Low-cost instrument measures 4-decade power

Using standard parts, a watt/watt-hour meter calculates power consumption for line-powered devices over an extremely wide measurement range—2W to 2 kW FS. And its multiple analog and digital outputs allow both direct and time-related power readings.

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If you must monitor the usage of costly electricity in commercial, industrial or consumer equipment designs, build the inexpensive but versatile watt/watt-hour meter described in this article. It resolves power measurements to as low as 0.1W, achieving 2% accuracy over 25±5°C. And it can determine the power consumption of any 115V ac unit, from large factory machines to small hand-held tools. The instrument requires only about $175 worth of off-the-shelf parts, whereas many conventional power meters cost much more and provide lower performance.

To handle a wide variety of power measurements, mostly in cases where energy conservation has high priority, the instrument provides three analog and two digital power-related outputs. One analog output—serving a 200-μA FS meter—displays power values in watts. Another furnishes 0 to 5V for driving strip-chart recorders, while the third supplies instantaneous-power-output levels for use in external-tracking applications. One of the digital outputs—a readout—indicates time-based or watt-hour readings; the second supplies watt-hour data for use by external equipment.

A look at the overall approach

The watt/watt-hour meter's design is straightforward (**Fig 1**). The device under measurement plugs into a standard 115V ac outlet mounted on the instrument's front panel. With line power applied, the ac voltage across the monitored load passes through a resistor divider and feeds (via an op amp) to an analog

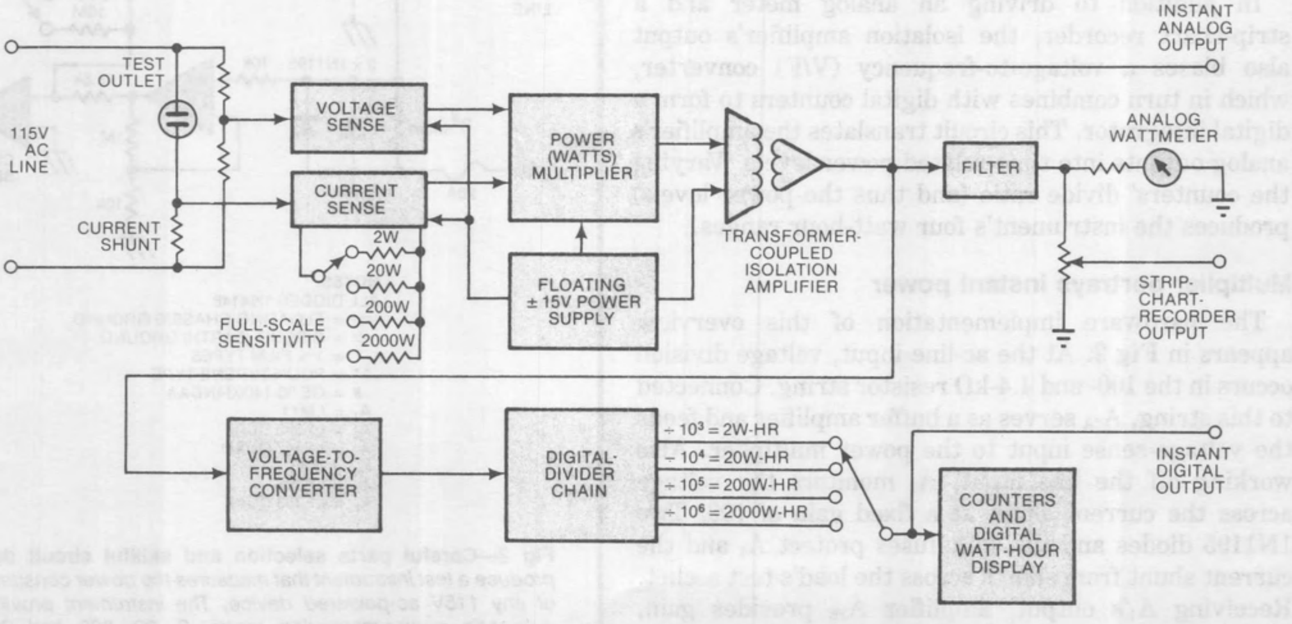


Fig 1—An inexpensive watt/watt-hour meter *incorporates (in series) a current shunt, voltage- and current-sense amplifiers, a power multiplier and a transformer-coupled isolation amplifier. These circuits generate amplitude-modulated pulses that represent the monitored device's instantaneous power consumption, measured in watts. Voltage-to-frequency conversion precedes a counter and a digital display of power levels in watt-hours.*

Single low-resistance shunt handles all four power ranges

power multiplier.

