

New Horizons Voltage Protection Circuit

Design Notes

New Horizons, a division of Global Health Labs

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Contents

1	Goals	2
2	Calculations	2
2.1	Detailed calculations for MOV + GDT impulse protection.....	2
2.2	Simulations	4
2.3	Let-through voltage tests	4
2.4	Fuse/Circuit Breaker.....	6
2.4.1	Off-PCB power inlet and breaker combination	6
2.4.2	Off-PCB breaker only	6
2.4.3	On-PCB breaker	7
2.4.4	Circuit breaker trip curves	7
2.5	Consider a 3- to 6-minute delay for reconnect	8
2.5.1	Delay.....	8
2.5.2	Optional indication that delay is active	9
2.5.3	Extended delay conclusion	9
2.6	Input and output connector flexibility.....	9
3	PCB Design Rules.....	10
3.1	Conductor spacing.....	10
3.2	Power conductor trace widths.....	10
3.2.1	Notes based on previous boards and calculations	10
3.2.2	Final design rules.....	11
4	Summary of Changes / Final Configuration.....	12

1 Goals

General design:

- Provide overvoltage and impulsive transient protection, aligned with the levels defined in voltage stabilizer performance specification WHO/PQS/E007/VS01.6 (even though it isn't a stabilizer).
- Use the structure of the New Horizons voltage protection design.
- No EMI filtering as that is built into appliances.
- Use an IEC 60320 C14 inlet so that it can accept a wide variety of standard input cords. Also provide a Type "F" outlet for the same reason.
- Provide an enclosure so that it can be used as an inline power protector.

Specifications:

- Withstand voltage > 500 VAC.
- Impulsive transient voltage at 2 kVpk results in a peak output voltage < 750 Vpk.
- Protect against and survive an impulse that happens when there is sustained overvoltage.
- Symmetric impulsive transient protection between line-earth and neutral-earth.
- Can work if the neutral and line are reversed, in other words when neutral-to-earth is not a small voltage.
- Low and high voltage cut-in and cut-out thresholds of 87 V / 95 V and 269 V / 273 V.
- Current rating: 10 A.
- Current protection: inexpensive on-board circuit breaker.
- IP rating: IP40 (1 mm objects excluded, no water protection).

2 Calculations

Note on terminology: The term "surge" is sometimes used to refer to transient overvoltage events that last less than a line cycle, and sometimes to line-frequency events that last between one cycle and one minute. To avoid confusion, we will use "impulsive transient" or "impulse" for the short event and "overvoltage" for events lasting longer than one line cycle. We will avoid using "surge".

2.1 Detailed calculations for MOV + GDT impulse protection

From page 5 of this document ([Littelfuse_GDT_Catalogpdf.pdf \(mouser.com\)](#)).

"After the transient has passed, the GDT will extinguish and again appear as an open circuit. In order to insure gas tube turn off at the zero crossing in AC applications, the current through the GDT once the transient has passed, must be less than the follow-on current rating of the gas tube. The follow-on current requirement can easily be met by placing a resistor in series with the gas tube. Littelfuse's AC series gas discharge tube surge arresters were developed specifically to protect AC power lines and normally will not require additional components to limit follow-on current."

However, we are using the Littelfuse CG3 series, and want to protect even in the event of overvoltage. We need an MOV in series unless we know that the mains would not be able to source 200 A (the follow-on rating of the CG3 series).

