A McINTOSH AUDIO AMPLIFIER INCORPORATING A TRIFILAR OUTPUT TRANSFORMER

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by

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The Writer

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The author also wishes to express special acknowledgement to the Arnold Engineering Company for so generously donating four of their Silectron "C" Cores for use in this problem.

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OBJECT

The main objective of this project was to allow a voltage to be placed on the screen grids of the output tubes in a McIntosh Circuit independent of the plate supply voltage. A trifilar output transformer was proposed for this purpose.

The amplifier was to have low distortion, reasonably linear response over the audio range, a maximum input of 2.5 volts, and output taps of 4, 8, and 16 ohms.

METHOD OF ATTACK

The method of attack of this thesis was as follows:

(1) Library reserach on the problem

(2) Selection of tubes

(3) Design of output stage

 (a) Operational values such as voltage, current, power output, and ratings

 (b) Design of trifilar output transformer

(4) Design of driver stage

 (a) Design of bifilar driver transformer

(5) Design of phase inverter

(6) Design of power supply

(7) Construction of all components

(8) Performance tests of assembled amplifier

INTRODUCTION

In the last few years high-quality audio equipment has been in great demand. More and more people are becoming aware of the great enjoyment that can be realized from music, speech, and entertainment played through a high-quality system.

At the present time there are many amplifiers that leave little to be desired in respect to frequency response. However, there are some amplifiers that do have defects which could be corrected.

Efficiency in an amplifier is a goal for which to strive. For this reason class "B" operation represents an ideal design criterion. The theoretical plate efficiency of class "B" operation is 78.5%.

In class "B" operation of a push-pull output stage, each tube conducts for one-half a cycle and the tubes are biased to cut-off. When class "B_1" is used, the grids are not driven positive at any portion of the cycle.

Obstacles to good frequency response and low distortion in an amplifier can sometimes be traced to leakage reactance and poor coupling of the output transformer. By means of modern winding techniques, good core material, and closely coupled windings, an output transformer can be made to have excellent response characteristics. When such a transformer is coupled to high quality networks, the overall effect will meet the expectations of even the most critical listener.

As a further refinement the application of feedback to an amplifier gives a more linear response and less distortion with a sacrifice in gain.

BACKGROUND OF PROBLEM

Until the past few years audio men shied away from the use of class "B" operation in audio amplifiers. This was due to a conduction transfer notch that was encountered in the output waveform. This phenomenon may be explained as a switching transient due to each tube in the output stage conducting for each half of a cycle. As one tube starts and the other stops conduction, a back emf is generated which appears as distortion in the output.

Around 1948 Frank B. McIntosh developed a new type of audio amplifier that incorporated a unity-coupled, bifilar-wound output transformer. The amplifier was driven class "B_1" and his design completely eliminated the conduction transfer notch heretofore encountered.

In his amplifier McIntosh designed his output transformer in a conventional manner. He then halved the primary winding, using one-half in the plate circuit and the other half in the cathode circuit. This still enabled each half cycle to complete its loop through the one-half of primary in the plate circuit and one-half in the cathode circuit. These bifilar windings were so oriented in the circuit as to produce zero a.c. voltage between adjacent turns. This meant the interwinding capacitance had no effect upon the charging current. The value of charging current now required is zero, since there is zero a.c. voltage between adjacent turns.

By this mode of operation McIntosh used essentially a regular plate to plate load plus a half-way step toward a cathode follower. This combination required a large voltage swing in the driver stage. For this reason he also used a bifilar-wound driver transformer to couple the driver stage to the output control grids.

In the McIntosh circuit excellent response and low distortion have been achieved. However, his arrangement has the limitation that it can be used only with equal plate and screen supply voltages. This is because McIntosh maintains the voltage from each screen grid to cathode constant by the unity coupling between the two halves of the bifilar winding.

OUTPUT STAGE

The output stage of this amplifier uses two 6L6's in push-pull class "B_1" operation.

To start the design, plate characteristics were run for the 6L6 beam power pentode with a screen voltage of 300 volts. By drawing the load line through the proximity of the knee of the zero grid bias curve for maximum output in class "B_1" operation and applying Fourier Analysis to determine the power output, plate input, plate and screen dissipations, and plate efficiency, the following results for 420 volts on the plate were obtained:

Composite load resistance - 6000 ohms
Power output - 33 watts total
Power input - 52 watts total
Plate dissipation- 19 watts per tube
Screen dissipation - 2.35 watts per tube
Plate efficiency -65%

These values enable the output to operate at maximum efficiency at full power, for the rated plate dissipation is 19 watts per tube and rated screen dissipation is 2.5 watts per tube.

Some important factors that must be considered in the design of audio frequency transformers are:

(1) The primary, since it includes the tube plates will be of considerable impedance.

(2) The input voltage will vary over a large range.

(3) The same output to input ratio must be maintained over a wide range of frequencies.

(4) A high efficiency is essential to avoid wasting of valuable audio watts.

