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Safety On The Bench: Hazards And Precautions In The Power Electronics Lab

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It's no mystery that we, as power electronics engineers go through tremendous pains and trials to deliver a product that fulfills the mission requirements demanded by the application and the market. These requirements include reliability, environmental, safety and electromagnetic radiation, conduction and susceptibility constraints, and in some cases heavy ion, gamma ray and neutron events.* We take all efforts to assure that the path of least resistance is upheld for the circuitry. This is the path of most resistance for us, but this is the duty.

The standards can vary from ambiguous to crystal clear across space, mil, medical, aerospace, defense, consumer, automotive, industrial. But what happens on the bench in the lab during prototype and evaluation stages—*before* the codified standards apply? Shouldn't that be safe too?

Further, the engineers of yesteryear were very familiar with lab and bench procedures and "building stuff with hardware." I've now seen virtual programs that put out degreed engineers that have never touched hardware. It is plausible that these folks will be evaluating power electronics hardware as "the guys that build stuff" are replaced. How, then, to keep this bench process safe?

Some labs will have rules. The rules are often general broadcasts like "no one works on anything over 40 V alone!" Some chasers from the lead solder days like "no food or drink in the lab" and "wash your hands when leaving" are often still posted and now perhaps "wear a mask" and maybe "don't touch anything". But I have not seen any reasonable assessment of safety requirements for a prototype effort.

Some engineers have done a *tremendous* job making the workplace safe. I've marveled at safety features in some labs: Deadman switches, contactors, cap bank dump switches, protective shields, delta-to-Y transformers right at the lab, separate service panels, and separate raceways for instrument power and the equipment under test. Fire extinguishers of proper type, clear documentation of every wire and node, ampacity of every branch known and documented, arc flash calculations and boundary distances for every branch, AED, first aid training, first aid kits, machine guards, training and E-stop switches.

For all of these things, I salute the engineers responsible. Others simply never knew or cared. The shipping deadline might have taken precedence and common sense dictated sensible procedure and equipment. But common sense is fleeting. My hope is that this brief discussion offers some useful insights to help keep my peers safe.

Please note that the information presented in this article is meant solely as an introduction to the topic of electrical safety in the power electronics laboratory to help engineers understand the possible hazards and possible safety measures. *This is by no means a complete work or a substitute for any OSHA, local, corporate or national training and safety guidelines.*

Working On A 100-W Offline Converter

To delve into this subject we have to quantify some things. First is the matter of energy level. If you are working on a 100-W flyback converter or LLC on the bench, what are your safety care-abouts? Clearly there is ac mains voltage present and you will have live nodes on the board derived from the ac mains. Galvanic isolation may be a good idea. Protective fusing can simply take the form of a mains-rated fuse. Energy limiting beyond this really isn't required.

But let's think through it. If we have, for example, a peak-current-mode-controlled (CMC) flyback controller, with no external energy limiting circuitry, the flyback will deliver continuous energy into a fault. If the output were perhaps 5 V, the output current would then be around 20 A. Dumping 20 A into a shorted electrolytic capacitor is enough to stink up the place with the nasty smell of boiling electrolyte. It's enough to blow the vent structure on the capacitor. The hot capacitor may than catch fire, in a UL 94V-0 world, where it won't propagate quickly, but it will smell bad.

**Microchip Technology's SiC MOSFETs, Schottkies and power modules play well into this arena up to about 1700 V and 1200 A. More information on these devices can be found here.*

What is needed to keep this safe? To consider this, let's consider the hazards in play.

Eye And Ear Protection And Ventilation

It's possible that you may launch a few of the power switches or integrated controller/power switches as part of the development effort. A "fault the output diode" mandate is usually enough to do this. Most new engineers have a real aversion to this, but it's essential to delivering a good product. If there is a gross fault, this fault may happen during product operation and it needs to be understood.

The event will dump considerable energy in a very short time (like a fire cracker). It may also throw some particles around the bench due to the expansive energy event and local plasma level heating. There may be some residual burning. Eye protection is very important. Use good safety glasses, with side shields and appropriate ratings.