- Choose an overvoltage withstand level of 566 VAC = 800 Vpk due to the characteristics of the available CG3 1.0L gas discharge tube.
- CG3 1.0L GDT
 - DC breakdown range of 800-1200 V, so it is guaranteed NOT to break down under the sustained AC overvoltage level chosen above.
 - Impulse breakdown at 1 kV/ μ s is 1500 V.
 - Arc voltage 25 V.
 - Follow-on current 200 A (RMS, I think). Per above, we need to limit current from the sustained AC to < 200 A.
- Assumptions for the calculation:
 - The mains source has nearly zero source impedance, so that the MOV is the only circuit element limiting follow-on current.
 - MOV voltage/clamp voltage curves are highly non-linear. For a given peak current, the RMS current will be lower than $I_{pk} / \sqrt{2}$. If we use the $\sqrt{2}$ relationship of a sine wave, we will be conservative.
 - With a peak mains voltage of Vpk, use the maximum clamping voltage curve to find the maximum peak current I_{pk} in the chosen MOV.
 - If $I_{pk} / \sqrt{2} < 200$ A (equivalently $I_{pk} < 280$ A), the GDT will extinguish.
 - For below, use the numbering scheme used in Littelfuse's components: TMOV20RPxxx E, where xxx is the Max Working RMS Voltage (not the varistor clamping voltage).
- To support mains of 566 Vrms = 800 Vpk, check three possible MOVs with different working voltages (**bold** is the chosen option):
 - 275 V working voltage MOV, gives $I_{pk} = 600$ A at 800 Vpk. This current is too high to guarantee extinguishing the GDT. Though if we take the ~25 V dropped across the GDT, and look up ~775 Vpk on the datasheet curve, it is somewhere around 300 A, or on the edge of working. Given the conservative nature of the peak $\leftrightarrow$ rms assumption, this one would probably be OK, but we won't risk it.
 - **300 V working voltage MOV gives $I_{pk} = 200$ A. This should be quite comfortable to extinguish the arc. Very roughly, the peak clamping voltage for a 2 kV 2 Ω impulse would be around the 875 V/500A level on the clamping curve because $875V + 25V + 500 A * 2 \Omega = 1900 V$ is close to 2 kV. Clamping at ~875-900 Vpk is not VS01.6 compliant, so we will need additional impedance and secondary clamping to meet that part of our requirements.**
 - 320 V working voltage MOV yields $I_{pk} = 40$ A. We don't need an MOV working voltage this high.
- Alternately, if we were designing a protection module that only needed to support mains overvoltage of 300 Vrms = 424 Vpk during an impulse event (not the final design, only an exploration), we could use lower voltage MOVs (**bold** would be the best option):

- 150 V working voltage MOV, $I_{pk} \sim 400$ A. This current is too high to guarantee extinguishing the GDT.
- **175 V working voltage MOV, $I_{pk} \sim 60$ A. This current works very comfortably to extinguish the arc. Calculating the clamp voltage for a 2 kV $2\ \Omega$ impulse, the curve point is ~ 510 V/800 A, or $510\text{ V} + 25\text{ V} + 800\text{ A} * 2\ \Omega = 2135\text{ V}$. 510 V_{pk} is well within the VS01.6 let-through limit.**
- 200 V working voltage MOV, $I_{pk} \sim 10$ A. We don't need an MOV working voltage this high.

2.2 Simulations

More detailed simulations are detailed in the accompanying simulation description file and the ECAD_sim folder.

Summary:

For simultaneous 566 VAC withstand and impulsive transient, we probably need an inductor and secondary MOV to limit the let-through voltage.

For the potential relaxed specifications where the circuit could withstand 566 VAC but can only survive simultaneous impulses and 300 VAC overvoltage, we still probably need a secondary inductor/MOV, due to the initial GDT spike. We might as well design for simultaneous withstand and impulse.

2.3 Let-through voltage tests

Before designing this board, we modified an earlier board with a similar protection circuit to test several configurations under impulsive transient conditions.

Test setup:

- GW Instek APS-1102A AC source supplying 220 V 50 Hz
- Haefely AXOS5 EMC Compact Immunity Test System (impulse generator) with voltage monitor to measure the input impulse to the device under test
- Tektronix P5200 high voltage differential probe to measure the output voltage (let-through)
- Tektronix oscilloscope
- Loaded with an AC/DC power supply that provides DC to about 300 W of resistive load. Tested both loaded and unloaded, which had little impact on the results.

Device under test:

- Same protection relay and control circuits as the final design.
- Same input impulse protection: Eaton MOTVP20V300N 300 V (working voltage) MOVs in a Y configuration and a Littelfuse CG3 1.0L gas-discharge tube to earth.
- Same output additional impulse clamping: Bel Signal Transformer HCTI-47-10.7 series inductor and Eaton MOTVP20V300N across the output.

Results

- With ± 2 kV impulses applied from line to neutral, the output voltage rose to about ± 675 Vpk. See Figure 1.
- With ± 2 kV impulses applied line to earth or neutral to earth, the output voltage rose to slightly lower levels, more like ± 650 Vpk. See Figure 2.
- With a ± 4 kV impulse line to neutral, the output voltage peak was ± 750 Vpk. When applied to earth, it was about ± 650 V.



Figure 1: Input and output voltages during +2 kV impulse applied Line to Neutral. Yellow is input (1 kV/div); green is output (250 V/div).