The output transformer uses the original idea presented by McIntosh, that is, the transformer is designed for a conventional push-pull output and the primary windings are halved. Half remains in the plate circuit while the other half is placed between the cathodes with consideration given to polarities. In addition a third winding is placed between the screen grids of the pentodes. This screen grid winding is introduced to alleviate the over-rated conditions of the original McIntosh Amplifier. McIntosh used over 400 volts on the screen of push-pull 6L6's, which is very considerably in excess of the maximum rating of 270 volts (design centre) and can exceed the rated screen dissipation. Besides allowing a reduced voltage to be placed on the screens, the screen winding will also allow a freedom of choice for the screen voltage supply.

The three windings of this modified version of the McIntosh output transformer are wound trifilar, again with proper consideration given to polarities. The polarity is such that the three windings are positioned to produce zero a. c. voltage between adjacent turns.

Knowing the plate voltage, the number of primary turns may be calculated from the transformer equation, $V = 4.44 N f B_m A$. By substituting constants for the values in inches and kilogauss, this reduces to $N_p = \frac{3490\ E_b}{B_m A f}$. Twenty cycles were used in this equation, at which point the response is to be down 3 db. This can later be improved by feedback. The flux density, B_m, was taken as 11 kilogauss for two Arnold Engineering "Silectron C Cores" (1) with a cross section of two inches times one inch per core. These conditions fix the number of primary turns at 1600, with a supply voltage of 420 volts and a space factor of 95%.

The corresponding number of secondary turns is then 42 for 4 ohms output; 59 for 8 ohms output; and 83 for 16 ohms output.

Since the transformer is trifilar, the turns between the screen grids are fixed and correspond to the number of primary turns already calculated. Therefore, a total of 2400 turns are needed in the total primary sections.

Figure 1 is the schematic diagram of the trifilar output transformer and shows the relative connections of the windings. Figure 2 shows the coil buildup. Number 27 Heavy Formvar was used for the primary windings and number 17 Heavy Formvar for the secondary. The secondary was sandwiched between the two primary sections. Five mil Kraft Paper was used in varying degrees for layer insulation.

Since the author had no experience with winding

(1) The Arnold Engineering Co. - Marengo, Illinois - Bulletin TC-103.

transformers, this transformer was wound by hand. It was found that the transformer was relatively easy to wind. It required three spools, each containing approximately 900 feet of number 27 Heavy Formvar wire for the primary sections. The three wires were fed from the three spools and wound as one wire; thus comprising the trifilar terminology. A spool of slightly less than 100 feet of number 17 Heavy Formvar wire was required for the secondary winding.

"C" cores present a mounting problem. This problem was solved by making a steel base, cutting four slots in the bottom, and inserting brass bands through the slots, up around the "C" cores. These bands were then bolted at the top. The base can then be mounted to the chassis. Due to vibration at low frequencies and high power, felt was inserted between the brass bands and the sides of the cores.

