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Ground Zero

A Real-World Look at Lightning

Living on a granite hill during a thunderstorm gives you a whole new respect for Mother Nature. To guard against paranoia, Jeff and Steve figure out how to automatically unhook their appliances before they become toast.

I know that some day I'll regret telling so many people this, but you see, we've had this little problem with thunderstorms. I know, you think I'm kidding. Isn't tornado alley in Oklahoma? Out west maybe, but Connecticut?

While storms are frequently predicted on hot summer afternoons around here, the reality is that there are very few severe storms and only one or two tornado warnings a year. That's the good news.

When a big thunderstorm occurs in Texas or Oklahoma, three vultures and a mountain goat might be the only ones who see the furious lightning display or even know it's happening. When it drops a 200-MPH tornado funnel, a few prairie dogs are often the only ones who have to rebuild their homes.

The bad news is that Connecticut is very small. Two traffic helicopters on opposite ends of the state have to be careful not to run into each other.

When a severe thunderstorm happens around here, everyone knows about it. When lightning strikes, it invariably hits something valuable. And, when a tornado funnel drops in a densely populated area, it doesn't miss.

Contrary to the paranoid description, however, my problem is not tornadoes. The infrequency and narrow path of a tornado make the odds of getting hit by one about the same as a 747 landing in the driveway.

My problem is lightning. And, location has everything to do with it. I live in one of the higher areas of Connecticut. By Colorado standards, it's barely a gopher mound, but 1000′ is high around here.

Unfortunately, underneath everything in this part of the state is probably the biggest slab of granite ledge east of the Mississippi. You can guess a few obvious consequences. For example, when my wife suggests I dig a hole, I don't even think about using a shovel. Short of dynamite, the only solution is the backhoe!

All that rock has an insidious consequence—earth grounding. More correctly, it's the lack of an effective earth ground that's the problem. Zap! Here's comes the lightning bolt, and where does it go? You guessed it—everywhere but down!

As you might expect, rock is a lousy electrical conductor. On my street, the earth-neutral grounding point at the electrical-service entrance is about as functional as the ground rod the electric company tries to drive into solid rock.

Prior to my all-out assault on the problem, I had a half-dozen lightning hits and over $20,000 in damages. My neighbor has had an electric blanket burned off his clothes line (it wasn't plugged in), seen flames coming from his power outlets, and had appliances blown off his counter. I've had TVs barbecued, computer equipment incinerated, and satellite systems destroyed.

The final straw was a few years back. While my wife and I were sitting on the front deck, we could hear a storm in the distance. Just as I said it would probably miss us, there was a brilliant flash and a deafening KAPOW!

A lightning bolt slammed into something right next to us. "Next to us" turned out to be my 15′ C-band satellite dish. I jumped up in time to see a cloud of steam rising from the recently melted LNA and what looked like smoke billowing from the garage. I grabbed a fire extinguisher and headed to the rescue.

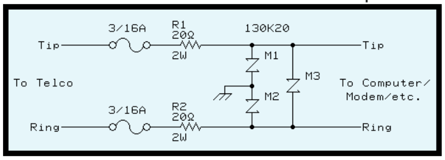

Figure 1—*The telephone line can serve as a lightning conduit. This circuit (shown in Photo 2) provides significant protection for both the phone equipment and user.*

Much to the EPA's chagrin, I'm sure, the smoke turned out to be freon. The lightning hit on the LNA had fed underground to the garage. Where the coax and control cables entered the house, the path of least resistance was out of the cable and into the central air conditioning lines.

As you might expect with all that power, it burned through the cables and copper tubing. Pow! Instant smog.

It was only because of the 2″ packed fiberglass insulation that I wasn't at a redwood-house–fueled wienie roast. When I saw how close we came to having everything torched, I got religion.

IT'S ALL IN THE GROUNDING

Scientists still don't fully understand lightning. Basically, it's a big discharge of static electricity that flashes toward the earth along a pilot leader.

This leader rushes down from the clouds in a series of discrete steps, ionizing the air as it goes. The final point is usually some elevated object on the ground. The bright lightning discharge we all see is the return stroke flowing back up the ionized path.

