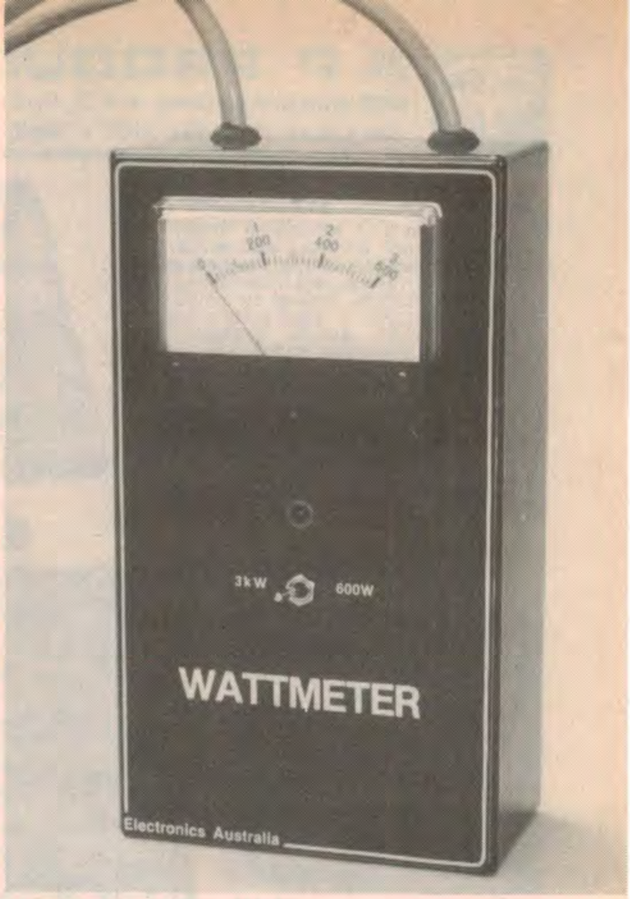
Measure your power consumption

Electronic Wattmeter

simple design uses an OTA



The unit described here will measure the power consumption of any mains appliance with a rating up to three kilowatts. It makes use of a special op amp called an "output transconductance amplifier" or OTA, for short.

by JEFF SKEEN & LEO SIMPSON

With the cost of electrical energy expected to rise relentlessly in the future, consumers will want to know how much energy each appliance uses. The first step in understanding energy usage is to measure the power required to run the appliance. Our wattmeter circuit measures the power used by any mains appliance including heaters, motors and transformer driven equipment such as TVs and microwave ovens.

Before we get started on the whys and the wherefores of the circuit and its operation, let us sort out a few terms. If we don't, some of our readers will be jumping down our collective throats for sloppy writing. That conjures up some interesting images, doesn't it?

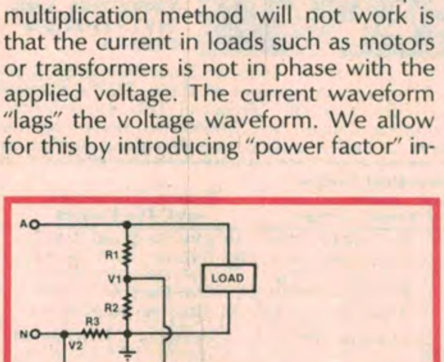
For a start then, let us make it clear that power is not consumed, although it is common usage for people to talk of "power consumption" and power bills. Nor for that matter, is energy consumed; it is merely transformed from one form into another. So electrical energy can be transformed into mechanical energy by a motor and then into potential, kinetic or heat energy.

But as far as the practical person is concerned, once the appliance is turned on and current begins to flow, energy has been used or consumed and that is that. Never mind the laws of conservation of matter and energy and concepts of entropy. What is entropy anyway? We "dunno" but there seems to be a hell of a lot of it about and it's increasing all the time.

When we talk about power consumption we really mean the power "demand" or requirement of an appliance. And that power demand is the product of the voltage applied and current which flows. So for a 2400W radiator, the power demand is the product of 240VAC and 10 amps which flows when the switch is thrown. Simple enough, so far.

