

New Horizons Voltage Protection Circuit

Impulsive Transient Suppression Simulation Notes

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1 Overview and background

This file describes simulation of different impulsive transient suppression options for the protection module. It supplements the Design Notes, adding more detail to its impulsive transient protection discussion. Files related to simulation are in the package's ECAD_sim folder.

The protection module is based on past circuit boards that included EMI filtering in addition to protection functions. The common mode choke on these past circuit boards was Bourns 7124-RC, with specification inductance 2.2 mH and DC resistance 20 mohm, maximum. Measured with a function generator, current probe, and oscilloscope: magnetizing inductance 3.22 mH at 1kHz; leakage inductance 146 μ H at 100 kHz. This choke is modeled by Lleak in the simulation schematics.

The X capacitor on past circuits was 22 nF (Cx in the simulation schematics).

2 Preparation and validation

2.1 Models

Some of the components that we may need for simulation:

- TMOV20RP420E (420 working Volts) on former PCBs.
- TMOV20RP385E (385 working Volts) if we don't relax the withstand requirement. But we most likely are relaxing it, so this is less necessary.
- TMOV20RP300E (300 working Volts) is already on the PCB and might be used in a revised circuit.
- TMOV20RP275E (275 working Volts) is a possibility for a revised circuit.
- TMOV20RP175E (175 working Volts) might be used if we don't support simultaneous impulse and overvoltage protection.

The models are based either on Littelfuse's UltraMOV models or simplified models that we made that tend to converge better in transient simulations. Littelfuse models are in the file `Varistors_UltraMOV_PSPICE_Model_lib.ckt` with names V20ExxxP. The simplified models are in the file `simpleMOVmodel.ckt` and have two versions: "typical" which match the Littelfuse static current-voltage characteristics with names of the form V20ExxxT, and "maximum" models which match the maximum clamping voltage found on the datasheet (for UltraMOV and TMOV, which are similar). The maximum models are named V20ExxxM.

Status of the various models:

Working Voltage	Littelfuse model	Simplified "typical"	Simplified "maximum"
420	Exists	Existed from previous work, and OK	Existed from previous work, and OK
385	Exists	Developed during this simulation effort	Created below
300	Exists	Developed during this simulation effort	Created below
275	Exists	Existed from previous work, and not terrible.	Existed from previous work, but model updated below
175	Exists	Developed during this simulation effort	Created below

2.2 Model generation procedure

The model is a subcircuit with an equation-based current source: $I = I_0 * (e^{(V/V_0)} - 1)$, plus some RLC values that correspond to the Littelfuse models. To find the model parameters:

- The maximum models start by taking two points from the maximum clamping voltage curve on the MOV datasheet: (I_1, V_1) and (I_2, V_2) . Assuming that I_1 and I_2 are $\gg I_0$, then calculate model values V_0 and I_0 :
 - $V_0 \sim (V_1 - V_2) / \ln(I_1 / I_2)$

- $I_0 = I_1 / (e^{(V_1/V_0)} - 1)$
- Put these into the subcircuit model.
- Simulate with a DC current sweep using the circuit in `MOV_validation.SchDoc`, and match the voltages to the curves. I have found that the I_0 value calculated above is typically too large and something closer to 0.3 -> 0.5 of the calculated value seems to simulate the maximum clamping voltage better.
- For the “typical” models, start by doing a simulation DC current sweep with the Littelfuse MOV in the circuit. Note two voltage points as above. Use those to calculate simple model parameters and then simulate those to validate.

2.3 Model validation notes

Maximum Clamping models

- Run with simulation with the 420 V models we had from before, and run from 100-1000 A. 100 A => 1.1 kV, 300 A => 1.2 kV, 1000 A => 1.3 kV. That seems to match both UltraMOV and TMOV datasheets.
- Change to the 275 V models from before and again run. Simulation does not converge when using the values that were in the models.
- Create the `MOV_model_calcs.xlsx` spreadsheet to help find model parameters.
- Repeat simulation of 275 V with the alternate values calculated with 100 A and 1000 A points from the datasheet ($V_0 = 65$ V, $I_0 = 2e-3$ A), we simulate 10 A => 550 V, 100 A => 700 V, 300 A => 775 V, 1000 A => 855 V. These are very close to the two datasheets, except for 10 A, because the datasheet is closer to 620 V.
- Calculate the 175 V model Maximum: (10 A, 390 V) (100 A, 450 V) (1000 A, 530 V) to get $V_0 = 34.7$ V and $I_0 = 6.5e-4$ A. It is closer to datasheet values to use $I_0 = 3e-4$ A.
- Calculate the 300 V model Maximum: (10 A, 675 V) (100 A, 775 V) (1000 A, 920 V), $V_0 = 63$ V, and while we calculated $I_0 = 1.2e-3$ A, $0.6e-3$ A gets closer to the datasheet maximum clamping voltages.
- Repeat for 385 V, as well.

Models for typical operation

- No notes... see the spreadsheet for some calculations and outputs. Simulation outputs are also placed in comments in the model files.

3 Transient simulations

All transient simulations use an impulse that is 2 kV line to neutral with a 2 Ω source impedance. They measure the input and output line-to-neutral peak voltages. Simulations use the circuit in the file `ComboWaveSim.SchDoc`.