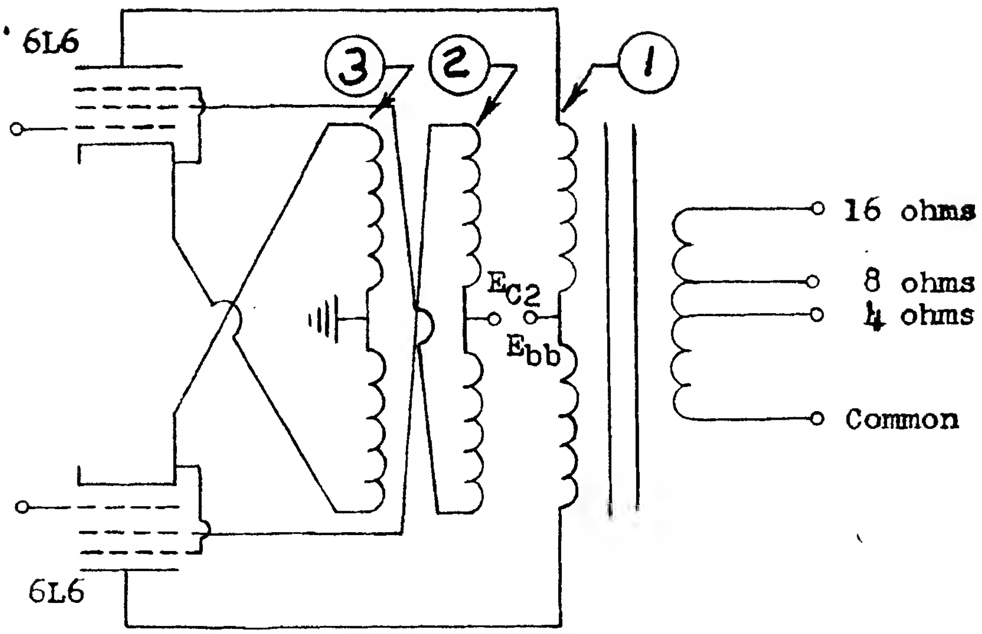

FIGURE 1 - TRIFILAR OUTPUT TRANSFORMER WINDING ARRANGMENT

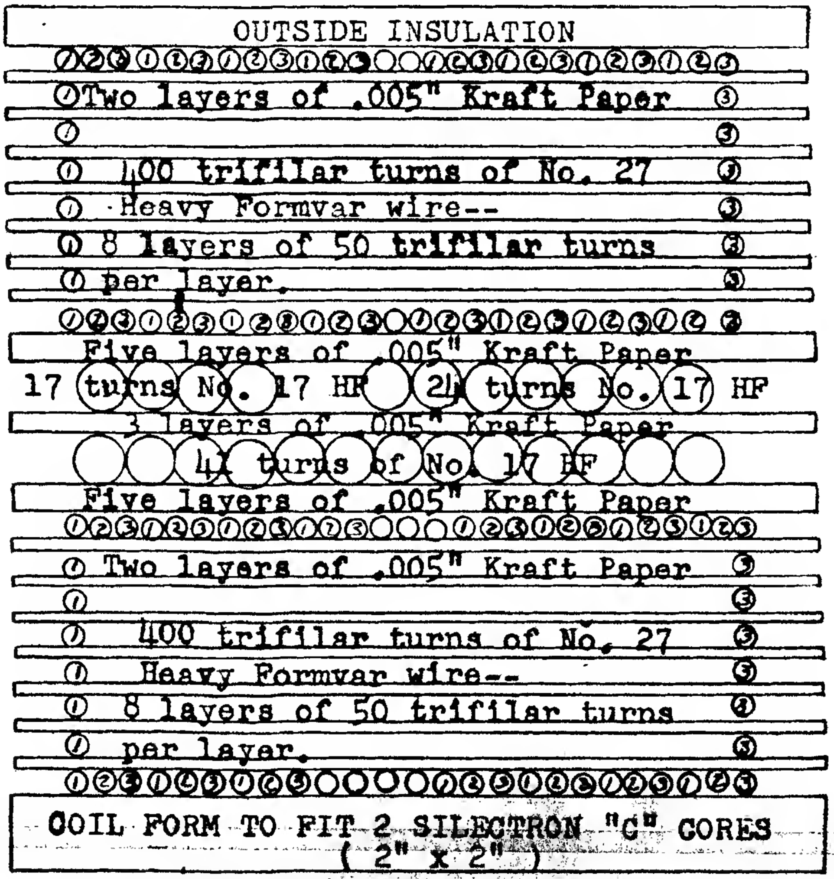

FIGURE 2 - TRIFILAR OUTPUT TRANSFORMER COIL BUILDUP.

DRIVER STAGE

The driver transformer was designed in the same general manner as the output transformer except that it is bifilar wound and has a one-to-one ratio between primary and secondary. The primary was designed to match an 80,000 ohm plate-to-plate impedance of a dual triode 6SN7GT.

Figure 3 is the schematic diagram of the bifilar driver transformer and shows the relative connections of the windings. The plate supply was chosen as 300 volts. From the dynamic characteristic of the 6L6 the fixed grid voltage was determined. At projected cut-off the control grid bias is approximately -34 volts. This is connected to the center tap of the secondary, E_{C1}.

Figure 4 shows the coil buildup. Two Arnold Engineering "Silectron C Cores" were again used having a cross section of one and one-half inches times three-fourths inch per core. The primary and secondary each have 2250 turns, 1125 turns each side of the center tap. The primary and secondary are both wound with number 28 Heavy Formvar wire, having 15 layers each side of the center tap, or a total of 30 layers, with 75 bifilar turns per layer.

This transformer was also wound by hand. The winding was similar to that of the output transformer, except that only two spools of approximately 2100 feet of number 28 Heavy Formvar wire were used.

The mounting arrangement was similar to that of the output transformer.

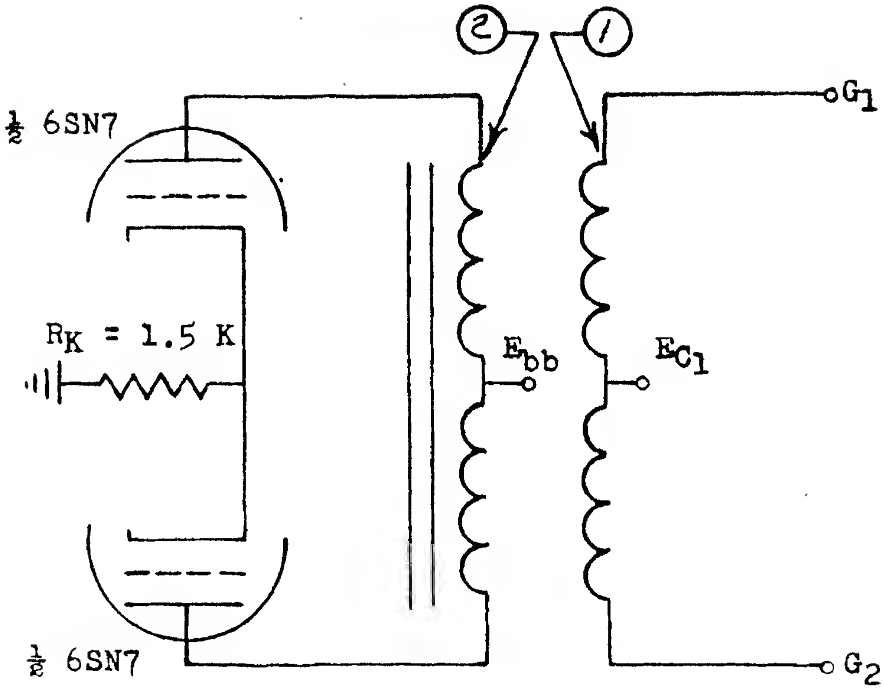

FIGURE 3 - BIFILAR DRIVER TRANSFORMER WINDING ARRANGMENT.

