Designing for reliability in high voltage applications

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High voltage design and manufacturing comes with an additional set of disciplines that must be applied in order to produce products with excellent long term reliability, often in harsh environments. As high voltage power supplies become increasingly compact and miniaturized, mastering these disciplines is essential to ensure long term and trouble-free operation in the field. Failure to properly apply these design and manufacturing principles can result in real-world MTBF's well below design expectations.

In school, we were taught that materials were either conductors or insulators. Air was said to be an insulator. However, lightning proves that air is not always an insulator. Welcome to the world of high voltage!

High voltage is like a caged animal; it never stops trying to escape. Taming and controlling it is the job of the high voltage engineer and/or physicist. A wide selection of insulating systems and materials are available today, but there are many factors that can cause these systems to break down and fail at voltages far below expectations. Once they break down, the result is nearly always catastrophic.

Early in my career, I started troubleshooting and repairing avionic high voltage CRT power supplies for first generation GPS systems and other demanding applications. In those early years I learned a lot about failure mechanisms that occur long after the typical warranty period had passed. Designing and building a high voltage power supply that can last through the warranty period is one thing, getting them to survive for years and years of continuous operation is another, especially when in harsh environments.

This article will highlight some of the more important considerations relating to designing a high voltage power supply that is reliable over the long term.

One of the first aspects of achieving reliability is taking account of the thermal cycling that can occur in a power supply. In addition to the effects of temperature changes, thought needs to be given to mismatched or incompatible materials with different thermal expansion coefficients and the mechanical stresses that can lead to insulation cracking over time. Other factors such as poor adhesion, age induced brittleness due to loss of plasticizers, excessive temperature swings, exposure to UV radiation, corona, ozone, mineral oil and harsh PWB cleaners/solvents are other factors that can lead to pre-mature failure.

The combination of material properties, environmental factors and product design can create unplanned side effects. For example, leakage currents can increase over time with the potential to eventually result in a hard-arc and catastrophic failure. Excessive leakage currents may create errors in high impedance feedback circuits resulting in voltage drift and stability issues over time and with changes in temperature. FR4 PWB substrates can be particularly vulnerable to contamination and absorbed moisture. Absorbed moisture lowers the glass-transition temperature (Tg) of FR4, making the assembly susceptible to field failures in applications with dynamic thermal conditions. Impurities, incorrect fillers or incomplete cure in encapsulation systems can cause excessively high leakage currents that are non-linear and erratic over time and temperature, potentially destabilizing the high voltage system. Another example is that high voltage circuits are particularly vulnerable to electrochemical migration. Moisture can facilitate ionic corrosion forming conductive filaments. Dendrite growth may occur from the redistributed metal ions. High voltage stresses accelerate these electro-chemical processes (though tin whiskers can form without the presence of an electromagnetic field).

Crystalline microstructures created by ionic migration create very high voltage gradients and electric field intensities, which may lead to premature breakdown between voltage nodes. Proper design and manufacturing controls are critical and typically need to exceed documented industry standards.

Electrostatic field-induced electron emissions can cause early life failures of insulation systems, especially in higher temperature environments. Electrical breakdown occurs when the electric field in the insulating material is strong enough to accelerate free charge carriers (electrons and ions) to a high enough velocity to knock electrons from atoms, ionizing the atoms. These freed electrons and ions are in turn accelerated and collide with other atoms, creating more charge carriers, in an avalanche cascade reaction. The insulator then becomes filled with mobile charge carriers, and its resistance drops dramatically. This ionic bombardment, along with the potential for exposure of the insulator surface to partial discharge, corona and ozone, rapidly deteriorates the insulating material until catastrophic failure occurs.

Impurities in the insulation materials such as trapped air (see Figure 1), liquids, moisture and foreign particles reduce the breakdown voltage. Encapsulating under vacuum mitigates trapped air and a well-developed, well controlled process is essential to ensure trouble-free encapsulation. In addition, incompatible materials may cause local pockets of uncured encapsulant due to the catalyst being drawn towards a foreign material and away from the base material. Insulating systems must be non-hygroscopic.

