voltage variations were increased in lieu of taking frequency tests. Spot checks taken later verified the validity of this assumption.
3. The first investigations revealed considerable drift contributed by the unbalanced operation of the rectifiers over the temperature and voltage range. This was in conformance with the general experience in the field. First emphasis therefore was placed on the minimization of drift in the rectifiers of the first stage, which was a conventional half-wave bridge.
4. An attempt was made to match rectifiers on the basis of their voltage current characteristics. The rectifier reverse current was measured at three voltage levels, the 0.5 volt per plate, the 1.0 volt per plate and the 2.5 volt per plate level. Variations of approximately 8% were noted. The forward direct voltage on the rectifier was measured at six different forward current levels, i.e., 1 ma, 2 ma, 5 ma, 20 ma, 50 ma, and 100 ma. Variations of approximately 10% were noted in this region. When assembled stacks of rectifiers failed to produce any matched pairs, one hundred unassembled one-inch-square selenium rectifier plates were measured and stacks of 6 plates (12 plates doubler connected were normally used in each side of bridge) assembled from selected plates. No two plates had all nine readings identical but it was possible to assemble stacks that had no differences greater than 5%. At this stage of the investigation two performance tests were being used to indicate matched rectifier stacks. One was to interchange the stacks in the bridge circuit. This was later found to be misleading. The other was to measure the drift over the temperature range. Both tests failed to

give more than fair correlation with the voltage-current measurements obtained on the rectifiers and the drifts encountered over the temperature range were far in excess of the 0.05 volt specification. The failure to correlate was attributed to two causes. One, and most important, was the failure of the rectifier voltage-current test circuit to duplicate operating conditions. The other was the interaction between rectifiers and reactors, particularly in the bridge circuit, which made isolation of their respective drifts difficult. Considerable effort was directed toward duplicating actual operating conditions in the test circuit by the addition of rectifiers and/or reactors, but little success was achieved. The most practical method appeared to be to match input stage rectifiers by comparison in the actual magnetic amplifier circuit. This comparison was obtained by interchanging rectifiers and noting circuit behavior under each condition. In the bridge type circuit this interchange yielded poor data due to the interaction among components. The trouble arose from the inequality of the four legs of the bridge. In order to effectively eliminate two legs of the bridge the first stage circuit was changed to the differential circuit where a half-wave magnetic amplifier stage is coupled to the following stage by means of differential windings. This circuit had been previously used in the Magnetics Division of the Naval Ordnance Laboratory to obtain higher gains than from the conventional bridge. It has also been suggested that since the number of rectifiers was reduced over the conventional bridge the matching should be easier. In addition the differential circuit permitted somewhat better control of distributed capacitances because the reactor power windings were now combined into one power winding. It should be noted here that a large percentage of the leakage current in selenium rectifiers at 400-cycle power frequency is capacitive current and that at the drift level required capacitive unbalance in rectifiers and reactors causes considerable trouble. After changing over to the differential circuit an effort was made to correlate several types of absolute measurements on the rectifiers with circuit performance, but without success. From this point on, input stage rectifiers were matched only by comparison in the actual differential circuit being used but with the output differential windings replaced by 100 ohm resistors. The circuit, however, still appeared to be far too sensitive to rectifier mismatch. To insensitize the circuit to the effects to rectifier mismatch a rectifier was added in the line feeding the differential stage. A large number of plates were used in this rectifier which was common to both legs of the differential circuit and the effect was to minimize reverse leakage differences in the rectifiers in each leg of the circuit. To reduce resetting action from

rectifier reverse leakage the reactors were wound with a relatively few number of turns. The line resistance was added to reduce quiescent current with its attendant heating drift and to minimize the effect of forward resistance differences in the rectifiers in each leg of the circuit.

5. Using the differential circuit with line rectifier and selecting leg rectifiers by comparison in the actual circuit, drift due to rectifier unbalance was minimized. As previously mentioned, however, this rectifier drift was not completely distinguishable from reactor drift. When the temperature is changed the impedances of the rectifiers change and these changes in impedance, quite apart from mismatch in impedance, change the flux setting on the reactors. The operation of the reactors around a new flux level brings out mismatch in the reactors not present when operating around the former flux level. Thus, with the rectifier only in the temperature chamber, the drift recorded may be due solely to reactor mismatch. This would seem to indicate that the reactors only should be placed in the temperature chamber to record strictly reactor drift. However, when the temperature is changed under these conditions the coercive force of the reactor core changes, the firing angle, or point of saturation in the half cycle of line voltage, also changes. This new firing angle on the conducting half cycle and changed impedance on the reset half cycle cause changed waveforms to be placed on the rectifier. The new waveforms with their associated harmonics bring out mismatches in the rectifiers not seen under previous conditions. Thus with the reactors only in the temperature chamber mismatch in the rectifiers may be contributing to the recorded drift.

6. As a result of these effects it was not possible to say with certainty that the drift due to rectifiers had been reduced to some specific value even after the above discussed changes were made. It was necessary to assume for the moment that rectifier drift had been minimized and to direct the effort toward minimization of drift in the reactors of stage one.

7. Considerable drift apparently was being contributed by the reactors. Selection on the basis of E-I curves did not yield the quality of matching necessary to guarantee low drift over the temperature range. This was attributed to the mechanical construction of the Orthonol tape-wound toroids which are subject to some mechanical stress under ambient temperature changes. To overcome this, laminated core material was adopted. It should be pointed out that as time was limited a full investigation of this problem of core construction could not

be carried out and subsequent experimentation may show the suitability of tape-wound toroids for operation over a large temperature range.

8. With laminated 4-79 molybdenum permennol cores in differential circuit connection plus line rectifier and selected leg rectifiers, the drifts experienced with the entire Stage I in the temperature chamber were now in the order of 0.1 volt. With this low temperature drift the most pronounced drift experience in the amplifier was now due to line voltage variations. For a line voltage variation of 100 to 130 volts drifts of several times the 0.05 volt specification were noted.

9. It was known that in the half-wave bridge magnetic amplifier the series-type reset circuit³ was less sensitive to line voltage variations than the parallel-type reset circuit. Accordingly, the first three stages of the amplifier under study were converted to series-type reset. This involved shunting the doubler connected rectifier in one side of the bridge for Stages II and III and changing the circuit in Stage I. It had been previously noted that sensitivity to line voltage variation was affected by the balancing method used. A study was undertaken that resulted in the resistance-capacitance trimming method⁴ for decreasing the sensitivity to line voltage changes. By following this method, which is outlined in the main body of this report, the line voltage drift can be reduced to a small fraction of the 0.05 volt total drift specification. Although the trimming technique fails to maintain the same voltage insensitivity over the temperature range it does reduce it to such a low value that it no longer is an appreciable amount of the 0.05 volt specification.

10. With the minimization of the voltage and temperature drifts in Stage I the open loop drift problem was essentially solved. The drift contributed by Stage II was an order of magnitude lower and it was assumed at this time that nominal selection of components for this stage and succeeding stages would be satisfactory.

11. It was now necessary to investigate the closed loop system where additional feedback connections were made, where the first two stages function as an integrator and where the low velocity error specification must be met, requiring near constant gain in the first two stages. These additions to the problem had to be met over the temperature range and for required variations in line voltage.

NAVORD Report 3595

12. Upon placing the positive integral feedback around the first two stages and closing the servo loop an unbalance was introduced. If the amplifier was rebalanced under these conditions the gain curve was distorted to cross the origin and remained unchanged at higher levels. This caused the gain curve to be non-linear and adversely affected the operation of the integrator. The unbalance introduced when the positive integral feedback loop was closed was due to distributed capacitance between the power winding and the control winding on which the feedback signal was placed. To prevent this the windings on the reactors of Stage I were sector wound and the feedback circuit made as symmetrical as possible. This resulted in essentially the same balance in both open and closed loop.