The voltage across a low-resistance shunt represents the current through the load. Even when measuring a 20A max flow, this shunt needs only 133 mV—a feature that eliminates high-resistance-current-shunt inaccuracies. Additionally, by accommodating all four power ranges—2, 20, 200 and 2000W FS—the single shunt eliminates the need to switch-in high-impedance shunts for high-sensitivity scales.

The instrument's measurement technique utilizes the low input error in a current-sense amplifier, whose output also goes to a power multiplier. Switchable gain within the amplifier makes possible the 4-decade sensitivity setting. A 4-quadrant configuration, the power multiplier produces an output representing the test load's true instantaneous-power product (E×I), regardless of the load's relative voltage and current phases.

Because the multiplier and its associated voltage- and current-sense amplifiers connect directly to the ac line, though, they require a floating ±15V power supply. Consequently, you can't safely monitor their outputs with grounded test equipment, such as strip-chart recorders. To deal with this problem, the multiplier's output drives an isolation amplifier that operates at unity gain but has no galvanic connection between its input and output terminals. The amplifier employs pulse-amplitude-modulation techniques in conjunction with a small transformer. By grounding its output, you can safely connect test equipment to all circuits following the transformer.

In addition to driving an analog meter and a strip-chart recorder, the isolation amplifier's output also biases a voltage-to-frequency (V/F) converter, which in turn combines with digital counters to form a digital integrator. This circuit translates the amplifier's analog outputs into time-related power levels. Varying the counters' divide ratio (and thus the power levels) produces the instrument's four watt-hour ranges.

Multiplier portrays instant power

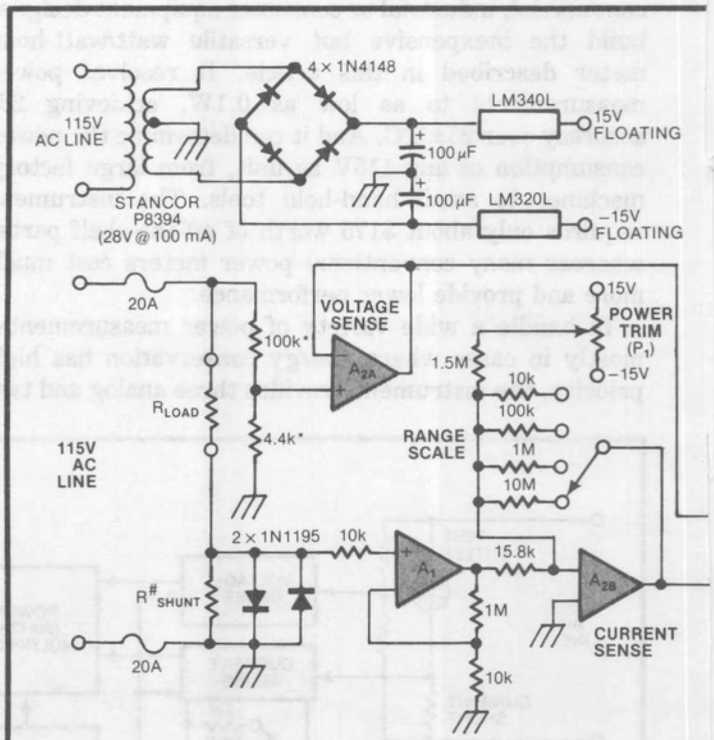
The hardware implementation of this overview appears in **Fig 2**. At the ac-line input, voltage division occurs in the 100- and 4.4-kΩ resistor string. Connected to this string, A_{2A} serves as a buffer amplifier and feeds the voltage-sense input to the power multiplier. Also working off the line input, A_1 monitors the voltage across the current shunt at a fixed gain of 100. Two 1N1195 diodes and two 20A fuses protect A_1 and the current shunt from shorts across the load's test socket. Receiving A_1's output, amplifier A_{2B} provides gain, calibrated wattage switching from 2 to 2000W FS and the power multiplier's current-sense input.

