

New Horizons Voltage Protection Circuit

Motivation and General Description

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1 Introduction

1.1 Background

Mains voltage conditions in some low- and middle-income countries (LMICs) can deviate considerably from the nominal or desired voltage, which is typically 230 VAC or 240 VAC. For example, a recent study [Hinman2019] of 303 facilities in two African countries found 15 of those facilities experienced mains voltages over 350 VAC for longer than a minute over the course of the 18-month data collection period. Four of those facilities had events over 450 VAC, and at least one 400 VAC event lasted for over 24 hours. A follow-on analysis [Hinman2021] of 347 facilities showed that 8% of those facilities experienced voltages greater than 415 VAC during the average 2.3 years of data per facility, and the maximum voltage was over 500 V.

Voltage that is too low or too high can damage equipment, so that it cannot perform its intended function. Fast high-voltage impulsive transients (sometimes called “surges”)¹ are another risk to appliances, whether the source is a remote lightning strike or large equipment turning on or off in the vicinity. This situation affects many kinds of equipment, but the potential human cost is high in the field of healthcare.

Voltage stabilizers are devices that compensate for variations in mains voltage. They often contain a multi-tap autotransformer and relays to switch taps, increasing or decreasing their output voltage as needed. They may also protect against high or low voltages or impulsive transients. The World Health Organization’s Immunization and Medical Device Performance Quality Safety group (WHO IMD-PQS) publishes a performance specification for voltage stabilizers intended to protect vaccine cold chain equipment [PQS/VS01.6]. This specification requires protection mechanisms for continuous overvoltage, continuous undervoltage, impulsive transients and other risks to equipment.

Many appliances, including those in a healthcare setting, do not require the voltage compensation feature of voltage stabilizers. Instead of using a compressor with a limited voltage input range (for

¹ 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. [Bollen2000, p. 18] To avoid confusion, we will use “impulsive transient” for the short event and “overvoltage” for events lasting longer than one line cycle.

example 198 V to 254 V), they incorporate so-called “universal” input AC/DC power supplies. These supplies are designed to work over worldwide nominal voltages between 100 and 240 V, often having operational ranges from 84 V to 264 V to accommodate mains voltage tolerances. Equipment using them can operate normally even if the mains voltage is much lower than many locations’ nominal 230 V.

However, these off-the-shelf AC/DC power supplies often do need additional protection against the higher overvoltage levels observed in LMIC healthcare settings. Protection devices are available on the market, either as separate devices that plug into a wall outlet and provide a protected outlet for appliances, or as modules that can be integrated into appliances. But these either do not protect up to observed voltage levels (500 V continuous); turn off relatively slowly, risking damage to equipment; or do not allow operation over the full voltage range usable to universal-input power supplies. Thus, a need exists for a protection mechanism to protect these power supplies.

1.2 Technical challenges

While protection-only devices do not need to comply with voltage stabilizer specification VS01.6, its requirements are a valuable reference point. That specification requires a voltage stabilizer’s peak output voltage during an impulsive transient (so-called “let-through” or “residual” voltage to be less than or equal to 750 V peak.

A common method of protecting against impulsive transients is to use a metal-oxide varistor (MOV) across the power input conductors of an appliance or other equipment, as in Figure 1. These devices are open circuit at normal mains voltages. As the voltage across them increases above a threshold, they begin to conduct strongly, and as a result the voltage between the line conductors is clamped. The challenge comes when choosing an MOV that can withstand 500 VAC. Because it must not conduct at voltages up to the peak of a sinusoid (500 Vrms is 707 Vpeak), its clamping voltage is necessarily higher than 707 peak volts. See for example the data sheet for thermally protected MOVs from Eaton Corporation [EatonMOVTP]. Model MOVTP20V465N/T is rated for operation at 465 V (less than required), but its 100 A clamping voltage is 1240 V.

A traditional MOV-only circuit cannot simultaneously meet both voltage withstand and let-through requirements. What is needed are protection devices and circuits that protect from both high continuous overvoltage conditions and also impulsive transients.

