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INVESTIGATION OF THE IMPACT OF TEMPERATURE AND HUMIDITY ON THE CAPACITANCE OF DIELECTRIC GEL USED FOR POWER ELECTRONICS

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Abstract

Offshore wind turbines are subjected to harsh environmental conditions which can include high temperatures and elevated levels of ambient humidity. Failure of wind turbines can often be the result of damage over time to the power devices used within converters, leading to significant downtime and maintenance costs. The absorption of moisture within the silicone gel used as a dielectric in power modules poses a potential reliability concern due to its altered electrical properties. Samples of a commercial dielectric gel recommended for use in power modules are subjected to harsh environmental conditions consisting of high temperature alone, high humidity alone, and combined high temperature and humidity. The electrical properties of the gel during these tests are measured using bespoke sensors, and the results of this testing are discussed. A notable increase in the capacitance of samples is observed for the combined high-temperature, high-humidity condition.

1 Introduction

Offshore wind turbines (OWTs) are subjected to harsh environmental conditions, which can cause stress on the switching components used in their construction. These converter components are recognised as the most frequent source of wind turbine (WT) failure, requiring extensive maintenance and repair due to catastrophic failures [1]. High temperatures within the converter enclosures or at the component level cause thermomechanical damage of devices, often arising from a mismatch of the coefficients of thermal expansion (CTEs) of the constituent materials. This can result in device degradation through bond wire cracking or lift-off, delamination of components, and degradation of the die-attach solder layer.

A recent study led by the Fraunhofer institute found a significant portion of field failures of WTs which could not be attributed to thermal degradation, indeed the conclusion of this research put forth ambient humidity as a failure driver [2]. Research has shown that the presence of humidity local to the power device can enhance the local electric field [3], and it has been shown that moisture can accelerate corrosion or electrochemical migration of device metallisation [4]. These factors point to concerns about device reliability in harsh environments with high levels of ambient humidity.

Typically, reliability research considering humidity makes use of accelerated testing to force humidity-driven degradation of devices under a static bias. A widespread technique is the high-humidity high-temperature reverse bias (H3TRB) test, which typically subjects devices to an ambient environment of 85 °C and 85% relative humidity (RH), with a fixed reverse bias of 80% of the device's rating. Most often, leakage current I_{CES} is used as the main degradation metric, with increasing I_{CES} relating to advancing device degradation, but little consideration is given to the insulation materials used within the device.

Inside a typical power module, silicone gel is used as the primary encapsulant, providing both electrical insulation and mechanical protection for the components within. Silicone gels have the propensity to absorb moisture when subjected to humid environments, and this has been shown to significantly reduce its breakdown voltage [5]. This naturally leads to reliability concerns when operating these devices in harsh environmental conditions, as the degradation of the insulation may result in catastrophic failure.

This paper investigates the influence of ambient temperature and humidity on the electrical properties of a commercial silicone gel. An effort is made to isolate the independent contributions of temperature and humidity alone on the gel's properties, and these results are compared to those with a combined setpoint environment. Attempts are made to characterise the temperature dependence of the relative permittivity of the gel, and basic gravimetric analysis is attempted to correlate moisture absorption with increasing capacitance of gel samples.

2 Methodology

Initial impedance measurements (1 kHz – 50 MHz) of gel taken from an IGBT module and placed between flat copper electrodes (30 x 30 mm) were taken in ambient conditions (approx. 22 °C and 50% RH) and after 10 hours at 90 °C and 90 % RH. The sample was placed in a controlled environment chamber for testing. The results are shown in Fig 1. We observe that the gel sample behaves in a capacitive manner up to resonance at approximately 10 – 20 MHz, and that the magnitude of the impedance is reduced slightly when subjected to a high-temperature high-humidity environment.

This is indicative of an increase in the sample capacitance and forms the basis of the testing detailed hereafter.

