

Class-A Power

After two and a half decades, John Linsley-Hood's Class-A power amp is still rated among the best. Here, John explains how to bring the design up to date, adding enhancements such as dc-coupled output.

The current debate, among the more reactionary of the hi-fi devotees, about the relative merits of thermionic valve operated audio amplifiers makes intriguing reading, if only because, in a sense, this is 'where I came in'. I will explain.

I have had an interest in the reproduction of music, principally from gramophone records, for a very long time. I made my first, two-valve, battery-operated, audio amplifier as a twelve year old school boy, some time before the outbreak of the 1939-1945 war.

This gave way – in the interests of economy, – to a series of mains powered amplifiers, which were usually combined with a radio receiver. Electricity from the mains was free, to me at least, whereas high-tension batteries had to be bought from my pocket money.

My early work culminated, in 1951, with the assembly of a luxurious kit for the highly esteemed high-fidelity Williamson 15W amplifier design. Although, by this time, I had my first proper job – in the electronics labs of the Sellafield nuclear research establishment in Cumberland – and cash was a bit more plentiful, I still wouldn't have built that particular, rather expensive version of the hardware if I hadn't heard through the lab grapevine that one of the research chemists had bought himself a Williamson kit, but, on receiving the parcel, lacked the courage to assemble its contents. Rumour had it that he was open to offers, and I was happy when he accepted mine.

This was an excellent amplifier, and was better, in my judgement, by a greater or lesser extent, than any of its predecessors of my own design, or, indeed, any of the other valve amplifiers, belonging to my friends, with which I had had a chance to compare it. It gave me great pleasure until early 1968, when I replaced it with a solid-state equivalent.

What I replaced it by, and the circumstances of this replacement, were described in an article in *Wireless World* in April 1969, entitled 'A simple class A amplifier'. This was a long time ago. In the light of the current debate, it seems possible that both my listening trials at the time, and an up-dated version of my original class A design, may be of interest to you. By up-dated, I mean using more modern components and delivering a bit more power output.

The Williamson Amplifier

In the inter-war years, with the improvement in audio quality of both gramophone records and radio broadcasts, considerable attention was paid to improving the quality of ac mains-powered audio amplifiers. A number of interesting designs were offered. These were mainly based on the use of push-pull output stage layouts. Relative to straight single ended circuits, push-pull stages would give greater output power for a given distortion level.

At that time, there were audiophiles who decried the use of push-pull output stage layouts. They claimed that the best audio quality was only obtainable from the much less efficient single ended arrangements, i.e. those in which the output valve had a simple resistor, choke or output transformer load. Interestingly, this is a claim which was examined and dismissed by Williamson at the time, but which has recently been resurrected.

Using negative feedback

Almost all valve operated audio power amplifiers require an output transformer to match the relatively high output impedance of the valve output stage to the low impedance load presented by the loudspeaker.

In general, the transformer is the most difficult and expensive part of the system to design and construct. This is because of the following conflicting demands:

- For a low leakage reactance – combining both leakage inductance and inter-winding capacitance – from the primary to the secondary windings, to avoid loss or impairment of high frequency signal components.
- For a low level of leakage inductance from one half of the primary to the other, to reduce the discontinuities due to push-pull operation, and the odd-order harmonic distortion resulting from these.
- For a high primary inductance, to give a good low-frequency response.
- For a low winding resistance, to avoid power losses.
- For a good quality grade of core laminations to ensure a low level of core-induced distortion, due to magnetic hysteresis and similar effects.

Intrinsic signal distortion of a valve amplifier stage could range from 0.5 to 10%, depending on its circuit form and operating characteristics. It had been appreciated for some time that such intrinsic distortion could be reduced significantly by applying local negative feedback. Various amplifier designs incorporating local negative feedback had been proposed. However, this still left the output transformer – however well made – as a major source of transfer and frequency response non-linearities.

