In Practice

High voltage power supplies, part 2 – still alive

AND THERE'S MORE. As there are so many related topics to be covered, this article has expanded into a trilogy. Consider this the 'bridging episode', which moves the plot forward but still leaves more to tell.

To understand all the circuit references in this article, you will need Figure 1 from last month's column **[1]**. To avoid confusion, this month's circuit diagram is numbered **Figure 2**.

TRANSFORMERS AND RECTIFIERS. As explained last month, many amateur HV power supplies have quite poor voltage regulation because we optimistically choose transformers that aren't big enough. More specifically, they have too high a primary and/or secondary resistance. A full wave bridge rectifier (**Figure 2a**) gives good voltage regulation with quite a wide range of winding resistances, so it normally the best choice for use with a surplus transformer. Full wave rectification using a centre tapped secondary (**Figure 2b**) will also give good regulation, although high voltage transformers of this type are less common because they require twice as many secondary turns.

The rectifier circuits in Figures 2a and 2b are called 'full wave' because they re-charge the reservoir capacitor with a pulse of current on every half cycle. In contrast, the voltage doubler circuit (**Figure 2c**) divides the reservoir capacitor into two separate halves that are only re-charged on alternate half cycles. The output voltage regulation can never be as good as a full wave circuit because the capacitors in Figure 2c are being left to discharge for about twice as long between top-up pulses. When those pulses of current do arrive, they will need to be larger, which makes this voltage doubler circuit very sensitive to the winding resistance of the transformer. The voltage regulation of a doubler circuit can be perfectly adequate for amplifier applications, but it can only be achieved using transformers that have been purpose-designed with very low primary and secondary resistances. Transformers that have not been specifically designed for voltage doubling will almost certainly give poor regulation at high currents. A session with the PSU Designer program **[1]** can save you much disappointment and rebuilding work.

The peak inverse voltage on the diode rectifiers shown in Figures 2a and 2c is 2.8 times the AC secondary voltage of the transformer (in Figure 2b it is 2.8 times the AC voltage on one side of the centre tap). In practice, the PIV needs to be very much higher, to handle the spikes or surges of voltage that frequently appear on our '230V' AC mains. Silicon diode rectifiers are only commonly available with PIV ratings up to 1000V, so practical high-voltage rectifiers are built up from strings of several diodes in series. Modern rectifier diodes do not need parallel resistors or capacitors, which may actually do more harm than good (see *In Practice* January and October 1997 for more information). You should simply use a large number of well matched diodes in series. The number of diodes required will depend on the output voltage of your power supply, and a typical recommendation for medium-sized amateur amplifiers is ten 1000V PIV diodes per leg of the rectifier. The diode most often recommended is the 1N5408, which is rated at 1000V PIV and 3A RMS forward current. Being an industry-wide favourite, the 1N5408 is also excellent value. If you buy all the diodes on a single bandolier, exactly as they came from the factory, the matching will be good enough. As with all power semiconductors, it is important to keep rectifiers as cool as possible, so mount them clear of the circuit board to allow free air circulation.

RESERVOIR CAPACITOR. Referring to last month's Figure 1, the reservoir or smoothing capacitor C1 needs to be rated for the maximum off-load voltage of the PSU, plus an allowance for unusually high mains voltages, plus a further safety margin of at least 10 – 20%. The total capacitance needs to be sufficient to reduce the AC ripple on the output voltage to a few percent, to avoid 100Hz AM sidebands on the transmitted signal. But a very high capacitance is not necessarily better, because it increases the amount of stored energy that could be dumped into the valve and other components in the event of a fault (which I'll deal with in part 3). A happy medium is about 30μF, and this will usually have to be made up from a bank of several lower-voltage electrolytic capacitors in series. Suitable capacitors will have a voltage rating of 400 – 450V DC, so your HV PSU will typically need 8 – 10 units in series (remembering that a voltage doubler requires an even number to create a centre tap). To make about 30μF from the series string, the individual capacitors will probably need to be 220 or 330μF. Thanks to the popularity of switch-mode mains power supplies, these capacitors are more readily available, smaller and better than ever before [1].