Figure 2: Input and output voltages during +2 kV impulse applied Line to Protective Earth. Yellow is input (1 kV/div); green is output (250 V/div).

2.4 Fuse/Circuit Breaker

We wish to use a circuit breaker for overcurrent protection, so that the user would not need to find replacement fuses. This can obviously be changed in future revisions of the design. It would also be nice to have trip characteristics that approximate the requirements of voltage stabilizer specification WHO/PQS/E007/VS01.6. Since this board is not a stabilizer, this is not a hard requirement.

The following sections are a scratchpad of notes taken during the search for an appropriate component. Costs are for 100-piece quantities during May and June, 2024.

2.4.1 Off-PCB power inlet and breaker combination

Schurter series 6135 snap-in panel mount C14 inlet + TA35 type 2-pole thermal breaker with 6.3 mm QC, IP40. 6135.0032.0210 10A version \$19.51. Tripping characteristics: 13.5A 40 sec-infinity, 20A 10-50 sec, 30A 4-12 sec.

Schurter series DG11 is screw or snap in, with pre-wiring between inlet and TA35 2-pole circuit breaker, and IP54. Has V-Lock cord retaining. Expensive. DG11-CBDWM100C0-000-C6135-331-880-00 screw in version is \$23.82 @ 100 pcs.

2.4.2 Off-PCB breaker only

Qualtek QMB-103-11C3N-3BA panel mount with threaded neck, press to reset with QC \$2.13 @ Mouser. 29 x 14 mm in plane of panel, sticks 22 mm deep + 11 mm more for QC terminals.

Carling Technologies CLB-103-11A3N-B-A \$2.39 35x14.5 mm in plane of panel, 43 mm to end of QC (long!).

Carling Technologies CMB-103-27G3N-B-A \$2.82 29x14 mm in plane of panel, ~33 mm to end of QC (shorter than CLB above).

Carling Technologies CTB-B-B-10 \$2.54. Long thin snap in from front with a protected rocker. 19.3 mm square front plate, 16 mm dia tube with QC on end. 39 mm tube, 9.4 mm more for QC.

E-T-A 1658-G21-02-P10-10A & 1658-G41-02-P10-10A Manual reset, either 3/8" or 7/16" thread, straight QC. As with the on-PCB versions in the next section, 14x32x(27+12) mm. Operation -20°C to +60°C. \$3.77

Schurter 4404.0004 panel mount snap in "fuse holder style" (long and thin) with QC \$2.18. Snaps in from the outside through a 16 mm diameter hole (or hole with flats) and has a 19 mm square face outside the panel. It is about 34 mm long, with the QC terminals another 10 mm long (and the terminals that go on the wires 20-25 mm more: total ~70 mm). Probably the best way to mount would be next to the output, so that wires could come from the input side of the PCB. Evan feels these snap-in mounts are problematic. It is also less clear how this one would be assembled/disassembled. Operation -5°C to +60°C, which is a smaller range than some others, but does meet the VS01.6 spec (-5°C to +43°C during use).

Schurter 4404.0022 and '0078 like above but threaded neck.

Schurter 4404.0032 like above but snap in from inside the enclosure.

TE Connectivity W28-XQ1A-10 and W28-XT1A-10 (different panel thicknesses) \$3.02 long thin with rocker like Carling CTB.

TE Connectivity W51-A121B1-10, \$3.22. Snap in from outside rectangular rocker switch/reset. 28x13 mm in plane of panel, 31 mm panel to end of QC. The “1” before the “B” in the part number is 125VAC only. B = illuminated

TE Connectivity W57-XJ2A22B10-10M, \$1.95. 29 x 14.6 mm in plane of panel, 22.6 mm deep + 12 mm more for QC terminals. Lots of part number variations for different bushings and QC arrangements, including some that are bent 90° and PCB compatible (non-stocked or long lead time, not a good option).

2.4.3 On-PCB breaker

E-T-A 1410-L210-L2F1-S02-10A fast acting thermal breaker with push-to-reset actuator. \$8.16. Similar models with vertical and horizontal actuator, including 1410-G111-L2F1-S01-10A \$12.91 with mounting threaded neck and PCB pins (or 1410-G110... with no threads). IP rating of operating area is IP40, which keeps out 1 mm objects but not dust or water.

