The Problem of Overvoltages

Electronic components have been designed to function properly when used within their specified current and voltage ratings. When these ratings are exceeded during operation, the component may sustain permanent damage and the equipment may cease to operate.

In response to overcurrent conditions, polymeric PTC (positive temperature coefficient) resettable fuses installed in series with these components have proven to be a reliable method of interrupting the current flow by switching from a low- to a high-impedance state. To protect from overvoltage conditions, solid-state thyristors may be installed in parallel with these components to switch rapidly from a high- to a low-impedance state in response to an overvoltage surge.

In telecommunications applications, the major sources of overvoltage conditions are lightning, and interaction with the AC power system usually in the form of power cross or power induction surges. Lightning surges may directly strike a telecom line, or may induce a potential rise when they strike a nearby ground.

Power cross surges occur when fallen AC power lines directly contact a telecom line. Power induction surges occur when AC power lines induce voltages in adjacent telecom lines, or when a nearby fault to ground subjects the equipment to a rise in system ground potential. All these threats can be addressed by providing coordinated overvoltage and overcurrent protection.
Overvoltage Protection
Overvoltage protection devices are connected in parallel with a load to limit the amount of voltage that can appear across the input to a telecommunications circuit, as shown in Figure 1. The overvoltage device appears as a very high impedance (virtually an open circuit) under normal operating conditions. When an overvoltage event occurs, the overvoltage device changes its impedance to divert current around the protected circuit to ground. Overvoltage devices are designed to protect not only telecommunications circuits but also maintenance personnel and subscribers. In addition, they must:

• Not interfere with the normal operation of the telephone service.
• Provide maintenance-free operation.
• Reduce long-term cost of the installation by minimizing maintenance time and system downtime.
• Allow the designer to easily meet industry standards.

Overvoltage Protection Devices
There are two categories of overvoltage protection devices: clamping and foldback (or “crowbar”) devices. A clamping device, such as a metal-oxide varistor or diode, allows voltages up to the designed clamping level to pass through to the load during operation. A foldback device, such as a gas discharge tube or a thyristor surge protector, reduces the circuit voltage to a low level in response to a surge that exceeds its breakover voltage. Foldback devices have a current-voltage (I-V) curve similar to that shown in Figure 6. A foldback device is normally in a high-resistance state for voltages below the breakover voltage. In this state very little current flows through the device. When the voltage exceeds the breakover-voltage, the device “folds back” or goes into a low impedance state, allowing the device to conduct large currents away from sensitive telecom electronics. The device will continue to remain in this low-impedance state until the current through the device is decreased below its holding current.

A foldback device has an advantage over a clamping device because in the foldback state very little voltage appears across the load while it conducts harmful

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Application</th>
<th>Overvoltage protection*</th>
<th>Market segment*</th>
<th>Region*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bellcore GR-974</td>
<td>Line protectors for telco equipment</td>
<td>Primary</td>
<td>Primary</td>
<td>U.S.</td>
</tr>
<tr>
<td>Bellcore GR-1089</td>
<td>Telco-owned network equipment</td>
<td>Secondary</td>
<td>Network</td>
<td>U.S.</td>
</tr>
<tr>
<td>FCC CFR47, Part 68</td>
<td>Subscriber-owned equipment</td>
<td>Secondary</td>
<td>CPE</td>
<td>U.S.</td>
</tr>
<tr>
<td>UL1497</td>
<td>Line primary protectors for subscriber-owned equipment</td>
<td>Primary</td>
<td>Primary</td>
<td>U.S.</td>
</tr>
<tr>
<td>UL497A</td>
<td>Line secondary protectors for subscriber-owned equipment</td>
<td>Secondary</td>
<td>CPE</td>
<td>U.S.</td>
</tr>
<tr>
<td>UL497B</td>
<td>Protectors for data comm and fire alarm circuits</td>
<td>Secondary</td>
<td>CPE</td>
<td>U.S.</td>
</tr>
<tr>
<td>UL1459</td>
<td>Subscriber-owned equipment connected to telco lines</td>
<td>Secondary</td>
<td>CPE</td>
<td>U.S.</td>
</tr>
<tr>
<td>UL1950, 3rd Ed</td>
<td>Information technology equipment</td>
<td>Secondary</td>
<td>CPE</td>
<td>North America</td>
</tr>
<tr>
<td>ITU K.11</td>
<td>Principles of protection</td>
<td>Primary/ Secondary</td>
<td>All</td>
<td>ROW</td>
</tr>
<tr>
<td>ITU K.20</td>
<td>Telecommunications switching equipment</td>
<td>Secondary</td>
<td>Network</td>
<td>ROW</td>
</tr>
<tr>
<td>ITU K.21</td>
<td>Subscriber terminal equipment</td>
<td>Secondary</td>
<td>CPE</td>
<td>ROW</td>
</tr>
<tr>
<td>ITU K.28</td>
<td>Semiconductor arrestor assemblies for telco installations</td>
<td>Primary</td>
<td>Primary</td>
<td>ROW</td>
</tr>
</tbody>
</table>

