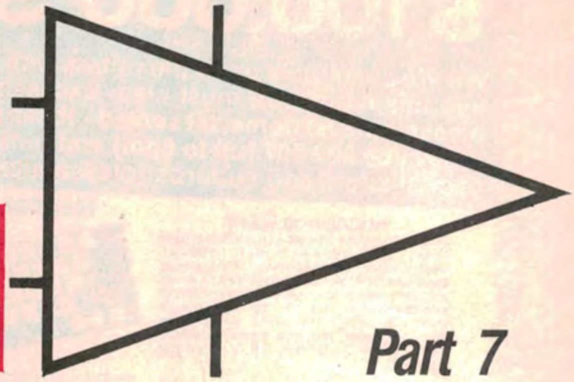
by BRYAN MAHER

OP AMPS Explained



Part 7

Many electronic measurements require the conversion of units to voltage or current. In this chapter we show how op amps can convert voltage to current and current to voltage.

The ability of operational amplifiers to perform many "conversion" functions sets them above and beyond ordinary amplifiers. We have taken a great leap forward, no longer considering the simple task of amplifying a voltage signal; we are actually asking op amps to convert one quantity into another!

Many quantities are involved on the electronic scene, aren't they? Signal voltage is probably mentioned most often, but many times signal current should be considered, measured, or otherwise known. Or sometimes the information output from an industrial or scientific process is actually contained in the frequency, pulse rate, period or risetime of a signal.

In this digital world, the ability to easily convert analog signals to digital and vice-versa would be a nice addition to our repertoire. As each conversion scheme is a world of its own, let us begin with the easiest. This month we devote ourselves to the conversion of a signal current to a proportional voltage; and the obvious inverse function.

Why?

In many electronic, scientific or industrial processes the rate of some vital quantity depends on the value of a current, with no easy relation to the associated voltage. Examples are:

1. The deflection angle of a moving coil galvanometer is truly proportional to its current; its voltage characteristic is uncertain due to the back EMF generated while the coil is moving.
2. The signal at the collector of a junction transistor is more a function of base current than base voltage.
3. The transport rate of ions in the scientific process "electrophoresis" is a function of a current, not a voltage.
4. The light output of a semiconductor laser is a function of the current applied, rather than the voltage.
5. The electrical output of a photosensitive diode is truly measured by the current provided, not the voltage.

"Why not just use a milliammeter or ammeter to measure your precious current" you interject! Well — the answer is "yes — by all means do that", if it's possible, or convenient. But if not, what then?

Other reasons

Steady currents can be simply read on a digital or analog current meter in many cases with no hassle. But there are exceptions. Difficulties may arise if the current is extremely small, or if the system is such that other effects forbid the use of a current indicator of high resistance.

In some important processes, many different currents are flowing in different circuits, and what is required is a single indication of their algebraic sum. Try doing that with your DVM!

Of course, if the current to be measured is fast-changing then a meter is out of the question if details are sought, unless all that is wanted is some average or RMS value. Recourse to an oscilloscope may then be mandatory, but the CRO only has voltage input

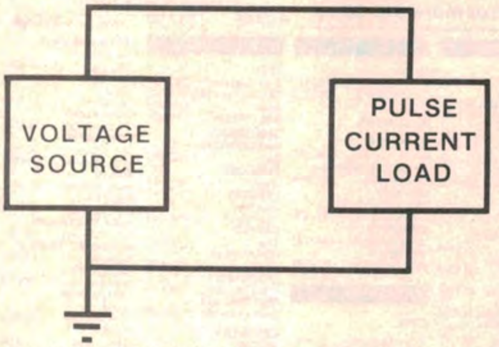


Fig. 1a: regulated voltage source supplying a load taking pulses of current.

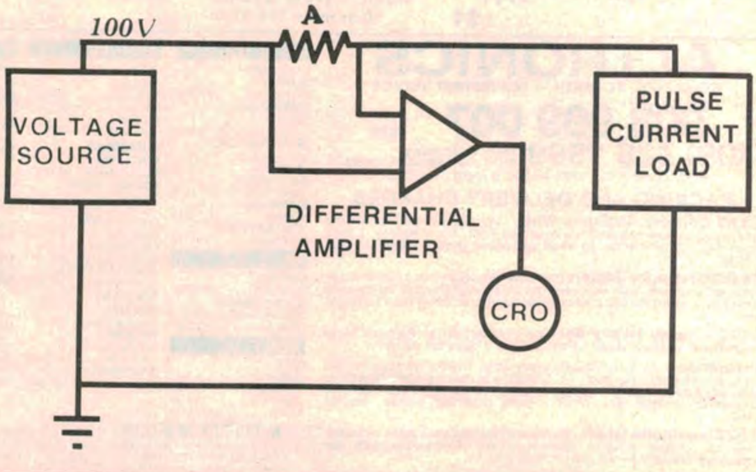


Fig. 1b: one possible measurement technique. The common mode voltage makes things difficult, however.

terminals! Obviously what's needed is a voltage proportional to that current to be measured. We need some sort of **current to voltage converter**.