For the radiator example above it is a relatively simple matter to measure the current and voltage and multiply the two together to obtain the power being delivered (or used). But for other appliances, such as those using motors or transformers, this simple method cannot be used.

The main reason that the simple multiplication method will not work is that the current in loads such as motors or transformers is not in phase with the applied voltage. The current waveform "lags" the voltage waveform. We allow for this by introducing "power factor" into the calculation. This is the cosine of the phase angle between the voltage and current.



This diagram illustrates the concept of the Wattmeter circuit.

With this factor in the calculation, the formula for power now becomes:

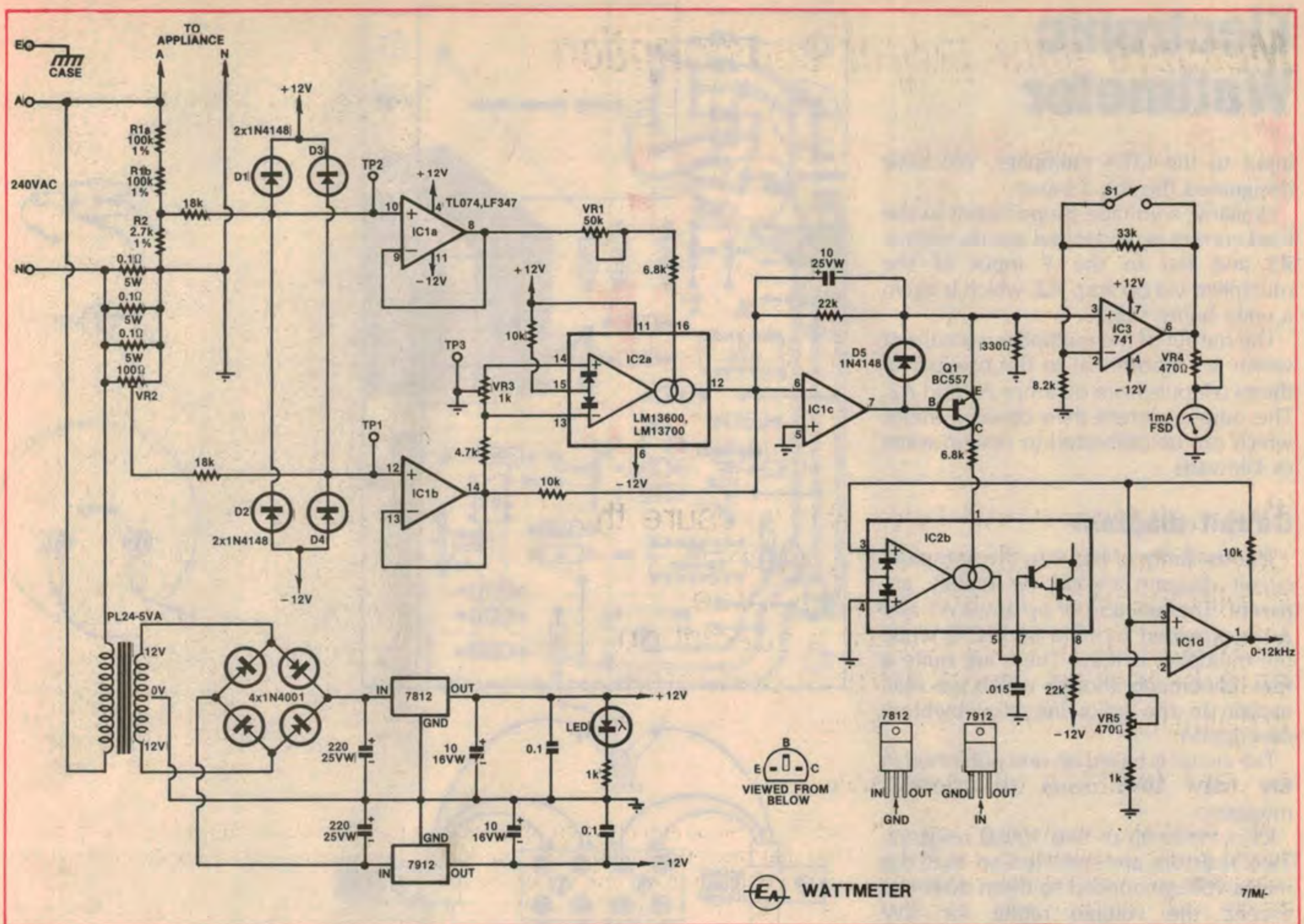
Power = V.I. $\cos\phi$

where ϕ is the phase angle and V and I are the RMS or effective values of these parameters. The "effective" value is important because it often cannot be measured accurately by moving coil meters.

Moving coil meters respond to the average value of the current through them and when they are used to measure sinusoidal waveforms (the 50Hz AC voltage waveform is a sinewave) the meter is calibrated to read the effective or RMS value. But if the waveform is not purely sinusoidal large errors will occur in the reading.

In practice, the 240VAC mains waveform can often be distorted and this can happen in many ways. For example, switching tones may be superimposed on the waveform or heavy transformer or Triac controlled loads may cause distortion by drawing rapidly varying currents during each half cycle. And as this implies, the AC load current waveform may be anything but a pure sine wave. For example, the current waveform for a transformer-driven appliance such as a TV set, VCR or stereo receiver will normally be a large spike in each half-cycle with a very high peak-to-average ratio. The current waveform for fluorescent light loads will be similar.

Similarly, the current waveform for a Triac controlled light dimmer will be



The LM13600 is a dual OTA package one of which is wired as a current-controlled oscillator for an add-on watt-hour meter facility which will be published in a later issue. Note that the circuit is tied directly to the 240VAC mains.

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heavily distorted, as the Triac chops the waveform every half-cycle.

Dynamometer

