By Iain McNeill

Back

A Mains Analyzer—How Clean Is Your Juice? Part 2

With the design complete, it's time to build and test the PC boards.

Once I had completed the design with simulations and procured all the parts, I started playing around with a box layout. I put the outlet sockets on the front and the four wall wart transformers at the back. Then I laid out the shunts in the middle with the prototype circuit board and squared everything off by putting the audio transformer on the left.

Checking the size of the panel meters, I saw that they would fit above the shunts, in between the outlets and the transformers. I then drew a line around all the parts, added ½″ to all dimensions for good luck, and started looking for a suitable box. Once the box was on order, I set about assembling the PCB.

ASSEMBLY

My preferred technique for building prototype circuit boards is using matrix or vector board, as with many of the projects in *audioXpress*. I use the small round plated-through-hole variety because I find this most resistant to accidental shorts yet flexible enough to simplify wiring. Starting with an IC or other active device and placing the Rs and Cs right next to their appropriate IC pins, I can achieve quite high component density (**Photo 1**). This is good for sensitive circuits because it minimizes loop areas and therefore EMI susceptibility and emissions.

I always take care to make sensitive nodes such as op amp inputs as short as possible by placing those components first. A quick mock-up on grid paper in pencil can speed up assembly and allows you to try a couple of options without having to get out the (de)soldering tools. I like to use leaded components because you can use the leads to actually wire up the circuit, bending and forming them just like real PCB traces.

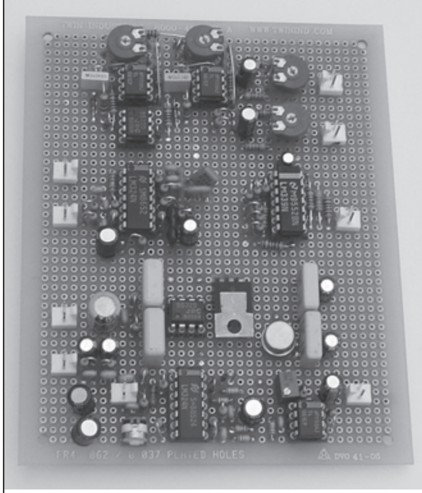

PHOTO 1: Prototype PCB, top side.

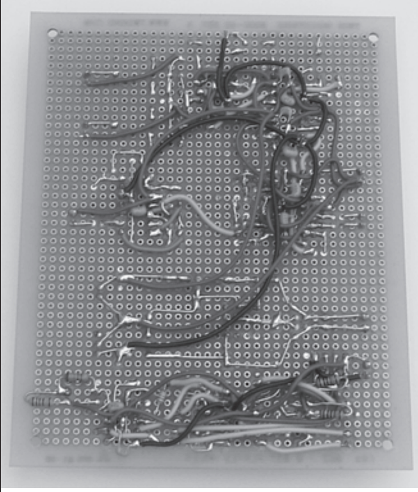

PHOTO 2: Prototype PCB, bottom.

Once all the components are inserted, soldered, and wired, I usually find that the only wiring left is power and ground. OK, maybe there're a few signal wires to run, but these are usually inter-stage connections, and using a neutral color such as yellow or white allows easy identification of these useful nodes for debugging. The prototype board I built is shown in **Photos 1** and **2**.

The only drawback to this prototyping technique occurs when you must change a component or, heaven forbid, add or redesign a stage. Not that this ever happens to me! It's always the component with a really complex lead formation that's soldered in many places that needs to be replaced, and usually I just clip the part off at the component body and solder the new one on the old component leads. Easy! However, judicious simulation beforehand pays big dividends at this stage.

Here's an important point regarding creepage and clearance: As with all high voltage designs, beware of lead-to-lead spacing to ensure you don't suffer from catastrophic flashover. The breakdown voltage for air is approximately 25kV per inch, or about 1000V per millimeter, which makes it seem quite easy, but this specification is for DC; when AC voltages are present you must use the peak voltage. You also need to consider that the mains voltage of 120V has a tolerance to it; I like to assume ±20%, so 120V AC RMS nominal becomes 212Vpk worst-case.

It's probably very unlikely, but not impossible, that the ground wire on the outlet under test could become connected to a different phase under a fault condition. I don't like surprises, so I decided to design for this event, and thus the worst-case peak voltage becomes 424Vpk. Double it, just in case it's a damp morning, and you want to withstand almost 1000V—now you can be confident that you won't have any flash-over. The pad to pad separation on my vector board was a bit less than a millimeter, so I made sure that there were two rows of unused pads between the line voltage and current measurement circuit and the ground leakage measurement circuit.

