Modeling Effects of Relative Humidity, Moisture, and Extreme Environmental Conditions on Power Electronic Performance

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Abstract: **Variations in the behavior of power supplies caused by environmental conditions require accurate characterization of the electrical behavior dependence with environmental conditions. This paper introduces models to help predict RH and other environmental factors influence on sensitive circuitry in power electronic systems. An application example of a high power density, high voltage DC-DC converter is used to verify the results.**

INTRODUCTION

In applications such as military, industrial, commercial or consumer electronics, certain equipment may contain devices highly sensitive to environmental conditions. Understanding the effects of these uncontrolled environmental conditions at the component and system levels and applying this knowledge during the design phase can improve the reliability of the equipment, thereby reducing failures and dropping maintenance costs. Some of the environmental conditions affecting electronic equipment and systems include moisture, dust, vibration, air cooling and heating [1], etc. The focus of this paper is to begin to quantify the effects of humidity on circuit board performance of power electronic equipment.

In the extreme, high humidity may lead to higher condensation of water on the metal surfaces. The concentration of molecules of water vapor rises with increasing Relative Humidity (RH). This molecular thickness of the layers of water may eventually permit ionic conduction that accelerates the rate of corrosion [2]. For instance in a data center or computer room, relative humidity has to be maintained between 45% and 55%, for optimal performance and reliability. If monitoring of RH is feasible, a warning alert below 40% and over 60% RH and critical alerts at 30% and 70% RH are recommended [3].

Purity and relative humidity (RH) of the operating environment are commonly ignored when designing high performance and reliable power electronics. Even for products which are moisture-sensitive, a RH between 35-65% is often maintained in manufacturing [4][5], yet there is limited knowledge of how to model RH on electronic performance. This research presents analytical models and experimental verifications to help predict environmental effects on electric circuits. A specific application for high voltage circuit operation is presented where the effects of high RH are more noticeable.

The most common techniques to characterize the amount of water vapor in the air are Absolute and Relative Humidity:

Absolute Humidity is defined as the amount of water vapor present at a specified temperature at a particular time and is measured in grams/cubic meter. As the temperature within a unit decreases so will the capacity of the air to retain its moisture resulting in any excess moisture condensing inside the equipment.

Relative humidity is defined as the ratio of the partial pressure of water vapor in a gaseous mixture of air and water vapor to the saturated vapor pressure of water at a given temperature. Thus, it is the ratio of how much energy has been used to free water from liquid to vapor form to how much energy is left.

There has been limited published research on RH effects on electric performance of power supplies [6]. However, significant research has been focused on certain materials used in the manufacturing of electronic equipment [7], [8] and [9]. In [7] a study of resistivity change in Bakelite (a specific thermal compound) as a function of temperature and humidity is presented. Similarly, in [8] a study of water absorption in epoxy composites is presented, where the electrical and mechanical properties of the composites significantly vary with water absorption. Each of these papers focuses on experimental measurements of specific materials and not on modeling or design of an entire power electronic converter. (In this paper we use a DC-DC converter as an example).

Power supply behavior is highly dependent on their mechanical structure and board layout [10]. Likewise, the effect of humidity on such power applications depends not just on the materials involved in the assembly of the components, but also on their dimensions and board layout. Furthermore, as suggested in this paper, there are specific component values and circuit implementations of the same functions (such as over-voltage protection) that are more robust against specified environmental conditions. Our present work provides an analysis of electrical properties in materials and components involved in the power system which is presented under various humidity conditions. We claim the following new

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models/outcomes, which are supported both through simulations and experimental results:

- A method to quantize the capacitance formed by placing a metallic enclosure in a close vicinity of a sensitive circuit is proposed.
- A method to quantize the resistivity variation of materials involved during the manufacturing and assembly of power electronic systems. The resistivity depends on variable environmental conditions.
- The resistivity variation effect on proper operation of sensitive electric circuitry is discussed using the new models. The models take into account both environmental conditions and mechanical properties in the electrical system.
- Design alternatives to counteract disturbance generated by variation of environmental conditions, are proposed, such as modifying dimensions of mechanical components, altering the placement of components in the PCB, or modifying routing of exposed conductive layers.