Up till now, the only instrument capable of making accurate power measurements under all the foregoing conditions has been the dynamometer. This is similar to a normal moving-coil meter except that it has two coils, one to replace the magnet in a moving-coil instrument.

The coils in the dynamometer are connected so that the magnetic fields they produce act to apply torque to the pointer. This torque is directly proportional to the product of the currents flowing in the two coils. So, in fact, the dynamometer is a device which can multiply two parameters, represented by currents, and display the result.

Used as a wattmeter for a single-phase 240VAC mains supply, the dynamometer is connected with one coil to monitor the voltage while the other coil monitors the load current.

One interesting point about the dynamometer is that the movement is usually highly damped so that the unit does not respond to rapid variations in the product of the two coil currents. Instead it responds to the average value of the products. In this respect the dynamometer can be regarded as an integrator as well as a multiplier. Dynamometers are usually very accurate, within ±1% of full-scale deflection.

Doing it electronically

The electronic equivalent of a dynamometer requires the use of a multiplier circuit. There are several ways of designing such a circuit but by far the most direct is to use a special type of operational amplifier known as an "output transconductance amplifier".

Well, what is so special about an OTA and how is it different from a normal op amp? An op amp is voltage-driven and its output is a voltage which is the product of the op amp gain (typically 100,000 or so) multiplied by the differential input voltage. So the normal op amp is a voltage amplifier with a fixed gain.

The OTA also has a differential input which is voltage driven but the output is a current. So instead of thinking in terms of voltage gain (ie, V/mV) for an OTA, we think in terms of "forward transconductance" which is expressed in millamps per volt or "mho" (ie, the reciprocal of "ohm"). The output current of the OTA can be easily converted back to a voltage by simply passing it through a suitable value of resistor.

There is nothing special about the fact that the OTA has forward transconductance (or g_m, as valve enthusiasts like to think of it) until you discover that the transconductance can be varied over an extremely wide range by a DC bias current. This bias current can be provided by a varying voltage source connected via a suitable series resistor. Thus, the OTA can be connected so that its gain is the product of two input voltages, ie, as a multiplier.