E-T-A 1658-A00-00-P10-10A auto-resetting thermal breaker. Called a “panel mount”, but this automatic reset version doesn’t have the threaded neck that allows you to mount it. Has two 6.35 mm QC male tabs. Overall height not including QC sockets on PCB is 40 mm (14 x 32 mm horizontal dimensions). Typical design life 1000 operations at 2x rated current. What is the cycle time of the auto-reset variety, and how long would 1000 operations last if the output were shorted (not clear from datasheet)? At 2x current, trips in 4-50 sec. \$3.59. There are also ones that have dummy threaded necks, available at Mouser. And one without a neck but with right angle QC to enable lower overall height but about 30 x 30 mm board area, 1658-A00-00-P13-10A, \$4.33.

E-T-A 1658-G21-02-P13-10A Manual reset, 3/8” thread, right angle QC to enable insertion onto PCB. Center of QC is 30 mm from inside of panel, and the QC reaches 8.5 mm from center line. Device width 32 mm, thickness 14 mm in this case. \$3.90

Schurter 4404.0102, \$2.24. Long thin like the 4404.xxxx with QC, except PCB pins to mount so that the long axis is parallel to the PCB. Operation -5°C to +60°C, which is a smaller range than some others, but does meet the VS01.6 spec (-5°C to +43°C during use).

Schurter 3-101-230, \$2.57. Similar to above, or to the 4404.xxxx where the QC project from the small end. In this case, PCB pins project instead of QC, so the long axis will be perpendicular to the PCB. 36 mm from back of panel to PCB.

2.4.4 Circuit breaker trip curves

Analysis of curves from likely candidates in the previous two sections. PQS VS01.6 (and VS01.5) have three defined points between the overload and short circuit sections in terms of maximum tripping times for currents as a function of rated capacity. These are hard to guarantee with any breaker’s actual curves, whether thermal only or thermal-magnetic. These are assuming 10 A and 23-25°C, where that makes a difference. Green row is the chosen component.

Model	Cost	1.5x trip range (sec)	7.2x max trip (sec)	10x max trip (sec)	Comment
PQS VS01.6		Max 120	Max 10	Max 0.1	
Carling Technologies CLB and CMB series	\$2.39 - \$2.82	20-4000	0.06-0.83	0.01-0.2	Wide range at 1.5x, fast at 10x
Carling Technologies CTB series	\$2.54	6-300	0.18-0.58	0.12-0.3	
E-T-A 1410	\$8-\$12	0.4-infinity	0.013-0.15	Curve ends at 8x ~ 0.01-0.1	Wide range at 1.5x, fast at 10x
E-T-A 1658	\$3.77	8-600	0.4-2	0.3-1.5	Slow
Qualtek QMB-103-11C3N-3BA	\$2.13	2-3600	0.045-0.65	0.01-0.22	Wide range at 1.5x, fast at 10x
Schurter 4404.xxxx and 3-101-xxx	\$2.18 - \$2.57	9-200	0.26-0.75	0.15-0.4	
TE Connectivity W28 series	\$3.02	4-40	0.18-0.55	0.13-0.3	
TE Connectivity W51 and W57 series	\$1.95 – \$3.22	8-100	0.23-1.2	0.13-0.8	
(for reference) ZingEar models used in Sollatek SVS04-22x		12-3600	0.38-5 at 5x, curve stops there	Unknown	Slow

2.5 Consider a 3- to 6-minute delay for reconnect

Voltage stabilizer specification WHO/PQS/E007/VS01.6 requires that stabilizers wait for 3 to 6 minutes after line voltage comes into range before turning on their outputs. This delay can help equipment avoid the stresses of repeated short voltage interruptions that can accompany the end of an interruption event. Certain compressor-based refrigeration systems require a delay before restart to allow pressures to equalize or to avoid repeated starts that can compromise long-term reliability. Since VS01.6-compliant stabilizers are mostly use for vaccine cold chain equipment, the delay requirement serves all these purposes.

2.5.1 Delay

The delay is generated by the time constant of R5 and C122. Once the input voltage is in range, node input_ok rises until it reaches 50% of the supply voltage.

$$T_{\text{delay}} = -R5 * C122 * \ln(1 - 0.50)$$

$$\text{Presently } T_{\text{delay}} = -1 \text{ M}\Omega * 4.7 \mu\text{F} * \ln(0.50) = 3.26 \text{ sec.}$$

To increase Tdelay to 3 minutes = 180 seconds, there are several things we can do:

Increase the switching threshold from 50%:

- Presently $-\ln(0.5) = 0.69$.
- If the threshold divider were 27.4 k Ω and 140 k Ω , both values already in the BOM, threshold is 83% or $-\ln(0.17) = 1.8$, increasing the delay by over 2x.