Any protection scheme doesn't prevent lightning from striking. It merely provides a low-resistance path for the lightning energy to ground. This path is the real issue.

A typical lightning bolt is 10–30 kA. The big strikes are as much as 100 kA (the power industry uses a 100-kA stroke with a rise time of 1.2 µs as its standard stroke).

Even if the path to ground were as low as 1 Ω, E = I × R tells us the DC voltage drop is 30 kV. If the resistance to ground is greater, then the voltage potentials are significantly higher.

Unfortunately, less technical discussions on the subject don't include the disastrous effects of inductance in this conduction path. Even with the massive lightning conductor used in the typical building lightning system, the inductance is on the order of 15 µH per foot.

The inductive voltage drop on a 20′ run of straight conductor with the industry stroke applied is on the order of one million volts! A conductor with lots of bends and twists has significantly higher inductance.

If the ground rod has a resistance of 10 Ω to ground, that adds another million volts along the path. Together, the total voltage floating around the building during the lightning strike is two million volts!

The voltage necessary to jump a spark through air is ~13 kV per inch, or 156 kV per foot. During a one or two million-volt strike on a building, you have to be careful about side flashes to any conductor that is grounded but not connected to the lightning system. That's why conducting bodies like equipment cabinets, machinery, metal rain gutters, and the AC electrical system have to be physically connected to the building's main grounding system.

When we casually speak of lightning taking the course of least resistance, we're talking about the flash-over. When lightning hits the cable TV line and isn't shunted to ground via a lightning arrestor and surge protector, the next stop is anybody's guess.

Short of putting up a tower to provide the proverbial zone of protection, defense comes by providing a conduction path with a lower overall impedance than alternative paths through your computer and fax machine.

The techniques are limited. The typical approach is to space lightning rods on the top of the building and use a heavy copper cable as a down conductor. Depending on the slope and area of the roof, there are standards regarding placement of the rods along the ridge versus around the perimeter (flat roofs are the most difficult).

If my house is any indication (part of the roof is shown in Photo 1), overkill is the typical installation choice. Counting the outbuildings, I have more than 25 lightning rods. The stranded copper cable is about a half inch in diameter, and 100′ of it weighs 20 lbs.

The fact that this is far from an exact science was illustrated by the professional installer's response to my observations. I pointed out that I've seen systems that employ sharp pointed rods as well as those that use large spheres. I've also seen light-gauge wire used as much as the heavy cable. His explanation was fascinating.

Apparently, there are two schools of thought in the lightning business. Most follow the convention that lightning hits the ground at a particular point because of the charge built up in that area of the ground.

By using very sharp points, the charge density at the point becomes high enough to leak off this accumulated energy, and it never gets high enough to attract a leader stroke. Because this happens over a reasonable period of time and at relatively low current, it also reduces the need for heavy stranded cable.

The other school of thought suggests that fate can't be deterred. If you're going to get hit, so be it. Just provide a good path to ground, and you'll be all right.

Round spheres handle the high energy density of a direct hit, and the heavy wire channels the load to ground. OK, so why is he installing heavy copper conductor and pointed rods, I ask? Insurance!

The points still supposedly reduce the target potential, but the heavy cable is there just in case that concept doesn't work quite as well as planned. I laughed.

The rods and down conductors are only half the system. It's the total impedance to earth ground that determines the voltage drop.

The building ground should have a resistance from 20 to 50 Ω. For most applications, this level is achieved simply by driving an 8–10′ copper-plated steel rod into the soil. Of course, the more conductive the soil, the better the ground.

But, my installation was at the other end of the spectrum—nonconductive rock without a lot of deep soil. The only solution was to create an artificial ground plane by burying cable around the perimeter of every building, attaching 25′ radial cables and ground rods (wherever they could be driven) every so many feet, and connecting all the building loops as one large grounding system.