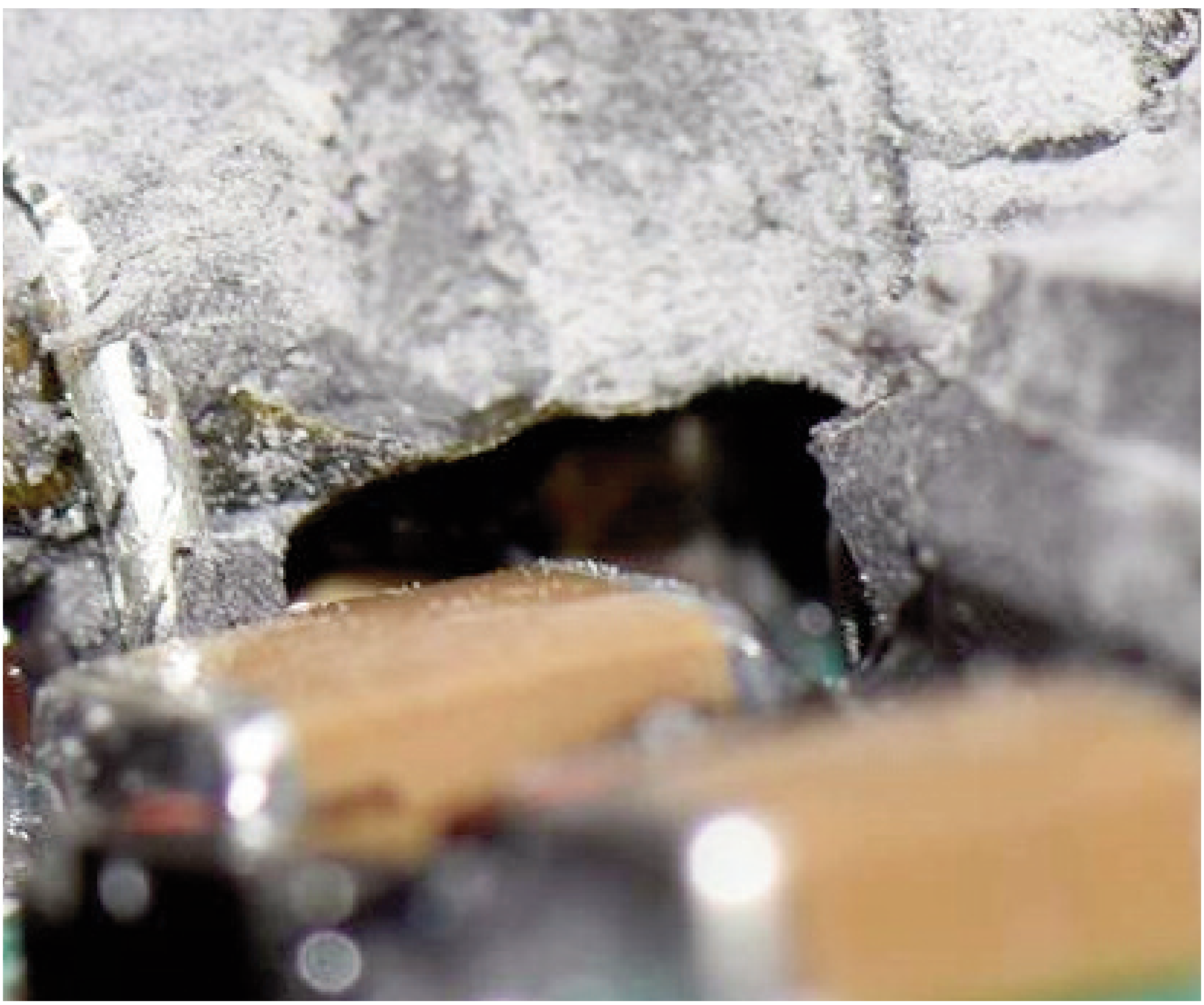

Figure 1: Example of a large air void in an encapsulated assembly

On the topic of insulation attention to the voltage gradient is also a factor. Coulomb's Law is related to the fact that the force is inversely proportional to the surface area of a sphere. Lack of proper voltage gradient control creates excessively high local electric field intensity and charge density. Paschens Law defines the non-linear relationship of voltage breakdown levels in gasses at various pressures. Avionic systems in particular must operate near the most susceptible area of Paschens Curve, requiring design and manufacturing processes of the highest standard.