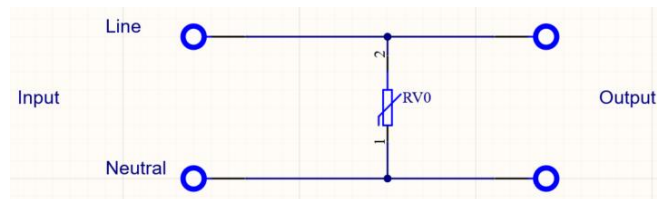


Figure 1: An MOV protects the output against impulsive transients.

1.3 Overview of a protection approach

This document describes an approach and specific circuit that can meet these requirements. Its control circuit operates over a wide range of input voltages with low power consumption, allowing voltages within the full range of universal-input power supplies while also disconnecting the output

when input voltages are less than or greater than that range. It is tolerant of overvoltage conditions that exceed the limit by small amounts for short periods of time, and it disconnects rapidly for input voltages that exceed a higher threshold that can cause rapid damage. It also protects against impulsive transients and can limit the let-through voltage during transients to lower levels than conventional circuits.

2 Design approach

A block diagram of the protection circuit is shown in Figure 2, which separates different protection and control functions. The New Horizons Voltage Protection Module is a representative implementation of the design concept.

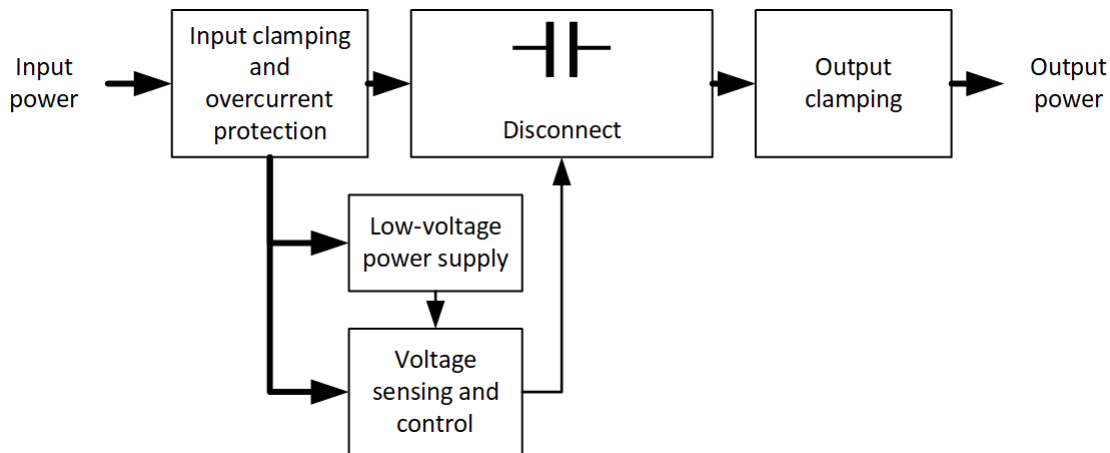


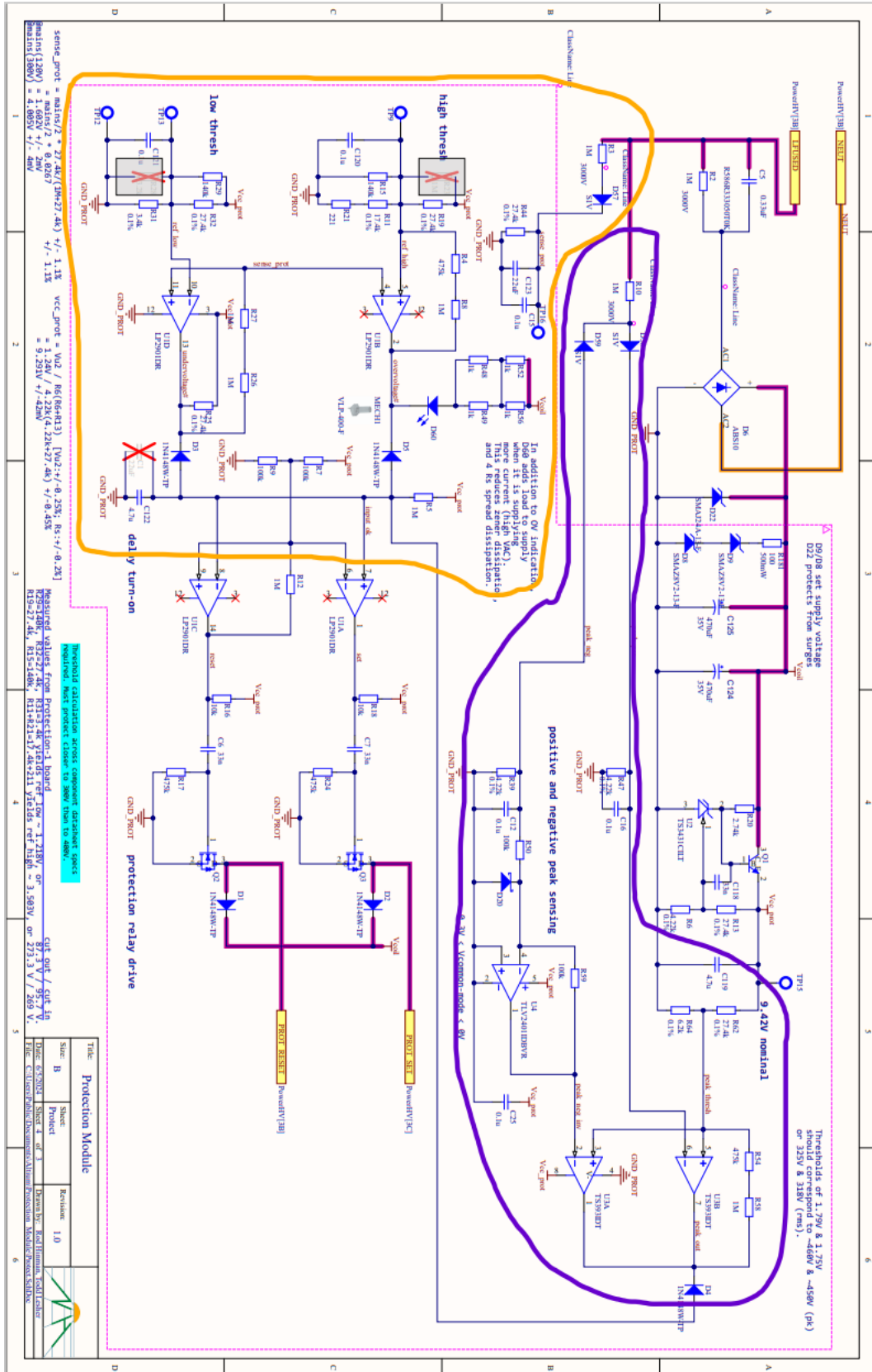
Figure 2: Block diagram of protection circuit

Overcurrent protection serves to prevent high currents drawn at the load from damaging the protection circuit or starting a fire. Various methods, such as fuses and circuit breakers, are appropriate depending on requirements of the end product.

2.1 Load disconnect

A load disconnect component separates the power input from the output to prevent potentially damaging low voltage or high voltage from reaching the load. Many types of controllable disconnect components can be used: electromechanical relays or contactors, solid-state relays (SSRs), thyristor devices like triacs, and the like. Relays and contactors are preferred when low losses in the switching element are desired, especially for higher power loads. Monostable relays have the advantage that they revert to a known (usually disconnected) state when input power is zero, but they require larger amounts of power to drive their actuating input than bistable relays or semiconductor disconnects like SSRs and triacs.

The control block senses the input voltage and drives the disconnect device to connect the input and output when input voltage is in a proper range, and disconnect when the voltage is out of range. Our protection module has two sensing circuits, shown on a schematic excerpt in Figure 3.



