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Introducing the Perfective 1

This noninvasive current meter features a clever circuit that YOU can build.

The problem with making current measurements using the standard mA meter is that the meter must be inserted into the measured circuit. These meters have internal resistance, which adds to the resistance of the circuit being measured. This causes a reduction in the circuit current, and thus a lower reading than expected. No more.

You know, what instigated this whole project was a student's comment in class one time. I was lecturing on the use of the milliammeter and explaining how the internal resistance of these devices often causes bad readings in a circuit. I commented that when we all get to heaven and St. Peter issues us our little mA meters, they will be PERFECT, with no internal resistance or resulting voltage drop.

The students took this with a sigh, but one in the back looked worried. I asked him what was wrong, and he replied: "Mr. Lorfin, I wonder if YOU will ever get to see one ..."

Well, I thought about this and realized how true that might be. So I decided that I had better invent one for myself while there was still time, if I was ever going to behold one's beauty.

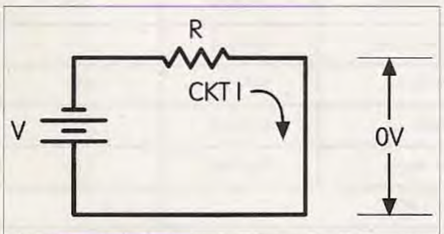

Fig. 1. Representative circuit showing current flow.

This project is the result.

P.S. The student made an A in the course.

In search of perfection

Sometimes, a circuit may be working perfectly until you make a current measurement, and it may not be working so well while you are making the measurement. Also, from the results of the measurement, you might mistakenly think that there is a defect in the measured circuit when there really is not one. This has been quite a problem for me and others in the past.

To fix it? Well, it was hard to imagine a standard DC-AC milliammeter that has zero measuring resistance and zero burden voltage. However, one day a thought came to me that resulted in this design, a design that has overcome this fault and resulted in the "Perfective Current Meter."

This instrument is not difficult for anyone to build. I built the prototype shown here for about $60. Let me hasten to add that this was going first-class, using new parts not obtained as cheaply as could have been.

In **Table 1**, I've listed the specified internal resistance and burden voltage values for one commercial DVM. In **Table 2**, we see some typical current readings, taken with random resistances and voltages, using the meter in **Table 1** and the Perfective 1 Current Meter, or Perf1. Note that the errors greatly exceed the rated accuracy of any digital current meter. Of course, in many circuits the error is not this gross; however, an error is always there, and most people tend to consistently fail to compensate for it when making current measurements.

In meters using protective fuses, these fuses can add to the internal resistance of the meter in addition to the normal shunt resistance, especially if they have not been selected so as to have minimal resistance.

One idea in use to reduce this problem is to use lower values of shunt resistors

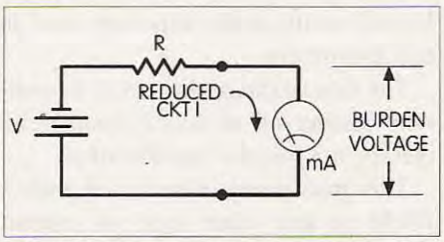

Fig. 2. Representative circuit showing added circuit resistance from standard mA meter.

Range	Ohmic Value	Burden Voltage (full scale)
4 mA	200Ω	800 mV
40 mA	20Ω	800 mV
400 mA	2Ω	800 mV

Table 1. Specified internal resistance and burden voltage values for one commercial DVM.

Applied Volts	Ohms	I w/Meter	I w/Perf1
7.5	25	280	306
10	125	82	84
2.5	15	142	166
5	15	295	340

Table 2. Table 1 readings versus Perf1 readings.

Frequency	P–P Burden Voltage
DC	Adjustable to zero
100 Hz	Virtually unmeasurable
500 Hz	
1 kHz	Approx. 0.5 mV peak, or less
3 kHz	
6 kHz	
30 kHz	Approx. 20 mV peak

Table 3. Burden voltage for DC and AC measurements using Perf1.

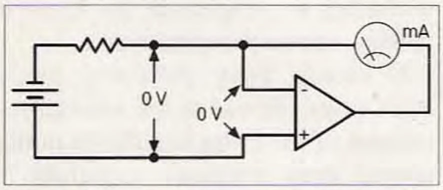

Fig. 3. Representative circuit showing perfective mA meter with zero burden voltage.

and amplify the shunt voltage. This is effective, but does not solve the problem as neatly as the approach used in this instrument.

The cited example of errors is common among all standard commercial meters, not just the one described.