At this point, D. T. N. Williamson, who was working at the time as a development engineer for the valve section of the GEC Research Laboratories, described a high-quality audio amplifier design, using the recently developed GEC 'kinkless tetrode' output valve, namely the KT66. In this design, a single overall negative feedback loop embraced both the whole of the amplifier and the loudspeaker output transformer.

With the exception of the output valves, which were triode connected KT66s, Williamson's design employed triode amplifier valves exclusively, because these had a lower intrinsic distortion figure. He also made use of extensive local negative feedback, provided by un-bypassed cathode-bias resistors. This had the additional benefit of eliminating the electrolytic bypass capacitors – a philosophy which is in accord with much of contemporary thinking.

Williamson also used non-polar rather than electrolytic high-tension reservoir and smoothing capacitors, in the interests of more consistent ac behaviour. Electrolytic capacitors were much worse at that time.

If overall negative feedback was to be applied without causing either high or low-frequency instability, careful design was essential – both in the amplifier stages and in the output transformer. These problems had frustrated earlier attempts to do this – but Williamson demonstrated that it could be done.

The performance given by his design, if his detailed specifications were carried out to the letter, was superb. The performance criteria of better than 0.1% thd, at 15W output, from 20Hz to 20kHz, and a gain bandwidth from 10Hz to 100kHz +/- 1dB, are at least as good as those offered by many of today's better commercial designs.

The series of articles written by Williamson, in *Wireless World* over the period 1947 – 1949 described the power amplifier and its ancillary units. This series had enormous impact on audio design thinking, and if I may quote the *WW* editor of the time, in his introduction to a reprint of all these articles.

"Introduced in 1947 as merely one of a series of amplifier designs, the 'Williamson' has for several years been widely accepted as the standard of design and performance wherever amplifiers and sound reproduction are discussed. Descriptions of it have been published in all the principal countries of the world, and so there are reasonable grounds for assuming that its widespread reputation is based solely on its qualities".

All in all, the Williamson was a hard act to follow.

Alternative hardware

The world had not stood still since 1951. My equipment had remained monophonic, while the rest of the audio world was changing over to stereo.

My main interest was in music, not in circuitry, so I thought it would be prudent to ask my ears what they thought of the alternatives, before I started to replace my hardware.

To this end, I built or borrowed six well thought-of audio amplifiers, my own Williamson, a Quad 2, two dissimilar but recently published class AB transistor amplifiers, a commercial 30W solid-state unit, and a simple Class-A unit of my own design.

I included the Class-A design out of curiosity. If it turned out to be any good, it would be cheap and easy to build. It was not expected to offer any special merit in performance.

In the event, as I reported at the time, (WW April 1969, p.152), the six amplifiers divided quite clearly into two separate tonal groups. The three class AB transistor amplifiers formed one group, while the two valve amplifiers and the simple class A amplifier formed the other.

To be fair, the differences between any of these were not very great – but they were audible. Once they were noticed, they tended to become more apparent on protracted periods of listening. Certainly, for me – and I was doing these tests for my own benefit – in these comparative trials, the two best were the Williamson and the class A. They were virtually indistinguishable. Of these two, the Williamson was vastly more massive and costly to construct.

The only remaining question was, if I replaced the 15W Williamson with the 10W Class-A design, would the output be adequate? Connecting an oscilloscope across the loudspeaker terminals showed that I seldom needed more than 2-3W from the power amplifier – even under noisy conditions.

I suppose that the final proof of my satisfaction with the class A transistor amplifier was that, a year or so later, I gave my old Williamson to a friend.

Valves versus transistors

Not all of the considerations of valves versus transistors relate solely to performance. It is worth bearing in mind that products involving obsolete technology will be disproportionately expensive, difficult to obtain and possibly of inferior quality.

Valves can also vary in operating characteristics from sample to sample – especially where two valves of the same type are obtained from different sources. Characteristics that can vary are mutual conductance, gain, operating grid bias, anode current impedance, and even usable anode voltage.