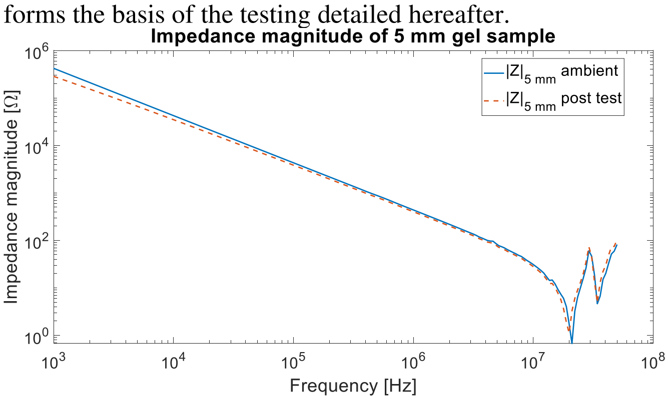


Fig. 1 Impedance magnitude measurements over 1 kHz – 50 MHz of a gel sample before (solid) and after (dashed) 10 h at 90 °C & 90% RH.

Dielectric gel samples were then subjected to varying ambient temperature and humidity conditions. Interdigital capacitor (IDC) sensors placed below cured gel were used to monitor changes in its impedance due to the changing environment. An image of the test samples is shown in Fig 2.

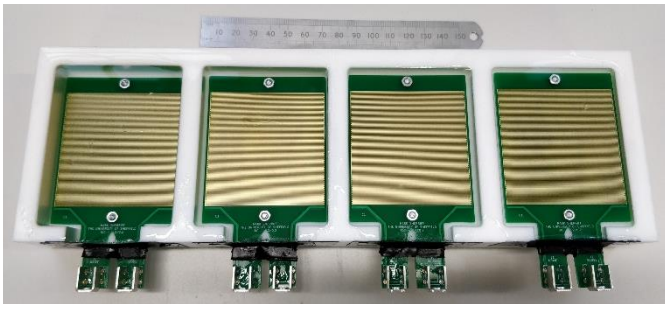


Fig. 2 Image of IDC sensors in PTFE mould with dielectric gel cured over top. Gel depths left to right: 20 mm, 15 mm, 10 mm, and 5 mm.

2.1 Test Setup

Test samples were placed inside an Espec SH-662 environment chamber, which controlled the ambient temperature and humidity throughout the test. A circulation fan inside the environment chamber ensured a homogeneous environment. From impedance measurements of the samples, a simple parallel RC model representing the IDC with gel was parameterised.

2.2 Sample Preparation

The samples consisted of IDC sensors placed in a PTFE mould, with dielectric gel cured over top. The gel studied was Wacker SilGel 612, which is an addition-curing two-component room-temperature vulcanisable (RTV-2) silicone rubber suitable for use in power electronics. The PTFE mould pockets were sized to provide different cured gel thicknesses: 20 mm, 15 mm, 10 mm, and 5 mm. The 20 mm thickness was chosen to be representative of the gel thickness found in an IGBT half bridge module. The gel was degassed in a vacuum chamber at -1 bar after mixing to remove any entrained air and was then poured from a low height into the mould, in line with processing guidelines. Dams were created from PVC tape to avoid leakage, and machine screws were used to secure the PCBs in place at the bottom of the mould. The samples were then degassed again before being left to cure at room temperature for 8 hours.

The design of the IDC sensors was based on [6], [7]. For the IDC, the total capacitance is equal to the sum of the capacitances of the unit cells, and is calculated using the following:

$$C = C_{UC}(N-1)L \tag{1}$$

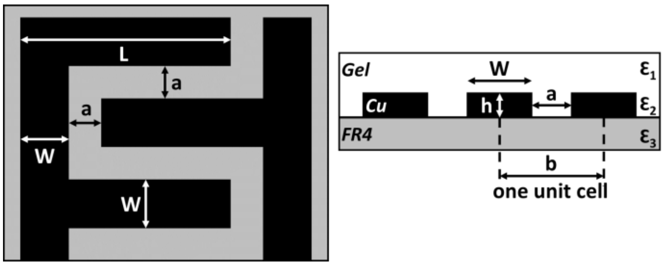
$$C_{UC} = C_1 + C_2 + C_3 \tag{2}$$

$$C_1 + C_3 = \varepsilon_0 \frac{\varepsilon_1 + \varepsilon_3}{2} \frac{K\left(\sqrt{1-k^2}\right)}{K(k)} \tag{3}$$

