BY DON LANCASTER

Measuring Power, A Cheap Extension Lock Out, A Correction, and More

JUST WHEN YOU FIGURE YOU'VE BEEN AROUND LONG ENOUGH TO SEE JUST ABOUT EVERYTHING, SOMETHING NEW OR DIFFERENT COMES ALONG TO MESS YOU UP OR OTHERWISE EMBARRASS YOU. CASE IN POINT ARE THOSE BRAND NEW BABY PICs from Microchip Technology. It turns out that they have highly unusual supply pins, especially for an eight-pin minidip.

There is a rule of thumb with this type of package that states that the highest pin is positive and the diagonally opposite pin is ground. Unfortunately, that rule is violated with these chips. Well, to make a long story short, a quick glance showed that pin 1, where I expected to find the positive supply, was labeled Vee-sub-something-or-other. Trouble was, it was V_{SS}, which, of course, is grounded. The positive supply pin, V_{DD}, was actually pin 8.

The moral of this story is that you should always carefully read the exact data sheet to make sure of all pin outs, especially before powering up your chip or even starting your PC-board layout. At any rate, Fig. 1 of the February 1997 installment of "Tech Musings" had the baby PIC pins backwards. I have corrected that in MUSE108.PDF on www.tinaja.com and in my Tech Musings reprints. Sorry about any inconvenience that might have been caused.

By the way, this is not the only part out there that could cause similar grief over backwards pins. For instance, in the National LM324 quad op amp, the positive supply goes to pin 4, while ground goes to 11, the exact opposite of what you might expect. Again, always double check before you power up any device.

Measuring Power

It is amazing how much trouble people can get themselves into when they don't have the foggiest clue how to make the most fundamental of AC power measurements. Especially as beginning lab students or whenever making absurdly wrong claims about circuit efficiencies.

If you try to measure AC or pulse circuit power using a voltmeter and an ammeter, your results will nearly always be utterly wrong, especially when phase shifts, harmonics, or any unusual waveforms are involved. It is trivially easy to create errors of 400 percent or higher, and never in your favor, of course.

The fundamental equation appears simple enough:

$$\text{watts} = \text{volts} \times \text{amps}$$

To find your power, you multiply your volts times your amps, right? Wrong! That equation only will work when you multiply instantaneous voltage times instantaneous amperage. In other words, your volts and amps must be in the same place at the very same instant. They must not change while you are doing the measurement.

The only correct way to measure power is to multiply an instantaneous voltage times instantaneous current, measured over some very brief time increment. Then, you sum all of those incremental measurements to find the longer term average power. Finally, you need to find what equivalent, continuous DC current is required to produce an identical value of average power. That equivalent, continuous DC current is also called the rms current, which is short for root-mean-square.

Circuits are the easiest to analyze when you normalize them. Let's start with a simple case. Assume we have a purely resistive one-ohm load. By Ohm's law, with a one-ohm load, the rms current will equal the square root of the average power.

Let's further assume we have a low distortion AC source that is a pure fundamental-frequency sinewave. Let us work with a positive half cycle of that sinewave.

Figure 1 shows us how we can crudely approximate a half sinewave using five rectangular steps. We take each step's current and average it to get the average current of 0.65. Next, we sum the currents squared to find each step's power, and then we divide by five (the number of steps) to find the average power. We take the square root of the average power to get the rms current of 0.71 for this waveform.

The figures we've derived for average and rms current are fair approximations of the true values, but are not exact. If we use more steps, we can get closer to the "real" answers. There's a neat-o math stunt known as integral calculus

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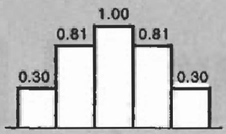
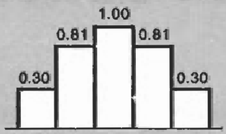
The **AVERAGE CURRENT** of a waveform is found as you would find any other average. Take narrow samples. Add each sample value, then divide by the number of samples. Here is a five step approximation to a half sinewave...



average current = (0.30 + 0.81 + 1.00 + 0.81 + 0.30)/5 = 0.65

The **AVERAGE POWER** of a waveform driving a one ohm resistive load is found by squaring the curent of each sample and summing them...

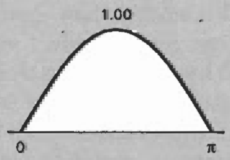


average power = $((0.30)^2 + (0.81)^2 + (1.00)^2 + (0.81)^2 + (0.30)^2)/5 = 0.50$

The **RMS CURRENT** of a waveform is the equivalent dc current you'll need to produce the same average power. For a one ohm resistive load, RMS current is found by taking the square root of the average power...

RMS current = $\sqrt{\text{average power}} = \sqrt{0.50} = 0.71$

For more accuracy, calculus integration is often used instead...



average current = $\frac{1}{\pi}\int_0^{\pi} \sin(\theta)d\theta = 0.637$

average power = $\frac{1}{\pi}\int_0^{\pi} \sin(\theta)^2 d\theta = 0.500$

rms current = $\sqrt{0.500} = 0.707$

Average current is highly wave shape dependent. Average current often will be a grossly misleading and totally useless way to try and measure circuit power. For accurate results, true rms measurements must ~always~ be made.