13. To assure meeting the low velocity error specification under all conditions, extensive dynamic tests were run at room temperature before any tests were run at different ambient temperatures. In these tests the slope of the gain curve and linearity of the gain curve sufficient to maintain near zero velocity error over the line voltage range of 100-130 volts were found. The velocity error was measured for six input velocities, 20 degrees per second at the control transformer shaft, 12 degrees per second, 5 degrees per second, -5 degrees per second, -12 degrees per second, and -20 degrees per second. This was repeated for each of the three line voltage levels, 100 volts, 115 volts, and 130 volts. This data was taken using fourteen different input stages after determining that the remaining three stages of amplification were satisfactory. The fourteen input stages were provided by first running one set of rectifiers with six different sets of reactors and then running one set of reactors with eight new sets of rectifiers. The results obtained were limits on the slope and linearity of the gain curve, necessary relative matching of reactors, and necessary relative matching of rectifiers.

14. After determining the requirements for room temperature operation the tests were repeated at the six velocities and three voltage levels for ambient temperatures of 0°C, -25°C, -50°C and +75°C. This data was taken using six different first stages where the first stage only was placed in the temperature chamber, and for two second stages, where the second stage only was placed in the temperature chamber. This data was not as good as expected, being slightly outside the 0.05 volt specification for several of the stages. This was attributed to moisture condensation on the components and subsequent tests verified this. Up to this point, in all cold temperature tests the amplifier had been placed in a

sealed plastic bag containing a drying agent. However, air leakage around the lead-in wires permitted sufficient moisture to condense on the amplifier to cause a drift in the order of the 0.05 volt specification. This drift was not identified as moisture drift but was assumed to be temperature drift. To correct this when it was discovered, the amplifiers were placed in metal containers having press tight lids equipped with lead-in headers. The seams were soldered thoroughly and the lid was sealed with Glyptol after a drying agent, Calcium Hydride was placed in the container. When the amplifiers were operated in this manner the drifts were reduced still further and were in the range expected.

15. The second stage drift appeared to be lower than the 0.05 volt specification as long as components were nominal. However, the drift was an appreciable fraction of the 0.05 volt allowable drift. This plus the fact that the input stage drift was marginal if high yields were expected indicated that a higher yield could be obtained and considerably lower drifts would result if the drift of Stage II was made to oppose the drift of Stage I. This could be accomplished by the fairly simple expedient of taking an open loop drift curve during fabrication of the particular stage, and upon assembly of the unit, connecting the stages so as to oppose the drifts.

16. The requirements on the amplifier were now well understood and specifications had been set on all components, gains, and linearities. Many specifications were satisfactory, while at the same time it was realized that they could be loosened when additional data were obtained on larger statistical samples. Since the purpose of the investigation was to show the practicability of manufacturing a drift insensitive magnetic control amplifier, it was felt that the first emphasis should be on completely specifying the problem and making conservative estimates of yields on components. Further experience on the part of the manufacturer should liberalize specifications and increase yields.

17. As a final check on the procedures outlined in the main body of this report a sample consisting of ten input stages and 4 second stages were tested under humidity free conditions and at the ambient temperatures, $+75^{\circ}\text{C}$, $+50^{\circ}\text{C}$, $+25^{\circ}\text{C}$, 0°C , -25°C , -55°C . At each temperature the static error was checked for line voltages of 100v., 115v., and 130v. The velocity error was checked for the three line voltages with the six input velocities discussed previously. In addition, the open loop gain curve of Stages I and II was taken at each temperature. Each amplifier stage was allowed to stabilize at each new temperature for at least seven hours. The results of these tests gave further verification to the specifications

NAVORD Report 3595

outlined. Figure 11 is a sample of the type of drift curve obtained from these tests.

18. As a result of this drift study the foregoing preliminary specifications and techniques for manufacturing drift insensitive magnetic control amplifiers were devised. The procedure outlined is considerably simpler than some manufacturing procedures now in use in this field and subsequent study should serve to further simplify it.

NAVORD Report 3595

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4. H. H. Woodson, E. T. Hooper, "External Trimming to Reshape the Hysteresis Loop of a Saturable Reactor" NavOrd Report 3564.