3.1 Simulate a previous protection board

This board should protect up to 700 VAC, more than we need. We simulate it here as a baseline, and to ensure the models converge.

Configuration:

- 420 V MOV and CG1.3L GDT in series before relay (but they don't conduct due to second MOV). The switch modeling the GDT is not connected to the circuit.
- The relay is assumed to be on.
- Second MOV after relay is 275 V (it says 300P in the image below, but the actual part is 275 V).
- CM Choke and 22 nF X capacitor on the load side of the relay.
- Essentially no load.

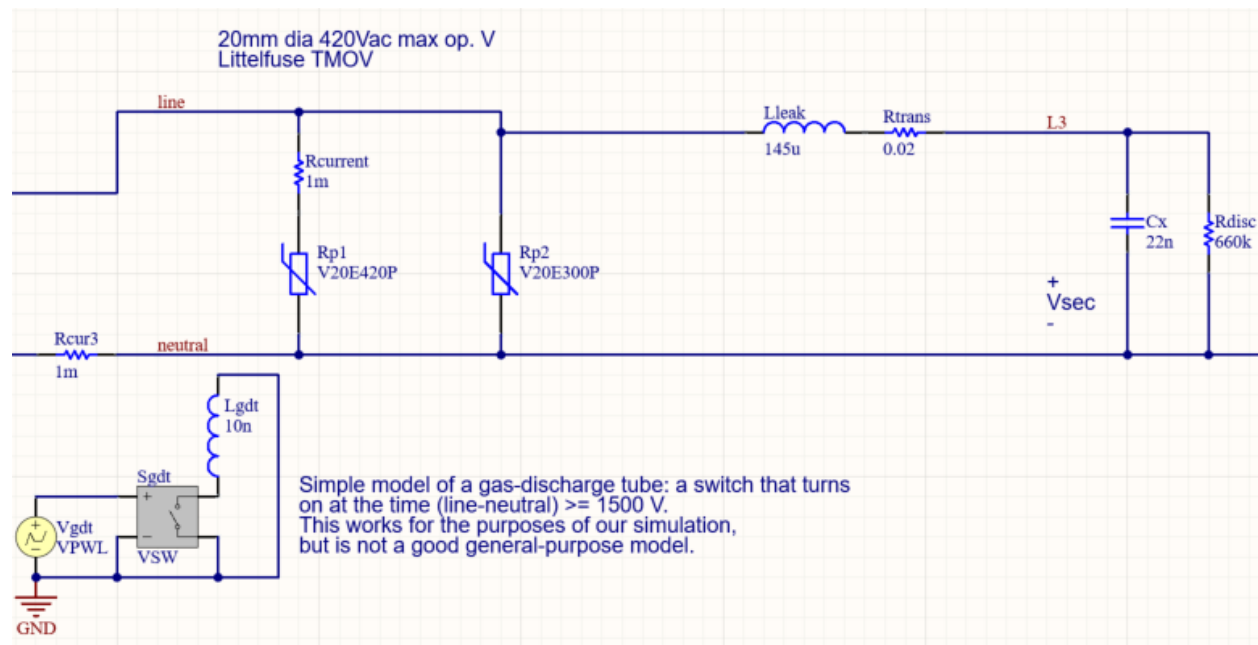


Figure 1: Simulation circuit of previous protection board.

Simulation results:

- Input clamped to 809 Vpk.
- Output rings to 1600 Vpk due to the LC tank circuit composed of the choke leakage inductance and the X capacitor.