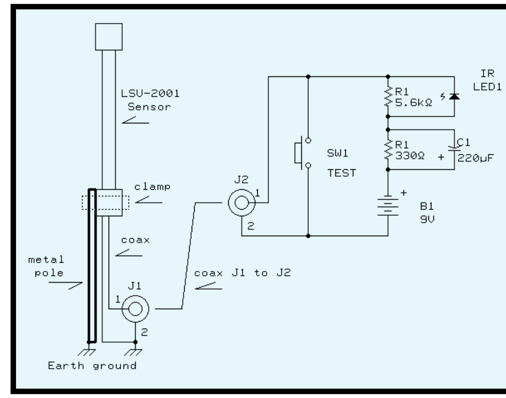

Figure 2—*An optically isolated pulse transmitter is connected to a low-cost McCallie Manufacturing lightning sensor mounted on a grounded pole on the roof.*

Jeff's a little luckier. His house has a steeply sloped roof and he only needs a few rods along the ridge. He also lives a hundred feet from a lake, so he also doesn't have the ledge or the grounding problems I have.

However, we both have a lot of sensitive electronics.

TRANSIENT VOLTAGE SUPPRESSION

Lightning protection falls into two broad categories—building protection and circuit protection. When lightning strikes, it creates an electromagnetic flux that radiates from the point of impact.

Like the windings of a transformer, this flux impulse induces a voltage on nearby conductors and electronic circuits. Depending on the proximity of the stroke, this transient voltage can be hundreds or even thousands of volts.

A number of techniques are available to protect electronic circuitry from the effects of voltage transients. These include the use of passive components (resistors and inductors) or devices with specific conduction characteristics to limit peak voltages.

The latter category includes gas discharge tubes (GDTs), reverse voltage breakdown diodes (TVSs), and zinc oxide varistors (MOVs). We'll just give you

#105

an overview for now, but next month, Joe DiBartolomeo starts a four-part MicroSeries with an in-depth look at surge suppression.

A GDT is a sealed tube containing an inert gas and two electrodes. When a high voltage appears across the terminals, the gas ionizes and a spark bridges the gap between the terminals, allowing current to flow.

The gas tube is like a crowbar device that short circuits the applied voltage down to less than 20 V. GDTs have very high surge capacity—on the order of 20 kA.

When a GDT is used across the AC power line, however, it must be combined with a circuit breaker. Once triggered by a transient, the GDT's 20-V clamping action effectively shorts out the 120 VAC as well.

The only way to reset the GDT is by blowing the breaker. GDTs are robust and efficient devices, but resetting the breaker from the crowbar action is a nuisance.

Typically, GDTs are used as main-power lightning arresters—often referred to as primary transient protection. Because their function involves a physical spark gap, they generally trigger at higher voltages than other protection devices. They can handle high current surges repeatedly without degradation.

Unfortunately, since their operation usually results in tripping the circuit breaker, GDTs are typically reserved for applications where a crowbar across the power line is a benefit rather than a nuisance.

Avalanche diodes are called by many different names (e.g., SAD, Transorb, TVS, etc). Basically, they're all just specialized zeners.

Their large PN junction blocks current flow until the voltage reaches a specific level when there is an avalanche of current flow. While considerably faster than GDTs, avalanche diodes are relatively low-current devices by comparison.

Their clamping characteristics are repeatable and do not degrade with continuous use (unless you exceed their surge-current rating). Avalanche diodes are ideal for low-voltage logic protection.

Photo 1—*Any effective lightning system starts with a good array of lightning rods spaced about every 20′ along the peak. The insert shows one rod in a little closer detail.*

While low-voltage avalanche diodes have some application as secondary surge protection, they are primarily used to protect semiconductor circuits from fast transients and ESD (electrostatic discharge). Avalanche diodes are frequently integrated within semiconductor components (e.g., communications line drivers) as well as attached across I/O lines and connecting wires.

Since they're designed to instantly clamp a transient and sacrifice themselves, avalanche diodes should be thought of as final protection.

MOVs are made of grains of zinc oxide bonded together in a disc form. They exhibit basic PN-junction zener characteristics. The typical 130-VRMS MOV (170 V_{peak}) has an initial conduction point of 205 V at 1 mA. Within 25 ns of reaching breakdown voltage, the internal resistance reduces from 5 MΩ to a level where as much as 10 kA can flow.

