Application Note
AN 16-001

Revision: 02

Issue date: 2024-10-07

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Keyword: humidity, condensation, reliability, environment

Effect of Humidity and Condensation on Power Electronics Systems

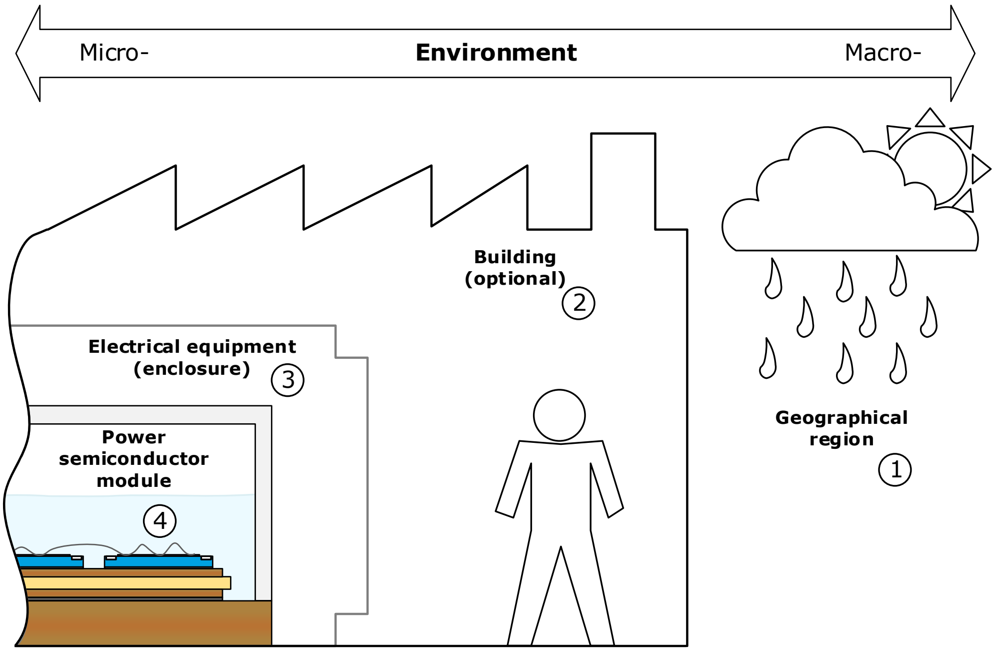
1. General

This application note describes the effect of humidity and condensation on power electronic systems. Design hints are provided to mitigate these effects for more reliable operation.

1.1 Definitions of environments

When discussing the "environment" around an electronics system, one must differentiate between the outdoor macro-environment and the micro-environments near or within the power semiconductor module (Figure 1).

Figure 1: Four different environments within an application

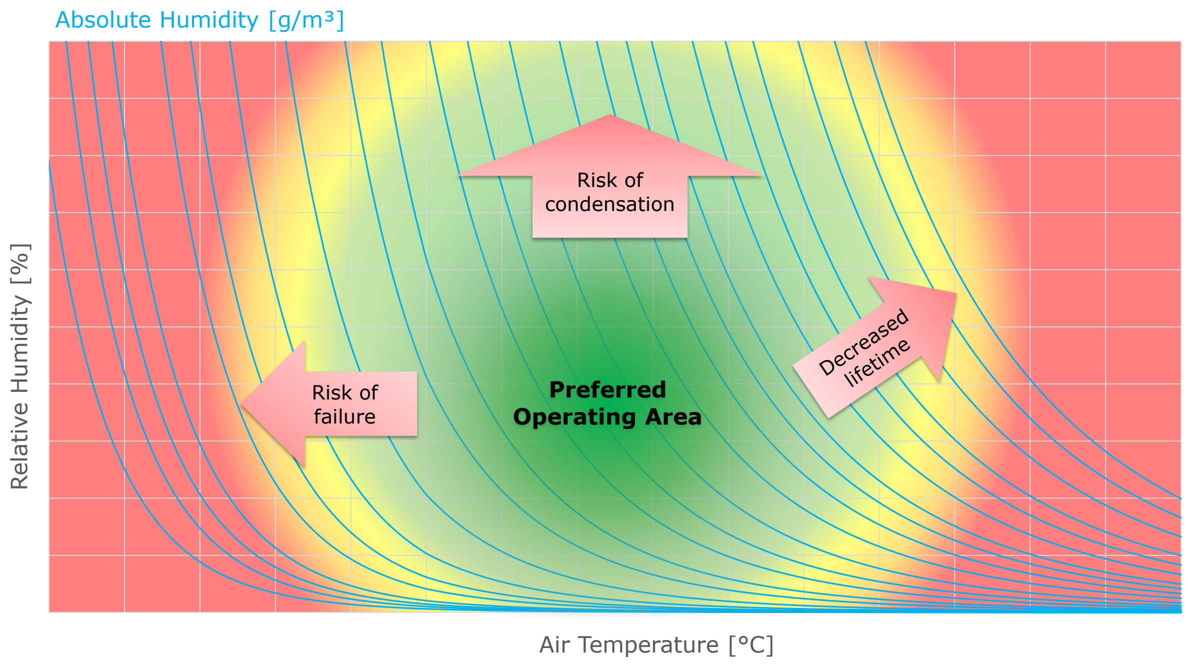


The outdoor macro-environment (Figure 1, ①) is generally well understood, with regular weather reports available, as well as standards defining the characteristics (temperature, humidity, pressure, etc.). Conversely, the micro-environments in (Figure 1, ④) and around (Figure 1, ③) a power semiconductor module are less well defined, though they are determined by the outdoor macro-environment and operation of the power electronics system (power level, cooling, etc.).

The IEC 60721-3-3 standard [3] defines the allowable macro-environmental conditions where electrical equipment will be installed (i.e. Figure 1, ①, ②). While this standard cannot be applied directly to the semiconductor modules (a component), it does give a clear definition of the outside environment that must be protected against (by means of an enclosure, etc.). Furthermore, the IEC "climatograms" (differing from the English word used in meteorology) provide an effective means of understanding the relationships between temperature and humidity, no matter in which environment they occur.

Figure 2 shows a generic example of such a climatogram where the air temperature and relative humidity are given on the major axes and the absolute humidity is plotted as a series of curves. Using three variables a preferred area of operation for power electronics systems can be defined, outside which damage or reduced lifetime could occur. The goal of the designer is to understand how these variables affect one another and keep the operating point of the system within the preferred operating area through system design and operation.

Figure 2: Preferred macro-environment for power electronics



1.2 Humidity

It is generally known that water in its most common form causes problems with electrical circuits due to its electrically conductive and corrosive nature. What is less commonly known is the effect that water has on electronics when in its gaseous state (water vapour). This vapour is diffused into the surrounding air and behaves according to the temperature and pressure in a given volume. The presence of water vapour in air is referred to as humidity and is defined in different ways:

> **Absolute humidity (AH):** The density of water vapour in air, typically expressed as grams/cubic meter [g/m³].
>
> **Relative humidity (RH):** The ratio of the partial pressure of the water vapour to the saturation vapour pressure, typically expressed as a percentage [%].

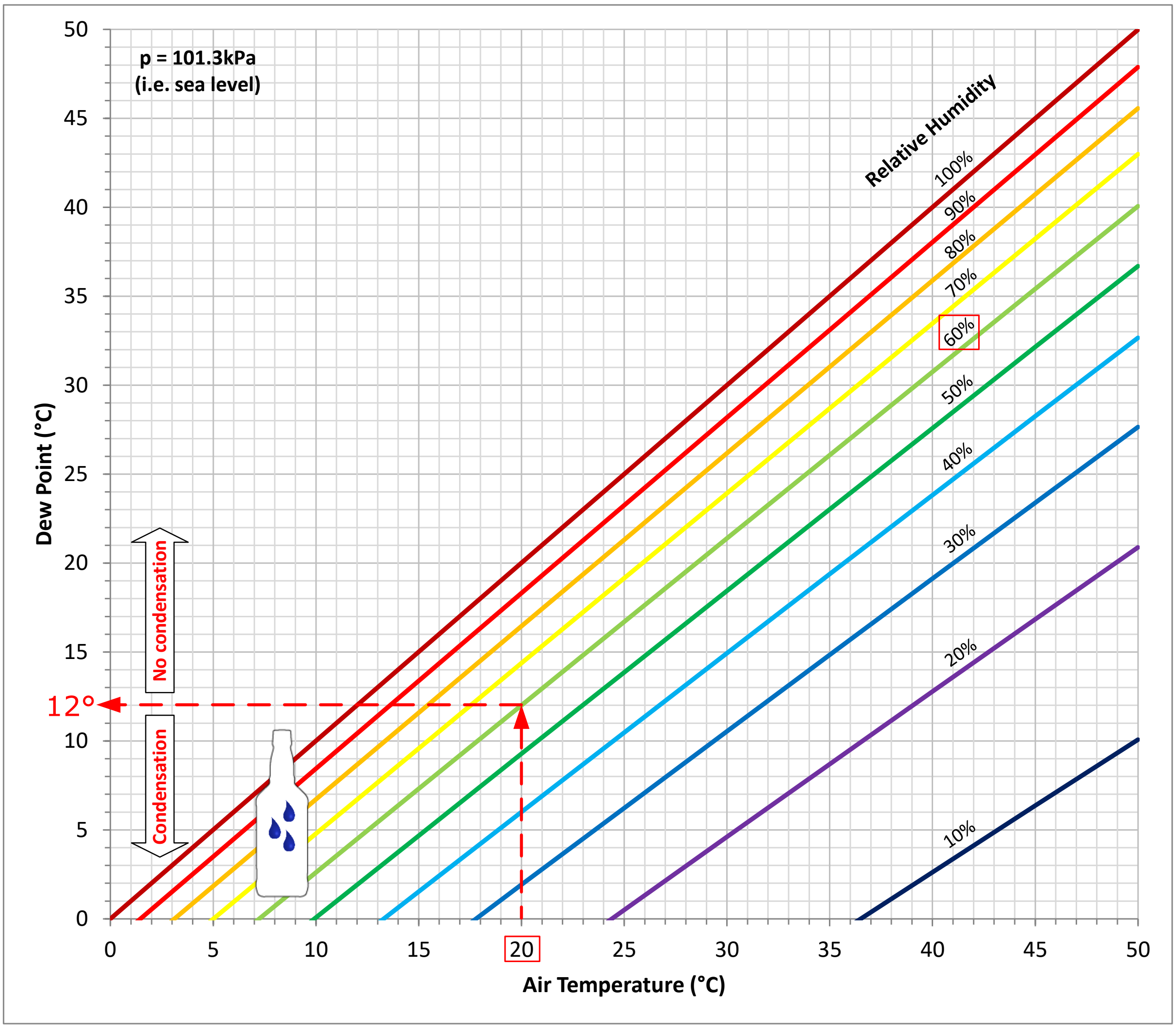
Absolute and relative humidity are interrelated and are functions of temperature and pressure. Most environment and product specifications use relative humidity as this can be easily measured using sensors. However, as will be shown the relative humidity for a given amount of humid air can change even if the number of water molecules remains constant.

