System Level Simulation of Moisture Propagation and Effects in Wind Power Converters

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Keywords

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Abstract

The aim of this work is to create a better understanding of the propagation of moisture and its effects in power electronic converters with the help of computer-aided simulations. Due to the interaction of humidity and temperature, a combination of multiple simulation models is required. Suitable measurement methods for parameter identification and validation will also be presented.

Introduction

The increasing use of power electronics even under extreme climatic conditions (e.g., e-mobility or offshore applications) can cause moisture-induced degradation mechanisms in electrical components [1, 2]. A more detailed understanding of moisture diffusion acquired by using computer-aided modelling at a system level should help to prevent critical degradation in the future.

The goal of such modelling and simulation is to identify critical combinations of load and climate, for example, with the aim to adjusting the variables that can be influenced (load) via the operational management. This includes preheating the power modules of the converter when the power electronic system is restarted after longer downtimes, during which moisture may have penetrated the power module. When the moisture has made its way to the chips, they can suffer from various degradation mechanisms when re-applying the operating voltage [3, 4].

Humidity Modelling under Dynamic Temperature Cycles

For an accurate simulation of moisture propagation in such complex systems as power electronic converters, the first step is to create a simulation environment that can reproduce the diffusion processes of water molecules. There are already many commercially available options for simulating diffusion processes, such as those of heat. However, these cannot be applied equivalently to diffusion and transfer of mass due to moisture concentration gradients across material boundaries, which are strongly dependent on the solubility of water in the materials [5].

The first publications in the field of moisture modelling in power electronics were realised with the help of electrical analogies [6, 7]. Just as resistors and capacitors can be used for thermal modelling, R-C networks were used to represent the diffusion and storage behaviour in so-called hygrothermal models. However, if thermodynamic effects are correctly represented, the use of electrical analogies quickly reaches its limits and becomes unnecessarily convoluted.

In comparison to modelling using electrical analogies, another modelling approach is based on Fick's second diffusion law, as proposed one dimensionally in [8, 9]

$$\frac{\partial c}{\partial t} = D(T) \cdot \frac{\partial^2 c}{\partial x^2} \qquad \text{with} \qquad D(T) = D_0 \cdot \mathrm{e}^{-\frac{Q}{k \cdot T}} \tag{1}$$

where c is the concentration of the particles, which can also be seen as the absolute humidity h_{abs}. D_0 is the diffusion constant of the respective material, Q is the activation energy of water, and k is the Boltzmann constant. This exists in analogy to the thermal behaviour based on the heat transfer equation

$$\frac{\partial T}{\partial t} = \frac{\lambda}{\rho \cdot c_{\text{p}}} \cdot \frac{\partial^2 T}{\partial x^2} \tag{2}$$

where Lambda is the coefficient of thermal conductivity, ρ is the material-dependent density, and c_{p} its specific heat capacity related to the mass.

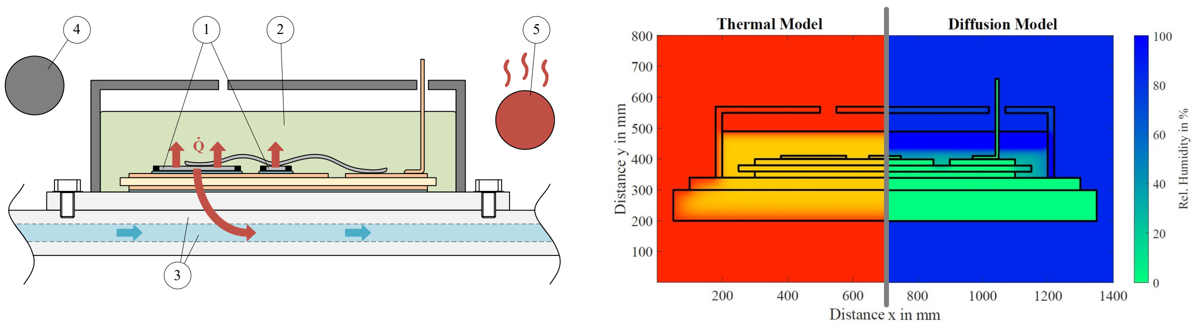


Fig. 1: Left: Cross-section of an IGBT module with power semiconductors (1) encapsulated in silicone (2) on a heat sink (3) with simplified additional heat sources, e.g., chokes (5) and moisture reservoirs, e.g., plastic components (4). Right: Example of the qualitative module cross-section shown in (a) viewed in the two-dimensional hygrothermal model - thermal on the left and moisture diffusion on the right.