This instrument, when used with a DVM or any other type of current meter, overcomes the problem to near perfection. DC burden voltage can be

				Approx. Cost ($)
I1	LED lamp	Red fixture	276-270	2.20
I2	LED lamp	Green fixture	276-271	2.20
1	Cabinet	3 x 5-1/4 x 5-7/8"	273-253	7.00
T1-4	Sets, binding posts	Nylon banana, individual	274-662	4.00
T5, 6	Binding post	Chassis mount, dual banana	274-718	3.50
6	Spade lugs	#6 terminal	64-3043	.25
SW1	Switch	SPST toggle	275-612	2.79
1	Tie point	2-point with ground	274-688	.25
1	Line cord	6 ft., 3-wire	278-1258	2.99
1	Grommet	5/16"	64-3025	.10
Q1	TIP 120 or equiv.	NPN Darlington, TO-220	276-2068	1.29
Q2	TIP 127 or equiv.	PNP Darlington, TO-220	RSU11371101	1.69
IC1	Op amp	LM358 low power	RSU11929072	.89
BR1	Rectifier	1.4 A bridge, round case	276-1152	1.19
BR2	Rectifier	1 A bridge, dip	276-1161	.99
D1, 2	Reg. diodes	LM385 n.a. Radio Shack		
	or	1N5221B 2.4 V zeners	RSU11673431	.89
	or	Any zener up to 4.3 V		
D3–7	Diodes	1N4000 series	276-1102	1.25
D8	Diode	1N34 germanium	276-1123	.11
C1–4	Tantalum	10/16 VDC	272-1436	3.60
C5	Electrolytic	10/35 VDC radial	272-1025	.59
C6	Ceramic	0.01/500 VDC	272-131	.49
C7–8	Ceramic	0.1/50 VDC	272-135	1.00
C9–10	Electrolytic	10/35 VDC axial	272-1013	1.20
C11-12	Electrolytic	3300/25 VDC radial	RSU11935368	2.60
R1, 4, 5, 13		1k	271-1321	.40
R2		470	271-1317	.10
R3		10k	271-1335	.10
R6 if used		180	271-1110	.10
R7	Carbon film, 1/4 W, 5%	220k	271-1350	.10
R8		10k 15-turn pot	271-343	1.49
R9–10		4.7k	271-1330	.20
R11–12		100	271-1311	.20
R14		56	RSU11344637	.10
F1	Fuse	Miniature 0.25 A PT	RSU11322864	.89
8	Nuts, bolts	Assortment	64-3011	.20
2	Standoff	1/2" #6 hole for main board	64-3024	.20
2	Standoff	1/4" #6 hole for PS board	64-3024	.20
1	Transformer	12 VCT @ 0.45 A	273-1365	4.99
1	Sonic device	Radio Shack	273-074	2.99
2	Heat sinks	For transistors above	276-1363	1.80
1 ea.		Main circuit and PS PCB		
		APPROXIMATE TOTAL		$59.00

Table 4. Parts list.

trimmed to zero, resulting in zero ohms internal resistance also. The burden voltage for DC and AC measurements using this instrument is approximately as shown in **Table 3.**

These measurements were taken at a current of 0.1 amp. Note that the frequency range here exceeds that of the standard DVM. Any existing burden voltage varies linearly with the amount of current; consequently, it is less for smaller currents being measured. It should be noted that the above burden voltage was measured at the SENSE terminals, which does not take into account test lead and connector resistance, etc. — more on this later.

How it works

The operation of this circuit is based upon the "burning desire" of an op amp to keep its two input terminals at the same potential. A feedback path from the op amp output to the inverting input gives an op amp capability to do this.

In this circuit, the op amp is connected as an inverting amplifier (see **Fig. 3**). The feedback resistor is the readout meter. The input resistor is the intrinsic resistance of the circuit into which the op amp is inserted. In order to keep its two input terminals at the same potential, the op amp provides output current of a magnitude to match the circuit current, but of opposite polarity; this is standard inverting.

Amplifier operation

The above results in an interesting situation — the two input terminals of the op amp appear to be shorted together; the circuit being measured does not realize that the op amp is even inserted into it. A low frequency op amp was specifically used here to greatly reduce any tendency for the circuit to oscillate while still providing sufficient bandwidth for the circuit. A drawback to this circuit is that the op amp must be able to provide the same current as is flowing in the circuit being measured, hence, the power transistor output stage and the relatively heavy power supply. For current ranges within the capability of the op amp itself, no transistor boost would be needed, and a lighter supply could be used. The power supply voltage can be quite low, in that the supply voltage only needs to be high enough to overcome the small voltage drop of the readout meter and to operate the op amp itself.