You're objecting again! Murmurings can be heard that sound like "What's wrong with simply passing your precious current through a resistor, and let the CRO measure the voltage drop?" Good question, and the answer is yes, provided the circuit will permit a resistor large enough to give a measurable voltage drop. An example will illustrate.

Fig.1(a) shows a regulated 100V constant voltage supply for a load which takes long pulses of small current. An oscilloscope is necessary, but how will we connect it? A Hall effect current probe would be ideal here, but if we do not own one we must settle for a voltage dropping resistor. But where will we place it?

If at A in Fig.1(b) a differential amplifier or oscilloscope is needed. But what about that 100 volt common-mode potential? Well — not impossible, only difficult. Then of course, the voltage at the load is no longer regulated; the resistor at A has spoilt that.

Let's try placing the resistor at B as in Fig. 1(c). Now we don't need a differential amplifier, and a single-sided CRO will suffice. The fly in the ointment is that some regulated voltage supplies are unstable if one side of their output is not connected directly to ground. Often you will get away with a low-value resistor in the ground line as at B, but a high value will give trouble. The problem is that if those current pulses to be measured are small, then you need a fairly high-value resistor at B to produce a measurable voltage drop.

A better way

We can place any value resistor we like in the earthed end of the current path, then use the virtual earth of an op amp to appear to short circuit it to ground.

Consider, if you will, Fig.2(a), an ordinary operational amplifier. Recall that the now-famous virtual earth at X isolates all voltages from the integrated amplifier input pin (2−). (The "virtual earth" at X is the result of feedback preventing much voltage appearing even though considerable current is fed to that point. X looks and acts like a low impedance.)

Only the signal current i remains at X. Therefore if we do a "stretch" as at Fig.2(b), and put Ri some distance away, we have not changed anything. V(in) and V(out) remain the same. Now stretch further as in Fig.2(c). Here Ri has moved right over into the left box, but current i is still the same and V(out) remains unaltered!

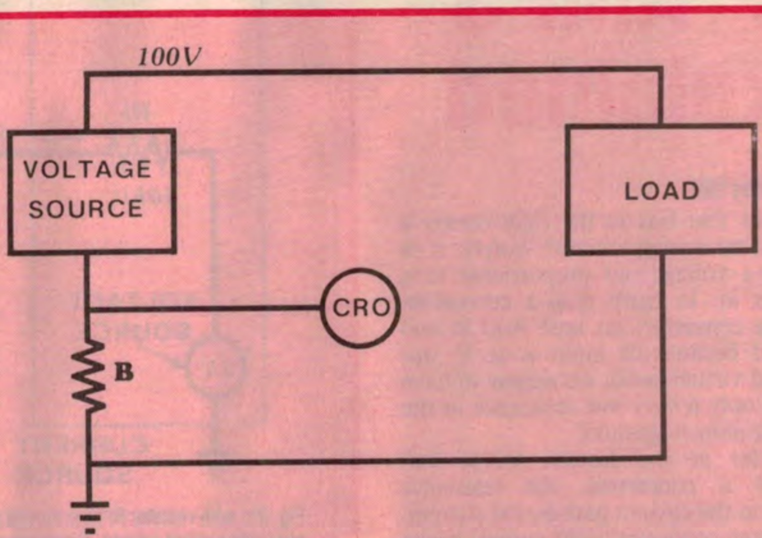


Fig. 1c: at first sight, this looks to be a better method for our pulse current load measurement. However, some regulated supplies are unstable if there is too much resistance in their ground return path.

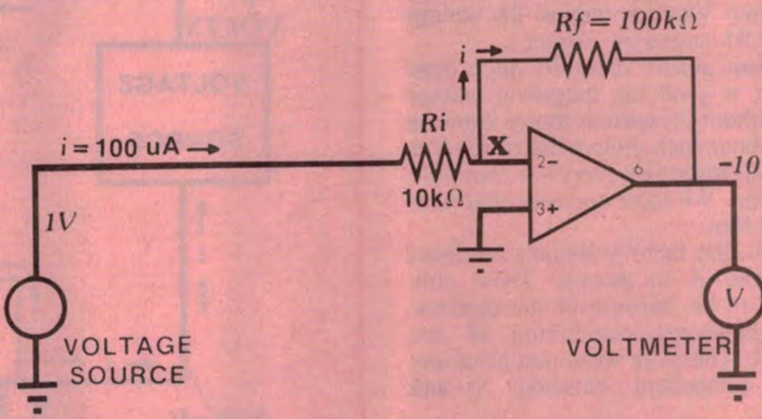
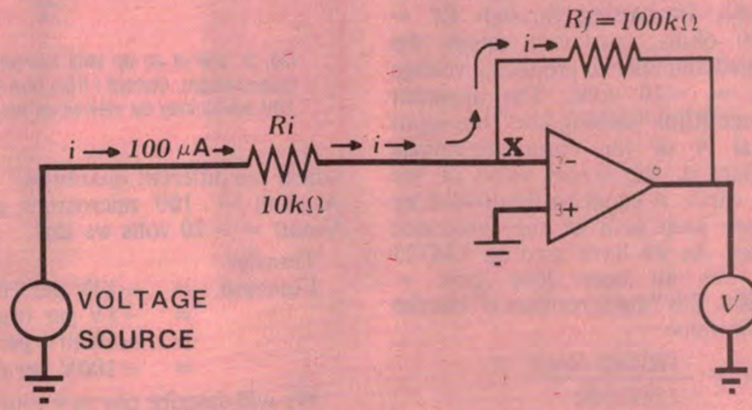


Fig. 2a: common op amp configuration. The virtual earth at X means that very little voltage appears at pin 2 (ie, X looks like a low impedance).



