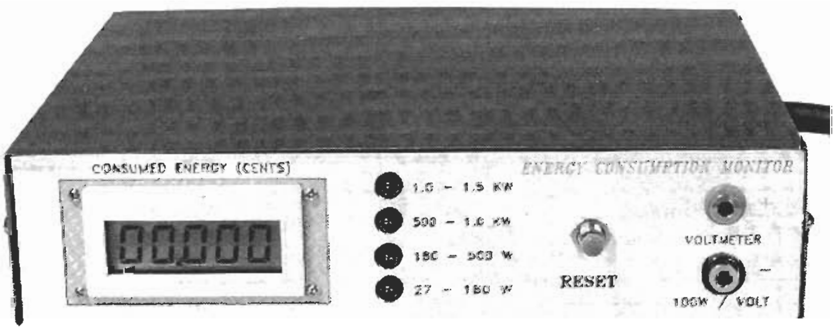
ENERGY CONSUMPTION MONITOR



Build this energy consumption monitor and find out how much it costs to run your household appliances.

PAUL BRULE

IF YOU'RE CONCERNED WITH ENERGY cost and conservation, as most people are, you'll be interested in our energy consumption monitor (ECM). Without the ECM, it's difficult for the average person to determine how much an individual home appliance costs to run. That's especially true for appliances with variable duty cycles such as a refrigerator which will have its compressor and fan motors, lights and other loads on at different times.

Our energy consumption monitor can display the accumulated cost in cents for the connected home appliance load. What did you spend to operate your toaster yesterday? What about your TV or air conditioner? Is the cost of energizing that spare freezer unit worth the few pennies saved when you bought your meat on sale? The ECM will help you to answer those questions quickly.

The ECM can also be used as a power meter by connecting a DMM to the voltage output of the monitor. Using the DC scale of your meter, each volt represents 100 watts. For example, a reading of 0.56 volts would translate to 56 watts.

To give you an idea of what the average residential Long Island, NY consumer pays monthly for operating various appliances, refer to Table 1. The monthly cost was based on a rate of 13¢ per kilowatt-hour (kWh). The average Long Island resident uses about 600 kWh's per month, which translates into a monthly electric bill of $91.81.

The current electric rates for the Long Island, NY area are among the highest in the U.S. and vary depending on the season and the total amount of kWh's used. The summer rates are 12.87¢ for 0–250 kWh's used and 14.1¢ for 250–350 kWh's. The winter rates are 12.87¢ for 0–250 kWh's and 12.33¢ for 250–350 kWh's. Of course electric rates will vary, depending on the size of your family, the region of the country in which you live, and the utility company who services you. The information provided is only a rough basis to compare your own power consumption to that of the *average* Long Islander. Let's see how this useful device works.

About the circuit

The ECM circuit consists of four sections, as shown in the block diagram of Fig. 1. A power converter generates a voltage that is proportional to the true or real power consumed by the load. That voltage feeds both a bargraph and a voltage-to-pulse converter. The bargraph gives an approximate indication of the amount of power used, and the voltage-to-pulse converter produces a pulse whose frequency is proportional to the power. The pulse triggers the counter module which displays the cost of powering the monitored load.

The power converter

In order to determine the actual power consumed by an appliance, we must find the phase angle between the voltage and current in the overall circuit. We know that

$$P = V \times I \cos\theta$$

where $\cos\theta$ is known as the power factor. Since the voltage of the monitored load is fairly constant at about 117 volts, we can say that the power is proportional to $I \times \cos\theta$. To obtain the phase angle, both the voltage and current must be monitored. Transformer T1 supplies the voltage, while the current-proportional voltage is obtained by stepping up (by a factor of 20) the voltage drop across shunt resistors R1-a–d via T2.