The modelling approach in this work based on Fick's diffusion laws is to be performed by a one-, two- or three-dimensional mapping of temperature and absolute humidity for the materials and topologies of the systems considered. An example is shown in Fig. 1 for a two-dimensional module cross-section, where the aim is to identify and predict critical scenarios with the help of the moisture distribution shown on the right. Here, the power semiconductor losses and the heat sink are not represented. Coupling with thermal models is always necessary, as visualised in Fig. 2, since the interrelations considered are strongly temperature dependent and linked via the diffusion coefficient $D(T)$. A schematic representation is given in Fig. 2, where the ambient temperature ϑ_{env} and the power dissipation at the chip are first passed to the thermal part of the model as input variables and the ambient humidity $h_{\text{rel,env}}$ is added afterwards in the diffusion model. It should be noted that the thermal model is not the same as in conventional thermo-electric modelling of power converters, since the temperature distribution especially in the opposite direction to the heat sink (through the electrically insulating silicone) is needed. The output goal of the model is to obtain the relative humidity $h_{\text{rel,comp}}$ at a certain place of interest in the system. This value can be used from experience of critical moisture levels in power modules to make predictions on the degradation state at these locations. This makes it possible to define location-specific moisture thresholds.

Thus, in addition to the ambient humidity and temperature, the load profile of the converter or drive system must be considered, leading to strong temperature fluctuations and therefore to fluctuations in the diffusion behaviour within the materials. It is necessary to identify heat sources within the converter cabinet whose dynamic cycles depend on the load profile. This can be achieved with the help of a higher-level system model (loss model), as presented in [10], to simulate load cycles and losses on the basis of realistic load profiles. The resulting power losses can be entered into the thermal part of the hygrothermal diffusion model (here in one dimension) via:

$$\frac{P_{\text{loss}}}{A} = \dot{q} = -\lambda \cdot \frac{\mathrm{d}T}{\mathrm{d}x} \tag{3}$$

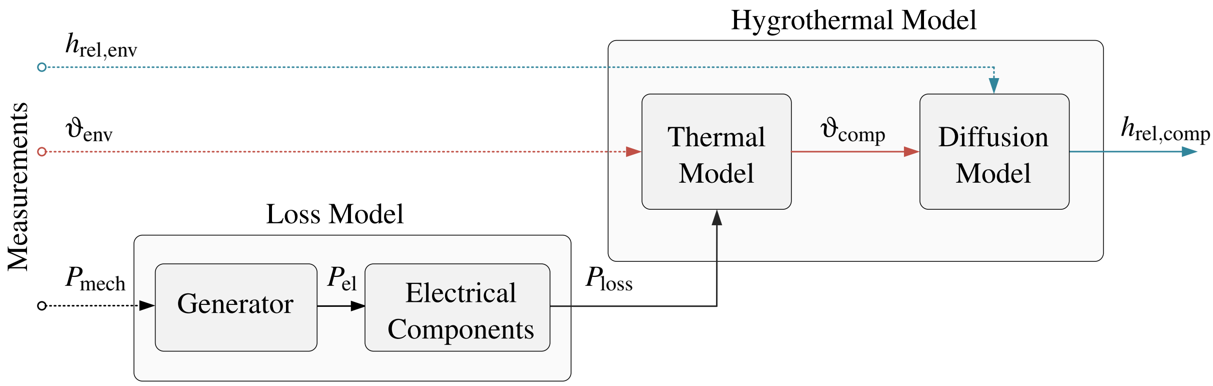


Fig. 2: Internal operation of the loss and hygrothermal model with weak coupling through thermal paths

Since the time constants of the material diffusion are significantly higher than the thermal ones, even at high temperatures, it is sufficient to use a quasi-stationary loss model using averaged losses, for instance over a period of the fundamental frequency, particularly when significantly longer time series of up to several months are considered.

In air, in addition to the mass flow J_{D} of diffusion, mass transport of water molecules occurs significantly faster via convection – forced by the fan or caused naturally by heat sources. For now, due to the long time constant associated with diffusion, this can be handled by making the assumption that the air has a uniform humidity. Computational fluid dynamics (CFD) simulation tools are suitable for more detailed consideration. CFD simulations are able to evaluate pressure differences of the ambient air volume so that a vector field of the air flow is created, which could be added to the diffusion mass flow J_{D} in future work.