Once my box arrived, I was able to do a dry run and see how all the parts went together. The front panel was predetermined for the mains outlets, so I measured everything and then produced a 1:1 scale drawing, centering the outlets on the front panel. I printed it out on my printer, taped it to the front panel, and drilled the screw holes and the four corners of each cutout. With a sharp blade I scored the outline of the cutouts using the corner holes and then used a Dremel to cut along the lines. Not as good as a punch or a nibbler, but sometimes you must use what you have.

Similarly, I made a drill template for the BNC connector, and after working out how much space all the wall warts would take, I drilled the five holes in the remaining space. I hot-glued all the wall warts to the back panel and left them to set.

Now I needed to align everything on the top panel. I made a template for the panel meters and added holes for four 1″ standoffs on which to mount the PCB. I then centered this complete module in the space between the wall warts, outlets, and monitor transformer to get a location on the top panel. I drilled, scored, and Dremeled as before. As you can see in **Photo 3**, one of the large holes became a bit too large—once again my trusty hot glue gun saved the day. **Photos 3–5** are pretty self explanatory, showing how it all came together.

TESTING

I started testing the PCB on its own with a signal generator and a scope, just to make sure everything was wired correctly. Using a signal of –40dBV input, I was able to see the amplifiers, filters, and the rectifiers were doing what I expected. After increasing the signal to 0dBV and sweeping the frequency, I noted that the glitch detector turned on right about 400Hz, and if I did bursts of 1V tone, the LED flashed for a good second, even catching just 1 cycle of 1kHz. It was time to go live.

Call me paranoid, but I unplugged the mains tester from the mains outlet every time I wanted to stick my hand in the box to connect or disconnect something. There's no real energy storage in the tester, so you don't need to wait for components to discharge, but I prefer to get into a calm, progressive rhythm when working with dangerous voltages. If I become tired or frustrated, I do something else for a while. I'm still alive to vouch for the efficacy of this method! However, to make the narrative less te-

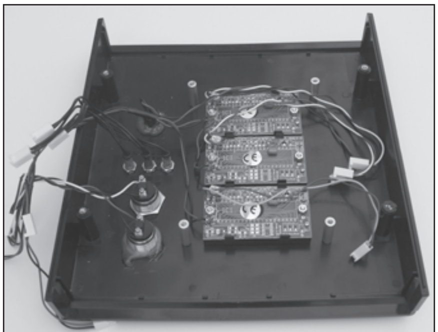

PHOTO 3: Case top assembly without PCB.

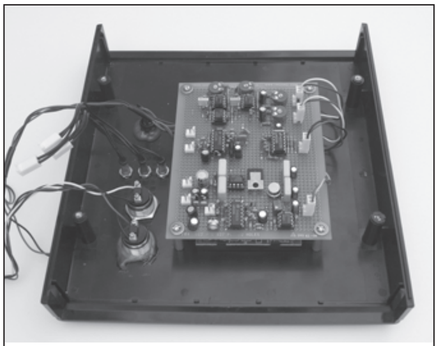

PHOTO 4: Case top assembly with PCB.

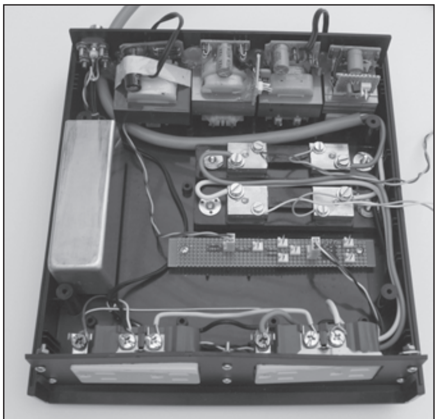

PHOTO 5: Case bottom assembly.

dious, I'll omit all my plugging and unplugging from the mains supply (trust me, there was a lot).

Setting up the meters is relatively easy. For the line voltage meter, I first set zero by removing the mains supply connector from the resistor divider board. With the 1.4kΩ resistor still in place shorting the input, I could adjust the last op amp offset voltage to zero the panel meter. I then reconnected the resistor divider board, tagged my multimeter on the live-neutral output terminals, and adjusted the gain so the panel meter read the same as my multimeter.

I zeroed the line current meter in the same way, with nothing plugged into the tester outlet sockets. I adjusted the offset pot to get a zero reading on the panel meter. To calibrate, you need to pull some current out of the tester, and I chose my soldering iron because it was handy.