RESISTIVITY AND RH

The electrical resistance of a material depends on its resistivity and its mechanical dimensions. The electrical resistivity of a given material is a sign of how strongly it opposes to the flow of electric current. A material which allows an easy path for current has low resistivity. The SI unit of electrical static resistivity is the ohm meter Ω-m. The electrical resistance can be defined as:

$$R = \int_{electrode1}^{electrode2} \frac{\rho}{A(l)} dl$$

where ρ: is the static resistivity (measured in ohm meters); R is the electrical resistance of a uniform specimen of the material (measured in ohms); l is the length of the specimen (measured in meters); A is the cross-sectional area of the specimen (measured in square meters).

Below, we give some resistivity specifications at 25°C ambient temperature for common thermal filler materials (completely cured) and metallic/non-metallic enclosures:

Gap filler materials (ρ_{th}): There are several manufacturers of gap fillers that are widely used in the industry. The requirements depend on the application, for example thermal transfer, conformity to uneven surfaces, drying time, etc. GAP FILLER 1000 (Bergquist Company); $\rho_{th} = 10^{11}$ Ω-m; T-putty 502 (Laird Technologies) $\rho_{th} = 5x10^{11}$ Ω-m; THERM-A-GAP™ 569, 570, 579, 580 (Chomerics) $\rho_{th} = 10^{12}$ Ω-m; THERM-A-FORM T644/T644G[1] (Chomerics) $\rho_{th} = 10^{11}$ Ω-m

Enclosure materials (ρ_c): Metallic enclosures are the preferred way for power systems; the main advantage of their use is the reduction of radiated noise and superior thermal transfer characteristics. However, there are some materials that offer easy use while keeping their isolative characteristics that are more suitable for certain applications. Aluminum $\rho_c = 2.82x10^{-8}$ Ω-m; Copper $\rho_c = 1.7x10^{-8}$ Ω-m ;Silver $\rho_c = 1.47x10^{-8}$ Ω-m; Hard rubber $\rho_c = 10^{13}$ Ω-m.

However, resistivity also depends on the material water content, for example, the epoxy resin mentioned in [7], shows a variation in its resistivity from 10^{18} to 10^{10} when the water content on the epoxy rose to 2.5% as it can be seen in Fig. 1.

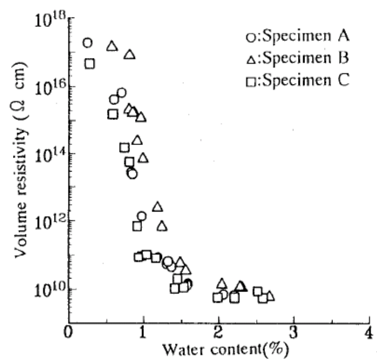


Figure 1. Dependence of Volume resistivity (ρ_r) of epoxy composites on water content.[7]

Also in Fig. 2, it is observed the variation in resistance for a Bakelite sample under different relative humidity conditions and 25°C ambient temperature [8].

As we can observe from the figure, the resistance of the Bakelite sample varies from 1000 MΩ at 20% RH to 60MΩ at 55% RH, furthermore the same sample at 80% RH shows a dramatic decrease to almost 10MΩ of resistance.

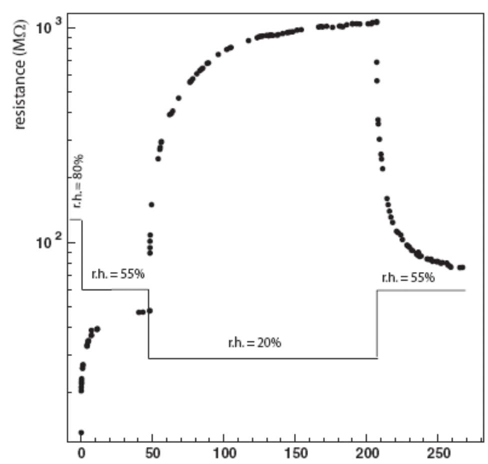


Figure 2. Bakelite resistance change at 25C and different relative humidity [8].