NAVORD REPORT 3595

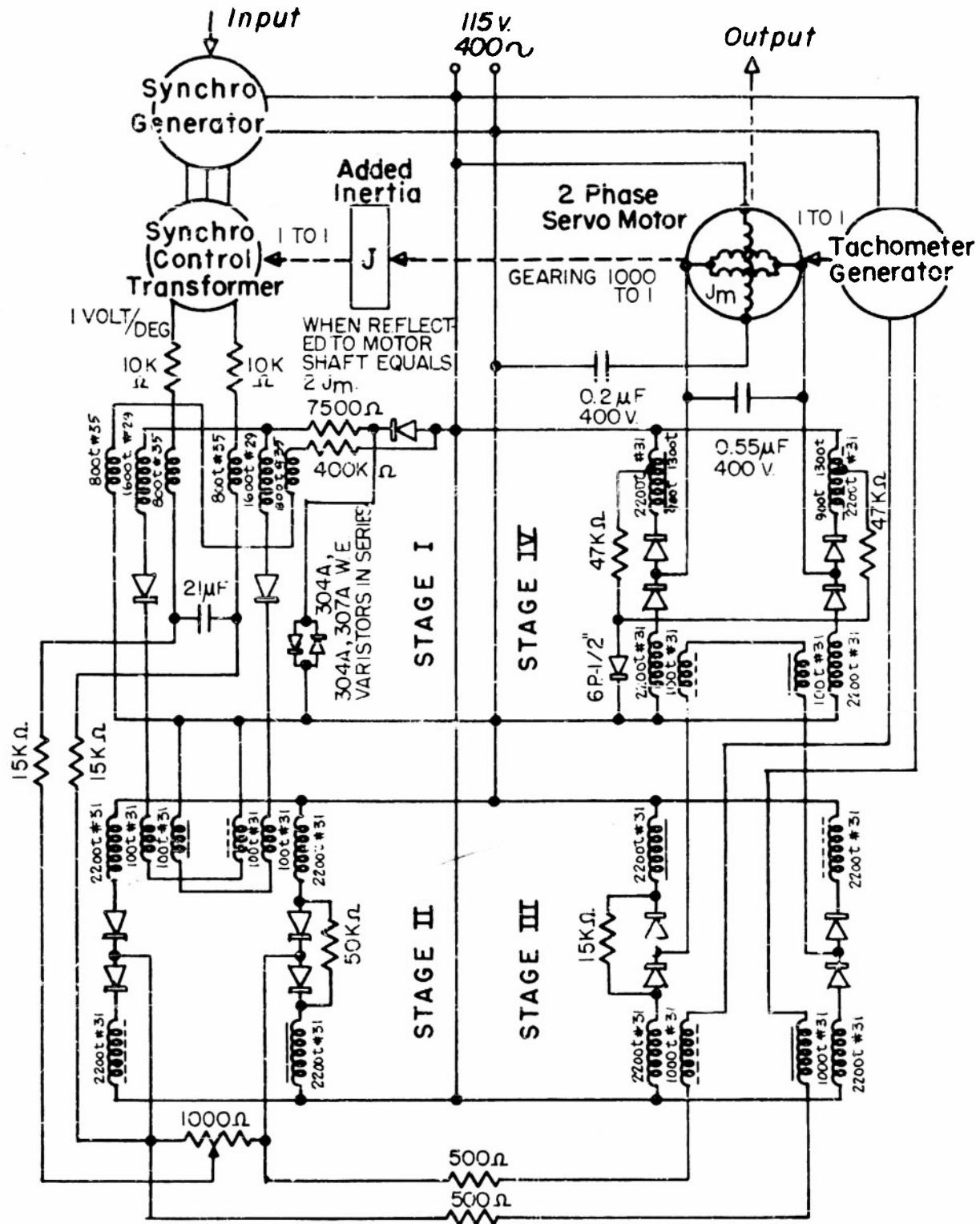


FIG. I - COMPLETE CIRCUIT DIAGRAM

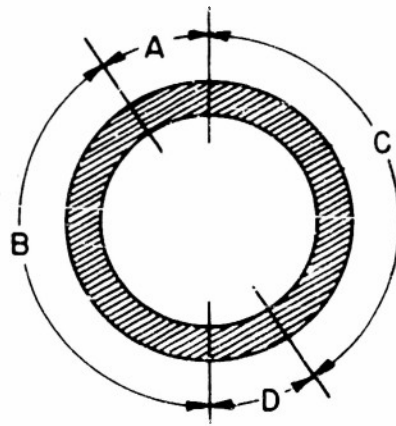


FIG. 2 - SECTOR WINDING LAYOUT

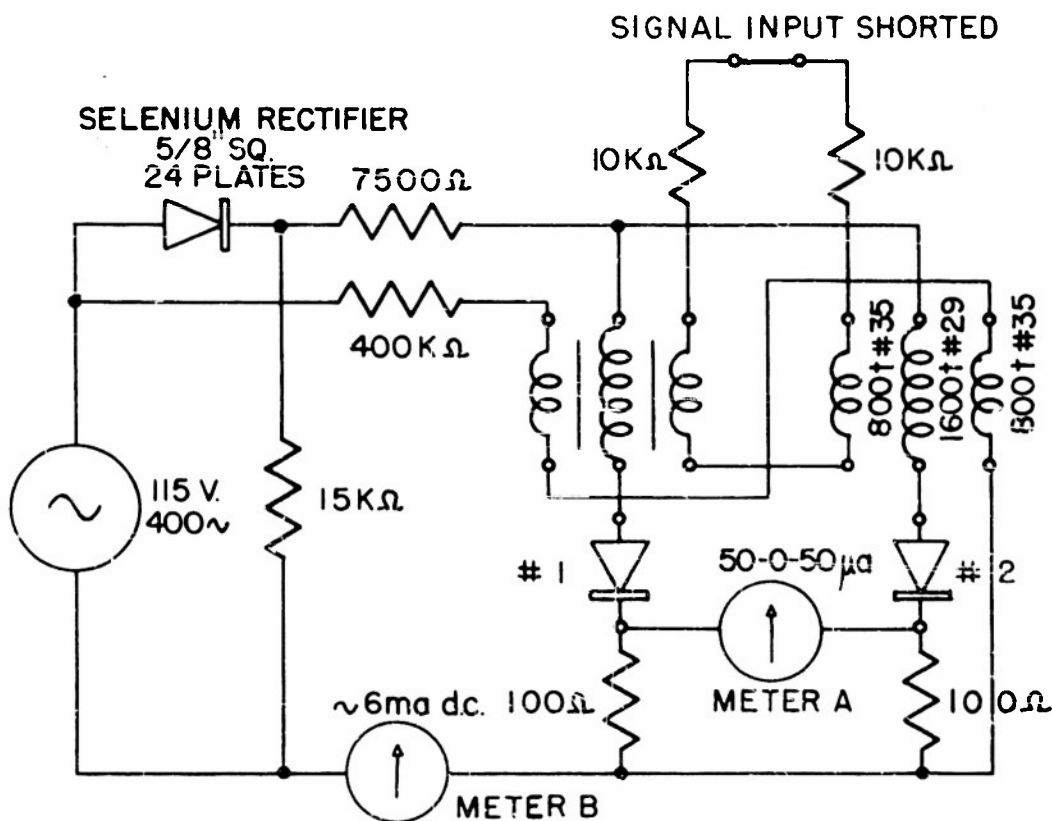


FIG. 3 - TEST CIRCUIT FOR STAGE I COMPONENTS

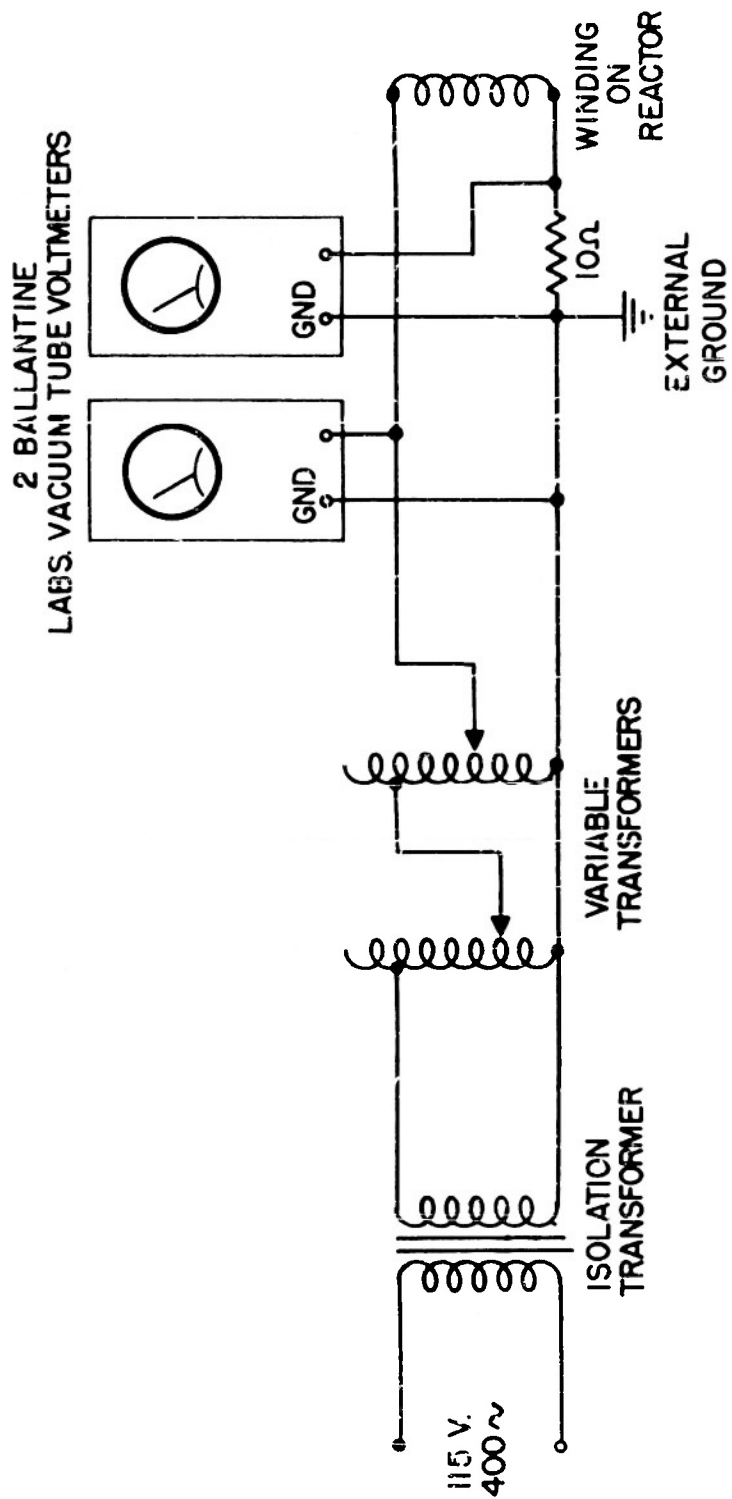
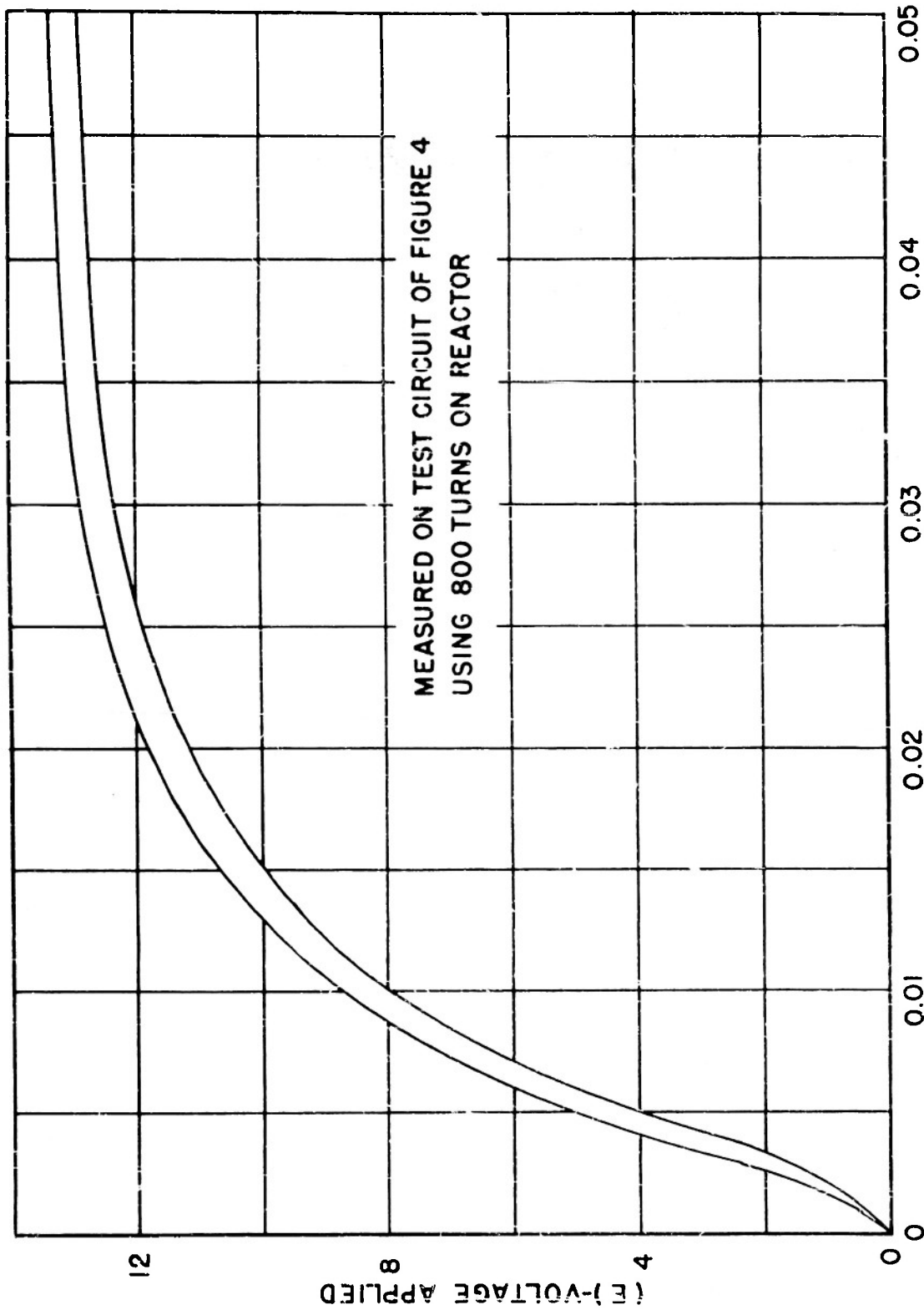