How the OTA is used in an electronic voltmeter circuit is depicted in Fig. 1. This shows a load connected across the active (A) and neutral (N) wires from the mains. The mains voltage across the load is monitored by op amp A1, via a voltage divider comprised of R1 and R2. A1 is a unity gain buffer stage which drives one

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input to the OTA multiplier. We have designated this the X input.

Similarly, a voltage proportional to the load current is developed across resistor R3 and fed to the Y input of the multiplier, via op amp A2, which is again a unity buffer stage.

The output of the multiplier is a current which is proportional to the product of the two inputs from op amps A1 and A2. The output current then drives a meter which can be calibrated to read in watts or kilowatts.

Circuit diagram

The similarity of Fig. 1 to the complete circuit diagram should be readily apparent. The function of op amps A1 and A2 is provided by IC1a and IC1b while the multiplier is IC2a. There are quite a few refinements though which we shall explain in the following blow-by-blow description.

The circuit is based on one published in the May 1983 issue of "Elektor" magazine.

R1 is made up of two 100kΩ resistors. Two resistors are specified so that the mains voltage applied to them does not exceed the voltage rating for ¼W resistors. R2 is a 2.7kΩ resistor and both R1 and R2 are specified at 1% tolerance to ensure accuracy.

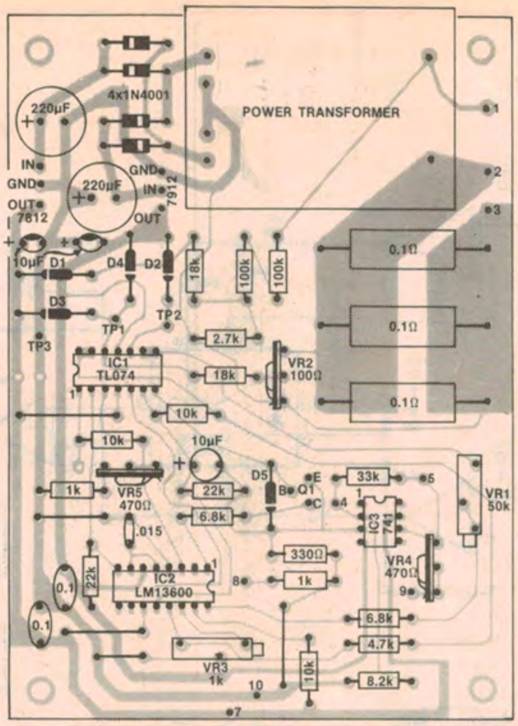
With 240VAC applied, the voltage across R2 is 3.2V RMS and this is fed via an 18kΩ resistor to the non-inverting input of IC1a. D1 and D2 provide input voltage protection for IC1a should the signal become excessive, as for example if a large transient voltage spike appears on the line.

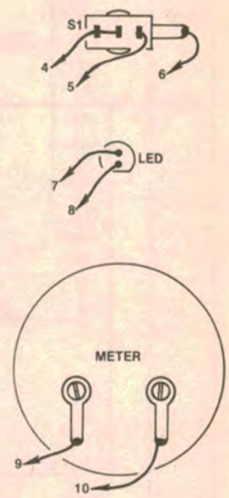
As noted before, IC1a is connected as a unity gain amplifier to buffer the voltage signal. The output of IC1 is then fed via VR1 and a 6.8kΩ resistor to the bias input on IC2a.

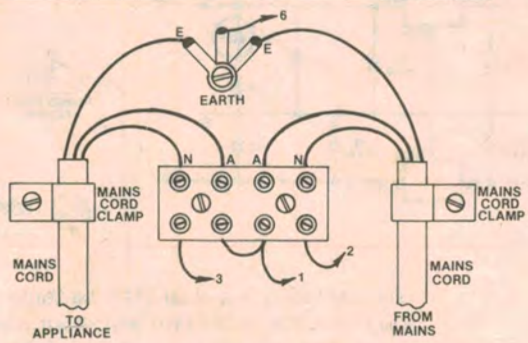
VR2 in conjunction with three parallel connected 0.1Ω resistors monitors the current drawn by the load. The signal from VR2 is fed via an 18kΩ resistor to the non-inverting input of IC1b which is also a unity-gain buffer. Its output signal is fed to the differential inputs of IC2a.