But beyond this, consider your ears too. If you are quietly taking data in a quiet lab, on a quiet floor and you are suddenly interrupted by a 140-dB noise burst, there is a good chance that you will react to this. Maybe a jump, a flinch or a twitch. If you can attenuate the noise blast, the jump will be far less. Consider having your hands in perhaps a cabinet, taking a measurement and then "POW"! You don't want to be flinching toward live mains voltages when that happens. Attenuate the blast with respect to your ears and you'll attenuate the reflex. A little planning wouldn't hurt either.

Also, consider covering other "essential live stuff" with Nomex or some other good flameproof insulation. With this, if you do flinch toward something, you have protection in place.

The ventilation is another absolute must. Burning electronics smells bad. I'm no chemical engineer nor am I a physician, but it seems clear to me that if ventilation can minimize the bad smelling stuff and get rid of it quickly, this is a good thing. Therefore I recommend good ventilation. If the ventilation in a properly designed pistol range is on the order of 400 CFM per active bench, good ventilation in the power electronics lab should have this number as an asymptote. Maybe a 200-CFM hood per bench.

A HEPA filter is probably a good idea too. It's been said that sharing is caring, but the folks sharing the AHU (air handling unit) probably don't want any aroma from your bench.

"Blast" Shield

Let's consider the energy levels in play, how the converter works and what a fault may entail. This is a 100-W flyback (Fig 1). If we are switching at 100 kHz, for this example, the energy storage levels are on the order of E' = 100 W, or 1 mJ transferred for each cycle.

In terms of input capacitance, perhaps the B+ capacitor is in the 470- to 1000-µF range, universal mains voltage may have this at around 400 Vdc. The maximum energy storage can then be calculated at $CV^2/2$. The capacitor can source 40 to 80 joules into a fault. The output capacitor is at a much lower voltage with a much faster refresh rate (read as much smaller). Its energy storage will contribute very little.

If we are tied to the ac mains voltage directly, we do have to consider the short circuit capability and the interrupt rating of the protective fusing in play. If the converter has reasonable inrush limiting, a 3-A, type 3AG 0.25-in. x 1.25-in. cartridge fuse may be chosen for the application directly tied in series to the ac mains. The $I^2{*}t$ rating of this fuse is around $14A^2{*}s$ (Littelfuse was chosen for this example).

The impedance of a faulted converter can be very low. Consider a shorted primary MOSFET. The loop consists of the EMI components (CM and DM chokes), inrush limiting components (in hot state), bridge rectifier, PFC inductor and catch diode (if used) and then the DCR of the flyback transformer, shorted primary-side MOSFET, shunt and traces.

