



Perkins Electro-Acoustic Research Lab, Inc.

Web: <http://www.pearl-hifi.com>

E-mail: custserv@pearl-hifi.com

86008, 2106 33 Ave. SW, Calgary, AB; CAN T2T 1Z6

Ph: +. 1. 403. 244. 4434 Fx: +. 1. 403. 245. 4456



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SYSTEM DESIGN FACTORS FOR AUDIO AMPLIFIERS

M. V. Kiebert, Jr., P. R. Mallory and Company,

Indianapolis, Indiana

Prior to going into purely technical details, it appears to be desirable that an evaluation be made and some conclusions drawn as to why there should be, and why there has been such disparity between the findings of the various A-B listening tests as variously conducted by ably qualified persons and groups; as between engineers and hi-fi enthusiasts on one hand, and the untutored (but honestly discriminating) public on the other.

It appears that a broader appreciation of the physiology and psychology of hearing, as well as an appreciation of esthetic values rather than an esoteric appreciation of a frequency response curve, IM tests, or some similar bit of electrical information is well past due and might well be considered at this time. (The word "bit" is used here in the sense of the computer specialist in that the electrical performance of an audio amplifier is only one small portion of a large and complex electro-physical system).

It appears that the Weber-Fechner law has been overlooked in most of these tests. For review it may be quoted as follows:

"The increase of a stimulus necessary to produce a just discernible increase in the resulting sensation bears a constant ratio to the total stimulus. It is sometimes stated in the form that the magnitude of the sensation produced is proportional to the logarithm of the stimulus. If the same law applied to the hearing sensation, then the fractional increase in intensity, which is just perceptible as a change in intensity, should be a constant independent of the intensity."

To bring this into focus, it might be appropriate to say that the majority of listeners to "poor" system (A) will logically find it not too objectionable to listen to "poorer" system (B), whereas listeners to an excellent system (A) will find considerable objection to an only slightly inferior system (B)! In the first case, the rate of degradation is relatively small in going from the poor system to the more inferior system. In the second case, the rate of degradation is very great and accordingly the Weber-Fechner law still holds with the result that the abrupt change in quality is very apparent and generally most objectionable: it is very likely that this point has been the reason for the apparent unsatisfactory correlation in many of the A-B listening tests.

In the following discussion on audio amplifiers, this point should be kept in mind with due care given to the consideration of the "fold-up"

characteristics of the amplifier with respect to the system in which it will be used. If an amplifier is used in a position and in such a way that the highest input peaks and transients never drive the high level stage to the overload point, then the problem is simplified. Occasional overloads do occur in most systems, however. Amplifiers driving loud-speaker systems are probably more often overloaded than other intermediate amplifier system elements. Good design generally dictates that the output stage shall be the first to overload and accordingly these studies are primarily concerned with output stage design.

Amplifiers in this design class are specified generally somewhat as follows:

- a.) Power output
- b.) Gain
- c.) Distortion
- d.) Frequency response
- e.) Noise level
- f.) Input and output impedances
- g.) Form factor (size and weight)
- h.) Input power requirements (Line)

The all important overload characteristic (fold-up characteristic) and transient performance requirement should also be made and considered as a part of the foregoing tabulation, unfortunately, however, neither of these is generally specified when audio amplifiers are considered. This point will be further brought out in the text.

In selecting the design of an audio amplifier, component availability, amplifier cost and potential shock hazard are the factors which generally restrict manufacturers to voltages in the order of 400 and 450 volts above a ground plane reference. If a plot were made of component cost as a function of supply voltage, it would be found that a sharp upward break occurs in the curve at the 400 to 500 volt point.

An amplifier designed to drive high level vibration equipment, or designed for laboratory measurement purposes, will require very low distortion. However, such amplifiers are operated generally with inputs which are constant and held at controlled levels in which peaks are never permitted to drive the output stage beyond the limit of its linear characteristic.

An amplifier designed to drive a tape recorder, or a cutting head is a more difficult task. These amplifiers, however, are also used under fairly well controlled conditions such that the likelihood of an overload peak is quite remote. Amplifiers designed to drive loud speaker systems are,

of necessity, operated near their maximum output region and accordingly the overload characteristic is of great concern. It is believed that in this application great attention must be given to the "fold-up" characteristic as well as to the specific design requirement. Not only is the design problem severe in this case, but the problem is made more acute as a result of the wide variation in output load impedance characteristics as presented to an amplifier by a speaker system, as the frequency is varied.

Any time two audio men get together there will inevitably result a discussion as to the merits of a triode output stage, the ultra-linear connected output stage, or the beam power connected stage. It is believed that most of this discussion is based on intuition, or emotion, rather than on fact. The following is a tabulation data taken on each of these three general types of circuits.

The assumptions and qualifications are shown as a part of Table I.

TABLE I

807's push-pull $E_{bb} = 432 \text{ V.}$
 $I_p \text{ (total)} = 100 \text{ ma. (50 ma./tube)}$
 $R_L = 6,200 \text{ ohms}$ plate - to - plate
 $(Z_g = 300 \text{ ohms, No Feedback})$
 General Radio 942-A Transformer

Type of Connection	Power Level Watts	I.M. (60 & 7000 c.p.s.)
Beam Power	10.4	GRID 4%
Ultra-Linear (50% tap)	10.4	CURRENT 7%
Triode	10.4	POINT 6%
Beam Power	12.1	GRID 7%
Ultra-Linear (50% tap)	12.1	CURRENT 8%
Triode	12.1	CURRENT 7%
Beam Power	13.8	GRID 12%
Ultra-Linear (50% tap)	13.8	CURRENT 10%
Triode	13.8	CURRENT 8%

It is cogent to comment on Table I and hope that some of the controversy may be quieted from now on out.

Up to the grid current point, the beam power connection will have lower distortion than either the ultra-linear or triode connections, but the output impedance looking back from load is higher. However, a small amount of feedback will readily overcome this minor disadvantage.

With a small flow of grid current the ultra-linear stage deteriorates less rapidly than the beam power connected stage. This is probably due to the feedback obtained by this connection. At this point the triode connected stage has exhibited only a minor increase in distortion.

With a higher flow of grid current both the beam power and ultra-linear connected systems exhibit relatively high distortion while the triode stage distortion increased but a negligible amount.

Two factors account for the foregoing phenomena.

When the grid circuits of these variously connected output stages are driven positive, it will be found that for a given positive grid voltage both the beam power and ultra-linear connections draw a materially greater grid current with a consequent driving regulation problem.

The second factor becomes apparent when the two sets of $I_p - E_p$ curves are examined. Either the beam power or ultra-linear connected stage must be so loaded as to have the load-line intercept the knee of the tube characteristic at the most positive grid excursion in order to secure maximum power output with minimum grid current. A small excursion beyond this point inevitably results in a rapid increase in distortion due to intercept of the diode characteristic. When the triode connection is used, the $I_p - E_b$ characteristic is entirely different and with sufficient grid drive may be fairly linearly driven down to 5 or 10% of the plate supply voltage. Beam power characteristics generally restrict the plate swing to 25 or 30% of the plate supply voltage. Extreme distortion levels occur if it is attempted to drive the beam power stage below this point. Generalized Figs. 1(A), 1(B), 1(C) and 1(D) illustrate these points.

From Figs. 1(A) through 1(D) it becomes apparent why the triode connected amplifier exhibits marked superiority over pentode or beam power connected stages when these are driven to high power levels - the triode stage "folds-up" gradually - the pentode or beam power stage folds abruptly and rather completely!

From the foregoing it is suggested that the very great merits of beam power stages (power sensitivity and low distortion) should not be overlooked. Not every user is going to try to get 6 db more level than he needs or can use for his application!

The triode push-pull connected output stage may be so connected as to have extremely low distortion - particularly if a nominal amount of feedback is used. The partially by-passed connection of Fig. 2 achieves this end.

$$\begin{aligned} I_3 &= I_1 - I_2, \text{ Output Current} \\ I_4 &= I_1 + I_2, \text{ Mid-branch Current} \end{aligned} \quad (1)$$

For triodes, the plate expansion

$$\begin{aligned} I_1 &= ae_1 + be_1^2 + ce_1^3 \\ I_2 &= ae_2 + be_2^2 + ce_2^3 \end{aligned} \quad (2)$$

(Note that the sign of ce_1^3 and ce_2^3 is plus for triodes) (and minus for pentodes.)

If E is driving voltage on grid #1 to ground and $-E$ is driving voltage on grid #2 to ground

$$\begin{aligned} e_1 &= E - kI_h \\ e_2 &= -E - kI_h \end{aligned} \quad (3)$$

Combining (1) and (2)

$$I_3 = I_1 - I_2 = a(e_1 - e_2) + b(e_1^2 - e_2^2) + c(e_1^3 - e_2^3) \quad (4)$$

$$I_h = I_1 + I_2 = a(e_1 + e_2) + b(e_1^2 + e_2^2) + c(e_1^3 + e_2^3) \quad (5)$$

Solving for I_h from (3) and (5)

$$I_h = -2akI_h + b(2E^2 + 2k^2I_h^2) + c(-6E^2kI_h - 2k^3I_h^3)$$

Neglecting higher order terms (which are small)

$$\begin{aligned} I_h &= -2akI_h + 2bE^2 \quad \text{and} \\ I_h &= \frac{2bE^2}{1 + 2ak} \end{aligned} \quad (6)$$

Combining (3), (4) and (6)

$$I_3 = 2aE - \frac{8kb^2E^3}{1 + 2ak} + 2cE^3 + \text{higher order terms.}$$

The co-efficient of E^3 , $2c - \frac{8kb^2}{1 + 2ak}$ may be made zero when

$$k = \frac{c}{4b^2 - 2ac} \quad \text{and } k \text{ will be positive when } 4b^2 - 2ac > 0$$

and $c > 0$. This is the requirement for zero third harmonic distortion and will hold provided neglected high order terms are small as they generally will be in the case of triodes. Note that within the approximation, the cancellation of third harmonic is independent of the signal level E .