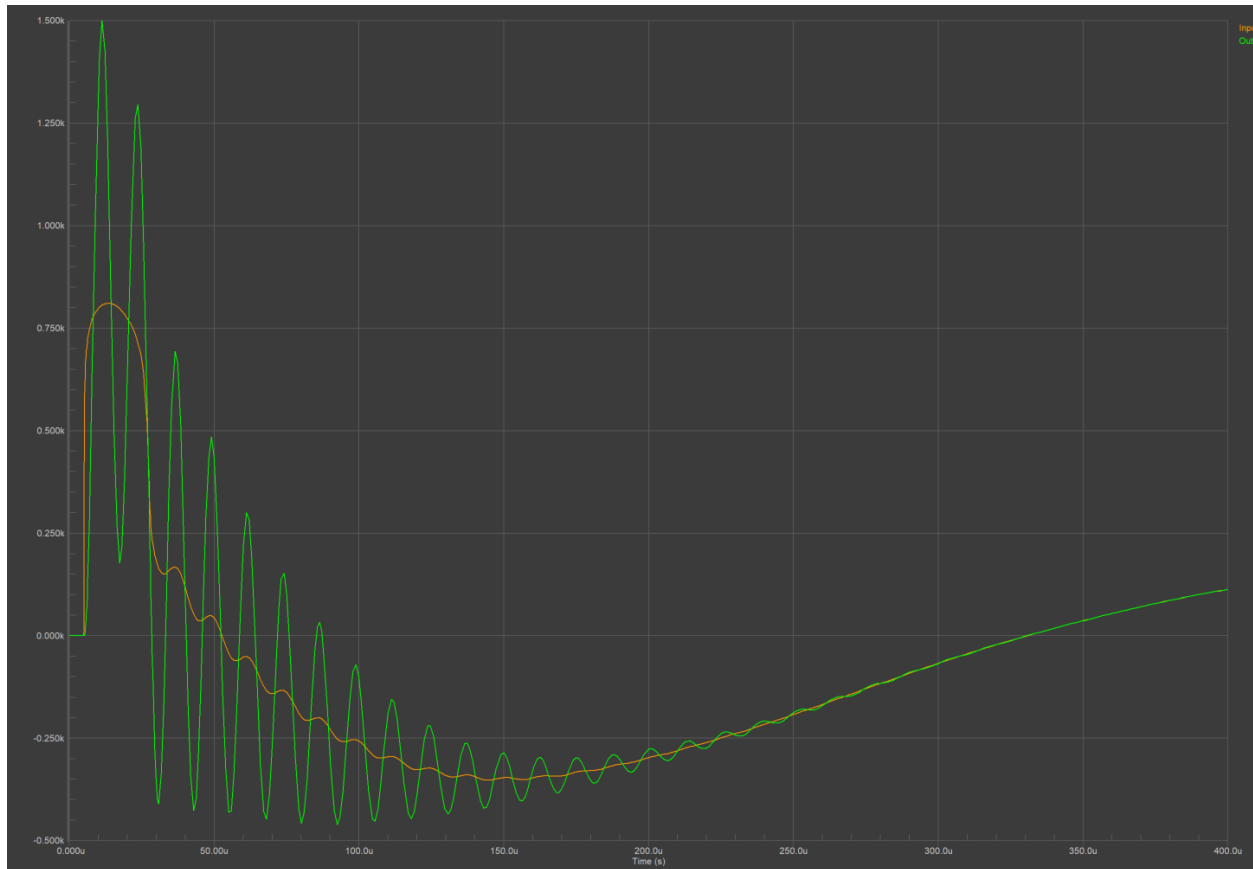


Figure 2: Simulation plot of previous board. Orange: input voltage, Green: output voltage.

3.2 New voltage protection circuit configurations

See discussion in the Design Notes document. This set of configurations (iterating toward a final design) protects against an overvoltage of 566 Vrms and extinguishes the GDT even if that voltage is applied at the same time as an impulsive transient.

Configuration 1:

- 300 V MOV and CG1.0L GDT in series before relay. The switch modeling the GDT turns on when $V_{\text{combo}} = 1450 \text{ V}$ (V_{combo} is inside the impulse/combination wave generator circuit). This level of 1450 V is between the GDT's maximum sparkover specs for rise rates of $100 \text{ V}/\mu\text{s}$ (1400 V) and $1 \text{ kV}/\mu\text{s}$ (1500 V).
- The historical CM Choke is in the circuit and the 22 nF X capacitor is on the load side of the choke.
- Second MOV after CM choke, in parallel with X capacitor and load.
- Essentially no load.

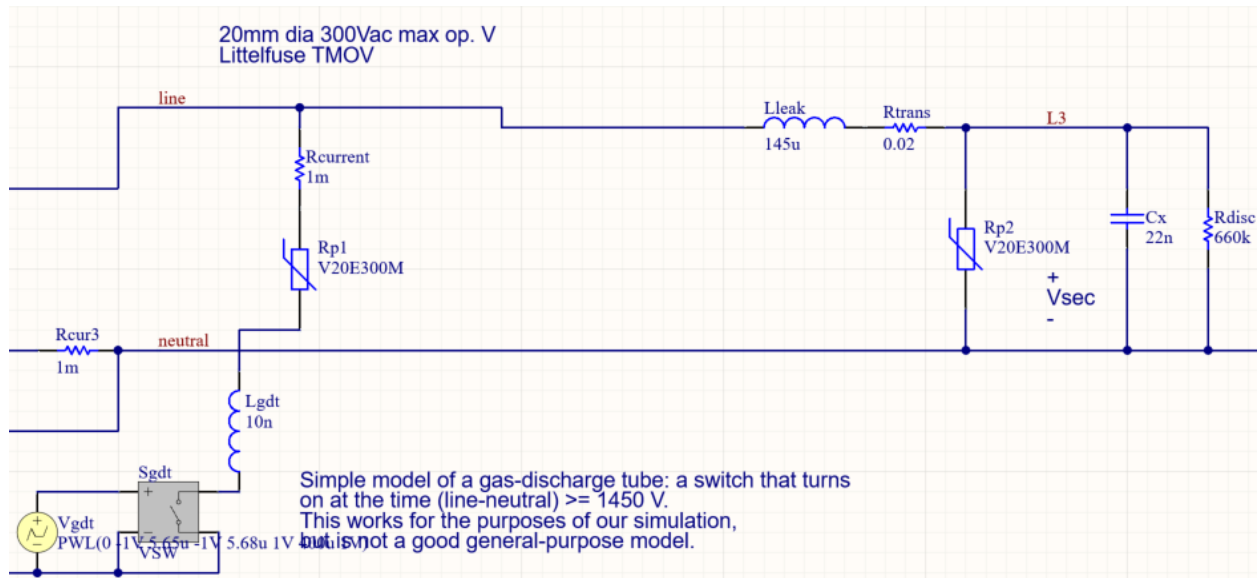


Figure 3: Voltage protection circuit configuration 1. Configurations 2 and 3 change component values or remove them, as described in the text.

