Stabilized Power Supplies Part 1

The basic theory of PSU design and how to prevent potential problems.

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Power supplies often seem to be the poor relations of the electronics scene when it comes to design, un unconsidered trifle to do the job of pumping primary power into your pet project, to be alliterative. One of my acquaintances, not so long ago, built himself an amplifier system with loving care and no expense spared. When he came to use it, it proved to be unstable.

He had obeyed all the rules about ground loops, shielding and all the rest, but he hadn't paid too much attention to his power supply. What problem could there be about that? — transformer, rectifier and a hefty great electrolytic capacitor — oh yes, and a bit of stabilization thrown in.

Easiest part of the project. Well, yes, but it was also the easiest part of the project to cause trouble, which in his case it did. In fact, the bit of stabilization he had thrown in proved to be his downfall. When his amplifier was supplied from a well designed, good quality power unit, it performed as it should.

The moral of this is that a power supply should never be dismissed as something a lot less important than the equipment it supplies. This applies particularly to those among us who dabble and experiment all the time with a variety of circuits and setups; the unit which supplies our power must be above reproach. When something isn't doing what it should, we want to make sure that the power supply is out of the running when we look for the cause.

This short series will introduce a few practical stabilized power unit projects which are reasonably simple to build and have good specifications. To get on our way, we begin this month with some of the elementary theory of stabilized supplies and the problems to be looked for (and avoided) in practical designs.

Types of Supply

Battery supplies and the basic transformer-rectifier-smoothing systems are not our concern here. We shall be interested in those circuits which can be classified under the two main headings of constant-voltage (C-V) and constant-current (C-C) supplies.

A particular power supply may be exclusively designed to operate in one or other of these categories, most commonly the former, but a design is possible in which both modes may be incorporated in a single unit. We begin by looking at the characteristics and evolution of both these systems.

Constant-Voltage Supplies

An ideal voltage supply is defined as an electrical source for which the output voltage remains absolutely constant irrespective of the current being drawn from it. This statement, of course, applies only to the maximum current capacity of which the supply is capable, No source can supply an unlimited current, but within the limit for which it is designed, a constant voltage supply will maintain a constant voltage output independent of the imposed load impedance.

A fully charged car battery is a close approximation to such an ideal source. A flat battery is anything but. When your car gives a despairing "clunk" on a cold and frosty morning, you will know what I mean.

The necessary condition for a constant voltage output is *zero* internal impedance. Fig. 1 shows us the real situation; here the voltage source is, for convenience, represented as a battery. This battery, like any other, has an internal resistance *r*. This resistance may be extremely small, but it is never zero.

When a load resistance *R* is connected across the battery terminals, the current *I* flows through *r* and *R* in series, hence in a part (*IR* volts) of the available voltage *E* is dropped across the internal resistance. The terminal voltage *V*(=E-Ir) is consequently *less* than *E* and depends entirely upon the current being drawn by the load.

In fact, of course, the full voltage will only be available at the terminals when the "load" is an open-circuit, an infinite resistance. Otherwise, the greater the current drawn, the smaller *V* becomes, hence the output is not independent of the load current and the source is not the ideal constant voltage supply we are (vainly) looking for. But we are well on our way if we can make the internal resistance extremely small.

However, there is a further complication. Any load device connected to a power supply is rarely of such a form that it requires a constant flow of direct current from the supply.

The load is not often made up of purely passive components such as resistors; active components such as diodes and transistors will be present in the load, hence the current drawn from the supply will be made up of an alternating component superimposed on the direct component. So it is not just a cosy matter of the supply having a zero source impedance at DC, it must have a zero source impedance at *all* frequencies in which the load is likely to be operating.

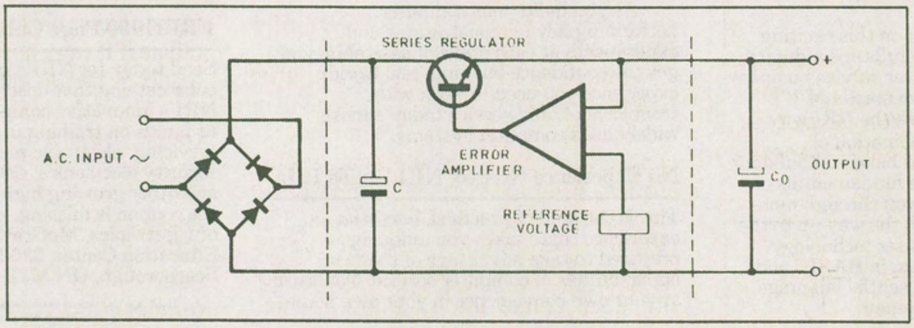

Fig. 3. The basic constant voltage regulated power supply.