Electrolytic capacitors have a finite service life so always buy new stock, in a single batch for good matching of all their characteristics. Before you buy, always check the RMS ripple current rating. Reservoir capacitors experience internal heating due to the AC ripple current passing through them. This current occurs in large pulses whose RMS value can be much higher than the smoothed DC output current. There are rules of thumb for estimating ripple current, but the PSU Designer program [1] will give you a much more accurate value. The voltage and ripple current ratings for standard 'commercial grade' electrolytics are quoted at 85°C, while 'high reliability' capacitors are rated at 105°C. The increased reliability is obtained partly through the manufacturing process but also by decreasing the ripple current rating. A 105°C capacitor will have a lower ripple current rating than the corresponding 85°C component, and will probably be larger and more expensive. With so many different factors in the balance, it is very difficult to generalise about the best overall value for money. However, *all* electrolytic capacitors will give a much longer lifetime of reliable service if they are kept cool. A good way to assemble a high voltage array of electrolytics is to fix them between two end plates of rigid plastic or Tufnol, secured with strong adhesive. Each aluminium can must be spaced a few millimetres away from its neighbours, both for insulation and to allow free circulation of air between them. If the whole assembly is mounted in a current of cool incoming air, the capacitors will last a very long time.

> "Do not touch any parts that have been at high voltage until you have first used a shorting stick to make absolutely sure they are safe."

The 47kΩ resistors connected in parallel with the electrolytic capacitors serve two purposes. One is to equalise the voltage across each capacitor in the stack, and the other is to provide a 'bleed' resistance which is *essential* to discharge the capacitors after the power supply is switched off. Both of these purposes require a fairly low resistance (not exceeding 100kΩ per capacitor), a high voltage rating and high reliability. The amplifier will spend most of its working life in the standby condition, where the voltage across the capacitors and resistors is at its highest, so the resistors need to be chosen accordingly. I strongly recommend using 3W or 7W metal film resistors for this application [1]. The 3W resistors are limited to a maximum of 350V, which means that 100kΩ is the only suitable value. With the 7W resistors you could use 47kΩ, which would give better voltage equalisation and a faster discharge when the mains is switched off (see below). A string of 8 – 10 equalising resistors will dissipate a considerable amount of heat, so they must be located *above* the electrolytic capacitors and provided with good ventilation.

This raises a general point about HV PSUs: many of the components generate a lot of heat, but for reliability they must all be kept as cool as possible. Therefore a HV PSU will always need good ventilation. But passive ventilation will not be enough to clear away pockets of stagnant hot air, and you must not leave openings that expose live components inside **[2]**. The answer is to use a large, low-speed computer fan to provide efficient cross-flow ventilation from one side of the cabinet to the other. Before you begin construction, take time to plan the overall layout of the PSU. For maximum effect with minimum noise, the fan should *blow* cool air into the cabinet, passing first over the most heat-sensitive components such as the electrolytic capacitors, and passing last over the largest and hottest components such as the transformer. The fan will prevent accidental access to live components on the inlet side (fit a finger guard, of course) and the transformer can often provide a safe access barrier behind the ventilation outlet.

