Reliability of Thyristor Technology

One of the inherent advantages of power semiconductors is increased reliability. Since the introduction of silicon technology in the 1960s, applications have grown from consumer products to heavy industrial products and, more recently, to demanding traction, aerospace and military applications. The reason for the wide acceptance of thyristor technology in expanded applications is its increased dependability.

By Ronald J. Yurko, Powerex Rectifier/Thyristor Business Unit Manager

Powerex thyristor technology is based on a foundation of industry leadership and expertise originating from its founding companies Westinghouse Semiconductor, General Electric and Mitsubishi Electric.

Demanding applications require semiconductor manufacturers to continue to invest in new technologies to ensure long-term reliability. The heart of this investment has been improving process controls for phase control thyristors to eliminate traditional failure mechanisms. Due to the growing demand for energy efficiency, the thyristor remains unmatched for performance, cost and reliability. Advantages drawn from the simplicity and compactness of these devices allow for continued demand in new applications, such as wind energy and small DC drives rated at a few kWs to convertors for HVDC rated at several GW.

For example, a Powerex SCR may be used in a crowbar application at an average DC voltage of 2600V. The failure rate from published curves would be 700 FIT, which is equivalent to a MTTF of 163 years of continuous application. If that same SCR were used in a traction application in a fleet of 25 locomotives, with each locomotive using four SCRs, an MTBF for any of the 25 locomotives to fail would be 163 years X .01 or only 1.63 years. In less demanding applications, where the voltage varies, time must be considered. For a chopped DC device performing at 50% duty, the failure rate would be half the value. In order to reduce failures, power electronic engineers can rely on a set of tools that ensure long-term reliability including:

- Proper SCR selection
- Employing simulation tools
- Proper mounting procedures
- Failure analysis tools used to ensure corrective action
- Measurement of device characteristics
- Understanding the specific application

Proper SCR Selection

Proper SCR selection must start with establishing the peak amplitude of nominal line voltage. For example, on a 600V AC line:

$$V_{O(max)} = V_{line} * \sqrt{2} = 660V * \sqrt{2} = 933V$$

A voltage rating with an overshoot factor of 2.5 should be used.

$$V_{DSM} > 933V * 2.5 = 2333V \rightarrow V_{DSM} = V_{DSM} = 2600V \text{ selected SCR}$$

Next, the best 2600V device must be selected from the manufacturer. The devices differ in size and current rating. The maximum allowed case temperature is selected from the device's data sheet. In a six-pulse, three-phase rectifier, each SCR carries 1/3 of the DC current, so a 120-degree conduction angle (rectangular pulse) is sought on the device data sheet. $I_{T(av)} = 1/3 * I_D = 1/3 * 3600A = 1200A$. With this known average on-state current, the selected SCR's specified case temperature (T_C) for a given maximum junction temperature (T_j) can be read from the datasheet. The selected device under these conditions will support a device specific Itsm surge current.

Employing Simulation Tools

Simulation software has become widely used in the industry to properly design power electronics and minimize failures. Circuit modeling is an essential tool in the design of power electronic applications. Both the on-state forward voltage drop and transient thermal impedance of high power SCRs and diodes are complex functions. The on-state forward voltage drop can be modeled by ABCD parameters. The transient thermal impedance has been shown to be well represented via four or five exponential terms representing the significant transient thermal time constants of the device. Powerex offers STARSim to its design engineers to quickly evaluate a given device in proposed or existing power electronic applications.

The Pspice waveforms for the Powerex T9G0 withstanding a 17000A single cycle surge is illustrated in Figure 1. Note that not only is the current waveshape through the SCR displayed but also the Vtm, power dissipation and, most importantly, the selected virtual junction temperature (T_j) waveforms. This simulation tool prevents failures in the design stage prior to building a stack.