Removing the neutral wire to the tester outlet sockets, I inserted my multimeter into the mains circuit, taking care not to short anything with the alligator clips and double-checking the meter jacks and settings (those 2A fuses are hard to find!). Again, I adjusted the measurement gain so the panel meter read the same as the multimeter. Setting the calibration at such a low percentage of full-scale probably isn't the most accurate way of calibrating this meter, considering the linearity problems of the rectifier stage, but my multimeter went only up to 2A so I had little choice. Besides, if a reading on a rack of equipment is approaching 20A, then it's getting too close to the circuit breaker rating anyway and corrective action is in order.

There is a bit of interaction between the zero and the cal pots on the ground leakage meter because the gain pot is ahead of the offset adjust stage. As you turn the gain up, any noise in the input signal produces an output at the rectifier stage, which you then must readjust with the offset null. A couple of iterations got me close enough, but if I were doing the project again I'd use the same scheme as the line voltage and current meters in which the cal pot is last in the chain.

All through this, the glitch detector LED has been on. Using my multimeter, I could see an AC voltage out of the filter and a DC voltage on the rectifier/RMS stage. I assumed it was 60Hz and I would need to improve the filter. That could wait for now so I chose to ignore it, not realizing that it was actually working perfectly!

OBSERVATIONS

I connected the monitor output of my mains tester to a line input on my EMU Systems soundcard and recorded a few seconds of mains waveform. After editing the .wav file to extract a couple of cycles, I plotted the mains waveform against a pure sine wave of the same amplitude and calculated the error between them as shown in **Fig. 7**. The mains waveform was obviously distorted but is still recognizable as a sine.

I wanted to see just how bad this mains waveform was, so I calculated the spectrum and plotted it against that of the pure sine wave of the same amplitude (**Fig. 8**). Both are windowed with a Blackman Harris window, and I used an FFT size of 8192 points as I did for all the spectra presented here. I then integrated all the energy from the linear FFT bins into 1/12 octave bands to get a smooth curve on a log frequency axis.

There are many fine software packages that will do this for you. CoolEdit/Adobe Audition is just one, but there's nothing quite like doing it the hard way, by hand. I use Matlab as my analysis tool of choice because it gives me infinite flexibility in how I handle the data, which is both a blessing and a curse.

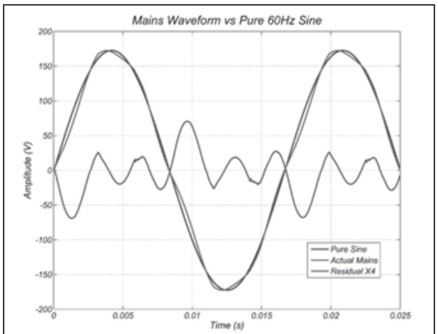

FIGURE 7: Mains waveform compared to pure sine.

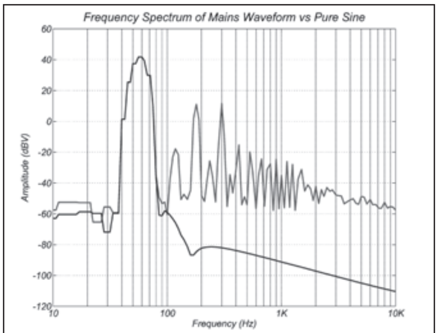

FIGURE 8: Spectrum of mains waveform vs. pure sine.

This first spectral analysis of the mains waveform on the monitor output was a real eye-opener. I stared at it dumbfounded, thinking there must be a calibration error. After checking and rechecking, I realized the math was correct. I still couldn't believe it and went straight back to my design notes to see where I'd messed up. Everything looked OK, so I ran a few more tests to try and debug this problem.

First I calibrated the monitor output circuit itself. Disconnecting the mains supply to the resistor divider R66-68, I connected the soundcard output to the top of the divider. I played a Maximum Length Sequence (MLS) pseudorandom noise signal into the divider and recorded the output on the monitor output jack. After processing the recorded signal, I plotted the monitor response (**Fig. 9**).

Everything appeared to be in order here so I put everything back together. I thought the problem may have something to do with the wiring in my house, so I made several recordings with different loads. First, I turned on my office lights (which are on a dimmer switch) to about 50% and took a reading, thinking that there would be significant noise generated by the triac switching in the dimmer. My laptop had a switching charger so I plugged that into the tester as well and taped a 3W, 100Ω resistor to the output and took another recording.

I then took readings for a 7A space heater and a 17A microwave (as measured on the line current display). Finally, I took a recording with the mains supply to the voltage sense resistor divider disconnected just to make sure I was actually measuring what I thought I was measuring. I was taking measurements using my laptop with a battery supply for the outboard soundcard so leakage currents shouldn't have been a problem, but I wanted to make sure.