The ECM is capable of accurately monitoring the effective power of inductive loads. If a capacitive load is connected to the ECM, only the apparent power, not the effective power, will be monitored, causing some degree of inaccuracy. That shouldn't pose much of a problem because just about all reactive household loads are inductive. However, some appliances such as refrigerators, freezers, and air conditioners use capacitor-start inductive motors, which are characterized by a high starting torque. Those types of motors will present a capacitive loading effect on the power line, but only during start-up, which is a very short time interval compared to

TABLE 1—AVERAGE WATTAGE, USAGE AND COST OF HOUSEHOLD APPLIANCES

Appliance	Wattage	Estimated Monthly Usage (Hours)	Monthly Consumption (kWh)	Monthly Cost*[1]
Food Preparation				
Broiler	1,140	6.3	7.2	$0.94
Coffee maker (drip)	1,200	9.8	11.8	$1.53
Microwave oven	1,450	10.9	15.8	$2.05
Oven range	12,200	4.8	58.6	$7.62
Toaster	1,146	2.8	3.2	$0.42
Home Entertainment				
Color TV (tube)	240	180.0	43.2	$5.62
Color TV (solid state)	145	180.0	26.1	$3.34
VCR	20	120.0	2.4	$0.32
Radio	71	100.9	7.2	$0.94
Stereo	109	83.3	9.1	$1.18
Refrigerator				
Frost free, 10-15 years old	—	continuous	141.2	$18.36
Ref./freezer, frost-free, 10-15 years old	—	continuous	153.0	$23.80
18-cubic foot ref./freezer, new	—	continuous	100.65	$13.08
16-cubic foot ref./freezer, new	—	continuous	77.66	$10.10
Air Conditioning				
Room AC, 6,500 BTU's*[4] (before 1980)	EER*[2] 7.2–930	116.0	108.0	$14.04
Room AC, 6,500 BTU's (after 1980)	EER 8.5–770	116.0	89.0	$11.57
Room AC, 6,500 BTU's (after 1980)	EER 9.5–680	116.0	79.0	$10.27
Central, 3-ton AC (before 1980)	SEER*[3] 8–4,500	180.0	810.0	$105.00
@ 12,00W/ton (after 1980)	SEER 9.5–3,790	180.0	682.0	$88.60
40,000 BTU's (after 1980)	SEER 11.0–3,270	180.0	589.0	$76.57
Fan (window)	200	150.0	30.0	$3.90
Water heater	—	—	350.0	$45.50
Washer (1 load/day)	512	16.8	8.6	$1.12
Clothes dryer (1 load/day)	4,856	17.0	82.6	$10.74
Dishwasher (1 load/day)	1,201	25.2	30.3	$3.94
Iron	1,100	—	5.0	$0.65
Vacuum	630	6.1	3.8	$0.50
Clock	2	708.3	1.4	$0.18
Blow dryer	1,235	6.8	8.4	$1.10

Notes*
1. The monthly cost is based on an average rate of 13¢/kWh.
2. Energy efficiency ratio.
3. Seasonal energy efficiency ratio.
4. BTU's/EER = watts.

All figures noted in this table were obtained from Long Island Lighting Company's (LILCO) Energy Conservation Department.

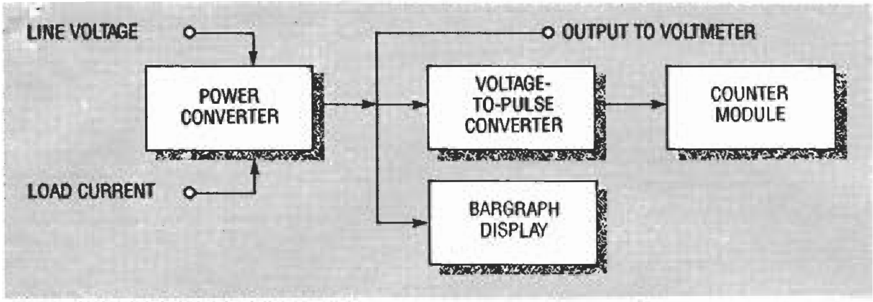


FIG. 1—THE BLOCK DIAGRAM of the energy consumption monitor.