Increase R5: Since LP2901 comparator input bias currents are -40nA maximum over its full temperature range, we can increase R5. The initial current through R5 = 10M Ω (upon entering voltage good range, where “input_ok” signal is ~0 V), is ~800 nA, 10x that of worst-case bias current. Bias current will speed up delay some, but shouldn’t cause the delay to fail.

Increase C122: In order to get 180 seconds with R5 = 10M Ω , C122 would need to be 11.7 μ F.

- One solution for the capacitor would be to use 3x 4.7 μ F for C122, adding ~\$0.26. Resistor cost would be minimal.
- Another solution would be to replace it with a 22 μ F 35V electrolytic like C123, which would be no extra cost.
- Or 22 μ F 16V X5R 0805 20%, which is \$0.08, meaning it would be a small cost savings to replace C122 with this component.

2.5.2 Optional indication that delay is active

If there were a 3-minute delay, users may wonder what is happening, so it would be helpful to have an indication that the delay is in progress. We could trigger another LED or a flashing LED to indicate delay is active.

Triggering: A circuit’s RESET# pulled down by a diode-OR of undervoltage#, overvoltage# and reset (so only enabled during the period between good voltage and relay on). Cost for 3 diodes: \$0.10 to \$0.30.

Indication:

- A solid LED driven by a FET/inverter/3-input NOR gate on those signals. We just need to make sure that the diode-OR output voltage is below FET V_{th}. Cost \$0.27 for LED and light pipe together \$0.18 for FET. (\$0.60 to \$0.90 total)
- An LED driven by a 555-type astable multivibrator with its RESET# input connected to the diode-OR above. Additional cost \$0.61 for low-current Renesas ICM7555IBAZ-T and a few cents more for passive components. (\$1.00 to \$1.20 total)

2.5.3 Extended delay conclusion

Do not change to an extended reconnect delay at this time, as the main target use for this module is to protect equipment containing AC/DC converters, not refrigerators. The above options may be explored further and used in the future.

2.6 Input and output connector flexibility

The board is built with IEC 60320 standard connectors to enable it to be used with location-specific power cords and connected between the mains outlet and equipment. Explore options for

components that are not inserted by default, but that if used would enable the board's use inside an appliance.

Spade/Tab type quick connects soldered onto PCB. **TE Connectivity/AMP 63849-1**, \$0.50 (for all 3 at an input or output). These can be placed roughly in the same location as the power inlet/outlets, so doesn't add to PCB size or reduce the copper width (much).

Header: **TE Connectivity/AMP Economy Power 1-1123724-3** header with 5 positions at 3.96 mm pitch, but with pins 2 and 4 removed for 7.92 mm pitch and 3 actual pins. 8 A rating, \$0.11. 7.96 mm pitch is close to the 9 mm pitch of input and 7 mm pitch of output connectors, so this could fit in the same location reasonably well, too.

3 PCB Design Rules

3.1 Conductor spacing

Initially, the spacing parameters were inherited from our previous projects.

- Mains high voltage to SELV (also functional earth) was initially 8 mm / 0.315". This was due to a project designed for Class II insulation. This is a Class I design, assuming that there is a protective earth connection. If we use 381 Vpk as the max working voltage, we get 4.0 mm / 0.1575", and if we use 800 Vpk, we get 6.4 mm / 0.252". **Use 4.0 mm as the design rule in Altium, see below for the output connector, but try to use wider spacing where we can.**
- Line input to Neutral was 1.5 mm / 0.059" for functional insulation from that same project. An alternate calculation using www.creepage.com and the following (functional insulation, pollution degree 2 or 3, mains 150-300V, working voltage 800 Vpk, no quality control) => 3.0 mm / 0.118". **Let's try to make this 3.0 mm.**
- Line input to node class "LineProt" (downstream of the protection relay) **3.0 mm / 0.118"**.
- LineProt (output) to Neutral **1.5 mm / 0.059"** (functional insulation working voltage up to 270 VAC).

Looking at conductor spacing in relation to the input and output IEC 60320 connectors:

- Input: 9 mm pin pitch on the input with the pads results in a 6.6 mm gap between the Line and Earth pads. We can barely get the 6.4 mm clearance from above to handle the 566 Vrms / 800 Vpk working voltage, but the traces won't be wide enough to handle 10 A.
- Output: 7 mm pin pitch results in 4.6 mm gap between the Line and Earth pads. Meets the 4.0 mm requirement calculated above for 270 Vrms / 381 Vpk working voltage.