It is to be noted that the grid current point should never be approached too closely (kept under 0.1 ma.) when this circuit is used. The use of single-ended, unbalanced feedback from the secondary of the output transformer is well adapted to this circuit. A typical application in a laboratory amplifier is shown in Fig. (3) wherein triode connected 6L6 tubes are used with 23 db of feedback. Distortion at the 4 watt level may be held to less than 0.01% for any measureable harmonic component.

In designing any audio amplifier there are always a number of engineering and economic compromises that must be considered, reconciled and accepted.

In an efficient push-pull amplifier operated class AB₁ or AB₂, it must also be appreciated that the lower the connected plate-to-plate load impedance the more severe the power supply regulation problem, but the easier the grid driving requirement (when the tubes are driven into the

grid current region). When beam power connected tubes are used, it is also a problem to secure a suitably regulated and the necessarily lower screen voltage.

In the design of the voltage (and power) driving stages for the high level output stages there are also a number of fairly major problems. These stages, however, are generally operated straight class A, thus avoiding some regulation difficulties. When triodes are used in the output stage, the driving voltages are necessarily large and present a design problem if distortion is to be kept to a reasonable value with the plate supply voltages nominally available at the driver stage.

In driving beam power or ultra-linear power amplifiers into the grid current region, it will be found that the driving voltages will be lower, however, the driving circuit regulation problem becomes much more acute due to the larger grid currents intrinsic with these types of circuits.

When beam power tubes are used in the output stage, either with the beam power connection or with the ultra-linear connection, care must be taken to use a sufficiently low value of plate-to-plate load resistance to preclude swinging into the diode knee portion of the tube characteristic on peaks of the plate conduction cycle.

Illustrative of the various distortion characteristics found in each type of circuit, are the following: Fig. 4(A) is an oscillograph picture of an over-driven, triode connected, beam power tube. Fig. 4(B) is the over-driven characteristic observed with either the ultra-linear connected or beam power connected tube circuit. In each case, the driving circuit impedance was the same and for all practical considerations the grid circuit had regulation as about as good as the present state of the art permits. With the triode connected circuit, it is noted that the peak is "rounded-off" rather than "cut-off" as in the beam power stage. With either beam power or ultra-linear stages the peak clipping is due to both plate and grid limiting while the triode stage the limiting is primarily a result of regulation in the grid circuit. Fourier analysis of these curves will immediately show up the lower distortion in the triode connected circuit.

From the foregoing it will be seen that the overload, or "fold-up" performance of the triode connected circuit is less deleterious than that of any of the beam power connected circuits - provided that appreciable amounts of feedback are not employed.

Curve I (A) is a plot of the distortion characteristics of a push-pull triode connected circuit while Curve I (B) is a similar plot of a beam power connected circuit. These are each plotted as a function of power output. No feedback was used in these cases. Again the more desirable (or less objectionable) characteristic of the triode connected circuit shows up - again qualified as regards to the amount of feedback employed.

In order to illustrate the effect of feedback, each of the above configurations were again checked after approximately 20 db of feedback were applied. Curves I (C) and I (D) illustrate the modified performance.

Parallel to the foregoing are Figs. 5 (A) through 5 (D) which are oscilloscope records of the output when a square wave is fed into the input of the amplifier with these various types of output circuits. In the first case the triode circuit of Fig. 4 (A) is recorded at a point just below a nominal overload point of 15 watts, then just above this nominal overload point at 20 watts.

Parallel to the foregoing are figures 5 (C) and 5 (D) which are oscilloscope records of the beam power circuit of Fig. 3 (B) taken at a point just below a nominal overload point of 20 watts, then just above this nominal overload point at 30 watts. From the foregoing, some rather obvious conclusions relative to application may be drawn.

The next item for consideration is evaluation of the optimum operating conditions of the output stage. This is a policy matter to be carefully selected by the manufacturer, based upon consideration as to whether or not he wants a "hot" item that has a specification which looks well in print but which may operate the output tubes above the tube manufacturers' specification and recommendation with consequent later deterioration in performance and tube life; or an amplifier which operates the output stage tubes conservatively with long, consistent and dependable performance but with a 2 to 4 db lower power output. The laws of nature, and the tubes and components available to the electronic industry operate consistently and, therefore, it is impossible to secure both the "hot" initial performance, and long time dependability.

In order to present some picture as to the general performance available from commonly used and available output tubes the following Table II has been prepared:

TABLE II
Performance Capabilities of
Commonly Available Output Tubes.
(Based on Manufacturers' design center
ratings per TETMA Standard M8-210)

TRIODE				
TYPE	If	Max. Ebb	Max. W. Input	AB ₁ Output Ebb = 400 V.
6AR6	1.2	300 V.	22.2 W.	---
6L6	0.9	250 V.	10 W.	17.5
807	0.9	400 V.	25 W.	15
161h	0.9	375 V.	24½ W.	---
5881	0.9	400 V.	26 W.	13.3
6146	1.25	400 V.	35 W.	19

BEAM POWER						
TYPE	If	Max. Ebb	Max. Egg	Max. Wsg	Max. W. Pl.	AB ₁ Output Ebb = 400 V.
6AR6	1.2	565 V.	300 V.	3.2 W.	19 W.	---
6L6	0.9	360 V.	270 V.	2.5 W.	19 W.	24.5
807	0.9	600 V.	300 V.	3.5 W.	25 W.	55
161h	0.9	375 V.	300 V.	3.5 W.	21 W.	50
5881	0.9	360 V.	270 V.	3.0 W.	23 W.	26.5
6146	1.25	600 V.	250 V.	3.0 W.	20 W.	55

The regulation problems must be carefully considered. In addition to the usual plate power regulation problem the use of the beam power connection also requires good screen voltage regulation if maximum power output and low distortion are to be achieved. Two relatively simple and effective circuits which will take care of the screen regulation requirement are shown in Figs. 6 (A) and 6 (B).

In power amplifiers where it is necessary and essential to have good regulation of the high voltage supply, it is economically feasible and technically practicable to employ a swinging choke and high perveance rectifier as exemplified by the 5V4, 5AW4, 5T4 or 5AU4 types of tubes.

When driving the output stage into the grid current region in Class AB₂, it is necessary to employ low impedance driving circuits with excellent regulation characteristics. Circuits which are adequate and suited for this purpose require good regulation of their supply voltage(s). Fig. 7 (A) and 7 (B) are two typical methods of driving the power stage grids into the grid current region.

In Fig. 7 (A) the rectification component of grid current shows up in the cathode follower plate circuit and must be accounted for in the design of the voltage supply to this stage. In Fig. 7 (B) the rectification component shows up in bias rectifier which must similarly be designed to consider the effect of grid current flow. In typical applications an average grid current of 50 ma. is nominal.

When triodes are used in the output stage relatively large grid-to-grid driving voltages are required, and accordingly this imposes a problem in the design on the voltage amplifier stage driving the output.

The low cost and readily availability of selenium rectifiers and diffused junction germanium rectifiers permits the use of a low current, negative supply which is not only most convenient for use with cathode follower drivers, but also serves as a required and practicable means of augmenting the positive plate supply to the voltage amplifier. A high voltage supply is essential in order to achieve reasonable linearity at high output voltage levels. The same negative voltage may, of course, be conveniently used for fixed grid bias on the final stage.

With the above negative supply available, the shock hazard of the installation will not be any greater due to the fact that while a total potential of 800 to 900 volts is available, only half of this voltage is "above" the reference ground plane.

When cathode follower drivers are used to drive the final stage without the use of a coupling transformer, the regulation problem becomes severe due to the fact that the grid current flow in the output stage requires extremely good plate circuit regulation for the cathode follower driver. In

order to secure this required good regulation a "kicker" type of circuit has been developed. This is shown in Figure 8. The circuit is quite straight-forward but does require the use of a dual triode in the cathode follower type regulator stage. The use of diffused junction germanium rectifiers as the diode elements simplifies the filament requirement, although the use of a heater type tube is entirely practical in this circuit. It will, of course, be necessary to have separate cathodes available if tubes are used.

The use of cathode follower drivers may also reduce component costs and/or help the frequency response and phase shift performance of the driving circuit if full advantage is taken of the cathode follower connection. Fig. 9 illustrates the proper connection of this inter-stage circuit for maximizing the R_1C_1 time constant by means of the cathode follower connection.

In order to obtain the best possible grid voltage wave form (and lowest driving impedance) it is possible and desirable to employ feedback over several of the preceding stages. Another advantage in doing this will be obtained through the establishment of equal gains, essentially independent of tube characteristics, on each side of the push-pull circuit, provided that the resistors indicated as R-1 and R-1', R-2 and R-2' in Fig. 10 (A) are carefully balanced. In addition to the reduced grid driving impedance (with improved wave form), the uniform gain on each side of the push-pull circuit now permits the practicable use of feedback from the primary of the output transformer to preceding push-pull stages. This also permits feedback to be applied across the sides of the push-pull circuit which experience has indicated will materially aid in reducing cross-modulation and distortion to a low value. Fig. 10 (B) is a block schematic of the problems and circuitry involved. The principles described in this paragraph will be later applied to a particular design.

In order to maintain the output stage in a desirable statically balanced condition, a D.C. servo-type of automatic balancing system has been devised as shown in Fig. 11. This circuit employs a D.C. differential amplifier followed by a cascode stage for the purpose of securing the proper phase relationships and maximum servo-gain while permitting ready static adjustment of the output stage. In addition to the self-balancing feature, this circuit may be so adjusted and operated as to permit automatic control bias variation in order to secure optimum output stage operation at all power levels. The previously described "kicker" modification may also be used with this circuit.

In the past, the basic Williamson circuit has been widely followed. This is a good amplifier unique by virtue of its relative simplicity and intelligent use of feedback. Considerable care must be used in the operation of this unit because of the severe and objectionable distortion that occurs when the grids of the power output stage are driven positive. An improved

version of the Williamson type amplifier was described in AUDIO ENGINEERING for August 1952. "The Williamson type Amplifier Brought Up To Date". Since the publication of this original article, simplification and many improvements have been made for the purposes of further reducing distortion, minimizing the effects of the wide range of tube characteristics normally encountered, simplifying construction and reducing the cost of the amplifier system.