D3 and D4 protect the inputs of IC1b from excessive input voltage. In the same way as D1 and D2, they conduct to clip any signals which are in excess of 12.6 volts peak.

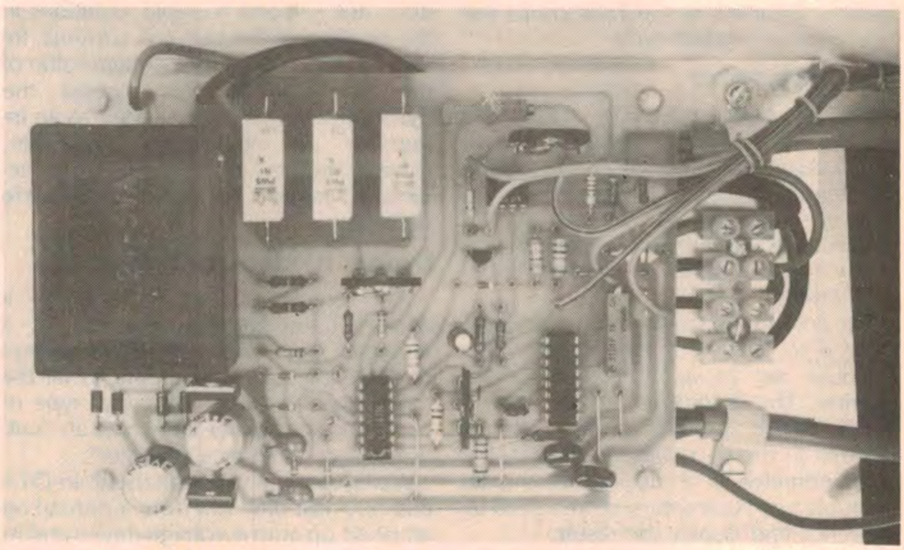
The output current from IC2a, which is a function of the product of the inputs at pins 13 and 16, is fed to a 10kΩ resistor to develop an output voltage. This is then fed to IC1c which has a gain of two and thence to IC3, the meter driving amplifier.







Note that R1a, VR2 and the three 0.1Ω/5W resistors must be left off the board until calibration has been completed.



IC3 has a switch across its 33kΩ feedback resistor so the gain can be changed from unity, giving a full-scale deflection of 3kW, to five, giving a full-scale deflection of 600W.

Q1, IC1d and IC2b are not essential to the operation of this circuit. They are included to provide for an add-on watt-hour meter which will be described in a later issue. Briefly, IC2b and IC1d form a current-controlled oscillator which delivers a signal frequency which is directly proportional to the power being registered on the meter scale. When this

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signal is fed to a suitable counter it is the basis of a watt-hour meter.

Q1 is a voltage-to-current converter for IC1c and diode D5 provides a forward current path to avoid reverse-biassing the base-emitter junction of Q1 when the output of IC1c is positive.

This concludes the description of the wattmeter circuit, apart from the power supply. This uses a transformer with a centre-tapped 24V secondary winding which drives a bridge rectifier and two 220μF/25VW filter capacitors to provided balanced supply rails of about ±17 volts. These are then regulated to ±12 volts DC with three-terminal regulators.

Construction

The construction of the wattmeter is straightforward but readers should note that when assembled and operating, the entire circuit may or may not be at full mains potential, depending on the correctness or otherwise of the mains wiring in the house or dwelling where it is used.

Because of this, the wiring of the wattmeter must be made on the assumption that it is all "live" and dangerous.

