A Mains Analyzer—How Clean Is Your Juice? Part 1

In the process of building a fast and safe way to test mains quality, the author discovers some dirty secrets of the mains supply you take for granted.

This project started out as a simple need to know how much current was being drawn from a particular electrical outlet by a client's equipment rack, together with an innocent curiosity as to whether there was any detectable noise on the electrical supply in general. What I learned along the way has radically changed my opinion of the quality of daily power use. While the project may be a bit over the top for one-time use, the various electronic blocks should be useful to many in a multitude of applications. The measurements I present should be required reading for anyone designing mains powered equipment.

STOCKING UP

I wanted to measure the line current being drawn from a particular outlet in a safe and convenient way. Not having a mains plug to banana adaptor or other suicidal device in my toolkit, measuring mains voltage and current was difficult, to say the least. I could have purchased a current clamp, but even these need a special mains cord or pigtail, so the live or neutral can be separated out for the clamp to loop around. You also still need a galvanic connection to measure voltage. A search on the Internet failed to find what I had in mind—a simple in-line device—so I decided to build my own special box.

In true engineering fashion I started by taking a step back to see the big picture; a simple ammeter was just a wasted opportunity. I figured that while I was at it, I should measure line voltage. And why not ground leakage current to highlight any dangerous fault conditions? Detection of outlet wiring faults would be useful, as would a Ground Fault Circuit Breaker (GFCB) tester.

As an aid to debug any problems uncovered, an isolated monitor output for connection to a scope or spectrum analyzer would be essential. To know when to use the monitor, you need to know whether there's noise or hash on the line, so let's add a glitch detector to increase the cool factor.

At the end of this brainstorming session, my behemoth ammeter included the following:

Line voltage display
Line current display
Ground leakage current display
Indication of outlet wiring faults
Indication of glitches or noise on line
GFCB test capability
Isolated line monitor output
20A load capability

POTENTIAL PROBLEM

As usual, I started by sketching a block diagram on a handy napkin and quickly made a few realizations. The first was that there is no obvious common "zero volt" reference. I wanted to pick a common reference point for the two current measurements (line and leakage), but concluded that the earth leakage circuit needed to be completely isolated from the line current and voltage circuits. If I referenced the line current circuit to neutral and the leakage current circuit to ground, and then connected to a faulty outlet that had neutral swapped with live, then I'd have 120V AC between the two input amplifiers, which is enough to cause any IC to go bang in a big way.

The next realization was that it would be very bad if something went wrong with this test box and interrupted the neutral and ground wires, causing all the attached equipment to float off the live wire. The use of wimpy wire, low power rating components, or fuses was unacceptable; this would need to be an exercise in overkill. I ended up with the block diagram in **Fig. 1**.

POWER CIRCUIT DESIGN

Looking on the Internet, I found some heavy-duty shunts rated at 50mV for 25A (i.e., 2mΩ). At rated current these shunts would dissipate 1.25W, and with their whopping 5″ × 1″ dimensions, I was confident that any residential circuit breaker would pop before these would. 14-gauge copper has a fusing current of around 160A so this is an appropriate cabling choice. I used the plug end of a damaged extension cord (from the last time the high school lad next door trimmed my hedge!) and quality outlet sockets to complete the power section.

METERS

I wanted digital panel meters to display the voltage and current measurements, and I found some 3½ digit LCD modules with ½″ high numerals for under $8 each at my usual surplus stores. I bought three. The meters had a full-scale input of 200mV, so I was going to need some amplifiers. I produced **Table 1** as a design aid.

The sensing signal input is the signal from the power circuit corresponding to the maximum expected voltage or current to be measured. In the case of the current, it is the signal from the 25A shunts at 2mΩ. This is a pretty small signal requiring rather large input gains. The voltage sense signal is from a resistor divider, and I chose the resistor values to yield the ideal amplitude signal, hence the input gain requirement is 1. I wanted the biggest signal through the precision rectifier to minimize errors.

Because I was working with ±5V supply rails, I needed to allow for peak versus RMS levels and also a hundred millivolts or so because the op amps can't quite hit the rails. I picked 3.1V as the optimum full-scale amplitude. The voltage sense circuit needs to cater to a mains supply 20% above nominal, so I chose the resistor divider to provide the 3.1V RMS for an input of 144V RMS.