Fog. 2b: "stretch" version of Fig. 2a. The circuit is electrically identicial to Fig. 2a — all we have done is to move Ri closer to the voltage source.

Sure, it's only a matter of viewpoint, but can't we call that box on the left a current source? It is, in fact, our voltage source in series with a resistor Ri. Such a combination resembles a current source.

It slowly dawns upon us that Fig.2(c) is a picture of a source of current, i, (in the left corner), and (in the right corner) something which is giving a voltage V(out) proportional to current i.

OP AMPS Explained

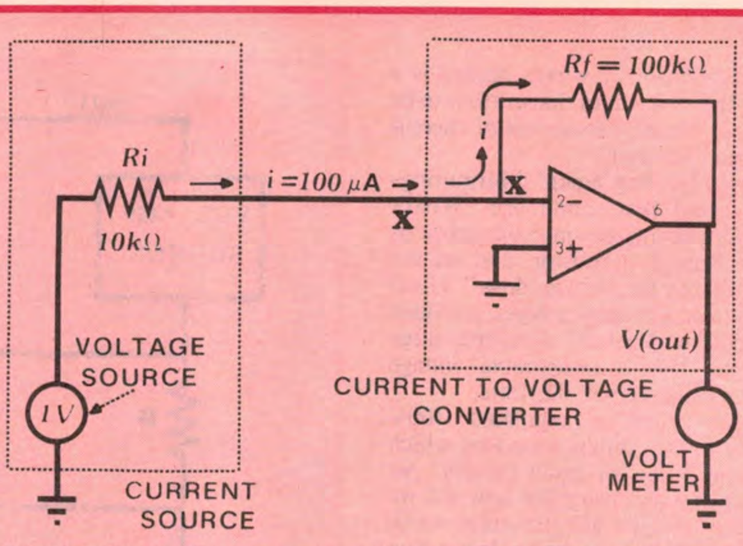


Fig. 2c: with resistor Ri now moved all the way to the left, we can regard the left hand box as a constant current source. Since the output of the op amp is a voltage (−10V in this case), the circuit behaves as a current to voltage converter. Note that Figs. 2a, b, c are all electrically identical.

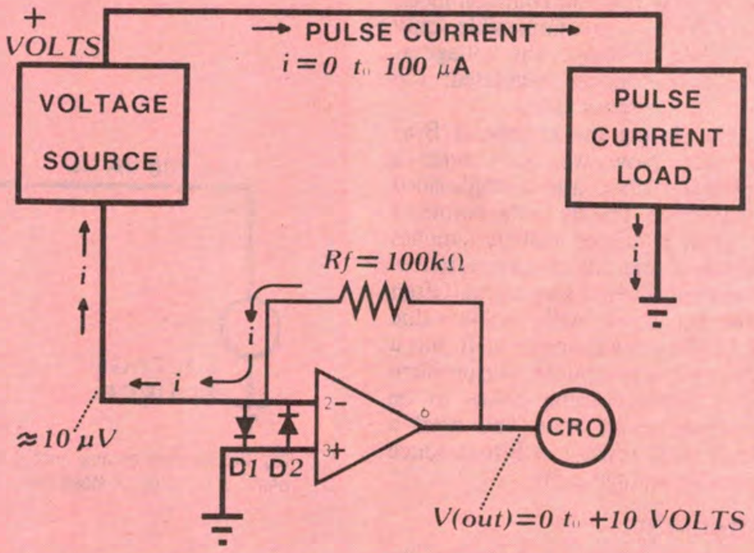


Fig. 3: use ot an op amp current to voltage converter to perform a difficult pulse current measurement. Current i from 0uA to 100uA gives a corresponding op amp output from 0V to 10V which may be viewed on the oscilloscope.

Converter

Is not that box in the right corner a current-measuring circuit? Surely it is giving a voltage out proportional to a current in. In truth it is a **current-to-voltage converter**, no less! And lo and behold! Because its input is at X, our beloved virtual earth, we appear to have placed only a very low resistance in the current path to ground!

As far as the current source (left corner) is concerned, the resistance placed in the current path by the current-to-voltage converter (right corner) is just the very low resistance of the virtual earth. But current i still flows through Rf, because there is nowhere else for it to go. As the voltage at X is almost zero, the output V(out) is (minus) the voltage drop in Rf caused by current i.

We can quietly make Rf quite large and get a good big (negative) voltage drop without the current source knowing much about such underhand tricks. X is still an apparent very, very low resistance to ground. We have our cake and have eaten it too!

Recall that there is actually no direct path from X to ground. There only appears to be, because of the dynamic voltage-balancing equilibrium of the feedback. Therefore we do not place any actual component between X and ground.