All of the circuit components with the exception of the meter are mounted on a printed circuit board measuring 100 x 140mm and coded 83wm8. This is housed in a standard plastic zippy box measuring 196 x 112 x 60mm.

No special order needs to be followed when assembling the PC board, although it is easier if some of the smaller components such as the wire links, resistors and diodes are mounted first. Take care with the orientation of

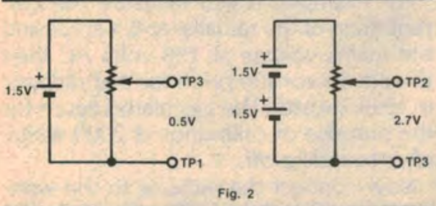


Fig. 2

polarised components such as the transistor, the diodes and electrolytic capacitors. No heatsinks are required for the three terminal regulators.

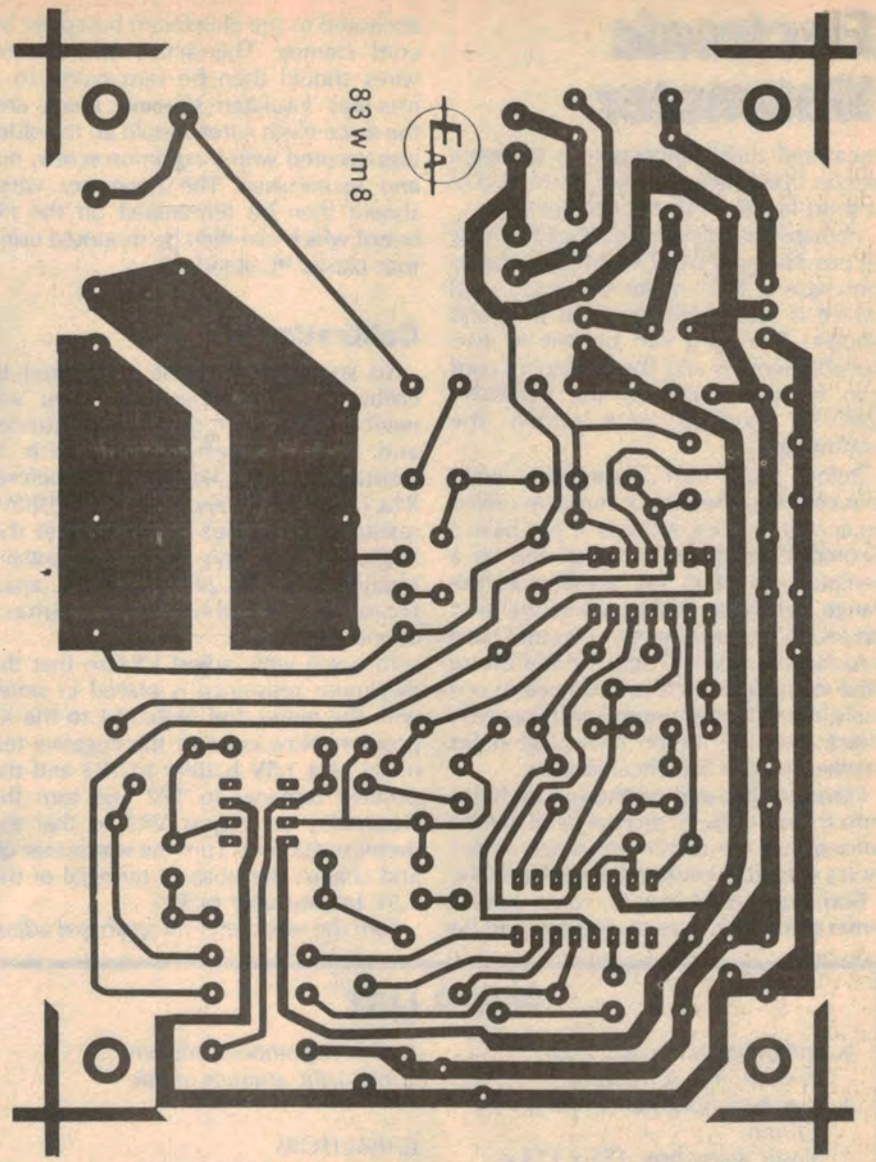
Omit these components

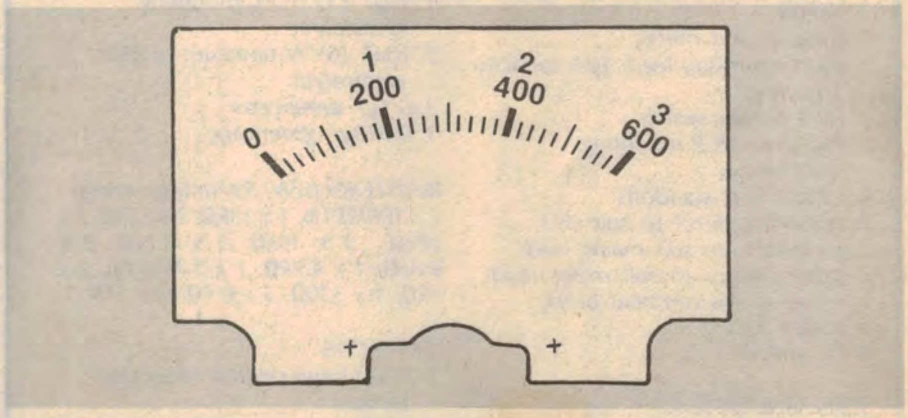
In order to be able to calibrate the unit it is necessary to isolate the circuitry from the 240VAC mains voltage. To this end, R1a, the three 0.1Ω/5W resistors and VR2 should be left off the PCB at this stage. When calibration is completed, these four components can be added.

With the assembly of the PC board complete it is most important that the remaining wiring details should be identical to those depicted on the wiring diagram we have included with this article.

When it is completed the wattmeter must have no exposed metalwork which is not earthed back via the mains. This means that not only must the metal baseplate of the case be earthed but so also must the metal bush of the range toggle switch.

Mains connection to the wattmeter is made via a three-core mains cord and three-pin plug and thence to a standard power point. The appliance to be





Here is the actual size artwork for the PCB and meter scale.

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measured then connects to a three-pin socket from the wattmeter, at the end of a short length of three-core flex.

Perhaps the easiest and cheapest way of providing the two cords required is to purchase a short mains extension cord which is fitted with moulded plug and socket. The cord can be cut to two suitable lengths and the remaining cord can be the source of the necessary 240VAC hookup wire within the wattmeter.