FIG. 4 - TEST CIRCUIT FOR MEASURING E-I CURVES



(1)-VOLTAGE ACROSS 10Ω RESISTOR

FIG. 5 - ALLOWABLE E-I CURVE FOR STAGE I REACTORS

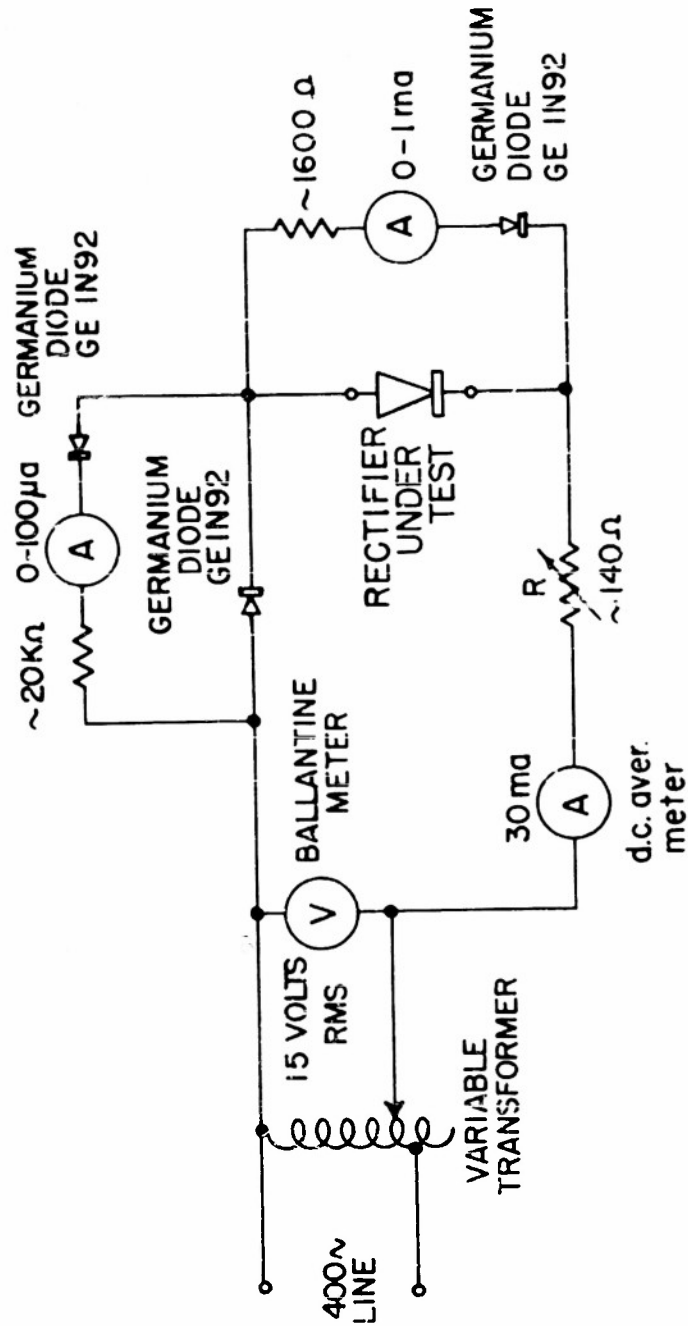
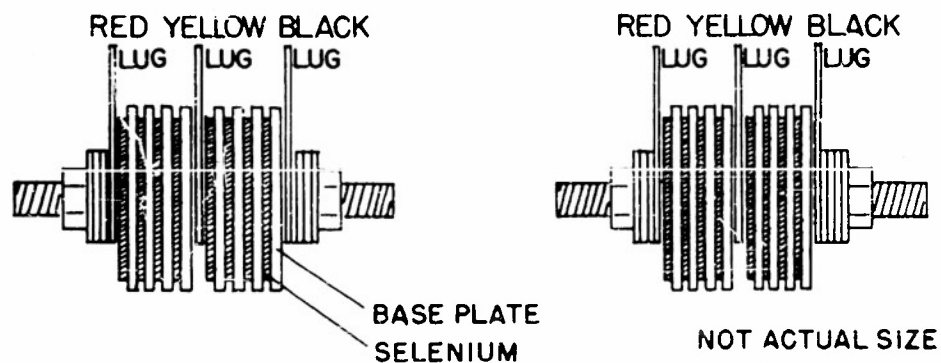


FIG. 6 - TEST CIRCUIT FOR STAGE II RECTIFIERS

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IT IS NOT NECESSARY TO MATCH
ALL FOUR SECTIONS WITH EACH
OTHER.

THE RED-YELLOW SECTIONS OF
EACH MUST BE MATCHED WITHIN
THE SPECIFICATIONS IN BOTH
METER READINGS.

THE YELLOW-BLACK SECTIONS
OF EACH MUST BE MATCHED WITH-
IN THE SPECIFICATIONS IN BOTH
METER READINGS.