The new Kiebert #1 Amplifier circuit is shown in Figure 12. This is an outgrowth of the original circuit but simplifies the power supply by omitting the time delay tube. The new unit employs parallel 5V 4's in the power supply for the purposes of providing automatic time delay for the high voltage while maintaining a relatively low impedance power supply as necessary and desirable for a relatively wide band amplifier of this type. Low frequency performance is also aided by improved decoupling circuitry and longer time constants in some networks. The low frequency stability characteristics have been improved by reducing interstage time constants between the 12AY7 and the 5687.

Since publication of the article on the "improved" Williamson circuit, which emphasized low hum and noise levels, greater attention has been paid to optimizing the input and driver stages in regard to their intermodulation characteristics by employing optimum circuit values which will most readily and satisfactorily tolerate the normal variations in tube characteristics as will occur from one lot of tubes to the next. (New lots of 12AX7's were available and tests also indicate that this tube might serve as a satisfactory replacement for the 12AY7 with but slight deterioration in performance). The circuit values for use with this improved input circuit are also shown in Figures 12 and 13.

In particular, it was found that the inverter section of the 12AY7 made a large contribution to the intermodulation distortion of the amplifier; this was found to be mainly a result of the fact that too low a plate supply voltage is generally employed in this stage. It was also noted that if the IM were to be kept low in the first stage, then the optimum cathode resistance should be approximately 270 ohms. Cross checks were made with a 6SN7 in this part of the circuit and exactly the same results were experimentally verified. Accordingly, then, the new Kiebert circuit employs a materially higher voltage as available for the plate supply to the inverter section of the 12AY7, and utilizes a 270 ohm resistor in the cathode of the input section. Under this condition of operation it was then possible to get 3 volts RMS out of each side of the inverter without measurable IM, this even in the case where four sets from tubes from three manufacturers were interchanged.

A two ohm resistance in series with the filaments of the 12AY7 input stage helps to stabilize the d.c. coupled operation of this stage and also helps to reduce hum susceptibility over a con-

siderable variation in tube characteristics.

The 5607 driver stage was next checked, but the originally specified components and circuit values proved to be optimum from the IM point of view.

After evaluation of the driver stage, the triode output stage was carefully examined and adjustments were made in order to determine the optimum by-pass point on the cathode resistor. The optimum bias tap point was found to be at a point 140 ohms down from the cathodes. (Note that this applies only to the triode circuit of Fig. 12. The entire cathode must be by-passed in the tapped beam power connection of Fig. 13.)

The output transformer situation was next investigated. Two outstanding units (the specific selection of which was a function of the particular tubes used, and whether or not push-pull parallel operation was utilized) were found, namely the General Radio 942-A and the Freed 18777. It is also understood that the new Peerless S-268Q, the ACRO, UTC and probably others would exhibit similarly excellent characteristics had they been available for test. These units are all characterized by low distortion, reasonably high primary inductance, low leakage reactance, and good power handling characteristics at both ends of the spectrum. These requirements are obviously necessary, the tight coupling being particularly required in order to minimize switching transients. The Freed 18777 was rated 2,800 ohms to 4, 8 or 16 ohms. The General Radio 942-A was 6,600 or 1650 ohms to 4 to 93 ohms loads.

The foregoing brings the improved Kiebert version of the Williamson circuit of Fig. 12 up to its finest point and provides an excellent amplifier with the IM held to 0.1% at 7 watts equivalent single signal output, to 1.0% at 11 watts, but like all amplifiers drawing grid current, the distortion goes to high levels as soon as the grids are driven positive.

In the case where the power stage 807 grids are driven positive the driving point (source) impedance of the 5607 is approximately 1,000 ohms on positive peaks with a consequent flattening off of the positive peaks with matters made even more acute when the 1000 ohm series parasitic resistors are considered. Accordingly then, an amplifier of this type will only exhibit extraordinary cleanness provided it is never required to deliver a high energy peak.

A modification of the foregoing circuit in order to utilize the "ultra-linear" connection is shown in Figure 13. A very real gain in performance is obtained when it is noted that at an IM level of 0.1% a power output of 13.7 watts equivalent single signal is obtained while at an IM level of 1.0% a power output of 24 watts is obtained. The relative output damping characteristics of the triode circuit and the "ultra-linear" were investigated. Approximately 20 db of feedback is utilized in the triode version, and approximately

24 db are utilized with the ultra-linear version. The ultra-linear version had greater gain because of the quasi beam power connection -- but this circuit also had a slightly greater amount of feedback because the original feedback resistors were left unchanged. In this case the net circuit gain is about equal to the original triode circuit. Under these conditions, the following was measured:

Comparison of midrange output damping

15 ohm load, 6 volt level; 500 c.p.s.

807's Triode Connected, Output = 0.542 ohm

807's Ultra Linear Connected, Output = 0.394 ohm

The circuit of Fig. 13 was next modified to use a straight beam power connection as shown in Fig. 14. Measurements again indicated that at an IM level of 0.1% a power output of approximately 14 watts equivalent single signal is obtained while at an IM level of 0.1% a power output of 33 watts is obtained. 24 db of feedback was stable and the output damping was just as satisfactory as in the other two cases.

A new series of amplifiers were investigated and carried to a quasi completion point. Power output, simplicity, and cost were the three main factors held as design objectives in this evolutionary program. In each case, particular care was taken to provide units with excellent I.M. performance as well as units with output damping characteristics in the range of 20 or 30 to one.

The first amplifier built under this program is shown in Figure 15. This unit employs a cathode follower driver and fixed bias of the output stage combined with a negative high voltage supply such that approximately 650 volts was available for the plate supply to the high level voltage amplifier driving stage. This amplifier provides approximately 15 watts output at a I.M. level of 0.1% and approximately 45 watts at the 1.0% I.M. level.

Figure 16 describes a beam power connected counterpart of the above. In this case, however, approximately 14 watts was available at a 0.1% I.M. level and 70 watts at the 1.0% I.M. level.

In order to more closely check the grid regulation problem and the desirability of the triode connection, the configuration of Figure 17 was evaluated and provision made to use the "kicker" circuit of Figure 8. With this circuit the improved grid regulation was very apparent and a materially better "fold-up" characteristic was obtained. At a power level of approximately 21 watts the I.M. was 0.1%, while 65 watts were available at the 1.0% I.M. level.

Figure 18 illustrates another configuration embodying a number of the circuit techniques previously discussed. This specific design pushes the output from only two conventional tubes, operated at rated levels, to about the maximum power level available from these tubes when

operated at nominal "receiver" voltages and in conventional circuits. In this amplifier it is essential that the high voltage power supply have good regulation such that peak plate currents of 290 ma., from a static level of 135 ma., will entail only a negligible voltage drop in high voltage supply. A beam power connection was used due to the lower grid voltage required and greater gain available with this connection. Self balancing of the output stage was not used because cost and complexity were also tied into the design requirement for this particular system.

As a result of a meeting with BBC engineers and the acquisition of one of their acetate cutters which required 87 volt-amperes to lay down a level which was still about 10 db. below direct cut levels ordinarily employed in this country, it was necessary to design a new amplifier of greater output capability.

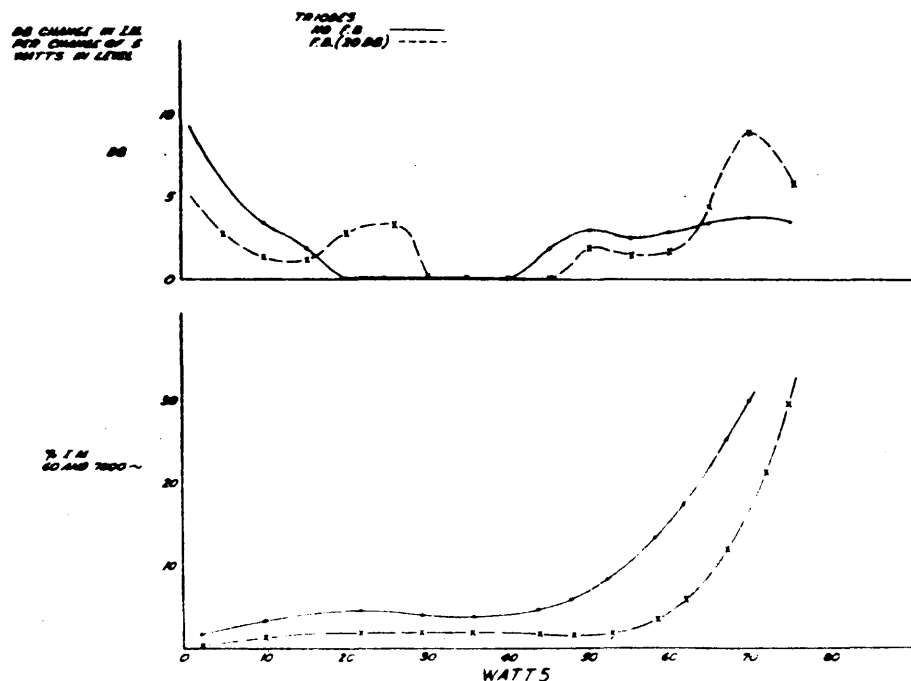
This new type of circuit is exemplified by Fig. 19. This amplifier has a normal rated output of 100 watts but is capable of putting out 200 watt instantaneous peaks with negligible IM distortion. The circuit is interesting in that the output stage efficiency is maintained at a relatively high level over a wide power range due to the fact that the output stage, as similar to the Brook amplifier, gradually changes from Class A operation to Class AB₂ operation with an

electronic, servo-type of automatic balancing of the static plate currents of the output stage, and simultaneous automatic optimum bias adjustment. The Freed #18777 transformer was specifically designed for use in this amplifier.