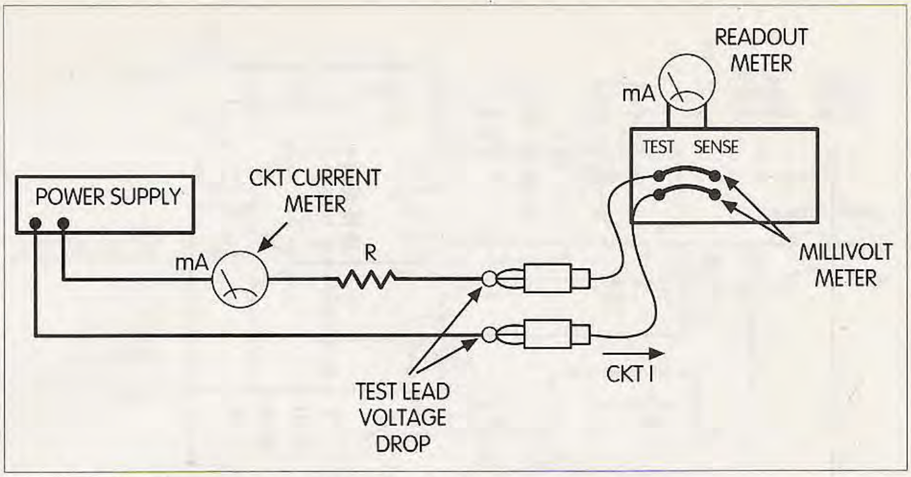

Fig. 4. Testing for proper operation. See text.

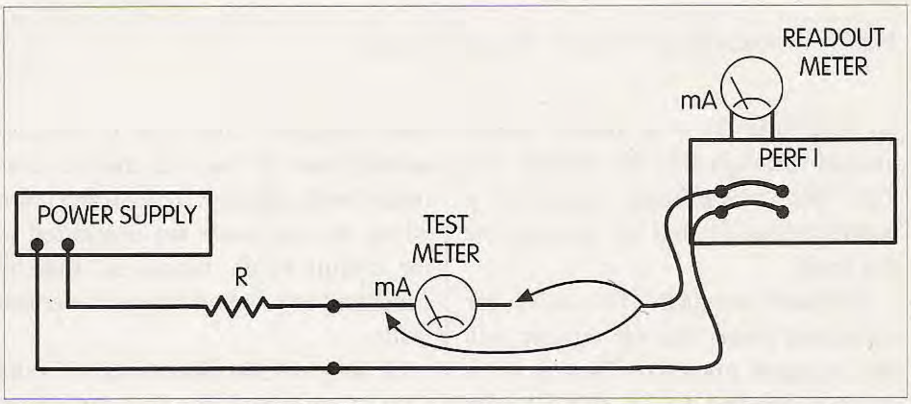

Fig. 5. Demonstrating the lack of added circuit resistance afforded by the perfective mA meter. See text.

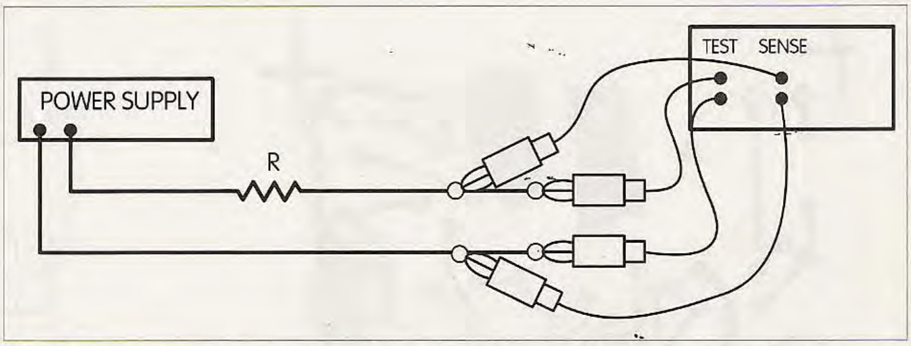

Fig. 6. Connecting so that test lead and connector resistance is canceled. See text.

The transistors (Q1 and Q2) are Darlington types for large current gain. Bias for the transistors is provided by D5 through D8. Note that D7 is a germanium diode. This combination of diodes resulted in the best biasing for good AC output capability and proper idle current. D5 and D8 are mounted on the heat sinks to provide transistor bias stability due to temperature changes occurring with transistor operation. R14 and C6 provide compensation to prevent the circuit from oscillating.