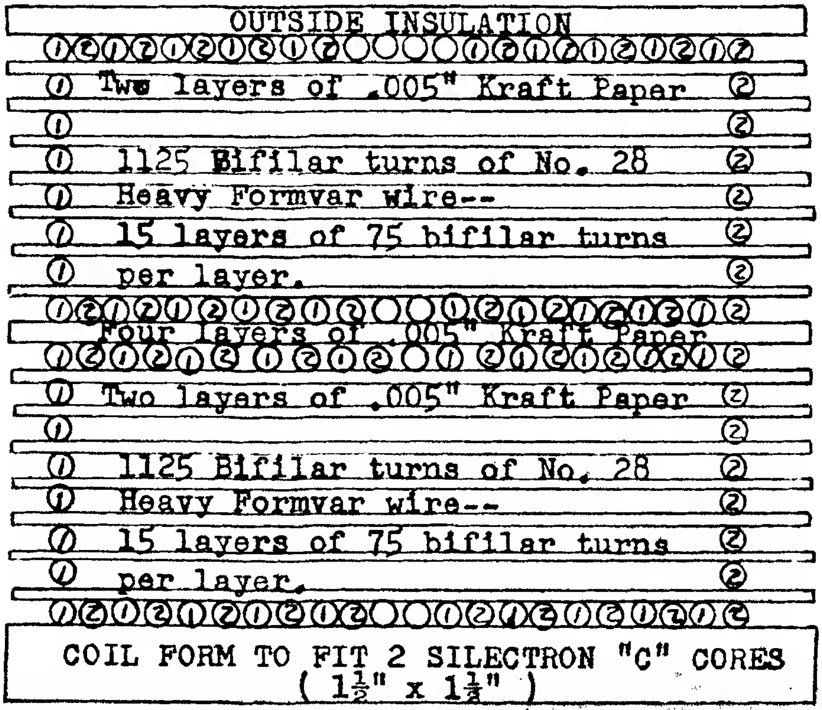

FIGURE 4 - BIFILAR DRIVER TRANSFORMER COIL BUILDUP.

PHASE INVERTER STAGE

The phase inverter incorporated in this amplifier is of the floating paraphase type. It is patterned after the phase inverter stage employed in McIntosh's 50 watt amplifier.[1] The plate is supplied d. c. voltage through a load resistance and the a. c. output is taken off and fed to the second tube, V_2 of Figure 5, through a separate load resistance.

A 12AX7 dual triode is used in the phase inverter stage. The supply voltage is 300 volts. R_{L_1} and R_{L_2} must be of suitable values to produce equal output voltages 180 degrees out of phase to the grids of the 6SN7GT. R_{L_1} and R_{L_2} are 20K and 40K respectively. A 15,000 ohm potentiometer was used as part of R_{L_2} for ease in balancing the circuit for equal output voltages to the 6SN7GT.

The capacitors were chosen as one microfarad to provide a relatively high reactance at the lower frequencies and thus maintain a more constant voltage.

(1) F. H. McIntosh and G. J. Gow, "Description and Analysis of a New 50 Watt Amplifier Circuit," Audio Engineering, Vol. 33, No. 12, pp 9-11, 35-40; December 1949.