Results:

- Input clamp at 854 Vpk, which is similar to our rough estimate of 875 V. This means we could not meet the let-through level of WHO/PQS/E007/VS01.6 with clamping at the input alone.
- Output clamped to 680 Vpk. This meets the WHO/PQS/E007/VS01.6 let-through limit of 750 Vpk, so we need that CM choke or some other source of inductance plus a secondary MOV. We might not need the X capacitor, though.

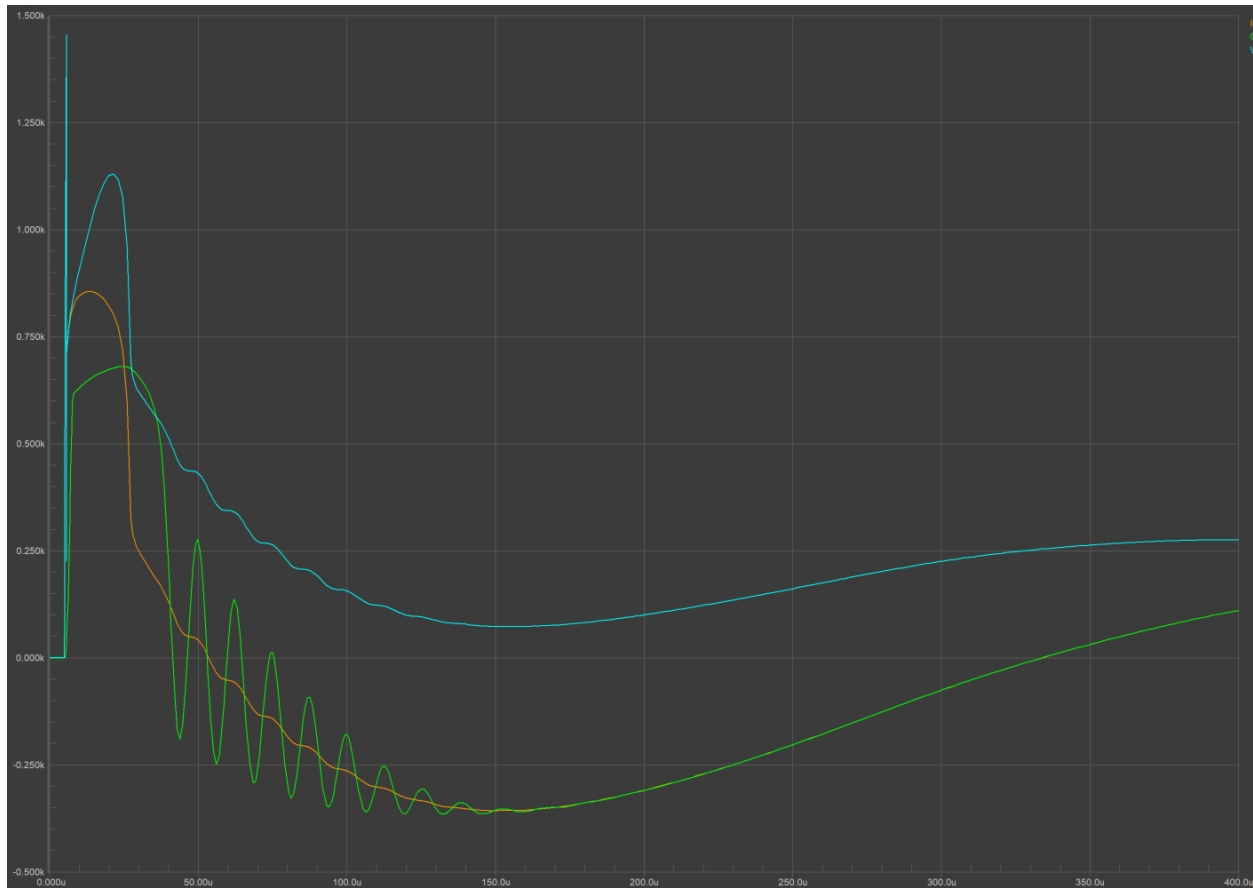


Figure 4: Configuration 1 simulation results. Cyan is an internal node in the combination wave generator, which is not shown in the schematic above; see the Altium simulation circuit. Orange is the input voltage and Green is the output voltage, the node labeled L3.

Configuration 2: remove the X capacitor. We get almost the same peak voltages, but with much less ringing after the MOVs stop conducting.

Configuration 3: remove the X capacitor and use an inductor instead of a common-mode choke. Also try smaller inductance values to lower the cost from the CM choke, which is \$4.01 @ 100 pcs.