Composed of amplifiers A_{3C} and A_{3D} and an LM394 IC's dual transistors, the multiplier—a variable transconductance type—uses its current-sense input to vary a 2N2222 transistor amplifier's gain. This amplifier receives A_{2A}'s voltage-sense output as its input.

At the multiplier's output, A_{3C} produces an output representing the load's instantaneous power consumption (**Fig 3, trace A**). This output in turn biases a pulse-amplitude-modulating isolation amplifier (A_{3A} and A_{3B}) and three transistors (Q_1 to Q_3).

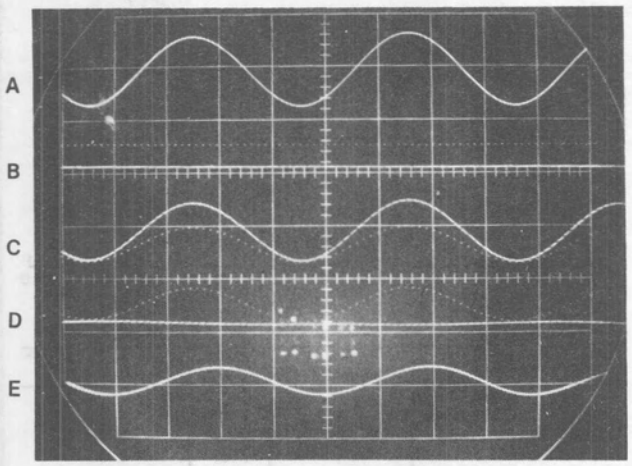
Generating an oscillator output (trace B), A_{3A} biases the Q_1/Q_2 switch connected across the transformer's primary. Meanwhile, A_{3B}'s negative input measures the pulses' amplitude at the transformer's primary. A_{3B} then servo-controls the pulses to the same amplitude as those received at its positive input (biased by the multiplier's output). Transistor Q_3 provides current-drive capability and completes A_{3B}'s feedback path.

Trace C in **Fig 3** illustrates how Q_3's emitter voltage changes to meet the servo-loop requirements. Trace D shows the pulses applied to the transformer. Note that these pulses' amplitudes form an envelope whose amplitude equals the multiplier's output.