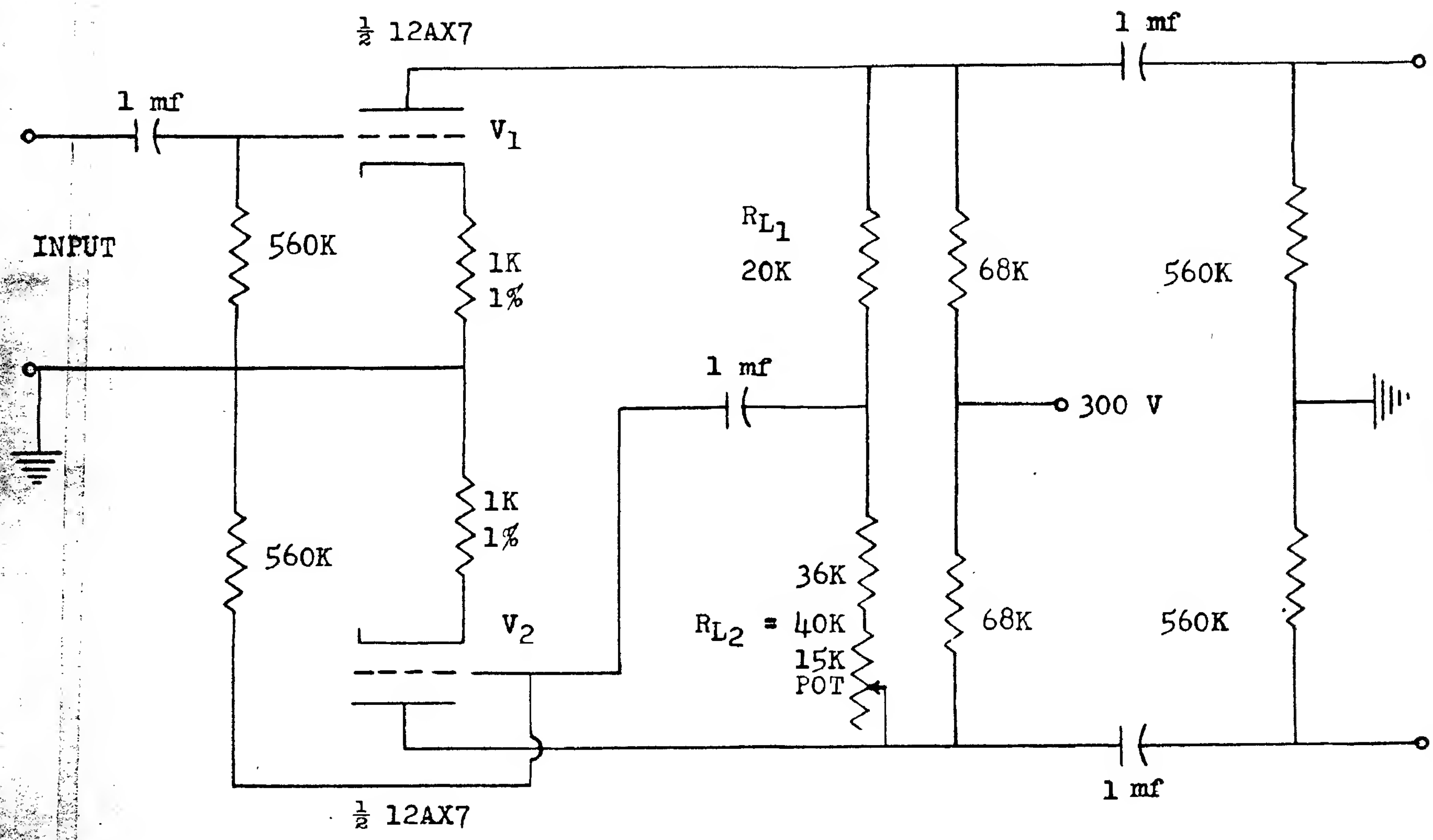

FIGURE 5 - PHASE INVERTER STAGE.

POWER SUPPLY

Figure 6 shows the circuit diagram used to supply power to the various stages of the basic amplifier and Heathkit Preamplifier.

The power supply consists of three separate supplies: the 5U4GB for the plates of the output tubes, the 5Y3GT for the output screen grids and the rest of the B(+) supply of the amplifier including the preamplifier, and a full wave bridge of selenium rectifiers for the bias.

Capacitor input was used for the 5U4GB and 5Y3GT supplies with a pi section filter including a suitable filter choke.

It is noted that 480 volts are specified for the output plate supply. This was originally dropped to 420 volts by a resistor. However, this arrangement radiated a large amount of heat; therefore the full 480 volts were applied to the plates without exceeding dissipation ratings.

The filament supply shows a hum control. This is located in the preamplifier.

A 6.3 volt filament transformer was modified to give 40 volts output when connected to a 6.3 volt tap on the power transformer. Four selenium rectifiers were used as shown in figure 6 and the negative bias voltage taken off a 10,000 ohm potentiometer to supply -34 volts to the control grids of the output tubes.