Let's be quantitative about Fig.2(c). The left current source sends current i = 100 microamps to the right to be measured. In passing through Rf = 100,000 ohms, current i causes the integrated amplifier to produce a voltage V(out) = −10 volts. The apparent resistance R(in) "looking into" the input terminal X of the current-to-voltage converter, ie, the actual value of the virtual earth, is equal to Rf divided by the open loop gain of the integrated amplifier. As we have used an LM725 which has an open loop gain = 1,000,000, this "input resistance" has the very low value:

$$R(in) = \frac{100{,}000 \text{ ohms}}{1{,}000{,}000}$$

$$= 100 \text{ milliohms}$$

Transfer function

We cannot say our circuit has a "closed loop gain" as that would make no sense. Instead we speak of a *transfer function*. Such an expression suits any converter circuit with inputs and outputs which are different quantities.

As i(in) = 100 microamps produces V(out) = −10 volts we say:

$$\begin{aligned} \text{Transfer Function} &= -10\text{V per } 100\mu\text{A} \\ &= -1\text{V per } 10\mu\text{A} \\ &= -100\text{mV per } \mu\text{A} \\ &= -100\text{V per mA} \end{aligned}$$

We will describe our new-found-toy to others as a *Current-to-Voltage Converter* and quote its Transfer Function and value of R(in).

Pulse currents

Now we can easily cope with that pulse current measurement problem. Fig.3 shows our pride-and-joy connected to display, on the CRO, **voltage pulses** proportional to the **current pulses** we wished to measure. Knowing the Transfer Function of our current-to-voltage converter, we simply calibrate the CRO screen graticule in microamps and measure directly. And we remember that the current measured at the bottom of the supply is the negative of the value flowing to the top of the load.

As the voltage source sees only the 100 milliohm virtual earth resistance between its zero terminal and true ground, we would be unlucky to run into instability problems.

You, most valuable reader, have probably already foreseen a possible problem in the hairy situation that would occur should the current-to-voltage

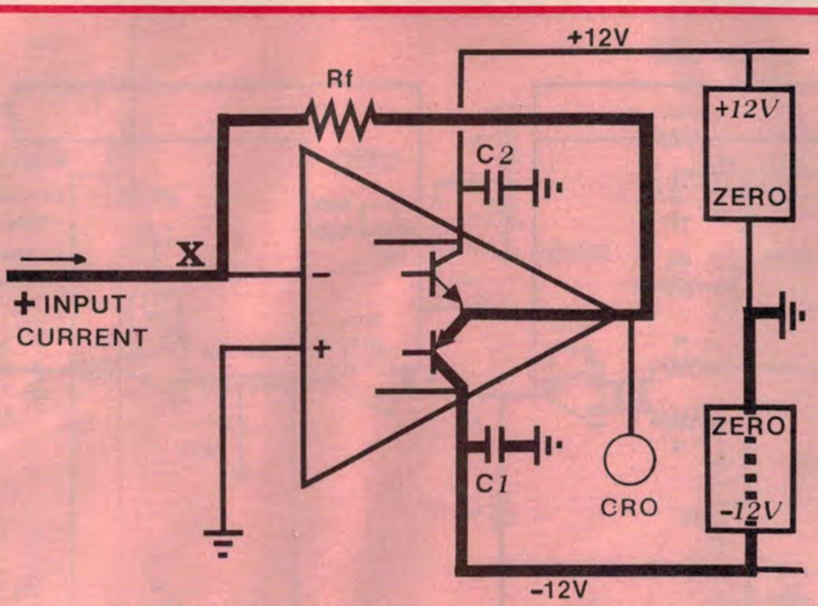


Fig. 4a: op amp current to voltage conveter. The heavy line shows the path of the positive input signal current.

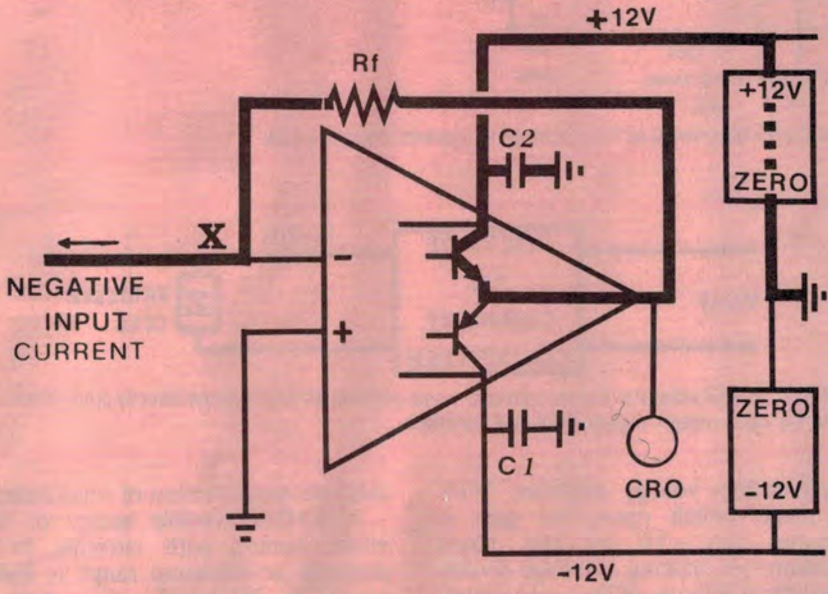


Fig. 4b: negative input signal path for our op amp current to voltage converter.

converter cease to function for any reason. But do not fret . . . just connect two back-to-back diodes D1 and D2 to ground.

