VINTAGE WORKBENCH

By Ian Batty

BWD's 216A hybrid bench supply

BWD was a major Australian electronics manufacturer from their founding in 1955 through to the 1980s and this hybrid (valve/solid state) power supply is from their golden era. The BWD 216A delivers 0-400V at 0-200mA and 0-250V at up to 50mA and has two 6.3VAC unregulated outputs. It was marketed as a general purpose laboratory power supply.

I recently purchased a BWD 216A power supply, which was originally released in the early 70s. I consider it a smart design; the way the circuit operates is quite intriguing. This unit had high quality construction and was a commercial success, selling over 40,000 units.

If you haven't heard of BWD, they were a famous Australian electronic test instrument manufacturer for many years. See the history panel for some details on the company.

BWD is still around in the same location at Mulgrave, Victoria, even to today. Over time, they have undergone multiple name changes, and are now called Observator Instruments.

While the BWD 216 was released around 1974, it includes five valves as well as numerous transistors and a couple of ICs. Why use valves in a relatively recent design? The main reason is that at the time, high-voltage, high-power semiconductor devices were not really available. Valves fit the bill just fine.

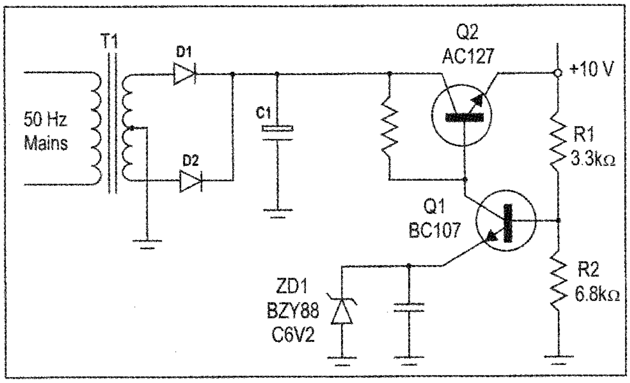
The 216A has two regulated outputs. One output can be varied over the range of 0-400V and supplies up to 200mA with an adjustable current limit, while the other delivers 0-250V at up to 50mA.

The two outputs are separate and floating, so they can be biased up to ±500V DC from Earth and can be "stacked" if necessary, eg, to give split rails.

Both outputs have an impressive regulation to 0.002%+3mV for a 10% line (ie, mains) variation over 100% of the load range. Ripple and noise is specified as <20mV peak-to-peak, 1mV RMS for the 400V output and <10mV peak-to-peak, 1mV RMS for the 250V output.

Recovery time for both outputs is <50μs for a 100% load step, to within 100mV. The 400V output can be used as a constant-current source with a setting between 20mA and 200mA while the 250V output has a fixed current limit of around 60mA.

The unit also has two bonus 6.3VAC



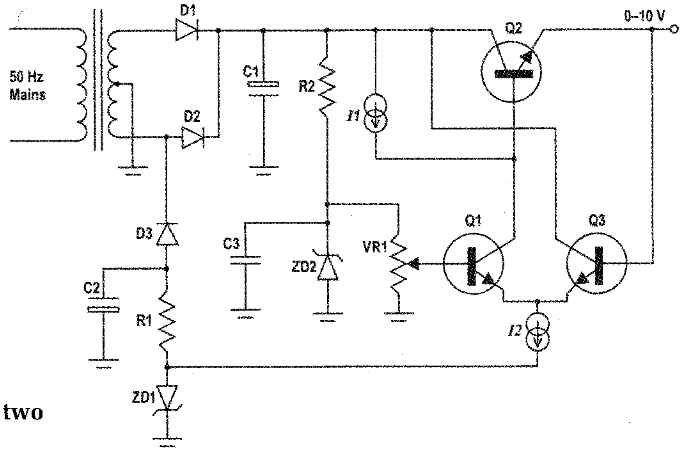


Fig.1 (left): a basic example of a series regulator made with two transistors and a zener diode.

Fig.2 (right): a more complex example of a series regulator, which can be adjusted for a zero output voltage and has improved regulation. It incorporates two constant-current sources (I1/I2) which pass a fixed current regardless of voltage.

outputs each rated at up to 3A.

One of the most impressive aspects of this power supply is that its specifications are still pretty good by today's standards, especially the line and load regulation and ripple/noise figures. And they achieved that almost entirely with discrete parts, many of which would be considered reasonably ho-hum these days.

As this power supply has a fairly involved design, I'm going to start by explaining some of the basic principles of voltage regulation and then expand my description to includes sections of the actual power supply circuit.

BWD 216 versions

The 216 and 216A differ mainly in how they generate the internal supplies to power the differential amplifiers. The 216 used voltage multipliers from 6.3VAC windings to produce the low-voltage comparator supplies while the 216A uses additional, dedicated 30VAC windings.

Series regulation

The 216A uses series regulation, where a variable resistance "pass" element between the mains-derived DC source and the output terminals controls the output voltage.

A negative feedback loop compares the output voltage to the desired voltage and adjusts the resistance of the pass element to maintain the desired output voltage regardless of load variations or current draw.

Practical regulators also sense the load current and increase the resistance of the pass element if an excessive amount of current is being drawn, cutting off the current flow to protect both the load and the regulator from either overload or a short circuit at the output.

By making the overload current limit adjustable, and making the over-current protection part of the linear negative feedback loop, the supply can also be used as a constant-current source.

A basic series regulator can be built with just three semiconductors, as shown in Fig.1: a reference diode (ZD1), pass transistor (Q2) and feedback transistor (Q1). Reference diode ZD1 provides 6.2V at Q1's emitter. Q2's base connects to a voltage divider wired across the output.

Q1 will start conducting when its base voltage reaches around 6.8V (ie, 0.6V above its fixed emitter voltage), which due to the feedback divider of R1 and R2, will happen when the output voltage is around 10V.