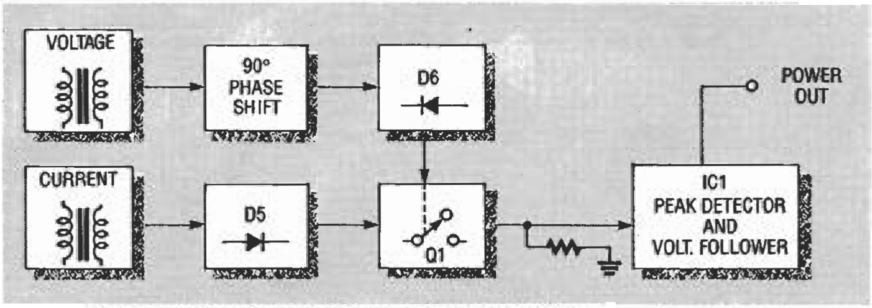


FIG. 2—THE BLOCK DIAGRAM OF THE POWER CONVERTER section of the ECM.

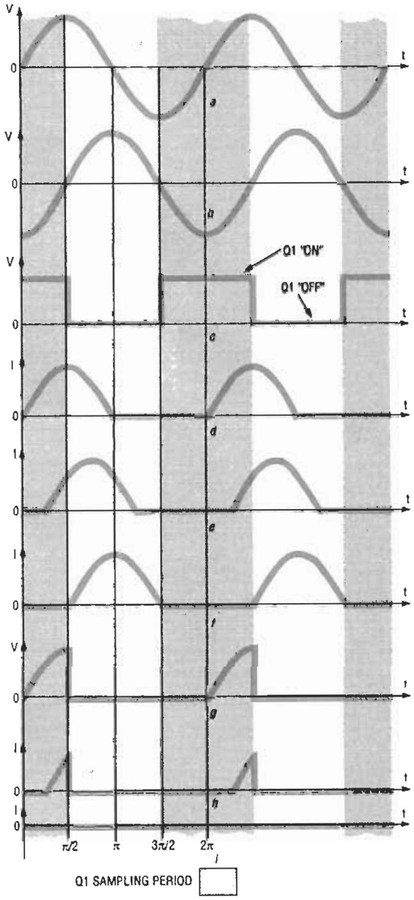


FIG. 3—POWER CONVERTER waveforms: sinusoidal waveform from T1 (*a*); T1 voltage is delayed by 90° (*b*); Q1 turns on when the delayed voltage goes negative (*c*); half-wave rectified current signal from a purely resistive load (*d*); half-wave rectified current signal from a resistive and inductive load (*e*); half-wave rectified current signal from a purely inductive load (*f*); when Q1 turns on, it captures the first 90° of the current signal of a resistive load (*g*); sampled current signal of a resistive and inductive load (*h*); sampled current signal of a purely inductive load (*i*).

the continuous operation of such appliances.

Figure 2 shows a block diagram of the power converter circuit. The voltage from the potential transformer T1 (Fig. 3-*a*) is delayed by 90° (Fig. 3-*b*), controlling transistor switch Q1 (Fig. 3-*c*), which turns on during the negative cycle of the wave. Now, let's consider how three types of loads are monitored: purely resistive, equally resistive and inductive, and purely inductive.

In a purely resistive AC circuit, the current is in phase with the voltage, therefore the half-wave rectified signal from the current transformer will look like that of Fig. 3-*d*. Since the switch (Q1) is on until the first 90° of the wave, the peak of that wave (Fig. 3-*g*) will be passed on to the peak detector consisting of IC1. We can now say that $V_{OUT} = V_{PK}$ of the current transformer.

In a circuit consisting of equal resistance and inductive reactance, the current will lag the voltage by 45°. That signal, when half-wave rectified (Fig. 3-*e*) and gated by Q1 will look like that of Fig. 3-*h*. As you can see, the switch allows only the first 45° of the wave to be sampled by the peak detector, therefore

$$V_{OUT} = V_{PK} \sin(90 - \theta).$$

since

$$\sin(90 - \theta) = \cos\theta,$$

then

$$V_{OUT} = V_{PK} \cos\theta.$$

An ideal inductor does not dissipate any power, and its AC current will lag the applied voltage by 90°. As a result, once the half-wave rectified current waveform (Fig. 3-*f*) of such a load is switched by Q1, the resulting output is zero, therefore

$$V_{OUT} = V_{PK} \cos\theta.$$

(Fig. 3-*i*.)