In normal operation, the few microvolts occurring at the virtual earth will never turn either diode on; except for their junction capacitance they are effectively not there. Only in case of failure of the op amp will they conduct and render the circuit safe.

Current path

To do the right thing we really ought to look into the question "where does the input current go?". Recall that while the virtual earth at X does provide a very low effective impedance to ground, there is no current path to ground there.

Fig.4(a) shows the actual current path as the heavy line in the case of positive signal current (inwards), while Fig.4(b) shows the picture for negative (outwards) signal currents.

Alternating input current, AC, of course flips about from one path to the other each half cycle. High speed changes in current find a path through the bypass capacitors C1 or C2 (as shown) while low speed changes and the DC component must flow through the power supply. Either way the signal current is heading for ground.

Limits

Readers who couldn't sleep will have

Fig. 6: full size PC pattern for current to voltage converter of Fig. 5 (see page 70).

observed that Fig.4 implies a limit to the value of current that can be measured by the current-to-voltage converter. Not only does the current flow through Rf, but it must also flow via the amplifier output transistor and the power supply. But no problem — we only want this circuit for the measurement of small currents anyway!

Large currents can always be done the conventional way by a simple series resistor in the current path, when a low value resistor will fill the bill without problems.

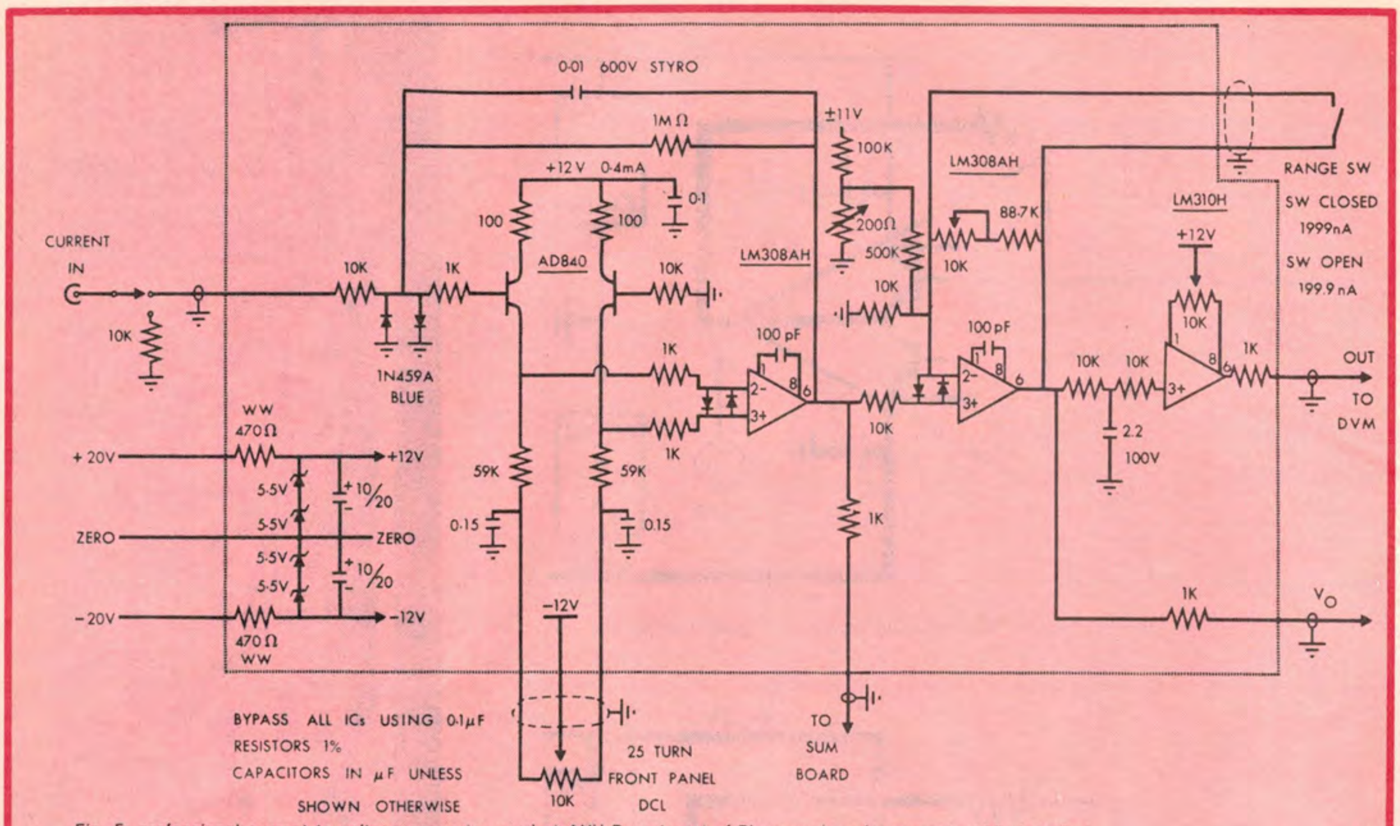


Fig. 5: professional current to voltage converter used at ANU Department of Pharmacology for currents 100pA to 2uA.