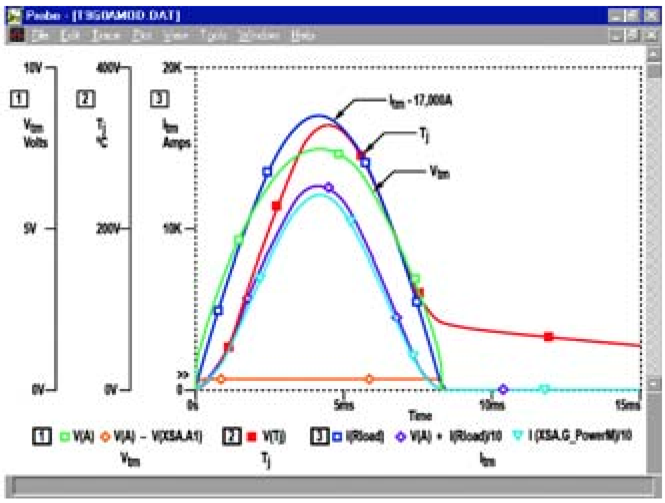

Figure 1: Pspice Waveforms for T9G0 SCR

Proper Mounting Procedures

Heat sink selection, cooling and RC snubber design are all prescribed by understanding the SCR datasheet. Many failures related to a device in an application can result in spite of selecting the correct conditions, and not exceeding the maximum case temperature, if the device is not properly mounted. Improper assembly techniques can lead to catastrophic failures. The amount of heat involved requires proper mounting to prevent excessive temperature rise or damage to the silicon. Proper mounting and surface preparation should be discussed with the manufacturer. The condition of the sink mounting surface is one of the most important details to be aware of during this process. Flatness, clamping force, surface finish and proper thermal compounds are all prescribed by Powerex to ensure long-term reliability.

Mounting pressures have been determined by empirical tests. Lowering the suggested mounting force can result in overheating while higher values can crack silicon or damage internal components. Mounting forces must be understood to ensure long-term reliability.

An SCR failure resulting from improper clamping would exhibit surface burns on the silicon. When a clamp does not exert uniform pressure on the SCR due to a parallelism error, poor heat dissipation occurs and eventual overheating. Presence of partial contact patterns on the cathodes contacts and surface burns on the failed SCR clearly indicate incorrect assembly which would lead to excessive operating temperatures. Indications of surface burns consistent with low clamping force are always identified with a correct failure analysis.

Figure 2 photos of failed semiconductors exhibit exposed copper in the bottom of the alignment hole, indicating that the alignment pin was too long or improperly inserted in the heat sink. The long alignment pin was the cause of the failure. Severe pitting due to arcing on the cathode and the anode suggest under-clamping. The improperly inserted alignment pin also caused the under-clamping.

Failure Analysis Tools

A number of factors exist that may lead to a failure. The device design and manufacturing controls are under the direction of the manufacturer. An active quality control program is employed to utilize the latest techniques to ensure reliability. Contamination in the silicon bulk region and contaminants on the junction surface or exposed during encapsulation are the manufacturer’s responsibility. Entrapped ionizable contaminants can and do cause gradual changes in a device.

Figure 2: Failure Due to Mounting Error Exhibits Silicon Melt on Cathode

At Powerex, tools such as a SEM (Scanning Electron Microscope) are employed to detect these issues in processing. Failure analysis includes 8D corrective action approaches to determine root cause and corrective actions needed. Figure 3 illustrated this solution tree analysis process.

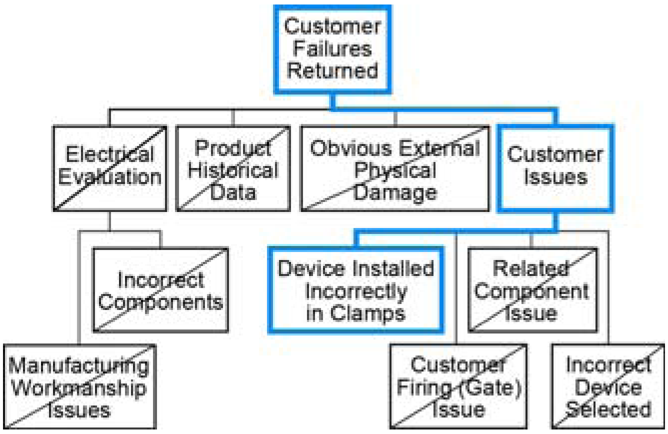

Figure 3: Solution Tree Analysis

The latest investments at Powerex include acoustic micro imaging systems that can detect voids in power semiconductors. In thyristor processing, silicon wafers are bonded to molybdenum anodes with an aluminum alloying process at high temperatures. New nondestructive tools, such as acoustic imaging, allow process engineers to monitor alloying, thereby detecting and preventing temperature increases during power dissipation in an application. Many causes of voids, as shown in Figure 4, have been detected and eliminated with the introduction of in-line monitoring.