1.3 Condensation

When water vapour present in air changes state from a gas into a liquid, it forms condensation on surfaces (or frost in low temperatures). The temperature at which condensation occurs is called the dew point and varies with the relative humidity.

Figure 3 shows the relationship between relative humidity, air temperature, and dew point based on a Magnus equation approximation. For a given pressure and humidity, if the temperature of a volume of air (or object) drops below the dew point, condensation will occur in that area. More specifically, the chart shows the temperature (dew point) at which the relative humidity of a certain volume of air will become 100% based on the overall conditions.

Figure 3: Determining dew point using the Magnus equation



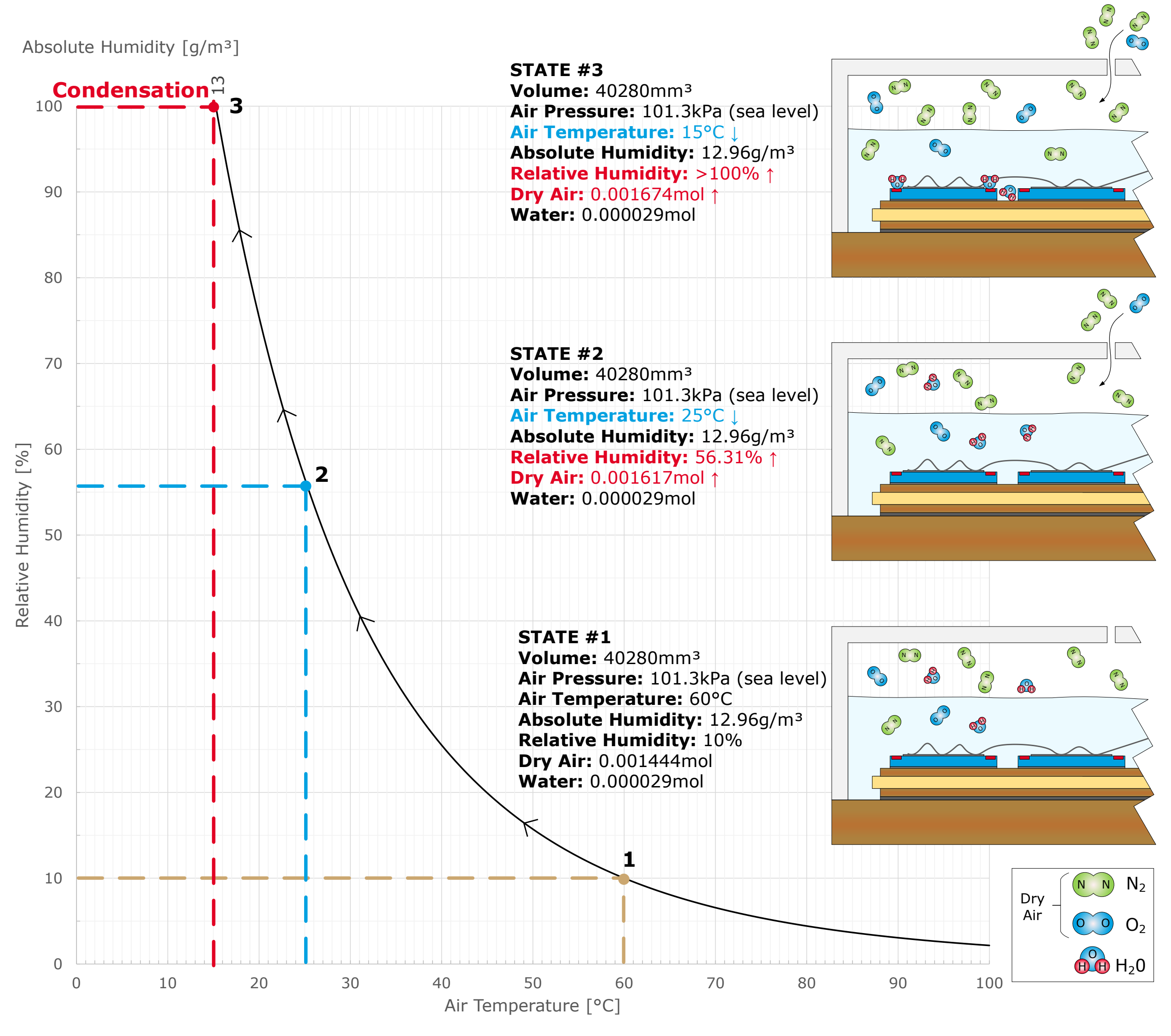
As a commonly used example, consider a room with a 20°C air temperature and a measured relative humidity of 60%. A chilled bottle of liquid (for example, 5°C) taken from a refrigerator and brought into the room will have water droplets condense on its sides. The chilled bottle has cooled the air in its immediate vicinity to below the dew point given on the chart (12°C). The air around the bottle has reached a relative humidity of 100%. In fact, any parcel of air in this environment that is cooled below 12°C will cause the moisture contained within to condense into liquid.

This effect can also occur in the micro-environment (Figure 1, ④) inside a power semiconductor module. The IEC climatogram provides an alternate method of calculating [4][8] when this condensation will occur and illustrates the variability of relative humidity even when the amount of water vapour remains the same (Figure 4). Using a hypothetical power semiconductor module, the following assumptions are made:

1. The volume of the module (and enclosed parcel of air) is fixed ($V_{State1} = V_{State2} = V_{State3}$)
2. The module is permeable (n_{total} is variable)
3. Pressure is dominated by the outside environment ($p_{State1} = p_{State2} = p_{State3}$)
4. The absolute humidity is fixed ($AH_{State1} = AH_{State2} = AH_{State3}$; n_{water} is constant because volume is constant)

In this scenario, when the temperature drops, the partial pressure of the water vapour reduces slightly according to the ideal gas law ($p \cdot V = n \cdot R \cdot T$). However, the saturation vapour pressure drops dramatically and since relative humidity is a ratio of these two values, the relative humidity increases.

Figure 4: Variability of relative humidity in a power semiconductor module



STATE #3
Volume: 40280mm³
Air Pressure: 101.3kPa (sea level)
Air Temperature: 15°C ↓
Absolute Humidity: 12.96g/m³
Relative Humidity: >100% ↑
Dry Air: 0.001674mol ↑
Water: 0.000029mol

STATE #2
Volume: 40280mm³
Air Pressure: 101.3kPa (sea level)
Air Temperature: 25°C ↓
Absolute Humidity: 12.96g/m³
Relative Humidity: 56.31% ↑
Dry Air: 0.001617mol ↑
Water: 0.000029mol

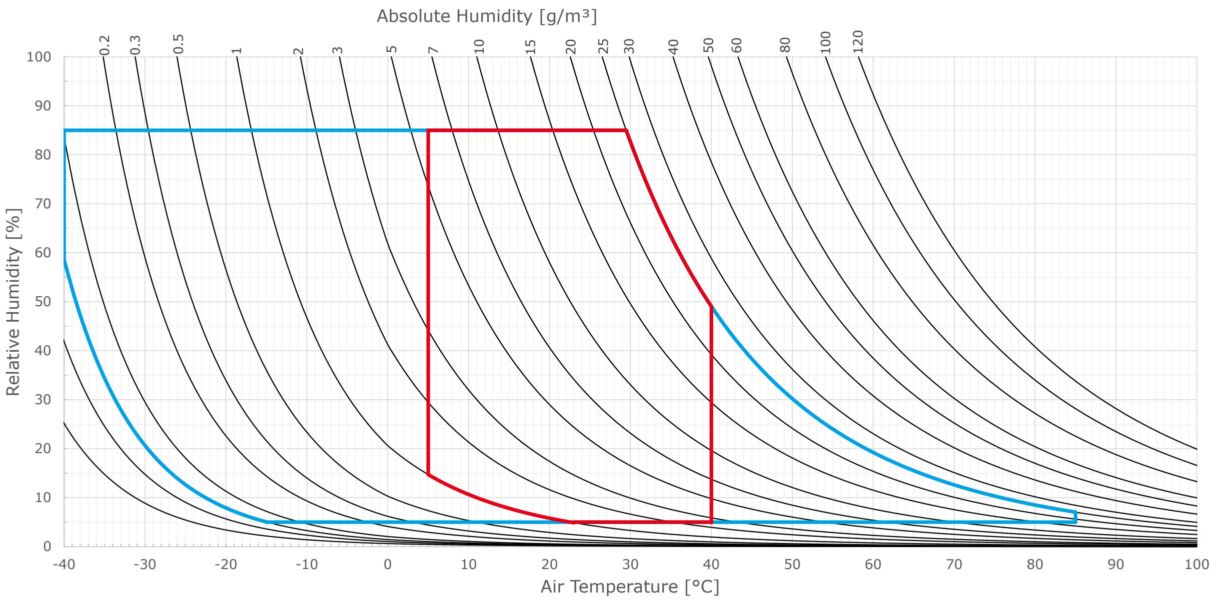
STATE #1
Volume: 40280mm³
Air Pressure: 101.3kPa (sea level)
Air Temperature: 60°C
Absolute Humidity: 12.96g/m³
Relative Humidity: 10%
Dry Air: 0.001444mol
Water: 0.000029mol

1.4 Standards

Presently there is no widely accepted standard that clearly defines the allowable micro-environment around a power semiconductor module. Power module manufacturers test a power module’s resilience to individual parameters (e.g. relative humidity, temperature) but stop short of firmly defining a complete environmental safe operating area. Instead, the manufacturers of the finished electrical equipment in which the modules are installed rely on standards such as the fore mentioned IEC 60721-3-3 to clearly define the allowable operating macro-environment (Figure 1, ①, ②) and must take steps to ensure that the internal micro-environment within the product is far away from the point of condensation and/or the limits of qualification tests (see 3.1). This application note is intended to provide guidance for achieving this.