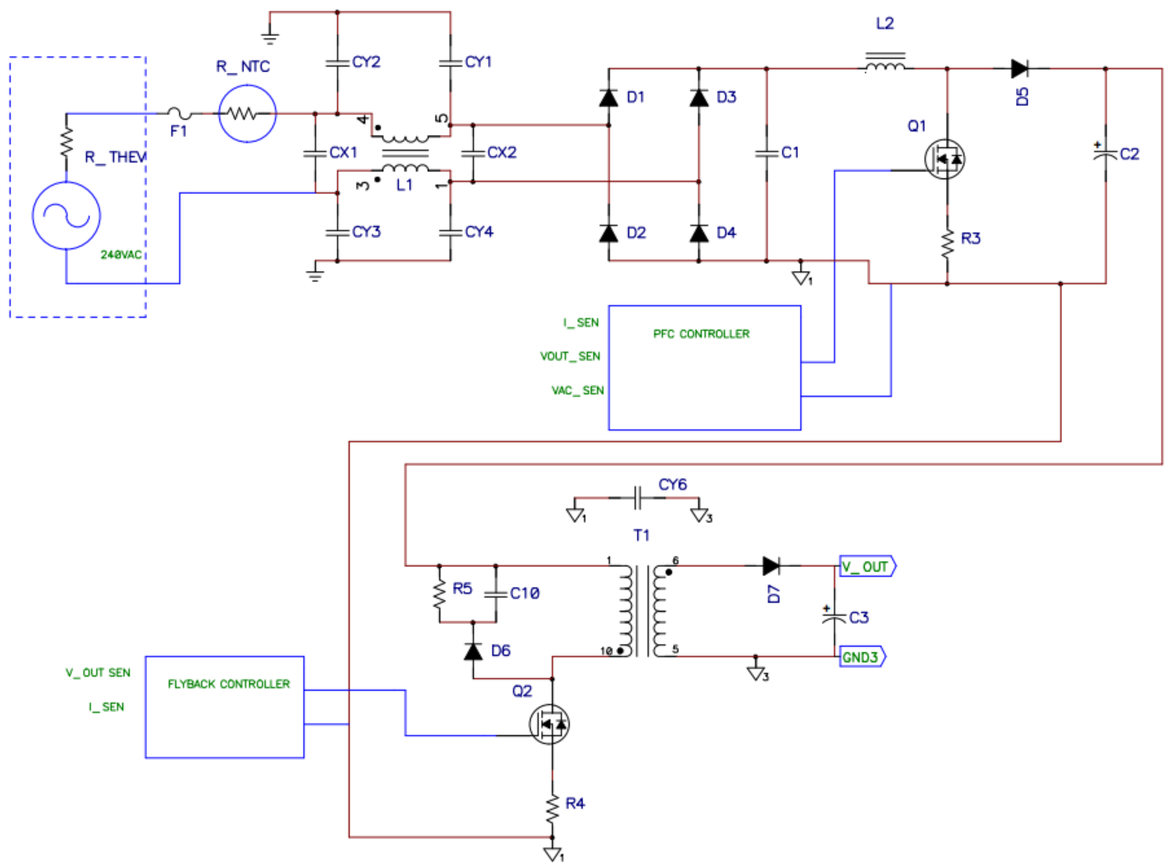

Fig. 1. Flyback and boost schematic.

For this converter, considering the above elements, the fault resistance is probably around 0.5 to 5 Ω. Let's guestimate around 5 Ω. At 240-Vac input, the fault current is then around 48 A. With this, the fuse will blow open in half of a mains line cycle. I calculated about 6 ms. The worst case arc flash energy flux can be calculated by:

Incident Energy (J/cm^2) = $((Vdc*I_{fault}*t) + CV^2/2)/D^2$

For 400-Vdc mains, at 48 A, for 6 ms at arms length or 45.5 cm, with 80 J of stored energy in the capacitor, we get an incident arc flash energy of roughly 0.1 J/cm^2.

To bring that into a common-sense analogy, the solar constant from the sun is often cited as 0.137 W/cm^2, on the equator at high noon. By this comparison, an arc flash resulting from working on a 100-W flyback converter at arms' length is approximately equivalent to 1 second of sun exposure in Bogota, Columbia at high noon. Not too bad.

What then is the weak link in this fault? Where does the energy go? Just looking at ampacities, the fuse will absorb a lot of the energy when it fuses open. But beyond this, it's also possible that the very low ESR of the B+ capacitor can store enough energy to quickly fuse open the bond wires on the primary-side MOSFET or perhaps even the shunt resistor in series with the source.

While the fault energy level at arm's length isn't bad, there should still be some sort of shield in place to supplement your safety glasses. Getting smacked in the forehead with flying package bits isn't much fun, but it's easy enough to place a small acrylic window in front of the equipment under test or rely on the enclosure (if the mechanical design is complete).

Old salt may know, but when the shunt resistor opens, the primary current *will* find a path back to return. This often happens by breaking over the gate oxide, flowing through the driver and perhaps even the PWM controller back to return. It's a mess. None of those components were designed for that. They often do hold up fairly well, but they don't survive.

If we are tied to a lab-grade, inverter ac source, the current limiting is much faster and it will source much less energy into a fault. It will be similar for a dc lab supply supplying B+. The incident energy considerations from a primary fault in this case are less.