If the output voltage rises above 10V, eg, due to a reduction in output loading, this will mean that Q1's base voltage increases, increasing its collector current.

As a result, the voltage at the base of Q2 will drop. Since Q2 is a simple emitter-follower, its emitter voltage (the output voltage) will fall until the circuit re-balances, with the output voltage again around 10V.

Likewise, if the output voltage falls (due to a heavier load), this will lower Q1's base voltage, causing it to conduct less current and allowing the base voltage of Q2 to rise. Q2 will thus deliver more current to the output and bring its voltage back up to 10V.

Of course, such a simple design has limitations, such as the fact that as Q1 and Q2 heat up and cool down, their base-emitter voltages change and so the output voltage will drift. And the output voltage can never be adjusted below 6.8V or else Q1 will never turn on. But it serves as a useful demonstration of the basic principle.

An improved series regulator

The slightly more complex design shown in Fig.2 allows adjustment down to 0V and provides improved regulation.

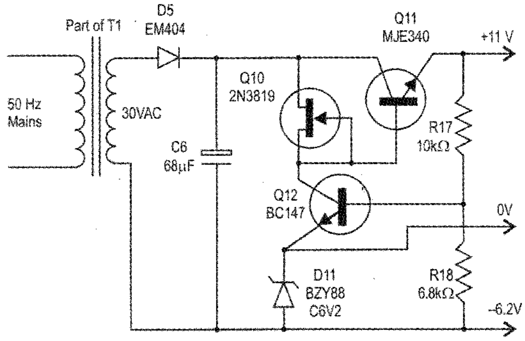
This diagram includes two "current sources", I1 and I2. These represent devices (or sub-circuits) are able to maintain a fixed current flow regardless of the voltage across the device.

Traditionally, Junction Field Effect Transistors (JFET) were used in this role with a zero gate bias. They are depletion mode devices, so an increased gate bias results in reduced channel current. With zero bias, they tend to act as a current source although the exact current varies considerably from device to device.

This means that JFETs used in this role are typically manually selected from a batch, based on the measured current with zero bias.

By the way, you may have seen "current regulation diodes" for sale. These are JFETs which are batch-selected to fall within a particular current range. The gate terminal is internally connected to the source via a resistor, so it is not exposed, resulting in a two-terminal device that looks like a diode.

The pass element is still labelled Q2. It needs a certain maximum base current to give the maximum output current. A resistor was used to supply this in the simpler version (Fig.1) but it will typically have a value less than



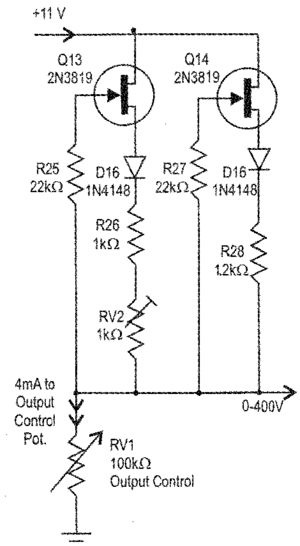


Fig.3 (above): the internal power supply produces the 11V, 0V and -6.2V rails used by the 250V and 400V regulator circuits.
Fig.4 (right): this 11V rail is used to produce a 4mA constant-current source which is varied from 0-400V using RV1, and is then fed to IC1B (Q1-3), shown in Fig.5.

1kΩ. So the voltage gain of Q1 will be low and regulation will be poor.

I1's constant-current characteristic gives it a very high impedance; in theory, it is infinite, though obviously, that is not possible in reality. So Q1's gain is maximised and regulation is improved.

Rather than using a single transistor for negative feedback, in this case, we have two: Q1 and Q3, which form a "long-tailed pair" differential amplifier.

The output voltage is fed back to the base of Q3, the inverting input, while the reference voltage is applied to the base of Q1, the non-inverting input.

This reference voltage is derived from the unfiltered DC supply by zener diode ZD2, via resistor R2 and bypassed by capacitor C3. It is then varied using potentiometer VR1 to provide a voltage between 0V and 10V to the base of Q1, which indicates the desired output voltage.

Because the reference and feedback voltages are applied to two different transistor bases now, the 0.6V base-emitter offset is cancelled out and thus temperature changes resulting in varying base-emitter voltages will not cause output drift.

That is assuming that Q1 and Q3 are kept at the same temperature but their dissipation will be low and they can be mounted in close proximity or even thermally bonded, so that is not difficult to arrange.

This also has the advantage that the reference voltage can be varied using adjustment pot VR1 right down to 0V; and so the output voltage can go down to 0V as well.

However, it then becomes necessary to provide a negative voltage at the emitters of Q1 and Q3 so that they can remain in conduction with a zero base voltage.

These emitters are connected to the second constant-current source, I2, and current flows through it to a negative supply which is regulated by zener diode ZD1.

The negative supply is generated by a separate rectifier/filter from the transformer (D3 and C2); the bias current for zener diode ZD1 is supplied via resistor R1.

Using a current source (I2) to define the current from the emitters of the long-tailed pair transistors also ensures maximum performance of the differential amplifier, giving a high common-mode rejection ratio.

This means that gain (and thus, regulation) is the same for all base-to-base voltage differences regardless of the actual voltage with respect to ground, ie, from maximum output to zero.

For more details on how this type of regulator works, refer to the book "Understanding DC Power Supplies and Oscillators" by Barry Davis.

This basic design shown in Fig.2 was used in the first-generation µA/LM723 regulator IC. Although it was the device of choice for many pieces of solid state equipment, it was limited by being a low-voltage design.

Valves in the output stage

Discrete semiconductor devices had limited voltage ratings at the time the BWD 216A was designed and it would have been impractical to design a 400V regulated supply using readily available semiconductors.