Most electrical equipment is designed to operate within an IEC 60721-3-3 climatic class 3K22 (formerly 3K3). In addition to temperature and pressure ranges, the 3K22 class gives an allowable range of relative humidity from 5% to 85%, without allowing condensation to form. Furthermore, the absolute humidity is limited to 25g/m³. While the 3K22 range only defines an allowable temperature range of 5° to 40°C, it is common to allow a larger temperature range (-40°C to 85°C) which results in an extended operating area as shown in blue in Figure 5.

Figure 5: Allowable macro-environments for electrical equipment per IEC 60721-3-3 class 3K22 (red) and with extended temperature range (blue)



2. Measurement

Relative humidity can be measured directly using a hygrometer. Modern electronic industrial types consist of a capacitive or resistive sensor that can be calibrated to accuracy as high as ±2% RH but may be above ±10% for un-calibrated or cheaper commercial types so caution must be exercised when interpreting results. Portable data logging types are typically coupled with a temperature sensor and advertised as “temperature/humidity data loggers” or “thermo-hygrometers”.

As the internal humidity of an industrial cabinet is usually influenced by outside weather, it is recommended that both the interior and exterior relative humidity are measured over a period of days or weeks to understand how weather and working conditions play a role.

3. Effect on Power Electronics

3.1 Humidity

Most industrial power semiconductor modules consist of a plastic housing containing chips that have been encapsulated in a cured silicone-based gel ("soft mould", "sil-gel") that provides electrical insulation between conductors. However, the module is not hermetically sealed (gas tight) so atmospheric gas can permeate the module through openings at power terminals, etc.

The soft mould also contains diffused air (Figure 6). Therefore, water molecules can also propagate through the soft mould in the same manner that they mix with air, albeit at a slower rate (e.g. 0.04mm/s @ 18°C, 1mm/s @ 100°C) [2]. Once inside the soft mould, the water molecules have the following effects:

1. Reduced blocking voltage: When the heat sink temperature decreases, the diffused air inside the silicone holds less moisture. Water molecules will therefore accumulate on colder surfaces thermally coupled to the heat sink, such as the substrate, terminals and semiconductor surfaces. Furthermore, the water molecules are attracted to the charged semiconductor surfaces due to their dipole characteristic and align themselves in the electric field (Figure 7R). This leads to disruption of electric field lines at the semiconductor edge termination that can lead to reduced blocking voltage.
2. Semiconductor corrosion: The effect of corrosion on semiconductor chip passivation is well-known [7]. With applied voltage and humidity, the chip edge passivation corrodes until breakdown occurs and the semiconductor fails. The semiconductor corrosion is a long-term aging effect that is investigated in power module reliability testing. The basic form of this testing is known as "High Humidity High Temperature Reverse Bias" (H^3TRB) testing. The proliferation of power converters in humid climates, coupled with decreasing area in each new chip generation, has led to the use of higher voltages (e.g. 80% of rated blocking voltage) in this testing. The higher voltage test is known as "High Voltage High Humidity High Temperature Reverse Bias" (HV-H^3TRB) testing.

Unfortunately, the resulting failures from these effects are usually catastrophic and it can be very difficult to identify conclusively that humidity as the root cause by examining only the destroyed module. The operating conditions of the system at the time of failure should be observed for possible indicators of humidity-induced failures, such as:

- Failure at no or low load conditions.
- Failure of non-switching circuit with voltage applied (e.g. brake chopper, battery charger in UPS unit, booster in solar)
- Failures occurring in the morning or evening.
- Failures occurring during commissioning or during start-up after long periods of downtime.

Figure 6: Water molecules diffuse into the silicone gel

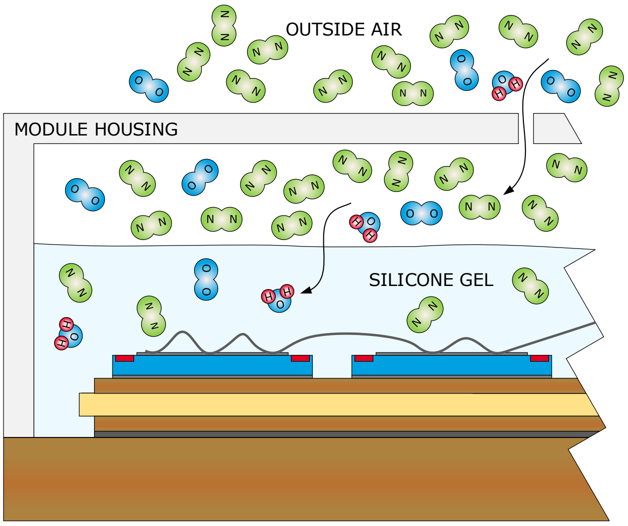
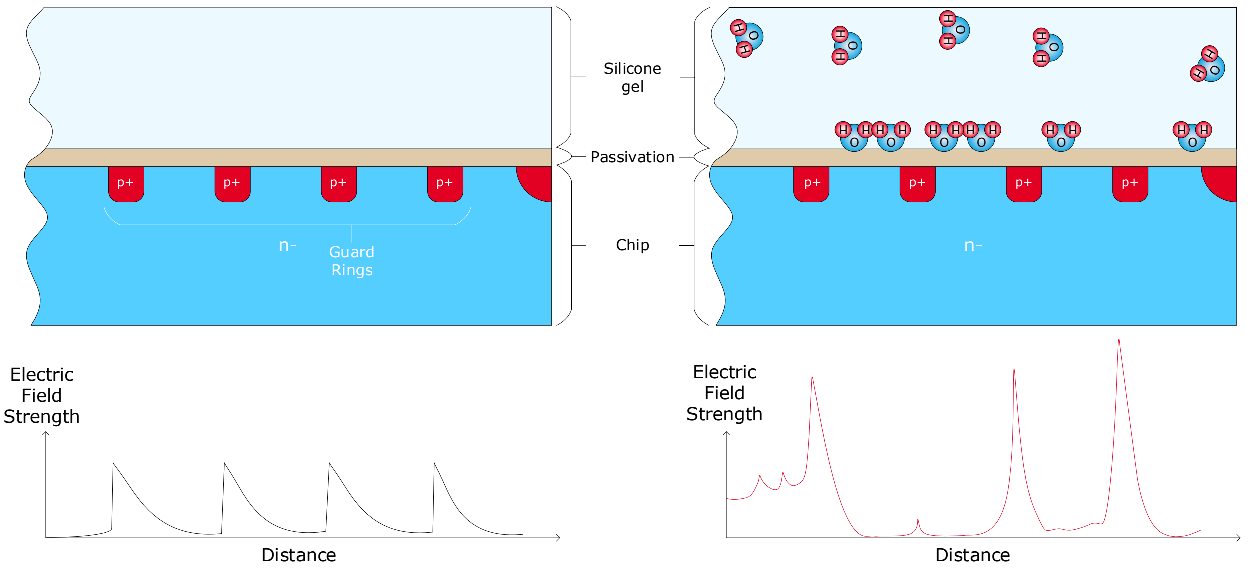


Figure 7: Disruption of voltage gradient at edge termination

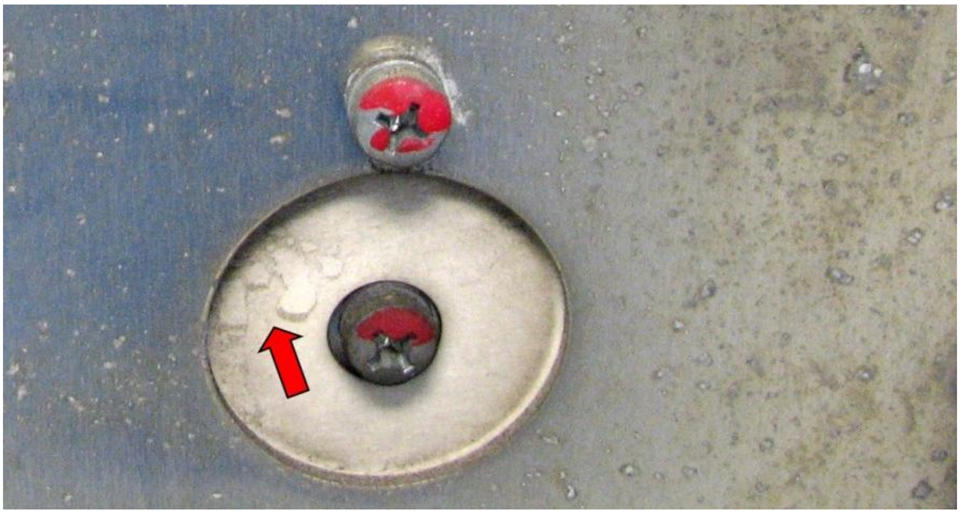


3.2 Condensation

Once water vapour has condensed into a liquid, the effects on electronics are much more obvious. Droplets of water forming on a heat sink may be an indication that condensation is occurring inside the power module. If possible, this condensation should be checked for during operation, as the water may evaporate when the unit is not operating and no evidence will be visible.

In the case of live conductors, such as in laminated DC link bus plates, liquid can compromise the voltage withstand of the insulation material. Evidence of past condensation can possibly be seen in the form of water marks, particularly on dirty surfaces (Figure 8).

Figure 8: Evidence of liquid having been present on insulation of a DC link assembly



4. Causes

4.1 Climate

Humidity is a naturally occurring phenomenon and on a macro level will vary with location and weather. It is generally understood that certain locations on earth are more prone to high humidity conditions than others (e.g. desert vs. tropics). However, even in relatively temperate climates, high humidity can occur depending on altitude, proximity to bodies of water, and seasonal effects.

4.2 Transport/storage

Power electronics shipped over long distances or stored for long periods may acquire water vapour within the packaging, potentially leading to catastrophic failure when voltage is applied. For smaller assemblies, a vacuum-sealed aluminium composite bag containing a desiccant (5.7) can mitigate exposure to humidity. Furthermore, commissioning procedures (5.3) can be employed to reduce relative humidity prior to applying power.

