# Field-measurement based hygrothermal modelling of the converter-cabinet climate in wind turbines

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## Keywords

«Wind Energy», «Reliability», «Humidity», «Measurements», «Modelling»

## Abstract

Power converters in wind turbines suffer from frequent failures. Root-cause analyses point to environmental influences as important drivers of converter failure. Based on comprehensive field measurements in wind turbines, we derive hygrothermal models describing the dependence of temperature and humidity in the converter cabinet on the ambient climatic conditions and turbine operation. The results show that lumped-parameters models of minimal complexity are suitable for describing the conditions with reasonable accuracy and that publicly available ERA5 reanalysis data may be used to consider the site-specific climatic conditions outside of the wind turbine. In addition, we demonstrate that the hygrothermal model derived for a turbine type can successfully be transferred to identical turbines operating in other countries. The models can therefore serve as a basis for refined requirement specifications as well as for the derivation of application-specific test procedures for power converters and their components.

## Introduction

Power converters in wind turbines (WT) show high failure rates. This causes considerable repair cost and downtime and ranks them among the most frequently failing subsystems of WT [1]–[3]. According to field-data analyses based on a worldwide and heterogeneous wind-turbine fleet reported in [4], the overall converter system failed with an average rate of 0.48 $a^{-1}$ per WT, with a third of the failure events being attributed to the core components of the converter, including the IGBT modules, driver boards, DC-link capacitors and busbars.
While power- and thermal-cycling induced fatigue effects in the power electronics have been found not to contribute significantly to the field failures, seasonal patterns and regional differences in the failure behavior indicate that climatic influences, in particular humidity, play a central role in the emergence of failures [5], [6].

This brings the climatic conditions into the focus that power converters in wind turbines are exposed to. Fraunhofer IWES has collected and analyzed field-measurement data from the converter cabinets of more than 30 wind turbines, including turbines at onshore and offshore sites, with fully or partially rated converters, with power converters located in the tower base, the nacelle or distributed over both places, and including both liquid-cooled and water-cooled converters. Air temperature and humidity inside the power cabinet have been found to be influenced strongly by the climatic conditions around the WT as well as by its operation [7].

The present work seeks to identify WT-type specific hygrothermal models from the abovementioned field-measurement data that are suitable for estimating the dynamic temperature and humidity conditions in the power cabinet based on the ambient conditions around the turbine and the active power fed into the grid. Such models offer the potential to simulate the temperature and humidity timeseries in turbines of the considered types at any possible location in the world based on the ambient environmental conditions at this site. This is valuable not only for deepened field-data based root-cause analysis, which is so far limited to the use of WT-external climatic conditions; it is also a powerful basis for requirement specification as well as for the derivation of application- and even region-specific test profiles for the reliability qualification of WT converter systems and their components.

## Modelling approach

In view of the available field data and information about the WT design, a grey-box modelling approach is chosen: In a first step, based on general knowledge about the turbine design and on the physical basic laws for heat and mass transport, a model structure is defined. In a second step, the parameters of this model are identified from the field data to achieve an optimal agreement between the measured and the simulated climatic conditions in the power-converter cabinet. The model is implemented as a lumped-parameter model (R-C network, see e.g. [8], [9]), making use of electrical analogies for the transport and storage processes of heat and moisture, respectively. The complexity of the model structure is kept as low as necessary to still achieve a sufficiently accurate representation of the climatic conditions in the power converter. As illustrated in Fig. 1, the hygrothermal model consists of a thermal model and a hygric model.

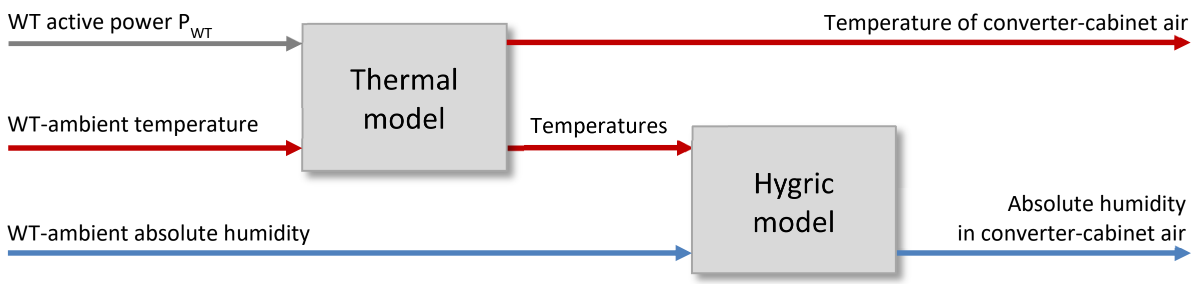


Fig. 1: Hygrothermal model for heat and moisture transport between the ambient air of the wind turbine and the converter-cabinet air