This all means that to bring this 3.1V full-scale signal down to the 200mV the displays expect, I need an output attenuator, which can most easily be obtained with another resistor divider around a calibration pot. With the system level planning complete, I could get down to the fun part.

CURRENT METERS

The current sense signal from the 25A shunts is 2mV per amp, so significant gain is required: 78 or about 38dB for the line current and 781 or about 58dB for the ground leakage current. 38dB is achievable in a single op amp stage, but 58dB is best split into two stages to ensure sufficient bandwidth and minimize offset voltage problems. For the line current sense amplifier, I used a standard differential stage with a Kelvin connection to the 25A shunt; the amplifier is shown in **Fig. 2**.

I DC-coupled the amplifier to ensure that I had good common-mode rejection at 60Hz and because the low source impedance of the shunt mitigated any input offset or bias problems. To ensure stability and to reduce noise, I rolled off the high frequency with C16 and C17 at 340Hz, so there was less than 1dB rolloff at 150Hz. Low-frequency rolloff is provided by C18 with a –3dB point at 5Hz.

For the ground leakage current sense amplifier, I needed 10× the resolution, so I chose a two-stage instrumentation amp (**Fig. 3**).

The signal I wanted to measure was the same order of magnitude as the input offset voltage for the LM324 op amps I used, so to minimize offset problems, I set the gain of the first stage slightly lower at only 26dB. This allowed me to use fairly low-value resistors, which also helped minimize noise. The classic instrumentation amplifier circuit used has excellent common-mode rejection, and, coupled with a Kelvin connection to the 25A shunt and twisted pair interconnects, the induced noise level should be acceptably low. A simple inverting op amp stage around U9C with a gain of 32dB provides the appropriate signal for the RMS measurement stage. Again, I rolled off at 400Hz to minimize noise.

My biggest mistake here was setting the amplifiers' input impedance way too high. It turned out that there was a significant leakage current flowing through the input amplifier from the mains supply to ground. This current developed a differential signal at the input due to the difference between the currents in the positive and negative amplifier input resistors (and to some extent the difference in the 1% resistor values). When your source impedance is 2mΩ, a high impedance is 1Ω. Why was I using a 10MΩ input impedance amplifier?

TABLE 1 Input and output gains for RMS

	max. expected signal	sensing signal input	input gain	output gain
line voltage	150V	3.125V	1	0.064
line current	20A	40mV	78	0.064
ground leakage	2A	4mV	781	0.064

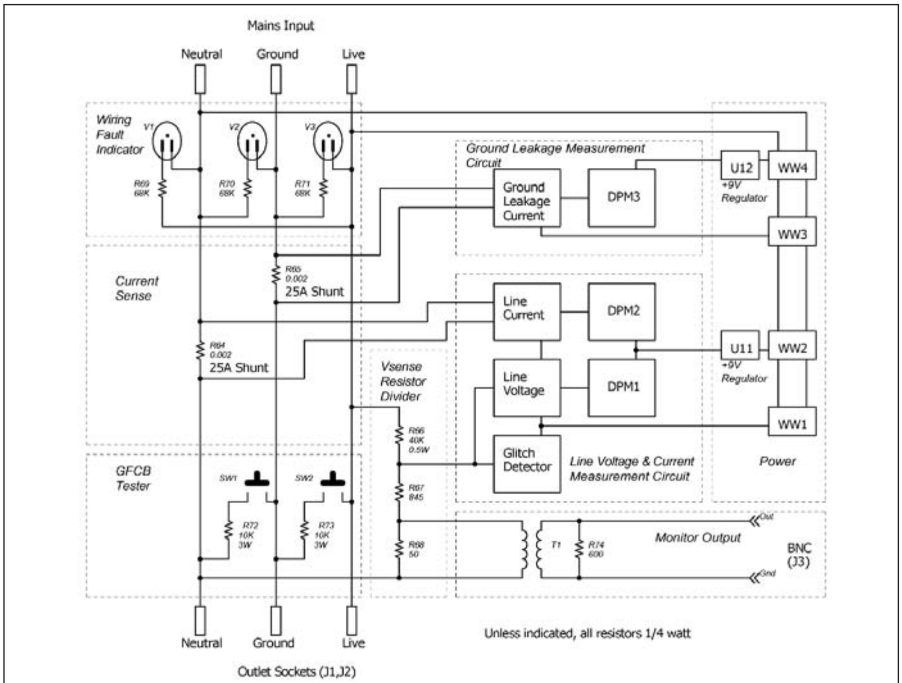

FIGURE 1: Top level diagram of the mains tester.