4.3 Changes in relative air pressure

The effects of air pressure at a particular location are already factored into the prevailing temperature and humidity in a macro-environment and thus atmospheric pressure can generally be neglected for a given application. However, in enclosures that have been sealed to outside air flow (e.g. IP65), a change in internal air pressure (typically due to a change in temperature) can result in high relative humidity within the enclosure. It is then a matter of:

1. Whether or not the water vapour inside the enclosure has been minimized or contained (see 5.7).
2. Whether elements within the enclosure drop in temperature below the dew point and cause condensation.

For sealed enclosures this air pressure differential may be reduced though the use of vents (see 5.6).

4.4 Changes in relative air temperature

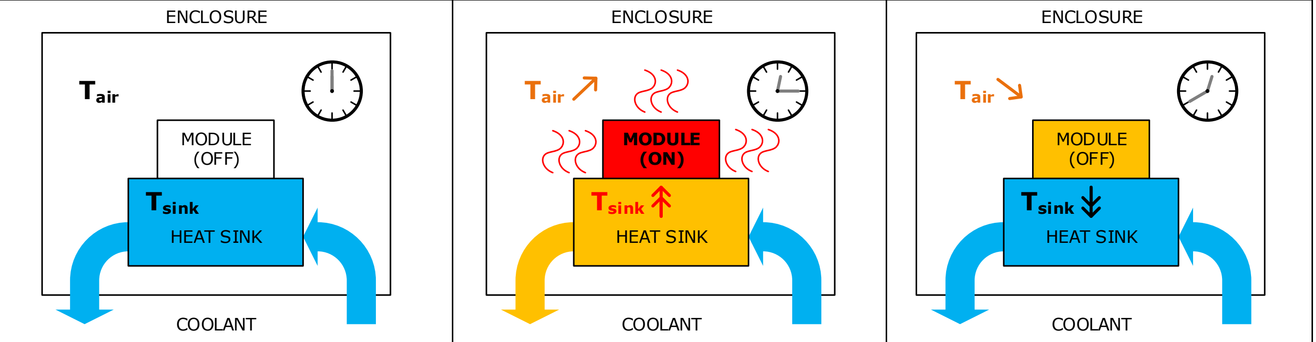
4.4.1 Operating point

One of the main causes for temperature disparities within a unit is the operation of the system itself. Electrical operation of the system causes the temperature of components and the internal cabinet air temperature to rise. A sudden change in operation can cause the heat sink to cool much more rapidly than the air temperature of the enclosure, possibly creating a condition where the heat sink temperature falls below the dew point. Therefore, it is critical to be aware of any changes from operation at full power to another mode, such as:

1. Light or no load.
2. Standby mode.
3. Unexpected interruption of operation (due to faults).

An explanation of how this can occur is given in Figure 9. Note that this risk is also present when the air temperature drops during the transition between day and night. As the inlet air temperature (fed from outside ambient air) on an air-cooled heat sink drops in the evening the heat sink may be cooled to below the dew point (calculated using Figure 3).

Figure 9: Possible temperature disparity due to system operation



1. Unit inoperative/standby. Coolant is applied to the unit at a temperature at or above the air temperature inside the cabinet.

$T_{air} < T_{sink}$

2. Unit operating. The heat sink heats up at a faster rate than the air temperature in the cabinet, but the air temperature eventually rises as well (due to module, heat sink, capacitors, inductors, etc.).

$T_{air} \approx T_{sink}$

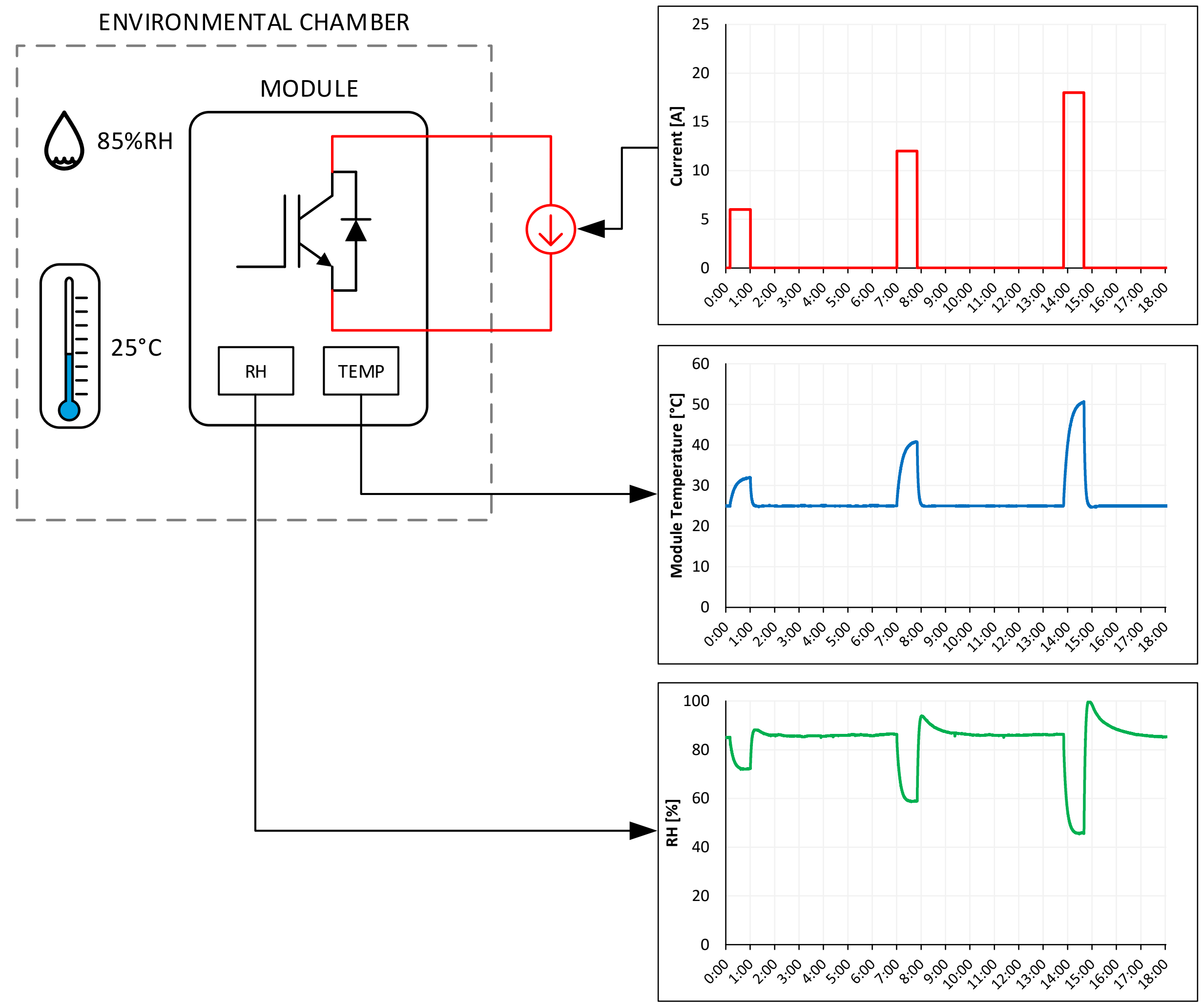
3. Unit shutdown/low load. Due to high flow of coolant (localized at the heat sink), the temperature of the heat sink drops faster than the air temperature. There is a risk of condensation on the heat sink.

$T_{air} > T_{sink}$

4.4.2 Pulsed operation (module)

Semikron Danfoss has performed testing with specially prepared modules where a relative humidity sensor is mounted on the power substrate near the chips (beneath the soft mould). The module (mounted to a forced-air-cooled heat sink) was placed in a chamber (Figure 10) with a fixed air temperature (25°C) and fixed relative humidity (85%). A current pulse of fixed duration was applied to the diode nearest the humidity sensor, followed by a cooling period to allow the module to return to its initial condition (temperature and humidity). Multiple pulses with varying magnitudes were used to investigate the effects of different temperature swings.

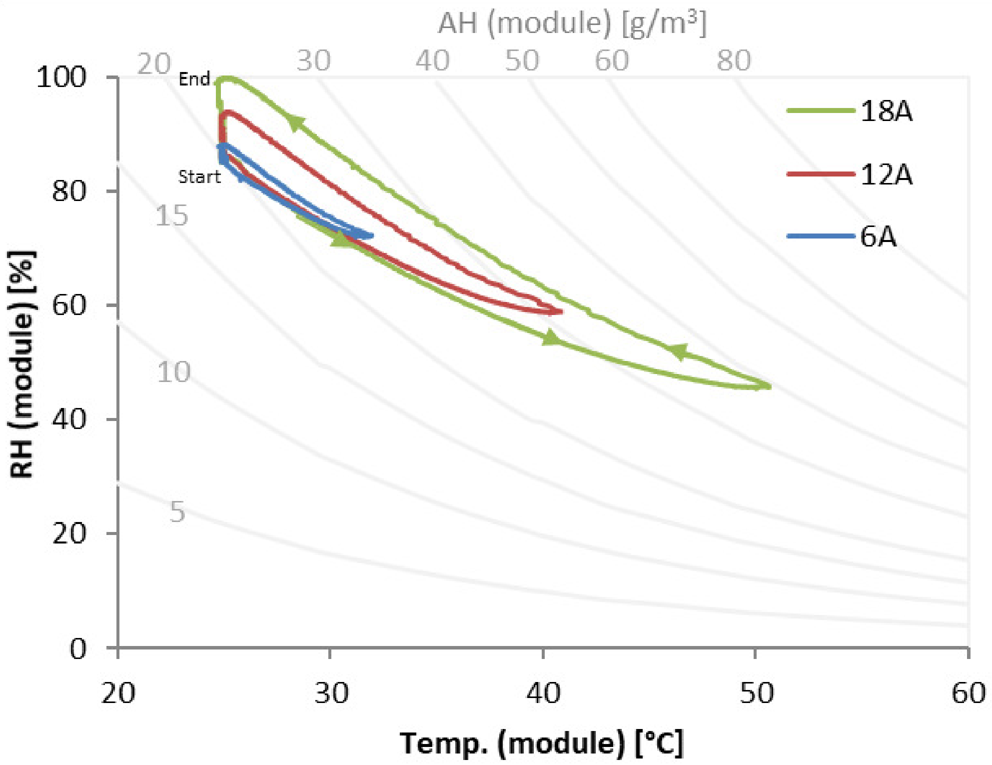
Figure 10: Pulsed operation under high humidity



The results of this testing are shown in the following three figures.