At this maximum current threshold, however, the MOV's clamping voltage can go as high as 600 V. This clamping threshold is determined by the MOV's grain density, and there is a wide range of operating voltages. MOVs are ideal for use both on the AC power line as well as low-voltage logic.

Because gas-tube crowbars and avalanche diodes need replacement when they sacrifice themselves, MOVs are used in 99% of power-protection products. Quite often, they're the only protective component in the device.

The only real downside to MOVs is that repeated high-current surges degrade their performance over time. In an application where a wide level of transient and surges are expected, GDTs are often used along with the MOVs.

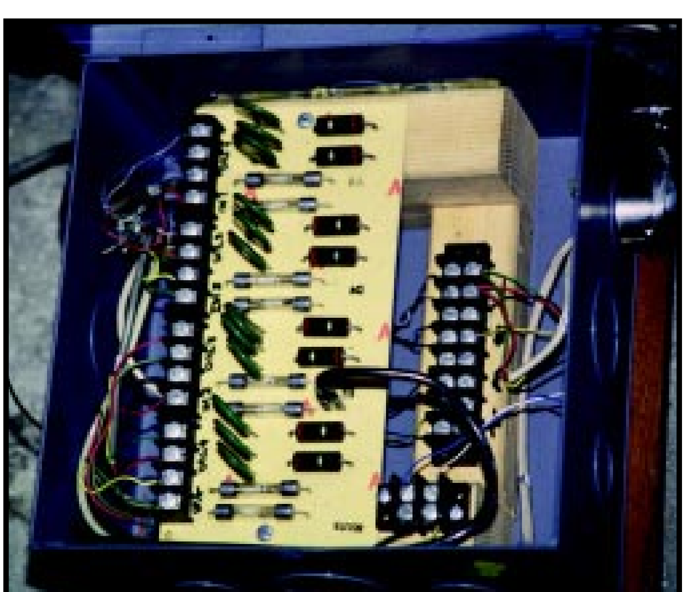

Photo 2—*The four phone lines entering the house have both differential and common-mode surge protection as outlined in Figure 1.*

MODEM AND POWER-LINE PROTECTION

Admittedly, I have a unique situation when it comes to lightning and surge protection. A simple lightning rod and single buried ground rod (like Jeff's) are more typical.

Once you solve the direct lightning threat, protecting a building from secondary invasions via the phone, cable, and power lines is the next order of business. There are two methodologies to this second line of defense.

The first method is to create a protective barrier using suppression devices. The second method is just a simple equipment-usage rule. When not in use, if the computer (or any piece of equipment) isn't plugged in, then nothing can hurt it. You have to decide which method is more practical for you.

All the discussion about various suppression components could lead you to believe we should use all of them. There are many exotic combinations of these devices, but those are generally intended for specialized applications.

Typically, a liberal sprinkling of MOVs provides a high level of protection at a reasonable price. The clamping voltage and physical placement of the MOVs are the only real issues.

There are two basic types of surges—common mode and differential mode. Common mode is when the surge potential is between the incoming line and the earth ground. A differential-mode surge is between two incoming lines with no reference to earth ground. All lines entering a building are susceptible to both.

Figure 1 illustrates a typical telephone/modem protection circuit. Photo 2 shows how I installed this circuit where my phone lines enter (the phone and cable companies provide the equivalent of a GDT connected externally).

Given the currents usually associated with phone communications, fusing might seem unnecessary. There isn't much that can help you in a close or direct lightning hit. If such an event occurs, the fuses are intended to simply disconnect the phone lines.