OP AMPS Explained

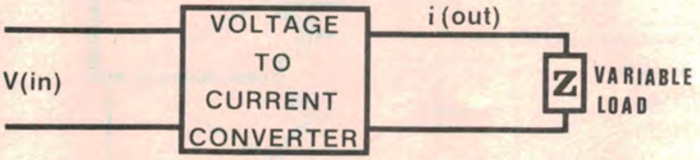


Fig. 7: an ideal voltage to current converter would generate an output current directly proportional to the input voltage, regardless of load variations.

Real application

An application in a scientific research laboratory, ANU's Department of Pharmacology, called for a number of current-to-voltage converters each capable of accurately measuring DC currents from ± 100 picoamps to ±2 microamps. The circuit used for each is shown in Fig.5. The current-to-voltage converter consists of the AD840 dual FET source follower and the first LM308AH acting together as an amplifier with the 1MΩ resistor above as the feedback resistor Rf. This composite amplifier was chosen to give high gain with very low noise.

As any DC input gate leakage current to the FET gate terminal (ie, to the amplifier) constitutes an error in the current measurement, the use of the AD840 with its low gate current kept overall accuracy high. A small capacitor across the one megohm Rf reduced noise while the back-to-back safety diodes used are blue 1N459A's chosen for lowest leakage. The multiturn potentiometer is to trim output to zero with no input.

The second LM308AH is an in-phase (non-inverting) voltage amplifier. With the range switch open, the gain is adjusted to +10 by the 10kΩ potentiometer, making a voltage divider (10kΩ:90kΩ). Closure of the range switch reduces the gain to +1. The 200Ω trimpot adds a tiny current to balance the LM308AH offset to zero.

The last stage, based on an LM310H voltage follower, is a bidirectional low pass noise filter of 22 milliseconds time constant and DC gain = +1. Its purpose is to prevent noise going to or returning from the digital voltmeter load. All integrated circuits on the board are double bypassed on positive and negative rail pins (pins 4 and 7) using 0.1µF ceramic capacitors.

Accuracy and stability are ensured by the use of 1% stable metal film resistors throughout and the use of very stable ±12 volt supply rails. Input power is from a stable regulated ±20V DC supply. All trimpots are 25-turn cermet or wire wound types. Such precautions in design are essential for the stable and accurate measurement of small currents.

A further possible source of error when dealing with currents in the picoamp or nanoamp range is leakage across the PC board surface from the supply rails or other live points to the amplifier input. As a preventative, the amplifier front end is surrounded by earth copper on both sides of the board as in Fig.6.

Voltage to current

For most conversion functions an inverse exists. This raises the interesting question "Can we dream up a method to convert a voltage into a current?" Using op amps can we generate a curent signal directly proportional to a given input voltage signal? Fig.7 illustrates the question.

We are asking for a circuit capable of sending a current i(out) through a variable load Z, with i(out) proportional to V(in), irrespective of what the load may be or how it may change. The mind boggles at the implications!