But what if the fault *doesn't* blow the fuse? What if the output capacitor of the flyback converter fails and draws a lot of current? The primary side only sees this as "load". The primary continues dumping $LI^2/2$ into the load at a rate of f_{SW}. As the resistance gets really low while the electrolyte boils off and stinks up the room, the flyback may go into current limiting as afforded by peak CMC operation and the duty cycle will limit to Dmin.

It's important to note that energy is still flowing. This is a "soft fault" in that there was no fire cracker emulation event, but the capacitor gets hot, and it may even burn. A full short circuit would likely push the converter into pulse skipping or hiccup mode reducing the dissipation into the cap substantially.

In this instance, the ventilation will be the best medicine, followed with an easy-to-get-to kill switch. It's also a great idea to have a CO_2 fire extinguisher nearby and a means to quickly snuff out a small, nonspreading UL94-V0 type fire event. Obviously a water-based fire extinguisher is a really bad idea, and the ABC dry-powder type extinguishers are also bad in that the dust will gather in all of your test equipment, contacts, membrane switches, etc. It makes for a lot to clean up if you are bold enough to remove the "do not remove" stickers on the equipment and go to it.

In terms of heat loading, I'd take my hat off to the lab designer that considered it, but a 100-W flyback will add little more heat to the room than the engineer sitting in front of the converter taking the measurements.

As for measurement technique, the right probes are needed. Use HV differential probes for mains or hot-side-referenced measurements. Use a current probe with reasonable insulation on the current measurement loop. For the secondary, use appropriate probes and technique. A clear understanding of the shock hazards involved is required of all those working in the lab, along with a partner system where perhaps one partner takes the measurements and the other partner has easy access to the kill switch, perhaps logging data off to the side.

I'd rather not discuss insulation system failure on the flyback converter. If your insulation system is failing, you are in need of engineering assistance well beyond that of safety equipment (Fig. 2).

Fig. 2. Tools and insulation for lab tests ranging from 1 kV to 30 kV.

Higher Current (Lower Voltage)

It's a small subset of the design and test work that we do on equipment, but in practice, I've found that when the dc output voltage exceeds the quantum work potential of the metals involved (like an arc welder exceeds the quantum work potential to transfer mass and then fuse the weldment—in the 20-V to 60-V Vout range (see Fig. 3)) and the currents are in the 20-A to 200-A range, bad things can happen fast. It's not a terrible arc flash hazard, the stored energies aren't that large, but the current can cause a tremendous amount of heating and burning and the voltage is often high enough to sustain the arc as conductors fuse open.

We didn't intend to build an arc welder, perhaps it was simply a high-current dc-dc converter. But at the same time, the traces can deliver high currents, overcurrent protect is set slightly higher than max current and a fault impedance is likely a bit higher than the full load impedance. In other words, this converter *wants* to pump that energy into that fault—the fault is often within the V-I operating range of the converter (Fig. 4).

For this scenario, careful considerations must be given to materials (UL94V0 at a minimum), creepage, clearance and ampacity. This is *not* the place to use thin traces and let them get hot. That's no different than the wire coming from the nozzle of the MIG welder fusing into the welded joint.

Fig. 3. MIG welder in action—fusion is well within the SOA of this converter.

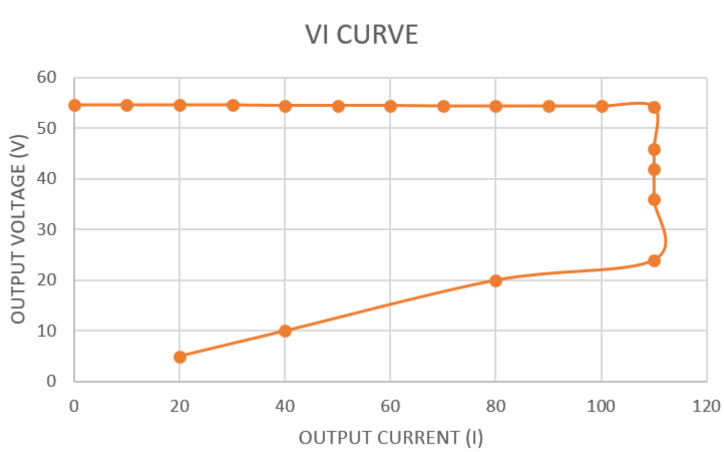

Fig. 4. V-I curve of rectifier output. Note that a fault can lie within the curve!!