As a result, the 216A uses a combination of valve and solid-state components, ie, it is a hybrid power supply. The valves are used as the pass elements: four 6CA7/EL34s in the 0-400V section and a single 6CW5 in the 0-250V section.

The control circuits use a combination of bipolar junction transistors (BJTs), junction field-effect transistors (JFETs) and silicon integrated circuits in the form of two CA3054 general-purpose dual differential amplifiers (one for the 0-400V section and another for the 0-250V).

Using thermionic valves as the output devices has another advantage which is that they can handle much higher dissipation than a semiconductor device without heatsinking, since they are made from glass and steel, rather than silicon which has a much lower failure temperature. And they are physically large and therefore more effective at radiating all that heat.

Using a valve pass element usually demands that the control circuit can drive the valve's grid voltage from near zero (for maximum output) to cutoff (for minimum output). The triode-connected 6CA7s require up to 90V of negative grid bias for full cut-off.

BWD took the innovative approach of referencing the control circuit positive supply to the regulated output, thus effectively "floating" it with the output voltage. This allows the control circuitry to work at low internal voltages.

The 216A takes a different approach to biasing as well. The control circuit applies a fixed 11V bias to the 6CA7 grids, then uses paralleled transistors to sink current from the valve cathodes. By controlling the equivalent resistance of the cathode-circuit transistors, it controls the output voltage.

The transistors need a maximum voltage rating of some 100V (to provide the -90V bias described above) but it's still the 6CA7 valves that handle the majority of the 600V DC unregulated supply, dropping this to the required output voltage.

0V output at the full rated 200mA load current (the worst case for dissipation) results in around 120W loss in the pass circuitry. As four valves are connected in parallel, each will dissipate up to 30W, just within the 6CA7's specified dissipation limit of 33W.

Circuit description

A complete service manual for the BWD 216A is available from Kevin Chant's excellent website, at siliconchip.com.au/link/aalx

This includes diagrams showing the circuit for each output separately, as well as a hand-drawn (and barely legible) complete circuit at the end.

Be aware that the circuit for the 0-400V output (BWD drawing 1204) in this manual, reproduced in Fig.6, has an error; it omits the biasing for the internal current generator at pin 3 of IC1, which connects to resistors R30 and R32. The correct connections are shown in Fig.5. Drawings 1205 and 910 in the service manual are correct.

The following is a somewhat simplified description of the circuit.

Mains transformer T1 has a split primary winding, allowing for 110VAC (85-137V) or 230/240VAC (185-260V) operation.

It also has eight secondaries: a 440VAC winding for the 0-400V DC regulator; a 290VAC winding for the 0-250V DC regulator; two separate 6.3VAC heater windings for the 0-400V regulator valves and the 250V regulator valve; two 30VAC windings for the solid-state sections of the two regulators; and two 6.3VAC windings brought out to the front panel to power external loads.

Let's start by looking at the two internal low-voltage power supplies for the solid state control circuitry. They are virtually identical, with one used for the 400V output and one for the 250V output. This portion of the circuit is shown in Fig.3.

The 30VAC from the transformer secondary is half-wave rectified by diode D5 and filtered by 68μF capacitor C6. The resulting pulsating DC is then regulated by a conventional and delightfully simple low-voltage regulator using transistors Q10-Q12, with zener diode D11 acting as the local reference voltage.

Q11, the NPN pass transistor, is controlled by NPN transistor Q12. 6.2V zener diode D11 is connected to Q12's emitter while a sample of the output voltage is applied to its base, after having been divided by a factor of 2.47 due to resistors R17/R18. JFET Q10 (selected for a suitable IDSS [drain-source current]) forms the constant-current collector load for Q12.

This supply's overall output is around 17V DC but it is referenced to the 0-400V output which is connected to the cathode of zener diode D11 (labelled "0V"). So the output at the emitter of Q11 sits at around +11V relative to the output voltage. This is used as the positive supply for the two differential amplifiers within IC1 and is also the source of the fixed +11V grid bias for valves V1-V4.

The -6.2V which appears at the anode of D11 (relative to the output voltage) is used as the negative supply for the long-tailed pair connections of these two differential amplifiers (IC1A/B), and in the current-sensing circuitry.

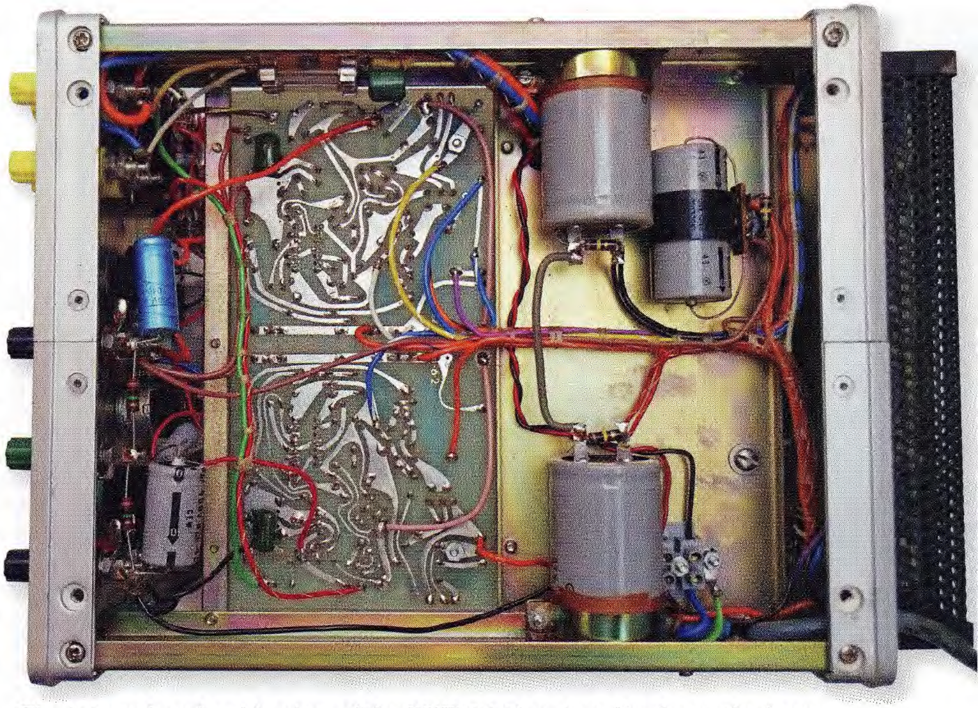
The +11V supply is also fed to 2N3819 JFETs Q13 and Q14 as shown in Fig.4, which combine to form a 4mA constant-current source, which is trimmed using trimpot RV2.