Parameter Identification and Validation Methods

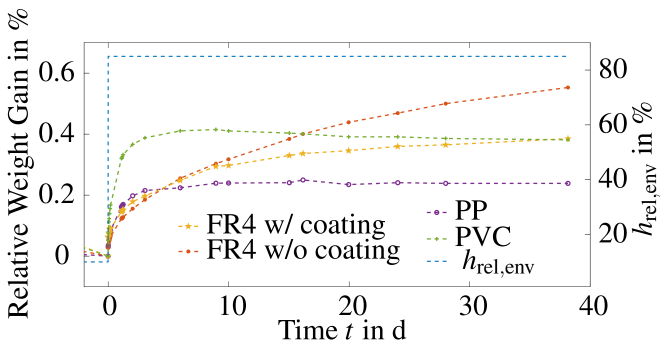
A theoretical analysis of such complex processes as diffusion and storage of moisture is made considerably more difficult by strongly material-dependent aspects. Parameters from literature might be hardly transferable due to the diversity of material compositions and must be verified with the help of test specimens using the materials investigated. Furthermore, an abstraction of the overall system is required due to the large number of different components used in a converter system. In the following, two pre-developed test concepts will be presented, which can be used for the parameterisation of hygrothermal models. Several types of materials are especially important due to their ability to store moisture: insolation materials like polypropylene (PP) or polyvinylchloride (PVC); epoxy as used for PCBs or insolating construction material (FR4); and of course silicone gel, as used in the power semiconductor modules.

Gravimetric Measurements

Critical parameters, such as the diffusivity or solubility of the plastic materials, can be determined, for example, via gravimetric measurements under controlled climatic conditions. The DIN EN ISO 12572 standard presents a method which uses a dehumidifying substance in an airtight cup which is covered and sealed by a thin specimen of the material to be tested. Here, the diffusion constant for a given temperature can be determined gravimetrically via

$$J_\mathrm{D} = \frac{\Delta \dot{m}}{A_1} = -D \cdot \frac{\mathrm{d}c}{\mathrm{d}x} \tag{4}$$

where A_1 is the cross-sectional area of the material and $\Delta \dot{m}$ is the weight increase per unit time. In this work, a simpler method is used. The mass of the tested material specimen in this paper is measured (without any enclosure or cup) at regular time intervals on a high-precision scale. All specimens have a nearly identical volume with a surface-to-volume ratio as large as possible. The tested materials (PP as used in component housings, FR4 with and without coating for PCBs, and PVC as used in cable insulation) need to be dried over an extended period of time (here at 10% relative humidity and 85°C for one month) [11]. The weights shown in Fig. 3 are normalised relative to the minimum weight in the dry state: $m = m_\mathrm{meas}/m_\mathrm{dry} \cdot 100\% - 100\%$. It will not be possible to achieve a completely dry condition in a finite time due to the ambient humidity which remains for technical reasons. After the drying, a humidity step is applied, also at a defined environmental temperature, which leads to an exponential approach of the weight of the materials to the steady state.



(a)

	Δh_abs (kg/m^3)	$D(T = 85°\mathrm{C})$ (m^2/s)
PP	3.37	2.68×10^{-11}
PVC	5.63	1.24×10^{-10}
FR4 w/	6.61	1.96×10^{-12}
FR4 w/o	8.19	1.55×10^{-12}

(b)

Fig. 3: (a) Gravimetric measurement of different materials at a temperature of 85°C; (b) Listed absolute water absorption and calculated diffusion constants

The different diffusion constants are clearly visible. Based on Fick's diffusion behaviour, the ratio of $m_{0.5}$, the mass at the time when 50% of the total moisture has been absorbed, to the total mass increase m_∞ can be calculated as a function of the square root of time. This can be rearranged to give D for the one-dimensional case of a thin test specimen with a thickness l [12]:

$$\frac{m_{0.5}}{m_\infty} = 4 \cdot \sqrt{\frac{D \cdot t_{0.5}}{\pi \cdot l^2}} \qquad \Leftrightarrow \qquad D = \frac{\pi}{16} \cdot \left(\frac{m_{0.5}}{m_\infty}\right)^2 \cdot \frac{l^2}{t_{0.5}} \tag{5}$$