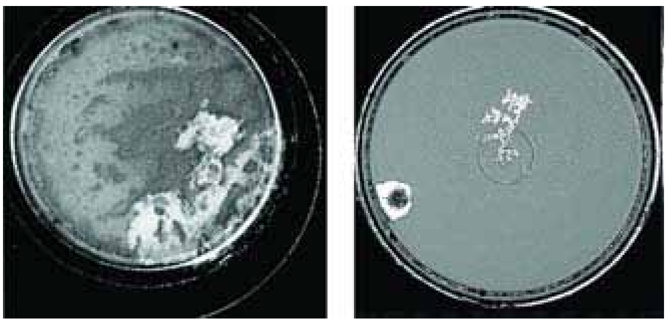

Figure 4: Examples of Acoustic Images of a Diode and an SCR that Overheated Due to Poor Thermal Dissipation

Although voids are controlled, the effect is greatly mitigated by double-sided cooling of both sides of the silicon. Residues left on the anode surface cause alloying voids. With excellent process controls, a completely void-free alloy becomes possible when precautionary measures are taken to reduce the amount of oxides present on the alloy surfaces. Heating rate and soak temperature are essential process parameters to avoid voids. With the use of Sonoscan imaging, engineers produce more reliable thyristors today than ever before. Alloyed thyristor technology has proven advantages over floating silicon technologies where thermal run-away leads to stress related gate area and edge failures due to temperature gradients in the construction. Improved alloying processing controls application advantages, allow Powerex thyristors to outperform dry interface construction floating silicon technology.

Measurement of Device Characteristics

SCRS cannot be constructed without consideration for silicon contact area and improved thermal impedance. The size of the cathode area has a direct influence on current carrying capability and better forward drop performance. As the SCR employs materials of greatly different coefficients of thermal expansion, the device will see temperature excursions in its application. Control over device component tolerances and finishes are necessary. Calibration of test equipment temperatures and test parameters must be closely controlled. Non-triggering devices usually are related to breakage of gate leads in the assembly. Solder fractures can occur in soldered devices.

The most typical failure modes are electrical due to di/dt, over voltage, dv/dt, thermal run-away, surge or a forward or reverse bias. Di/dt is by far the most prominent application problem for SCRs. It results from current and power density issues during turn-on that lead to hot spots in the device. Application specific di/dt guidelines result in proper device selection and a good gate drive. These types of failures are best discussed with the manufacturer. There are two kinds of di/dt failure modes: thermal fatigue and thermal runaway. Both failure mechanisms can be handled adequately by design. The failure period must be controlled by limiting the initial speed of plasma spreading and the length of the turn-on line for both the first and second triggering. Higher di/dt ratings result in smaller active areas, lower current ratings, lower surge ratings and higher thermal resistance. As with many semiconductor trade-offs, di/dt needs to be understood for the intended application.

It is possible to turn on a SCR without exceeding the device V_{drm} with the gate open circuited. If a transient voltage is applied across the anode to cathode, a current will flow through the forward bias junctions. This will turn on the SCR, which is undesirable. Over temperature leads to thermal run-away in leakage current in the blocking state. As temperature climbs over the rated junction temperature, the leakage current flowing at the blocking voltage can lead to power loss. In the worst case scenario, this will melt silicon as the power generated can no longer be dissipated. New testers that accurately measure dv/dt capability and blocking voltages at higher temperatures are employed to ensure long-term reliability. Figure 5 shows a tester's result of a dv/dt waveform.