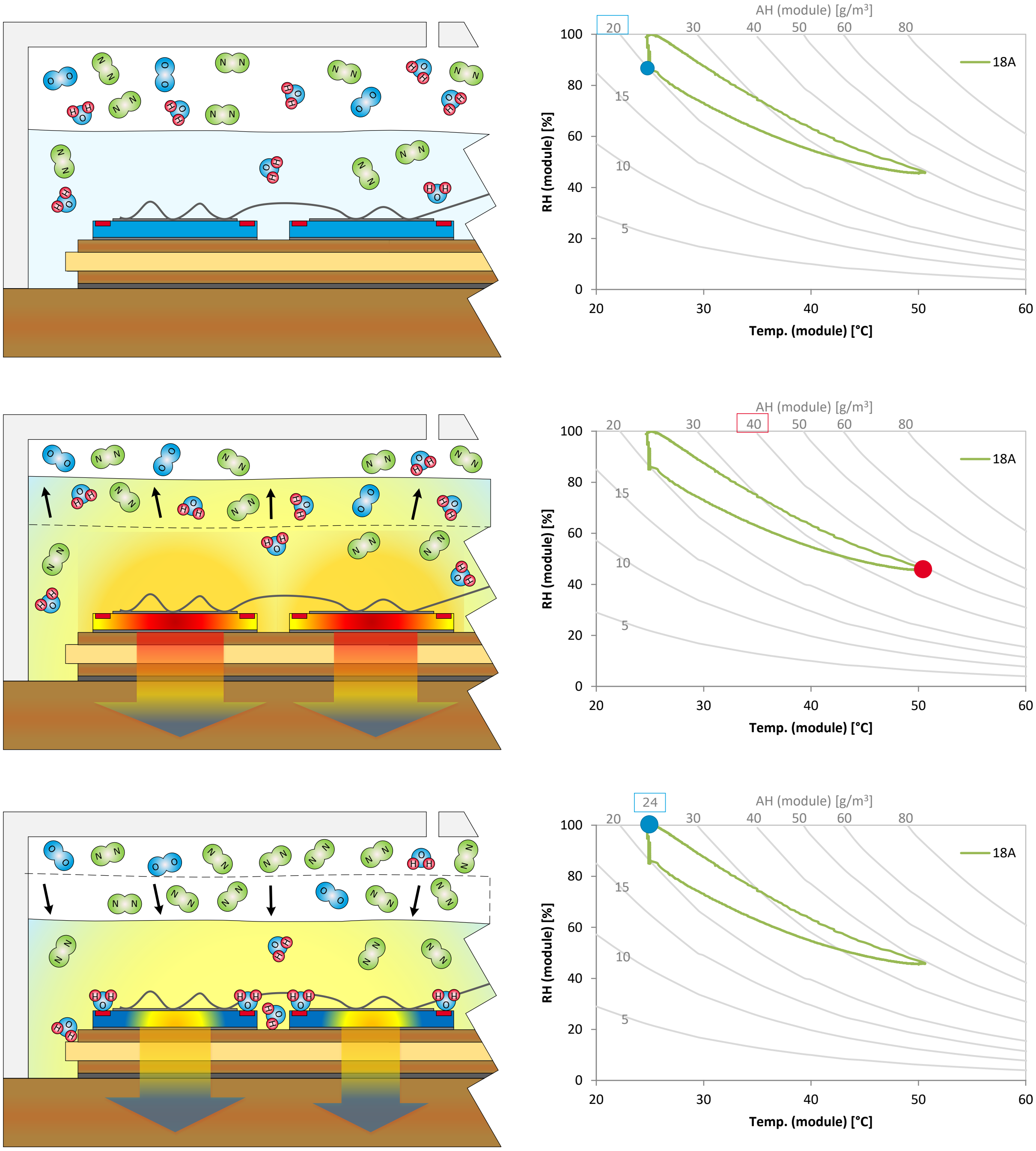
In Figure 11, the relative humidity drops when the device is heated by the applied power pulse. As the device cools, the relative humidity rises and overshoots the initial value. Furthermore, the amount of overshoot in the RH is dependent on the change in temperature. If the initial relative humidity is high (e.g. RH = 85%), it is possible that this overshoot leads to condensation (RH = 100%) within the module.

Figure 11: Humidity-temperature response under three different current pulses (25°C)



Depending on the load current, the soft mould heats up and expands (Figure 12), absorbing more water vapour. The warmer the soft mould, the greater the expansion and water vapour absorption. This effect can also be seen in Figure 11, where the absolute humidity within the soft mould is greater at a load current of 18A (40g/m³) than at 12A (30g/m³) or 6A (25g/m³).

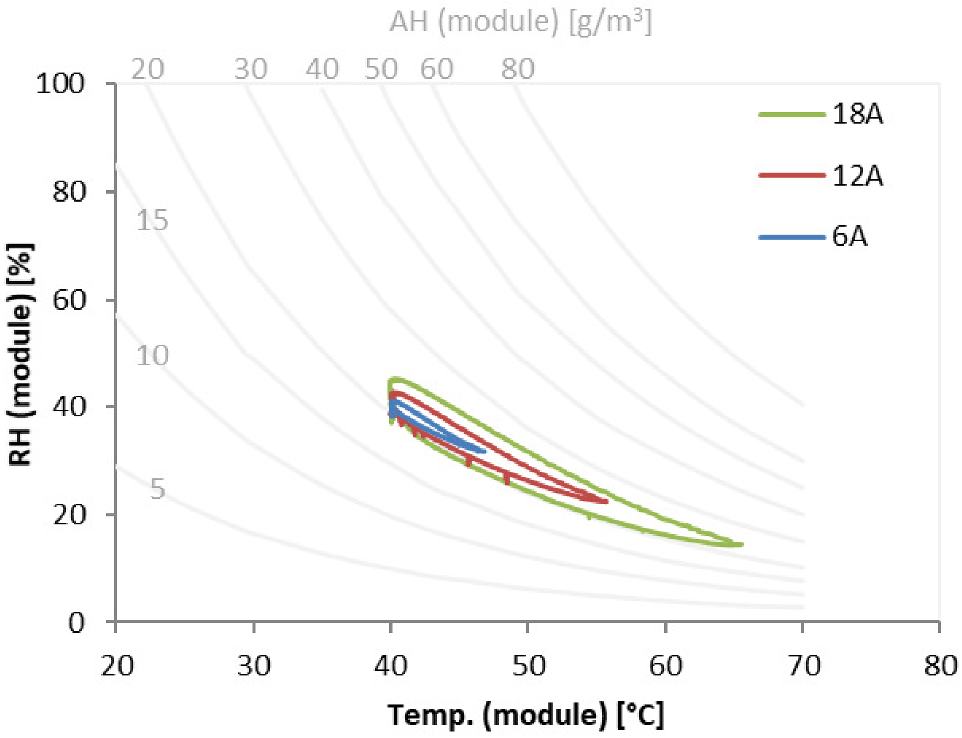
Figure 12: Retention of moisture after heating



In power modules, the path of heat flow is designed to be most efficient from chip down to the heat sink. This path is characterized by a thermal time constant. If the chip is cooled to such an extent that the thermal time constant is much smaller than the soft mould diffusion constant (how quickly the soft mould can release the moisture to the environment), there is a risk of the chip falling below the dew point (similar to the chilled bottle example given in 1.3). That is to say, the chip is cooled quicker than the surrounding soft mould. Eventually, the excess moisture in the soft mould is released to the environment until an equilibrium between internal moisture/temperature in the module and external moisture/temperature in the climate chamber is established.

Figure 13 has the same starting absolute humidity as Figure 11 but the starting temperature is 40°C with 40% relative humidity. The absolute humidity is the same at the final temperature of each load current. Nevertheless, there is still an overshoot in humidity that correlates with the load current. The overshoot is smaller compared to Figure 11. In conclusion, prior to the start of operation after transportation/power down, a heat up of the power module (by means of heating up the heat sink) is advantageous. It leads to lower relative and absolute humidity in operation and can extend the lifetime.

Figure 13: Humidity-temperature response under three different current pulses (40°C)



4.4.3 Temperature differentials within a cabinet

As a result of operating point (4.4.1) or cabinet design (6), condensation may occur on certain areas (cold spots) within the cabinet. Experience has shown the following areas have the highest risk:

1. Fresh air inlet ports.
2. Coolant inlet manifolds and piping.
3. Outer (metallic) walls of the cabinet.
4. Heat sinks and any components to which they are thermally coupled.
5. Areas with low air flow relative to other portions of the cabinet.
6. Large (dense) metallic components with a long thermal time constant.

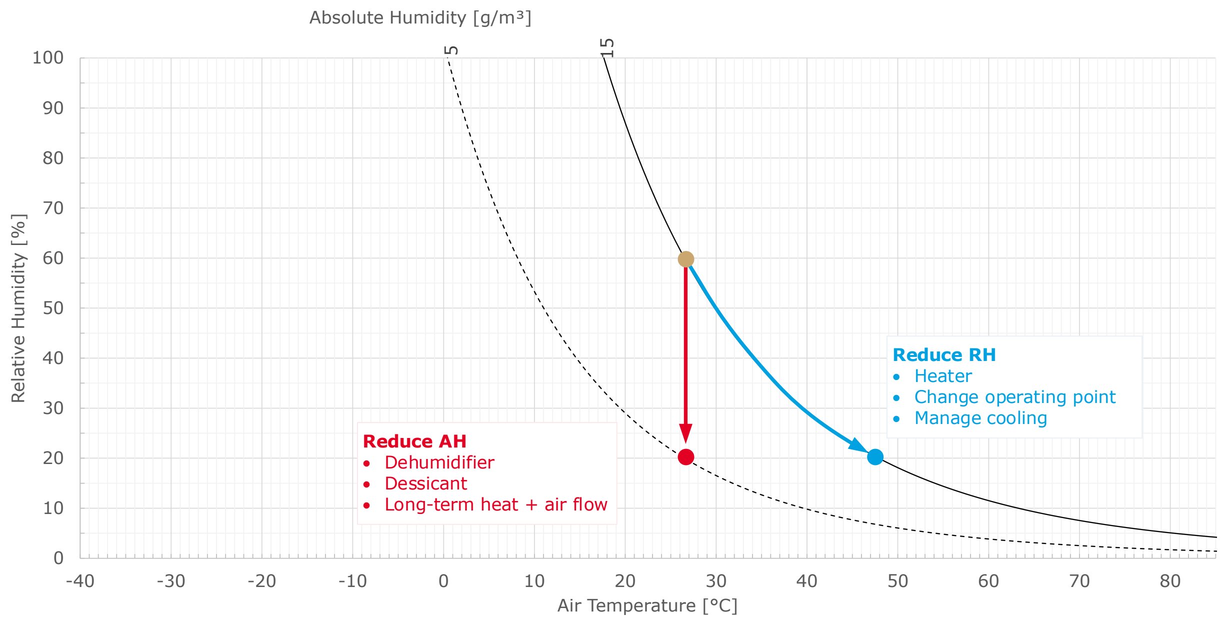
Condensation on cabinet ceilings and walls may drop onto the power module, electronics or bus bars, causing short circuits.