The first sensing circuit, shown circled in orange, has a slower response time and is used for both low-voltage and high-voltage turn on/off. The slower response time allows the device to keep the output connected during brief brownouts or loss of input voltage instead of nuisance tripping. It also keeps the output connected during brief moderate overvoltage events, voltages that are low enough that the secondary surge protection block and the load can withstand.

The second sensing circuit, shown circled in purple, has a much faster response time and measures both the positive-going and negative-going peaks of the mains waveform. It is used to turn off the output in less than half a line cycle when the input voltage rises above the “moderate overvoltage” level described above. A line cycle lasts 20 msec for a 50 Hz mains frequency. These higher overvoltage levels can rapidly damage the secondary surge protection and load, so it is important to remove them as soon as possible.

A preferred implementation of the disconnect is a bistable (or “set-reset”) relay. This type of relay only requires pulses of energy to change its state from connected to disconnected, and this energy can be stored in capacitors. A bistable relay lessens the average power required from the control’s power source in comparison to a monostable relay, which would require continuous power to hold the relay in its connected state. The control circuit generates “reset” pulses immediately upon determining an overvoltage or undervoltage condition. It can be configured to delay generating a “set” pulse when the voltage is acceptable to wait for mains voltage to become stable. The time constant of R5 and C122 sets that delay.

2.2 Control power source

The control block derives its power from the mains voltage, and because it must supply power when the output is disconnected, it uses the unprotected input voltage. It must therefore be able to operate up to the high-voltage withstand rating of the circuit. It must also be able to supply power at input voltages lower than the low-voltage cutoff threshold. Ideally, it should have a low component cost.

One preferred implementation shown in the attached schematic is a capacitively coupled power supply. It uses a smaller high-voltage capacitor and larger low-voltage storage capacitors in a rectified divider arrangement. The power supply voltage is thus proportional to the input voltage up to a clamping value provided by a clamp device such as a Zener diode. One advantage of this implementation is that the high-voltage capacitor is the only element that needs to withstand higher voltages. No switching power supplies containing high-voltage transistors and potentially producing electromagnetic interference (EMI) are required.

The amount of power available for the control circuit and set-reset pulses increases as the mains voltage increases. The capacitor sizes need to be managed so that there is enough voltage and stored energy available to sense and produce pulses when the mains voltage is near the low end of the desired range. Additionally, power dissipation in the voltage clamp must be managed at the high end of the voltage withstand range.

2.3 Impulsive transient protection

Impulsive transient protection is split into two portions, components connected to the input, and components on the output side of the disconnect device. The input components provide the

primary protection, while the rest provide secondary protection that creates a low let-through voltage during an impulsive transient.

2.3.1 Primary protection

One method known in the art to overcome the challenge of providing impulse protection while also maintaining high overvoltage tolerance is to place clamping and so-called “crowbar” devices in series, as shown in Figure 4. The MOV clamping device absorbs the energy of the impulse as in a traditional design. The crowbar device depicted in the diagram is a gas-discharge tube (GDT), though thyristor-based devices can also be used. These devices are open circuit until a threshold voltage has been reached, and then latch into a highly conductive state, where the voltage across them is almost zero. Thus, they are akin to throwing a metal bar like a crowbar across the power lines. In this application, the GDT threshold voltage is chosen higher than the peak withstand voltage (707 V_{peak}). This prevents MOV conduction during sustained overvoltage conditions.