This current is fed to 100kΩ wirewound potentiometer RV1 and so a voltage of between 0-400V appears at the top end of RV1, depending on its rotation.

The two FETs are wired in parallel to provide this reference current and each has source biasing, which gives a more stable current.

That's important since any instability in this reference current will be amplified and will cause variations in the output voltage.

Since RV1 is wired as a rheostat, it dissipates a maximum of 1.6W when the output is set to 400V. A wirewound pot can easily cope with this sort of dissipation on a continuous basis.



The internal underside view of the BWD 216A primarily shows the large capacitors and a few resistors.

The two differential amplifiers

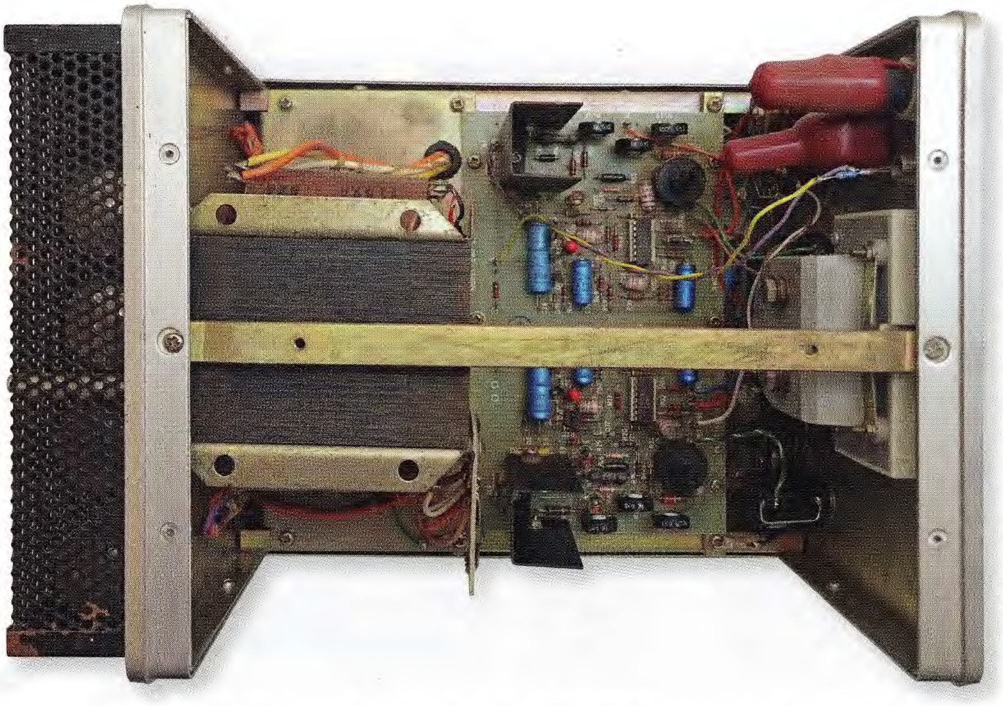
Both differential amplifiers (IC1A & IC1B) are contained within a single CA3054 IC.

This IC includes two balanced transistor pairs, along with transistors which operate as constant-current sinks for the common emitter connections. Each amplifier has an operating frequency range extending to 120MHz and gives a voltage gains of up to 40 times.

The 0-400V reference from RV1 is fed to pin 13 of IC1B, while the supply's output voltage is applied to pin 2, in both cases via 2.2kΩ resistors. This provides the negative feedback to adjust the cathode current of V1-V4, via transistors Q7-Q9, controlling the output voltage as described above.

Keep in mind that all of this circuitry is operating anywhere from 0-400V DC above ground, depending on the output voltage. This is the clever part of the design; the control circuitry is bootstrapped against the 0-400V supply, allowing it to operate at low voltages while controlling a high-voltage output.

To make the following description easier to understand, I have re-drawn part of the 0-400V regulator circuit in



The internal top view of the 216A shows the large power transformer at left, with the main PCB populated the two differential amplifier ICs, which were manufactured by AWA, along with other discrete components.

Fig.5: a simplified circuit of the 0-400V regulator portion of the BWD 216A. Some components have been left out of this circuit for clarity, including the 470pF capacitor and 6.8kΩ resistor wired in series between pins 1 & 2 of IC1B.