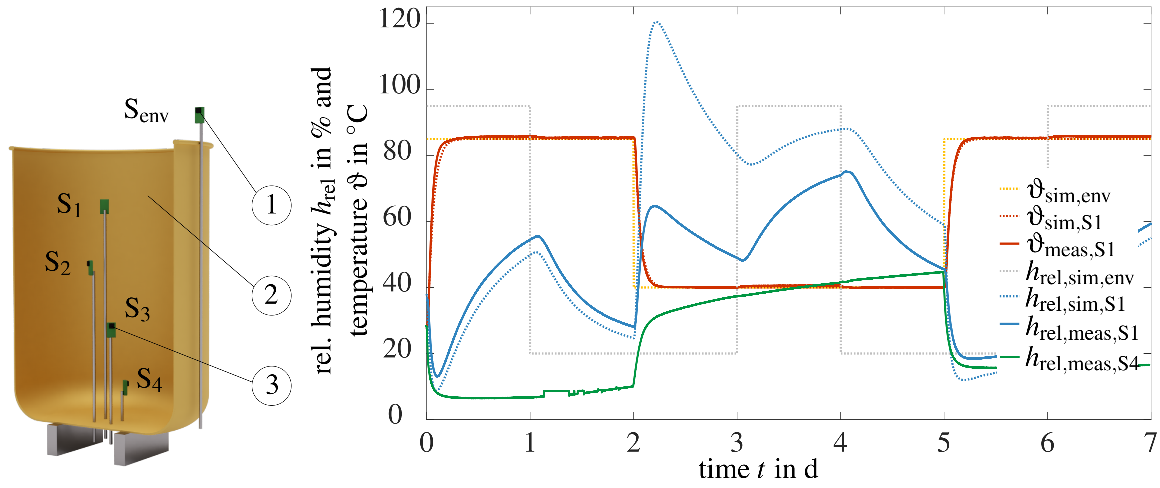
It should be noted that PP has already reached its maximum weight after one week, while this has not yet been reached in the FR4 samples even after more than one month. Also with some materials, such as PVC, the weight decreases after reaching a maximum, which could be due to the fact that the material itself reacts with the water molecules and the reaction products are outgassed due to the relatively high environmental temperature. The easiest way to circumvent this effect is to precondition the samples in advance with high ambient humidity.

Diffusion Time Behaviour using Moulded Humidity Sensors in Silicone Gel

Due to its physical contact with the power semiconductor, the insulating silicone gel inside the modules plays a key role in the accumulation of water on the chip surface. Therefore, a method is presented here for recording dynamic humidity curves and their temperature dependency with the help of commercially available sensors moulded into the silicone. This method can be used to derive the coefficients of the specific silicone by matching, or to validate the simulation with parameters from other tests. For this purpose, a stainless steel cup is filled with silicone as shown in Fig. 4 (a), in which the sensors of type Sensirion SHT31-ARP on a tiny PCB are mounted and connected via the bottom of the cup. The only diffusion exchange possible with the environment is through the upper surface. Based on [8], different stationary temperatures are set, while a dynamic humidity step is specified in both directions in order to measure the temperature diffusion dependency. In addition, it can be seen in Fig. 4 (b) that the sensor (in this case, only the measurement profiles of the sensors 1 and 4 are represented) show increasingly low-pass filtered behaviour compared to the environment with increasing depth of the sensors.

The dashed lines show the corresponding simulated temperatures and relative humidities from a 2D version of the silicone encapsulated test specimen. The identical ambient conditions were given to the simulation model.

The large deviation from the measurement between days 2 and 3 is discussed in the following paragraph. In addition to the temperature-dependent diffusion, another effect can be observed in Fig. 4: between



(a) (b)

Fig. 4: (a) DUT: (1) environmental sensor, (2) silicone cast in stainless steel cup (diameter: 10 cm, height: 13.5 cm) and (3) moulded sensors at 30 mm spacing; (b) Dynamic moisture diffusion behaviour within the silicone at different ambient temperatures and relative humidities using data from the measuring setup

days 2 and 5, the humidity at sensor S_4 increases continuously, although the ambient humidity at sensor S_{env} fluctuates significantly. This can be attributed to the storage effect of the silicone layers lying over sensor S_4. It can thus be confirmed that moisture storage effects within the materials can lead to strongly deviating humidities in systems compared to their environment. This measuring method, however, is only useful in potting compounds such as silicone. For plastics like the ones shown earlier, a gravimetric measuring method is still recommended.

Another observation results when the measured relative humidity in the silicone is converted into an absolute humidity using the known dew point curve for air, which indicates the ratio of absolute, maximum humidity to temperature (Fig. 5 (a)). This approach is important to consider because the sensors are calibrated for relative humidity in air and not in silicone.

The difference between simulation and measurement of the relative humidity between days 2 and 3 in Fig. 4 (b) can be explained by taking a look at the calculated absolute humidity in Fig. 5 (b), where the data from sensor S_1 shows a drop within the measured absolute humidity. This is an effect that the simulation model based on Fick's diffusion (correctly) does not represent. A drop of this magnitude can only be explained by the antiproportional dependence on the increasing temperature at this point. Here it can be seen that the use of the dew point curve for air in silicone is not valid. As a further investigation, described in the following section, a dew point curve equivalent to that in Fig. 5 (a) must be determined for silicone.