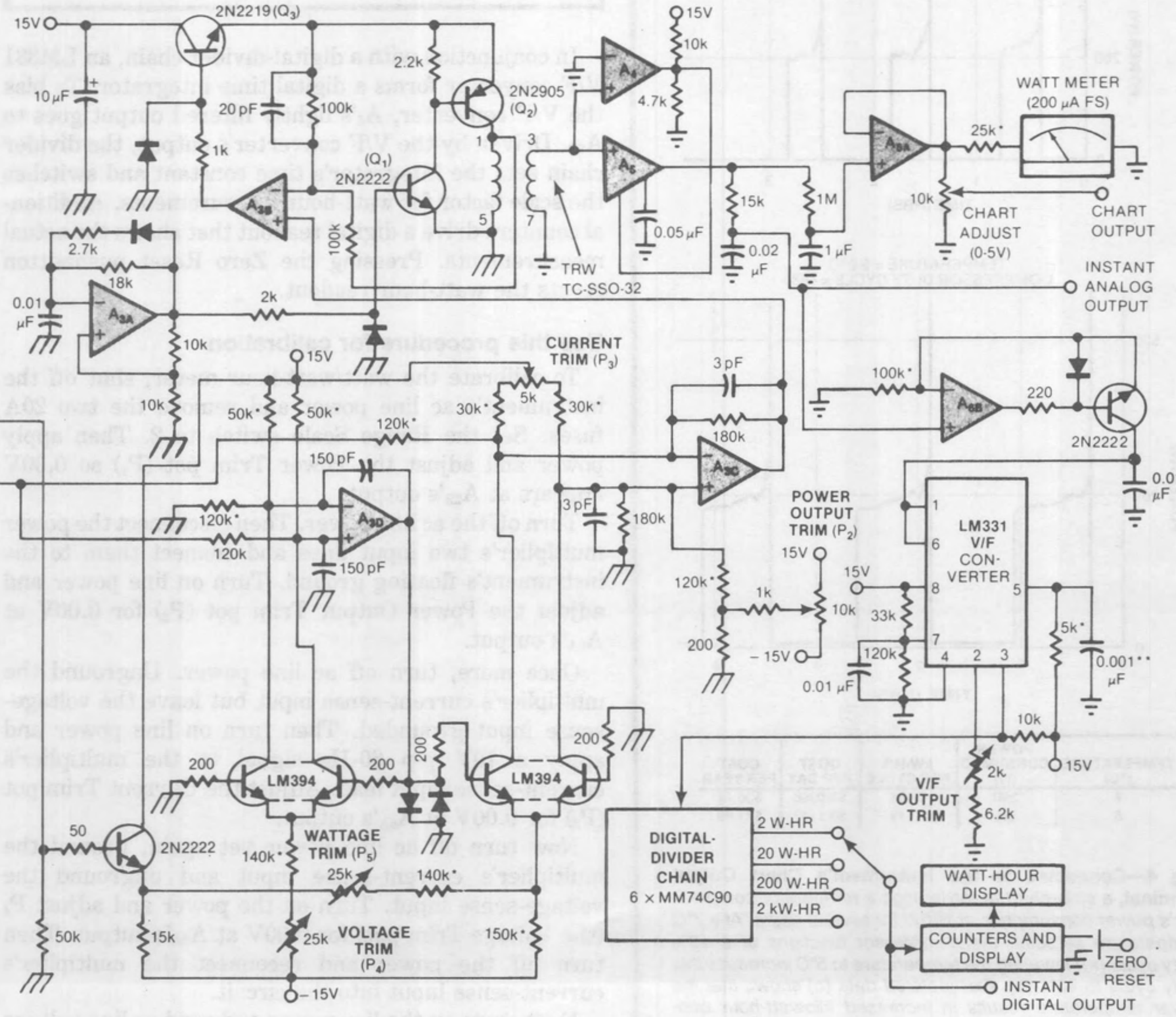
NOTES:
ALL DIODES 1N4148
/// = FLOATING CHASSIS GROUND
⏚ = CIRCUIT (EARTH) GROUND
* = 1% FILM TYPES
** = POLYSTYRENE TYPE
\# = GE 50-140034NDAA
A_1 = LM11
A_2 = LF353 DUAL
A_3 = LF347 QUAD
A_4 = LM311
A_5 = LF398
A_6 = LF353 DUAL

Fig 2—Careful parts selection and skillful circuit design *produce a test instrument that measures the power consumption of any 115V ac-powered device. The instrument provides a 4-decade power-measuring range—2, 20, 200 and 2000W FS—at 2% accuracy and over 25±5°C. Three analog and two digital outputs accommodate a wide variety of internal and external power-measurement applications.*