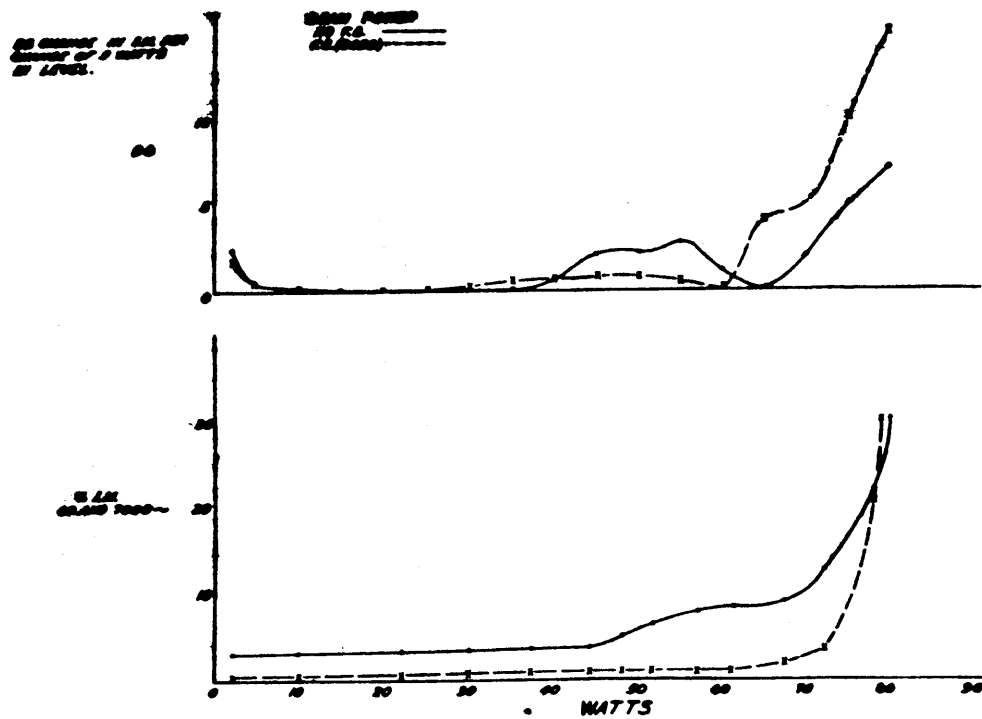
The foregoing covers a considerable range of equipment. For home use there seems to be no need or justification for use of an amplifier with an output rating in excess of 10 to 20 watts at an I.M. level of 1% or less.

In the design of higher level audio equipment one important point became apparent. Cathode emission of cathodes or filaments is quite sensitive as regards operating temperature (voltage) if distortion is to be held to reasonable levels on peaks. While specifications normally permit a $\pm 10\%$ variation - the tubes don't know this. At a point about two to four percent below rated voltage emissivity starts to limit on peaks. Over-voltage reduces tube life and may give difficulty as a result of increased grid current.

The design of good audio amplifiers is an interesting bit of relaxation for an engineer - but also costly as regards to time, materials and test equipment. Experience indicates that each design must be carefully evolved and meticulously tested before it becomes a practicable system. I hope that the foregoing material may be of interest and help to the engineer building a hi-fi system.



Curves I(A) and I(C).



Curves I(b) and I(D).

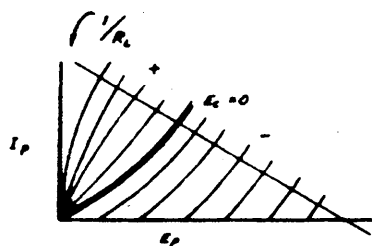


Fig. 1(a) - Triode.

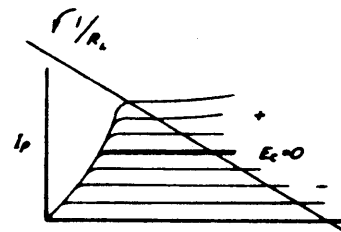


Fig. 1(b) - Beam power
(or ultra-linear).

Generalized plate characteristics.

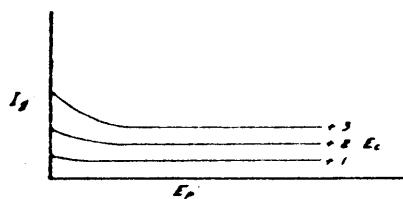


Fig. 1(c) - Triode.

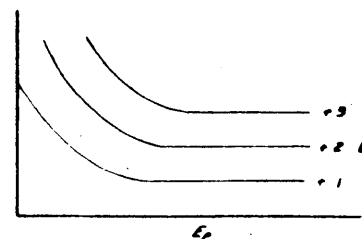


Fig. 1(d) - Beam power
(or ultra-linear).

Generalized grid characteristics.

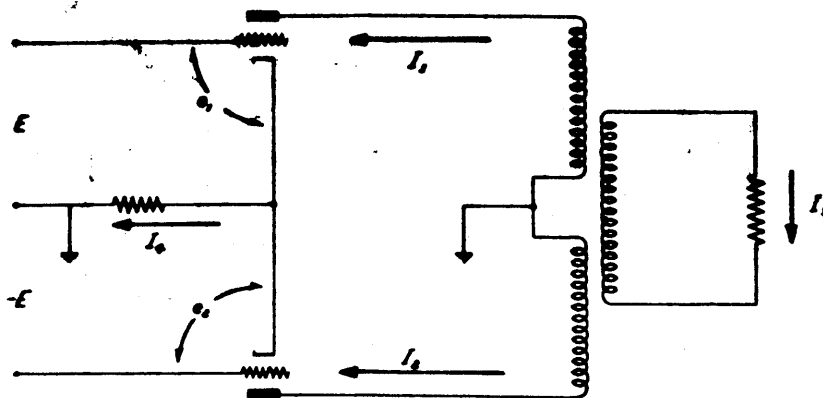
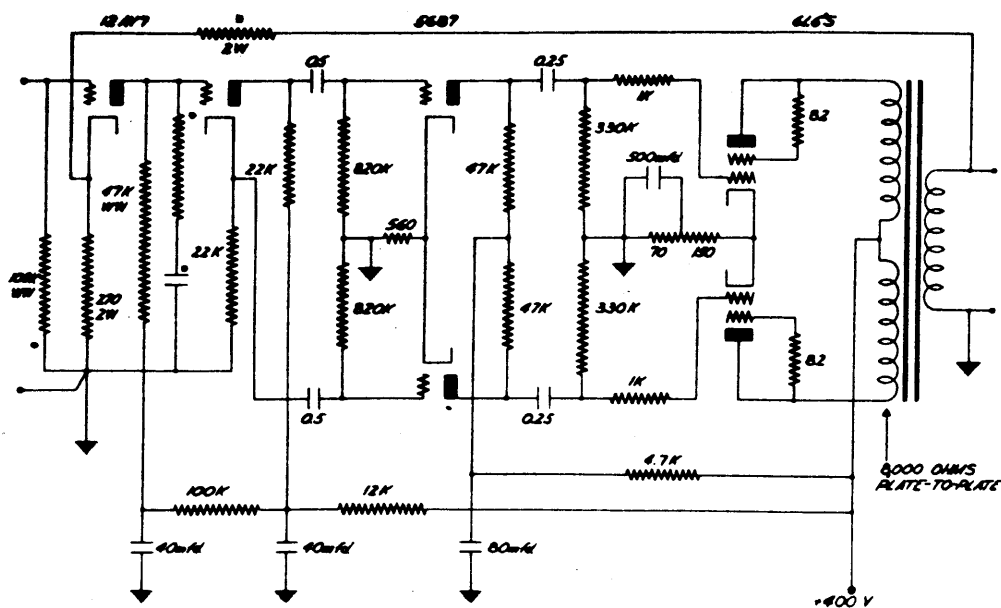


Fig. 2 - Triode third harmonic cancellation circuit.



*Value depends on specific output transformer.

Fig. 3 - Low distortion laboratory amplifier.

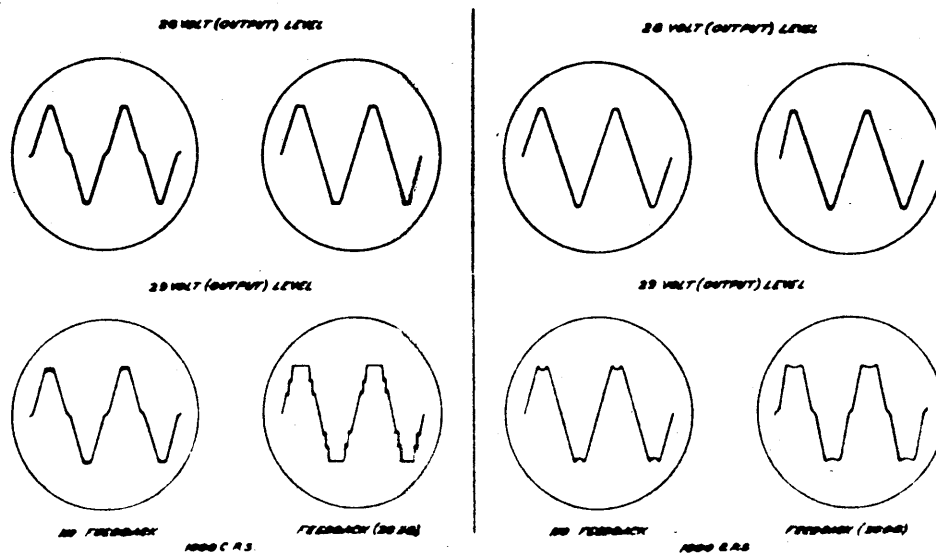
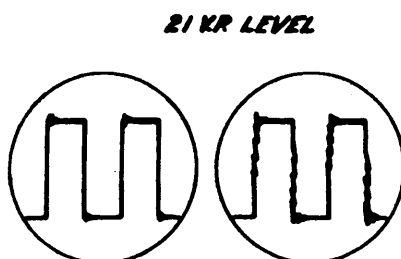
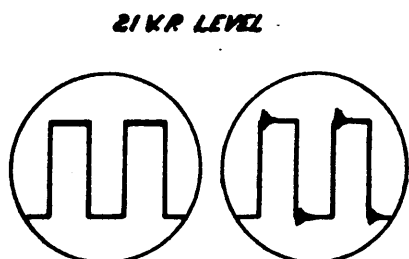
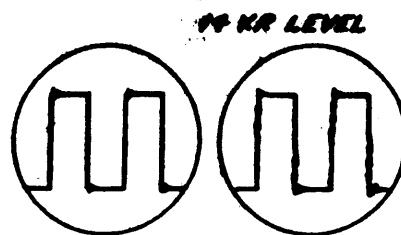
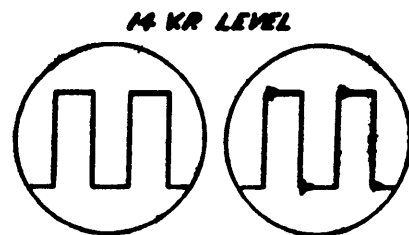


Fig. 4(a)
Sine wave inputs-triode.