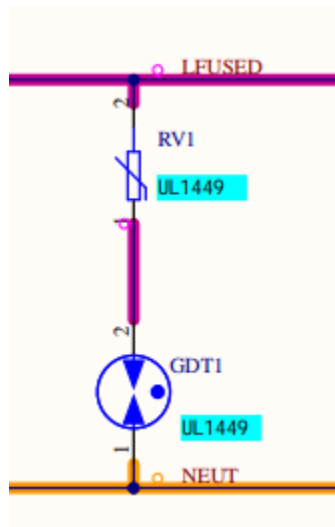


Figure 4: MOV and GDT in series between line and neutral conductors

In the presence of an impulsive transient greater than the threshold, the GDT turns on and the transient is applied across the MOV. The MOV clamps as in a traditional circuit, limiting the peak voltage. The MOV also helps turn the GDT off again after the transient has disappeared. When the mains voltage is at normal levels, the MOV will stop conducting. This lets the ionized gases in the tube recombine and the GDT will also become non-conductive.

This approach has been known in the art; one application note explaining semiconductor crowbar devices is [Littelfuse2019]. Recently components that combine the GDT and MOV in a single device have been brought to market, for example [Bourns2021].

2.3.2 Secondary protection

The primary protection can reduce the let-through voltage during an impulsive transient to a fairly low level, while the secondary protection circuit can clamp more to ensure that the level is safe for AC/DC power supplies. Secondary protection consists of an impedance between the disconnect relay and the output in conjunction with another clamping or crowbar device between the line and

neutral conductors, as in Figure 5. In this preferred implementation, the impedance is an inductor and the clamp is an MOV, possibly the same type as on the primary side. If electromagnetic interference filtering is required, filtering and secondary protection can be combined into the same component.

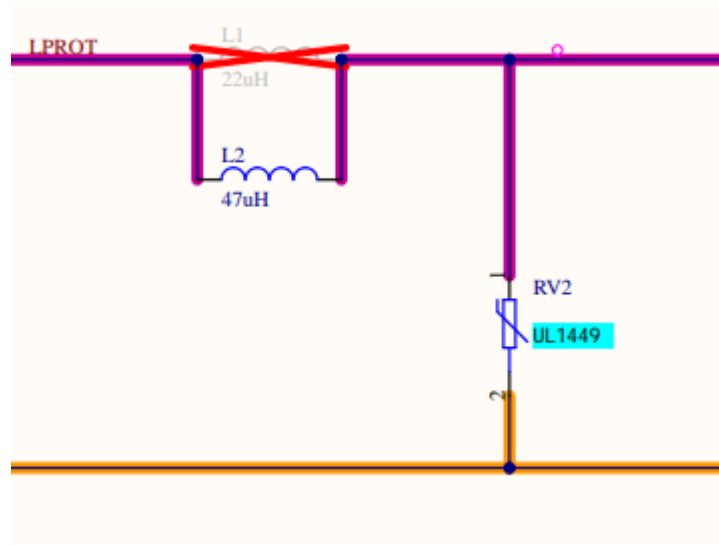


Figure 5: Secondary protection consisting of an inductor between input and output, as well as a clamping MOV at the output. In this schematic, two alternate inductors are possible, only one is used at a time.

In operation, the intermediate impedance allows the input and output voltages to differ and also slows the rise of or limits the current flowing through it. The secondary MOV clamps at a lower voltage than the primary MOV due to this reduced current. Because the relay disconnects input and output for sustained voltages that could cause MOV conduction, it does not need to have a series GDT, reducing cost and lowering overall let-through voltage.

An alternative implementation is described in [Bourns2021]. The impedance is provided by a semiconductor device that rapidly transitions from high to low conductivity when the current through it reaches a threshold level. The MOV is replaced by a semiconductor crowbar device that is analogous to a gas-discharge tube. In this implementation, if the output voltage rises above the crowbar's threshold, it conducts, shorting the output wires. The current rises rapidly, and the series impedance transitions to the low conductivity state, thus limiting the current and protecting the output.

The series impedance device can potentially replace both the inductor and relay, since it provides a switching function. However, it still has some resistance in the high conductivity state and thus produces losses and attendant heating of the circuit. It is probably not appropriate for high power applications. It also does not disconnect for low input voltages as the relay solution does.

3 References

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Revision History

Date	Person	Changes
2024-12-04	Rod Hinman	Initial version
2025-05-12	Rod Hinman	Update to share via docs.2to8.cc.