[1] Low modulus interface compound for heat transfer applications involving fragile electronic components. This is the material used for the application example and simulation results.

These drastic changes in resistivity due to normal variation in RH of the environment, causes a significant reduction on the isolative properties of materials such as the ones used for gap fillers.

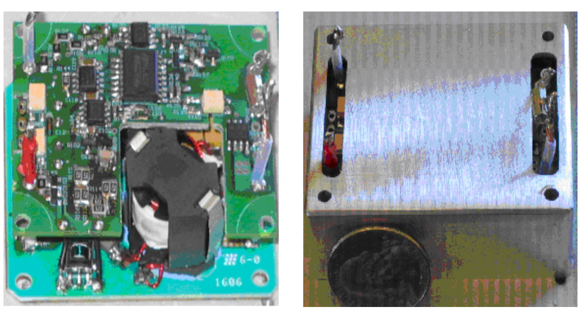
METHOD FOR MODELING RH EFFECTS ON RESISTIVITY

Generalized Approach

Because the effects of RH (with possible dust in the air) depend on power converter size, geometry, components and board layout, it is difficult to provide detailed step-by-step modeling procedures to quantify environmental influences for all power converters. Instead, we present a general guideline below and then introduce a specific DC/DC converter as a case study that clarifies the details of the approach as it is applied to a specific application.

The general method proposed has the following steps:

1. Using nominal environmental conditions (nominal resistivity) derive the resistance between the enclosure and the electrical nets in the board.
2. Integrate the effect of variable RH in the resistivity of the material.
3. Define the resistances in a given system by identifying the current paths generated in the assembly. Integrate these resistances in the electrical model of the original circuit.
4. Simulate the effect of different environmental and mechanical conditions in the performance of the circuit.



(a) (b)

Figure 3. Half-bridge converter with (a) and without (b) compound and aluminum enclosure

Application DC/DC Converter

In order to understand the general modeling approach, we will apply it to a specific high voltage, high power density DC-DC Converter. Once the modeling details are understood for this converter, the approach can more easily be applied to other power electronic converters to model RH effects on resistivity and circuit behavior.

Consider the DC-DC converter designed to drive an IGBT module used in an Army electric vehicle for up to 85°C at full power (100W). Fig. 3 illustrates a prototype of a DC-DC converter; 600V (500V-680V) to 28V (nominal). The mechanical dimensions of the enclosed converter are approximately: 1.95”x2.3”x1”. The peripheral circuitry is mostly contained on a standard material board. It is called the “control board”, and is placed on top of the power board using through-hole pins, as seen in Fig. 3(a). Thus, what we notice from this typical converter is that the input voltage is high and the converter is quite small and compact, making components close to each other. Further, because of the specified limited space, the distance between the aluminum enclosure and the control board is minimal, between 2mm-5mm. To provide insulation between the high voltage circuitry in the control board and the enclosure, a thermally conductive material (Chomerics: THERM-A-FORM T644/T644G) was used as a filler.

APPLICATION EXAMPLE: MODELING RH EFFECTS ON CIRCUIT RESISTIVITY

In this section we use the modeling procedure to investigate the generation of electrical resistance by using a metallic enclosure of the DC-DC converter in Fig. 3

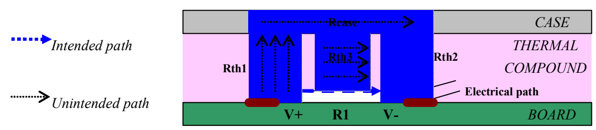


Figure 4. Equivalent circuit for resistance/conduction paths on assembled converter

Fig. 4 represents the current paths that are originated in a given circuit, including the effect of additional components, which are mechanically connected to the electrical parts. Components such as an enclosure and an interface material, often placed during the manufacturing/assembly phase, have significant electrical effects on the complete system.