Before you start assembling components into the case it must be drilled to accept the power cords. If you have a Scotchcal label you can use this as a template to mark the position of the range switch for drilling. While we used an MU45 meter from Altronics and have produced a scale to suit, we are aware that many constructors may have to use a slightly different meter. For this reason there are no meter mounting holes marked on the Scotchcal label.

Having drilled and cut the various holes into the case, the Scotchcal label can be affixed and the meter and range switch holes cut into it using a sharp utility knife.

Both input and output cords should enter the plastic case at one end and be anchored to the aluminium baseplate by cord clamps. The active and neutral wires should then be terminated to a four-way insulated terminal block and the three-earth wires should go to solder lugs secured with a common screw, nut and lockwasher. The necessary wires should then be terminated on the PC board which can then be mounted using four plastic PC standoffs.

Calibration

No special equipment is required to calibrate the wattmeter but you will need a multimeter, three 1.5V batteries and two potentiometers with a resistance around 1kΩ. As noted before, R1a, (100kΩ), VR2 and the three 0.1Ω/5W resistors should not be installed at this stage, so that the PCB is essentially isolated from the 240VAC mains, apart from the transformer primary connection.

To begin with, adjust VR4 so that the maximum resistance is placed in series with the meter and switch S1 to the X1 position. Now connect the negative terminal of a 1.5V battery to TP3 and the positive terminal to TP2 and turn the wattmeter on. Adjust VR3 so that the meter reads zero. Turn the wattmeter off and change the positive terminal of the 1.5V battery over to TP1.