- L = 50 μ H, 20 m Ω gives 718 Vpk at output in simulation.
 - Bel Signal Transformer HCTI-47-10.7, 47 μ H (29 μ H at rated DC current), 16 m Ω typ., 10.7 A rated DC current (causes max. 30°C rise). Vertical orientation toroidal, 0.65"/16.5mm thickness, 1.28"/32.5 mm maximum diameter or height above PCB. \$1.26. **This is the 47 μ H component used in the impulse tests.**
- L = 22 μ H, and 10, 20, or 32 m Ω gives 750 Vpk at output (therefore, the parasitic resistance is not much of a factor).
 - Bourns SRP1265CC-220M 22 μ H, 32 m Ω typ. 10Arms rated (causes 40°C rise), 12A saturation, shielded SMT 12.5 mm square and 6.2 mm high. \$1.06. SMT will be less costly to assemble, too. **This is the 22 μ H component used in the impulse tests.**

- Bourns 2205-H-RC or 2205-V-RC 22 μH (13 μH at rated current of 10.3A, which causes max. 30°C rise), 10 m Ω , both through-hole toroids 1" dia and 0.55" thick. \$1.68 for the horizontal version, \$2.82 for the vertical.
- L = 10 μH , 20 m Ω gives 775 Vpk at output. The let-through voltage is too high, so this inductor is too small.

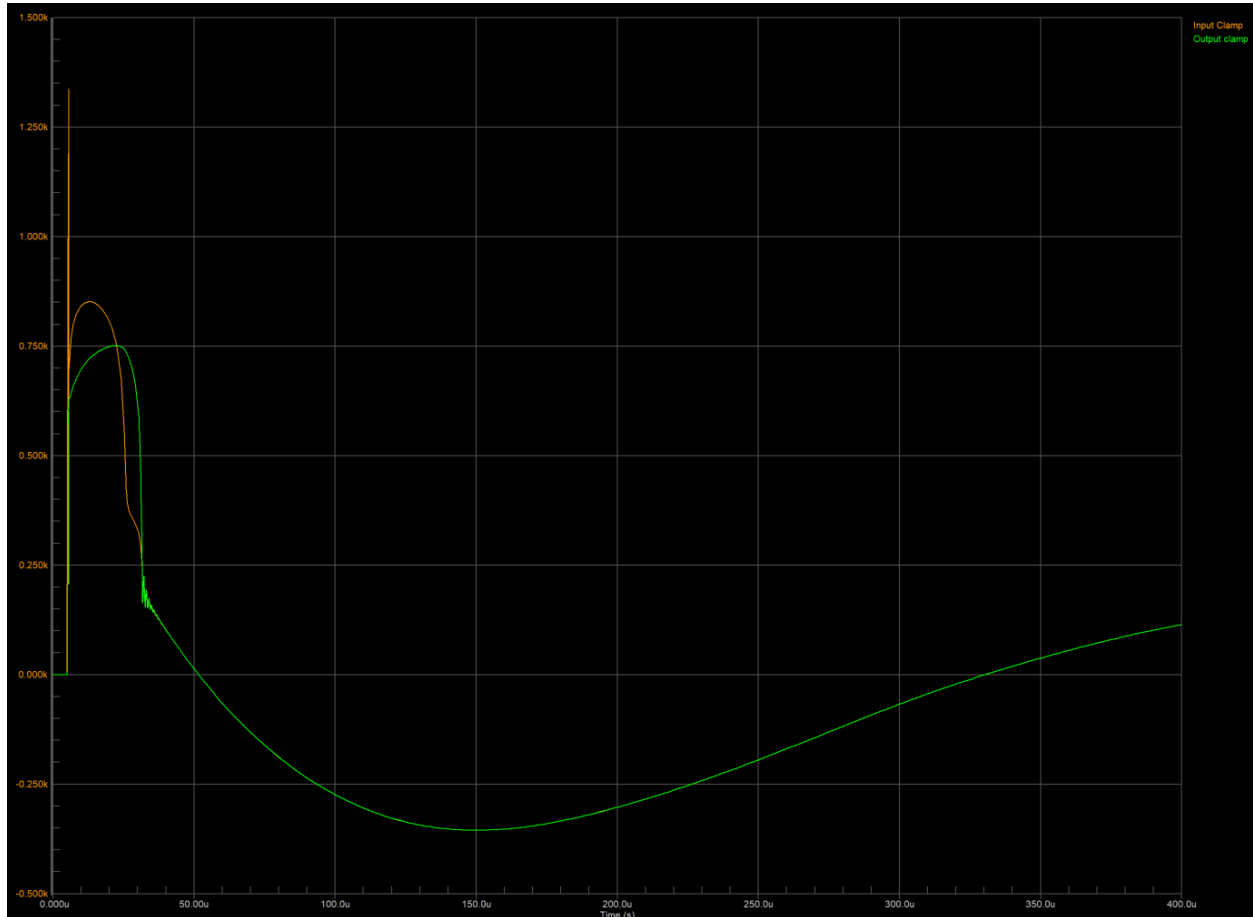


Figure 5: Simulation output for configuration 2 (22 μH 32 m Ω). Orange is the input voltage and Green is the output voltage, the node labeled L3.

Note:

The simulation does not consider inductor saturation. The simulated inductor current peaks at 90 A, well above the 12 A saturation specification. We will need to see how the circuit performs with actual impulsive transient testing.

3.3 Abandoned lower-capability configurations

These configurations protect against an overvoltage of 566 Vrms and can extinguish the GDT if an impulse is applied at the same time as line voltage up to 300 Vrms. This configuration was abandoned, see the Design Notes.