By comparison, the performance characteristics of, say, a range of 2N3055 epitaxial base output transistors are almost identical, whether made in the Philippines or in Toulouse.

Again, all valves deteriorate in use, exhibiting a gradual loss of cathode emission over a typical 3000 hour service life. If a valve is persistently over-driven, the heating of the anode may cause the metal to out-gas. This impairs the vacuum essential to proper operation, and shortens the valve's life.

A further consideration is that valves are high voltage devices, which can be dangerous. And the need for high working voltages can lead to more rapid failure of other components in the circuit – especially capacitors.

The class A design

My original design is shown in Fig. 1. This is still a valid design, except that the MJ480/481 output transistors are now obsolete. However, they can be replaced by the more robust 2N3055. In this case, the epitaxial-base version of this device should be chosen rather than the homotaxial, since the f_T of the output transistors should be 4MHz or higher.

As I commented, at the time, the design gave a somewhat lower distortion if the h_{FE} of Tr1 was greater than that of Tr2. This caused the output circuit to act as an amplifier with an active collector load rather than an output emitter follower with an active emitter load.

A simple modification which takes advantage of this effect is the use of a Darlington transistor such as an MJ3001 for Tr1. At 1kHz, this reduces the distortion level at just below the onset of clipping from about 0.1% down to nearer 0.01%. As before, the residual distortion is almost exclusively second harmonic. Also, as before, it fades away into the general noise background of the measurement system as the output power is reduced.

While this transistor substitution seems to be a good thing, it was not a modification whose effect I was able to check, in listening trials, against the Williamson. As a result, for the sake of historical fidelity, I would still recommend the use of epitaxial-base 3055s as Tr1 and Tr2.

I have checked all the other changes which I have proposed with the exception of the power increase.

Improving performance

With regard to the original 10W design, as published, I feel the following improvements will be beneficial:

- Provide a more elegant means of controlling output transistor operating current by including a variable resistor in the base of Tr2.
- Arrange the circuit so that it would operate between symmetrical power supply lines, allowing the amplifier to be directly coupled to the loudspeaker.
- Increase output power from 10 to 15 watts per channel
- Up-grade the smoothed but not regulated power supply arrangement.

In my postscript to this design, which WW published in December 1970, I suggested both alternative transistor types and an improved method of adjustment and control of the output transistor current flow, Fig. 2.

Although, in theory, this layout should give a superior performance, when I changed my prototype amplifier to this arrangement, I found little change in measured thd and I couldn't hear any difference in sound quality.

Although directly coupling the amplifier to the loudspeaker will not have much effect on thd, it is still beneficial since it eliminates the output coupling capacitor. The most obvious way of doing this is to rearrange the input layout, around Tr4, so that it becomes the input half of a 'long-tailed' pair.

I am reluctant to do this because this would alter the overall gain/phase characteristics of the amplifier. It would also require additional high-frequency stabilisation circuitry, with all its incipient problems of transient intermodulation or slew-rate limiting.

Fortunately, the need to remove the dc offset at the output can be achieved without altering the good phase margins of the design, by simply injecting an appropriate amount of current into the base circuit of Tr4.

Output power and dissipation

In essence, all that is required to increase the power output from the amplifier is to increase the rail voltages and the standing current through the output devices. Restrictions are that power consumption must remain within the confines of what the mains transformer and rectifier can deliver. Also, the heat-sinks must be able to dissipate the extra heat and the output transistors must be adequately rated.

For a 15W (sinusoidal) output into an 8Ω load, an $11V_{RMS}$ drive voltage is required. This, in turn means a $31V_{P-P}$ voltage developed across the load, and an output current into the load of 2A. Since the circuit is a single-ended configuration, in which the collector current will not increase on demand, this means that the output transistor operating current must be at least 2A to allow this.