Note that the readout meter is connected from the transistor emitter junctions (the output, T6) back to the inverting input of the op amp (through T5, T1, jumper, T3, and R5 to pin 6) and that the noninverting input of the

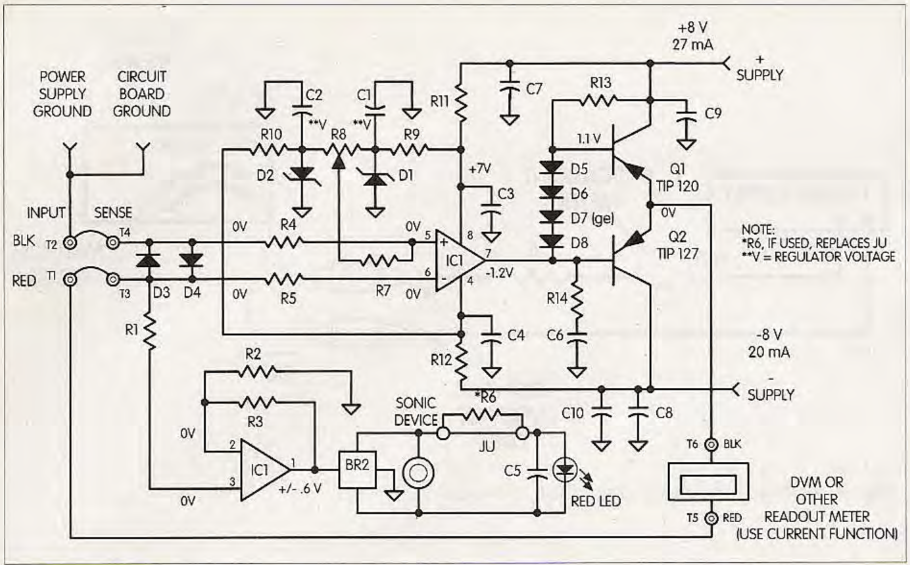

Fig. 7. Schematic of complete unit, less power supply.

op amp (pin 5) is at power supply ground (through R4, T4, jumper, and T2). The circuit being measured is connected to T1 and T2 through the test leads.

The sense terminals, T3 and T4, are the actual points that the op amp will hold at equal potential. They are normally connected to T1 and T2 with short jumpers. They can be disconnected from T1 and T2, and be connected with separate leads to the point where the test leads are connected to the circuit being measured, thereby canceling any voltage drop in the test leads.

Op amp offset adjustment, (+) and (–), is provided by two regulated voltages applied to the 10k pot, R8. Adjustment of R8 will apply any desired amount of offset voltage to pin 5 through R7. Regulation of these voltages was done in the prototype using the LM385 regulators. If these are inconvenient to obtain, any type of regulator device will suffice, provided that it will operate satisfactorily from a 5 volt source. See the parts list, **Table 4**. If a different level of regulated voltage is used here, you might desire to change R7 — use about 100k per volt of regulated voltage for ease of adjustment.

Since the circuit should normally have virtually no voltage present across the input terminals, voltage here indicates that there is a problem of some kind, such as an open readout meter circuit. Warning of this, or other problems, is provided by the second section of the op amp package. This section amplifies any voltage present here, turns on the red panel lamp indicating a circuit malfunction, and activates the sonic device.

The sensitivity of this warning circuit can be adjusted by the value of

Fig. 8. Main PCB, foil side (100%).