Suppose by way of an example we have a 25V DC constant voltage power unit having a negligible source resistance at DC but a five ohm resistance at a frequency of 1kHz. If this supply is connected to a load which draws a steady current of 1A on which is superimposed a 1kHz current having peak excursions of +/-0.1A (see Fig. 2), the power supply will deliver an output which is varying sinusoidally between 24.5V and 25.5V at a 1kHz rate.

Don't confuse this situation with mains "ripple" coming from the power unit. Connecting an additional smoothing capacitor across the output terminals is not necessarily going to improve things, in fact, in some cases it can make things worse.

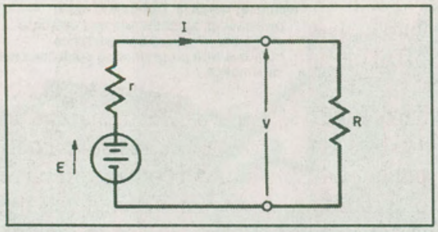

Fig. 1. The circuit conditions for a constant voltage output.

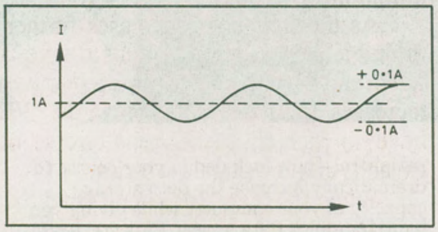

Fig 2. The effects of superimposing a 1kHz current with peak excursions of +/-0.1A on a load that draws a steady 1A.

Additional to the fact that our power supply fails to provide us with a truly constant voltage, there is the possibility that the variation in the output will be coupled into some other load or to some other part of the connected circuitry fed from the supply. This can constitute an undesirable coupling which may result at best in noisy performance from low level amplifier stages or at worst oscillation over the entire system.

Because it is not possible to build a power supply having zero source impedance at all frequencies, all practical designs have to be a compromise between the ideal and whatever the state of the art happens to be at the time. Of course, for amateur experimenters and dabblers in general, many of the sophisticated features of a high quality power unit design are perhaps academic, but it is necessary to be aware of such aspects for all that. Many a frustrating problem can often be traced back to a poorly designed power supply.

Basic Circuit

The basic constant voltage regulated power supply is shown in Fig. 3. If consists of the conventional rectifier (usually a "diode bridge") and a reservoir capacitor *C*, followed by a series regulator transistor controlled by a feedback amplifier, a reference voltage (which may be adjustable) and an output (smoothing) capacitor C0.

The amplifier may be in integrated circuit form or made up from discrete transistors. Whatever its form, it continuously controls the conductance of the series transistor so as to maintain the two amplifier inputs exactly equal; hence the voltage at the output terminals is held equal to the reference voltage.

The amplifier, for this reason, is often known as the *error* amplifier. There are of course a number of practical variations on this setup, but the overall function comes to the same thing.

Suppose for the moment we imagine the circuitry between the broken lines in Fig. 3 to be eliminated, so that we have the most simple power supply of rectifier bridge and filter capacitor C0 alone. The output impedance of the supply will be that of the capacitor.

Since we want the output impedance to be as small as possible, a large value electrolytic is used in this position. This is all right at frequencies between DC and a few thousand hertz, but the impedance of any capacitor (particularly electrolytics) is not capacitive at all frequencies.