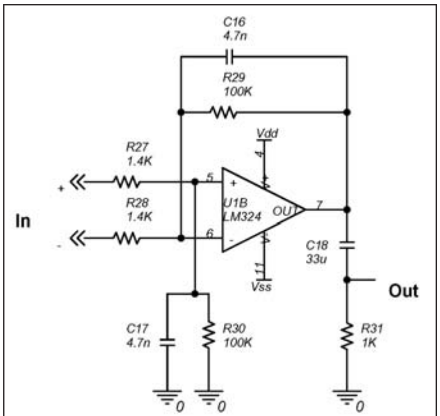

FIGURE 2: Line current input amp.

I tied both inputs to amplifier ground with 50Ω resistors and the improvement was impressive. The noise voltage developed due to the leakage current flowing in the input resistors was reduced so much that I was now able to zero out the display where before the offset had been too great. All that noise had been running up the RMS detector past where the offset null could adjust.

POWER SUPPLY

It wasn't until I got the panel meters home and played with them for a while that I discovered a design quirk with them; they need a 9V supply that floats with respect to the voltage you are trying to measure. Not a problem for a battery-powered hand-held meter, but definitely a wrinkle in the design when you need additional input circuitry for gain and RMS averaging. It looked as though I needed two supplies for each meter.

When I discovered the ground-neutral isolation issue, the power supply requirement increased to two wall-warts (AC adapters). Now with floating display supplies I needed a grand total of four wall-warts. This was becoming ridiculous. After much hand-wringing and pacing, I convinced myself that it was better than using batteries, the wall-warts were free (I bought a gross some years ago), and the extra weight would lend an air of quality to the final product (I should be in marketing!). I chose to use a favorite trick of cracking open the wall wart, cutting the plug prongs off with my large dykes, and hot-gluing the transformer to the base of the (insulated

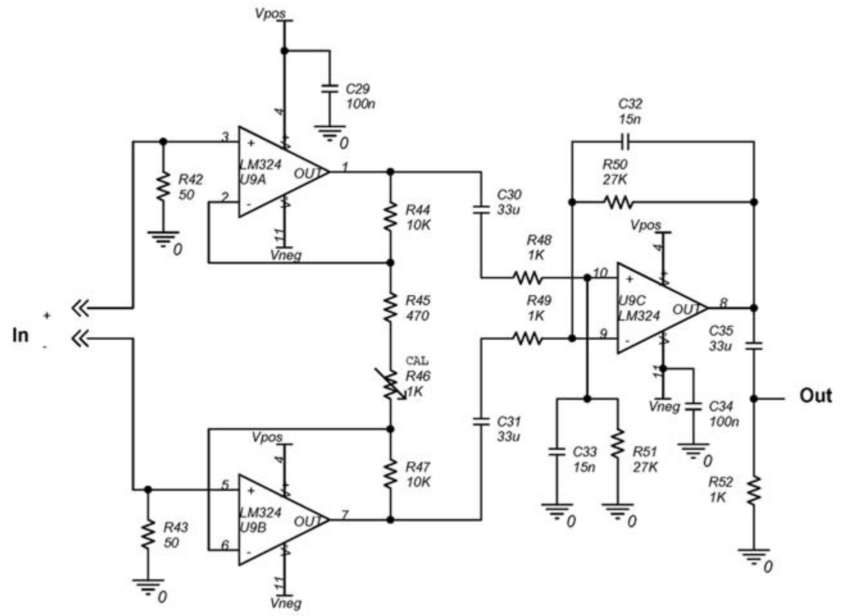

FIGURE 3: Ground leakage current input amp.

plastic!) enclosure for a fast, cheap power supply.

For the ground leakage meter circuit I used the wall wart output unregulated. There's not much to this circuit, and all stages are seeing the same signal. I even split the supply with a couple of 1k resistors for a Vcc/2 virtual ground with no problems.