The schematic of the energy consumption monitor is shown in Fig. 4. Components R6–R8 and C5–C7 form a 90° phase shift network which switches Q1 on via R9 and R10 during the negative-going part of the wave. The voltage present at the secondary of the current transformer (T2) is half-wave rectified by D5. Diodes D3 and D4 limit the secondary voltage to approximately 40 volts peak to protect D6 and Q1 from excessive voltage should a high-current surge occur. When Q1 is turned on, it will couple any of the half-wave rectified signals to R11, and to the peak detector consisting of IC1-*a*, D7, C9, and R12. The wiper of R11 is set to calibrate the peak detector output so that it produces 1 volt for every 100 watts consumed by the load. Finally, that voltage is buffered via the voltage follower IC1-*b* to feed an external voltmeter, the bargraph meter, and the voltage-to-pulse converter.

The voltage-to-pulse converter is basically a voltage controlled oscillator (VCO). The power voltage (from IC1-*b*) charges C10 via R13 and R14 until the capacitor voltage attains the trigger voltage of the Schmitt trigger, consisting of IC2, R16, and R17. Once triggered, the negative voltage swing from the output of IC2 quickly reverses the capacitor charge via R15 and D8, and is ready to repeat the cycle again. The higher the voltage feeding the RC timing network, the higher the pulse repetition, or frequency, will be. That pulse is used to increment the counter module through voltage-divider resistors R18 and R19. Diode D9 assures that the counter sees a pulse of the proper polarity. A nice feature of the display counter is that it is powered by a single AA battery mounted on the back. That makes sure the count is retained if the ECM is