Fig. 4(b)
Sine wave input-beam power.

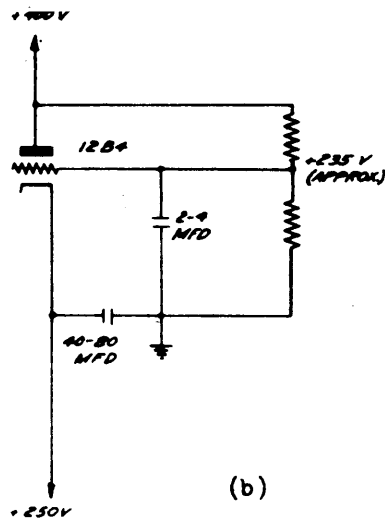
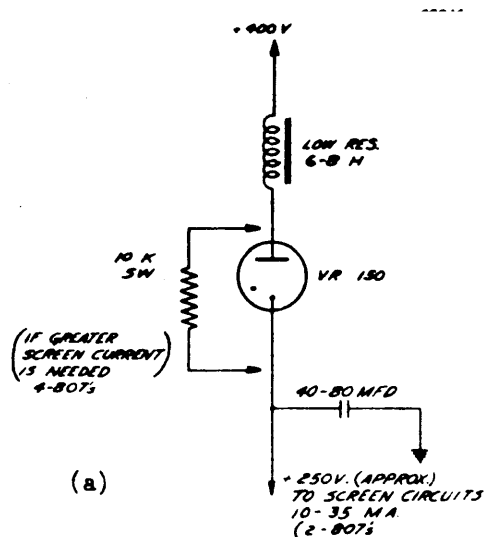


NO FEEDBACK FEEDBACK(20dB)
SQUARE WAVE INPUTS-TRIODE
1000 C.P.S.

NO FEEDBACK FEEDBACK(20dB)
SQUARE WAVE INPUTS-BEAM POWER
1000 C.P.S.

Fig. 5(a) and 5(b)

Fig. 5(c) and 5(d)

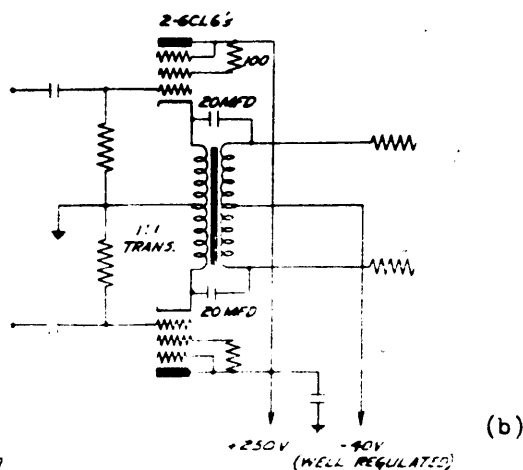
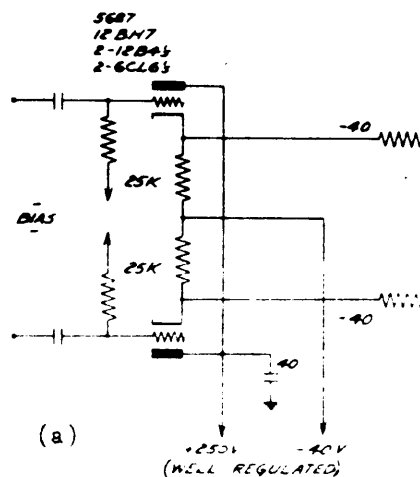


(a)

(b)

Fig. 6

Screen supply circuits. (a) Gas tube dropping circuit;
(b) cathode follower dropping and regulator circuit.



(a)

(b)

Fig. 7

Driving stages for class AB₂ circuits. (a) Cathode follower; direct coupled driving stage.
(b) Cathode follower; transformer coupled driving stage.

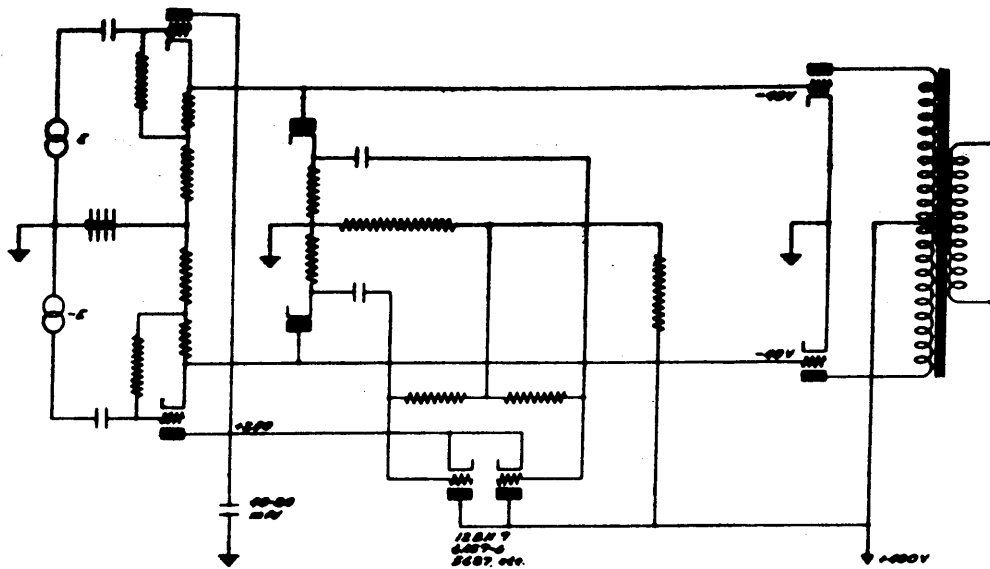


Fig. 8
Kiebert "kicker" circuit. Improved grid regulation for AB 2 operation from cathode follower driver stage.

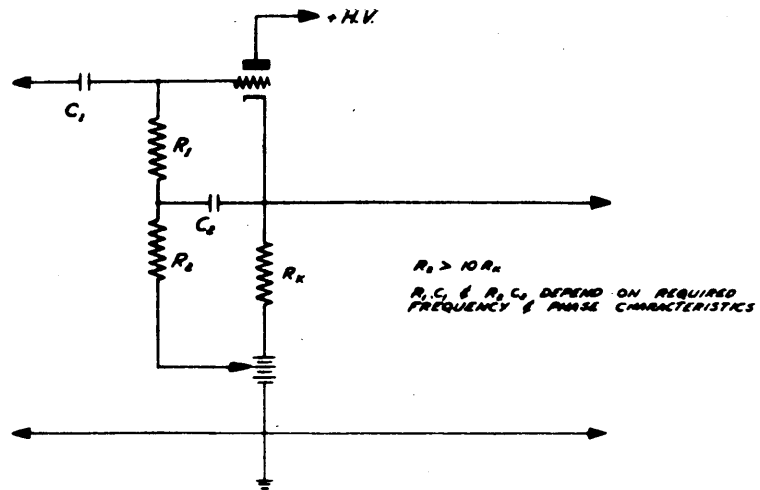


Fig. 9 - Cathode follower input coupling for larger RC time constant

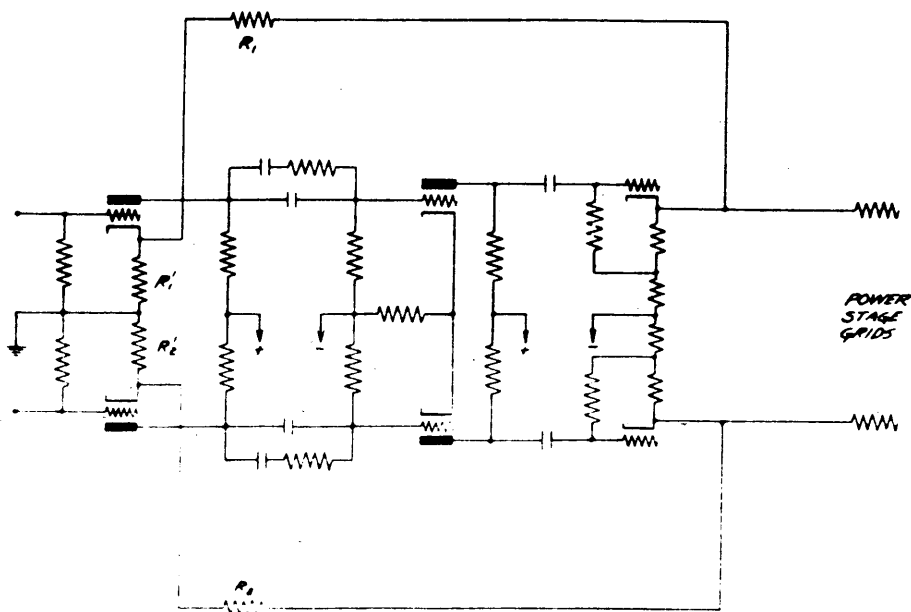


Fig. 10(a) - Low impedance driver.