$$C_2 = \varepsilon_0 \varepsilon_2 \frac{h}{a} \tag{4}$$

$$k = \frac{a}{b} \tag{5}$$

Where C is the total capacitance of the IDC, and C_{UC} is the capacitance of a unit cell. The number of digits is represented by the parameter N. For the partial capacitances: C_1 is the capacitance resulting from the fringe electric field above the traces through the dielectric gel, C_2 is the parallel-plate capacitance involving the gel between the PCB traces, and C_3 is the capacitance from fringing below the traces, through the FR4 material. The parameters ε_0, ε_1, ε_2, and ε_3 are the vacuum permittivity, and the relative permittivities of the material above, between, and below the traces, respectively. Moreover, $K(k)$ is the complete elliptical integral of the first kind, computed here via arithmetic geometric mean method. The remaining parameters pertain to the IDC geometry and are shown in Fig 3.



a *b*

Fig. 3 Diagrams of IDC showing dimensions: (a) top-down view, (b) cross-sectional view.

Electrostatic simulations using ANSYS Maxwell were performed on various IDC geometries to identify the major contributor to the capacitance via inspection of the local electric field strength. The results of these simulations showed that the primary contributor to the overall capacitance on a per unit-cell basis was the area in between the PCB traces, which the theory models as a simple parallel-plate relationship (4). Consequently, the design targeted a high number of digits and thick copper to increase the sensor capacitance and hence sensitivity to variation.

The PCB substrate was FR4 with a thickness of 1.6 mm, and a 2 oz. copper pour was chosen for the traces, with an estimated thickness of 70 µm. Trace widths and separations were chosen to suit the minimum PCB manufacturing capabilities of 0.2 mm for both. The number of digits was set to 145. Analytical models and simulations showed that variance in the electrical properties of the gel above and in between the PCB traces would change the device capacitance. The tests presented here were conducted to validate these analyses.

2.3 Test Procedures

Three main test procedures were carried out on the samples. Test A varied the temperature setpoint in a stepwise fashion every 15 hours while attempting to maintain a fixed ambient humidity. This test was intended to characterise the temperature dependence of the dielectric gel, such that the gel's dielectric properties could be accurately modelled at a given temperature in future work. Test B varied the ambient humidity stepwise every 24 hours, with a fixed ambient temperature. Test C varied both ambient humidity and ambient temperature and held this combined setpoint for 120 hours of test, this test also contained gravimetric analysis on a separate lightweight gel sample to attempt confirmation of the diffusion mechanism.

A summary of these test procedures is given in Table 1. As a preconditioning step, samples were dried out in the environment chamber at 95 °C and 20% RH for at least 24 hours.

Table 1 Summary of test procedures

Test ID	Step	Temperature [°C]	Humidity [% RH]	Duration [h]
A	1	95	20	15
	2	80	20	15
	3	60	20	15
	4	40	20	15
	5	20	20	15
B	1	30	30	24
	2	30	60	24
	3	30	90	24
C	1	90	90	120
	2	90	30	12
	3	30	30	12

During testing, measurements of impedance magnitude and phase were taken using an Omicron Bode-100 vector network analyser (VNA). Per manufacturer guidance, an external bridge was used due to the high expected impedance of the samples. The parallel RC model was parameterised via measurements of impedance magnitude and phase. A frequency sweep measurement (1 kHz – 50 MHz) was carried out automatically every 30 seconds – as there were 4 samples in the mould, the effective sampling rate per sample was once every 2 minutes. Four samples with different thickness of 20, 15, 10 and 5 mm were analysed.

3 Results and Discussion

3.1 Test A – Temperature-only Setpoint Results

The test was designed with stepwise decreases in temperature to limit any moisture absorption of the samples that might occur between the preconditioning phase and reaching the first test setpoint. Results for this test showing the percentage change from start-of-test values of inferred parallel capacitance are provided in Fig 4. The frequency chosen for inspection was 2.5 kHz, as this offered the best measurement sensitivity: providing a balance between high measurement noise at lower frequencies, and a loss of the capacitive behaviour at higher frequencies. From the results, one can see a fractional increase in capacitance with reducing temperature. Hence an increase in temperature alone (i.e., with fixed ambient humidity) gives rise to a decrease in parallel capacitance to within a percentage point. Considering an increase in temperature from the 20 °C to the 95 °C setpoints, the reductions in parallel capacitance per sample are 1.05%, 1.38%, 1.48% and 1.67% for the 5 mm, 10 mm, 15 mm, and 20 mm samples, respectively.