The results are shown in **Fig. 10**. Reassuringly, the measurement for the background noise floor with the resistor divider disconnected was at least 30dB down at all frequencies, so it would seem that I really am measuring the mains supply. Amazingly, this background level represented 100μA of mains leakage flowing through R74, the 600Ω on the transformer output. Maybe a bigger box to try to reduce the roughly 2nF of stray capacitance causing this current would have been prudent, but I was happy with the 30dB signal-to-noise that I had.

The mains spectra for different loads through the mains tester didn't produce significantly different results. It wasn't until I got up to 17A through the box to power my microwave oven that the spectra changed noticeably. There's a big increase in the 2^{nd} and 3^{rd} harmonics with about 300mV RMS of 120Hz and over 2V RMS of 180Hz noise. The 3V RMS of 300Hz is relatively unchanged, although still bothersome. On this particular outlet, the line voltage dropped only 2V for the 17A load, which would suggest a mains source impedance of around 118mΩ. I was quite close to the panel, so I guess you could get maybe 5 or 10 times that on a really long run.

Everything was behaving properly and it began to sink in that this was, in fact, what was coming out my wall socket. The mains supply is noisy, really noisy. About 10V RMS noisy.

WHERE THIS HIGH-FREQUENCY NOISE COMES FROM

When you think about all the appliances connected to the mains supply, which ones present a purely resistive, linear load? I can't think of any. Even a simple incandescent lamp goes through a temperature-dependent resistance function every mains cycle. DC supplies only really conduct in short bursts when the mains supply is greater than the voltage on the smoothing capacitors and the rectifier diodes are forward biased.

Switched mode power supplies are prolific, promoted by their environmentally friendly power efficiency. They take their power in pulses at many times the mains frequency and probably contribute much noise at frequencies beyond the 20kHz limit of my analysis tools. Supply all these devices through a highly reactive grid network, and it's no wonder the mains supply is distorted.

HOW BAD CAN THINGS GET?

Is my experience normal or do I have grounds for complaint? I searched the Internet for specifications and information. Most power companies think in terms of current because this is what they have to manage; the volts are fixed, after all. Most of the specifications I have found refer to current distortion rather than voltage distortion and use a couple of different Total Harmonic Distortion (THD) definitions.

One method computes the harmonics against the fundamental, the other against the total combined signal. This latter definition, favored by the utilities, is known as Total Demand Distortion (TDD). The astute will notice that TDD can never exceed 100%—what specmanship! The reality is that high THD in the current waveform is almost the norm considering the lack of linear loads, but when the harmonic content approaches the magnitude of the fundamental 60Hz supply, it doesn't really matter whether it's 90% THD or 190% THD. The grid is being stressed and customers are probably having serious problems. The power companies must keep control of harmonic content.

I found one voltage specification from Europe, EN50160 (or maybe EN61000), that suggests the following spectral limit to mains harmonic content. The limit scales with whatever the local line voltage is, which makes sense, and is specified in terms of the harmonics. I converted the spec for 60Hz and 123V and derived the limits for my house as shown in **Table 2**. Adding this limit to the spectral plot of **Fig. 8**, I was horrified to discover that things could actually become much worse before the power

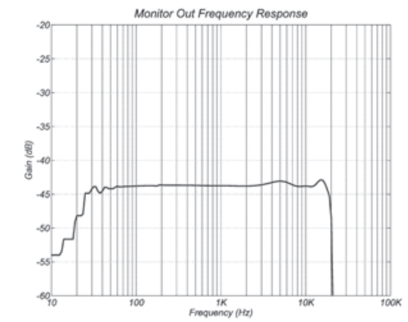

FIGURE 9: Monitor output frequency response.

company would get involved, as you can see in **Fig. 11**.

Figure 11 also shows a measurement I took at a different site—an industrial park in a factory building that was 50% powered by solar panels on the roof. Not only was there the heavy machinery of neighboring businesses, HVAC units, and office appliances, but there was also the step-up circuits, inverters, and synchronization systems of the solar generator. Add in all the noise from the electronic ballasts of the interior lighting, and you begin to understand where the extra 20dB of high frequency (>1kHz) noise comes from. The voltage waveform of this industrial supply is equally ugly (**Fig. 12**).

It turns out my residential supply was actually better than average quality! This was becoming downright depressing. The thought of actually connecting this to any of my gear made me feel queasy.

WHY SHOULD I CARE?