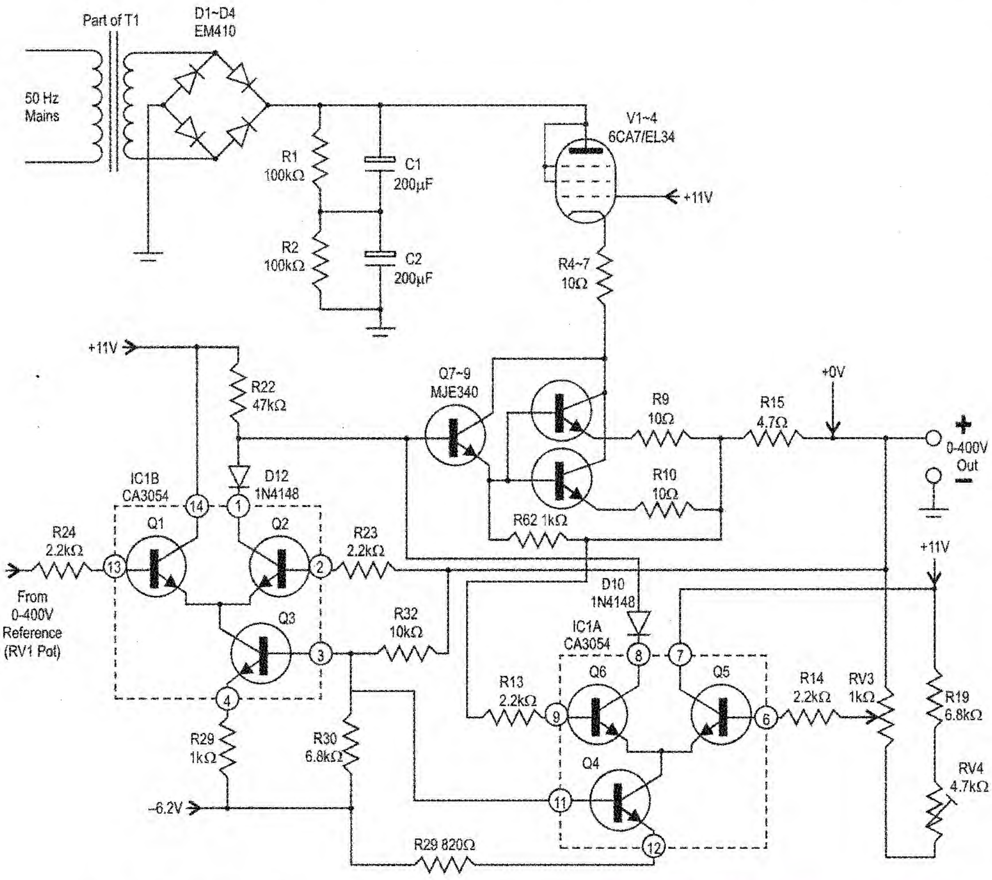


Fig.5, with the internal transistors in the CA3054 ICs shown, so you can see exactly how the circuit works. Note that I have simplified this somewhat, omitting some components which are not critical to understanding how it works.

While differential amplifier IC1B is used to control the output voltage as described above, IC1A provides the adjustable current limit. Since the maximum current setting is equal to the supply's maximum current rating, this also protects the supply against overload.

A compensation network comprising a 470pF capacitor and a 6.8kΩ resistor wired in series is connected between output pin 1 and inverting input pin 2 of IC1B, to stabilise the feedback loop and prevent oscillation (not shown in Fig.5).

The error amplifier's output current at pin 1 passes through diode D12, to the base of NPN transistor Q9, which controls the output stage. 47kΩ resistor R22 provides the current to drive Q7-Q9 and the current flowing through D12 and into pin 1 of IC1B is subtracted from the current flowing into the base of Q9.

This arrangement gives high current gain, and (importantly for any amplifier circuit) presents a high input impedance, giving excellent regulation accuracy.

IC1A works similarly to IC1B but instead of amplifying the difference between the output voltage and the desired voltage, its pin 9 inverting input connects to one end of R15, a 4.7Ω 0.5W wire-wound resistor which is used as a shunt, to measure the output current. As the current increases, so does the voltage across this resistor.

Its non-inverting input connects to the wiper of potentiometer RV3 which is connected to the opposite end of R15 and to the +11V supply rail via some padding resistor, including trimmer RV4.

Thus, RV3 allows the user to control how much current flows through R15 before output pin 8 of IC1A goes low, forwarding-biasing diode D10 and reducing the output voltage. This will then (normally) reduce the output current and the circuit will stabilise at a particular current level, as set using RV3.