FIG.7 - DOUBLER CONNECTED RECTIFIER MATCHING

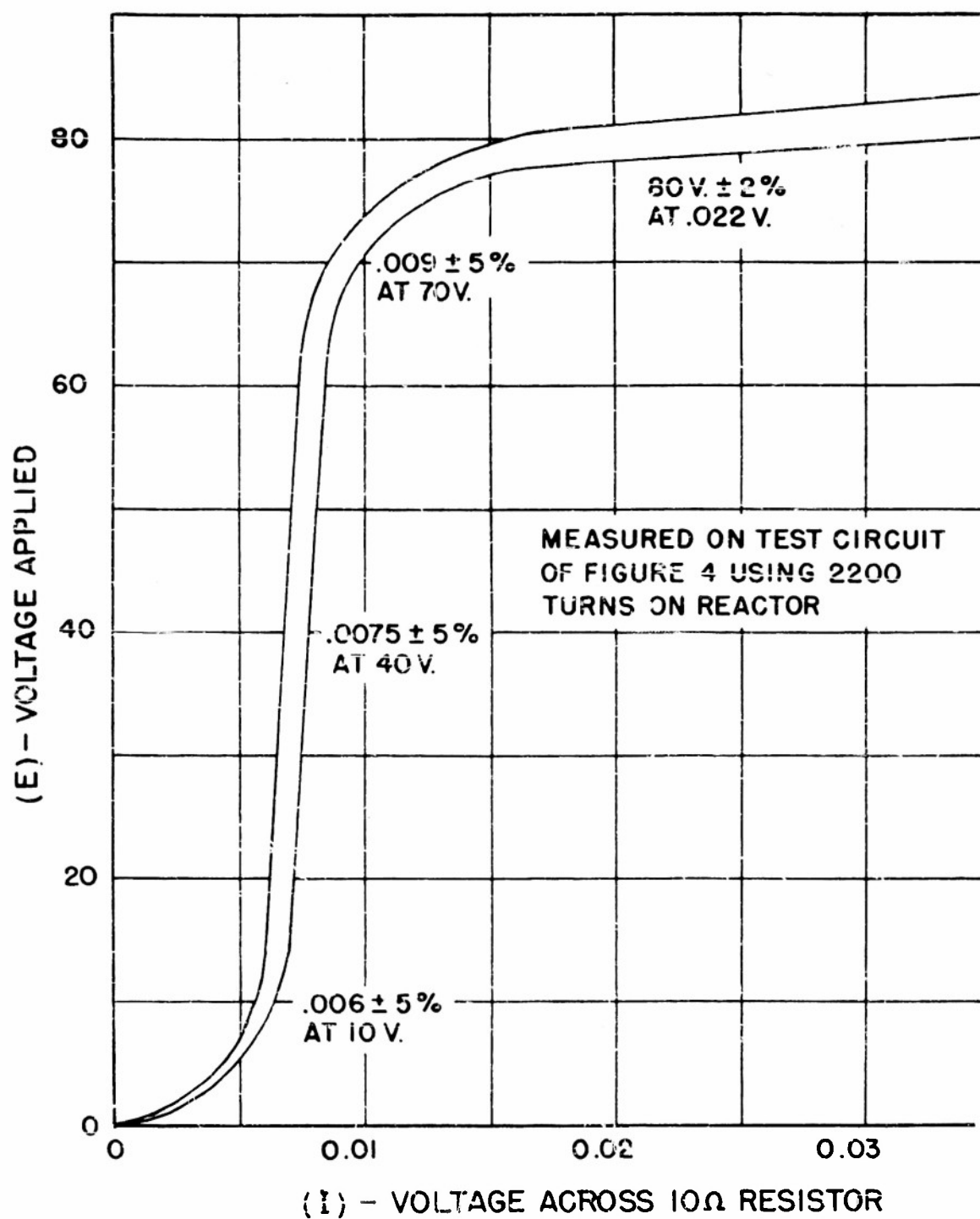


FIG. 8 - ALLOWABLE E-I CURVE FOR STAGE II REACTORS

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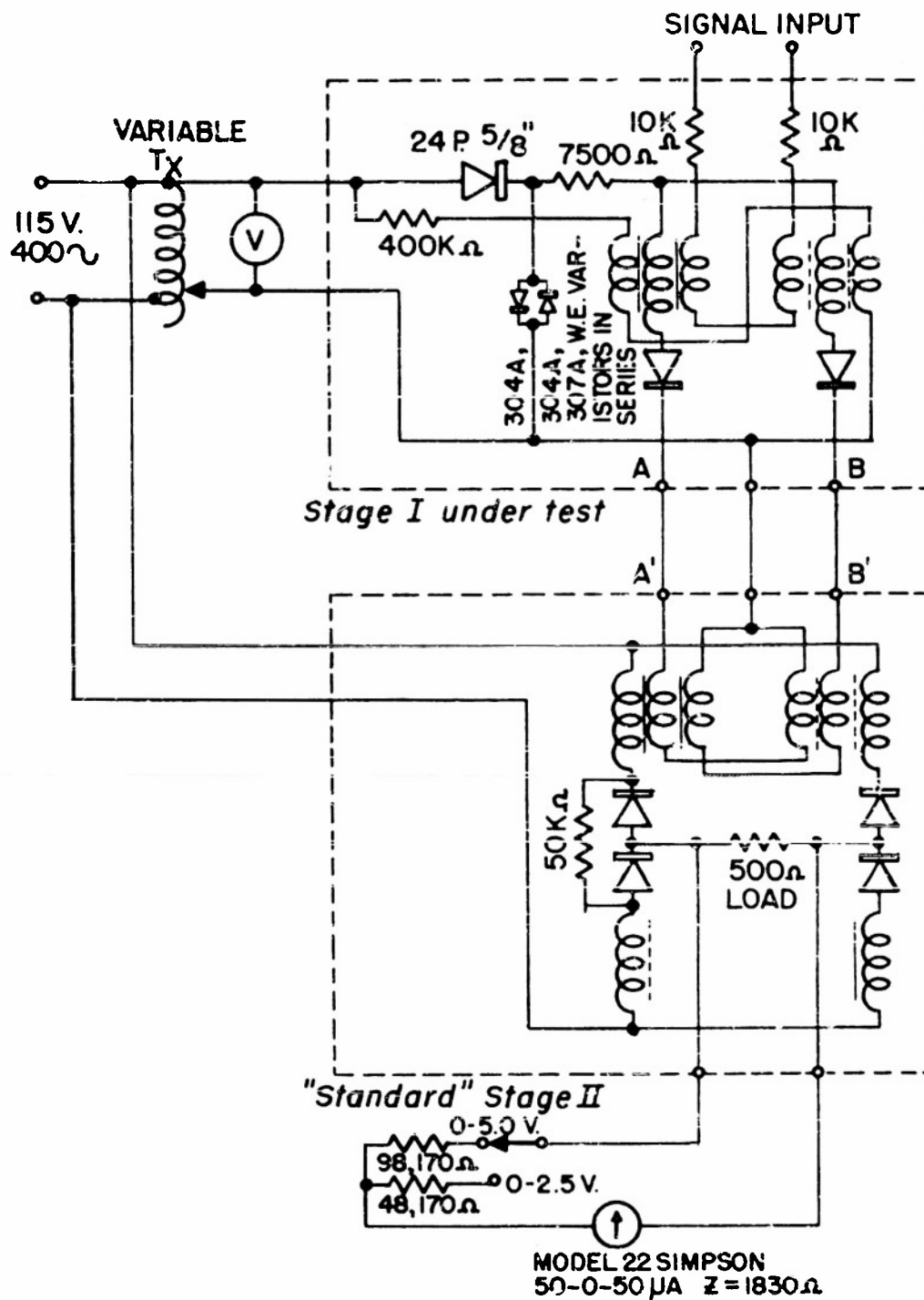