While it doesn't register high on the arc flash or shock hazard scale, this is probably one of the toughest design arenas. Similar procedure to that used with the 100-W flyback should be used in this case, perhaps with the addition of a good long sleeve welding shirt and a little more emphasis on the kill switch. Until the design is completely vetted, don't let this run on its own for extended periods of time.

Higher Power—A 20-kW Inverter

Thus far, we've approached the development task and bench testing of a small, mains-operated flyback converter. Eye and ear protection, a small shield, good ventilation, a kill switch, proper fusing, a CO^2 fire extinguisher, and a partner system were required. But what about larger power electronics equipment?

If we're designing a 20-kW inverter for example, the failure modes are similar, but the magnitudes of incident arc flash energies go up substantially. A nice touch in this case is to plan ahead if possible. If the converter is to run directly off of ac mains voltage, I recommend installing a delta-to-Y transformer in the lab with its own subpanel. This allows the neutral to be bonded locally. If there is a fault to neutral, the fault currents stay in the lab rather than running through other equipment or branches.

Another nice thing about a delta-to-Y transformer (Y on the lab side) is the fact that it doesn't pass triplen harmonics from the lab back to the fed side (delta). The transformer should be chosen to support the load and the K-factor ratings with appropriate headroom. The cooling in the lab may need to be adjusted for the additional heat loading.

The addition of a variac stack, wired in Y connection to the transformer output is an excellent idea for testing over line voltage. Again, allow appropriate headroom, heat loading accommodations and ventilation.

To revisit the incident arc flash energy, for this 20-kW converter, the line currents at 480 Vac are a little more than 24 A. An appropriate breaker or fusing device may operate in the 50- to 200-A range. Thermo-magnetic circuit breakers for motors often require longer delays to trip due to startup events and high inertial loads. The capacitors in the inverter get a lot larger, and then there's the matter of rotating energy stored in the load (motor).

If the dc link voltage is at approximately 700 V, and the capacitor bank is on the order of 5000 µF (for 50-Hz mains), we have a stored energy of 1225 J. Rotating energy in the machine may well be in the range of 4000 J if the rotor and flywheel is a 15-kg disk spinning at 3000 RPM with a 6-in. diameter. This is a lot more energy than the flyback. The fusing may take five or six line cycles to open and the fault currents may be in the 500-A range. To look at this incident arc flash energy, we can calculate:

$$((700\text{ V} * 500\text{ A} * 120\text{ ms}) + (1225\text{ J}) + (4000\text{ J}))/(45.5\text{ cm})^2$$

Or an incident energy of 22 J/cm^2.

This is a serious number. It requires additional distance (no longer working at arms' length). It also requires PPE (a welding jacket), full face shield, more ventillation and more shielding. This incident energy is equivalent to several seconds of heavy arc welding. No one would do this in short sleeves and a t-shirt with no eye protection.

Clearly I'm not recommending a #12 tint visor welding mask (really hard to see through that on the bench), but certainly some flash protection is required for the eyes and the skin. A welder's jacket with good sleeves may be a good idea and this is usually the point where I reach for my class II HV gloves and protectors. Great dielectric, great protection.

Just as a point of reference, if your building electrician was changing out the mains breaker feeding your bench, he'd be wearing similar clothing to what I describe as a matter of regulations (see the table).

Table. PPE table NFPA70E 130.7.