For the line current and voltage meter I needed a regulated supply because the thresholds for the glitch detector are derived from the supply lines and I wanted consistent, repeatable trigger levels. Also, the glitch detector and meter circuits are seeing different signals and so to prevent any possible interaction, I buffered the Vcc/2 split with an op amp to provide a controlled, low impedance ground reference.

The datasheet for the panel meters indicated that 11V was the maximum supply and I know these wall warts can put out 15V no load. Just to be safe, I threw in a couple of 7809 regulators I had lying around to regulate the panel meter supplies to 9V.

Grabbing a bunch of wall warts, I assigned four as follows.

- A 7.5V, 200mA rated wall wart delivering 10V no load to drive the ground leakage current meter circuit. Even at 200mA this will provide >±4V to keep the LM324 in control.
- For the panel meters, a pair of 9V rated 500mA wall warts to provide a minimum of 11V even under line sag/brown out conditions. I grouped the line voltage and current panel meters on one wall wart. The 11V minimum is because the 9V regulators need at least a 2V drop to stay in regulation. The quality of the panel meter reading stability depends on the quality of this supply.
- For the line voltage and current meter and glitch detector circuits, I used a 12V rated 500mA wall wart with a no load voltage of 17V. Because I wanted ±5V regulators for this circuit, I needed a wall wart that could guarantee at least 14V for the circuit load. Pulling 100mA (a pessimistic estimate), this wall wart delivered over 16V with a supply of 123V. A quick bit of Ohm's law led me to believe the source impedance of this transformer was around 5Ω, so I would get 14.5V for 96V in (-20% line sag). Your performance may vary.

MEASUREMENT CIRCUIT

The next piece to design was the measurement circuit—there are three of them. I wasn't after extreme accuracy—I'll use my calibrated multimeter if 5V or 100mA is going to make a difference—but I wanted a useful, linear range. The problem with just using a diode bridge is the forward voltage drop. 1.4V may be OK in a power supply design, but when my supply rail is only +4.5V, this represents a huge chunk of the available range. An Internet search produced several favorable references to the circuit in **Fig. 4**.

The way I see it, for the positive half cycle presented to the input, D4 conducts, D3 blocks, and the pair of op amps acts together as a unity gain buffer producing a positive half cycle at the output equal to the input. On negative half cycles, D3 conducts, D4 blocks; U3A therefore acts as a buffer and U5 is now an inverting unity-gain amp, again producing a positive half cycle equal in magnitude to the input. Both diodes act within the feedback loop of the op amps so their forward voltage drop is canceled. In reality, the exponential V-I curve of the diodes causes significant errors close to zero, so you want to put the largest signal you can through this circuit for best linearity and precision.

As has been done for centuries, I approximated the RMS averaging circuit with a simple R-C low pass filter (R36, C22) by assuming that I would only ever be measuring pure sine waves (which, as I discovered much later, is not actually the case for mains power). I chose the time constant of this circuit to be half the update rate of the LCD panel meter (which is 500ms), so I would get a quick but stable reading. I picked R to be 10kΩ to keep C reasonable because the 500kΩ input impedance of the LCD panel meter would allow such a high impedance at this point. Besides, I had an X0.064 attenuator to add in between.

WIRING FAULT INDICATOR

Nothing clever or innovative here. I just wired three neon bulbs with their limiting resistors across the three mains wires as follows: amber live-neutral, amber live-ground, red neutral-ground. You want to see both amber neons come on; you'll want to fix anything else immediately.

Many neon indicators come with a limiting resistor already attached. The ones I used from Radio Shack had a 6.8kΩ resistor, which makes for a nice bright neon. However, during testing in the case where the ground line is floating, the live-ground and neutral-ground neons both came on when I really wanted only the live-neutral neon to glow. I think the neons fire at about 45V and then need only microamps to sustain; the two neons in series still had over a milliamp flowing through them.

Fast-forwarding to the answer, I cut open a commercial wiring tester and discovered that they used 68kΩ resistors. I removed the Radio Shack-supplied resistors and replaced them with 68kΩ. The neons still come on, but now they're very dim and it's easy to tell the difference.