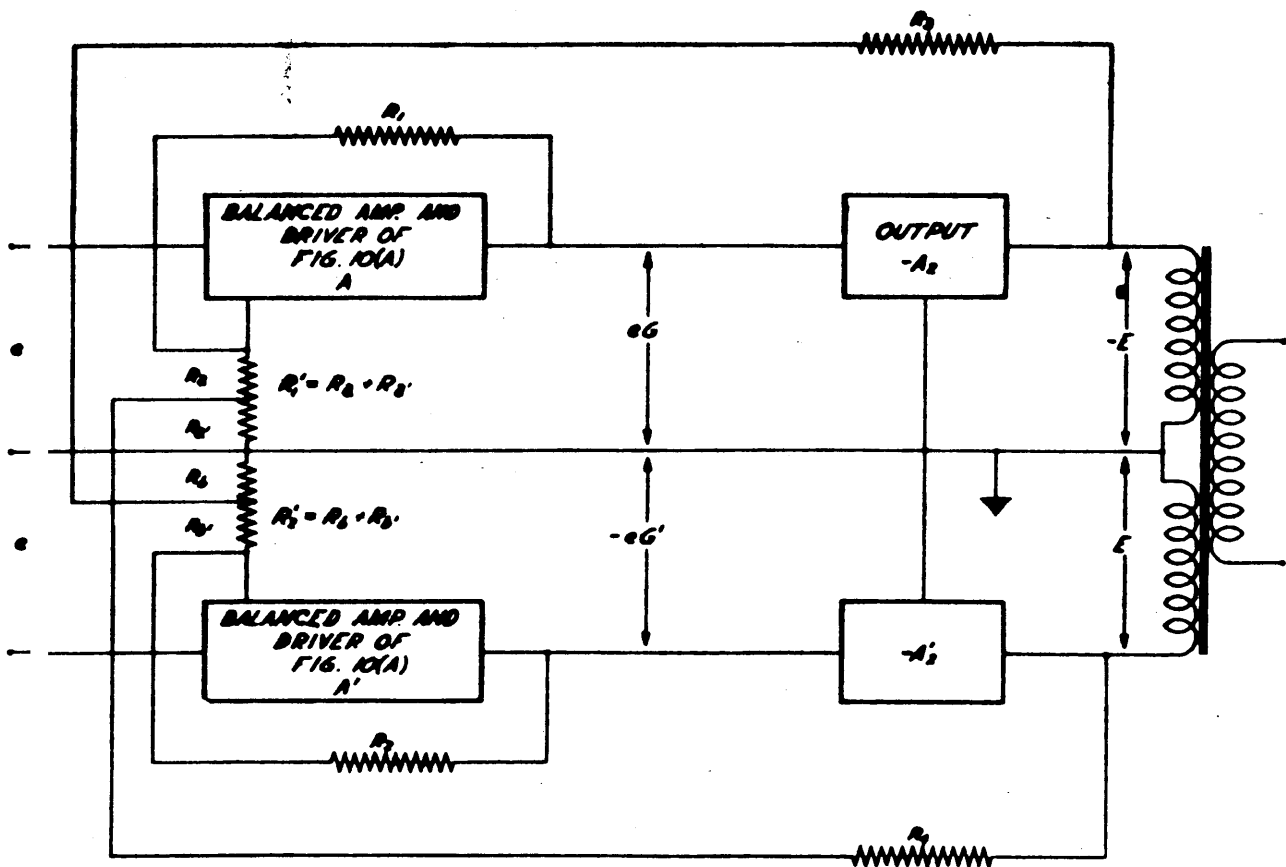


Fig. 10(b) - Block diagram, balanced, low I.M. balanced feedback circuit

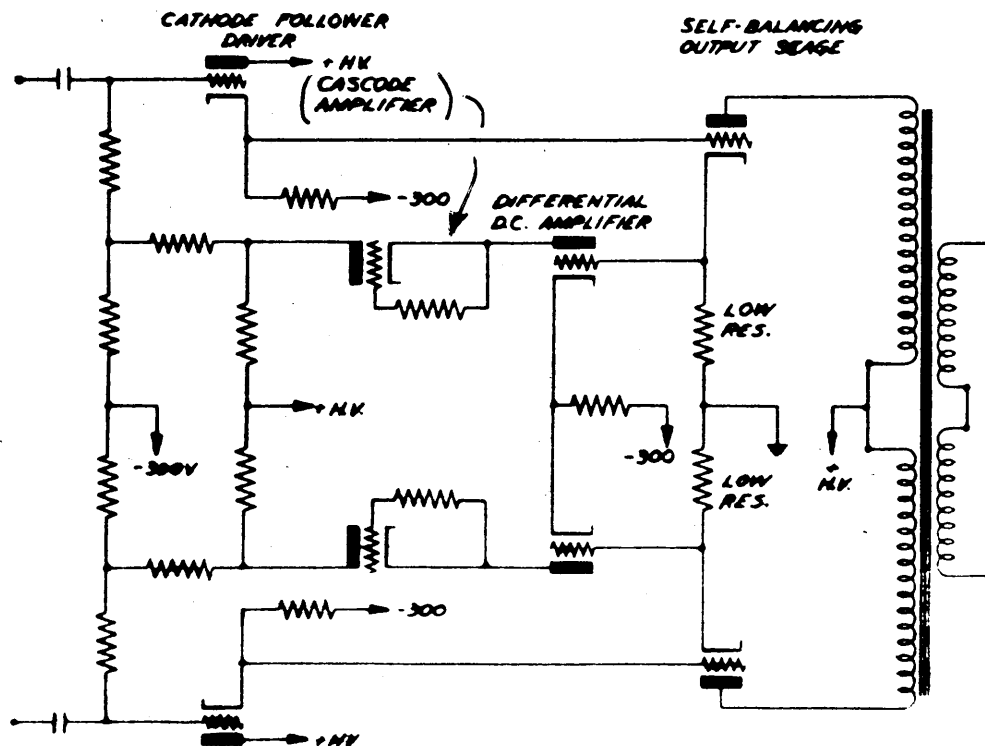
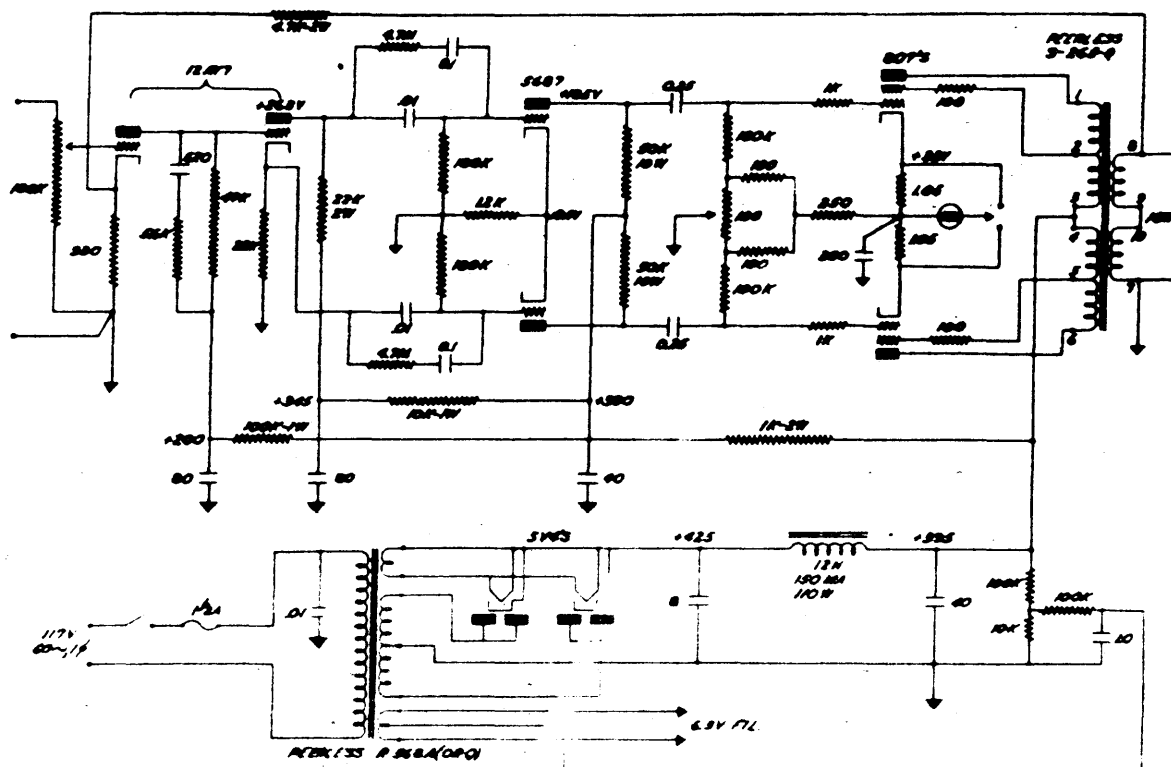
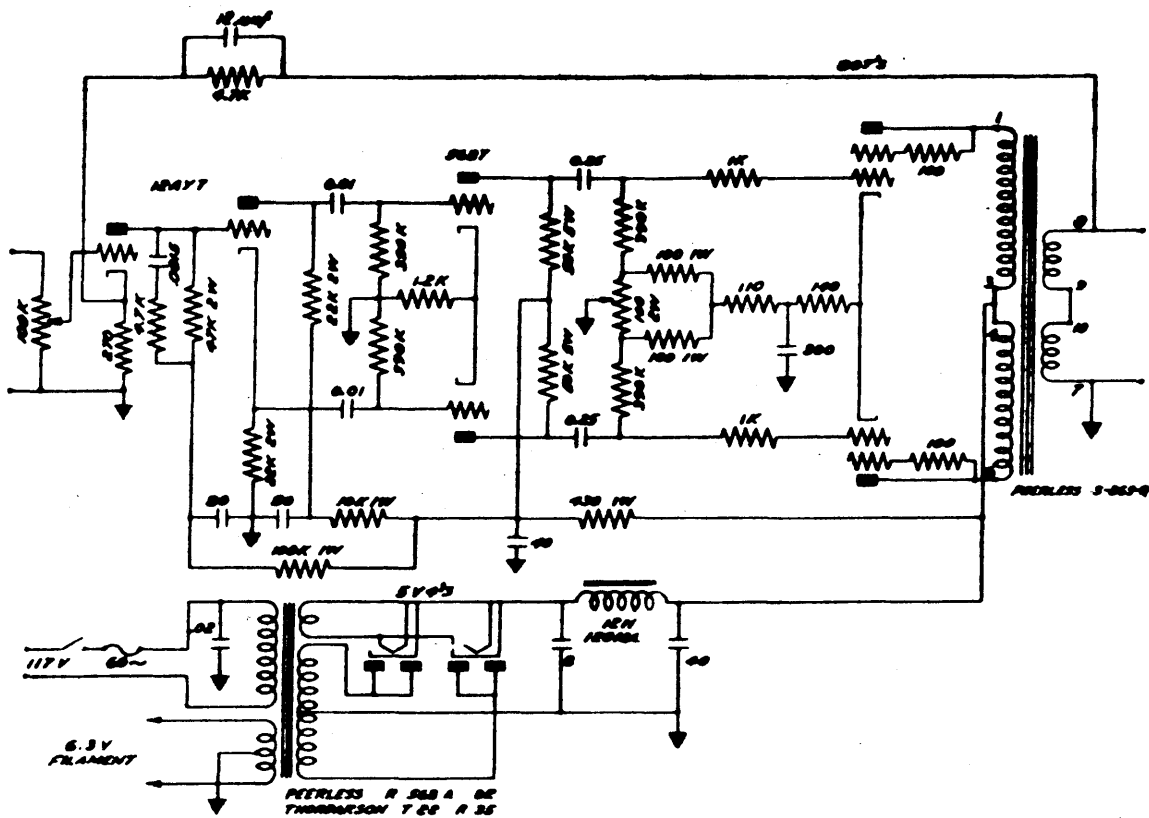


Fig. 11 - Servo-balanced push-pull output.