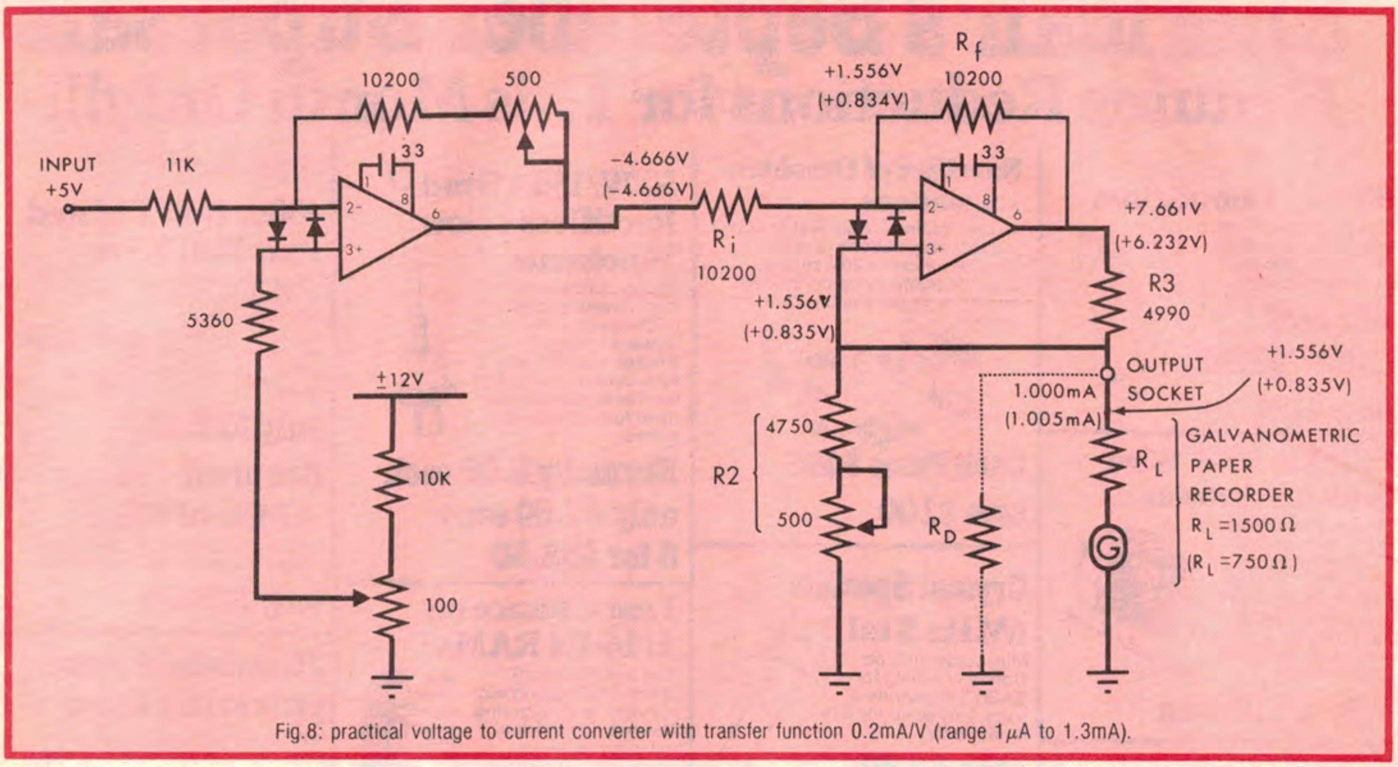


Fig.8: practical voltage to current converter with transfer function 0.2mA/V (range $1\mu A$ to 1.3mA).

OP AMPS Explained

If V(in) swings positive then negative, that means i(out) is required to flow outwards then inwards. If V(in) is a string of voltage pulses, then i(out) is to be a similar string of current pulses. And all this is to happen despite any changes that may occur in the load Z. If V(in) is held constant, then i(out) must remain constant; even if the resistance of the load Z were to double, or treble, or halve.

Such a circuit would have a Transfer Function expressed as so many "milliamps per volt". For example, if the transfer function is 20mA per volt and an input signal V(in) varies from zero to 1.5 volts, then the output current i(out) is required to vary from zero to 30mA simultaneously no matter what value the load impedance may be.

An example could be an industrial process where the load Z is a chemical solution, the resistance of which is subject to erratic changes. Or perhaps the load Z is a moving coil in a magnetic field (say a large pen motor of a chart recorder). Then Z will be a complex active impedance which also generates a back voltage of its own with movement.

Even with such a load, the current should continue to be proportional to V(in).

Voltage compliance

It's not hard to see that in making such a demand we imply that our proposed voltage to current converter must automatically adjust its output voltage continually to make up for any changes in the load. Such self-adjustment of output voltage is called the "voltage compliance" of the converter. If Z were to change to higher impedance, then the voltage provided by the converter would have to rise to keep the current output to the stated value.

There must be some limit to such action, and it is called the "maximum voltage compliance" of our design. If the impedance of Z were to rise higher still, then our circuit could no longer follow; it would have reached the "limit of its variables".

The proposed circuit will somehow sense the load current, perhaps by using the voltage drop in a series resistor to provide feedback for some sort of op amp circuit. The output impedance of the unit should also be high, so that changes in load impedance will appear insignificant. (We recall that a circuit's output impedance is the rate dV/di, the small change in output voltage divided by the small change in output current which caused it.)

Practical circuit

The accurate practical circuit, Fig.8, has for its first stage a buffer amplifier, gain −0.95, driving the second stage, the actual voltage-to-current converter which supplies output current to a load consisting of a galvanometric paper recorder pen motor shown as G and R_L. We see that i(out) flows from the integrated circuit pin 6 through sampling resistor R3.

The voltage and current measurements shown on the figure are for +5 volts input and a (nominal) 1500Ω galvanometer as load. Also shown in brackets are readings measured at similar circuit points for same input but for a 750Ω load.

Observe that for either value of load resistance the output current through the load is almost the same, changing only by 0.5%. To accommodate the changed load and keep the same current the voltage at the output socket has automatically changed itself from +1.556V to +0.835V. Normal operational amplifier feedback changes the voltage at the second integrated circuit pin 6 until the input voltages at pins 2 and 3 almost equal. Therefore the voltage drops across Rf and R3 are equal.

We will skip over any urge for a detailed analysis, except to say that of those aforementioned voltage drops, the first is a function of V(input) while the second is a function of output current. It is this relationship by which the whole circuit keeps the output current through the load directly proportional to input voltage.

The transfer function of the circuit Fig.8 is 0.2mA/V and better than 0.1% accurate in the range 1.0 microamps to 1.2 milliamps.