GFCB TESTER

GFCBs are excellent safety devices and are required by code wherever water is nearby. However, they can be a source of nuisance trip problems, especially when used with equipment that has Electro-Magnetic Interference (EMI) filters on the mains input connector. These filters have capacitors from live and neutral to ground to filter high-frequency noise from the mains line. The problem is that a 100nF capacitor will also pass over 4mA of 60Hz leakage current into the ground line. Two such devices, and you're really close to the trip current of your GFCB.

Other household appliances such as negative ion generators also have high ground leakage currents. Just to complicate things, an installed GFCB can also protect regular, non-GFCB outlets further downstream, so you may be connected to a protected line without even knowing it. The last thing you want is the GFCB popping right in the climactic final action scene of your Saturday night movie. Fortunately, you can use this GFCB tester function to safely see whether your home theater outlet is protected.

The tester simply places a resistance across either live-neutral or live-ground to cause a leakage current to flow. I have a figure of 8mA stuck in my head for the trip current of a GFCB, but I couldn't quote a source. I decided to inject around 12mA because that required a very standard 10k resistor. The worst-case power dissipation is 2W (for +20% line voltage). I paralleled up four ¼W, 47.5k resistors to make a 1W, 12k resistor and called it good enough. I know, if I keep pressing the GFCB test button long enough, I can make smoke come out.

GLITCH DETECTOR

The idea behind this circuit was to indicate whether there was any noise riding on top of the 60Hz mains waveform. This noise could be high-frequency hash from switching supplies, load noise from electrical machinery, or just the transients generated whenever any piece of electrical equipment in the neighborhood is turned on or off. The presence of such noise on the mains supply would place an additional burden on the power-supply filtering of any sensitive audio gear and potentially cause some unexpected behavior or audio artifacts. Choosing a detection threshold for this noise proved to be more difficult than I thought, but I started out as follows.

If any power-supply-borne noise was to be inaudible on a typical line-level signal, then it would need to be well below –90dBV. Having measured some of my circuit designs in the past for their ability to reject noise on the power rails (known as power-supply rejection ratio, or PSRR), I knew that 90dB rejection was difficult, but possible, to achieve with careful design, so it seemed as though 1V of noise was a good threshold for concern. Technically, this should be 1V on the secondary, but because the

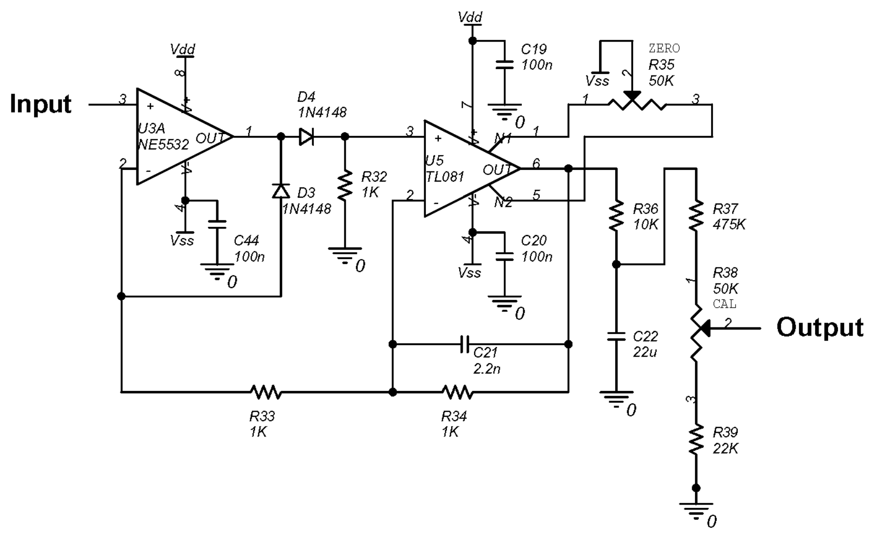

FIGURE 4: Precision full-wave rectifier.

secondary could be anything from 5V to 500V, I decided to just use this threshold straight on the mains voltage directly. Detecting a 1V signal in the presence of a second 120V signal takes some careful design; I took out my napkins.

I started with a simple R-C high-pass filter feeding a window comparator to detect positive- or negative-going spikes. Using the same voltage sense signal as the line voltage meter gave me 2.5V RMS 60Hz signal as input. The equivalent threshold of 1V on 120V was therefore 21mV on this 2.5V input signal, and the idea of running comparators with ±21mV thresholds made me nervous.