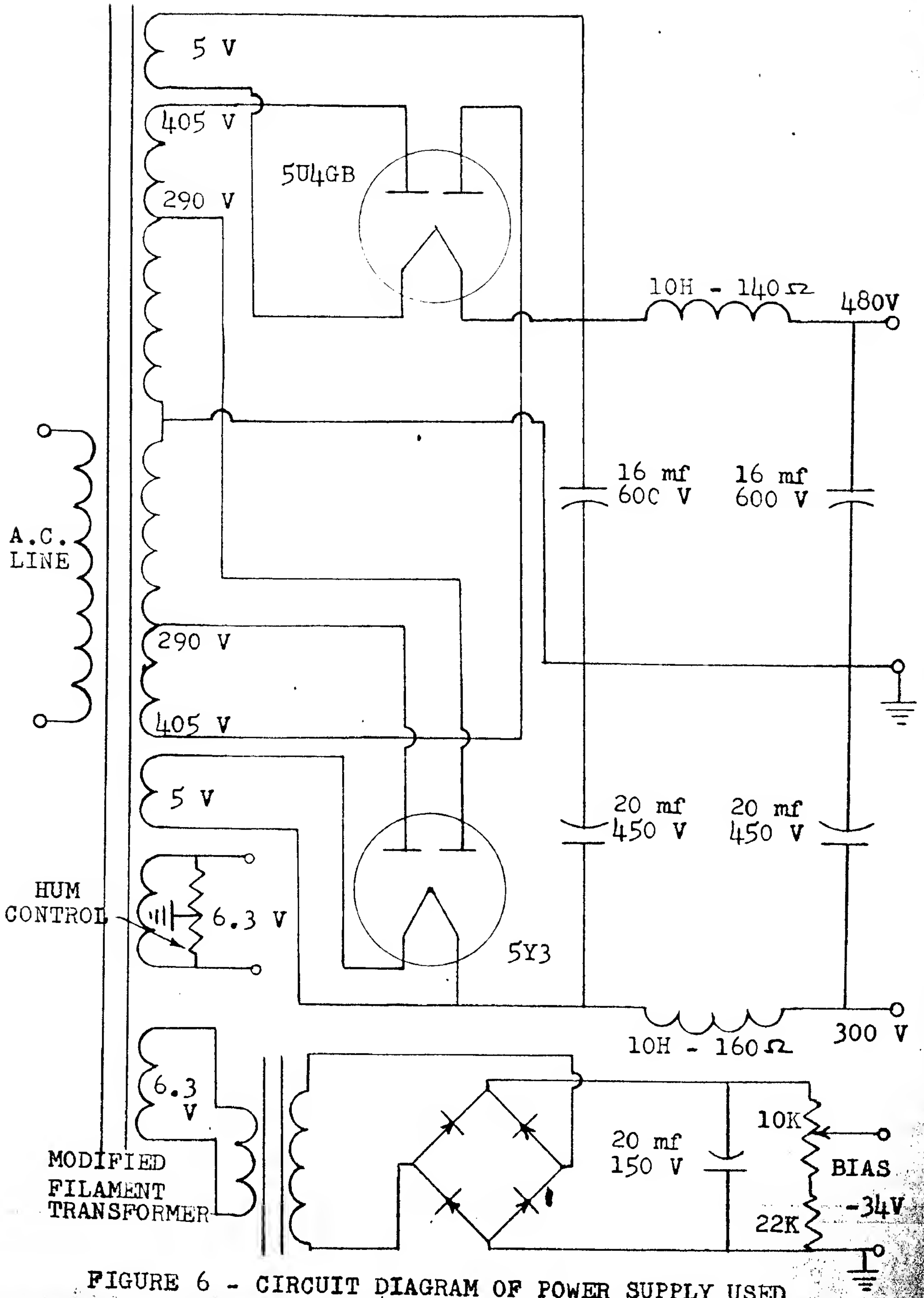

FIGURE 6 - CIRCUIT DIAGRAM OF POWER SUPPLY USED WITH McINTOSH TYPE AUDIO AMPLIFIER.