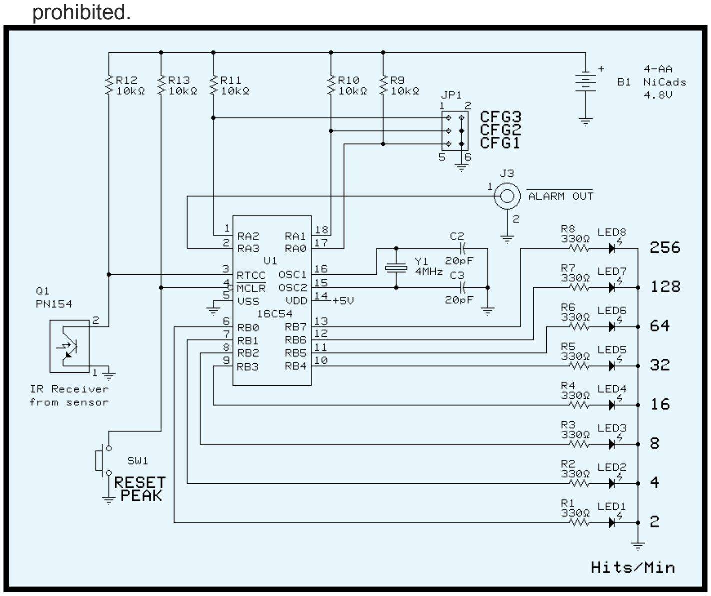

Figure 3—*The optical pulses are received from the lightning sensor and converted to a hits-per-minute LED indicator.*

Interestingly, a telephone line is an isolated signal. Devices attached to it only require differential-mode protection. The two common-mode connected MOVs are there not to protect the modem or phone, but to protect the user.

While most phones use high dielectric plastic, a 10-kV common-mode surge could easily make the user be the path of least resistance to ground. The two common-mode connected MOVs prevent this.

Protecting the AC power line uses the same three-MOV configuration. Large MOVs, affectionately called doorknobs, are used at the power-line entry. Smaller MOVs (e.g., the 130K20) are used in the individual circuits or directly at the equipment power source.

UNPLUG THE COMPUTER!

The absolute best way to protect equipment from power-line, phone, and cable surges is to simply disconnect it when not in use. This seems obvious, but it's a nuisance having to plug and unplug entertainment centers and computers. It's only after you've had major damage that such inconvenience seems like a viable alternative.

Jeff is aware of my situation. I suspect that the reason he has lightning rods installed at all is from hearing my horror stories.

Unfortunately, while the concept is sound, implementation isn't that simple. Jeff has a big family and just can't unplug everything when he leaves for the office.

I have the luxury of unplugging the simple stuff like TVs and stereos, but devices like time-lapse recorders, auto-answering computers, and fax machines can't just be left unplugged. The optimum situation would be to unplug the equipment automatically only during dangerous conditions. When the storm passes, connections are restored.

We're aware that commercial devices exist to do this task. Unfortunately, their lofty price leaves them in the category of airport landing systems.

Without a source for a reasonably priced "thunderstorm switch," Jeff and I decided to make one. Conceivably, all it would take is a lightning sensor, decision logic, and a means to connect and disconnect the attached equipment.

AUTOMATIC THUNDERSTORM SWITCH

We can watch for rain, listen for thunder, and count the seconds after seeing the flash. These are the obvious indications of a threatening situation. There are many less obvious indicators as well.

The energy propagated from the current flow of a lightning strike contains wideband energy. Everything from 100 Hz to 100 MHz is produced.

Emissions below 100 kHz travel along the wave guide formed by the earth's surface and the lower ionosphere. With respect to the earth (ground), the air around the strike becomes charged, and there is a direct relationship between the amount of charge and the distance from the strike.

We located a minimum-cost lightning sensor from McCallie Manufac-

Photo 3—*It will have to wait for next summer to be tested, but Jeff has attached the lightning sensor to the greenhouse roof.*

turing. Of the two models available, we chose the LSU2001, which is priced around $50.

Simple circuits are also provided for adding a meter or LEDs to monitor live data, or you can connect the sensor through an optocoupler to a PC. Optional software lets you count and graph storm data (providing you wish to keep the PC on day and night).

The manufacturer suggests mounting the LSU2001 on a well-grounded metal pole. The higher above ground it's mounted, the farther away you'll be able to detect lightning strikes.