Additionally, the circuit would need to be operated at high impedance, so as not to load the line voltage meter. This made applying a mV or two of hysteresis on the comparators tricky. Adding the requirement to attenuate the 3.5V peak of the 60Hz signal down to below the 21mV threshold meant that the high-pass break frequency needed to be 8 octaves above 60Hz (8 octaves at 6dB/octave = 48dB attenuation), or 15.4kHz. This wasn't going to detect much audio band noise!

I needed a better filter. One of my favorite tricks for steep slope filters is to design a peaked (high Q) second order filter and then add an RC on the output at a slightly higher frequency (for a high pass, lower for low pass) to flatten out the passband. I chose the multiple-feedback design[1] shown in **Fig. 5** because it allows you to adjust the Q and the break frequency independently with resistor value changes.

This third order filter achieved the –42dB minimum attenuation at 60Hz with a break frequency of 400Hz, which I deemed to be acceptable. One small detail about this filter: You need a controlled source impedance. Raising the signal source impedance to even 100Ω degraded the Q of the filter so there was no way I could use the signal off the roughly 1kΩ resistor divider. I was already committed to using multiple packages of op amps, so I added a buffer to guarantee a stable low source impedance.

With that pesky 60Hz signal out of the way, I could now gain up the residuals to allow a reasonable detection threshold level which I arbitrarily set to ±1V by a resistor divider chain R8, R9, R10. The detector is shown in **Fig. 6**.

Adding 1% hysteresis on the comparators ensured clean switching when a glitch was detected. The LM339 comparators that I used have an open collector output that can sink a respectable current, typically 16mA. This meant that I could add a capacitor, C10, to ground on the output and stretch any detection output pulse so that it produced a visible flash on the indicator LED.

When one of the comparators detects a glitch, it turns on its output transistor, which discharges the capacitor. The capacitor then must charge up through the pull-up resistor, R15, once the output transistor turns back off. Because I had a pack of four comparators, I used one more, U2C, to clean up the capacitor charge waveform and drive an LED.

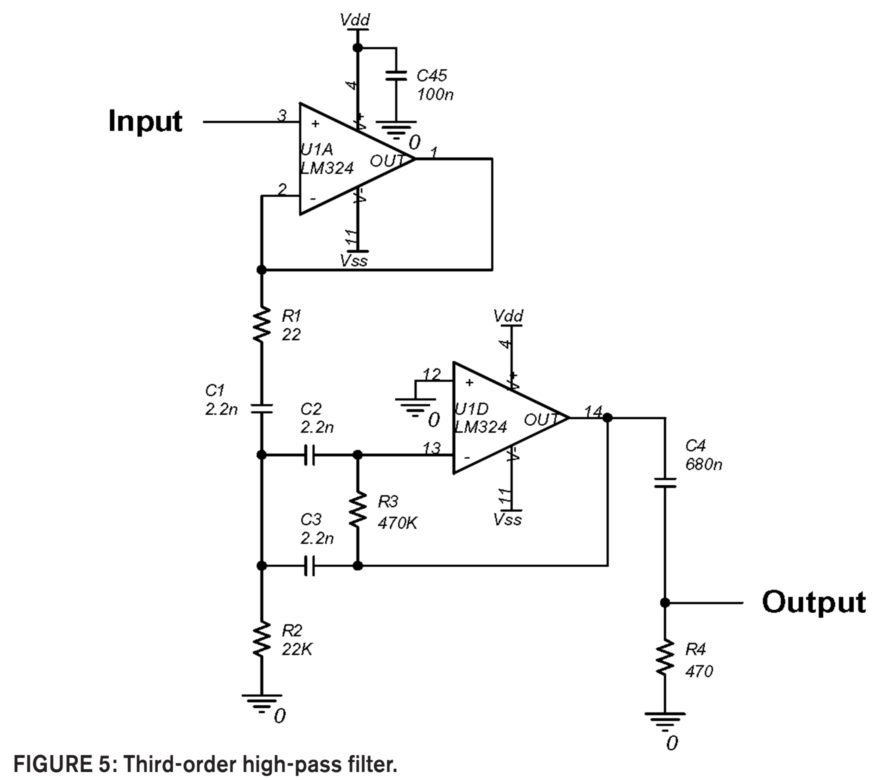

FIGURE 5: Third-order high-pass filter.