At very low frequencies, the impedance of a capacitor is mainly reactive with a bit of resistance and is relatively large, anyway. At high frequencies the impedance is no longer purely capacitive reactance but has associated with it both

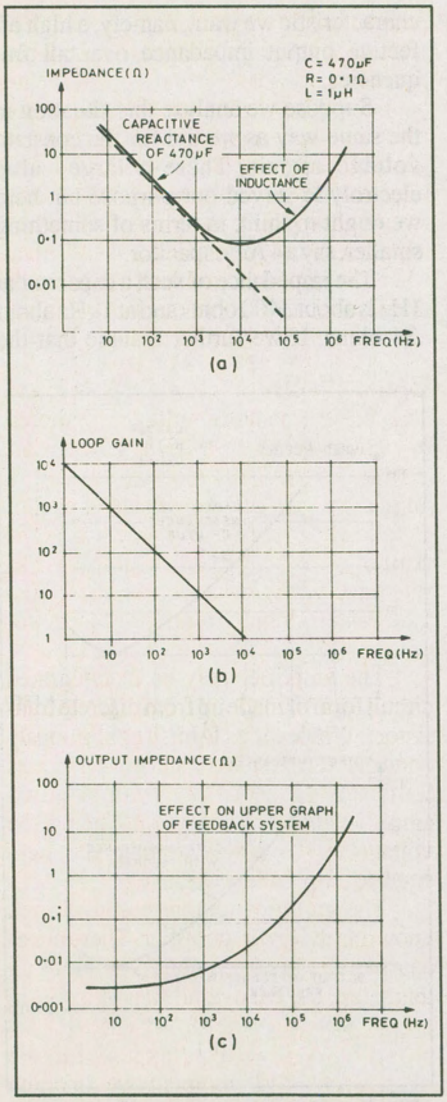

Fig.4.(a) Impedance versus frequency characteristic using a 470u electrolytic capacitor, (b) loop gain and (c) overall output impedance.

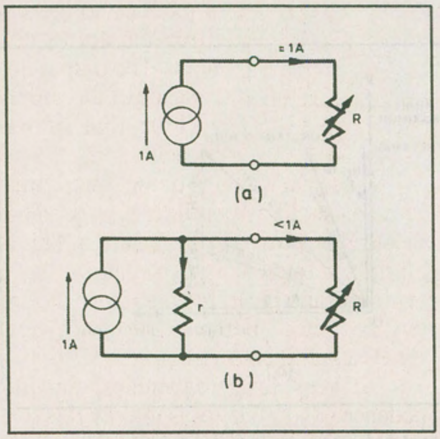

Fig.5. Idealized constant current source and (b) the practical effect of the internal resistance "r" on the output.

resistance and inductance resulting from the finite connecting leads and the constructional form of the component.

For this reason it is common practice to shunt an electrolytic with a small value ceramic capacitor having a negligible inductive reactance at the highest operating frequency. It is not enough just to think about the 100Hz ripple frequency coming from the rectifier.

Impedance Versus Frequency

A typical impedance versus frequency characteristic for a 470uF electrolytic capacitor is shown in Fig. 4(a). We have assumed that this capacitor has a resistance of 0.1 ohm and an inductance of 1uH.

The impedance (almost purely capacitive) at 10Hz is 34 ohms and at 1kHz it is 0.34 ohm. The resistive component of 0.1 ohm becomes effective before this frequency is reached and the curve, which would otherwise follow the broken line, levels out at the impedance minimum of 0.1 ohm.

As the frequency increases further, the inductive component begins to have its effect and the impedance (now inductive) increases from this point onwards. WE have, in effect, a resonant circuit of capacity and inductance in series.

When the regulator circuit is added, its effect is to make the supply output impedance at each frequency *lower* than the impedance of the capacitor alone by a factor equal to one +loop gain of the feedback amplifier at the same frequency. This result comes from feedback theory.

Since the loop gain of the amplifier will be very much greater than one over most of the frequency band of interest, we can treat (one +loop gain) as being simply (loop gain). Hence supposing the amplifier gain to be 10,000 (10/4) at 1Hz falling linearly to unity at 10kHz (10/4Hz) as shown in Fig. 4b, the characteristic of Fig. 4a becomes that of Fig. 4c which shows the resulting *overall* output impedance of the supply.

This is a big improvement over the first graph, particularly for frequencies up to about 5 X 10/4Hz where the impedance remains below 0.1 ohm. At frequencies up to 10/3Hz the amplifier gain is high and the output impedance is correspondingly low, less than 0.01 ohm. At frequencies from 10/3 to about 10/4 the output impedance remains reasonably low because some amplifier gain remains and the impedance of the output capacitor is also low throughout this range.