The most severe problems caused by this harmonic content affect the power utility company[2,3]. For instance, large capacitor banks used to correct power factor have lower reactance at higher frequency so the harmonic content causes overheating and premature failure. Multiple-of-three harmonics (3^{rd}, 9^{th}, 12^{th}, and so on), known as triplens, cause large currents to flow in the neutral line of three phase supplies causing overheating and possible failure. Transformers need to be derated to prevent overheating due to highly distorted current waveforms.

Some problems that affect consumers

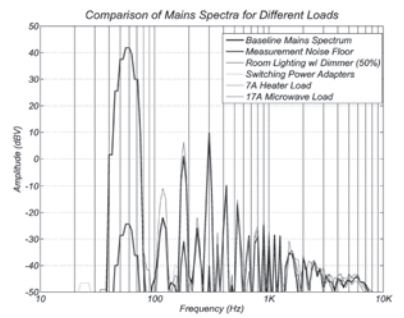

FIGURE 10: Spectra of mains waveform for various loads.

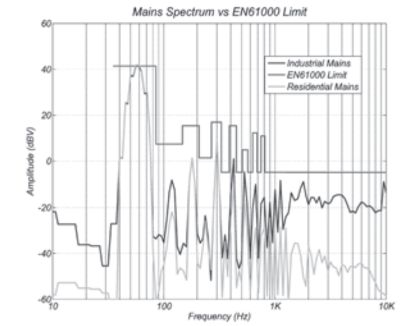

FIGURE 11: Mains spectra for industrial and residential service vs. EN61000 limit.

Table 2

Harmonic order	relative voltage(%)	frequency (Hz)	limit (dBV)
1	100	60	41.8
2	2	120	7.8
3	5	180	15.8
4	1	240	1.8
5	6	300	17.4
6	0.5	360	-4.2
7	5	420	15.8
8	0.5	480	-4.2
9	1.5	540	5.3
10	0.5	600	-4.2
11	3.5	660	12.7
12	0.5	720	-4.2
13	3	780	11.3
14	0.5	840	-4.2
15	0.5	900	-4.2
16	0.5	960	-4.2

in the home: nuisance tripping of circuit breakers and fuses has been attributed to high harmonic content[2,3] of the mains supply. The harmonics more easily couple capacitively into adjacent wired networks such as the telephone system, causing irritating buzz on phone calls or, more problematically, degrading DSL connections due to high error rates. The high neutral current problem in three phase systems can manifest itself as a significant voltage between neutral and ground, which exacerbates common mode hum problems. If I were starting this project knowing what I know now, I would definitely add a fourth meter to measure this neutral-ground voltage.

The biggest concern from my perspective is the additional burden on the power supply design to make sure all this high-frequency noise isn't propagated into any precision, sensitive audio electronics. Having designed many power supplies, crossovers, and filters, I know how hard it is to get deep attenuation with real-world passive components. With some trepidation this time, I got out my trusty napkins to see whether I was in trouble.

Assume for now that your speaker puts out 90dBSPL (at 1m) for an input signal of +9dBV (2.83V) and that you want the mains hum to be inaudible, say below 30dBSPL. Then the total RMS noise level input to the speaker must be below –51dBV. From my measurements, with multiple harmonics at 10dBV, I'd say you need a good 70dB attenuation from mains input to speaker output to ensure this. Just to illustrate this by means of a typical 100W class B transistor amp, that attenuation is provided by the following means.

The mains transformer steps down all voltages by a factor of 4, or -12dB. The power supply filter capacitors provide only 20dB of attenuation due to the fact that the Effective Series Resistance (ESR) of most large caps is of the order of hundreds of milliohms versus transformer secondary source impedance of an ohm or so. The remaining 38dB of attenuation must be provided by our friend negative feedback; by comparing the output voltage to the clean (you hope) input voltage and driving the output transistors with an error signal, the output transistors can be made to block any noise on the power supplies. This is PSRR, and a careful design can achieve upwards of 60dB.

In my house, with my class B amplifiers, it looks as though I have a small margin (my speakers are quiet). But what about a tube amplifier with a step-up power supply? Now the harmonics are gained up by the mains transformer. Fortunately, in this case the currents flowing are much reduced so the supply source impedance can be increased.

For instance, adding 10Ω in series with the HT line before the filter capacitor will achieve an extra 20dB attenuation, with the ESR of the filter cap being unchanged. But in a design with no feedback, you need to ensure that somehow you provide the remainder of the required attenuation. I haven't played with feedback-less tube designs, but I now have a whole new respect for them and their designers!