FIG. 9- TEST CIRCUIT FOR STAGE I

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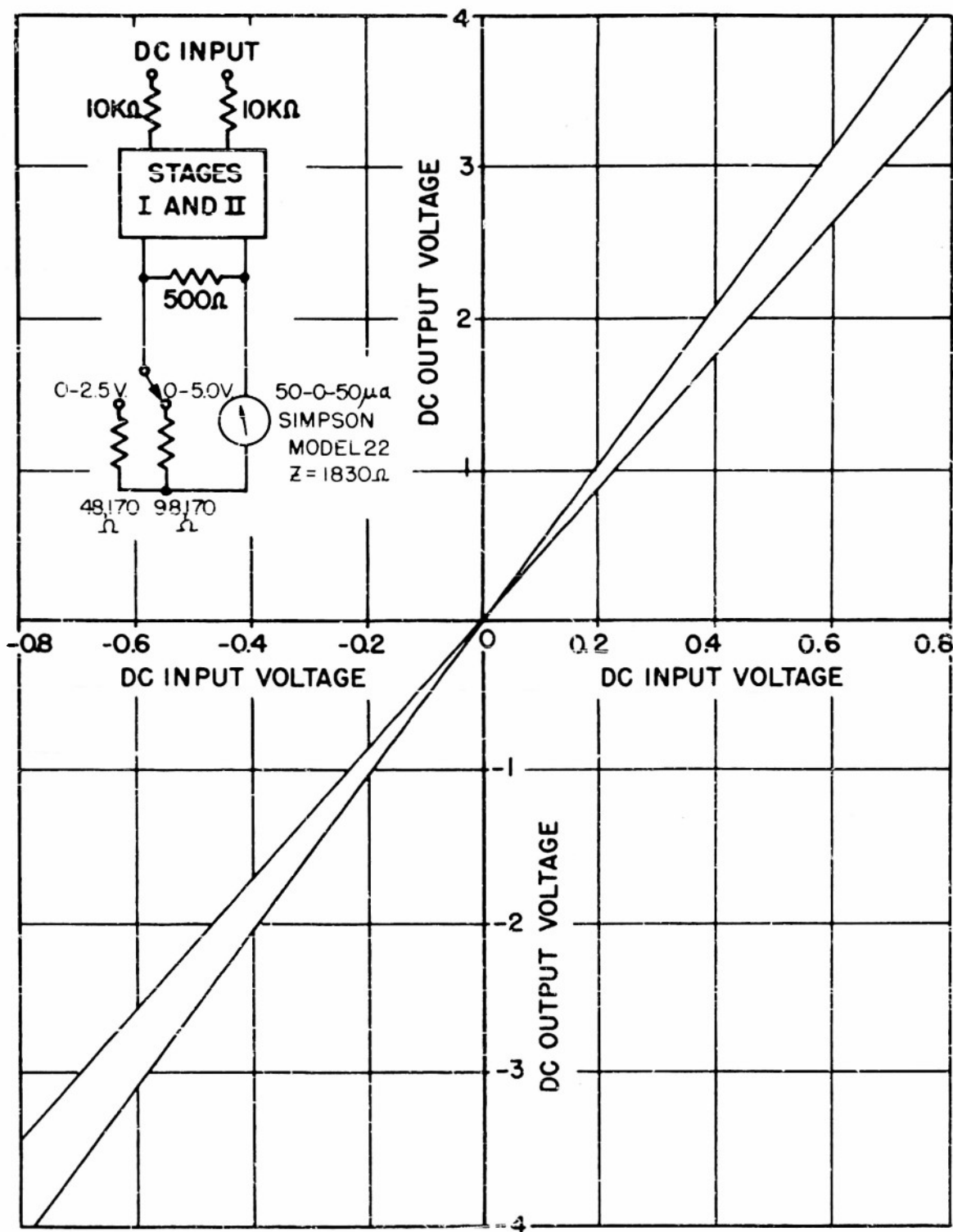


FIG.10-GAIN CURVE FOR FIRST TWO STAGES

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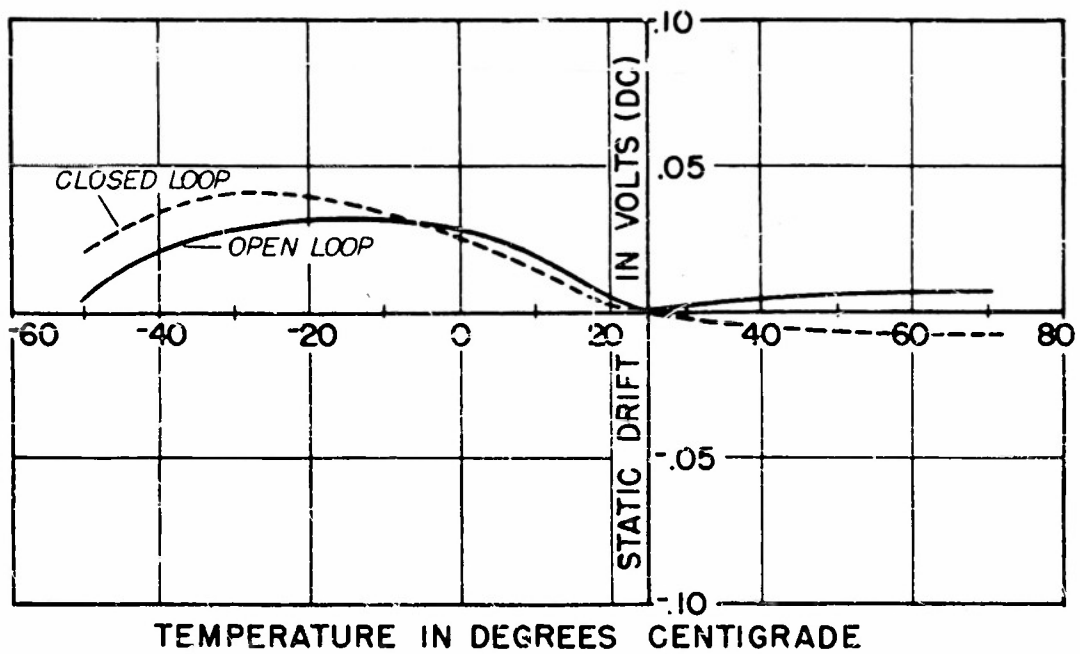
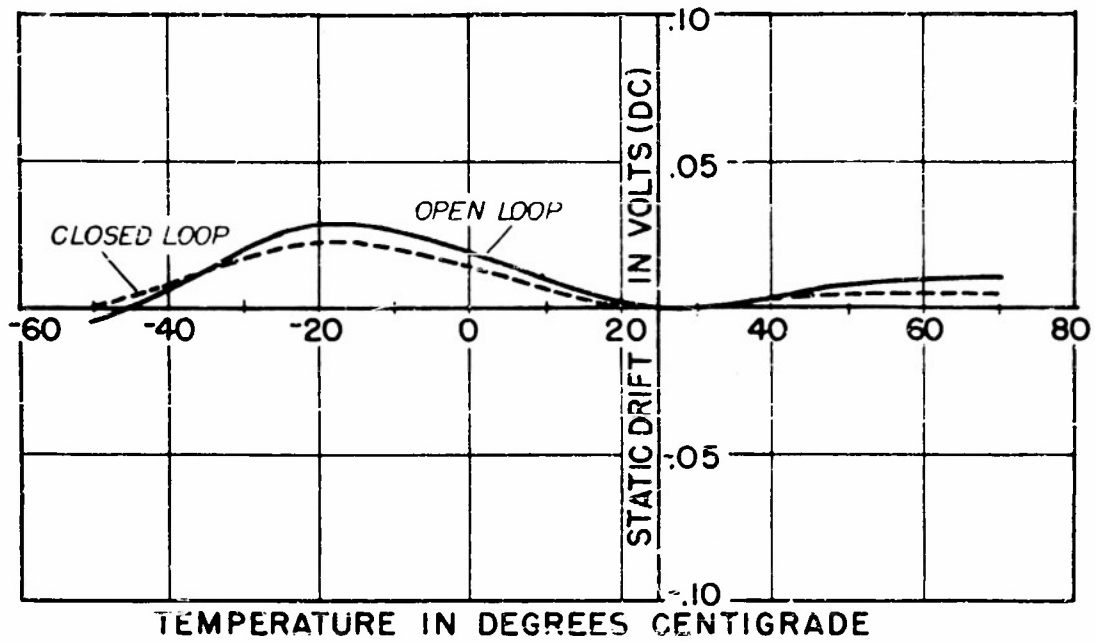