With the circuit shown, using the improved current control layout – which is rather less efficient than the boot-strapped load for Tr3 which I originally proposed – the rail voltage needed is $\pm 22V$.

This will lead to a dissipation, in each output transistor, of 44W. Prudence suggests that a heatsink having a rating of no more than $0.6^{\circ}C/W$, should be used for each output pair.

Most 2N3055s have a V_{ce} of 60V, a maximum collector current of 15A, and a maximum dissipation, on a suitable heatsink, of 115W. However, RCA's 3055, and its complementary MJ2955, are rated at 150W.

Working conditions for the output transistors are entirely within the devices safe operating area, so no specific overload protection circuitry is needed. Even so, the inclusion of a 3A fuse in the loudspeaker output line would seem prudent.

DC offset cancellation

Figure 3 shows the full circuit for one channel of the 15W Class-A audio amplifier. I have inserted a 15V three-terminal regulator ic into the positive rail to prevent any unwanted signal or hum intrusion into the emitter of Tr4.

It is easy to set the dc offset to within $\pm 50mV$. The offset does not change greatly with time, although this assumes that Tr5 is not allowed to warm up too much. This is because the base-emitter potential of this transistor controls the operating current, which in turn, affects the output dc offset.

Small-signal bandwidth

In the original circuit the small-signal bandwidth was 10Hz–250kHz, $\pm 3dB$, which was needlessly wide. Because of this, I have added an input high-frequency roll-off network, R3/C2, to the input circuit to limit the top end response to some 50kHz. This assumes an input source impedance of $10k\Omega$ or less.

As it stands, the low-frequency $-3dB$ point is about 7Hz. It can be lowered even further, if necessary, by making C1 larger – say to $1\mu F$.

Supplying power

As was shown in the 1970 postscript, it is possible to operate this amplifier from a simple rectifier/reservoir capacitor layout. Fig. 4 is an example. The only penalty is a small 100Hz background hum, probably about 3mV in amplitude. However, I feel that, if you are seeking the best, a proper regulated power supply is preferable, Fig. 5.

The circuit shown for the current booster pass transistors, Tr1/Tr2, is one suggested by National Semiconductor. It takes advantage of the internal current limiting circuitry of the 7815/7915 devices to limit the short-circuit current of these ICs to 1.2A. By choosing the correct ratios of R5:R7 and R8:R10, the short-circuit current drawn from Tr1 and Tr2 will also be limited.

For a satisfactory ripple free dc supply of $\pm 22V$, the on-load voltage supplied to the regulator circuit should be $\pm 27V$.

Performance

I prefer measurements made with appropriate instruments to judgements based on listening tests.

Measured distortion is less than 0.1% near the onset of clipping. It fades away into the background noise level of the measuring system as output power level is reduced.

For me, the fact that the distortion given by this circuit is almost pure second harmonic is more persuasive of its performance than any 'golden eared' judgement of tonal purity.

If you then add the observation that the circuit remains stable on a square-wave drive into typical reactive loads, I am not surprised that its performance was capable of equalling the Williamson on listening tests. No significant overshoot is observed on the square-wave, and stability is achieved without the need for internal high-frequency compensation arrangements.

So, as a final thought, if any of you want to find out how a top quality valve amplifier like the Williamson sounds, you can find out at a tenth of the cost of building one by making up this Class-A design. It has the additional advantage of incorporating readily available and modern components.