Configuration 1:

- 175 V MOV and CG1.0L GDT in series before relay. The switch modeling the GDT sparkover still turns on when $V_{\text{combo}} = 1450$ V.
- No MOV or X capacitor, but the 22 μH inductor from the previous section Configuration 3 is still in place.
- Essentially no load.

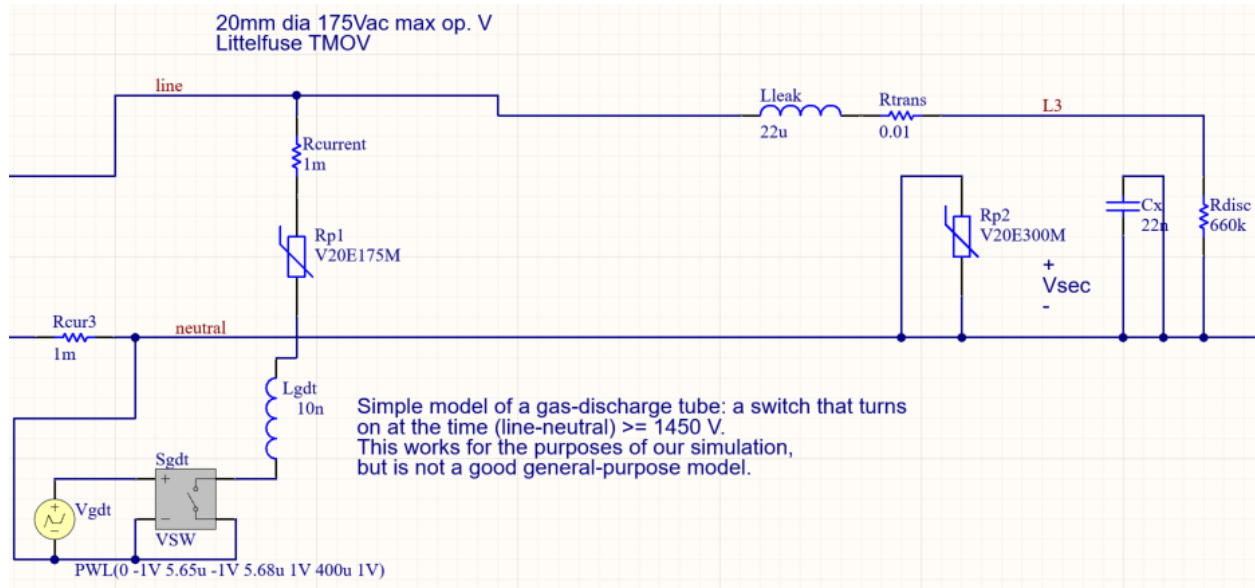


Figure 6: Abandoned configuration 1.

Results:

- Input and output are clamped at 500 Vpk. There is an initial spike on both the input and output to ~ 1.5 kV before the GDT starts conducting, see figure below. This spike was present at the input in the previous configurations but was removed by the secondary MOV clamp at the output.
- The inductor doesn't have any effect because there is no load. It was easier to simulate with it in the circuit than to remove it and node L3.

Conclusion:

- We may need either a second MOV or the X capacitor in conjunction with the inductor to remove that spike.