With RV3 at the top of its travel, IC1A's input pin 6 receives the full

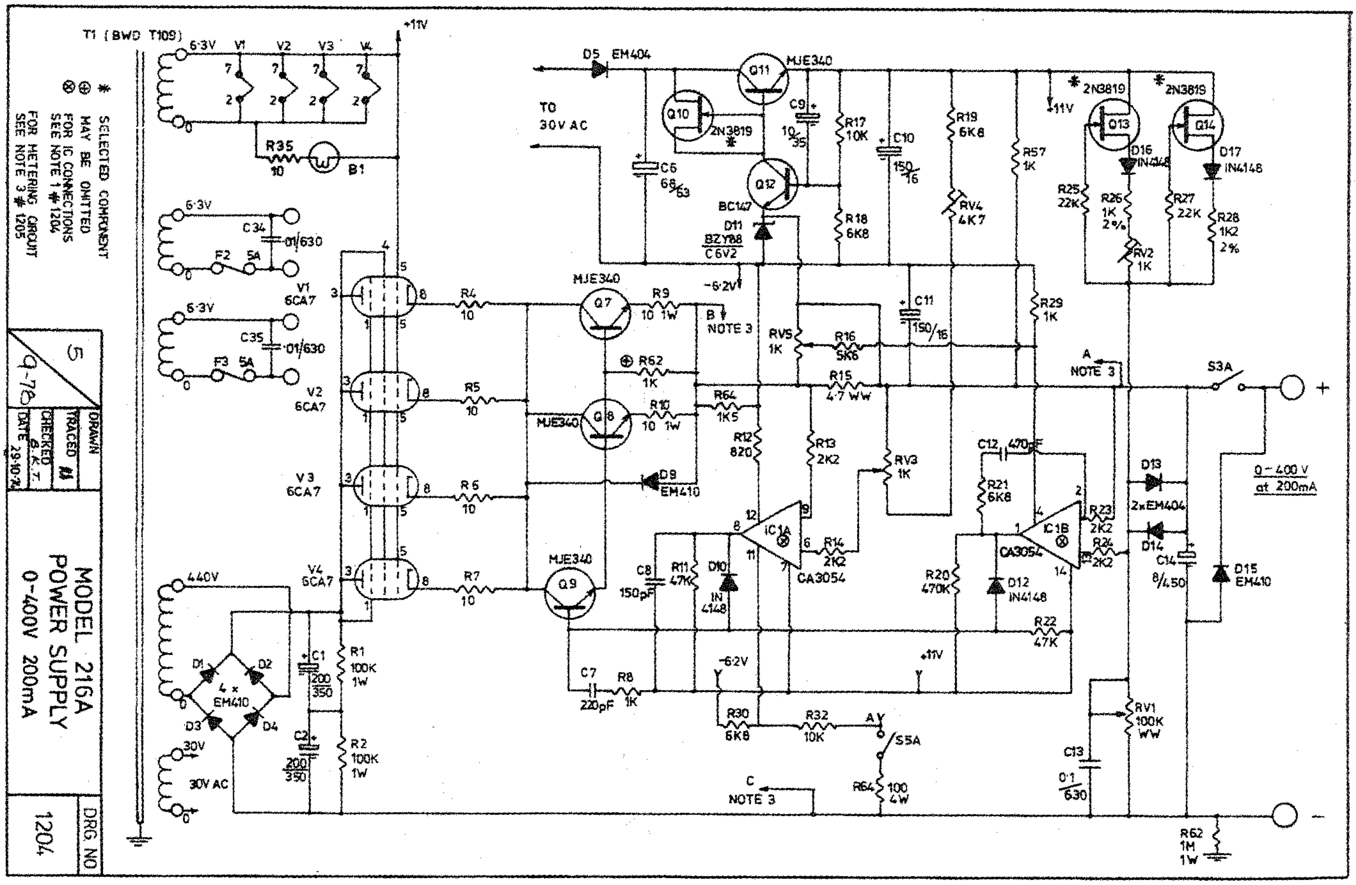
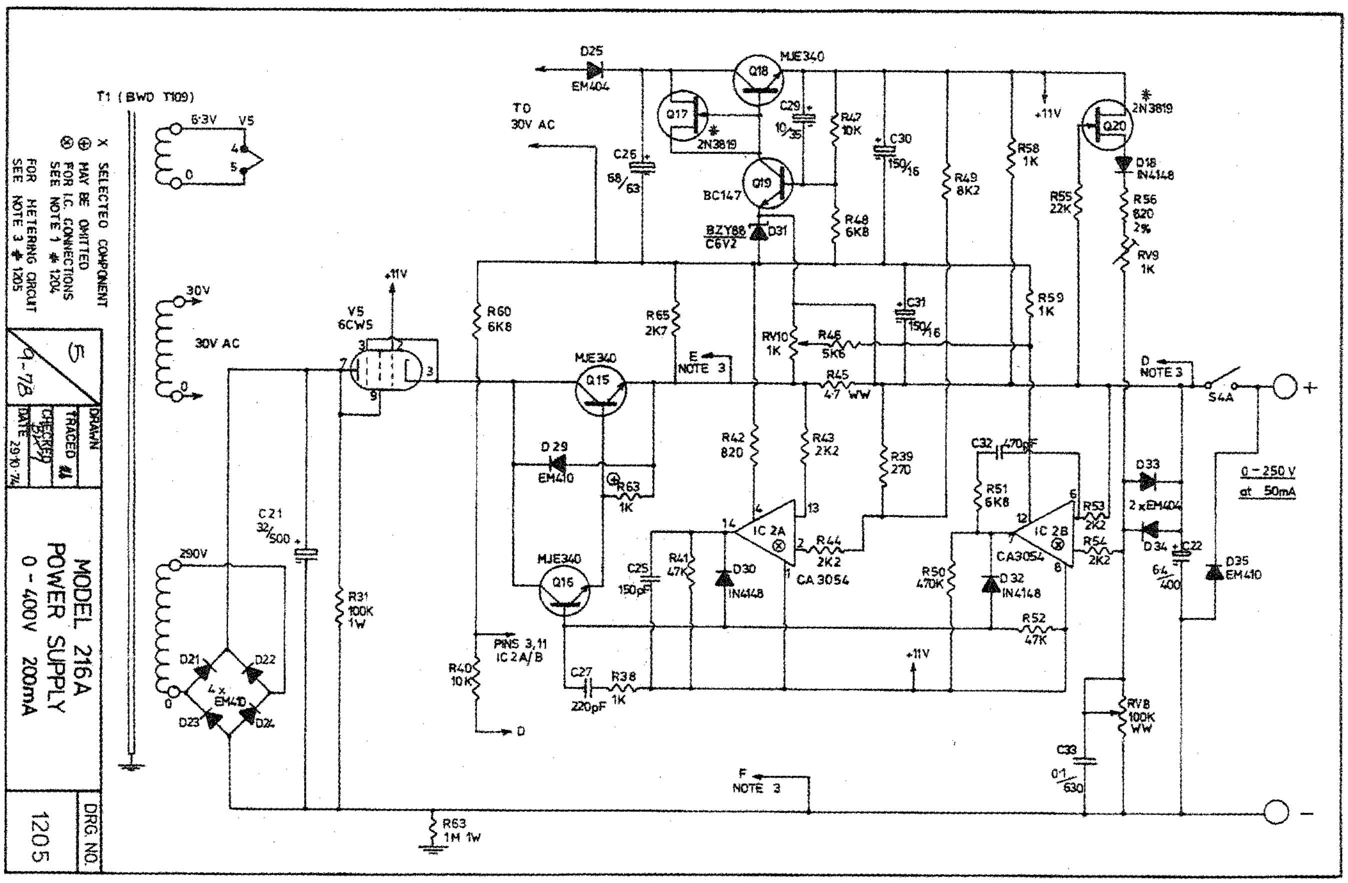


Fig.6 (above): the 0-400V 200mA regulator section of the BWD 216A power supply, reproduced from the service manual.