The purpose of the enclosure is the protection of the electronics within. Sometimes, the enclosure also serves as an electro magnetic filter. Materials commonly used in enclosures include metals such as aluminum, copper, etc or hard plastics. For interface materials dielectrics or highly electrically isolative materials are often used. They usually are very conforming, to accommodate the various profiles and fill all the space between the circuit and the enclosure.

Whenever there is a difference in potential between two electrodes (conductors), there is a current path between them. The intended current path takes place through the electrical component. The unintended paths occur through the interface material and enclosure. Our goal is to model these current paths and explain their influence on circuit performance.

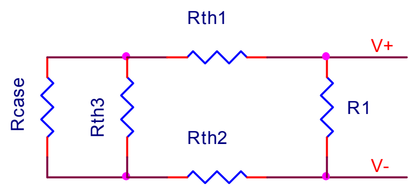


Figure 5. Equivalent resistive model of paths in Fig. 4

Consider a resistor, R1, on the control board for our high voltage DC-DC converter application example, as illustrated in Fig. 4, with terminals at potential V_+ and V_-. The differential of voltage causes a current to go through R1, since this current path is actually the desired conduit. However, when the thermal compound and enclosure are placed on top of the given structure, other current paths are generated. As Fig. 5 shows, the real effect of the thermal compound can be interpreted as a modified resistance R_{1eq} which takes into effect resistances R_{th}'s and R_{case}, i.e.

$$R1_{eq} = R1 // (Rth1 + Rth2 + Rcase // Rth3) \quad (1)$$

For example, suppose that the control board of the DC-DC converter in Fig. 3 uses the commonly used under-voltage / over-voltage protection DC-DC converter shown in Fig.6. The circuit consists of a resistor divider (R1 and R4) that follows V_{in} and results in V_{inUV}. The output signal "UV" toggles between two states based on the comparison: HIGH and LOW. Specifically, the circuit is designed for under-voltage lockout to shut off the switches in the converter has 2% hysteresis, i.e. 490V-500V. There is also a similar over-voltage protection circuit on the board.

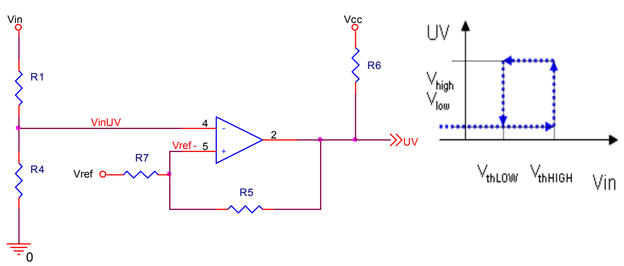


Figure 6 Under-Voltage Sense Circuit with Hysteresis

The LOW state operates when the positive input of the comparator (V_{inUV}) is lower than the negative input (V_{ref-}). When the comparator is in this state, the transistor in the output (open collector) conducts. If designed correctly, the transistor goes into saturation and brings the output voltage UV, close to ground, namely *Vlow*. Specifically, if $Vin > V_{th\ LOW}$ then $UV = V_{LOW}$ where

$$V_{th\ LOW} = \left(\frac{V_{ref} - V_{low}}{R7 + R5} R5 + V_{low} + I_{in}(R4 // R1) \right) \frac{R1 + R4}{R4} \quad (2)$$

where I_{in}, is the input bias current to the comparator and depends on the operating temperature (T) and the supply voltage (*Vcc*). V_{low} is the output transistor saturation voltage, also defined as the low level output from the OPAMP. V_{thLOW} and V_{thHIGH} are the lower and upper hysteresis input threshold voltages, as illustrated in Fig. 4.