3.2 Power conductor trace widths

3.2.1 Notes based on previous boards and calculations

Based on the previous boards with similar current-handling requirements, we are going to use 2 oz. copper for this one as well.

Previous design notes from those boards in dark green:

- Assume ambient temperature around the PCB is 60°C (43°C outside the enclosure + some heating inside).
- Assume PCB can withstand up to 100°C. Refs:
 - 140C http://www.plasticsintl.com/datasheets/Phenolic_G10_FR4.pdf.
 - 130C <http://www.epdtonthenet.net/article/8609/FR4-Laminate.aspx>
 - “UL says 105C and normally I use 95C”
<http://www.electrodepot.com/electrodesign/max-fr4-pcb-temperature-and-lifetime-396307-.htm>
- Schurter panel-mount 8A circuit breakers used in a previous design:
 - May not trip at all for currents up to 1.35x rating = 10.8A
 - At 1.5x (12A), it trips between 25 sec. and 400 sec.
- Using the calculator from <http://www.smps.us/pcb-calculator.html>, based on IPC-2152. 40°C rise, 1 oz. copper, 0.062” PCB thickness, and no nearby copper plane to dissipate heat:
 - 11A => 0.252” = 6.4 mm (or 0.126” for 2 oz. copper cladding)
 - 12A => 0.300” = 7.6 mm (or 0.150” for 2 oz.)
- Remember that these values are for a 40°C rise, so the traces would be getting pretty toasty. We should use wider traces wherever possible, and aim for **at least 0.300” for 2 oz. copper for an 8A breaker**. Earth ground traces should be substantially wider than Line and Neutral to provide a margin of safety in case ground needs to carry current.
- Checking the copper thickness’s potential impact on design rules, our common vendor Sunstone Circuits says 2.0 oz. Cu can have 0.005” traces and spaces, which is not much of a limitation at all. We would want larger design rules for lower cost anyway.

3.2.2 Final design rules

After choosing the Schurter 4404.0102 10A PCB-mount breaker, update the calculations based on that component’s trip times and the 2 oz. copper width needed to support that current continuously with the same assumptions (Ambient 60°C; maximum PCB temperature 100°C; 2 oz. Cu; 0.062”/1.6mm thick PCB; no copper plane because the return path is on the other side of the PCB; and IPC-2152 widths, the “revised” value from the calculator).

Current (A)	Trip time range (seconds)	2 oz. copper width to operate continuously	Comment
10.0	Infinite	0.110” / 2.8 mm	
10.5	Infinite	0.120” / 3 mm	Or essentially infinite. It might be designed to open within an hour, but that isn’t specified and the curve is hard to read.
13.5	18-3000	0.185” / 4.7 mm	
15.0	9-200	0.220” / 5.6 mm	

20.0	3-23	0.361" / 9.2 mm	Use this width or more (10 mm) wherever possible.
72.0	0.26-0.75	3.210"	Fortunately, 0.75 seconds isn't continuous, so we don't have to support this current long enough to require such wide traces
100.0	0.15-0.4		Same

Summary: we probably want 400" / 10 mm where we can. Earth ground traces should be substantially wider than the line and neutral traces.

4 Summary of Changes / Final Configuration

Final configuration for the Rev. 1 modular board:

- Input: IEC C14 connector. Alternatively, we can omit C14 and insert quick connect spades, but the two options cannot be inserted simultaneously.
- Output: IEC "F" outlet. Two alternates are to omit the outlet and insert either an AMP/TE Economy Power connector or quick connect spaces. Again they cannot be inserted simultaneously.
- Impulsive transient Line to Neutral:
 - Input 300 WV MOV in series with a CG3 1.0L GDT supports up to 566 Vrms.
 - 47 μ H toroidal inductor between relay and output.
 - Output 300 WV MOV at the output provides secondary clamping.
 - Tested at ± 2 kV to clamp around ± 675 Vpk at the output.
- Impulsive transient Line or Neutral to PE:
 - Two 300 WV MOVs in series between L and N should not conduct for voltages up to 600 Vrms.
 - Single CG3 2.5L between these MOVs to PE withstand a hipot test.
- Schurter 4404.0102 10A PCB-mount breaker.