Figures

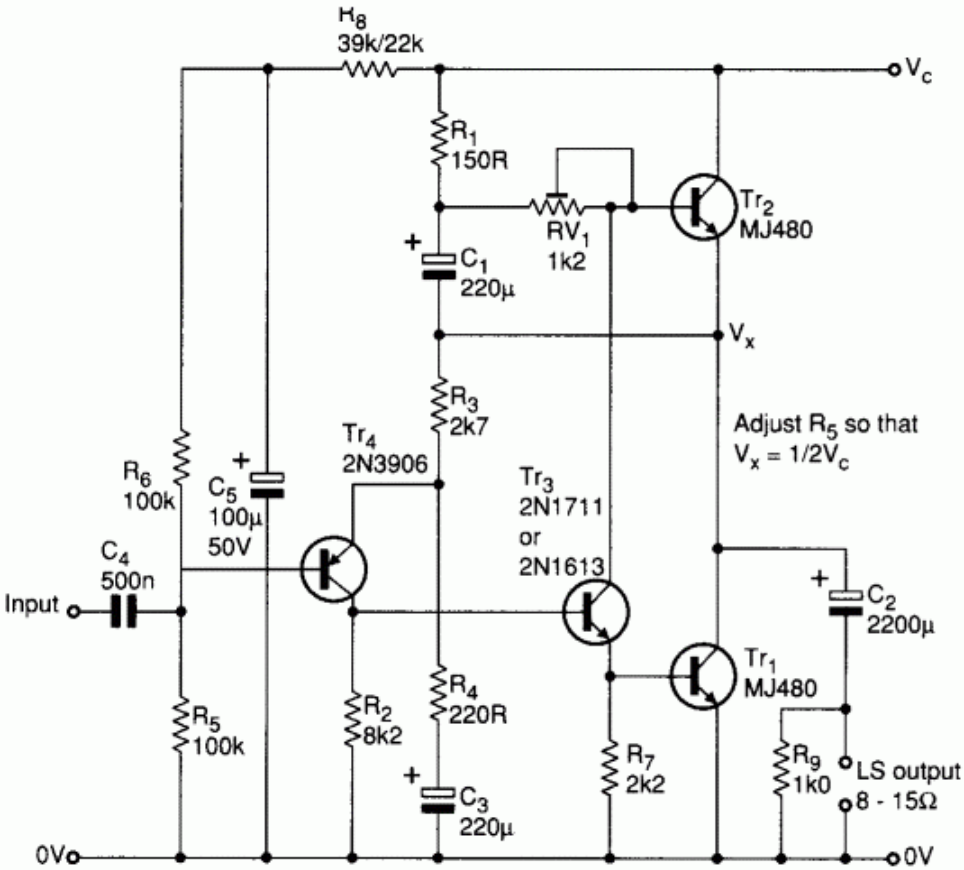


Fig. 1. Original 10W Class-A design is still valid, but the power devices are now obsolete.

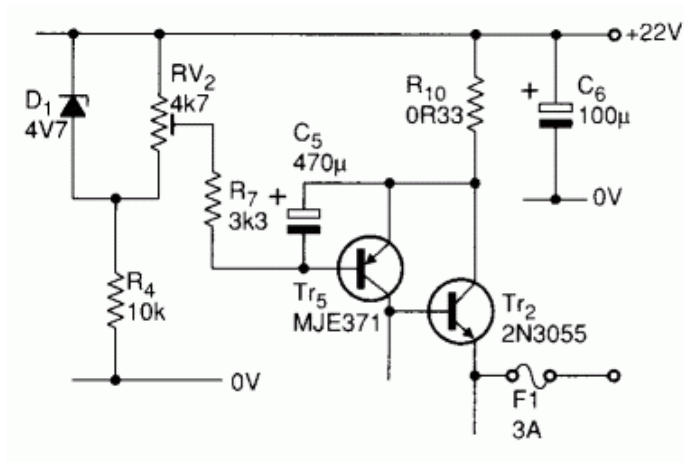


Fig. 2. Improved method of adjusting quiescent current, suggested as a postscript to the original design.