At those higher frequencies which are beyond the upper bandwidth figure for the amplifier the output impedance is and remains inductive, depending solely on the characteristics of the output capacitor and the effect of the wires connecting it to the actual output terminals. And, of course, anything beyond that. The curves are illustrative only and are not derived from any actual power unit, though they are quite typical of practical systems.

From all this it might seem that by making the gain of the amplifier large enough we could achieve the magical zero output impedance. Alas, this is not so. No amount of gain, however great, will be enough to reduce the output impedance to zero.

But this doesn't mean that a zero impedance is impossible to achieve. It is possible, but only by employing positive feedback; just enough positive feedback, in fact, to cause the feedback amplifier to oscillate if it were not held within a negative feedback loop having overall stability.

This call for sophisticated design procedures which are not easy for the amateur to achieve; and in any case such configurations remain for the most part in a designer's laboratory and rarely have significant practical applications. But it's a thought, perhaps, for those of us who like to dabble in such things.

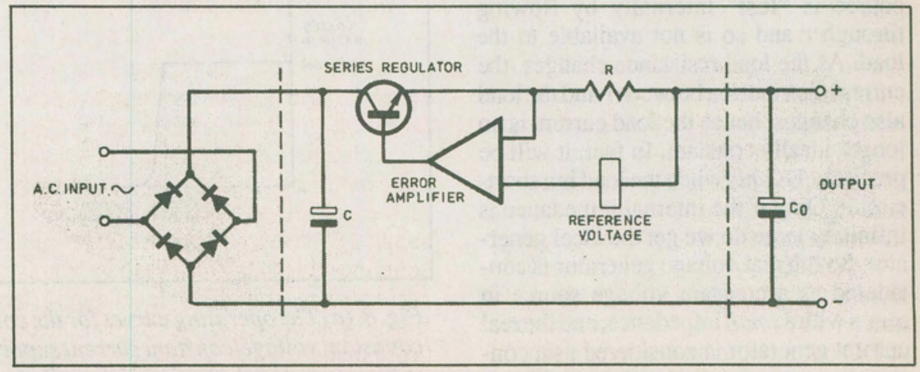

Fig.6. Block diagram for a constant current regulated power supply.

Constant-Current Supplies

An ideal current supply is defined as an electrical source for which the current remains absolutely constant irrespective of the voltage demanded by the load. Such a constant current source is generally required for specialized applications and is not so much in demand as constant voltage.

However, there are applications where constant current is a necessity; it may be that a stable magnetic field is required from an electromagnet. If the coil of the magnet is simply placed across a constant voltage source, the current through the coil will depend upon the resistance of the coil. This could change through ambient temperature variations or as the result of self heating. So the current would change and the magnetic field strength might vary sufficiently to invalidate the circuit tolerances within which it operated. If the current can be held constant irrespective of what the coil resistance or the applied voltage does, the problem does not arise.

We have seen that the ideal voltage source should have a zero output impedance. Because it is possible that the load resistance connected to a constant current supply may vary with time, an ideal current source must have an *infinite* internal impedance at all frequencies.

This concept might be more difficult to understand than it was in the case of a voltage source. Let me illustrate with a simple example. Fig. 5a shows a hypothetical generator that will deliver a current of, say 1A irrespective of whatever value the load resistance *R* takes, including a short-circuit. This is the ideal case. In real life, something is present which prevents this happening. This something is again the internal impedance which we represent this time as a resistance *r* in *parallel* with the perfect generator, see Fig. 5b. In this situation some of the 1A current supplied by the source is "lost" internally by flowing through *r* and so is not available to the load. As the load resistance changes, the current distribution between *r* and the load also changes; hence the load current is no longer ideally constant. In fact, it will be precisely 1A *only* when the load is a short-circuit. Only if the internal impedance is infinitely large do we get the ideal generator. So the real voltage generator is considered as a constant voltage source in series with a *small* impedance, and the real current generator is considered as a constant current source in parallel with a *large* impedance.

Basic Circuit

The block diagram of a constant current regulated power supply is shown in Fig. 6. The bridge rectifier and reservoir capacitor are identical with that of the constant voltage supply, and the other component parts are similar in form also.