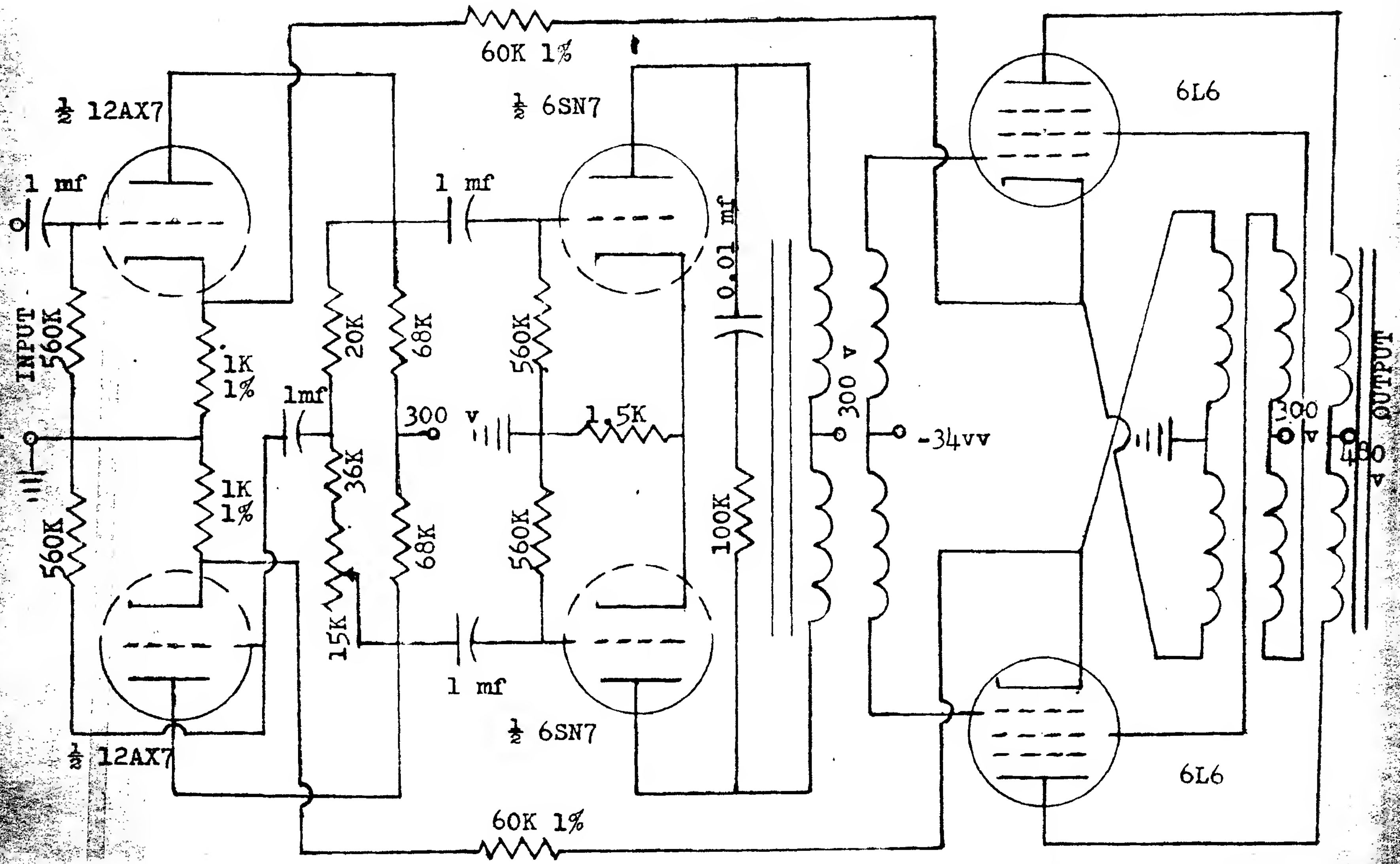

FIGURE 7 - CIRCUIT DIAGRAM OF McINTOSH AMPLIFIER INCORPORATING A TRIFILAR WOUND OUTPUT TRANSFORMER.

RESULTS AND PERFORMANCE

Complete Amplifier

Figure 7 shows the complete circuit diagram of the McIntosh Amplifier using the trifilar output transformer.

This shows an additional feedback loop from each of the output cathodes to the phase inverter cathodes. It was found that approximately 16 db of feedback would drive the amplifier into oscillation; therefore the final amplifier uses one-half this value.

Problems Encountered

The only real problem encountered was a loud irritating oscillation when the amplifier was turned off. This problem was solved by the .01 mfd capacitor and 100K resistor placed across the plates of the 6SN7GT driver tube. This is shown in figure 7.

Two Per Cent Distortion-Power Relations

Figure 8 shows the Two Per Cent Distortion-Power Relations. In this test the amplifier was driven to produce 2% distortion in the output. A plate circuit efficiency of 60% was attained between 1600 and 7000 cycles per second. The power at this value was 47.5 watts. At the low end of the audio range the power drops very rapidly.

Plate and Screen Dissipation

Figure 8 also shows the plate and screen dissipation for the above conditions. The plate dissipation also includes the transformer losses. The rated plate dissipation of 38