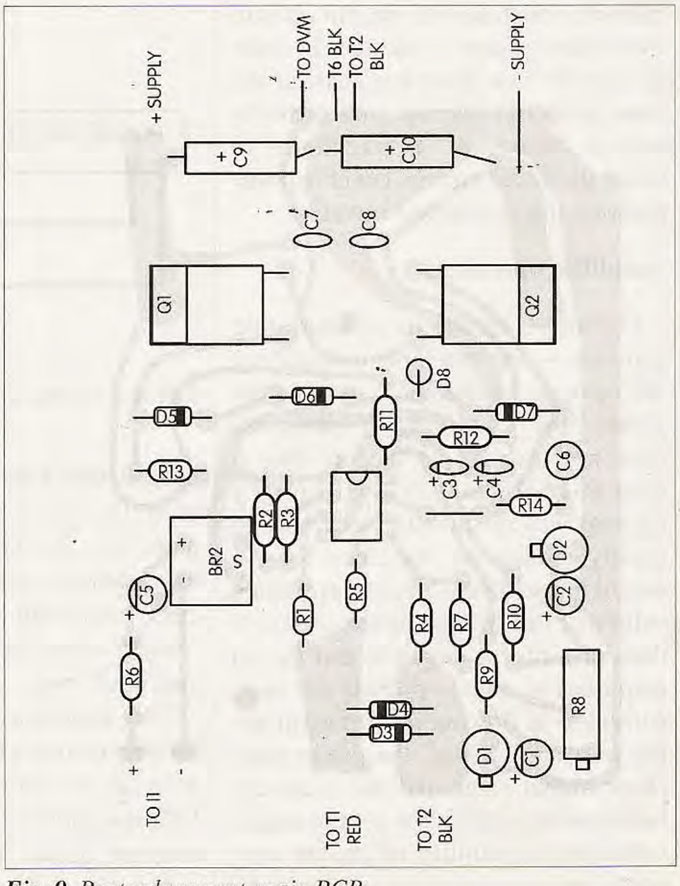

Fig. 9. Parts placement, main PCB.

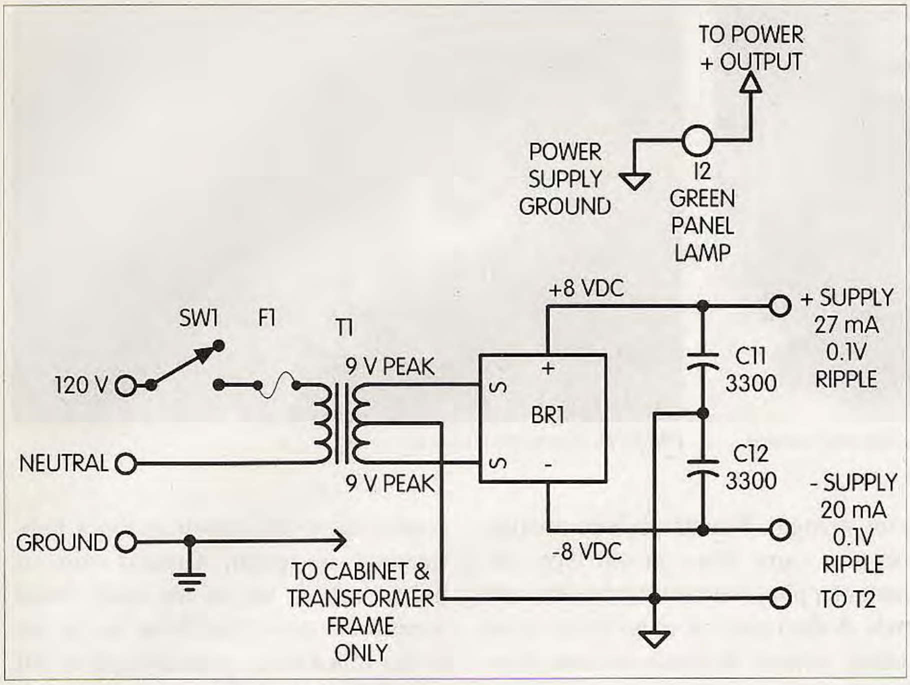

Fig. 10. Power supply schematic.

R3. R6 is necessary if a standard LED is used. It would be jumpered for LEDs with a built-in limiting resistor. The small sonic device was soldered directly to the LED pads on the bottom of the circuit board, being mounted so that it points out from the side of the board. Two diodes, D3 and D4 at the input terminals, offer a path for current to flow (but with voltage drop) from the measured circuit, if this instrument is turned off or is otherwise inoperative.

The power supply used here is good for about 0.5 amp of current; however, a heavier supply will permit a much greater current measurement, as the output transistors are rated for 5 amps. The particular heat sinks used here would not be suitable for more than about 1 amp of steady current flow with the supply voltage of 5 volts or so. This supply voltage is sufficient to operate the circuit while resulting in minimal heating of the output transistors. For this reason, it is suggested that whatever changes might be made, you should not use a supply voltage higher than this. Using the power supply featured, current measurements above approximately 0.5 amp can result in lowered power supply voltages and increased ripple, which will most likely cause the circuit to malfunction.

Building the circuit

Note that all parts can be obtained from Radio Shack except the circuit boards. There are no parts used here that are critical as to tolerance. All parts listed can be substituted with equivalents. Construction is straightforward.