## Data underlying the model development

The hygrothermal models are derived using the following data:

- Temperature and humidity timeseries measured in the WT converter-cabinet air during the measurement campaigns as described in [7] (temporal resolution: 1 min, 15 min or 30 min)
- Timeseries of the active power fed into the grid from the same turbines, typically from the Supervisory Control and Data Acquisition (SCADA) system (temporal resolution: 10 min)
- Site-specific environmental data: ambient temperature and humidity timeseries (a) collected outside of the WT as part of the measurement campaigns, or (b) from the publicly available ERA5 reanalysis data [10], which provide hourly estimates of many atmospheric and oceanographic variables based on global modal data, covering the earth on a grid of approximately 30 km x 30 km. Please refer to [11] for further information on the ERA5 reanalysis data and to [7] for information on how these data have been processed for the present work.

We use different parts of the available timeseries for parameter identification and for model validation, respectively. The model accuracy is assessed by means of the root mean squared error (RMSE) between simulated and measured temperature and humidity timeseries.

## Thermal model

Following the approach presented in [8], the analogy of heat and charge transfer summarized in Table I is used to model the heat transfer between the WT environment and the power cabinet by means of a simple R-C network.

**Table I: Analogy of thermal and electrical quantities (adopted from** [8])

| **Thermal quantity** | **Symbol** | **Unit** | **Electrical quantity** | **Symbol** | **Unit** |
|---|---|---|---|---|---|
| Temperature | T | K | Voltage | U | V |
| Heat flow | $\dot{Q}$ | W | Current | I | A |
| Thermal resistance | R | K/W | Resistance | R | Ω |
| Heat capacitance | C | J/K | Capacitance | C | F |

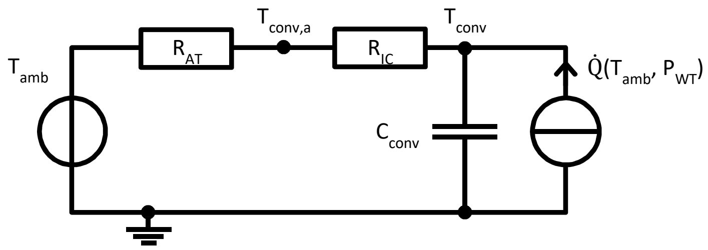


Fig. 2: Thermal R-C network for heat transport between WT-ambient air and converter-cabinet air

Fig. 2 shows the thermal network resulting in case of a wind turbine with the power converter located in the tower base: The WT-ambient temperature $T_{amb}$ corresponds to an ideal voltage source. The thermal resistances of the WT tower and the cabinet enclosure are lumped in the resistor $R_{AT}$, including the convective heat transfer between air volumes and solids as well as conductive heat transfer. (Note that a first model structure also contained a thermal capacitance in this part representing the thermal mass of the tower wall; however, the simplified model structure without this element shown in Fig. 2 provides equally accurate results and is therefore given preference.) $T_{conv,a}$ denotes the air temperature inside the converter cabinet, for which measured timeseries are available. The thermal mass of the converter equipment inside the power cabinet is lumped into the heat capacitance $C_{conv}$.

The overall heat flow released into the converter components equals the losses generated inside the converter $P_{loss}$ reduced by the heat flow withdrawn by means of the cooling system $\dot{Q}_{cool}$. In the R-C network, it is represented by an ideal current source applying the heat flow $\dot{Q}$.

### Operating-point dependent heat release into the converter

The overall heat released into the cabinet-internal converter components varies with the electrical load, i.e. with the operating point of the turbine. Modelling it poses a particular challenge: While the power losses generated inside the converter can be calculated from the converter design and the electrical load condition, the heat flow transferred to the WT-ambient air by means of the cooling system is unknown.

In the present work, we therefore derive the resulting operating-point dependent heat release into the converter directly from the field data. For this purpose, we undertake an intermediate step in which we limit the consideration to time periods with quasi-stationary conditions. These are characterized by variations of $T_{amb}$ and $T_{conv,a}$ by no more than ±0.5 K and variation of the WT active power by up to ±2.5% of the turbine's rated power. In a stationary state, the R-C network reduces to the equivalent circuit shown in Fig. 3.