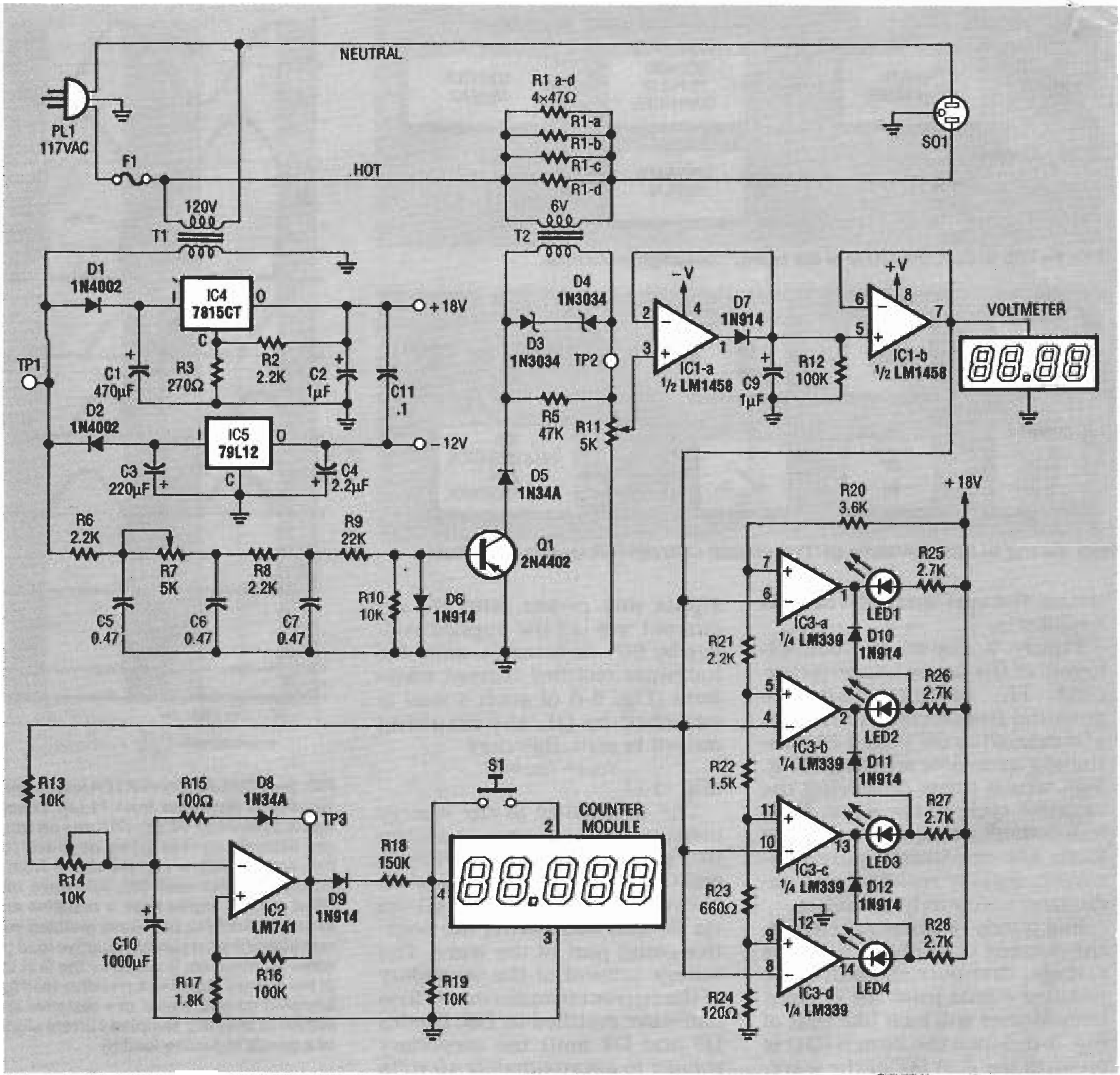


FIG. 4—THE SCHEMATIC OF THE ECM; R6–R8 and C5–C8 form the 90° phase shift network, which switches Q1 on. R11 calibrates the peak detector output so that it produces 1 volt for every 100 watts consumed by the load.

unplugged, or in the event of a power failure.

At the heart of the bargraph is IC3, a quad comparator. The power voltage drives all of the comparator's inverting inputs while each of the non-inverting inputs are tied to different voltage references derived by the voltage divider network of R20 to R24. As the voltage signal increases above the reference voltage level, the open collector output of that particular comparator goes low, switching its corresponding LED on. Diodes D14, D15, and D16 ensure that the previously lit LED is turned off as the power increases, thus allowing no more than one LED to remain on at a time.

The power-supply section is fairly straightforward. The transformer's (T1) voltage is half-wave rectified, and is then filtered by C1. The voltage divider R2 and R3 is used to boost the output voltage of regulator IC4 to approximately 18 volts. IC4 could easily be replaced with a 7818 voltage regulator, thereby eliminating the need for R2 and R3 (a shorting jumper would have to replace R3). Except for the voltage-divid-

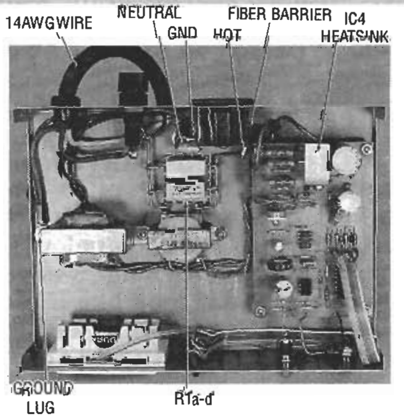


FIG. 5—HERE IS THE FINISHED prototype. It's a good idea to use standoffs to mount the transformers so that R1-a–d's connections are adequately spaced from the case. The author also used a fiber barrier between the PC board and the AC socket for added protection.