Sensitivity is related to the differential charge between the air and ground—about 0.15 V/m. Put it twice as high, and it will be twice as sensitive.

They suggest that setting it 5′ high covers 15 miles, 10′ covers 50 miles, and 25′ covers 150 miles. The latter is enough to cover all of Connecticut, Rhode Island, and Massachusetts from our location.

Jeff wasn't enthusiastic about erecting a pole in his yard, and I wasn't volunteering to make like the Statue of Liberty.

However, since both of our roof peaks already had well-grounded lightning rods installed, attaching the sensor there made the perfect compromise location (see Photo 3).

The sensor has two wires leading out of its plastic enclosure. A coaxial connector would have made this a much cleaner job.

The coax was soldered to the wires and covered with tubing to make it watertight. The coax needs to be earth grounded so the sensor's internal circuitry can operate properly.

Interestingly, the sensor documentation comes with more warnings than any other piece of apparatus we've seen lately. Perhaps rightly so. If there's one thing you don't want, it's to provide a direct path for lightning into your house.

It's strongly recommended, for this reason, that the sensor's signals be isolated optically from your equipment and powered by its own battery. This setup also prevents line noise from interfering with the sensor. Figure 2 shows how it's done.

Battery longevity is essentially its shelf life. Power is only consumed when the air-to-ground potential rises above ~1.4 V. When this happens during a lightning strike, the circuit produces a pulse that flashes an infrared LED (LED1).

The IR LED points at a phototransistor directly or via a fiber-optic connection. The LED and phototransistor combination functions as an optoisolator. The greater the distance between them, the greater the isolation protection.

BLACK BOX IT

The sample data distributed with the sensor demonstrated that the effective number of hits per minute the sensor picked up during a thunderstorm ranged from 30 to well over 300 (within a 100-mile radius, I suppose this is acceptable).

Personally, I'd be heading for the cellar if I saw an indication of a 300 hits-per-minute storm, but Jeff was fascinated at knowing the actual quantity. He included eight LEDs to provide a visual display of the hits per minute as a power of two.

Using this method, the first LED indicates two hits; the second, four hits; the third, eight hits; and so on. The last LED indicates 256 or greater hits per minute. The LEDs are off under clear-sky conditions.

To count hits from the sensor, Jeff used the T0CK1 input on a PIC16C54 microcontroller. Figure 3 shows the circuitry for this simple display. Besides the eight directly driven LEDs and T0CK1, there are three bits for configuration and a single-bit alarm output. The configuration bits choose how the alarm output functions.

The output can be a 250-ms momentary pulse or continuously low during an alarm condition. The alarm trigger point is selected using the first two configuration bits. The four combinations select the hits-per-minute turn-on point of any of the upper four LEDs as its trigger level.

The software's main loop contains a 3-s counting period, followed by a total of the last 20 periods (total over the last 1 min.). The total counts are transposed into a byte with the proper bit high to enable an LED indicating the appropriate range.

Because you want to know if the storm is moving toward or away from your location, it's important to know about the past. Therefore, the PEAK count is displayed as a steady-state LED.

The PRESENT count is indicated by XORing the present count with the LEDs such that if PEAK and PRESENT are the same (as in a storm moving toward you), the LED flashes.

However, once PRESENT starts dropping, the peak-count LED remains steady and the present-count LED flashes. Now, you can tell immediately which direction the storm is heading. The PEAK value can be reset by pressing the reset button.