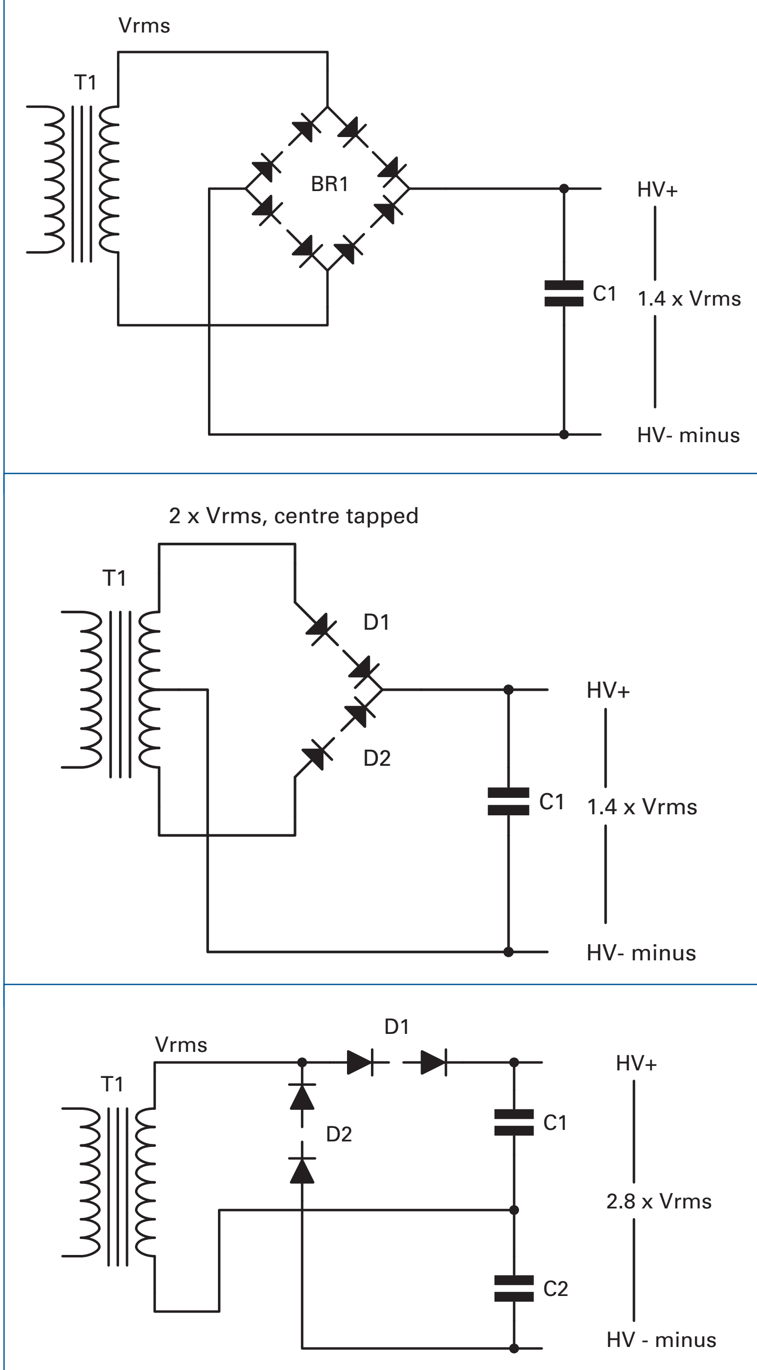

FIGURE 2: (a) Full wave bridge rectifier, (b) Full wave centre-tapped, (c) Voltage doubler.

DISCHARGE TIME. A 220µF or 330µF capacitor in parallel with a 47kΩ or 100kΩ resistor will have an RC time constant in the range of 10 – 30 seconds. That means the PSU will remain dangerous for *several minutes* after it has been switched off, until the capacitor stack has completely discharged. Safeguards against this hazard can take several different forms, and for 'Defence in Depth' you need barriers of several different kinds. The simplest (and not to be sneered at) is to buy time by ensuring that a large number of screws must be removed to gain access inside the cabinet. Because some things can only be done with the PSU outside of its cabinet, fit some internal covers to prevent accidental contact with HV while you're mind is distracted.

Another important safeguard is to build a voltmeter permanently into the PSU, as indicated in Figure 1 last month, so you can watch how slowly the HV comes down. A suitable string of high-voltage resistors will look very much like the string of equalising resistors for the electrolytic capacitors discussed above. You'll find more information about safely measuring high voltages in the April 1994 and October 2005 columns.

Yet another safety option is to fit an additional bleeder resistor across the HV supply to discharge the capacitors more quickly. This also helps with voltage regulation by preventing the output voltage from soaring towards the peak value of the AC secondary voltage when off load. The disadvantage is such a resistor will be large and expensive, and all the time the HV is switched on it will be wasting a considerable amount of heat. For example, a 100kΩ bleed resistor could discharge a 30µF capacitor to safe levels within about 15 seconds; but at 3000V it would be dissipating 90W continuously. For reliability a bleed resistor should be operated well below its maximum power rating, so you'd be looking for a 100kΩ 200W resistor; a very substantial component [1].

Your final safety barrier should always be a 'shorting stick'. This is a heavily insulated lead with a large crocodile clip attached to the chassis at one end, end the other end fixed to an insulated handle so it can be touched onto live components from a safe distance. *Do not touch any parts that have been at high voltage until you have first used a shorting stick to make absolutely sure they're safe.* This is an unbreakable operating rule of HV engineering – and after the first fat spark from somewhere you had firmly believed to be 'dead', you will understand why!

NOTES AND REFERENCES

[1] For more information, follow this month's links from the 'In Practice' website.