Fig.7 (below): the separate 0-250V 50mA regulator section of the power supply.



voltage drop across R15 while at the other end of RV3's travel, this input receives a smaller proportion of R15's voltage drop.

An output current of 20mA will create a drop across R15 of some 100mV. With RV3 set to the top end of its travel (minimum current limit on the front panel), this will put IC1A's internal transistor Q6 into conduction, drawing current through D10 and R22, overcoming Q2's voltage control function and reducing the forward bias on transistors Q7-Q9.

As IC1A becomes active, the entire supply can no longer give a constant output voltage, but becomes a constant-current supply instead. At the other end of RV3's travel, the output will deliver its full rated 200mA, assuming trimpot RV4 is correctly adjusted to give the correct voltage at pin 6 of IC1A.

So diodes D10 and D12 allow IC1A and IC1B to independently lower the output voltage when either the voltage or current is above the set-point, without having to "fight" each other. In other words, they form a "wired-or" type network.

Adjustable transient response

A change in the output voltage (when operating in constant-voltage mode) or load current (when operating in constant-current mode) will put the circuit out of balance and its overall negative feedback will cause it to rebalance and return the output to the desired value.

How quickly this happens is a measure of the circuit's transient response. The 0-400V section includes an adjustable positive feedback network (see manufacturer's notes) that allows trimming of the output's dynamic response (via trimpot RV5, not shown on Fig.5) to be optimal.

Generally, you want the output to "undershoot" rather than "overshoot" but it should undershoot by as little as possible to give a fast transient response.

High-voltage source and pass circuitry

The output of the 440VAC secondary from the transformer is fed to a bridge rectifier formed by diodes D1-D4, charging the 200µF 350V filter capacitors C1 and C2 up to around 600V DC. Note that since these capacitors are in series, they effectively form a 100µF 700V capacitor.

It is parallelled by 100kΩ bleed resistors R1/R2 which help to compensate for any difference in leakage currents which may occur in C1 and C2. Without R1/R2, this could cause the capacitors to charge unevenly and one could be charged above its 350V rating.

The resulting 600V DC is applied to the anodes of the four parallelled triode-connected 6CA7/ EL34s (V1-V4). The 6AS7/6080 twin triode often used in power supplies is limited to 250V DC but the 800V DC rating of the 6CA7 valves makes them an ideal choice here.

Cathode resistors R4-R7 compensate for differences in the valve characteristics, so they share the load more or less evenly. The cathode control circuit contains paralleled transistors Q7/Q8. These are in turn controlled by emitter-follower transistor Q9, which forms a Darlington Pair with Q7/Q8.

Although the transistors are in series with the valves, their primary purpose is to control valve cathode current rather than act as primary pass elements.

Essentially, the valves amplify the voltage across the transistors, "shielding" them from the high voltage difference which would otherwise cause breakdown and destruction.

Working on this unit

If you've just powered down one of these supplies and want to work on it, you will have to be careful with the charge on the two 200µF 350V filter capacitors for the 0-400V regulator and the 32µF 500V filter capacitor for the 0-250V regulator.

These can retain a substantial charge for several minutes after switch-off and could give a lethal shock if not fully discharged before working on the circuit.

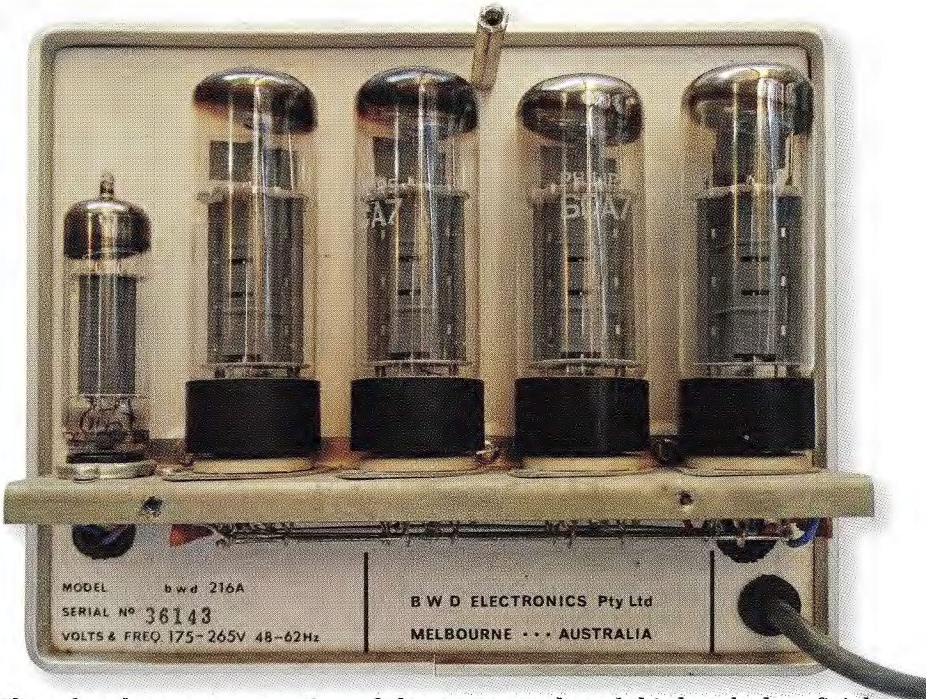
Discharging high-voltage capacitors with a screwdriver looks pretty impressive. Hopefully, if you do this, you'll escape injury from flying vaporised metal. But I recommend against it. Such actions cause massive current spikes and it's quite possible that this will destroy solid-state components.