Another major red flag goes up for class D amps. In class D you typically switch the output transistors hard on and hard off at a very high frequency and then filter out as much of the high-frequency noise as possible. You can't filter out any audio frequency noise because that would defeat the object of the amp.

The class D amps I have seen connect the power supply, noise and all, to the output with a very low impedance, typically just a few ohms. That's only a couple of dB of PSRR for a typical 8Ω speaker. This implies that any noise on the power supply of a class D amp effectively connects directly to the output. Buyer beware!

Finally, preamplifiers for low-level transducer input are even more sensitive. For a low impedance moving magnet cartridge putting out 500µV or –66dBV,

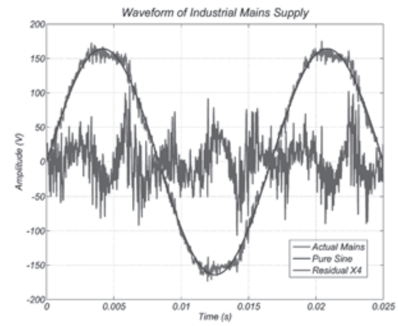

FIGURE 12: Industrial mains waveform vs. pure sine.

you need an impressive 160dB PSRR from your mains supply. This makes a compelling argument for batteries, especially if you factor in mains leakage current effects as well.

WHAT NOW?

Having been alerted to the fact the wall outlet is really a conduit for broadband noise, I feel obliged to take a look at the spectrum up to the RF bands. My soundcard samples up to 192KS/s, which will give me almost 100kHz bandwidth, although I'm not sure how wideband my audio transformer is. Beyond that, I'll need to visit some of my radio engineer friends and borrow a real spectrum analyzer. I'm sure there's some interesting surprises higher up the spectrum just waiting to be discovered.

Never again will I be satisfied with a simple transformer, bridge, capacitor power supply—it's just not good enough for audiophile-quality electronics. The