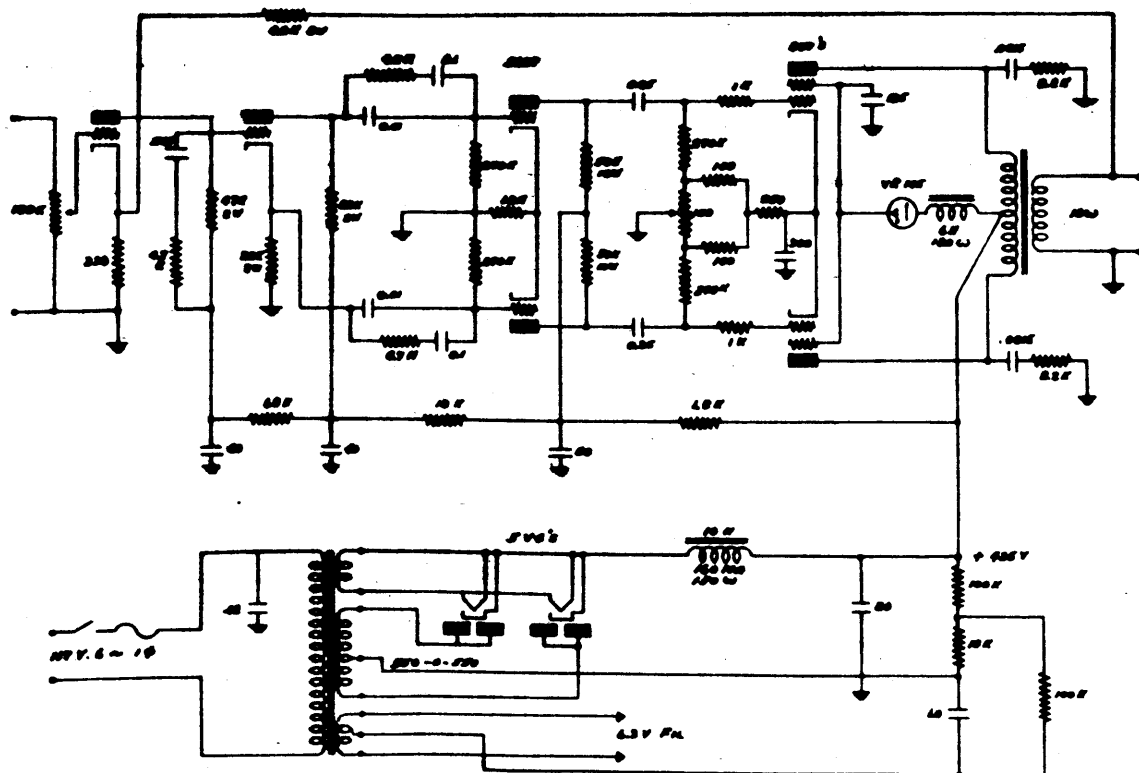


Fig. 14 - Kiebert beam power 33-watt amplifier.

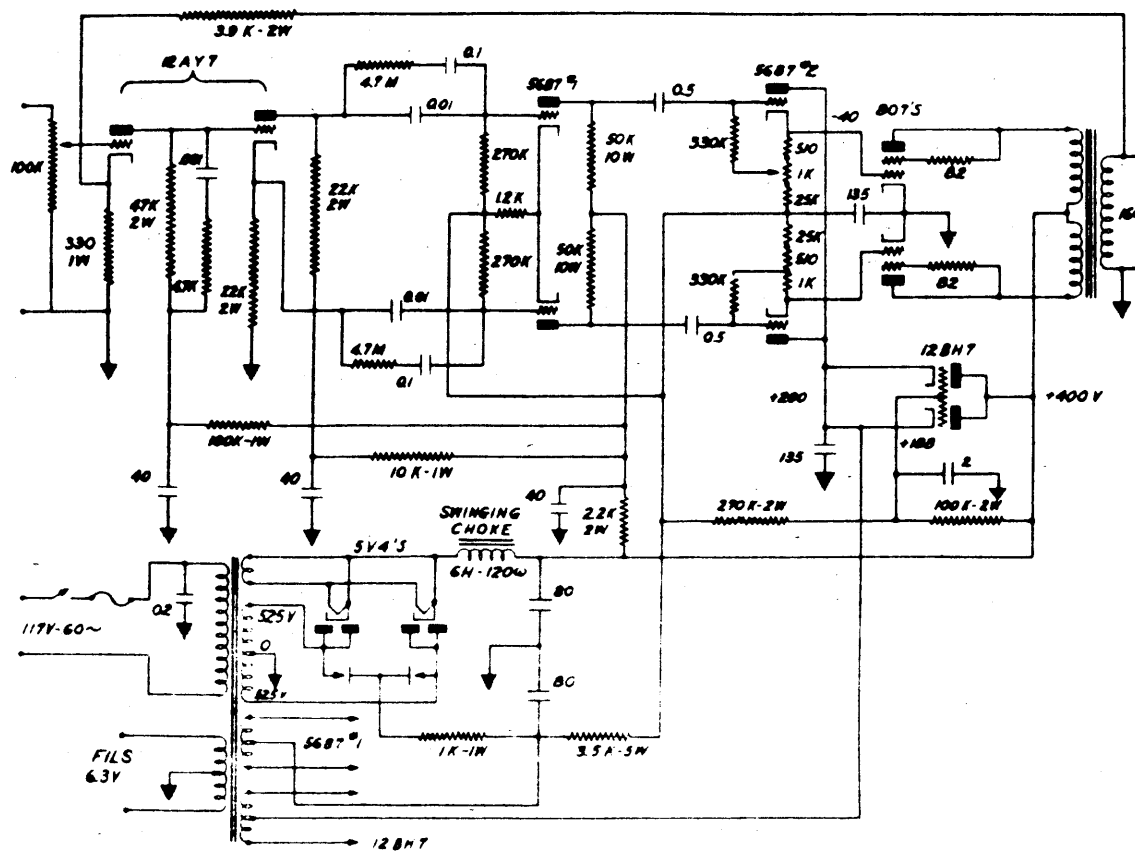


Fig. 15 - Kiebert 45-watt amplifier.

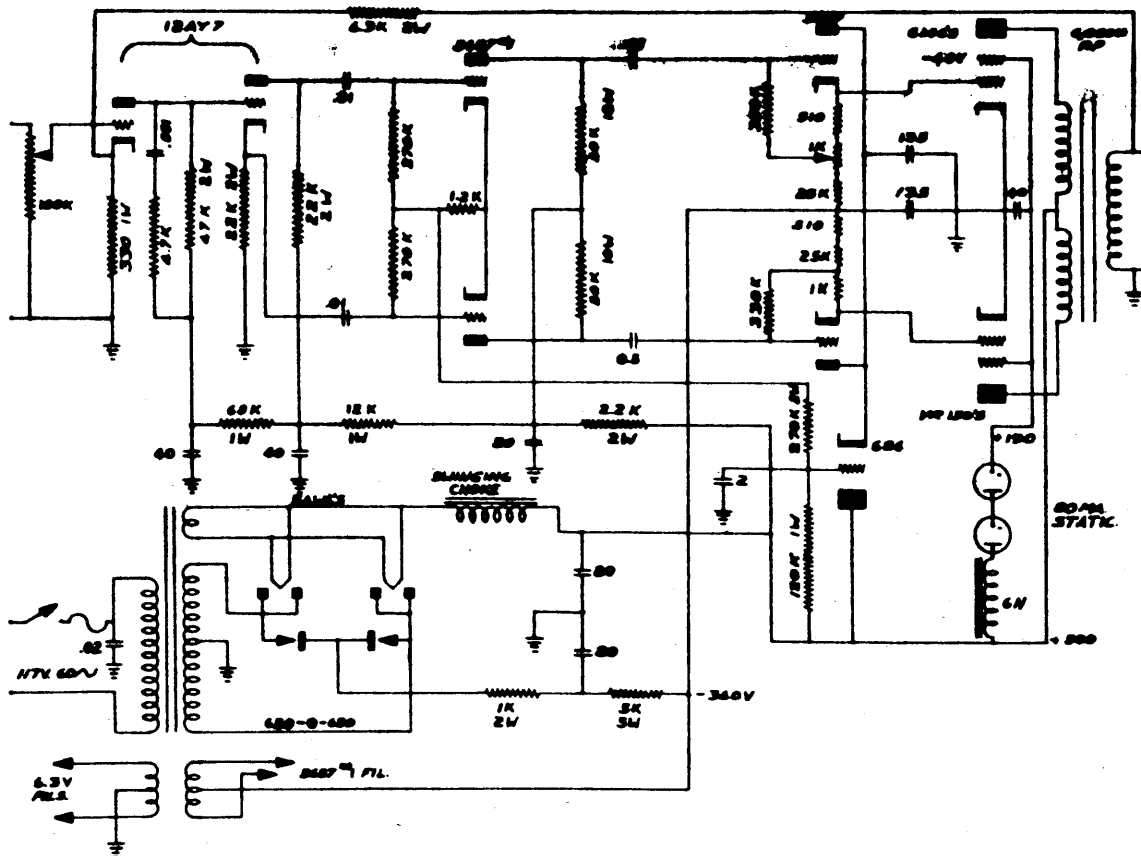


Fig. 16 - Kiebert 70-watt beam power amplifier.