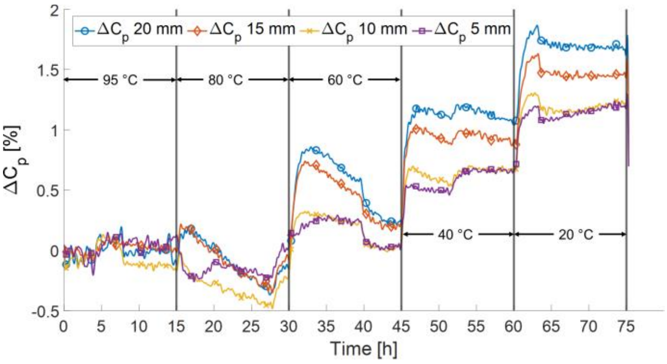


Fig. 4 Percentage changes in gel sample parallel capacitances at 2.5 kHz under varying temperature stress. Samples: 20 mm in blue (circles), 15 mm in orange (diamonds), 10 mm in yellow (crosses), and 5 mm in purple (squares).

This test aimed to characterise the temperature dependence of the gel's dielectric constant. Using (1) – (5), the IDC geometry and measured capacitance can be used to calculate the relative permittivities of the gel samples across the temperature range, shown Fig 5. These results indicate that although the dielectric constant of the gel is generally reduced for increasing temperature, there are only slight changes in its value over the temperature range investigated. However, all measurements showed a significant reduction from the datasheet value of 2.7.

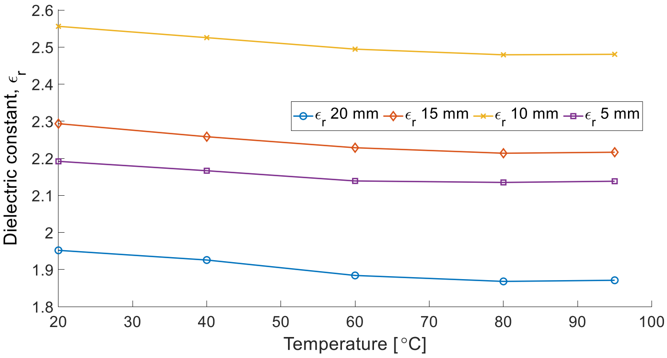


Fig. 5 Estimated gel sample relative permittivities for varying temperatures. Samples: 20 mm in blue (circles), 15 mm in orange (diamonds), 10 mm in yellow (crosses), and 5 mm in purple (squares).

The estimated relative permittivities were reduced by 2.45%, 2.95%, 3.36% and 4.14% for the 5 mm, 10 mm, 15 mm, and 20 mm samples, respectively, from 20 °C to 95 °C.

Notably, the results present a minor correlation between the thickness of the gel sample and changes in the calculated relative permittivities or inferred parallel capacitances due to varying temperature conditions.

3.2 Test B – Humidity-only Setpoint Results

To isolate the effect of temperature from humidity-influenced changes of the gel's electrical properties, the humidity-only setpoint test held a fixed ambient temperature of 25 °C. The starting setpoint for the test was 25 °C and 30% RH. The results are provided in Fig 6 and indicate a notable increase in parallel capacitance for the increasing RH setpoints.

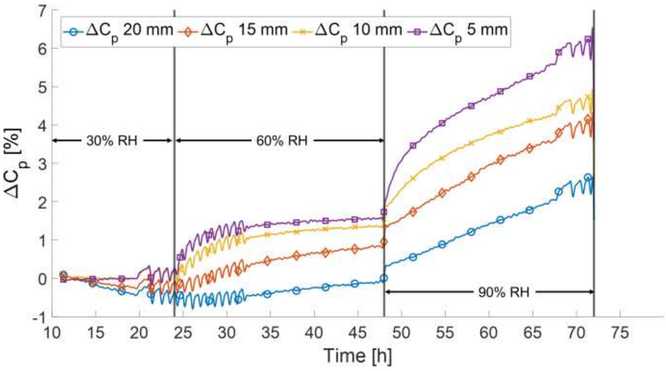


Fig. 6 Percentage changes in gel sample parallel capacitances at 2.5 kHz under varying humidity stress. Samples: 20 mm in blue (circles), 15 mm in orange (diamonds), 10 mm in yellow (crosses), and 5 mm in purple (squares).