FIG. 1—THE RMS CURRENT of any waveform is the exact amount of continuous current you have to apply to get the same average power.

that can let you sum up an infinite number of infinitely narrow steps, giving us the "real" answers: a sinewave's average current is 0.637 peak, and its rms current is 0.707 of the peak value. You can find more on this in an introductory AC circuit-theory book.

Incidentally, plain old analog AC panel meters measure an average current. Further, those wrongly assume that you always have a continuous and low-distortion fundamental-frequency sinewave and simply fudge their results by multiplying all meter readings times 1.11072, a number that only relates the ratio of the average current and rms current of a clean half sinewave. If you do not have such a waveform, the reading is wildly low.

Three Mistakes

When it comes to measuring power, there are three mistakes that most beginners usually make:

1) Assuming the voltage and current are in phase: Voltage and current will be in phase only in a pure resistive load. They should be 90 degrees out of phase with a pure inductive or pure capacitive load. And they should be 180 degrees out of phase when you are actively sourcing rather than sinking current. In short, any phase from 0 to 360 degrees could be encountered with a real world load. You can find more on this in MUSE100.PDF on www.tinaja.com.

For example, say you have a typical linear AC load driven from a clean sinewave, and you measure 100 volts and 3.0 amps with a pair of panel meters. Depending on the phase, the wattage could end up being anything from minus 300 watts through 0 to plus 300 watts. There is simply no way to correctly measure AC power using an ordinary voltmeter and ammeter! Do not even think of trying it!

2) Assuming a clean sinewave: Whenever you are using parts of sinewaves (as in an AC power controller) or pulses, then you **must** use some "true" rms current-measurement scheme, which is not trivial. There's two main routes to handle weird waveforms: You can apply rectangular approximations or math calculus to analyze the rms to average ratio, or you could use Fourier Series to deal with the waveform as a fundamental sinewave plus its significant odd and even harmonics. More on this can be found in MUSE90.PDF on www.tinaja.com.

Measuring the current of a train of pulses using any analog panel meter will give us wildly wrong answers. Figure 2 shows us why your meter reading will be both way low and dead wrong every time. Let's consider a train of repeating pulses. If we assume a 1-volt supply and a 1-ohm resistive load, a squarewave will have a duty cycle of 1:1, the average current will be 0.5 amp, and your average power will be 0.5 watt. The rms current will be the square root of the average power, or 0.707. Your rms current will equal 1.414 times the average current.

Next, consider a pulse with a 19:1 duty cycle. The average current will be 0.05 amp and the average power will be 0.05 watts. Your rms current will again be the square root of your average power, or 0.22361. This time, your rms current ends up a whopping 4.472 times the average current. Which means that a typical meter current reading will measure low by a factor of four or so! A crest factor (or the peak-to-rms ratio) is one measure of how extreme a waveform is. That 19:1 duty cycle pulse has a very high crest factor of 4.47. Just about all true rms current measurement schemes place definite limits upon how high a crest factor is permitted. Exceed their crest-factor limit and your results will miss by a country mile.

3) Ignoring waveform harmonics: Weird waveshapes get their shape by having lots of higher harmonics. On any low duty cycle pulse, the lion's share of the energy lies in the harmonics and not in the fundamental. Dozens and sometimes hundreds of harmonics could end up being important. Your power company tends to get very upset when you draw harmonic energy instead of using fundamental energy. Such waveforms are now, in fact, illegal in Europe.