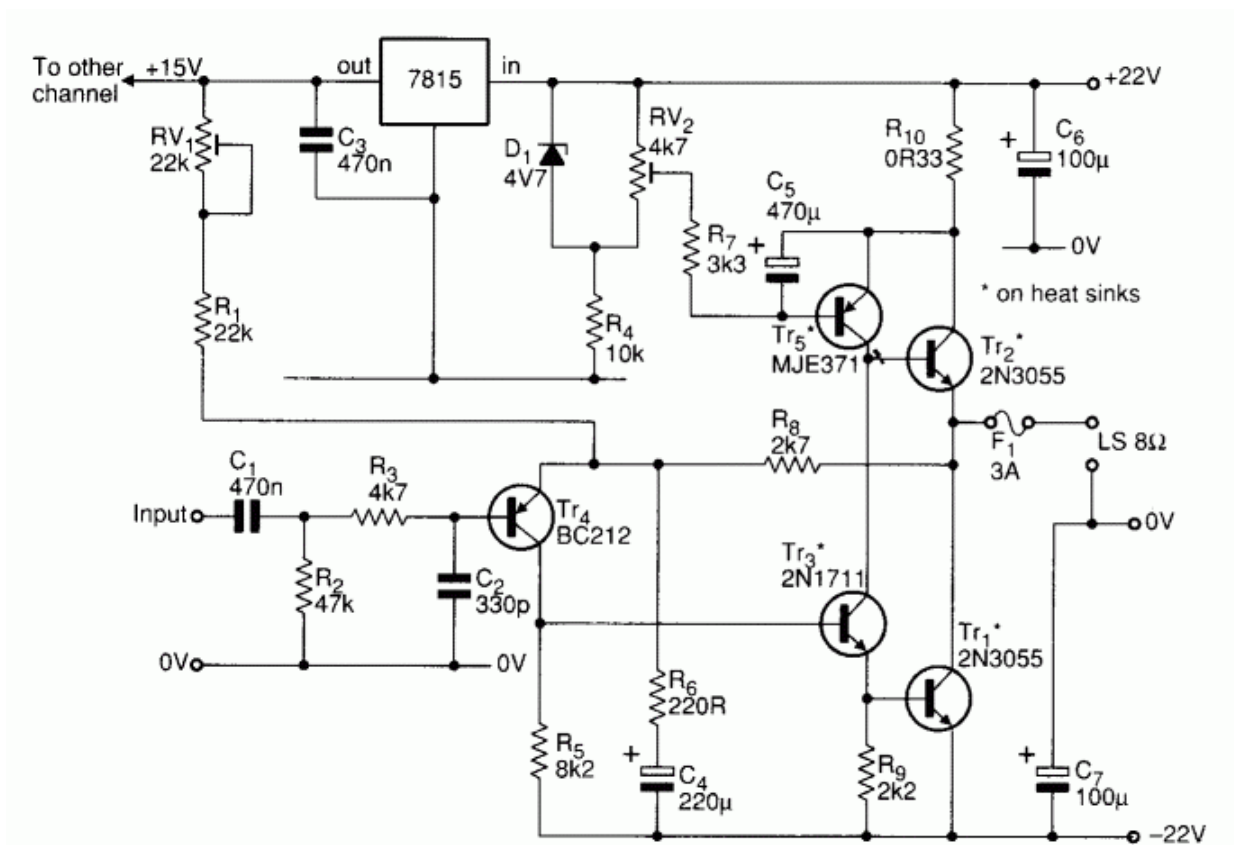


Fig. 3. One channel of the enhanced 15W Class-A design incorporating – amongst other things – direct loudspeaker coupling.

Note: There is an error in this diagram. The negative end of C4 should be connected to the 0V (earth) point and not the -22V supply rail as shown. Failure to do this will result in excessive hum due to supply rail ripple being injected into the negative feedback path (Tr4 emitter).