We will now demonstrate/model that the RH/moisture content of the thermal compound may noticeably influence the values of voltage lockout protection for typically assumed component values in this high voltage application. We must first replace the values R1, R2,… R7 by $R1_{eq}$ $R2_{eq}$,… $R7_{eq}$ using (1). To do this, we note that the cross sectional conduction area for *Rth1* and *Rth2*, varies from the resistor pin area to the case area, and it is represented as $A_{th} \sim w_{pin}$ x a_{pin} => w_{case} x a_{case}. Similarly the cross sectional conduction area for *Rth3*, corresponds to the area between pins and can be calculated as $A_1 \sim w$ x l. For *Rth1* and *Rth2* the length of the path is *l*, while for the *Rth3* is *L* (distance between the pins), resulting in the following resistances:

$$Rth1 = Rth2 = \rho_{th} \int_0^l \frac{\partial y}{(w_{pin} + w_y)(a_{pin} + a_y)};$$

$$w_y = \frac{y}{l}(w_{case} - w_{pin}) \quad a_y = \frac{y}{l}(a_{case} - a_{pin}) \quad (3)$$

$$Rth3 = \rho_{th} \frac{L}{A_1}; \; Rcase = \rho_{th} \frac{L}{A_c}$$

Using manufacturer supplied ρ_{th} values that depend on RH, we have created curve fitting and data extrapolation programs in MATLAB that calculate the above integrals. For the undervoltage (or overvoltage) protection circuit elements, we show, in Fig. 7, that both R1 and R4 can noticeably change depending on the RH and distance to the case. The resistance gets reduced by the water contents in the filler. While at low water levels such as 0.2% the effect is unnoticeable, at 1% the effect is dramatic. Additionally it is also observed from Fig. 7 that the lower the thickness of the thermal compound the more the equivalent resistance gets affected.

Applying the values of the new equivalent resistances and using (1)-(3), it is possible to calculate V_{thLOW} – or with similar equations V_{thHIGH} - as shown in Fig. 8.. Notice that for just 1% water content at *2mm* distance from the case, the simulations show that the designed V_{thLOW} = 490V actually reduces to 470V. Similarly, Fig. 8 illustrates how the 1% water content reduces V_{thHIGH} from 500V to 479V. Here we assumed that the R1=3MΩ and R4=15.4kΩ are fixed (precisely measured). Thus, tolerances of the resistors may even magnify the changes in the voltages even more. We remark that the models predict that the over-voltage protection circuitry changes similarly (even a little more drastic).

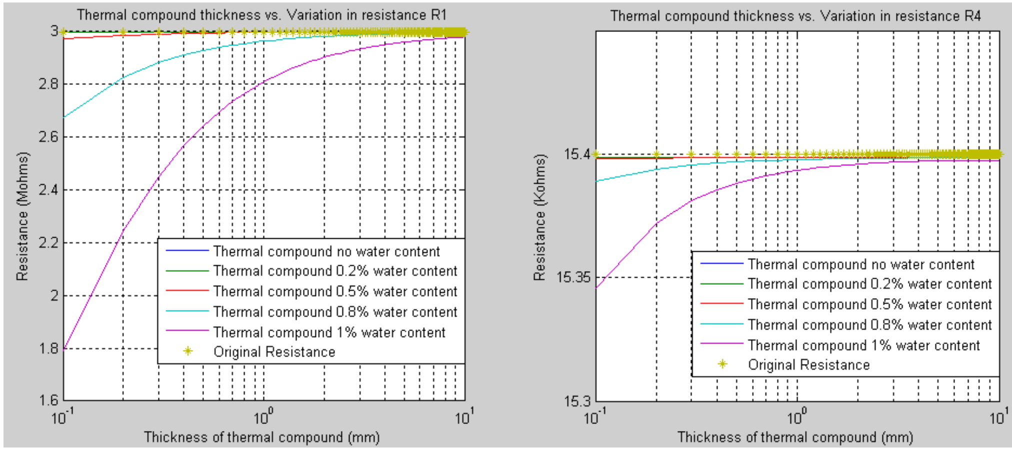


Figure 7. Variation in resistance R1 (a) and R4 (b) using thermal compound at 25°C