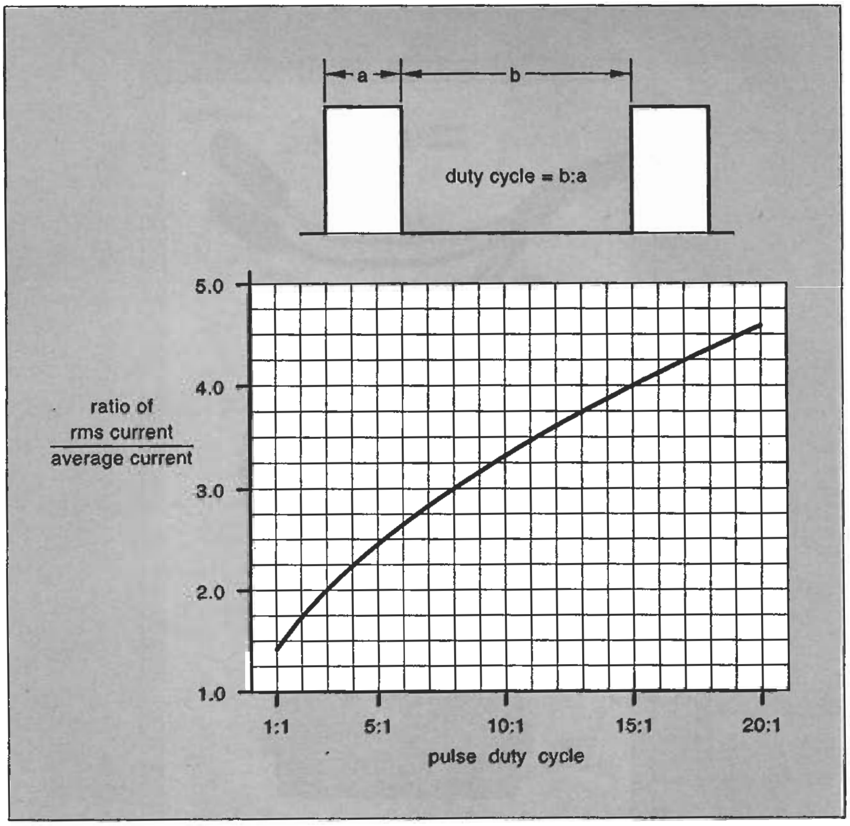


FIG. 2—LOW DUTY CYCLE PULSES might involve surprisingly low average currents. Their power can only be measured by using premium, "true rms" instruments. Ordinary panel meters and VOMs are all average responding, giving you absurdly low results that are certain to be dead wrong.

rms Options

How can you measure rms current or calculate real power? As we've seen, for typical measurements made most of the time, reading a voltmeter and an ammeter and multiplying the two together will not hack it, especially with bizarre waveforms, high harmonics, pulses, when there are phase shifts between voltage and current, or when you don't know the exact waveform you are looking at. In all of those cases, most any dual meter measurement will just about always be dead wrong. One reason is that any traditional panel meter is an average measuring device, and the product of some average most assuredly will not equal the average of the products.

Instead, you have to ask "what is the equivalent DC current you need to get the same quantity of consumed power?" As we have just seen, this equivalent DC current is also called the rms current. Measuring true rms current never has and never will be easy, as there is layer upon layer of subtlety. To do the task, there are four popular rms measuring techniques. They are heat matching, the graph method, multiply and average, and math rule. Let's look at those.

1) The heat method: Make your current waveform heat a resistor. You take a second resistor that's under identical thermal conditions and then route an adjustable DC current to it. When the temperatures match, the rms currents will exactly match. A bolometer is one example of a microwave method of measuring rms currents or power levels using that technique.

2) The graph method: First obtain accurate waveforms of your voltage and current. Divide those up into very narrow increments, increments that are so narrow that both the voltage and current remain nearly constant within each interval. Then multiply each interval's volts times its amps, sum and average all the power from each interval to get the average power, and take the square root of your average power to find the rms current. A digital oscilloscope can greatly simplify that method.

Whenever your load resistance is something different than 1 ohm, you should take the square root of your average power divided by the load resistance. That is known as scaling. You can find more on normalization and scaling in my *Active Filter Coobook.*

FIG. 3—HERE'S HOW TO INSTALL a 99-cent extension phone lockout. Commercial devices that do the same thing might cost $11 each, or more.

3) Multiply-and-sum method: Take any fast analog or digital multiplier chip and use it to continuously multiply volts times amps to get instantaneous power. Then sum and average to find the average power. Finally, take the square root of the average power to find the rms current.

Analog Devices is one source for analog multiplier chips optimized for rms current measurement. You can start with their classic AD536A, or use the newer and lower power AD737.

Incidentally, the numbers can get out of hand for even moderately high crest factors. Thus, any commercial rms measurement scheme will always exactly spec the maximum allowable crest factor and it must be observed for accurate and useable results. Fluke and Tektronix are two prime sources of true rms current-measuring test instruments.

4) The rule method: This technique does what we just went through above. You integrate the square of a math-definable waveform to find your average power. Take the square root of your average power (scaled, if needed, for resistance) to get your rms current. Then find the "correction factor" of the ratio of rms to average power. An ordinary meter could then be used as a temporary stand-in to let you measure rms power. But that method is only accurate on the exact waveform you have just analyzed, and even then only on a purely resistive load.

Note that your "correction factor" will always be considerably higher than 1.11. Watch that detail.

Despite the above, true rms calculations are easy and fun to do using the general purpose PostScript computer language. I've placed a FINDRMS.PS file to both the Math Stuff and the PostScript library shelves of www.tinaja.com. There's also a new FINDFOUR.PS file that does a complete classic Fourier harmonic analysis of your chosen waveforms.

An Aside

Note that your average current is always waveform dependent! Figure 2 leads us to a rather curious and unexpected result. Assume you have a pair of dimmers or AC phase power controllers. If you connect one to a 110-volt light bulb and the second to a 32-volt light bulb, then light them both to nearly full brightness, your duty cycle will be rather high on the 110-volt bulb and extremely low on the-32 volt bulb.

You would certainly expect that rms current to be the same for both bulbs at identical power levels, since, among other reasons, that is how rms current is defined. But, as Fig. 2 clearly reveals, your average current measures something like three times higher on a 110-volt light bulb! Why?

It's because the average current is duty-cycle dependent and is thus an utterly meaningless measure of the circuit power or efficiency. The FIND-RMS.PS program also can show how average current measurement errors vary with Triac phase angle for exact dimmer waveforms.