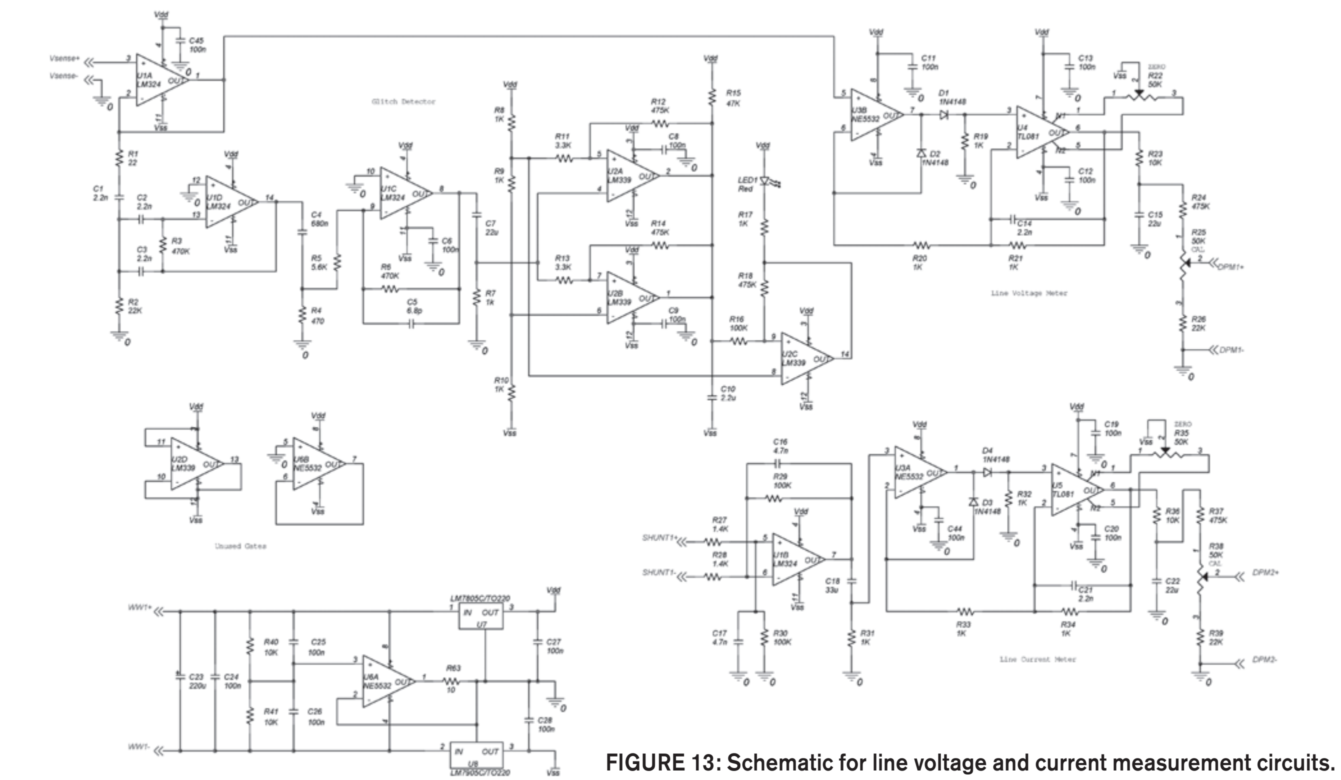

FIGURE 13: Schematic for line voltage and current measurement circuits.

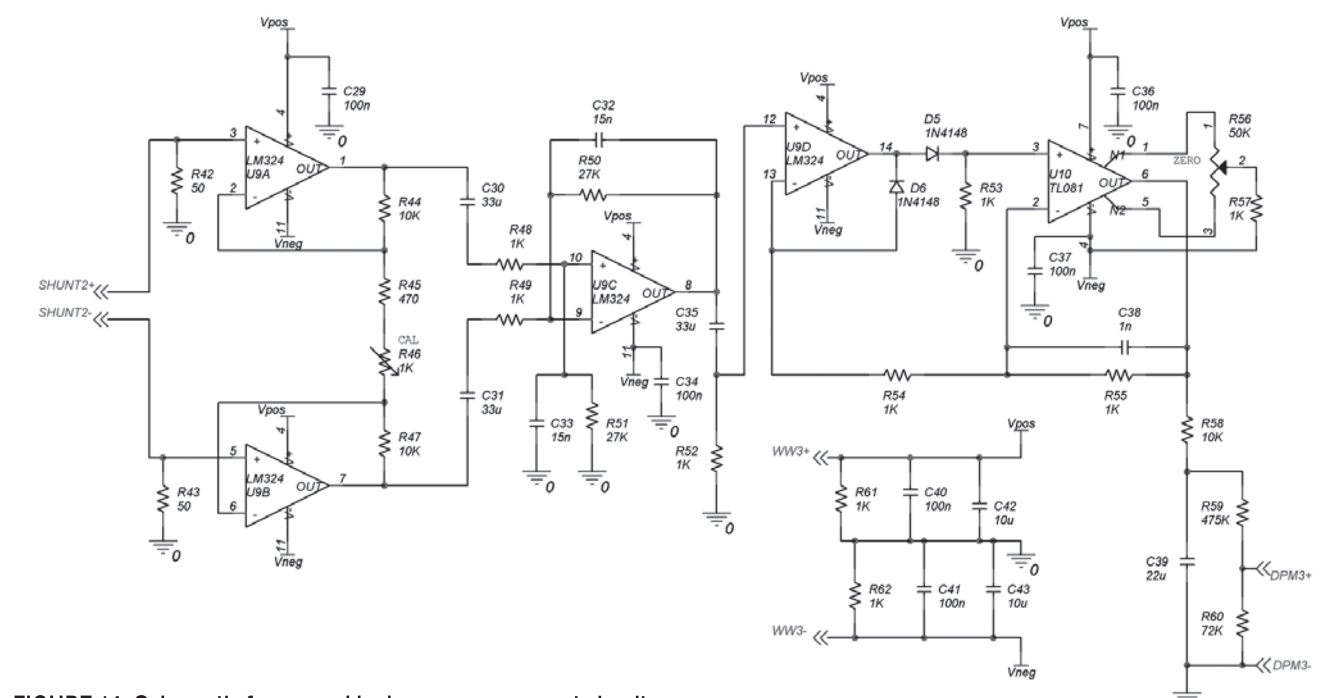

FIGURE 14: Schematic for ground leakage measurement circuit.

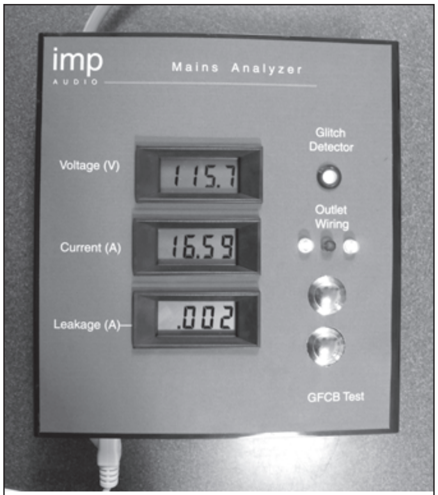

PHOTO 6: The completed Mains Analyzer in action.

power supply for the 21st century needs to provide appropriate impedance to the mains supply from DC to light and much more broadband attenuation than a transformer-capacitor can provide. I should no longer contribute to the problem, so I want to research power-supply designs that present a purely resistive load, keeping the current waveform sinusoidal and in-phase with the voltage waveform. Noble goals, I'm sure.