FIG. II--DRIFT OF SAMPLE FIRST STAGES

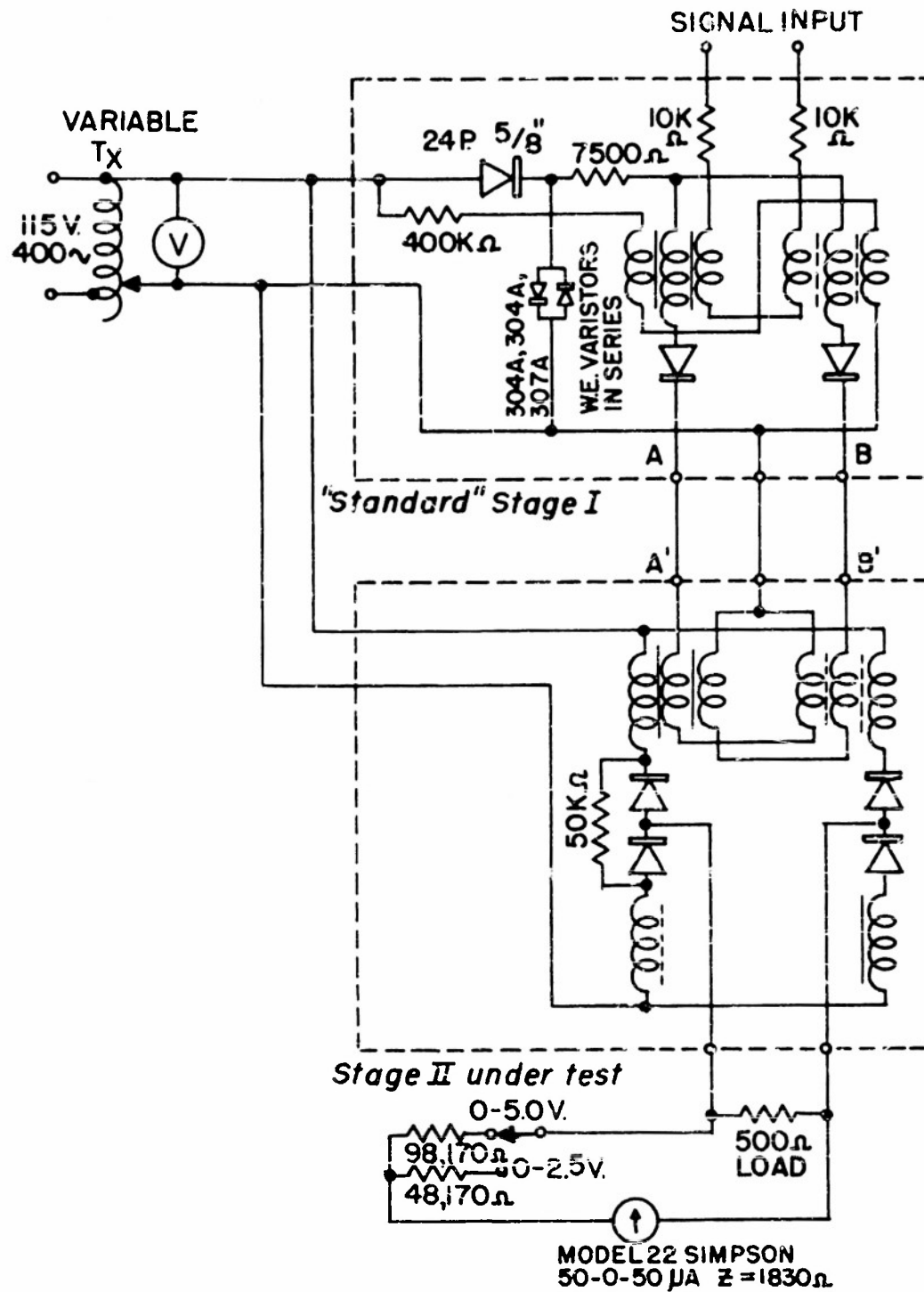


FIG. 12 - TEST CIRCUIT FOR STAGE II

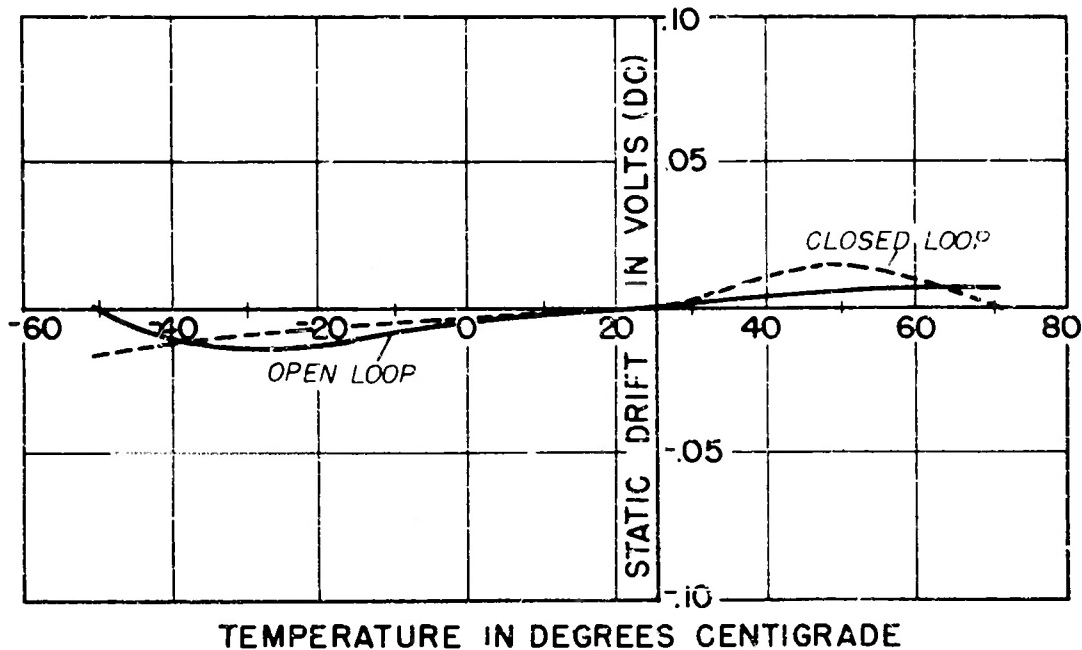
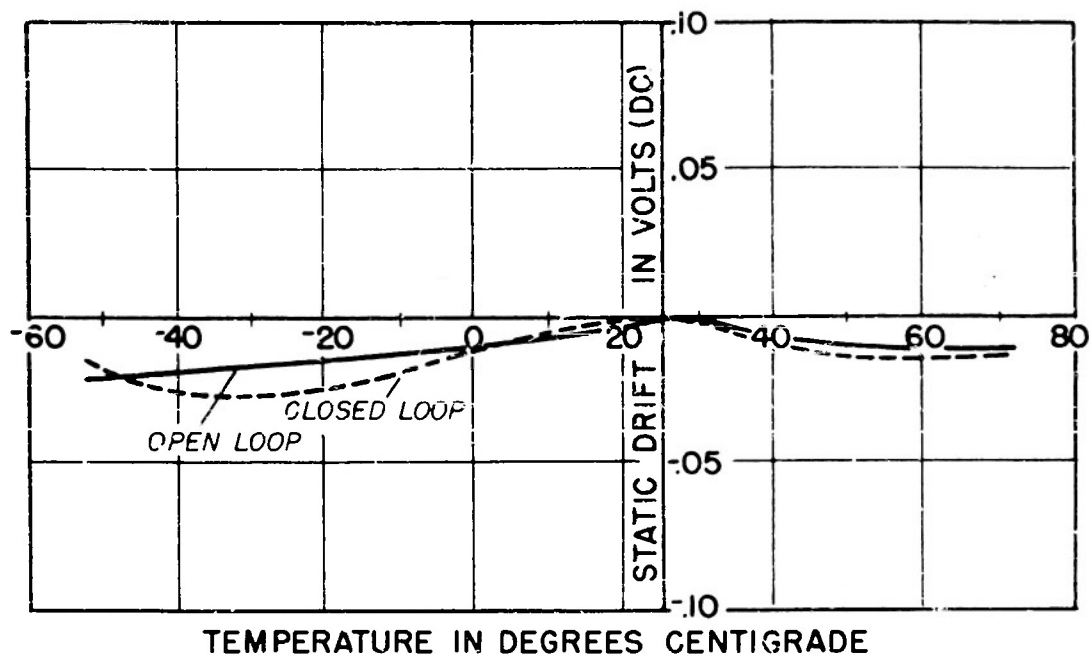