*CPE = Customer Premise Equipment; ROW = Rest of World
surges away from the load. Conversely, a clamping device remains at the clamping voltage during a surge. The power dissipated in the foldback device is therefore much lower than in a clamping device, allowing a much smaller device to be used to conduct the same amount of surge current.

**Agency Requirements for Telecom Applications**

A large number of agency requirements are imposed upon telecommunications circuits to simulate lightning, power cross, and power induction. The most common specifications come from Bellcore, FCC, UL, and ITU as shown in Table 1.

These agency specifications have recognized that hazard level (for example, lightning peak current or short-circuit current) and hazard frequency are typically inversely related. Therefore, it is appropriate that telecommunications equipment should continue to operate after more frequently occurring lower-level hazards, whereas safety should be the primary requirement after infrequent high-energy hazards.

As a reflection of this principle, the specifications include tests for which the pass-fail criterion is that the equipment must continue to be operational. Examples of these types of tests include the FCC Part 68 Type B surge, the ITU Criteria A requirements, and the Bellcore GR-1089 Level 1 requirements.

Other more severe specification tests have pass-fail criteria that merely require the equipment not to create a fire hazard or a safety hazard or impair network operation (though it would be desirable that the equipment continue to function). Examples of these types of tests include the FCC Part 68 Type A surge, the ITU Criteria B requirements, and the Bellcore GR-1089 Level 2 requirements.

Lightning waveforms are defined by their peak open-circuit voltage, their peak short-circuit current ($I_{PP}$), and the open-circuit and short-circuit waveforms. The waveforms are specified by the rise time and the decay time ($\tau_d$). The rise time is defined as the time from 10 percent to 90 percent of the peak value ($t_r$) times a constant 1.25. The decay time is defined as the time from the beginning of the wave to 50 percent of the peak value after the peak has occurred. For example, a 10/1000 100 A wave has a peak current of 100 A, a 10 $\mu$s rise time (8 $\mu$s from 10 A to 90 A), and a decay time to 50 A of 1000 $\mu$s. Figure 2 shows a typical lightning overcurrent waveform.

The integration of voltage, current, and time defines the energy transferred to the protective device—higher energy surges require larger, more rugged devices to meet the requirements. A comparison of various lightning surge requirements by specification appears in Table 2.

In response to a transient surge, a thyristor folds back to provide a low-impedance path to ground. The circuit must contain enough impedance to limit the surge current below the peak pulse current ($I_{PP}$) rating of the thyristor. In addition, the overcurrent protector should be specified so that it does not operate during a lightning pulse.

For power induction and power contact, the thyristor will remain in a high-impedance state as long as the fault voltage is below the device breakover voltage. If the fault voltage exceeds the breakover voltage, the thyristor will conduct a large surge current to shunt the harmful energy away from the load. The overcurrent protection devices are designed to shunt high-energy large current surges while maintaining high input impedance in normal operation.
Table 2. Comparison of various agency lightning surge requirements by specification