Connection of some wiring is critical in order that current flow does not contribute to offset voltage:

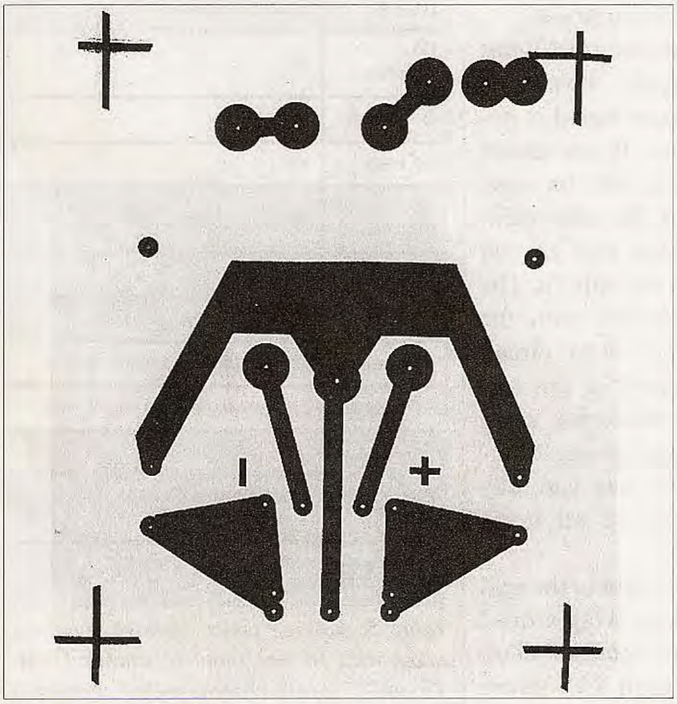

Fig. 11. PS PCB, foil side (100%).

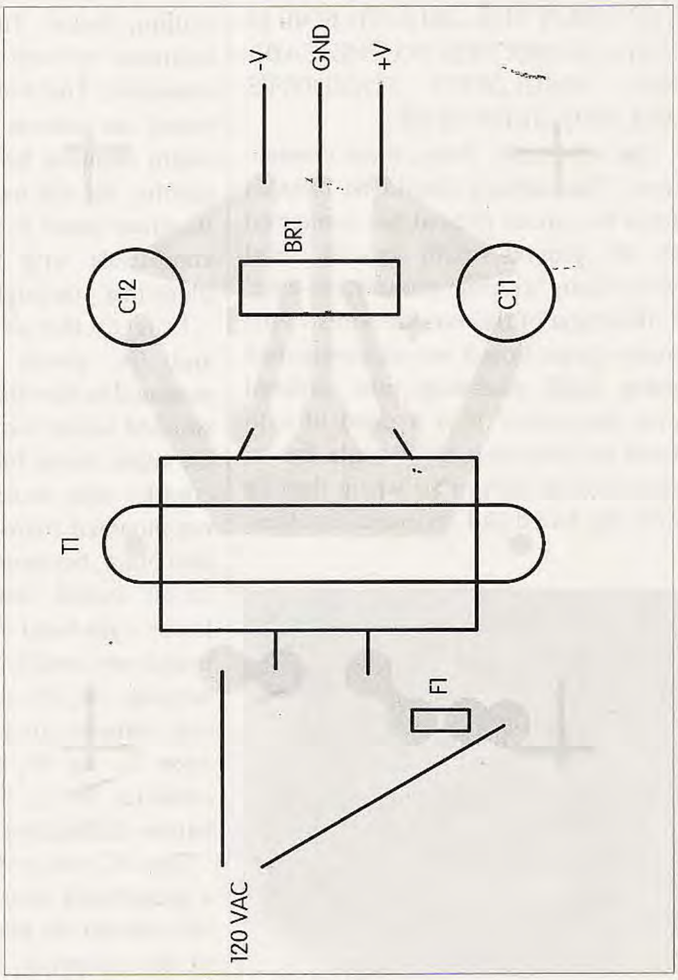

Fig. 12. Parts placement, PS PCB.