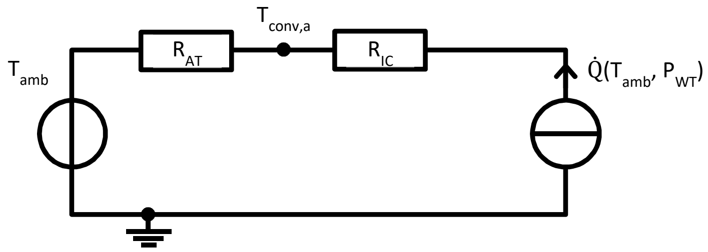


Fig. 3: Thermal R-C network for stationary conditions

In this case, the heat release into the converter is related to the temperature difference between cabinet air and ambient air through:

$$\dot{Q} = P_{loss} - \dot{Q}_{cool} = \frac{T_{conv,a} - T_{amb}}{R_{AT}} \quad (1)$$

Fig. 4 illustrates how the field data from periods with quasi-stationary conditions can be used to derive a regression function that expresses the temperature difference ($T_{conv,a} - T_{amb}$) as a function of the WT active power $P_{WT}$ and the ambient temperature $T_{amb}$.

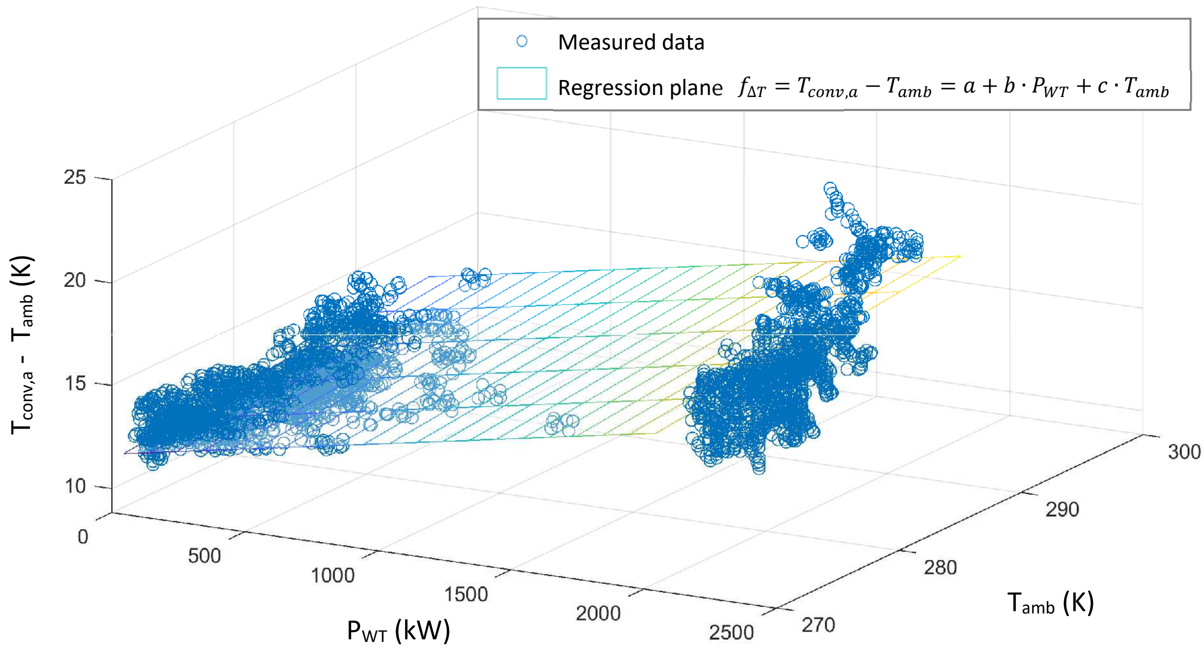


Fig. 4: Derivation of the operating-point dependent heat release into the converter from field data by means of regression, based on periods with quasi-stationary conditions

For the sake of enhanced model quality, two different regression functions $f_{\Delta T}$ are determined for every turbine: one for periods in which the turbine is in operation ($P_{WT} > 0$ kW) and one for standstill periods in which the turbine does not feed active power to the grid ($P_{WT} \leq 0$ kW) due to a lack of wind, faults, or maintenance.