If you can't be bothered to wait a few minutes to let the parallel resistors discharge these capacitors, try connecting a 4.7kΩ 5W resistor across them.

Chassis layout and clean-up

The major components are mounted on the chassis, with the five valves (four 6CA7/EL34s and one 6CW5/EL86) inside a protective cover at the rear. Smaller components are mounted on a printed circuit board, with the 0-400V DC section on the left and the 0-250V DC section on the right.

I acquired three of these supplies at



The valves have a warmup time of about 15 seconds and this has the beneficial side effect of preventing switch-on surges if a load is connected.

BWD a short history

1960~1980 was a Golden Age for Australian manufacturing and electronics was no exception. Back then, we designed and made test equipment that was the equal of even world-leading manufacturers such as Tektronix and Hewlett-Packard.

Our best-known local hero was BWD who supplied bench, laboratory and storage oscilloscopes, a large-screen (17-inch) oscilloscope, function/sweep/signal generators and power supplies among other devices.

Founded in 1955 by John Beesley, Peter Wingate and Bob Dewey, they first occupied premises in Auburn, Melbourne near the Geebung hotel. Friday afternoons down the pub would have given a foretaste of California's Silicon Valley a decade or so later. The company prospered, moving to 333 Burke Road, Glen Iris and ultimately to Mulgrave.

BWD was eventually purchased by McVan Instruments, which continues business in Mulgrave.

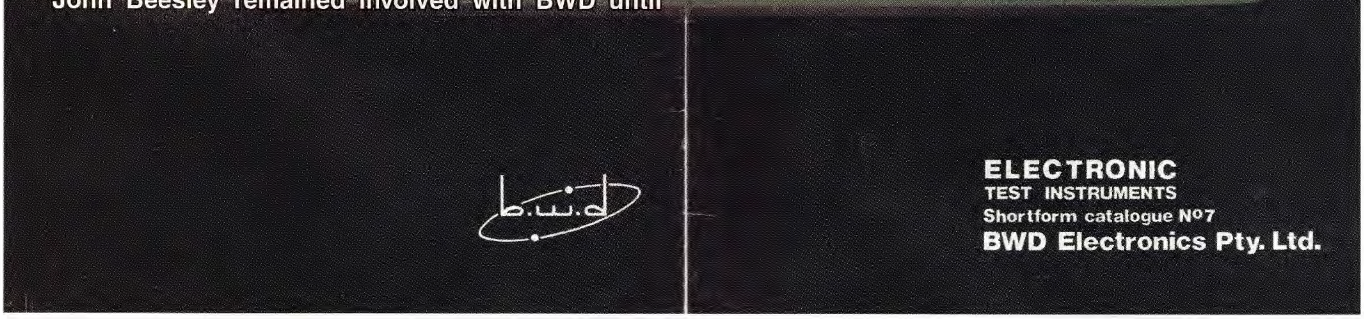
John Beesley remained involved with BWD until 1989 when he went to work for Cochlear, inventors of the Bionic Ear.

The 216's Instrument Handbook lists sixty-four parts suppliers, all either entirely local or local distributors of overseas products. Oh, for the glory days of Aussie manufacturing!

BWD gear satisfied educational, service department, research and scientific consumers. Sound design, reliability and ease of use made equipment such as the 216 popular and sought after.

While some designs were intricate, BWD's local presence made service data easy to acquire and repairs could be made quickly and easily.

The 216 was apparently a very successful design. The set described here has a serial number of 35,109 and the final version of the service manual (Issue 5) applies to units with serial numbers over 40,000, so at least that many were made.



a giveaway at a local TAFE last century. They were ex-lab equipment and two were in good cosmetic condition but the third was missing some bits. It had obviously been Christmas-tree'd for parts.

I picked the best one and gave it a good clean-up. I then tested it. I couldn't get an output of more than about 150V DC from the 0-400V supply. This suggested that one of the reference JFETs (Q13 or Q14) was dead, preventing the full 400V from appearing across voltage adjustment pot RV1. I replaced both, restoring the 400V output to its full adjustment range.

The 250V output tested OK. All five valves checked out 100%, so I used one of BWD's test sheets (still in the handbook) to check the other functions of the supply. Some calibrations were a bit off but were easily brought back to spec.

The only special components are the two CA3054 ICs (available online) and the meter, so any other faults can be fixed pretty easily.

Note that there is a potential problem with this design. If the 100kΩ output control pot (RV1) goes open circuit, the current source will drag the reference voltage up towards 600V. This will greatly exceed C14's voltage rating and it could explode. If you are using a BWD 216 power supply and the 400V output voltage suddenly skyrockets, turn it off at once.

Replacement wirewound pots are available online from overseas. Be sure to get a type with a power rating of at least 2W. I've added 400V zener chains across RV1 in my 216s so that if the pot does go open, I'll just get an uncontrollable 400V output as a warning, and hopefully no explosions. A crowbar circuit would be an even more elegant protection mechanism.

Conclusion

This is a great piece of test gear. Like many of BWD's offerings, it's an example of local Aussie design that compares favourably to the best imports in its price range.

Applying a full load of 200mA to the 400V supply dropped the output by only 7mV, a reduction of 0.0017%. The valve pass elements do mean there's an initial warmup delay of some 15 seconds for full operation but that's hardly unreasonable.

The two independent supplies provide lots of options. Some of my favourite vintage aircraft radio and television gear requires a +400V HT supply but also demands a -150V bias supply and the 216A can easily supply both.

If you see one of these in fair condition, I suggest you snap it up. The most common fault is an open Output Control pot and a subsequently exploded electrolytic filter capacitor across the output terminals (C14).

These faults are easily fixed, and you'll have a high-performing, reliable power supply that'll power all things "valve" from hearing aids up to medium-sized valve TVs and most military radios.

Watch out, though, for a meter with a detached pointer – the aluminium used appears to oxidise with age and fall off. SC