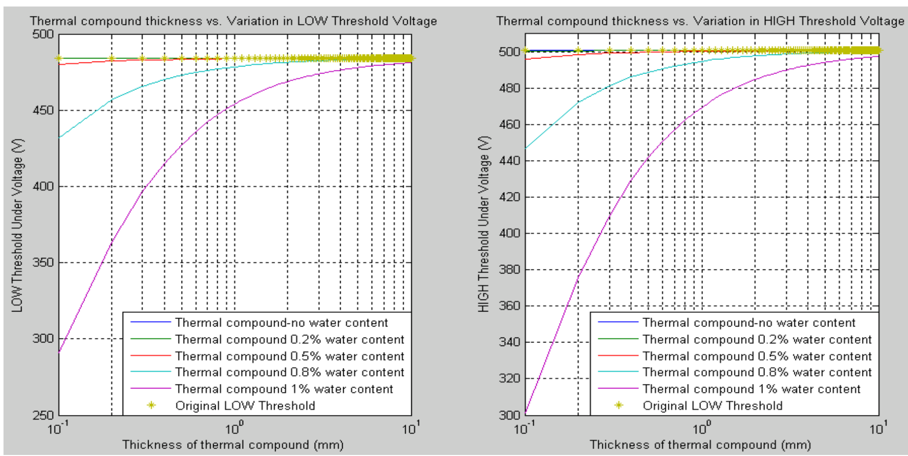


Figure 8. Variation in V_{thLOW} and V_{thHIGH} in under-voltage lockout circuit, using thermal compound at 25°C

Experiments vs. Simulation: Two test converters were built with the same dimensions and component specifications. Under-voltage (and over-voltage) protection was measured without thermal compound or enclosure to be precisely V_{thLOW} =490V and V_{thHIGH} = 500V, as designed.

Moist thermal compound is added and the measurements are retaken. Experimentally measured lockout voltages drop 10V or more for each converter – as our models suggest. Further, we perform >150 hours burn-in in 85C drying of the thermal filler to eliminate moisture content. After drying, the lockout voltages return to their design specifications, indicating that the cause of performance change is truly due to the moisture content of the thermal filler.

In some applications the shifting in the measurement will not be of major significance. However in other applications where the measurement circuit is a safety signal, the shift has to be kept to a minimum. There are several ways to deal with this type of measurement shift:

1. Keep the thermal compound thickness at a point that guarantees no shift in measurement. For our protection circuit, an engineer may now decide to keep 10mm of thermal compound thickness. Then the shift in the threshold voltage due to the thermal compound is unnoticeable.
2. Account for the shifting when designing the circuit. The models presented in this paper may be helpful to create conservative design estimates.
3. Reduce the values of large resistors, which in our example would lead to lower values of R1 and R4.

If the application allows it, the simplest solution is to keep the thermal compound thickness to a level that avoids the measurement shift. In this case the circuit does not get affected and no correction is needed. In some applications this solution is not acceptable due to other constrains like

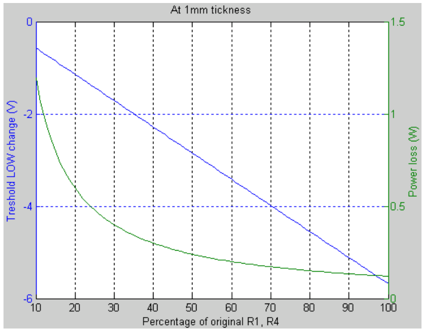


Figure 9. *Under-voltage threshold and Power Loss for different values of R1 and R4 at 1mm thermal compound thickness with 0.8% water content.*

mechanical restrictions (space limitation) or thermal margins (reduced thermal flow).

If the second option is selected the amount of shifting has to be known (modeled) before the manufacturing process. This shift is required to adjust the circuit with the modified impedances, or to adapt the specifications to the new threshold levels. In other words accuracy gets affected.

The third option is to reduce the values of large resistors in the circuit. Although by selecting this option, the specifications of the circuit are not compromised; by reducing the value of the resistances power loss is increased. In other words efficiency is reduced.