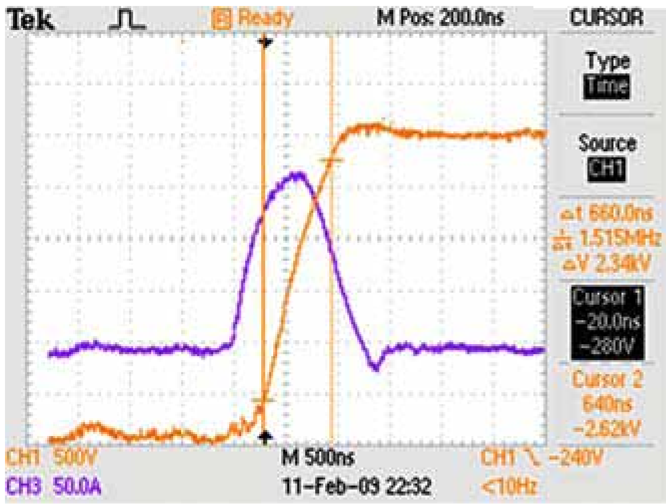

Figure 5: Dv/dt Waveform

Surge testers are employed to ensure that an SCR is able, while operating within its junction temperature rating, to handle a surge current of considerable magnitude without failure. When the rated surge occurs, the junction temperature will rise above the rated junction temperatures. This time is typically short and, due to the thermal constant of the device, the heat generated is difficult to dissipate. If the surge repeats, the device may not have time to cool within its rated temperature. Powerex engineers can detect surge related failures upon examination. Figure 6 depicts a Powerex surge test circuit employed to validate reliability.

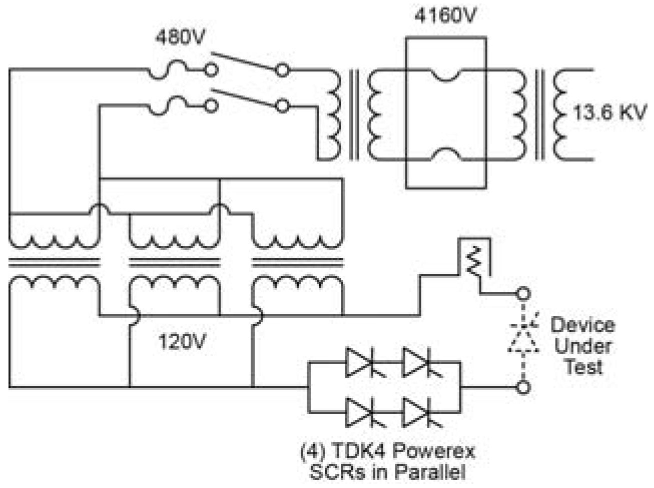

Figure 6: Surge Test Circuit (30kA) Powerex ITSM

Understanding the Specific Application

When a selected device cannot meet the application total blocking voltage capability, SCRs must be connected in series to provide sufficient safety margin. The $I_{R(rec)}$ specification is the magnitude of reverse recovery current. This is the peak reverse current flowing through the SCR when it is turning off. Part of this current is transferred into the RC snubber network, resulting in a reverse recovery transient voltage spike. This voltage spike must be less than the device rated voltage or it will fail. Increasing the recovery current spec will result in an increase in transient voltage. Customers will typically ask, "Is there enough safety margin in this application such that we will not cause a higher failure rate by this specification increase?" Series applications SCRs are matched on $I_{R(rec)}$ based on:

- 125°C (Hot) testing
- $\Delta I_{R(rec)}$ matching = a string of SCRs as determined by application
- Avoids Q_{RR} / Q_{RA} estimation and inaccuracy
- Demonstrated success at multiple customers over many years of service

Powerex provides matched SCRs for series-connected stacks by providing serialized data with the shipped thyristors. The automated test sequence employs barcode scanners, as shown in Figure 7, to capture parametric test data for storage, record retention and sorting of SCRs for shipment. For increased current ratings, serialized data allows Powerex to match on-forward drop to meet customer requirements.

Figure 7: Barcode Scanner

In conclusion, selecting the correct SCR from the manufacturer begins with a thorough review of the application that will allow the power semiconductor manufacturer to employ simulation tools and software to predict device behavior in the conditions outlined. Advances in quality control techniques, semiconductor processing methods and nondestructive testing capabilities have come a long way to improve device reliability for the ever-demanding role of thyristor technology.

www.pwrx.com