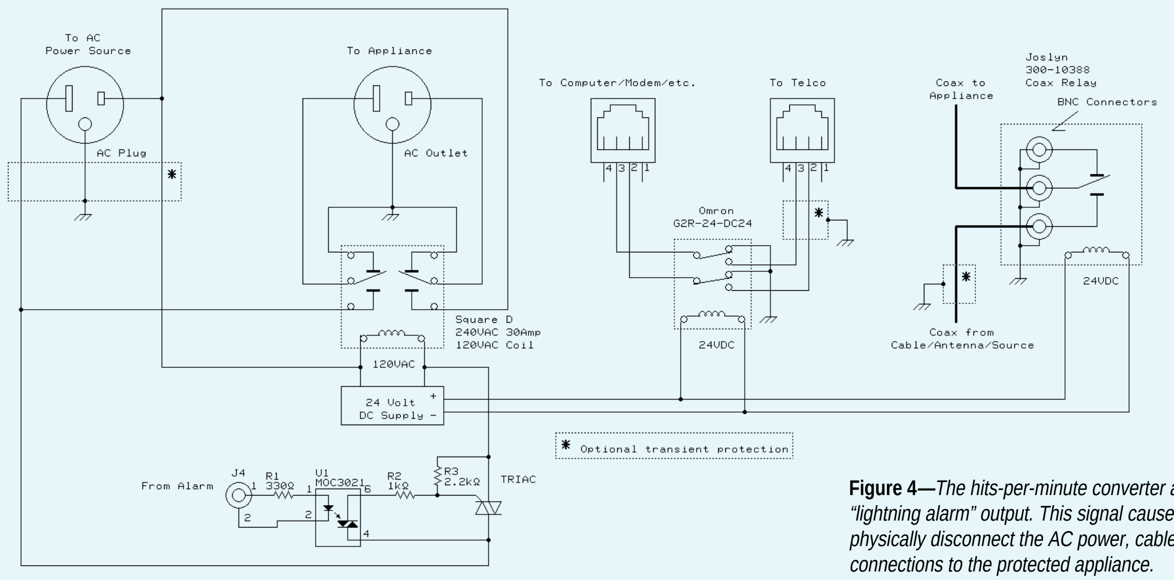

Figure 4—*The hits-per-minute converter also generates a "lightning alarm" output. This signal causes the circuit to physically disconnect the AC power, cable, and phone-line connections to the protected appliance.*

Although Jeff's software only takes up about a quarter of the 16C54's available code space, all of its registers are used. The majority are taken up by the 20 table entries doing the 3-s counting samples.

Only five other registers are used by the code for the rest of the functions. When no LEDs are on, the circuit requires only about 3 mA (add about 10 mA per LED).

Obviously, this whole circuit could operate from three alkaline batteries, but if it's mounted where you plan to view the thunderstorm's progress, trickle charging four NiCd batteries would be better. After all, when you need the information most to either pull the plug or tell you that conditions are all clear, you don't want to depend on a tired set of batteries.

Figure 4 is the switch's connect/disconnect section. This particular configuration accommodates AC power, coax, and phone lines.

The 16C54's alarm output (set for steady-state output mode) drives an optoisolated triac switch controlling the AC power relay. The circuit's normal condition is for the alarm output to be high and the relays energized. A small DC power supply, connected in parallel with the AC power relay coil, controls the coax and phone relays.

The switches' output connections are made to the normally closed contacts. When the power is off or an alarm condition exists, the relays are deenergized. This connects the equipment side of things to ground, where it provides the greatest protection.

While the normal spacing of the relay contacts is less than ¼″, should a high-voltage surge enter the line side of the switching unit, any place it arcs within the relay will be at ground. Certainly, if you incorporate MOV suppression in addition, such voltage levels shouldn't even exit at the relays.

We didn't include those MOVs and surge-suppression components on the schematic, but we indicated their proper placement. If you're already using protection devices on these lines, you may not need to include them inside as well.

WAITING FOR SUMMER

Winter isn't the best time to test lightning-detection equipment in Connecticut. We'll have to wait a few more months before the circuits get a real workout. Jeff might have his set to trigger on the 30 or more hits per minute, but I suspect I'll want to start thinking of alternatives at 2!

Considering how many of you live in southern states (or the Southern Hemisphere, for that matter), we're sure a number of you will have the opportunity to thoroughly test all this under ideal conditions long before we will.

We invite you to let us know about your tales of discovery and what we can expect. Perhaps by next fall, we'll have sufficient information for an update to the design. ■

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SOURCES

Stormwise LSU-2001 lightning sensor
McCallie Mfg. Corp.
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PIC16C54
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I R S

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403 Not Useful