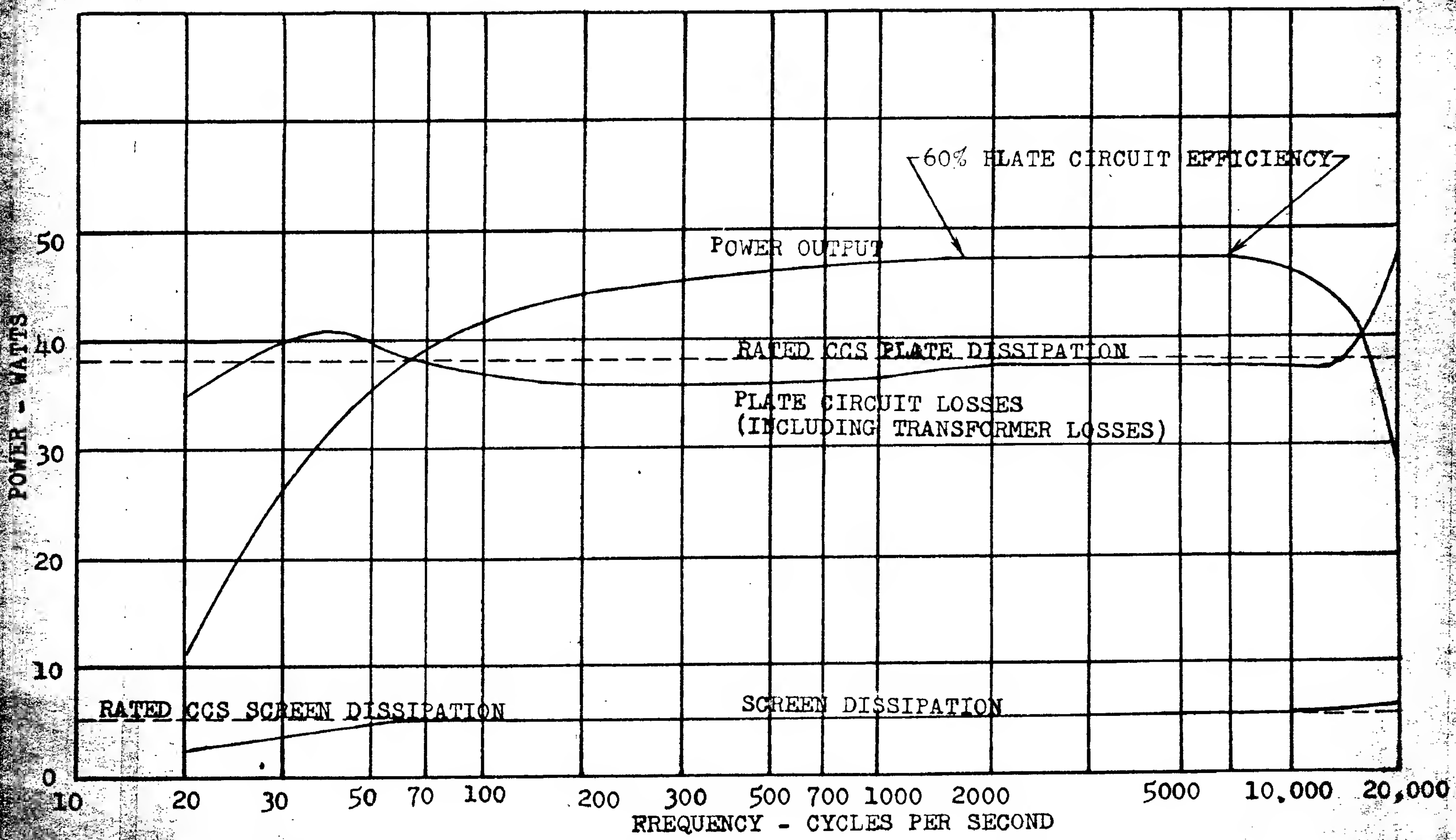

FIGURE 8 - TWO PER CENT DISTORTION - POWER RELATIONS

watts for both output tubes is shown by the dotted line. At the 60% plate circuit efficiency the plate circuit losses attains a value of 37.5 watts. At approximately 40 cps the plate circuit loss curve peaks, then is below rated dissipation to around 15,000 cps at which point it starts to rise rapidly.

The rated screen dissipation for both tubes is shown by the dotted line at 5 watts. The screen dissipation follows the rated value out to around 12,000 cps and is only 5.5 watts at 20,000 cps.

Frequency Response and Distortion

Figure 9 shows the frequency response of the amplifier and corresponding distortion curves.

The zero db curve or 47.5 watts is the previous 2% distortion-power relation curve plotted to a db scale.

Tests were run with the input held constant to produce outputs of 25, 10, and 1 watt. At these power outputs the frequency response is flat over the audio range for all practical purposes. In fact, at 10 watts the response is down .5 db at 10 cps and 3 db at 40,000 cps for the high end.

The lower curves of Figure 9 show the per cent distortion for the various inputs held constant. It will be noted that the distortion at higher powers rises very rapidly at the low end of the audio range.

Open and Short Circuit Tests

Open and short circuited output tests were run on the amplifier. The duration of time was ten minutes for each test. Both tests had on effect on the amplifier. This has a great advantage in case of accidental open or shorted output.

CONCLUSIONS

The laboratory tests of this amplifier show it to have reasonably good characteristics. The amplifier will attain a 60% plate efficiency at 2% distortion and 47.5 watts. Also the amplifier is very insensitive to open or shorted output. It can tolerate a great mismatch of output tubes, even removing one output tube allows the amplifier to respond very well.

The Heathkit Preamplifier worked very well with the basic amplifier, although the preamplifier induced hum at high power.

Thus the goal of allowing a voltage to be placed on the screen grids of the output tubes independent of the plate voltage and still obtaining the high performance of the McIntosh Amplifier has been achieved.

BIBLIOGRAPHY

1. McIntosh, Frank & Gow, Gordon. Describtion and Analysis of a New 50 Watt Amplifier Circuit. Audio Engineering. December 1949.
2. Connelly, F.C. Transformers. Pitman & Sons Ltd. 1950
3. Henney. Radio Engineering Handbook. McGraw-Hill, 1941.
4. Smith. The Radiotron Designer's Handbook-Third Edition, 1941.
5. Allegnehy Steel Company. Magnetic Core Materials Practice.
6. Seely. Electron Tube Circuits. McGraw-Hill, 1947.
7. Terman. Radio Engineering, Third Edition. McGraw-Hill, 1947.
8. Sah, A.P. Quasi-Transients in Class "B" Audio Frequency Push-Pull Amplifiers. Proc. I.R.E. Nov. 1936.
9. Bereskin, A.B. A High Efficiency-High Quality Audio Frequency Power Amplifier. Paper presented to Professional Group On Audio, 1954.
10. Langford-Smith. Radiotron Designer's Handbook. Fourth Edition, Radio Corporation of America, 1953.