Turn the wattmeter on again and adjust VR1 so that the meter again reads zero. Adjust VR4 so that the wiper is set at about half rotation then repeat the procedure of connecting the positive terminal of the 1.5V battery to TP2 and TP1 and adjusting the respective trimpots.

Turn the wattmeter off, construct the calibration circuits shown in Fig. 2 and connect these to the indicated test points. Turn the wattmeter on and adjust VR4 for a meter reading of 3000W.

We estimate that the current cost of components is approximately

$65

This includes sales tax

That completes the calibration procedure except for the setting of VR2. R1a, VR2 and the three 0.1Ω/5W resistors can now be installed. The three latter resistors should be raised off the board by about three or four millimetres to avoid any possibility of charring the board when the resistors get hot. When a 10A load is connected, the three resistors will dissipate a total of 3.3 watts, which is enough to make them quite warm.

To set VR2 accurately, and thus take account of the tolerance of the current monitoring resistors, you will need a high current resistive load, such as a 2400W radiator, and a multimeter which can read up to 10 amps AC and 240VAC. Essentially what has to be done is to use the multimeter to measure the load current drawn by the radiator for a given mains voltage, and calculate the power.

For example, if you measure the current drain of the radiator at 8.4 amps and the mains voltage at 238 volts AC then the power consumption for that radiator is 1999.2 watts. The calculated figure for the purpose of calibration is 2000 watts, after rounding off.

Now connect the radiator to the wattmeter and adjust VR2 to give the calculated reading. Remember that VR2 is nominally in the neutral side of the mains circuit but it could be at full mains voltage. **This means that adjustment of VR2 must be done with a screwdriver with a fully insulated blade.**

If you do not have access to a suitable multimeter, VR2 should be set so that the wiper is all the way over towards D5.

That completes the description of our new wattmeter. The oscillator associated with IC2b need not be adjusted unless you build the companion watt-hour counter board which will be described in a future issue.

PARTS LIST

1 Printed circuit board, code 83wm8, 138 x 100mm.
1 Scotchcal front panel, 193 x 110mm
1 plastic zippy box, 195 x 113 x 60mm
1 MU45 1mA FSD moving coil meter
1 scale to suit meter
1 short extension lead, 10A capacity (see text)
1 SPST toggle switch
1 PL24/5VA PCB mounting transformer
4 12mm PCB standoffs
1 mounting bezel to suit LED
2 grommets to suit mains lead
2 cable clamps to suit mains lead
1 4-way mains terminal block
4 solder lugs
3 PC stakes

SEMICONDUCTORS
5 1N4148 diodes
4 1N4001 diodes
1 7812 three terminal regulator
1 7912 three terminal regulator
1 BC557 small signal transistor
1 TL074 operational amplifier
1 LM13600 or LM13700 transconductance amplifier
1 741 operational amplifier
1 red light emitting diode

CAPACITORS
2 220μF 25VW PC-mounting electrolytics
1 10μF 25VW PC-mounting electrolytic
2 10μF 16VW tantalum or RBLL electrolytic
2 0.1μF greencaps
1 0.015μF greencap

RESISTORS (¼W, 5% unless stated)
2 x 100kΩ 1%, 1 x 33kΩ, 2 x 22kΩ, 2 x 18kΩ, 3 x 10kΩ, 1 x 8.2kΩ, 2 x 6.8kΩ, 1 x 4.7kΩ, 1 x 2.7kΩ 1%, 2 x 1kΩ, 1 x 330Ω, 3 x 0.1Ω 10% 5W.

TRIMPOTS
1 100Ω large vertical mounting trimpot
2 470Ω large vertical mounting trimpots
1 1kΩ multiturn trimpot
1 50kΩ multiturn trimpot

MISCELLANEOUS
Hook-up wire, machine screws and nuts, solder etc.