5. Mitigation Techniques

Mitigating humidity and/or condensation within an enclosure can be roughly divided into two approaches (Figure 14):

1. Reduction of absolute humidity: Removal of water vapour (drying) through dehumidifiers, desiccants, or a combination of long-term heat plus air flow.
2. Reduction of relative humidity: Increase of air temperature through heating (dedicated heater or system operating point)
   a. Control of individual component temperature (e.g. heat sinks) to avoid falling below the dew point.

Figure 14: Approaches to mitigating humidity



While it is clearly best to address humidity concerns in the cabinet design process (see 6), some of the following mitigation techniques can be implemented after installation. Coolant (air or liquid) management versus load conditions is a relatively inexpensive method before implementing heaters and dehumidifiers in fielded units.

5.1 Fan control (air-cooled system)

In the case of forced air-cooled systems, the heat sink temperature is regulated by varying the speed of the incoming air. The temperature of the heat sink is monitored and the fan speed is adjusted to prevent air below a minimum temperature from passing over the heat sink fins.

To implement this method the heat sink temperature close to the modules (or better yet, the sensor inside the power module) is monitored and a set point is selected. Below the set point, the fan is completely off (or operating at minimum speed). After the set point is reached, the fan starts to operate and increases speed as the temperature increases. At high loads, the fan operates at full speed. In the event the unit suddenly reduces output at full load (e.g. fault), the fan should switch off immediately to avoid the high humidity behaviour described in 4.4.2. This regulation method is costly but has the advantage that the stress on semiconductors and fan is low. In addition, overall system efficiency may be increased by reducing the power consumed by the fans when the converter load is low.

Some users implement simple on/off fan control (“bang-bang” or hysteretic) using a bi-metal switch on the heat sink. This has the disadvantage that the fan can be rapidly aged by the switching especially in the case of AC fans with motor start capacitors. More importantly, the lack of a precise control loop causes rapid switching between "full on" and "full off" airflow resulting in large temperature swings and additional aging in the semiconductor module. For example, an additional junction temperature swing of just 10°C reduces the module power cycling ability by a factor of 4 to 5. Therefore, this method of control is not recommended.

5.2 Coolant temperature control (liquid-cooled system)

The coolant temperature should be warm enough such that the heat sink surface temperature never drops below the dew point. Ideally, the coolant temperature should be above the internal cabinet ambient temperature. Two methods for coolant temperature control are proposed (Figure 15):

1. Use of a three-way thermostatic control valve.

   At low temperatures (a common set point is between 25°C and 30°C) the coolant will flow through a bypass loop and not through the heat exchanger. Upon reaching the set point, the valve starts to open and tries to keep the temperature constant. At higher power, the coolant flows entirely through the heat exchanger.

2. Use of a coolant heater.

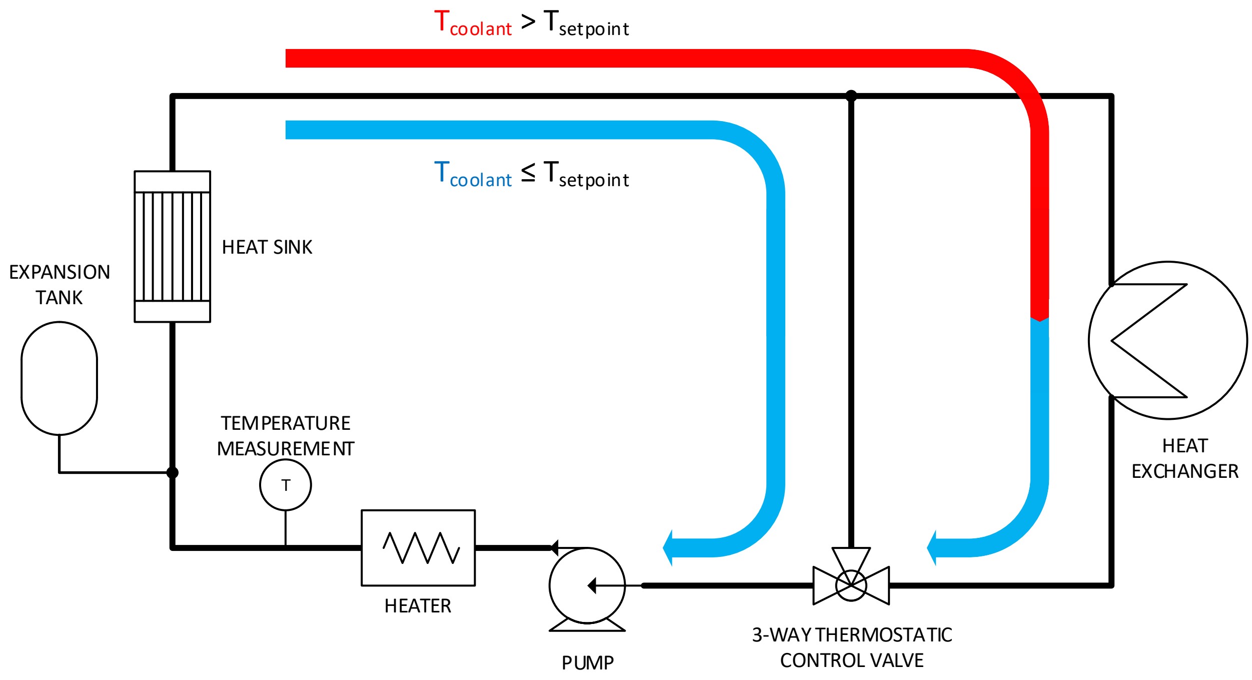
   Heating of the coolant is necessary to:

   a. Reduce localized relative humidity inside or near the power module after commissioning and when restarting after a long period of idle operation before applying voltage.

   b. Prevent condensation on the heat sink when the internal cabinet air temperature is hotter than the heat sink.

When using an efficient heat exchanger and/or operating at full power, the inlet temperature is normally several degrees above the ambient temperature. At high internal cabinet temperatures with low load and high humidity, it may be necessary to increase coolant temperature further to prevent condensation.

Figure 15: Coolant loop with bypass and heater

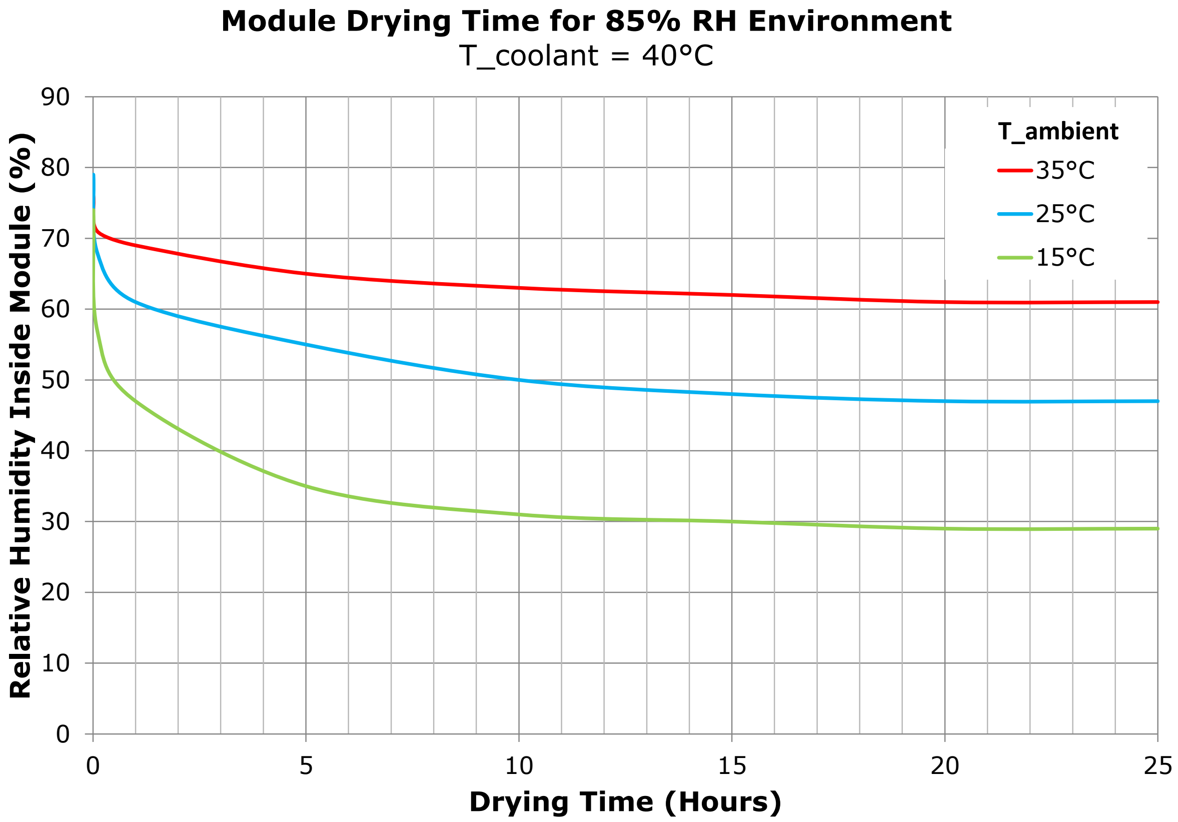


5.3 Pre-heating procedures prior to start-up

Experiments with power modules in an environment with 85% relative humidity have shown that using a coolant temperature at least 5°C hotter than the ambient air temperature will reduce the relative humidity inside the module.