MONITOR OUTPUT

Finally, I wanted to be able to quickly hook up a scope or analyzer to look at the mains waveform without risk of electrocution. I chose a 600Ω audio transformer that I knew had primary-to-secondary isolation exceeding the worst-case 205V peak you could expect from the wall outlet. I actually used a 1500V rating transformer for my own personal safety. It seemed like an easy job: 1V RMS signal from a 600Ω source resistor + 1:1 transformer + 600Ω load = perfect mains reproduction.

What I forgot to consider was that the primary inductance of the transformer I was using was only about 37Ω at 60Hz, and this loaded the 600Ω source resistor so much, it actually dropped the reading on the line voltage meter. A few napkin scribblings later, it dawned on me that there's no way I'm going to drop a 1V signal onto a 4Ω resistor to get flat bandwidth down to 60Hz. That would be a power dissipation of 30W! Not wanting to buy another (higher) quality audio transformer, I finally decided to compromise as follows:

As a mains monitoring device, it's OK to relax bandwidth to 120Hz or even 180Hz, especially if you have a known, constant attenuation at 60Hz that can be compensated for.

Reducing signal level actually increases measurement bandwidth because saturation at low frequency is the limiting design factor for the transformer. However, I must maximize signal level and optimize operating impedances to combat both inductive and capacitive coupling of mains-related signals.

A quick redesign of the resistor divider to drive the transformer with a 50Ω source, using the preexisting 845Ω resistor and 40kΩ (modified from 70kΩ) composite dropper resistor, and I was back in business. I call the dropper resistor "composite" because it's made from multiple paralleled resistors. This increases the power rating of the composite resistor. The worst-case line voltage sense signal error due to transformer impedance loading was limited to under 1%.

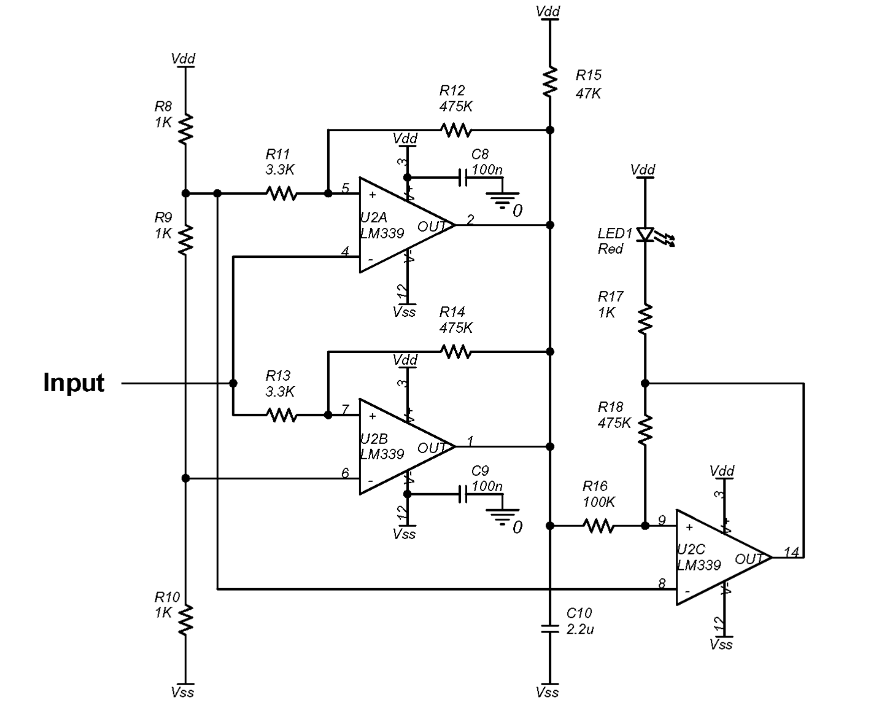

FIGURE 6: Window comparator.

Warning: Mains voltages are lethal. Please use caution and intelligence when working with exposed mains circuits. Consider this project only if you are comfortable working with high voltages. As a precaution, make sure you are not working alone and keep one hand in your pocket when probing live circuits. I accept no responsibility for any damage or destruction caused by careless interaction with mains electricity. aX

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