Considering the end-of-setpoint values, the increase in parallel capacitance on a per sample basis from the 30% RH condition to the 90% RH condition were 5.90%, 4.38%, 4.22% and 2.97% for the 5 mm, 10 mm, 15 mm, and 20 mm samples, respectively. The magnitude of the increase is shown to depend on the thickness of the gel. This provides further credence to the hypothesis of moisture absorption by a diffusion process, as the thicker samples would have a longer diffusion path length and hence the sensor at the bottom of the gel would increase in capacitance more slowly.

3.3 Test C – Combined Temperature and Humidity Results

The impact of combined high temperature and high humidity were investigated in the final test. Fig 7 shows the percentage change in the inferred parallel capacitances of the gel samples at 2.5 kHz over the course of the test. After 120 hours at the 90 °C, 90% RH setpoint, the capacitance values are increased by a large amount from their starting values. In percentage terms, the increases were 76.12%, 65.26%, 63.29%, and 57.90% for the 5 mm, 10 mm, 15 mm, and 20 mm samples, respectively. The increases appear to depend on the thickness of the gel sample; the thinnest sample saw the greater change, while the thickest sample saw the least change.

A cool-down period where first the chamber RH was reduced to 30% for 12 hours, and then the chamber temperature was reduced to 30 °C for 12 hours was included at the end of the test. This illustrates some recovery in the changes of the gel electrical properties, provided sufficient recovery time.

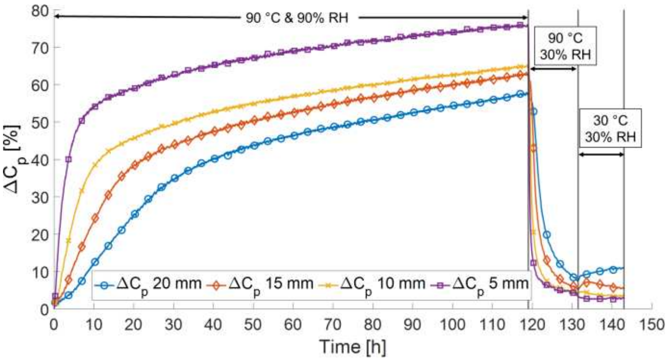


Fig. 7 Percentage changes in gel sample parallel capacitances at 2.5 kHz under combined temperature and humidity stress. Samples: 20 mm in blue (circles), 15 mm in orange (diamonds), 10 mm in yellow (crosses), and 5 mm in purple (squares).

3.4 Discussion

From the test results, it is evident that although temperature and humidity alone each have an impact on the electrical properties of the dielectric gel, the impact is far less than that of the combined temperature and humidity condition. With increasing ambient temperature alone, the inferred parallel capacitance of gel samples was observed to reduce slightly, reaching a maximum reduction of 1.67% in the 20 mm sample. For this condition, a weak correlation was found between the change in inferred parallel capacitance due to temperature and the thickness of the gel samples.

With increasing ambient humidity alone, the inferred parallel capacitance was observed to increase by up to 5.90% in the 5 mm sample, and there was a notable inverse correlation between increasing thickness of gel samples and the magnitude of parallel capacitance increase. That is, the thinner gel samples responded more quickly and to a larger extent than thicker gel samples, over the course of the test. Consequently, a thicker dielectric coating is assumed to provide a greater degree of protection from harsh environments. Naturally the implication of increased device volume makes this option undesirable from a converter design point of view.

For the combined temperature and humidity condition however, the change in inferred parallel capacitance was observed to be far greater. In the 5 mm sample, this value increased by 76.12%. These results highlight the potential for gel-related reliability concerns of power devices operating in a harsh environment of high ambient humidity and high temperature. The presence of absorbed moisture may lead to accelerated corrosion of device metallisation. Increases in the gel capacitance could also potentially lead to an effective reduction in the Partial Discharge Inception Voltage (PDIV) of a switching device's insulation.