EQUIPMENT	ARC FLASH PPE CATEGORY	ARC FLASH BOUNDARY
Panelboards or other equipment rated 240 volts and below Parameters: Maximum of 25 kA available fault current; maximum of 0.03 sec (2 cycles) fault clearing time; minimum working distance 455 mm (18 in)	1	19 Inch
Panelboards or other equipment rated greater than 240 volts and up to 600 volts Parameters: Maximum of 25 kA available fault current; maximum of 0.03 sec (2 cycles) fault clearing time; minimum working distance 455 mm (18 in)	2	3 Feet
600-volt class motor control centers (MCCs) Parameters: Maximum of 65 kA available fault current; maximum of 0.03 sec (2 cycles) fault clearing time; minimum working distance 455 mm (18 in)	2	5 Feet
600-volt class motor control centers (MCCs) Parameters: Maximum of 42 kA available fault current; maximum of 0.33 sec (20 cycles) fault clearing time; minimum working distance 455 mm (18in.)	4	14 Feet
600-volt class switchgear (with power circuit breakers or fused switches) and 600-volt class switchboards Parameters: Maximum of 35 kA available fault current; maximum of 0.5 sec (30 cycles) fault clearing time; minimum working distance 455 mm (18in.)	4	20 Feet
Other 600-volt class (277 volts through 600 volts, nominal) equipment Parameters: Maximum of 65 kA available fault current; maximum of 0.03 sec (2 cycles) fault clearing time; minimum working distance 455 mm (18 in.)	2	5 Feet

Working on the 20-kW inverter also requires a better blast shield than the flyback. Perhaps a 1-in. acrylic panel, tinted with the previously discussed PPE for the engineers (again, jacket and gloves) and additional working distance. Mount up the current probes, Rogowskis, diff probes, then get back a little bit before energizing the inverter.

But again, what if the fuse or breaker doesn't trip for the fault? Perhaps the rotating machine lost a phase and begins cogging wildly (for perhaps a PMSM). This is where we have to venture beyond electrical safety and consider the mechanics involved.

If the motor were just sitting on site, not bolted down to anything, a cogging event could make the machine move *rapidly*. Consider a gyroscope where the flywheel undergoes a fast change in speed (eg: torque). The machine moves! We don't want this on our bench. There's enough to worry about without a motor frame thrashing about.

So bolt any rotating machines down properly, make sure all alignments to a dynamometer, torque transducer, etc. are well within recommended tolerances, use the proper couplings, and shield and ventilate the machines well. For an R & D machine, perhaps a secondary means to hold it in the event of severe cogging is a good idea, like a hanger bearing over a driveshaft. Not precision containment, but a means of mechanical support through a fault.

Even Higher Power—Power Converters For EVs

There are even more considerations working in the 20-kW power range, but that is not the whole story as yet. Another very popular application at present involves 100 HP to 500 HP machines, inverters and battery banks for propulsion applications, both on and off road. With this, again, the incident energies ratchet up, but with a large battery in the system, the stored energy becomes *very* large.

The dc link capacitance may be a little larger than in the last example, but the big energy storage vessel in the room is the battery. This is likely in the 300 V to 800 V range and 200 to 500 Ahr. In terms of energy storage this is 60 kWhr to 350 kWhr range or roughly 216 MJ to 1260 MJ range. And then there's the realization that some battery chemistries can go exothermal if they are overdischarged or overcharged. This hazard *must* be carefully attended to.

Some ways to do this include an internal battery management system, careful monitoring, an internal interrupt contactor, a redundant interrupt contactor, and then perhaps a lab contactor (I recommend a locomotive contactor with magnetic blow outs for arc quenching). The battery must then have an absolutely rugged enclosure. In terms of arc flash, this is a bomb. The battery has the energy of 1/20 to ¼ ton of TNT. It must be absolutely understood and accounted for.

If the protection contactor or fusing opens at perhaps 500 A and takes 20 ms to open on a 700-V battery, the source can deliver an arc flash energy of 7500 J to the electronics under test. The capacitor bank may be in the 5000-µF range at 700 V, thereby storing 1225 J.