Figure 16 describes the results of such a test in which the humidity beneath the silicone gel inside a module was measured as warm coolant (40°C) was applied in a high humidity environment with different ambient temperatures.

Figure 16: Results of experiment involving heated coolant to reduce humidity



In this particular experiment, the steady state value of relative humidity is reached within 24 hours and the characteristic roughly follows an inverse exponential curve. Based on the above test results and experience with real applications, the following is recommended:

1. For systems where there is risk that the power electronics module has been exposed to high humidity during transportation or storage prior to initial operation (commissioning), coolant with a minimum temperature of 25°C and at least 5°C above the ambient air temperature should be applied for 24 hours prior to the application of high voltage (>50VDC).
2. For commissioned systems (installed outdoors or in high humidity environments) that have been inoperative for more than 8 hours, coolant with a temperature at least 5°C above the ambient air temperature should be applied for 1 hour prior to the application of high voltage (>50VDC).

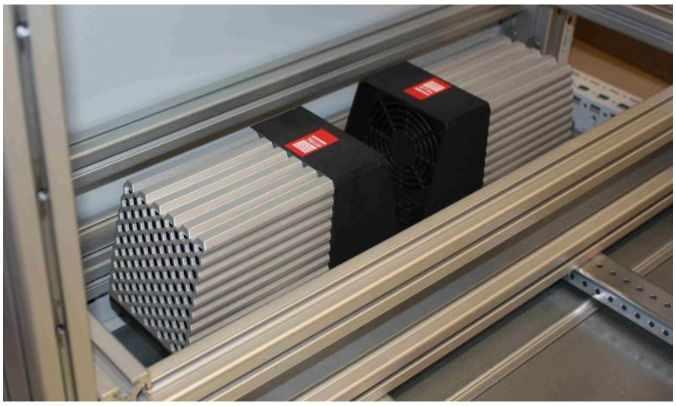
5.4 Cabinet heaters

As described previously, for a fixed absolute humidity, increasing the ambient (dry) air temperature will decrease the relative humidity. Industrial cabinet heaters (Figure 17) are commercially available to facilitate this. Consisting of a resistive heating element, thermostat and occasionally a fan for air circulation these units serve to:

1. Reduce relative humidity inside a cabinet after initial commissioning.
2. Drive humid air out of a cabinet through vents.
    a. Note that the application of heat does not by itself "dry" the air as the water molecules are still present and must be removed from the system through air flow or other means (e.g. desiccants)
3. Prevent condensation from forming on internal cabinet walls/ceiling.
4. Prevent condensation on internal metal parts when the external ambient gets hotter.
5. Pre-heat an electrical cabinet prior to operation (if the minimum operating temperature is not met) and protect the electronics during operation in low ambient temperatures.
6. Maintain active parts at higher-than ambient temperatures during standby.

While simple on/off operation is possible with a temperature set point (e.g. with a thermostat), a heater can also be controlled by a hygrostat to ensure that the air temperature inside the cabinet does not fall below the dew point. Heaters should be placed at the bottom of the cabinet and should have sufficient power to heat the inner ambient to a defined level at a low external ambient temperature.

Figure 17: Two 800W heaters installed in the base of a 2000mm x 800mm x 600mm cabinet



5.5 Dehumidifiers

The most direct method of humidity reduction is to remove the moisture from the air using a dehumidifier. A dehumidifier consists of a cooled coil over which the humid air is forced. Moisture in the air condenses on the coil and is drained or pumped out of the system. Industrial cabinet dehumidifiers are available that differ from their commercial counterparts in the following ways:

1. Compact size to dry a pre-defined volume.
2. Condensate drain hose or pump for directly evacuating moisture outside the cabinet.
3. Internal thermostat/hygrostat for control or ability to interface with cabinet humidity/temperature controller.
4. Lower voltage operation to run off available control power (e.g. 24VDC).
5. More robust construction for continuous operation and higher cycling rates.
6. Mounting provisions (e.g. DIN rail, brackets).

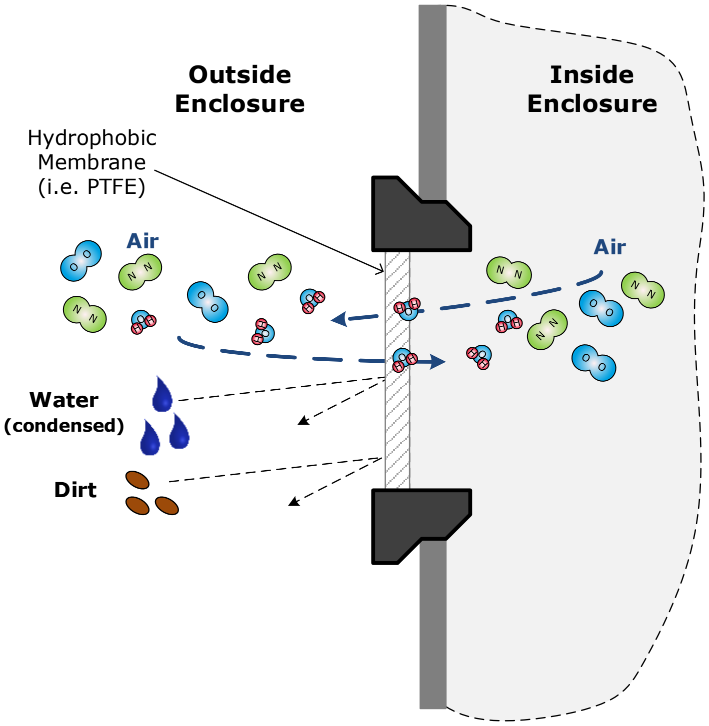
Dehumidifiers are typically placed at the bottom and side of a cabinet and the condensate hose is routed through the wall or floor to drain outside. Consideration should be given to making sure air circulates through the dehumidifier, either through internal cabinet fans or by positioning the internal dehumidifier fans.

Dehumidifiers are viewed as an expensive addition to a system but their cost is a small fraction of the total investment in high power (500kW+) systems placed in humid environments and the cost of a humidity-induced failure (explosion) is much higher.

5.6 Vents

For small, sealed enclosures where it is necessary to equalize pressure, specialized snap-in or screw-in vents are available [5]. These vents incorporate a semi-permeable hydrophobic membrane that allows vapour to pass through while keeping out water droplets and other contamination (Figure 18). It is important to understand that these vents may allow water vapour to pass through so they do not necessarily reduce the absolute humidity. However, they are important in ensuring that a mismatch in pressure does not occur resulting in high relative humidity inside the enclosure.

Figure 18: Vent plug operation



5.7 Desiccants

Desiccants are hygroscopic materials that absorb and store moisture from the air. They normally consist of a silica gel (or other natural material such as clay) packaged in a permeable membrane through which moist air can pass. Because they entrap water vapour, their capacity is limited and they will eventually become saturated. For this reason, desiccants are typically only used during transportation of sealed containers for entrapping residual water vapour. In an open system they will quickly become saturated and lose their effectiveness. Most silica gel desiccants contain some visual indication of the amount of moisture they contain (e.g. blue when dry, pink when moist). Desiccants can be reused by heating them to drive out the entrapped moisture.

5.8 Removal of DC link voltage

As noted in 3.1, applied voltage accelerates long-term corrosion of the semiconductor metallization. Many power electronic systems have long periods of standby operation where a high voltage is present on the DC link but the system is not processing any power. In these applications, discharging the DC link when the system is standby mode could improve lifetime in high-humidity environments where this corrosion mechanism may be present. As this typically requires opening a contactor and a discharge (and pre-charge) process, this technique must be considered in the design process in a system and may be difficult to implement after system design (e.g. additional wear may be incurred in other components from repeated cycling).

6. Example Designs

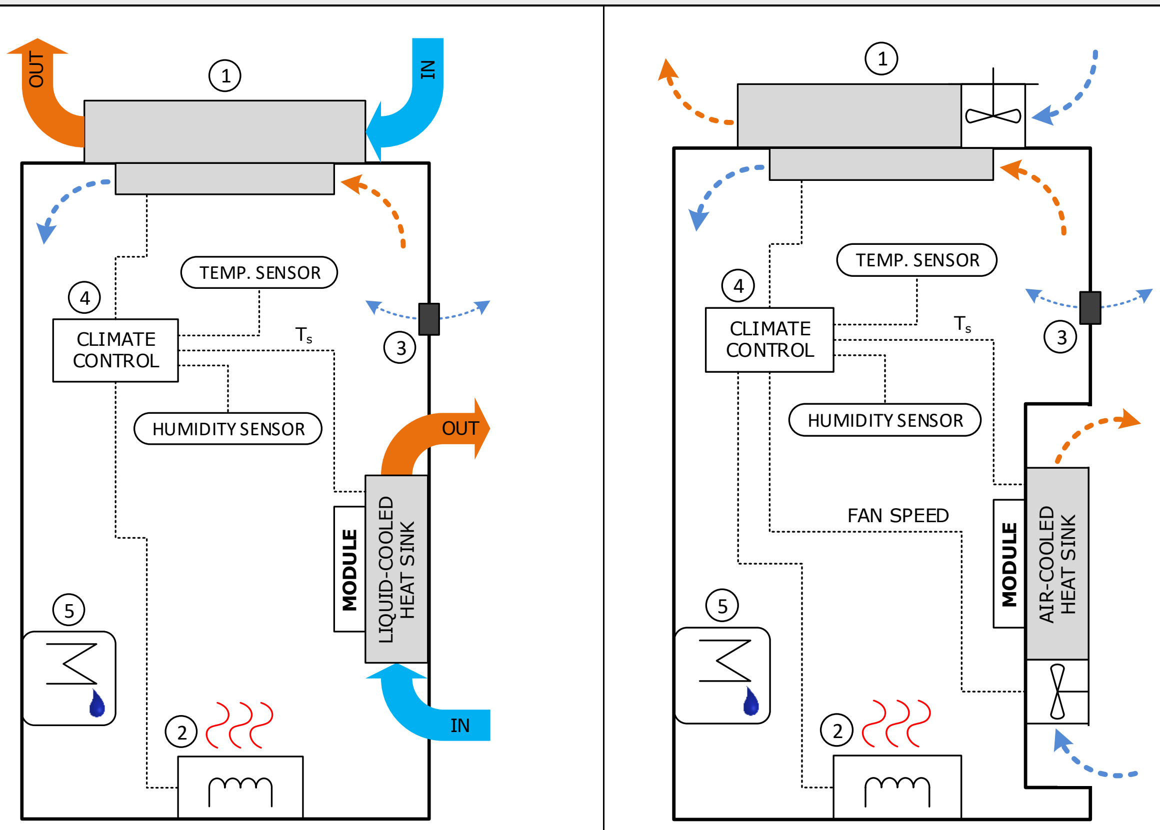
The external macro-environment (and its associated pollution, temperature and humidity levels) is usually the main factor in determining whether an electrical cabinet is required to be sealed.