However, instead of comparing the reference voltage with the output voltage, the error amplifier compares the reference voltage with the *voltage drop* caused by the output current flowing through a current monitoring resistor *R*. The action of the feedback loop is then similar to that of the constant voltage system; the conductance of the series transistor is varied in such a way that the voltage drop across *R* is maintained equal to the reference voltage, thereby holding the output current to a fixed value.

In a constant current supply, the output impedance without feedback is made up of the output capacitor C0 effectively in parallel with the current monitoring resistor *R*. This assumes that the impedance looking back into the series regulator and the rectifier is small compared with the resistor.

The effect of current derived feedback is then, from feedback theory, to *multiply* the effective value of the monitoring resistance by the loop gain of the amplifier throughout its frequency range, this increased resistance still remaining in parallel with the output capacitance. And at this point we meet another problem. Since the output capacitor behaves as a low impedance, particularly as the frequency increases, a large value electrolytic of the kind conventionally put across the output terminals of a power unit for its so-called smoothing effect is actually working to the detriment of the constant current characteristic we want, namely, a high effective output impedance over all frequencies.

Suppose we analyse this situation in the same way as we did for the constant voltage circuit. There a large value electrolytic served our purpose but here we ought to think in terms of something smaller, say a 47uF capacitor.

The impedance of such a capacitor at 1Hz is about 3400 ohms and at 1kHz about .34 ohms. If we further assume that the

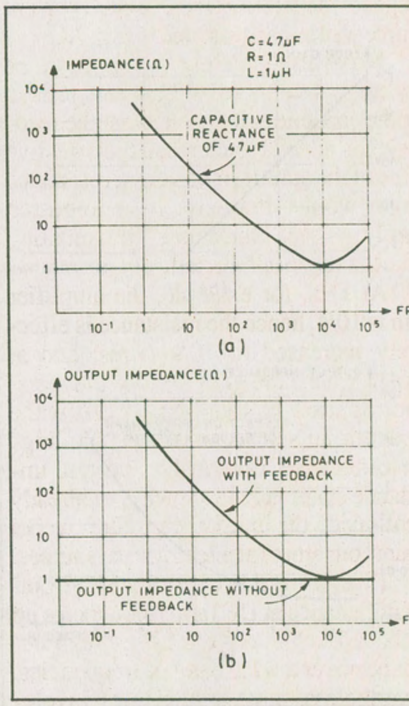

Fig. 7. (a) Impedance versus frequency characteristic of the output circuit using a 47u electrolytic capacitor, and (b) overall output impedance of the constant currrent source with feedback.

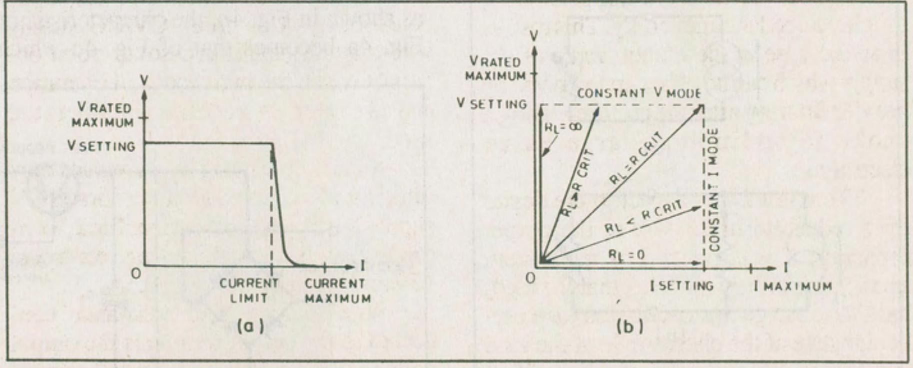

Fig. 8. (a) The operating curves for the constamt voltage supply (CV) and (b) the copnstant voltage/constant current supply (CV/CC). The switchover or limiting point is determined by the setting of the voltage and current controls.

current monitoring resistor is one ohm (a common value), then the impedance versus frequency characteristic of the output circuit will be as shown in Fig. 7a.