The Lichtenecker-Rother dielectric mixing theory allows one to obtain the resultant dielectric constant of a mixture of liquid dielectrics by the volume fraction of the logarithms of the constituent materials [8]. With the assumption that the dielectric constant of moisture absorbed by the dielectric gel is similar to that of water, one can adjust its value to reflect changes in temperature. Similar adjustment can be made for that of the gel, though based on the results herein, the difference is negligible. Hence, we can compare the expected increase in mass gain of the gel samples to provide the increase in capacitance observed during the combined setpoint test.

To provide the capacitance increase observed after 120 h at the high-humidity high-temperature condition, the 5 mm sample would require a mass increase of roughly 42.92%. This required mass increase is in severe disagreement with prior published research showing saturation of a silicone gel at 0.71% mass increase due to moisture absorption [9].

The stated density of the dielectric gel is 0.93 g/cm^3, slightly less than that of water at 1 g/cm^3. That these densities are expected to reduce slightly in elevated temperatures notwithstanding, it is possible that a scenario where absorbed moisture concentrated or condensed at the PCB surface at the bottom of the gel occurred. This would give rise to a far greater increase in inferred parallel capacitance for a relatively small proportional increase in the gel mass.

A repeat of the combined setpoint test was performed on two sets of samples simultaneously, using 20 mm and 10 mm samples only, with one set placed upside-down in an inverted orientation. The results from this test are provided in Fig 8.

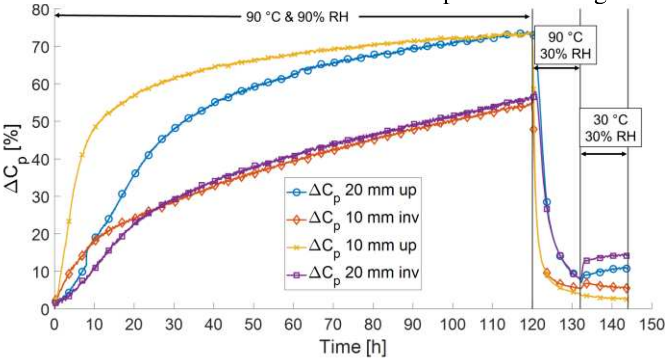


Fig. 8 Percentage changes in gel sample parallel capacitances for the inverted test. Samples: 20 mm upright in blue (circles), 20 mm inverted in orange (diamonds), 10 mm upright in yellow (crosses), and 10 mm inverted in purple (squares).

Although sample inferred parallel capacitance in the inverted orientation increased more slowly and to a lesser extent than those in the upright orientation, an increase of over 50% was recorded. Evidently, orientation is an important factor in the gel's absorption of moisture, however more detailed investigations are required to explain the discrepancy between mass gain and capacitance gain.

4 Conclusion and Recommendations

Samples of dielectric gel cured to different thicknesses were subject to a series of 3 tests, where the impedance of an IDC sensor at the bottom of the gel was measured while the samples were subjected to changing ambient humidity and temperature. The tests investigated the impact of temperature alone, humidity alone and combined temperature and humidity on the parallel capacitance value inferred from the impedance.

For the temperature-alone condition, the gel sample capacitances were reduced by a maximum of 1.67% (20 mm sample). A weak correlation between this change and the gel thickness was identified. Results from this characterisation of the gel showed little change in the relative permittivity in elevated temperatures.

In the humidity-alone test, gel sample capacitance was observed to increase, with the rate and magnitude of increase elated to the thickness of the gel. The 5 mm gel sample showed an increase of 5.90% whereas the 20 mm sample increased by only 2.97% by the end of the test.

The combined temperature and humidity test saw the greatest change in this capacitance value, increasing by 76.12% in the 5 mm sample. This result would require a mass gain far more than the acknowledged saturation point of the gel. This led to a hypothesis of moisture pooling at the base of the gel, which was tested with samples in an inverted orientation. Inverted samples showed reduced capacitance increase, but not enough to explain the discrepancy between mass gain and capacitance gain. Consequently, recommendations are made to avoid upright module configurations.

5 Acknowledgements

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