Finally, for the mains tester, when I get a spare afternoon, I'm going to drop the impedances around the line current input amplifier to reduce the rectifier offset due to mains leakage. I think R27, 28 = 50Ω, R29, 30 = 3300Ω, C16, 17 = 120nF will help center the zero pot (it's way over to one end on mine) while keeping the gain structure intact. I'm also considering changing the ground leakage current meter to be a ground-neutral voltage meter, although it may be better to just add a switch to the existing voltage meter—the jury's still out on that idea. In the meantime, I'm going to collect some data on ground leakage currents in typical installations.

There's also the open question of what's the right threshold for the glitch detector. At the moment it seems good for my house. On a quiet day (electrically speaking) it goes out and I can make it go on and off by turning on my office lights. But then I know I have a particularly quiet supply. *aX*

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3. Power System Harmonics, PG&E Power Quality Note. www.pge.com/docs/pdfs/biz/power_quality/power_quality_notes/harmonics.pdf.

PARTS LIST

Reference	Description
R63	10Ω, 1%, ¼W
R1	22Ω, 1%, ¼W
R42, 43, 68	50Ω, 1%, ¼W
R4, 45	470Ω, 1%, ¼W
R74	600Ω, 1%, ¼W
R67	845Ω, 1%, ¼W
R7-10, 17, 19-21, 31-34, 48, 49, 52-55, 57, 61, 62	1kΩ, 1%, ¼W
R27, 28	1k4Ω, 1%, ¼W
R11, 13	3k3Ω, 1%, ¼W
R5	5k6Ω, 1%, ¼W
R23, 36, 40, 41, 44, 47, 58	10kΩ, 1%, ¼W
R2, 26, 39	22kΩ, 1%, ¼W
R50, 51	27kΩ, 1%, ¼W
R15	47kΩ, 1%, ¼W
R69-71	68kΩ, 1%, ¼W
R60	72kΩ, 1%, ¼W
R16, 29, 30	100kΩ, 1%, ¼W
R3, 6, 12, 14, 18, 24, 37, 59	470kΩ, 1%, ¼W
R46	1kΩ trimpot (any)
R22, 25, 35, 38, 56	50kΩ trimpot (any)
R64, 65	25A shunt, 50mV (2mΩ)
R66	40kΩ, 5%, ½W (see text)
R72, 73	10kΩ, 5%, 3W (see text)
C5	6p8F, 5%, 16V, ceramic
C38	1nF, 5%, 16V, ceramic
C1-3, 14, 21	2n2F, 5%, 16V, ceramic
C16, 17	4n7F, 5%, 16V, ceramic
C32, 33	15nF, 5%, 16V, ceramic
C6, 8, 9, 11-13, 19, 20, 24-29, 34, 36, 37, 40, 41, 44, 45	100nF, 20%, 16V, poly
C4	680nF, 10%, 16V, poly
C10	2µ2F, 20%, 16V, electrolytic
C42, 43	10µF, 20%, 16V, electrolytic
C7, 15, 22, 39	22µF, 20%, 16V, electrolytic
C18, 30, 31, 35	33µF, 20%, 16V, electrolytic
C23	220µF, 20%, 16V, electrolytic
LED1	LED, red, ultrabright
D1-6	1N4148, 100V, 200mA signal diode
U1, U9	LM324, quad op amp, 14 pin DIP
U2	LM339, quad comparator, 14 pin DIP
U3, 6	NE5532, dual op amp, 8 pin DIP
U4, 5, 10	TL081, single op amp, 8 pin DIP
U7	78M05, +5V regulator, TO220
U8	79M05, -5V regulator, TO220
U11, 12	78L09m +9V regulator, TO92
J1, J2	dual outlet, 3 prong
J3	BNC connector, chassis mount
WW1-4	AC adaptors (wall warts), various (see text)
T1	audio transformer, 600Ω, 20Hz – 20kHz
V1, V3	neon, amber, chassis mount with resistor
V2	neon, amber, chassis mount with resistor
SW1, SW2	pushbutton, chassis mount
DPM1-3	digital panel meter, 3½ digit, 200mV f.s.