PARTS LIST

All resistors are ¼-watt, 5%, unless otherwise indicated.
R1-a–d—0.39 ohms, 5 watts
R2, R6, R8, R21—2200 ohms
R3—270 ohms
R4—not used
R5—47,000 ohms
R7, R11—5000 ohms, trimmer potentiometer
R9—22,000 ohms
R10, R13, R19—10,000 ohms
R12, R16—100,000 ohms
R14—10,000 ohms, trimmer potentiometer
R15—100 ohms
R17—1800 ohms
R18—150,000 ohms
R20—3600 ohms (see text)
R22—1500 ohms
R23—680 ohms
R24—120 ohms
R25–R28—2700 ohms

Capacitors
C1—470 µF, 35 volts, radial electrolytic
C2, C9—1µF, 35 volts, tantalum
C3—220 µF, 63 volts, radial electrolytic
C4—2.2 µF, 35 volts, radial electrolytic
C5, C6, C7—0.47 µF, 100 volts, polyester
C8—not used
C10—1000 µF, 16 volts, radial electrolytic
C11—0.1 µF, 50 volts, ceramic

Semiconductors
D1, D2—1N4002 diode
D3, D4—1N3034, 39 volts, Zener diode
D5, D8—1N34A germanium diode
D6–D12—1N914 diode
Q1—2N4402 PNP transistor
IC1—LM1458 dual op-amp
IC2—LM741 op-amp
IC3—LM339 quad comparator
IC4—LM7815 or LM7818 voltage regulator (see text)
IC5—LM79L12 12-volt negative voltage regulator
LED1—red LED
LED2–LED4—green LED

Other components
F1—15-amp fuse
SO1—chassis-mount, grounded AC socket
T1—18 volts (or 24 volts), 200 mA transformer
T2—6 volts, 200 mA transformer (connected as a step-up transformer)
Counter module—LCD electronic counting module (Radio Shack number 277-302)
S1—momentary SPST push button switch
Miscellaneous: 2 chassis-mount banana sockets, fuse socket, strain relief, PC board, hardware, wire, metal enclosure (Radio Shack 270-272A).

NOTE: The following items are available from Paul Brule, 12L67 Harbourview Rd., Port Colborne, Ontario, Canada L3K 5V4. An etched and drilled PC board, $15.95; a kit consisting of all resistors, capacitors, semiconductors and PC board for $59.95; a lettered faceplate and template which fits a Radio Shack 270-272A case, $7.95. Please include $2.50 for shipping and handling. All prices are in US funds.

er resistors, the negative supply is basically a mirror image of its positive counterpart.

Construction

Figure 5 shows the authors completed prototype. Transformers T1 and T2, SO1, F1, LED1–4, counter display, S1, J1 and J2 are mounted on the enclosure, while the remaining secondary circuitry is installed on a single-sided PC board. The foil pattern is provided if you would like to make your own, or you can obtain an etched and drilled board from the source mentioned in the parts list. Mount and solder all components according to the parts placement diagram shown in Fig. 6, observing correct polarity. The 7815 regulator should be fitted with a heat sink. You can do that by drilling a ½″ × 1-½″ × 1⁄16″ piece of aluminum and mounting it to the T0-220 case.

The ECM should be enclosed in a suitable metal case as hazardous line voltage is present. It is important to use no. 14 AWG or heavier gauge wire for all primary wiring. Make sure the neutral side of the plug corresponds to that of the socket. The photograph in Fig. 5 shows where the hot (power supply black lead) and neutral (white lead) conductors are connected.

Grounding should be made by terminating the green grounding conductor of the power-supply cord and socket ground lead to a closed-loop connecter. Mount the connector through the transformer mounting screw and secure to the chassis ground through a star washer to bite through the painted or plated metal case. You can also sand the paint away to make a good contact. Resistors R1-a–R1-d should be adequately ventilated by using a louvered enclosure top. Those resistors could get quite hot if constant heavy loads over 1000 watts are monitored.

Now it's time to mark a decimal point on the counter display. Using a fine-tip black felt pen, mark the decimal point on the display between the third and fourth digit so that, when the monitor is properly calibrated, each count represents 1⁄1000 of a cent.