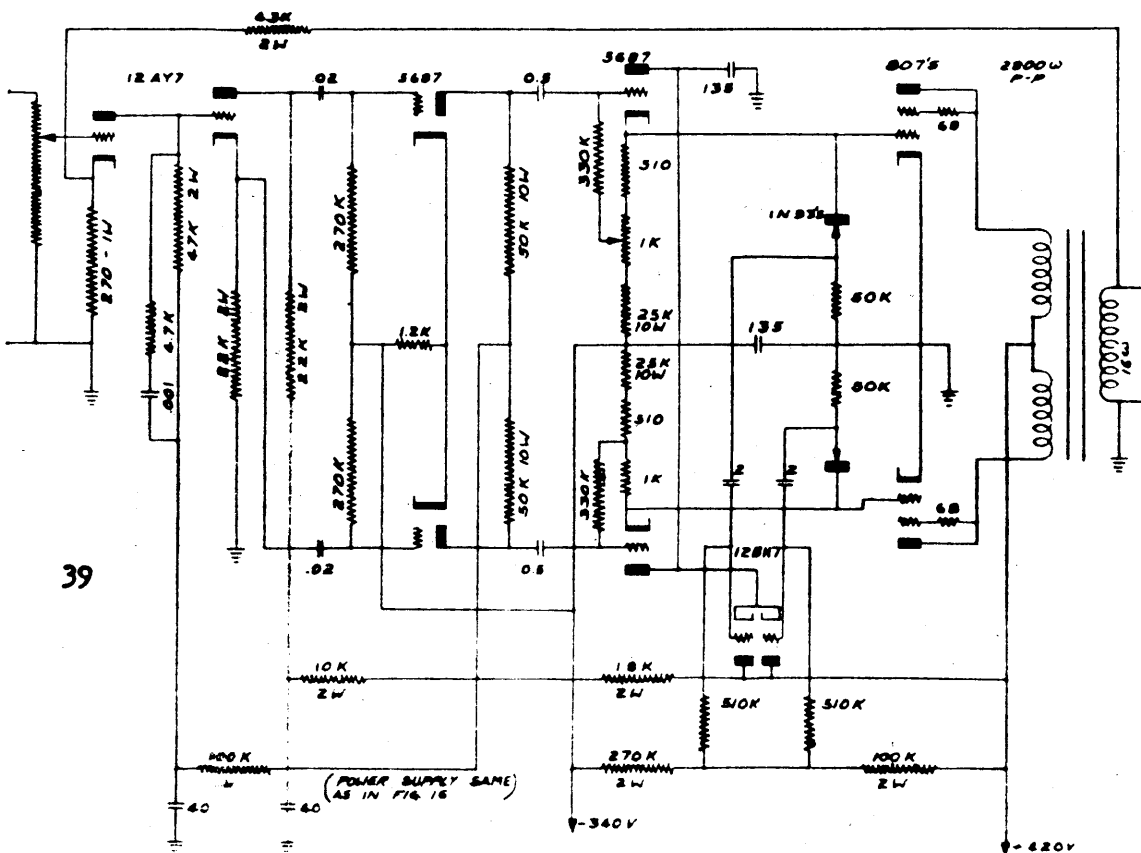


Fig. 17 - Kiebert 65-watt amplifier.

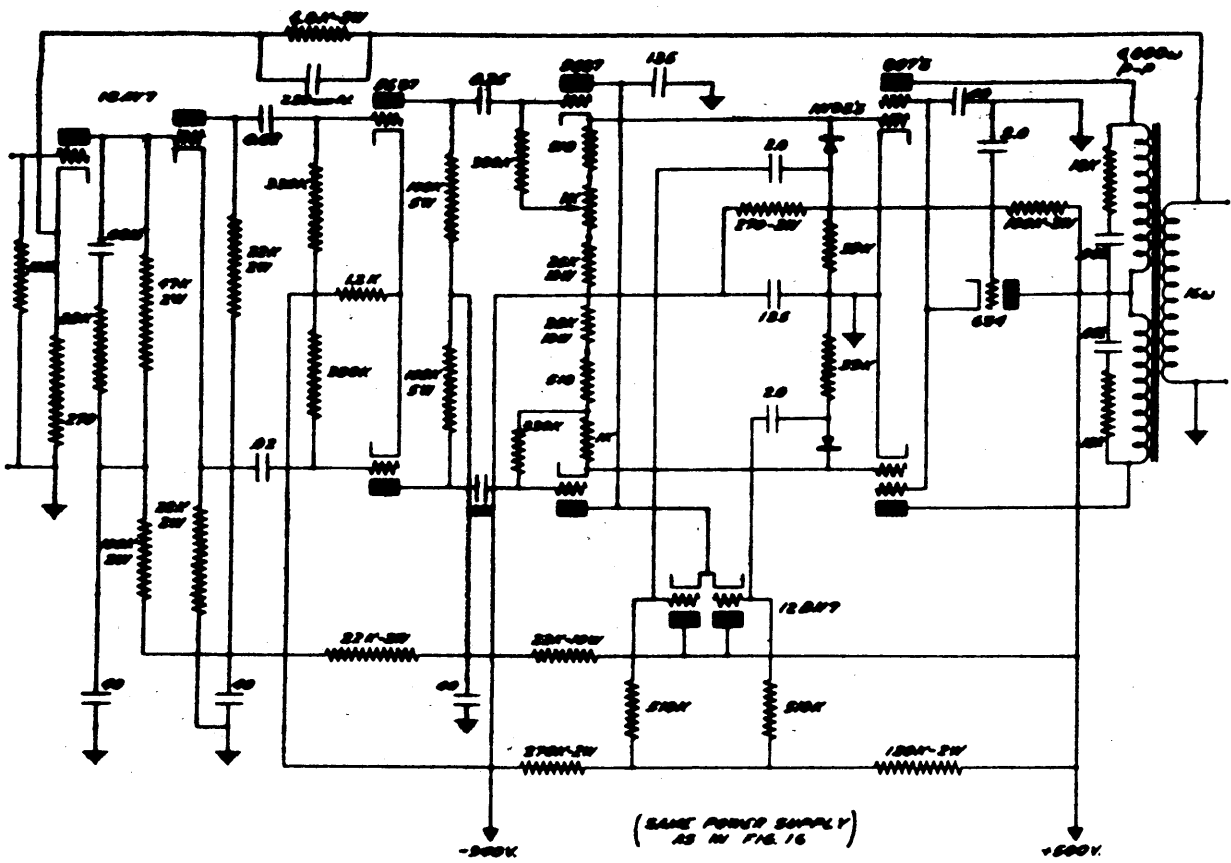


Fig. 18 - Kiebert 87-watt amplifier.

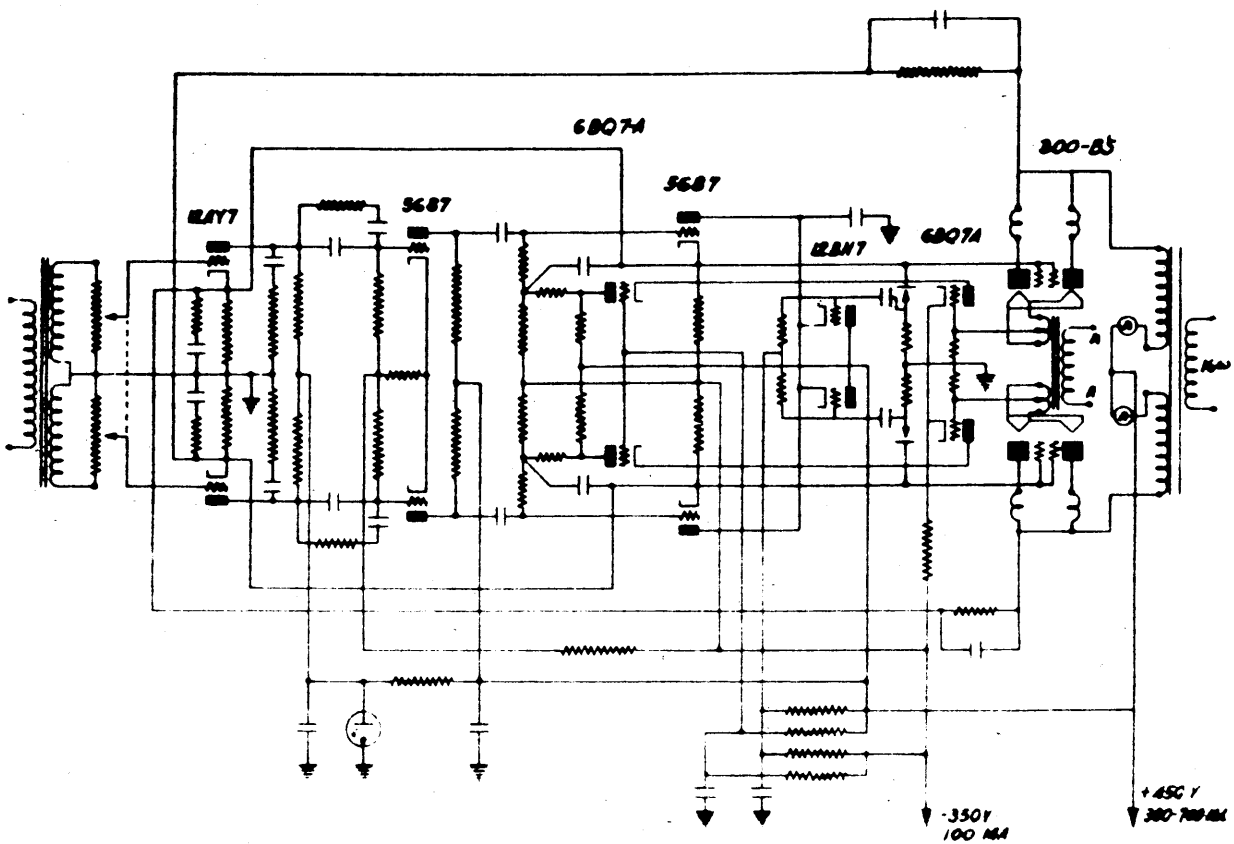


Fig. 19 - Kiebert 100-watt distribution amplifier.