<table>
<thead>
<tr>
<th>Agency standard</th>
<th>Open-circuit voltage waveshape (µs)</th>
<th>Peak voltage (kV)</th>
<th>Short-circuit current waveshape (µs)</th>
<th>Peak current (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bellcore 1089</td>
<td>Surge 1 10/1000 10/1000 µs</td>
<td>0.6</td>
<td>10/1000 µs</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>Surge 2 10/360 10/360 µs</td>
<td>1.0</td>
<td>10/360 µs</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>Surge 3 10/1000 10/1000 µs</td>
<td>1.0</td>
<td>10/1000 µs</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>Surge 4 2/10 2/10 µs</td>
<td>2.5</td>
<td>2/10 µs</td>
<td>500</td>
</tr>
<tr>
<td></td>
<td>Surge 5 10/360 10/360 µs</td>
<td>1.0</td>
<td>10/360 µs</td>
<td>100</td>
</tr>
<tr>
<td>FCC Part 68 – Type A</td>
<td>10/160 10/160 µs</td>
<td>1.5</td>
<td>10/160 µs</td>
<td>200</td>
</tr>
<tr>
<td></td>
<td>9/560 9/560 µs</td>
<td>1.0</td>
<td>9/560 µs</td>
<td>100</td>
</tr>
<tr>
<td>FCC Part 68 – Type B</td>
<td>9/720 9/720 µs</td>
<td>1.5</td>
<td>9/720 µs</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>5/320 5/320 µs</td>
<td>1.0</td>
<td>5/320 µs</td>
<td>100</td>
</tr>
<tr>
<td>ITU K.17</td>
<td>10/700 10/700 µs</td>
<td>1.5</td>
<td>5/310 µs</td>
<td>38</td>
</tr>
<tr>
<td></td>
<td>9/720 9/720 µs</td>
<td>1.5</td>
<td>9/720 µs</td>
<td>38</td>
</tr>
<tr>
<td>ITU K.20</td>
<td>10/700 10/700 µs</td>
<td>1.5</td>
<td>5/310 µs</td>
<td>25/100</td>
</tr>
<tr>
<td>VDE 0833</td>
<td>10/700 10/700 µs</td>
<td>1.5</td>
<td>5/200 µs</td>
<td>50</td>
</tr>
<tr>
<td>RLM 88, CNET</td>
<td>0.5/700 0.5/700 µs</td>
<td>1.5</td>
<td>0.2/310 µs</td>
<td>38</td>
</tr>
</tbody>
</table>

Notes: *For ITU K.20, secondary protector must be able to accommodate 25 A lightning, primary protector must accommodate 100 A.

 protector needs to be designed to prevent the resulting current from damaging the equipment or causing a fire. To provide fully resettable protection, the overcurrent protector must also protect the thyristor from damage under these conditions. Thus the continuing and safe operation of the equipment depends on careful coordination between the overvoltage and overcurrent protectors under a variety of fault levels and fault durations.

Device Construction and Operation

To understand how SiBar devices assist telecom equipment in meeting industry specifications, the four symmetrical layers of a thyristor chip may be drawn as shown in Figure 3.

Reviewing the left hand side of the symmetrical “chip,” the layout can be simplified to depict two transistors and a P-type resistor as shown in Figures 4 and 5.

During normal operation, voltage is applied across the two terminals. As voltage increases from anode to cathode, avalanche breakdown in the PNP transistor
allows current to begin to flow. The increasing avalanche current flows from the anode through the PNP transistor and then through the P resistor to the cathode. Voltage across the P resistor as a result of I biases “on” the NPN transistor. When the NPN transistor is biased “on,” the PNP is rapidly switched “on,” causing the device voltage to fold back. The device is latched “on” due to the collector current of the PNP driving the base of the NPN transistor, and the collector current of NPN driving the base of the PNP.

SiBar devices are N-type devices and have an I-V characteristic as shown in Figure 6. Terminology for specific points of the I-V curve are defined as follows:

- \( I_P \) (nonrepetitive peak pulse current): The rated maximum value of peak pulse current of specified amplitude and waveform that may be applied without damaging the device.
- \( I_T \) (on-state current): The current through the device during the on-state condition.
- \( I_H \) (hold current): The minimum current required to maintain the device in the on-state.
- \( I_{BO} \) (breakover current): The instantaneous current flowing at the breakover voltage, \( V_{BO} \).
- \( V_{DM} \) (off-state voltage): The maximum DC voltage that may be applied while keeping the device in the off-state.
- \( V_{T} \) (on-state voltage): The voltage across the device in the on-state condition at a specified current, \( I_T \).

**Device Design Parameters**

**Off-state current (\( I_{BO} \))**
The off-state current is the amount of current that flows through the device during the off-state condition. This current should be as low as possible to minimize loss in the circuit. The off-state current is measured at \( V_{DM} \), the maximum off-state voltage.
Hold current (I_h)
The hold current is the current flowing through the device, below which the device resets from the “on” state to the “off” state. The designer must confirm that the supply current in the circuit would drop below the hold current of the thyristor after a transient event, thus ensuring that the device will reset.