When wiring T2, remember to wire the 6-volt winding across the shunt resistors R1-a–R1-d so that you're using it in a step-up mode.

Locating a 3.6K resistor for R20 may be rather difficult since that is a non-standard value. The author happened to have a few of them in his parts collection, but you may consider wiring a 3.9K and a 47K resistor in parallel to obtain that value.

Calibration and testing

Before applying power to your circuit, double check your wiring. If you're using IC sockets, leave IC1, IC2, and IC3 out of the circuit. Apply power and check for +18 volts and −12 volts at the outputs of IC4 and IC5, respectively. Those voltages may be slightly lower by a fraction of a volt. If you have removed the IC's and the voltages are okay, then unplug the unit, install the IC's, re-apply power, and re-check the supply voltages.

The next step is to check the transformer phasing. In order to do that, temporarily install a jumper from ground to the cathode of D5. Now connect a 100-watt light to the load socket. Using a voltmeter on the AC scale, make sure the voltage between TP1 and TP2 is lower than that measured between TP1 and ground. If it isn't, reverse the two PC-board connected T2 leads. Recheck and remove the jumper.

With *NO LOAD* connected to

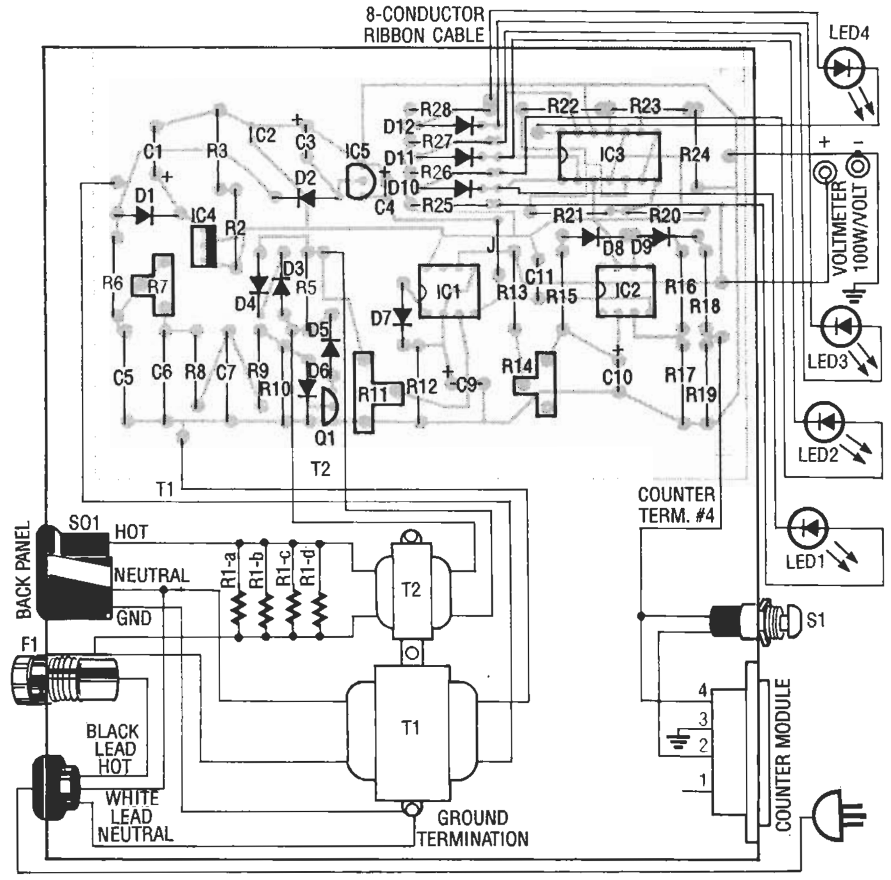
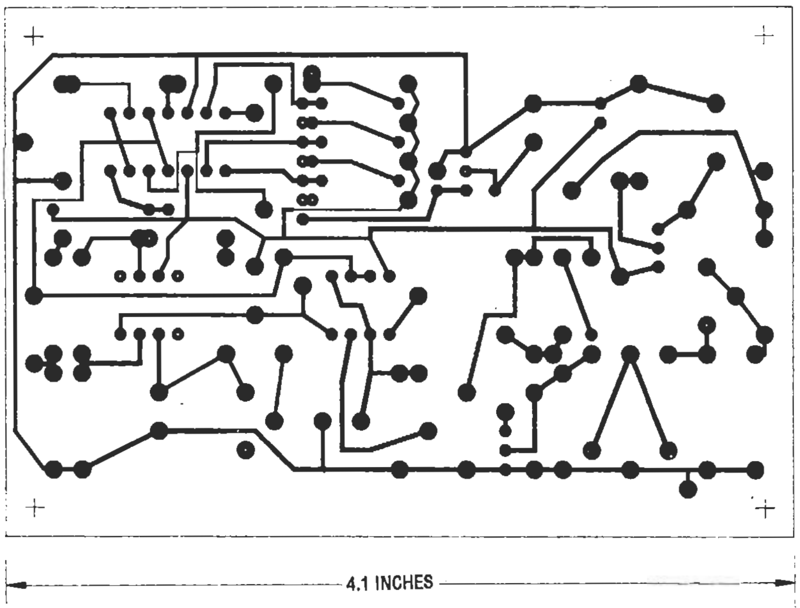