Output impedance

The matter of output impedance

should be considered. Remember the quantity is defined as

$$R(out) = \frac{dV(out)}{di(out)}$$

But for a constant input we would like constant i(out), meaning no change in current, ie:

Ideal di(out) = 0

But this ideal division by zero implies that the ideal R(out) should be infinitely large. Our real circuit, Fig.8, should then be constructed and set up so that R(out) is as high as possible. The circuit accomplishes this by adjustment of the 25-turn wirewound 500Ω trimpot forming part of R2.

The output impedance of the circuit is resistive in nature at DC or low frequencies, and its value is a maximum when:

$$\frac{R3}{R2} = \frac{Rf}{Ri}$$

Practical values for this ratio will only hold good following adjustment if all resistors retain their values at all ambient temperatures. Therefore only 1% low drift metal film or wire wound resistors and 25-turn trimpots are used throughout and the circuit is operated from well-bypassed very stable ±12 volt rails.

Actual R(out) values achieved as a function of adjustment of R2 can easily reach a few megohms as shown in Fig.9. Sceptical readers may jump up and down a bit at the negative values of R(out) indicated but your author (bless him) swears that these readings are real and honest. Negative values of R(out) are easily achievable.

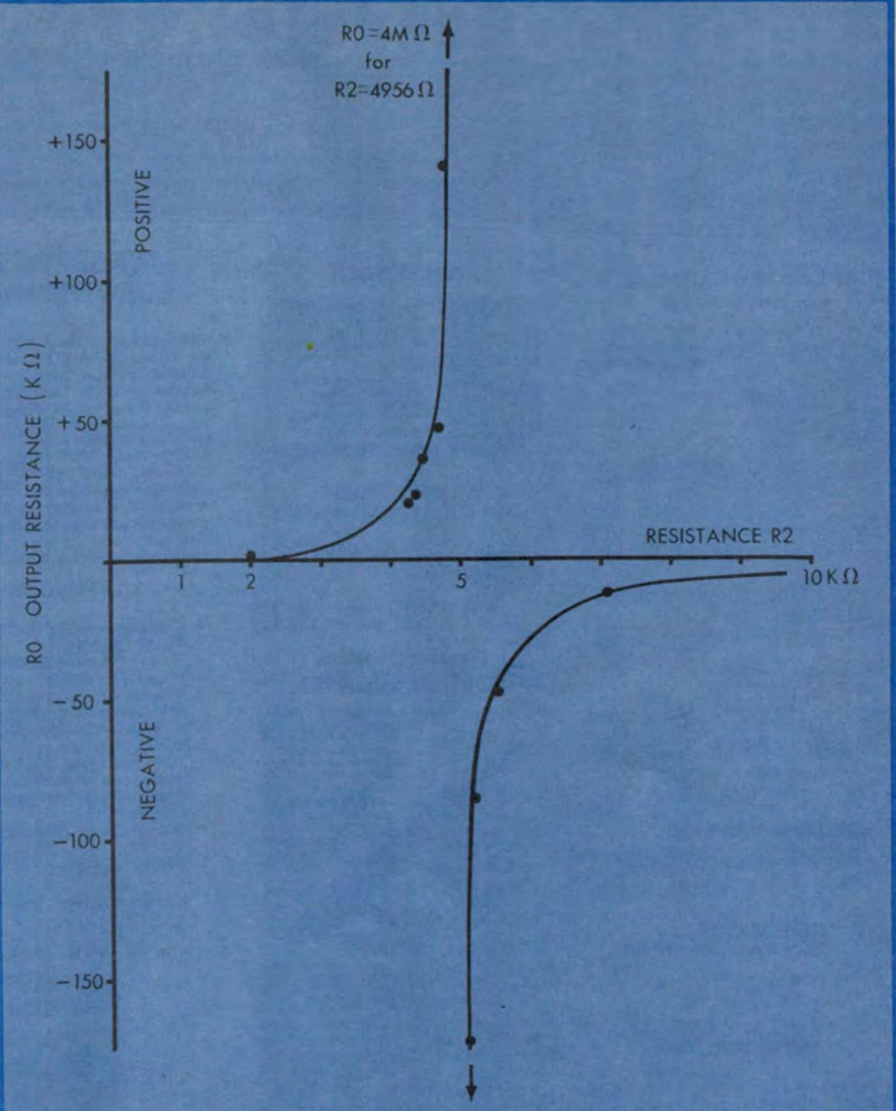


Fig.9: output impedance of the voltage to current converter shown in Fig.8 as a function of R2. Positive and negative values are equally possible.

Damping

Voltage-to-current conversion circuits are often designed for driving moving coil instruments, galvanometers or loudspeakers. For some of these, infinite or very high source impedance is not the ideal, as this leads to overshoot and undamped oscillations in the response. Rather, a particular value of source impedance is sometimes wanted to give the deisred damping characteristics.

This circuit provides for any nominated source impedance to be achieved by inserting a damping resistor of that value in the position marked R_D in the diagram. The source impedance, as far as the load is concerned, is now a few megohms in parallel with R_D which is approximately the same as R_D. For the case of galvanometers, sometimes R_D is chosen to give critical damping, ie, fastest movement without overshoot.

Next month we continue this series looking at designs converting random pulse rates or frequencies to voltages and vice-versa.