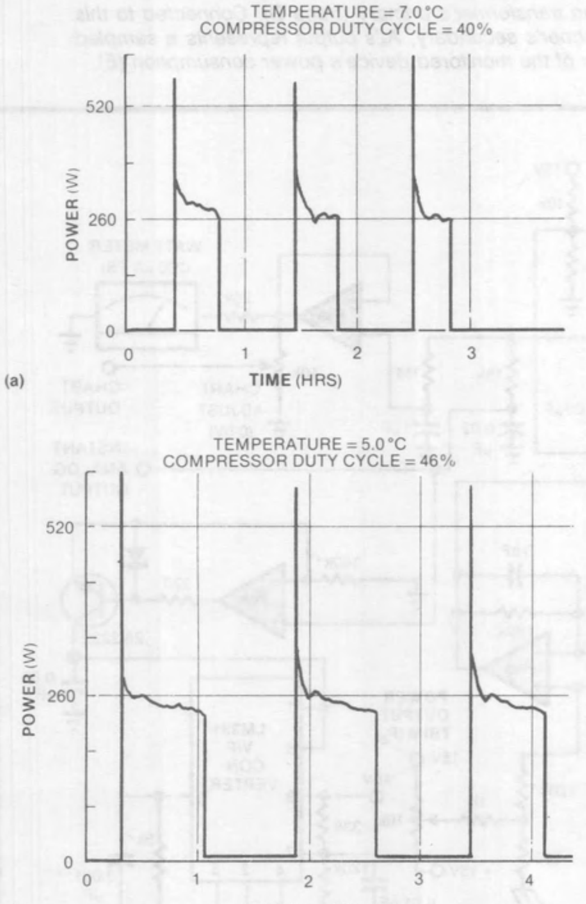
TRACE	VERTICAL	HORIZONTAL
A	5V/DIV	
B	50V/DIV	
C	5V/DIV	2 mSEC/DIV
D	10V/DIV	
E	10V/DIV	

Fig 3—During instrument operation, the power multiplier's output *(trace A) represents the monitored device's instantaneous power consumption. Biased by this output, A_{3A}'s oscillator output (refer to* **Fig 2***) biases the Q_1/Q_2 switch (trace B). Completing the feedback path to A_{3B}, Q_3 changes its emitter voltage to maintain servo-loop needs. Via Q_1, Q_2, Q_3, A_{3A} and A_{3B}, amplitude-modulated pulses arrive at the isolation transformer's primary (trace D). Connected to this transformer's secondary, A_5's output represents a sampled version of the monitored device's power consumption (E).*



Pulse sampling and filtering smooth out power-signal levels

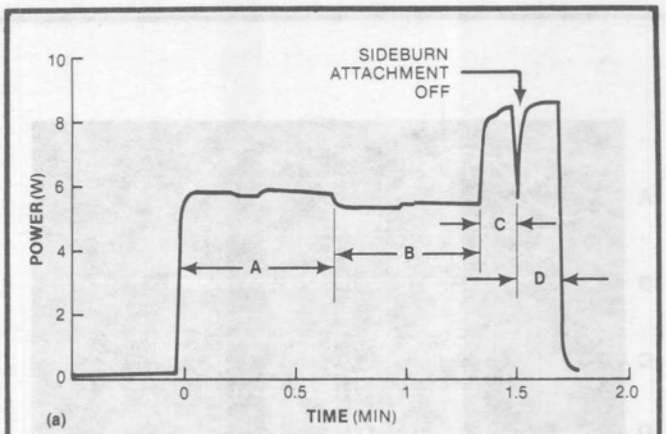
The amplitude-modulated pulses appear at the transformer's secondary, which is referenced to the instrument's earth ground. Each pulse's amplitude gets measured by a sample/hold amplifier (A_5) whenever A_4 generates a Sample command. Lightly filtered by the 15-kΩ, 0.02-μF network, A_5's output provides a sampled version of the load's instantaneous power consumption (trace E). Heavy filtering by the 1-MΩ, 1-μF network's time constant produces a smoother version of the sampled power signal. This signal drives the watts analog-meter and strip-chart-recorder outputs via the A_{6A} buffer.



TEMPERATURE (°C)	POWER CONSUMED (W)	kW-HR PER CYCLE	COST PER DAY	COST PER YEAR
7	260	0.104	$0.0998	$36.44
5	260	0.119	$0.1147	$41.89

(c)

Fig 4—Connected to the instrument's Chart Output terminal, *a strip-chart recorder logs a refrigerator compressor's power consumption at 260W for several hours. At a 7°C temperature setpoint, the compressor functions at a 40% duty cycle* ***(a)****; lowering the temperature to 5°C increases this duty cycle to 46%* ***(b)****. Extrapolated data* ***(c)*** *shows that the lower temperature results in increased kilowatt-hour consumption per cycle and therefore in higher operating cost.*