Maximum off-state voltage (V_DM) rating
The V_DM rating defines the maximum voltage that may be applied while keeping the device in an “open-circuit” condition. To minimize nuisance operation, the designer must select a device that has a V_DM greater than the peak ringing voltage plus the DC supply voltage.

Breakover voltage (V_BO)
The breakover voltage, V_BO, is the voltage at which the device folds back. The breakover voltage is the maximum voltage that will appear across the device and the circuit that it is protecting. The designer should ensure that the circuit can withstand voltages up to the maximum V_BO level without damage.

On-state voltage (V_T)
The on-state voltage is the voltage across the device when it has folded back. The breakover voltage is the maximum voltage that will appear across the device and the circuit that it is protecting. While not directly a critical parameter in selecting the device, V_T may be used to calculate the power dissipated in the device when it is in the on state. The higher the V_T for a given current, the higher the power dissipated by the device.

Peak pulse current (I_PP)
The peak pulse current rating is dependent upon the transient waveshape. The circuit must be designed to ensure that the surge current expected during operation is within the device ratings.

Maximum current rate of rise (dI/dt)
The dI/dt rating is the maximum rate of current rise the device can withstand without being damaged. The damage of a device under dI/dt occurs when the concentration of surge current is applied on a localized area of the thyristor chip.

Maximum voltage rate of rise (dV/dt)
The dV/dt rating of the device is the maximum rate of voltage rise the device can withstand without turning on. For voltage rates of rise greater than this value, the device could potentially fold back without exceeding the breakover voltage.

Capacitance (C_O)
When inserted into a circuit, the device capacitance loads the protected circuit. Like all thyristors, the measured capacitance of a SiBar device depends on applied voltage and frequency.

Peak on-state surge current (I_TSM)
SiBar devices are typically used in coordination with overcurrent protection devices like the PolySwitch TR series. To design the appropriate protection circuit, the designer needs to know the performance of the overvoltage device when it is subjected to a power cross or power induction surge. Testing and modeling of the SiBar devices have been performed to determine the maximum allowable current for various time durations, and the results are typically shown as I_TSM vs. time. For resettable protection designs, the I_TSM curve of the thyristor should lie above the time-to-trip curve of the resettable overcurrent protection device.

Device Reliability Testing
The following reliability tests are conducted on SiBar devices to ensure long-term performance:

Auto clave (PTH)
This test measures device robustness against moisture penetration and the resultant effects of galvanic corrosion.

High-Temperature Storage Life (HTSL)
This test accelerates failure mechanisms that are thermally activated through the application of extreme temperatures.

Temperature Cycling (TC)
This test evaluates the device’s ability to withstand both exposure to and transitions between extreme temperatures. The test also exposes excessive thermal expansion coefficient mismatch between materials.

High-Humidity, High-Temperature Reverse Bias (H3TRB)
This test measures the moisture withstand of plastic encapsulated devices under high temperature and voltage bias.

High-Temperature Reverse Bias (HTRB)
This test measures the robustness of devices against simultaneous high temperature and voltage stress.
Agency Approvals
Raychem’s SiBar devices have been tested and have gained UL Recognition per UL497B.

Design Considerations
When selecting devices for a particular application be sure to ask the following questions:

1. What is the maximum required off-state voltage?
The maximum off-state voltage rating of the device (VDM) must be greater than the maximum system continuous operating voltage, defined as the sum of the peak ringer (AC) voltage plus the DC battery voltage.

2. What is the required protection level?
The maximum breakover voltage of the protection device should be lower than the minimum failure level of all system components to be protected.

3. What peak pulse current is required? What agency approvals are required?
SiBar devices are designed to assist equipment in meeting the requirements of various regulations. Choose the appropriate SiBar TVB series by matching the SiBar peak pulse current ratings to the regulatory specifications. Alternatively, consider the resistance of the overcurrent protection device and, if necessary, add additional resistance to reduce the specification pulse current to within the chosen device rating.

4. What hold current is required?
The hold current defines when the overvoltage device should “reset” (switch from low impedance to high impedance) to return the system back to normal. The device IH must be greater than the source current of the system or else the SiBar device will continue to stay in the low impedance state.

5. Has proper coordination between the overcurrent and overvoltage devices been achieved?
Compare the ITRV curve of the thyristor to the time-to-trip curve of the overcurrent protection device. Ensure that the overcurrent device trips before the thyristor device fails under relevant fault conditions.