FIG. 13 - DRIFT OF SAMPLE SECOND STAGES

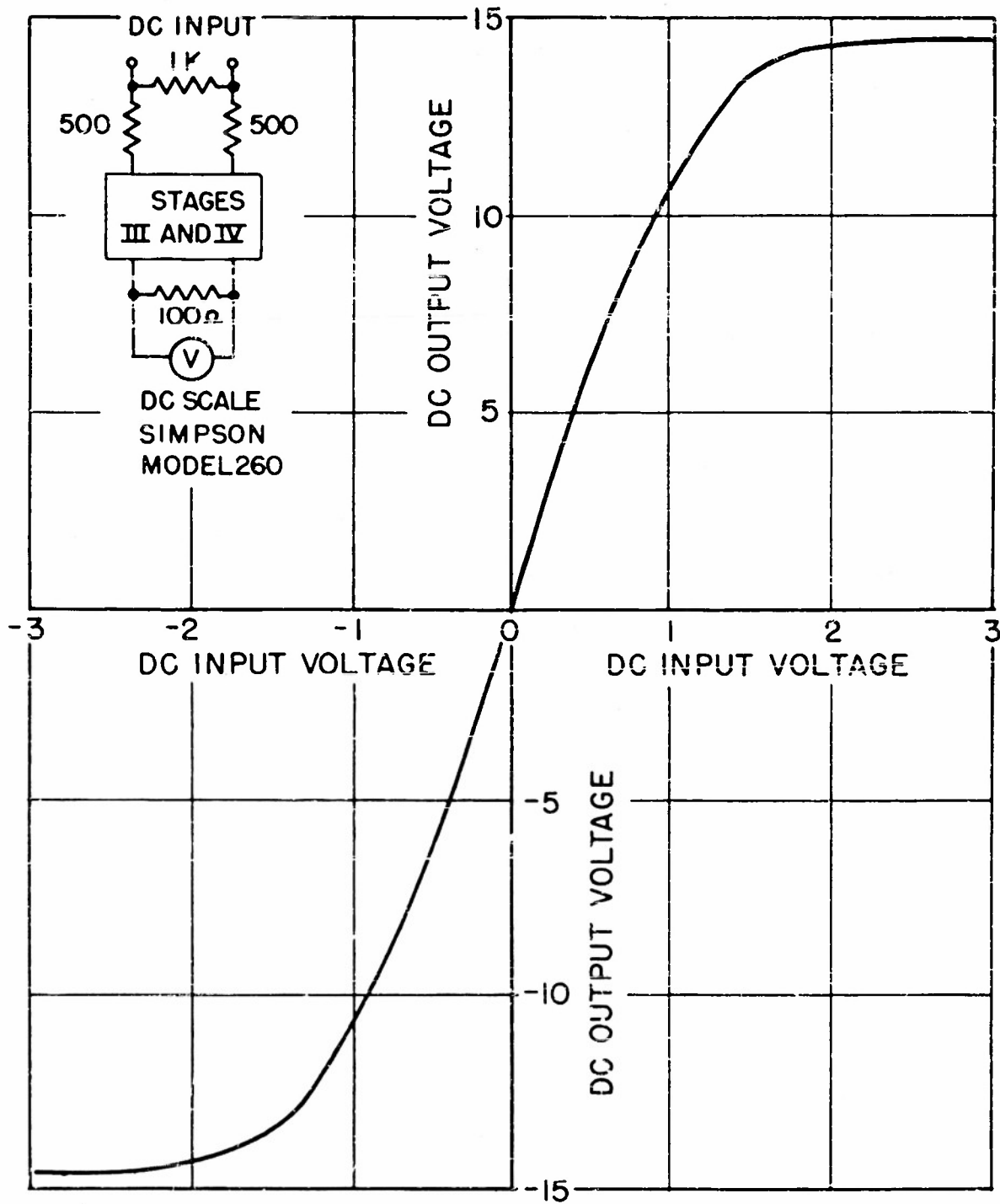


FIG.14 - GAIN CURVE FOR LAST TWO STAGES

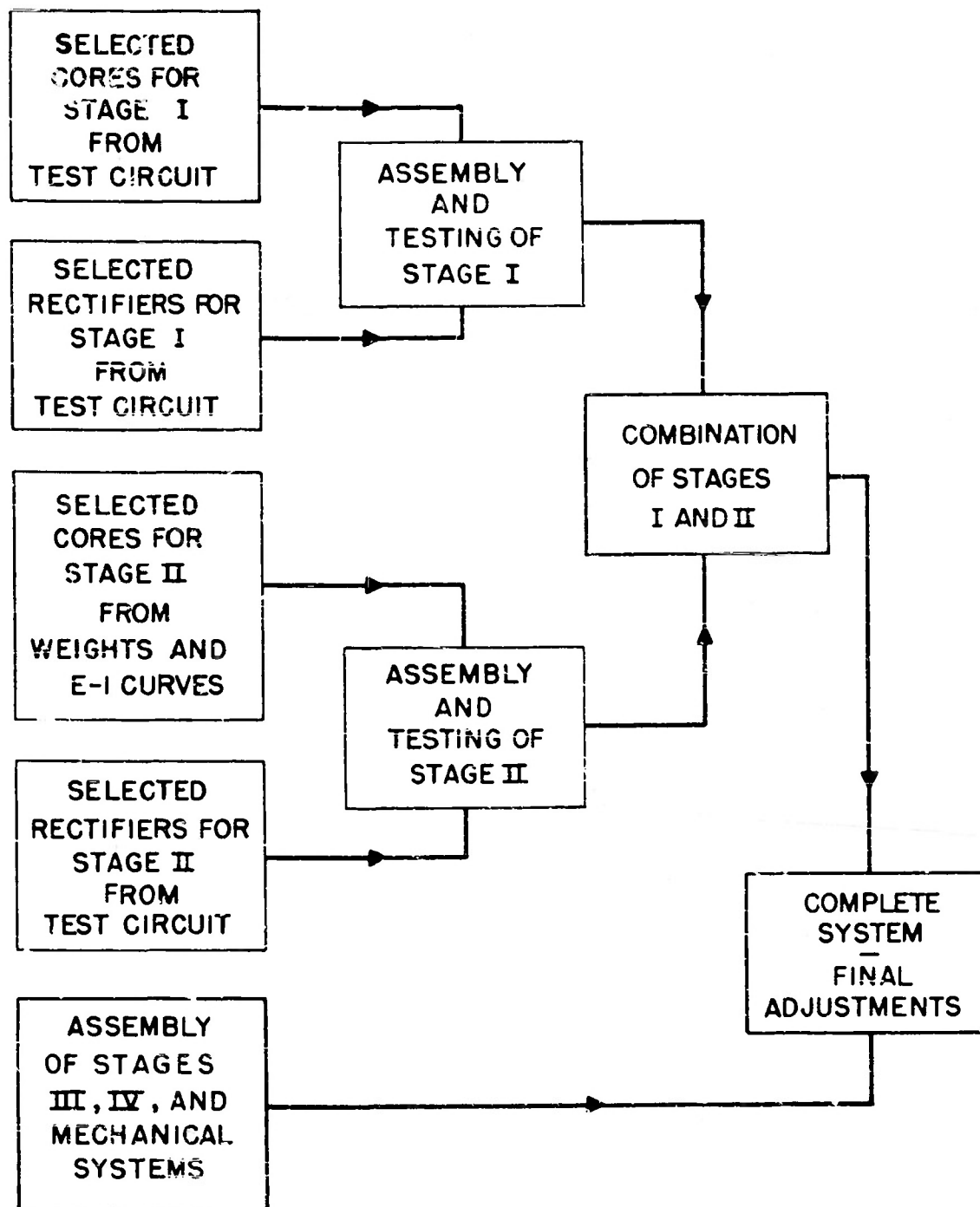


FIG. 15 - FABRICATION PROCEDURE

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