FACIAL AREA	POWER CONSUMED (W)	WATT-HOURS	COST PER SHAVE* (CENTS)
CHEEKS (A)	5.8	0.173	0.00692
UPPER & LOWER LIPS (B)	5.4	0.123	0.00492
RIGHT SIDEBURN (C)	8.4	0.063	0.00252
LEFT SIDEBURN (D)	8.4	0.061	0.00244

*BASED ON $0.04 PER kW-HR

(b)

Fig 5—Monitoring the power consumption *of a small electric razor via a strip-chart recorder, the watt/watt-hour meter generates instantaneous readings over short intervals* ***(a)****. With this accumulated data, you can make detailed power-cost calculations* ***(b)****.*

In conjunction with a digital-divider chain, an LM331 V/F converter forms a digital time integrator. To bias the V/F converter, A_5's lightly filtered output goes to A_{6B}. Driven by the V/F converter's output, the divider chain sets the integrator's time constant and switches the scale factor for watt-hour measurements. Additional counters drive a digital readout that shows the actual measurements. Pressing the Zero Reset pushbutton resets the watt-hour readout.

Use this procedure for calibration

To calibrate the watt/watt-hour meter, shut off the instrument's ac line power and remove the two 20A fuses. Set the Range Scale switch to 2. Then apply power and adjust the Power Trim pot (P_1) so 0.00V appears at A_{2B}'s output.

Turn off the ac line power. Then disconnect the power multiplier's two input lines and connect them to the instrument's floating ground. Turn on line power and adjust the Power Output Trim pot (P_2) for 0.00V at A_{6A}'s output.

Once more, turn off ac line power. Unground the multiplier's current-sense input but leave the voltage-sense input grounded. Then turn on line power and apply a 10V p-p 60-Hz signal to the multiplier's current-sense input lead. Adjust the Current Trim pot (P_3) for 0.00V at A_{6A}'s output.

Now turn off ac line power yet again, ground the multiplier's current-sense input and unground the voltage-sense input. Turn on the power and adjust P_4 (the Voltage Trim pot) for 0.00V at A_{6A}'s output. Then turn off the power and reconnect the multiplier's current-sense input into the circuit.

Next, turn on the line power and read ac line voltage with a precision digital voltmeter. Plug a known load (eg, a 1% power resistor) into the instrument's test outlet. Adjust the Wattage Trim pot (P_5) until the analog meter reads the correct wattage (watts equals line voltage times load resistance).

Finally, turn off line power and disconnect A_{6B}'s positive input line. Then turn on the power and apply 5.00V to A_{6B}'s positive line. Adjust the V/F Output Trim pot (P_6) until the LM331's output at pin 3 runs at 27.77 kHz. Then turn off line power and reconnect A_{6B}'s positive input line.

A watt/watt-hour meter calibrated in this manner can accurately measure the power consumption of any 115V ac-powered device, large or small. Connecting the instrument to a home refrigerator demonstrates its prowess with large equipment: In one test, the refrigerator operated for 3½ hrs at a temperature setpoint of 7°C **(Fig 4)**, and each time its compressor turned on, it consumed approximately 260W. As the compressor warmed up, power consumption actually decreased slightly. Changing the refrigerator's temperature control to 5°C increased the compressor's duty cycle by 15%. This power change reflects directly in the unit's per-cycle kilowatt-hour consumption.

Connecting the watt/watt-hour meter to an electric razor demonstrates its ability to monitor small equipment. In this setup, the meter recorded the electric razor's power consumption during a face-shaving exercise **(Fig 5)**. Note that various facial areas cost more to shave than others.

Time-related power computations revealed that a complete daily shave costs about $0.09 per year. If this is excessive, a user could economize by growing a beard. **EDN**

Author's biography

Jim Williams is a design engineer with National Semiconductor Corp's Linear Applications Group, Santa Clara, CA, specializing in analog-circuit and instrumentation development. Previously, he worked as an analog-systems and -circuit consultant at Arthur D Little Inc and directed the Instrumentation Development Lab at the Massachusetts Institute of Technology. Jim studied psychology at Wayne State University and in his spare time enjoys skiing, art and collecting antique scientific instruments.