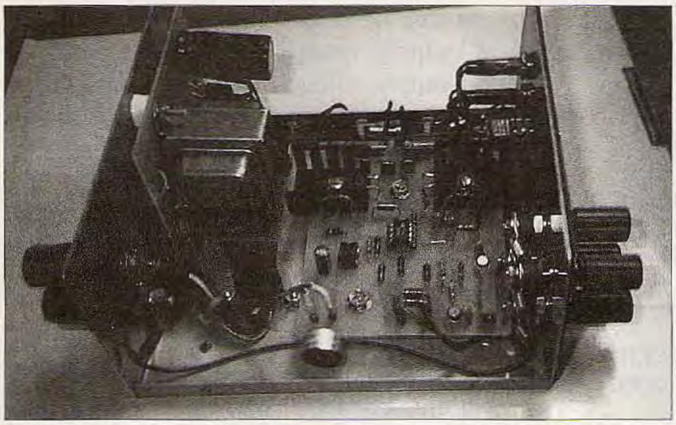

Photo A. *Inside view showing placement of boards and wiring.*

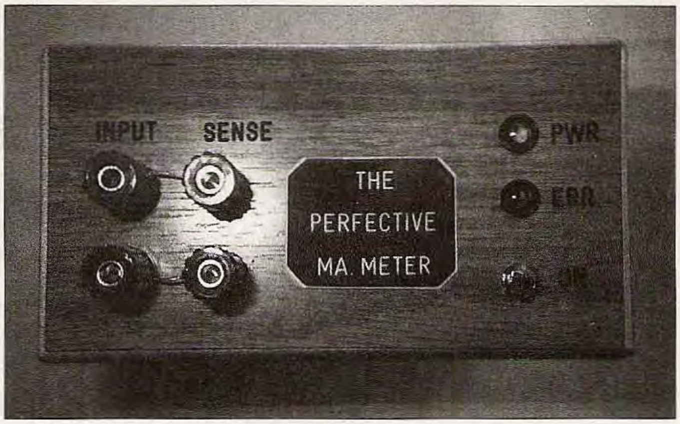

Photo B. *Front panel view.*

A. Power supply ground wire directly to the BLK INPUT TERMINAL.

B. Circuit board ground wire connected as above.

C. RED INPUT terminal (T1) directly to the RED METER terminal.

D. RED SENSE terminal (T3) to the INVERTING op amp input.

E. BLK SENSE terminal (T4) to the NONINVERTING op amp input.

F. WHEN MOUNTING THE POWER SUPPLY BOARD, BE CERTAIN THAT THE GROUND FOIL IS NOT CONNECTED TO THE CABINET. INSULATED STANDOFFS ARE REQUIRED HERE.

The schematic shows these connections. The cabinet should be isolated from the circuit ground but connected to AC ground (earth ground, third wire) along with the transformer core. Connection of the various wires to the main circuit board was accomplished using small wire-wrap pins soldered onto the board. It is a good idea to bend the pins at a right angle for an eighth of an inch or so where they fit onto the board pad, to increase solder-joint strength. Female push-on connectors that came from an old type "D" computer plug were soldered to the wire ends. A short piece of snug-fitting shrink tubing around the push-on connectors is in order.

Being able to separate the board from the wiring is wonderful, should you have to remove it from the case. Due to the tight fit of everything inside the cabinet, you must carefully consider the mounting of all items before drilling holes! The circuit board is mounted by two screws on 3/8-inch standoffs. The hole positions on the board are shown on the artwork. I might mention here that the standard spacing for the banana jacks used on the front panel is 0.75 inches. This is compatible with the double banana plugs that you might desire to use.

I suggest that all cabinet panel items and the power supply board be mounted before the main board is positioned inside the case. If you mount the main board first, it will, for sure, conflict with some of the other cabinet-mounted items when they are put into place, because of the tight fit. The on-off switch can conflict with the lower right-hand corner of the circuit board very easily, so a bit of this corner was cut off at a 45-degree angle (see artwork) to ensure proper clearance. To say the least, very carefully consider the mounting of all items before drilling holes!

The AC cord was brought in through a grommeted hole. A tie wrap around the cord on the inside, tightened close to the grommet, is used as a strain relief. The neutral and hot wires are connected to the terminals on a two-terminal tie point. Ground wire is bolted with a lug to the case. Small wires were connected from the tie lug to the transformer primary and on-off switch (hot wire). Be very careful with routing, insulation, and connection of the hot wire. I always place a piece of shrink tubing around the on-off switch to cover the hot wire terminals. A large

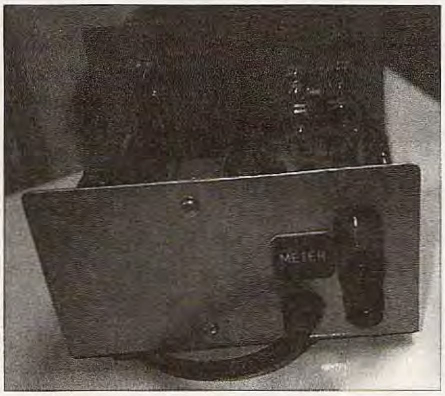

Photo C. *Rear view.*

IC1 Pin #	Volts
1	±0.6
2, 3, 5, 6	zero
4	−7
7	−1.2
8	+7
D1, D2	Equal to regulator voltage
Q1 collector	+8
Q1 emitter	zero
Q1 base	1.1
Q2 collector	−8
Q2 emitter	zero
Q2 base	−1.2
+ Power supply current drain = approx. 27 mA	
− Power supply current drain = approx. 20 mA	
Power supply ripple = 0.1 V P-P	
Power supply ripple @ 0.1 A current = 0.2 V P-P	
Power supply ripple @ 0.4 A current = 0.65 V P-P	

Table 5. *Voltage chart. Voltage readings taken with 10 meg input resistance DVM, T1 and T2 open, readout meter connected to METER output jacks on rear.*

piece of shrink tubing was placed around the tie point to cover it.