Meanwhile, the rotating load may be in the 10-kJ or 20-kJ range. Clearly this is *not* to be worked on at arm's length. I *strongly* recommend spending extensive time perfecting the gate drive, tuning double pulse waveforms to perfection, verifying the PWM controller, mitigating ringing, oscillations and nearfield coupling mechanisms, verifying contactor and E-stop functionality and making sure electrical noise susceptibility is as good as needed in the design.

Then, the equipment should be instrumented in a separate room with proper motor mounting and battery containment. No one in the room when testing. And have a clear procedure for a fault, fire suppression system, etc.

A Few Words On Grounding

While this is a critical topic to cover, there is no way I can adequately cover it in the current article. To be sure, instrumentation and metrology should be appropriately grounded. Beyond that, grounding circuitry under test must be considered on a case-by-case basis.

Bench safety for power electronics design work is nothing to take lightly. Browse NFPA 70E and you will see some gruesome pictures of what arc flash can do to equipment and engineers alike. Most any safety lecture will start with a collective notion of safety and then pose a question to the effect of "whose responsibility is this?" If there's a test, the right answer is usually that "Your safety is your responsibility," but there's more to it than that. Our duty goes a bit beyond. In providing the path of least resistance and fulfilling the mission requirements, we have to make certain that the work is safe and carried out in a safe environment.

Finally, this brief work is no substitute for a comprehensive safety review and lab plan. It serves as a framework, a beginning to the discussion. Please share comments and suggestions.

Preliminary Lab Safety Checklist

This is not a comprehensive safety plan, but rather some suggestions.

- Do your homework first. A) Simulation, modeling and nearfield analysis. B) Energy-limited double-pulse testing, short circuit testing and fault testing. Make sure all waveforms are best possible. C) Mitigate ringing and address noise coupling. Remember "It works great in simulation, thereby we are done!" is a *non-starter*.
- CO_2 fire extinguisher nearby, not stuffed under equipment under test.
- Eye and ear protection.
- PPE in the form of full face shield (perhaps slightly tinted), welding jacket, class II gloves, and denim jeans.
- Ventilation.
- Appropriate cut-off switches, contactors, and E-stop gear—easily accessible and easily found.
- Blast shield.
- Never work alone.
- Define and understand shock hazards.
- Define and understand incident arc flash energies and safe boundaries, test appropriately.
- Mechanical safety: all motors, fixtures, dynos properly sited and secured. Use guards on open shafts.

- Staff training for all that have access to the lab. What say a purchaser or marketer walks in when the equipment is energized and under test? An outside vendor? They have to know what they are seeing and where the hazards are, which isn't always likely. Better to restrict the access, perhaps having them peer in through a window.
- Safety training for all staff doing the work. CPR and "stop the bleeding" are good additional measures.
- Evacuation plan.
- Regular inspections.
- OSHA 30 training.
- No clutter.
- AED (automated external defibrillator) and first aid kit. Know where they are and know how to use them.
- Regular safety training updates.

Again, this is a preliminary discussion. A beginning. Under no circumstance or situation should this be considered a complete guide. Local, OSHA and company guidelines must be considered. May your electrons flow as intended and please be safe.

About the Author

Paul Schimel is a principal power electronics engineer in the Aerospace and Defense group at Microchip Technology. He has over 24 years of theoretical and hands-on experience in power electronics, spanning military, aerospace, automotive and industrial markets. Paul's work regularly includes module design, dc-dc converter design, device-level analysis, root cause analysis, failure analysis, EMI mitigation, PCB layout, control loop compensation, inverter design, transformer design, rotating machine design, bench-level measurement and validation techniques and system-level analysis/comprehension.

He has designed dc-dc converters from milliwatts to megavolt-amps, inverters to 5,000 HP. He is a licensed professional engineer (PE) and holds two FCC licenses (First Class Radiotelephone and extra class amateur). In addition, Schimel holds three patents on power electronics matters.

For further reading on power supply-related safety and compliance issues, see How2Power's special section on [Power Supply Safety and Compliance](#).