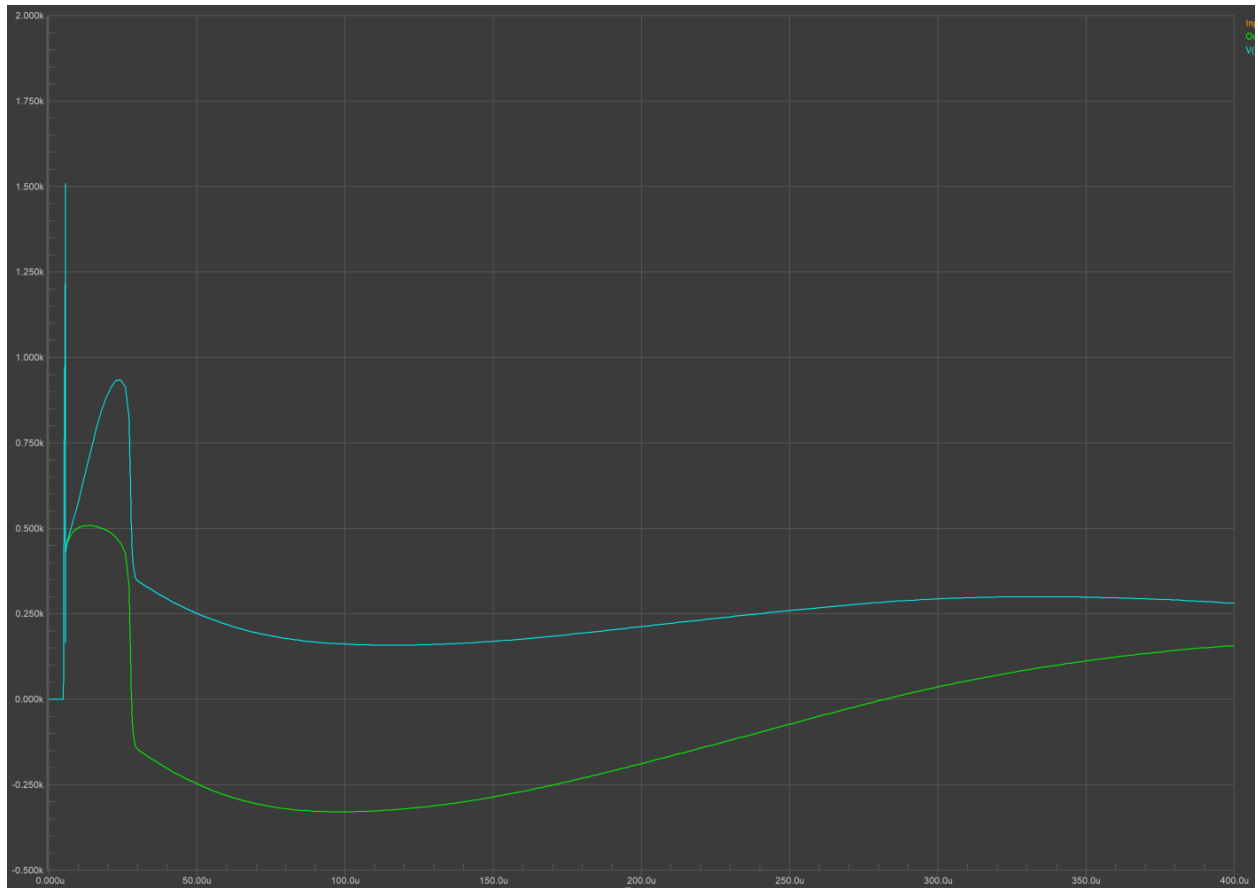


Figure 7: Simulation output of abandoned configuration 1.

Configuration 2: Add the X capacitor back in an attempt to filter that spike. But now the output rings up to 1.1 kV due to the LC ring excited by the clamping action, see below. It will be interesting to see what this looks like in real-world tests and loaded.

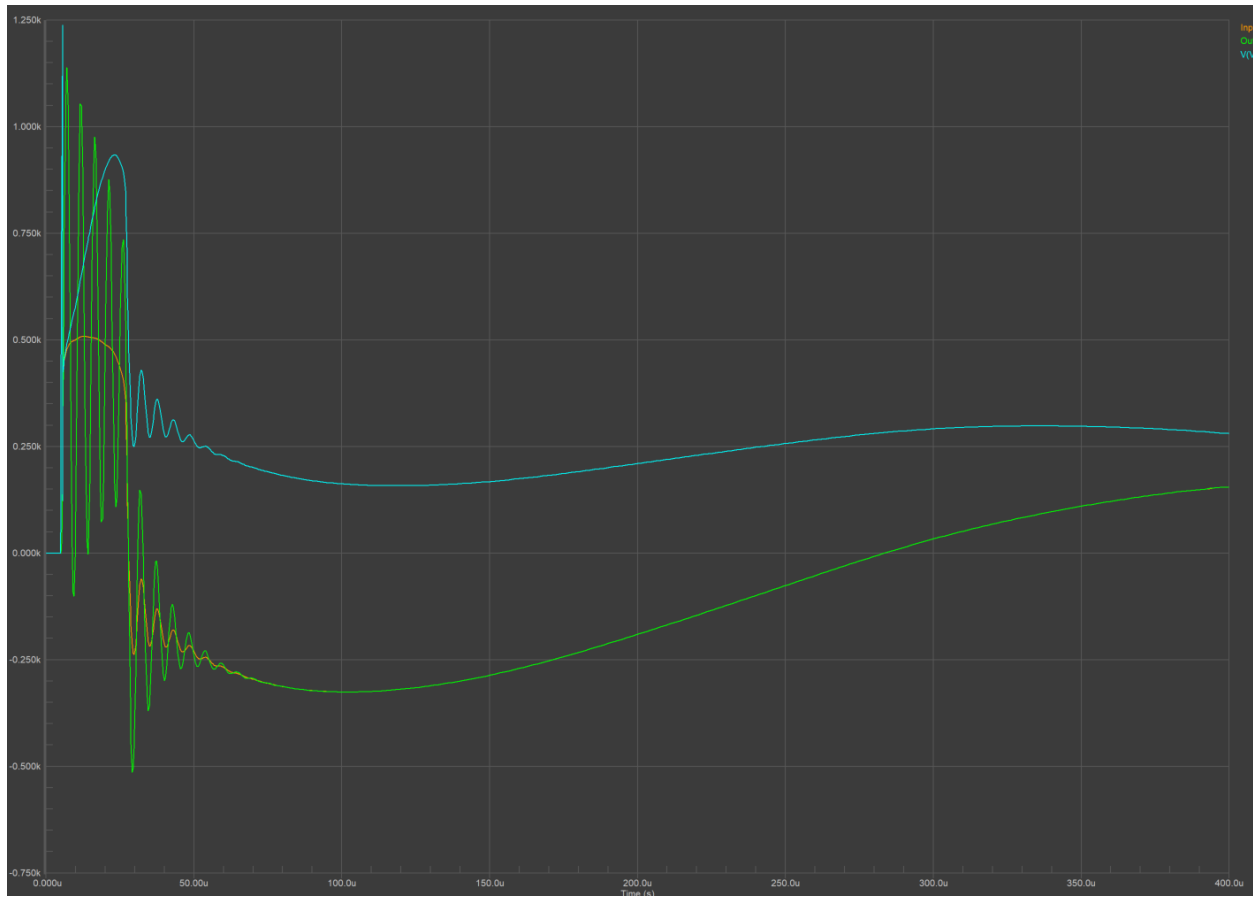


Figure 8: Simulation output of abandoned configuration 2.