While the capacitive reactance is dominant, the impedance falls as the frequency increases, but the inductive component takes over at around 10kHz and causes the impedance to rise again. If we take the gain characteristic of the feedback amplifier to be the same as that mentioned for the constant voltage supply (Fig. 4b), and combine this with Fig. 7a, the overall output impedance of the constant current source will be as illustrated in Fig. 7b.

Now this graph may not appear to be any improvement over the characteristic for the capacitor alone, but what the feedback has done is to increase the effective value of the parallel monitoring resistance which would otherwise have appeared simply as a one ohm shunt. This shunting effect has been eliminated.

At 1Hz, for example, the amplifier gain is 10/4, hence the resistance is effectively increased to 10/4 ohms; and at 100Hz where the gain is 10/2 the resistance appears as 10/2 ohms. So it is the capacitor impedance which is "spoiling" the otherwise favourable output impedance state; the reason why, as already mentioned, the output capacitor works against our aim of an ideal current source.

Thus, while the supply has a high output impedance at DC (and frequencies up to about 1Hz) it does not have a high impedance over a wide band of frequencies. Nevertheless, most applications involving constant current supplies require a high impedance only at DC and are not severely affected by the low impedance at high frequencies.

The problem is sometimes reduced by removing the bulk of the output capacitance from the circuit, so permitting a higher impedance generally. This results in an increase in the output ripple of the supply which can be offset up to a point by heavier filtering after the rectifier, using a choke in addition to large value electrolytics.

There is another aspect to the desire for a reduction in the size of the output capacitor; if it is omitted or made very small, there is the possibility that the feedback loop can go into oscillation for a particular state of the phase angle of the load impedance. This usually shows itself as oscillation at a very low or a very high frequency.

There is not a lot to be gained from an extremely high gain amplifier either. No finite amount of gain will ever cause the output impedance to become infinite. Like its constant voltage counterpart, it *is* possible to provide positive feedback to give an infinite impedance at DC but this is fraught with design problems not recommended for amateur project work.

Current Limiting

It is not desirable that a power supply unit should be able to provide a maximum *instantaneous* current. The reasons for this are: (a) it might be damaging to the series regulator, and (b) it might be sufficient to blow a fuse or trip a circuit breaker on the power supply by suddenly charging a large load capacitance.

Consequently, it is necessary for a power unit to have some sort of current limiting protection circuit which will restrict the maximum output current under any imposed load condition. This protection circuit may have a fixed or an adjustable current setting.

When a supply is being used well below its rated current maximum, it is still possible that although the supply unit itself is in no danger, the load circuit may be unprotected, in so far as the magnitude of the current available, even though limited, is much higher than the normal load requirement. A careless or accidental interconnection with the load circuitry might allow a large current to flow in part of it and cause damage. Consequently, it is necessary to make the current limiting point adjustable rather than fixed so that the current limit can be set to a value which cannot damage the load device even in the event of an inadvertent short-circuit during experimentation or setting-up.

Any constant voltage supply incorporating a current limiter is essentially a unit having a built-in adjustable constant current supply. This situation must not be confused with a "true" CV/CC supply where an automatic crossover point occurs between the two modes of operation and two separate feedback amplifiers are used.

An example using actual values may illustrate this point better. On a normal CV supply having a preset current limit, let us suppose we have set the voltage control to 15V and the current level to 0.5A.

With a large load resistance connected to the output terminals the output voltage will be 15V and a small current will flow into the load. As the load resistance is reduced, the current will rise but he voltage will remain at 15V until the load resistance reaches 30ohms.

The current will then be at its permitted maximum of 0.5A. Any further decrease in the load will not increase the current but the voltage will fall rapidly, reaching zero when the load is a short-circuit; the current, of course, still remains at 0.5A.

This is the operation of a normal constant-voltage current- limited source. For the true CV/CC supply, the transition point corresponds to an automatic switchover from the CV feedback amplifier to the CC feedback amplifier; decreasing the load from that point on keeps the current at a constant 0.5A while the output voltage drops by exactly the right amount to maintain that current constant through the load provided.

The switchover point occurs at the critical value of the load, R/crit determined by the settings of the voltage and current controls. Fig. 8 shows the operating curves for the CV supply at (a) and the CV/CC supply at (b).

Next month, zener diode stabilizers and fixed regulators using the 78/79 series as an example. ■