To some it may seem like a good idea to combine different insulation materials to ensure adequate voltage withstand capability. However, mismatches in the permittivity of insulators results in uneven electric field intensity across the insulator; Kirchhoff's Law applies. Concentrated electric field intensity can cause the breakdown of an insulator. Parasitic capacitance may cause uneven voltage distribution, especially in AC applications. Voltage and current transients applied to components and materials may cause instantaneous catastrophic failure, or damage may accumulate over time and reduce the robustness of the system until failure occurs. Since energy (in Joules) equals ½ CV2, the stored energy transferred during a discharge rises very quickly with increases in voltage.

Repeated transient pulses, such as those encountered during external arcing events, can place uneven voltage and thermal stresses on components and materials while parasitic elements, such as capacitance and inductance, come into play during transient events resulting in unexpected behavior such as inductive bounce on the high voltage output or uneven voltage distribution across internal components. The components and materials used in the design must be selected to withstand these events and stresses.

Health and environmental concerns mean that brominated flame retardants have been replaced by other materials such as aluminum trihydrate (ATH) compounds as additives to encapsulating materials to meet flammability requirements, such as UL's 94-V0. At temperatures of 220 degrees C and above, ATH breaks down and releases 35% of its weight as water vapor. When an arc occurs in a high voltage system, it can create plasma, with temperatures exceeding 2000 degrees C. However, I have seen materials break down at temperatures well below the published specifications under moderate electric field intensity. The release of water vapor by ATH is beneficial to mitigate flame propagation, but is particularly undesirable in high voltage insulating systems.

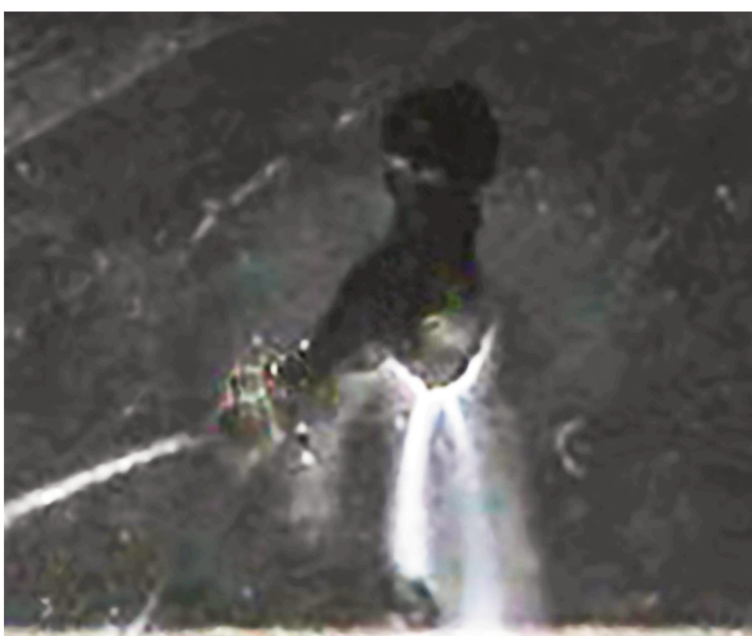

Figure 2: White powder residue remains after this particular epoxy formula broke down under electrostatic field stress and temperature cycling. The powder shows the path of the leakage current.

As the reader can observe many potential design issues need consideration in a high voltage system and the points raised above are just some of them. Since design or manufacturing issues can take years to manifest themselves, each must be understood and considered prior to a new product or process release. Careful attention to detail during design and manufacturing is required to avoid latent defects. The proper application of electrical engineering, mechanical engineering, chemistry and physics are all required when designing high reliability high voltage products and manufacturing processes. Proven processes do exist that produce high voltage products able to operate for decades, even in harsh environments.

An example of a high voltage application operating in a harsh environment is that of the over 5,000 neutrino sensors, that are buried two kilometers deep in the Antarctic polar ice at the South Pole. Each sensor incorporates a digital optical module (DOM) that uses an XP Power high voltage power supply. Operating continuously at down to -40 degrees Centigrade, and with a service life of 20 years, reliability is critical since there is no opportunity for repair the sensor. The DOMs have been operating in the ice for over ten years and no high voltage failures have been reported. The calculated mean time to critical failure (MTTCF) of the power supply came out to 123 years.