Configuration 2 simulated with a $60\ \Omega$ load ($\sim 1\text{ kW}$ at 230 V) is shown below. There is still an initial spike, but it is down to around 800 V :

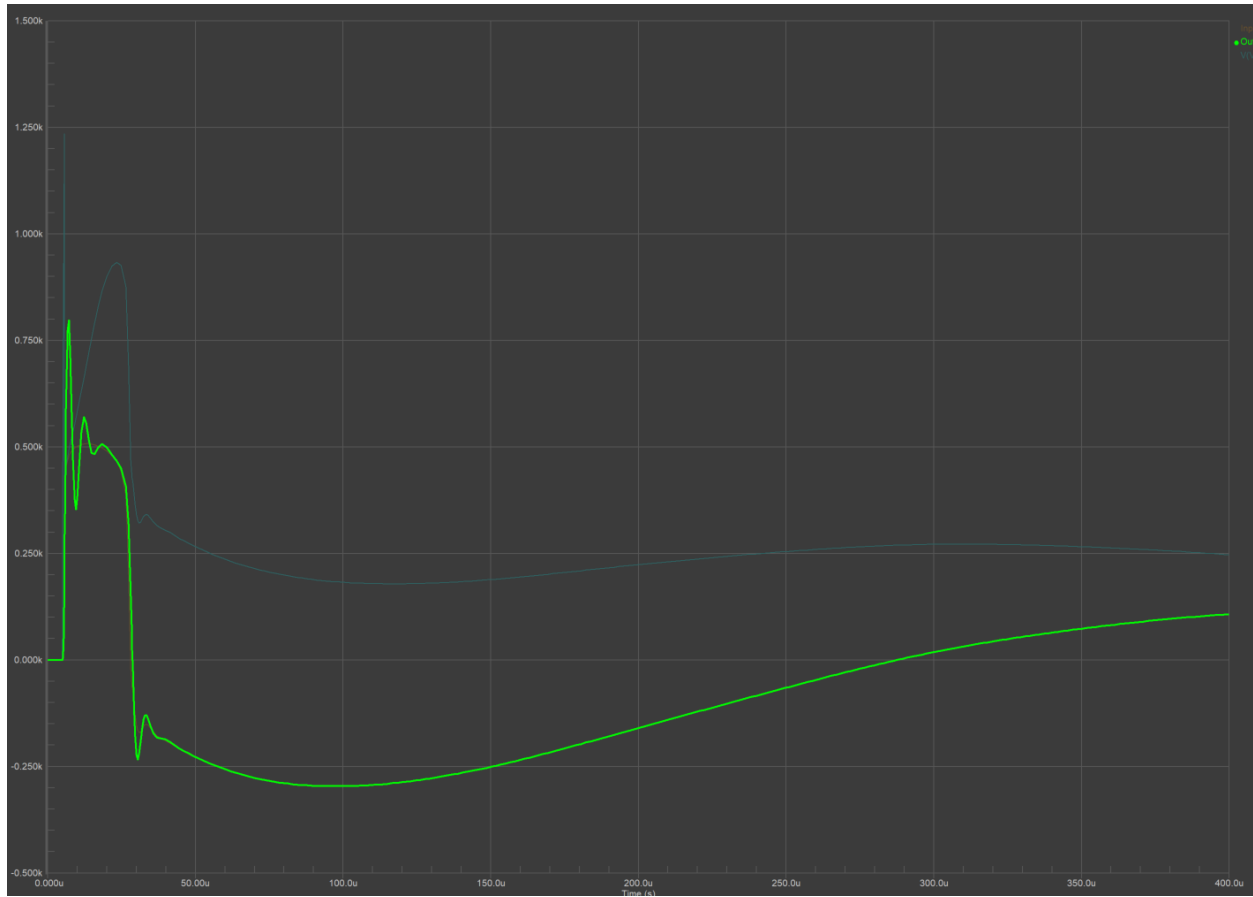


Figure 9: Abandoned configuration 2 simulated with a 60 Ω load.

4 Summary

- The configuration that can extinguish the GDT even at an overvoltage level of 566 VAC:
 - Needs an inductor and secondary MOV to keep let-through < 750 Vpk.
 - Inductance of 22 μ H and an MOV with 300 VAC maximum working voltage are sufficient.
 - An X capacitor is not required.
- The configuration that survives 566 VAC overvoltage, but does not extinguish the GDT for voltages above $\sim$ 300 VAC:
 - The main clamping slower peak is 500 Vpk < 750 Vpk, but it has a microsecond-scale spike before the GDT starts conducting.
 - In simulation it needs an inductor and secondary MOV to remove the brief spike.
 - We should test performance on an actual circuit to see if we can avoid the additional components.

- If we need the additional components, we might as well use the more robust configuration above.