Test for proper operation

It would be a good idea to first read pertinent voltages as shown on the schematic to see if yours correspond. Connect the readout meter to the "METER" terminals and put it into the current function. Ranging is done by adjustment of the READOUT meter. Jumper the input and sense terminals together as shown on the schematic. Apply NO input. Now check your voltages against those listed.

Connect a variable DC voltage supply through about 50 ohms to test leads going to the INPUT terminals (**see Fig. 4**). A millivoltmeter or oscilloscope can be used to record millivolts at the SENSE terminals. Apply a steady current of 200 mA through the resistor to the test leads. This 200 mA from the supply should be indicated by both milliammeters. These two readings should agree. Adjust the 10k pot, R8, for zero millivolts at the SENSE terminals. Vary the current from 0 to 400 mA, and note that the SENSE voltage should not vary by more than approximately 0.1 mV, max. This variation is the input signal voltage to the op amp; this will vary some from one op amp to another due to differences in gain of the devices. A much greater variation of voltage here with current means that the SENSING is not proper, possibly due to incorrect wiring of the terminals. If this test checks out, you can then measure the millivolts present at the test lead clips. This will be very small and due to the resistance of the test leads and INPUT terminal connection resistance (the banana plugs). This voltage will vary with current and will be equal to the total resistance of the leads and connections multiplied by the current flow. The method of eliminating this is discussed later.

Testing for accuracy

First, obtain two digital current meters and connect them in series. Determine their comparative accuracy at different current levels. Next, connect one to the Perfective 1 Current Meter output terminals and connect the other to read input current. Generate a current flow and compare the readings. Reverse the input polarity of current flow into the Perfective 1 Current Meter and determine comparative readings of output for the positive and negative current flow; these should be very close. You should be certain the offset adjustment (R8) is close to zero, as this will cause a difference in the above readings if not. Tests on the prototype have been within less than 1% of each other.

Demonstrating the action

Try using different values of voltage and resistance; connect the circuit as shown in **Fig. 5**. Take a reading on the READOUT meter. This will be the reading you will get without the aid of this instrument due to the resistance of the TEST meter. Now jump around the TEST meter as shown in **Fig. 5** and note the increase in current reading on the READOUT meter. This is the true circuit current that will flow when no meter is inserted into the circuit or when you are using the Perfective 1 Meter.

This difference illustrates the usefulness of this instrument. The greatest difference will be evident when the range setting of the TEST meter is such that you get closest to full-scale reading on it.

Using the Perfective 1 Current Meter

This circuit was designed to be used with any type of current meter. Of course, to measure AC current, the meter in use will have to have this feature. Observing polarity of connection will ensure a proper polarity indication on the meter readout when in the DC function.

Normally, the SENSE terminals and the INPUT terminals will be wired together by short wire jumpers connected directly between the two. As mentioned before, the only point of connection where the burden voltage will be zeroed is at the SENSE TERMINALS. The test leads connecting the measured circuit, as well as INPUT TERMINAL connection resistance, will cause voltage drop (burden voltage) due to the current flow. This voltage drop has been measured at around 20 mV or so and will vary with the characteristics of the test leads used.

If you is desire to have the resistance of the TEST leads zeroed out, separate SENSE leads should be connected from the SENSE terminals directly to the point of connection of the TEST leads (see **Fig. 6**). This will naturally require four leads going from the instrument directly to the measured circuit. Of course, the jumpers between the two sets of terminals should be removed for this type of REMOTE SENSING. It is important that the SENSE test leads be connected to the measured circuit itself next to the point where the TEST leads are connected, not to the clips of the TEST leads. This will ensure that the TEST lead clip resistance will be zeroed out also.

A confusing problem can result from the negative leads of test instruments and/or circuits being connected together through the third-wire ground of the AC line cord. Oscilloscopes normally have their negative lead connected to the third-wire ground. Some multimeters do also. To prevent this problem, you can use a three-to-two-wire adapter on the AC line cord of the offending instrument to remove this connection. To test for this, use an ohmmeter to see if negative leads are connected to the third-wire ground terminal on the AC line cord.