In Fig. 9, a tradeoff between accuracy and efficiency results from this selection is shown. The figure shows the difference in power efficiency vs. variation of the threshold voltages when de distance between the board and the enclosure is 1mm. It is observed that in order to maintain a low power loss a loss in the accuracy of the threshold voltage is required.

RH EFFECTS ON CAPACITANCE

In the application example the enclosure is a thin aluminum sheet (0.050in thickness), the exposed paths in the board are the pins of the components (see Figure 3) soldered on the top side of the board and the dielectric could be either air or thermal compound, working under variable environmental conditions. The distance between the board and the case is considered to fluctuate between 2mm-6mm. The top enclosure dimensions are about 60mm x 51mm and the height of the enclosure is about 26mm.

For simplicity, the enclosure will be considered to be grounded, and can be used as the reference for all other voltages potentials in the circuit. Fig. 10 proposes the models for the casing. As it can be seen from Fig. 10 the capacitance between the electrodes can be separated in to two main regions. C_{top} represents the capacitance between the path on the board and the top wall on the case. C_{side} represents the capacitance between the path on the board and each side wall on the case, and therefore, there are four C_{side} capacitors.

Therefore, referring to Fig. 10, all capacitances formed between the given electrical net in the board and the enclosure are considered and added.

$$C_{th} = C_{top} + C_{side1} + C_{side2} + C_{side3} + C_{side4} \qquad (4)$$

$$\mathrm{C_{side}} = \int_0^{d_{side}} \frac{Q}{\varepsilon\, A(l)}\, dl \qquad where \quad A(l): A_{pin} \rightarrow A_{side}$$

$$\mathrm{C_{top}} = \int_0^{d_{top}} \frac{Q}{\varepsilon\, A(l)}\, dl \qquad where \quad A(l): A_{pin} \rightarrow A_{top}$$

$$Considering \quad A_{side} << A_{top} \quad and \quad d_{side} >> d_{top}$$

$$then \quad C_{side} << C_{top} \quad therefore \quad C_{th} \approx C_{top}$$

The capacitance C_{top} is calculated by using equation (4), where the length of the electric field is d_{top} and the cross sectional area goes from the area of the net in the board (pin area) A_{pin} to the top case area A_{top}. Similarly the capacitance C_{side} is calculated by using equation (4), where the length of the electric field is d_{side} and the cross sectional area goes from the area of the net in the board (pin area) A_{pin} to the top case area A_{side}.

Fig. 11, shows the resulting capacitance generated between exposed electrodes in the printed circuit board and a metallic enclosure placed in close vicinity. The material used for the application example showed in the figure is rubber. As it was expected the capacitance rises with the water content as a result of the increment in the permittivity of the material[2].

Another important conclusion is the dependence of capacitance with the distance between electrodes. At small thermal filler thickness the capacitance increases dramatically while at distances of more than 4.5mm the variation is minimal.

In Fig. 12, the capacitance is calculated assuming that the space between the exposed electrodes (in the printed circuit board) and the metallic enclosure is filled with air. The air is assumed to have some impurities, specifically water content[3]. Similarly to the previous case, the capacitance increases with higher water content in the air, as well as with smaller separations between the exposed pads in the board and the enclosure. It is important to point out the higher water content percentage in this example, given that free air is more susceptible to attract water impurities than materials such as rubber or mica which are generally used for gap fillers.

[2] The material used for thermal filler in the actual application example is Chomerics T644. This material is a Boron Nitride and glass composite, similar to a rubber material. Relative permittivity used 6.7.

[3] For this calculation the relative permittivity of the air is assumed to be 1.00054.