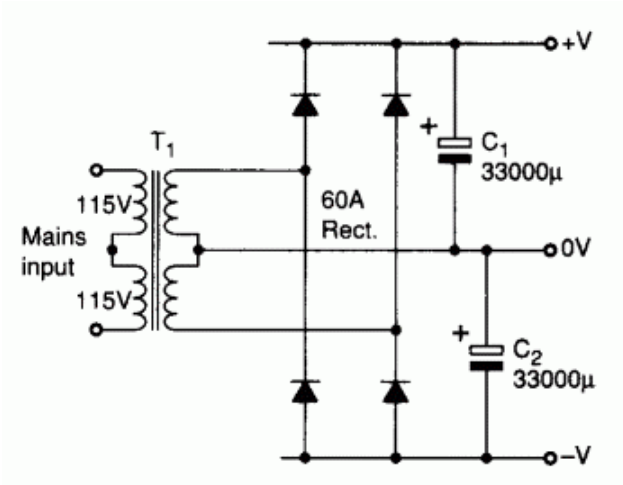


Fig. 4. Simple but adequate dual-rail supply using a single bridge.

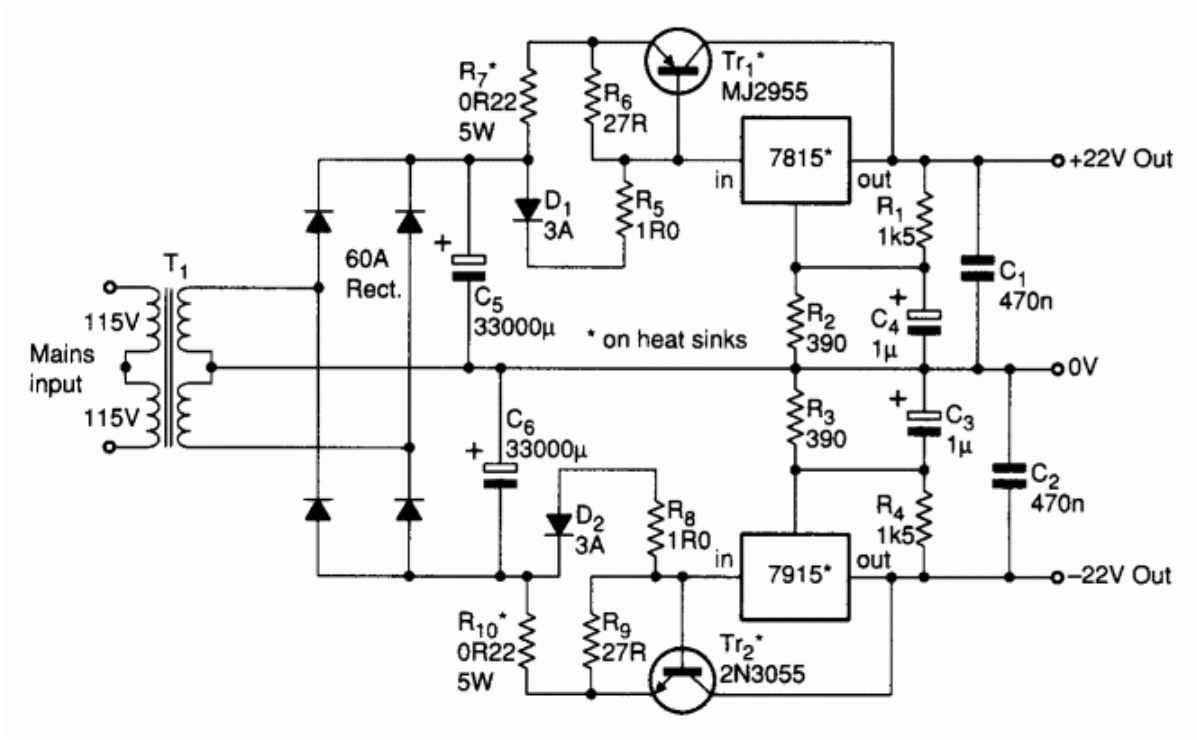


Fig. 5. Regulated power supply for the Class-A amplifier uses boosters around the three-terminal regulators. These take advantage of the regulators' current-limiting feature.