FIG. 6—PARTS PLACEMENT DIAGRAM AND WIRING connections. Use 14 AWG wire for all primary leads, and make sure you wire the hot and neutral leads of the power supply cord to the proper terminations on the AC socket.



THIS IS THE FOIL PATTERN of the solder side of the PC board.

the ECM, connect a jumper between the +18-volt supply and TP2. Connect a DC meter to the power-voltage output and check to see that the voltage varies from 0 to approximately 16.5 volts as R11 is varied from one end to the other. As you do that, the LED's should increment at about 0.27, 1.8, 5, and 10 volts. Now, using the formula

$$V_{CAL} = 36/\text{rate},$$

where V_{CAL} is the calibration voltage and rate is your cost in cents per kilowatt-hour (check your billing statement or power company for that rate). Adjust R11 to read that value on the voltmeter. That will enable you to calibrate R14 so that you obtain one pulse per second (1 Hz) at TP3. A doubling or halfing of V_{CAL} should approximately double or half the pulse rate. Remember, each pulse represents 1/1000 of a cent.

Disconnect the jumper used in the previous procedure and connect a 100-watt light as a load. Using an oscilloscope, monitor the waveform at TP2 and set R7 so that the sampling ends at the very peak of the incoming waveform, which should look like the waveform of Fig. 3-*g*.

Finally, power calibration is the last to be performed. With the 100-watt light connected adjust R11 so that a DMM, connected to the external voltmeter jacks, displays 1.00 volt DC. You may want to verify that wattage by measuring the voltages across shunt resistor R1, and the line. With those two voltage readings, the power maybe calculated using the formula

$$P(\text{watts}) = V_{SHUNT} \times V_{LINE}/R_{SHUNT},$$

where R_{SHUNT} is the shunt resistance (four 0.39-ohm resistors in parallel = 0.0975 ohms). V_{SHUNT} is the voltage drop across R1 and V_{LINE} is the AC line voltage.

That completes the assembly and calibration of the ECM. There is one point that should be mentioned here. The voltage to pulse converter will not start until there is a load of approximately 30 watts, meaning that the counter will not increment unless the load is heavier than that value.

For those of you wondering if investing in an energy consumption monitor is worthwhile, consider this: You'll be able to determine how much it costs to run a particular appliance for a certain length of time. So it's easy enough to figure out if it's actually cheaper to run the microwave oven for five minutes or the conventional oven for ten minutes, and so on. Using the energy consumption monitor, you'll also be able to determine if buying extra meat at really good sale prices actually saves you money in the long run. The greatest advantage of the energy consumption is keeping one step ahead of your power company. **R-E**