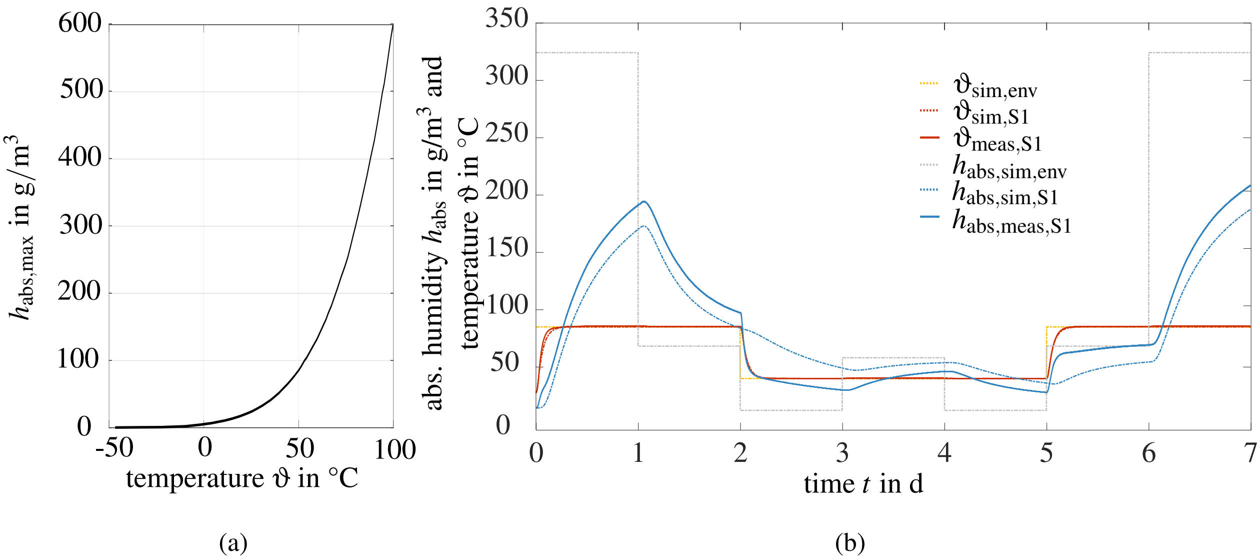


Fig. 5: (a) Dew point curve of water vapour in air; (b) absolute humidity in the silicone calculated with the dew point curve from (a) based on the measurements and simulations from Fig. 4

Optical Measuring Method for Silicone Dew Point Detection

Due to the fact that commercially available sensors like the Sensirion SHT31-ARP used in this work are calibrated for the relative humidity in air, the dew point behaviour of the silicone gel must also be determined. It is assumed that the so-called fogging of the gel occurs when the dew point is reached and small water droplets appear inside the gel. This leads to an intransparency of the material which can be detected. The basic procedure of the measurement is as follows: first, a specific relative humidity (for example 85%) is set in the environment of the test specimen at a high temperature like 85°C for faster diffusion. As soon as a steady state of relative humidity is reached inside the silicone, the ambient temperature can be lowered as quickly as the climatic chamber allows, until an optical measuring sensor reveals a clearly perceptible cloudiness in the otherwise transparent silicone. The temperature existing in the silicone at this point corresponds to the dew point temperature.

To determine the absolute humidity in the silicone associated with the previously measured dew point temperature, a gravimetric measurement of the silicone must also be carried out. This is accomplished under the same initial environmental conditions as the optical measurements. Here, too, the same procedure can be used as for the gravimetric measurements performed on the plastics described above [13, 14]. This procedure is to be repeated for different relative ambient humidities, resulting in a dew point curve for the silicone. With the help of this curve, it is possible to obtain information about the relative humidity in the silicone using commercial sensors encapsulated in the silicone, which is of special interest when investigating the degradation mechanisms affecting the power semiconductors [15].

Conclusion

For a better understanding of moisture penetration within complex systems – which are exposed not only to ambient conditions but also to thermal fluctuations due to load cycles – it is necessary to develop hygrothermal simulation models which, above all, accurately represent the interaction between temperature and humidity. For this purpose, a number of different parameter identification and validation procedures need to be carried out, including those presented here. Furthermore, next to the analysis of the relative humidity as a prediction of condensation risks, a look at the absolute humidity is always relevant as a verification of whether the scenarios considered (for example in sealing compounds) are valid. In addition, a coupling with further simulation models, which addresses both the convection overlaying diffusion and the realistic calculation of power losses as thermal input for these models, is the object of current analyses.

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