For the purposes of this discussion, a sealed (closed) cabinet is defined as one having an IEC ingress protection (IP) rating of 65 or higher [6]. This means the cabinet is protected against dust ingress and low power water jets sprayed from any direction. However, this also implies that the air flow between the inside of the cabinet and the outside environment is limited and therefore differentials in temperature and pressure might occur. Conversely, an open cabinet is defined as one in which there is a free exchange of the outside air with the inside of the cabinet.

6.1 The ideal sealed cabinet

Figure 19 shows an ideal sealed cabinet design incorporating all possible humidity-mitigation elements. In practice, not all of these elements may be required.

Figure 19: Suggested elements for an ideal sealed cabinet design



a. Liquid-cooled system

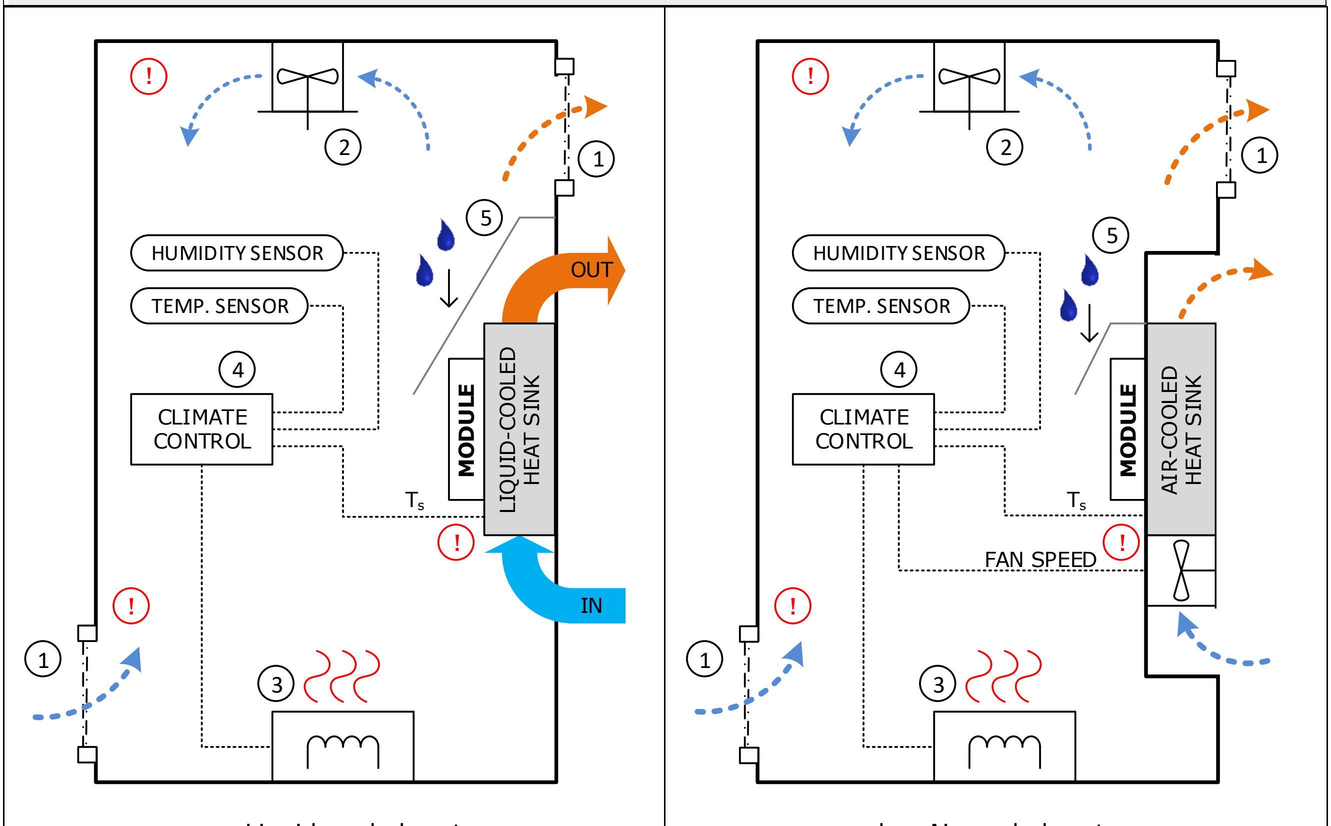
b. Air-cooled system

1. **Air-to-water (or air) heat exchanger:** Cools internal air without exchanging internal and external air. Also provides circulation inside cabinet to prevent formation of hot or cold spots.
2. **Heater:** Keeps relative humidity low and maintains minimum operating temperature.
3. **Vent:** Prevents internal air pressure from increasing above external atmospheric pressure.
4. **Climate control:** Control system (e.g. PLC or portion of system controller) to monitor internal humidity, air/heat sink temperature and adjust heater/fans as necessary.
5. **Dehumidifier:** Condenses moisture present in the internal cabinet air and drains it outside.

6.2 The ideal open cabinet

Figure 20 shows an ideal open cabinet design incorporating all possible humidity-mitigation elements. In practice, not all of these elements may be required.

Figure 20: Suggested elements for an ideal open cabinet design



a. Liquid-cooled system

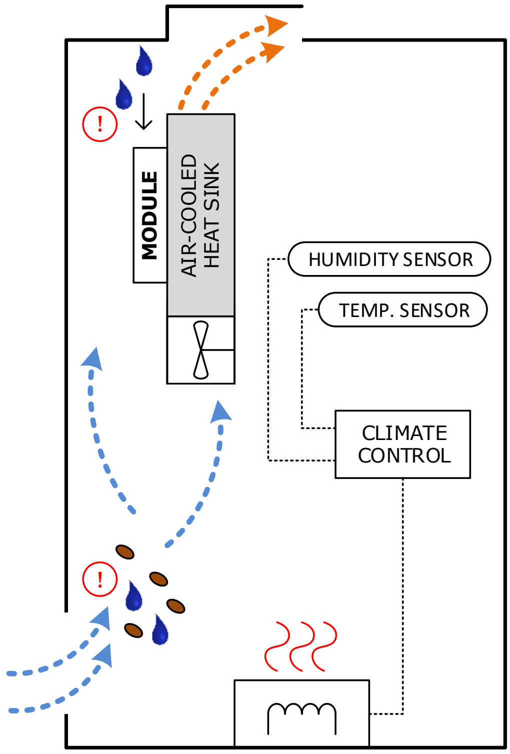
b. Air-cooled system

1. **Air inlet and outlet:** Positioned to provide cross flow. May incorporate a fan (with filter) at the inlet or outlet.
2. **Circulating fan:** Provides air movement to minimize formation of hot or cold spots.
3. **Heater:** Keeps relative humidity low and maintains minimum operating temperature. Care must be taken to ensure that all components are heated to the minimum temperature prior to bringing in outside cooling air since some components (e.g. heat sinks) have a large thermal mass and require more time to reach equilibrium.
4. **Climate control:** Control system (e.g. PLC or portion of system controller) to monitor internal humidity, air/heat sink temperature and adjust heater/fans as necessary.
5. **Critical areas (!):** Areas such as exterior cabinet walls, air inlets and heat sinks may be at an increased risk for condensation, particularly when the air inside the cabinet becomes much warmer than the outside air. In severe cases, it may be necessary to provide a drip shield to prevent condensation from dripping on electrified parts. In the case of liquid-cooled systems, the (cool) inlet should already be below the (warm) outlet to avoid trapping air in heat sinks. This has the added advantage of ensuring that the condensation-prone inlet does not drip directly onto the power module.

It should be noted that in both recommended air-cooled cabinet designs the air channel for the heat sink is separated from the rest of the cabinet (Figure 19b and Figure 20b). All too often, the configuration shown in Figure 21 is used, where the entire air-cooled assembly is placed inside the cabinet and all components are subjected to the same air as is used to cool the heat sink. This has the following drawbacks:

1. The large volume of air brings in particulate pollution (dust, dirt) that settles on circuit boards and electrical connections, reducing clearance and creepage distances for voltage withstand. Adding inlet filters can help, but these reduce the effective flow rate of the air and become dirty quickly (and are often not serviced regularly or removed entirely by maintenance staff).
2. The possible condensation on heat sinks and air inlets/outlets is now at risk of directly interacting with water-sensitive components (circuit boards, conductors) since they are now in the same compartment as the heat sink.
3. Compared with Figure 20b, the larger volume of air brings in a proportionally larger volume of moisture inside the cabinet, amplifying the risks of condensation at inlets/outlets. Furthermore, the higher flow rate results in higher temperature differentials, possibly pushing certain areas below the dew point.
4. Climate control measures such as heaters are less effective as the volume of air they are trying to regulate is much more dynamic due to the high air flow rate.

Figure 21: Not recommended cooling configuration



7. Summary

Power electronics are at risk from water in both the liquid (condensation) and gaseous (humidity) states. A failure can occur either in the short-term (voltage flashover) or long-term (corrosion). Mitigation starts with understanding the relationships between absolute humidity, relative humidity, and temperature around the power electronics (macro-environment) and inferring what might be the environmental conditions inside a power semiconductor module (micro-environment). Steps can then be taken either through system design (e.g. air flow, temperature control) or operating point (e.g. coolant control) to reduce the conditions where high relative humidity or condensation may occur near or inside a power semiconductor module.

Symbols and Terms

Letter Symbol	Term
AH	Absolute humidity
RH	Relative humidity
T	Temperature
p	Pressure
V	Volume
n	Amount of gas (in moles)
R	Universal gas constant

A detailed explanation of the terms and symbols can be found in the "Application Manual Power Semiconductors" [2].

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