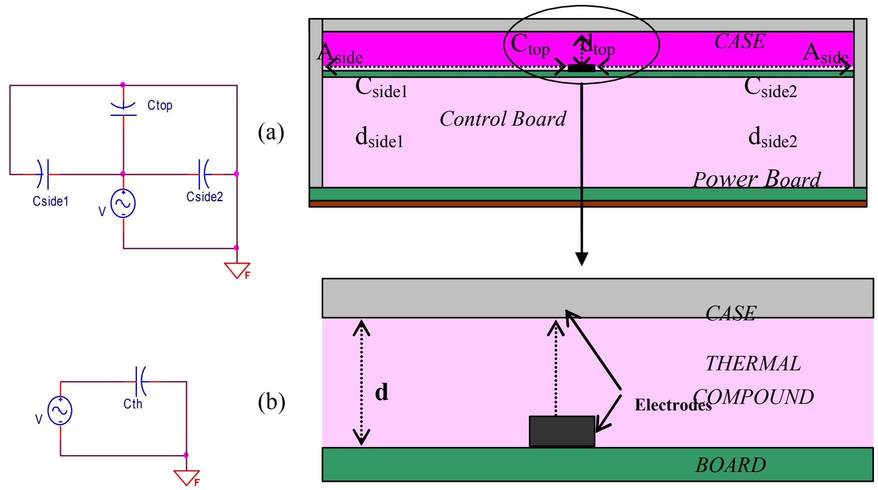


Figure 10. Proposed method to be studied to analyze capacitive effect, C_{th} on the resistor when adding an enclosure

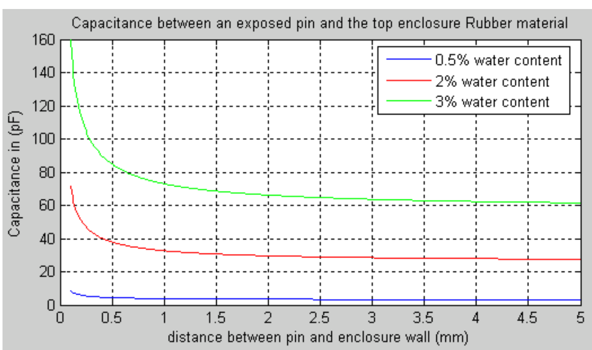


Figure 11. Capacitance between exposed pin and enclosure-rubber

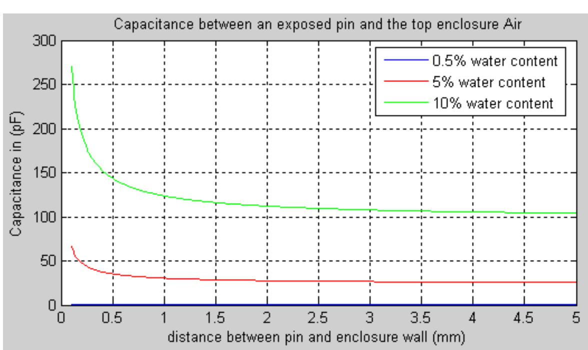


Figure 12. Capacitance between exposed pin and enclosure-free air

CONCLUSIONS

A study of the effect of harsh environmental conditions on the resistivity and permittivity of insulators is presented. The study focuses in the humidity effect for the electrical properties of thermal compound and/or air. The proposed models are applied to an application example circuit for high voltage operation where the humidity effect is noticeable.

Two approaches have been investigated to address the problem of modeling external components under variable environmental conditions. The first method calculates the resistivity variation of materials involved during the manufacturing and assembly of power electronic systems. The second approach quantizes the capacitance created by placing a metallic enclosure in a close vicinity of a sensitive circuit is proposed. The model takes into account the variation of permittivity with humidity.

The proposed methods not only take into effect the environmental conditions but also the mechanical properties of the electrical system. Alternatives for design to counteract the disturbances generated by the variation of environmental conditions may include: modifying dimensions of mechanical components, altering the placement of components in the PCB, or modifying routing of exposed conductive layers.

The above contributions begin to provide the designer with the understanding of the environmental conditions influence over sensitive circuitry. Furthermore, the proposed method provides a way to quantize the effects at given environmental and mechanical conditions, and more importantly, provides a way to achieve an efficient use of space for worst case environmental conditions.

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