### Equations representing the thermal model

The resulting set of equations underlying the thermal model is:

$$\frac{dT_{conv}}{dt} = -\frac{1}{C_{conv} \cdot (R_{AT}+R_{IC})} \cdot T_{conv} + \frac{1}{C_{conv} \cdot (R_{AT}+R_{IC})} \cdot T_{amb} + \frac{1}{C_{conv} \cdot R_{AT}} \cdot f_{\Delta T} \tag{2}$$

$$T_{conv,a} = \frac{R_{AT}}{(R_{AT}+R_{IC})} \cdot T_{conv} + \frac{R_{IC}}{(R_{AT}+R_{IC})} \cdot T_{amb} \tag{3}$$

The model parameters to be estimated by means of parameter identification are the thermal resistances $R_{AT}$ and $R_{IC}$ and the thermal capacitance $C_{conv}$. $T_{amb}$ and $f_{\Delta T} = f(T_{amb}, P_{WT})$ are the time-dependent input signals, while the air temperature inside the converter cabinet $T_{conv,a}$ is the output signal of the model.

## Hygric model

Using the analogy of mass and charge transport summarized in Table II, also the moisture transfer between the WT environment and the power cabinet can be modelled by means of an R-C network. At the current stage, the model does not cover the occurrence of condensation. The structure of the R-C network for the moisture balance is shown in Fig. 5.

**Table II: Analogy of hygric and electrical quantities (adopted from** [8]**)**

| **Hygric quantity** | **Symbol** | **Unit** | **Electrical quantity** | **Symbol** | **Unit** |
|---|---|---|---|---|---|
| Moisture concentration | c | $kg/m^3$ | Voltage | U | V |
| Mass flow | $\dot{m}$ | kg/s | Current | I | A |
| Diffusion resistance | $R_D$ | $s/m^3$ | Resistance | R | Ω |
| Volume | V | $m^3$ | Capacitance | C | F |

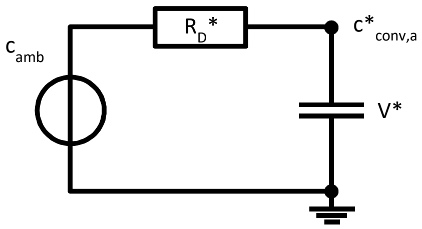


Fig. 5: R-C network for moisture transport between WT-ambient air and converter-cabinet air with equivalent quantities and parameters marked by (*)

The diffusion paths between the ambient air and the cabinet-internal air through gaps are represented by a lumped diffusion resistance $R_D^*$. The moisture storage in the cabinet air is modelled by means of a lumped equivalent volume $V^*$. It is important to note that, as explained and derived in detail in [8], transformation to equivalent quantities and parameters is necessary whenever the system-internal temperatures differ from the ambient temperature or different materials are involved. This takes account of the fact that, in the balanced state, there is no equilibrium of the water vapor concentrations but of the water vapor partial pressures.

### Equations representing the hygric model

While the thermal model consists of a set of linear equations, the temperature dependence of diffusion and solubility coefficients as well as the transformation to equivalent quantities introduces nonlinearities into the equations of the hygric model. After expressing V* and $R_D$* according to the theory and equations in [8] and [12], the resulting set of equations representing the hygric model is:

$$\frac{dc^*{}_{conv,a}}{dt} = \frac{1}{k\cdot(273\ K)^{1.8}} \cdot T_{conv,a} \cdot T_{amb}^{0,8} \cdot \left(c_{amb} - c^*{}_{conv,a}\right) \tag{4}$$

$$c_{conv,a} = c^*{}_{conv,a} \cdot \frac{T_{amb}}{T_{conv,a}} \tag{5}$$

In these equations, k is a constant parameter to be identified from the measured data, $c_{amb}$ and $T_{amb}$ are input signals, $T_{conv,a}$ is an input signal provided by the thermal model and the moisture concentration (i.e. absolute humidity) in the converter-cabinet air $c_{conv,a}$ is the output signal of the hygric model.

## Results and Discussion

The grey-box model identification, simulation and visualization has been implemented using MATLAB (Release 2022a). The results are presented and discussed in the following.

### Measured and simulated climatic conditions in a wind-turbine converter

In Fig. 6 to 8, we present the results for the case of an onshore WT in the UK with doubly fed induction generator and liquid-cooled partially rated converter, the latter located in the tower base. The WT has a rated power of approx. 2 MW. Fig. 6 shows the measured temperature timeseries through the entire measurement period together with the simulated temperature timeseries obtained from the identified thermal model and the varying operating point of the turbine. Note that the model parameters have been identified using the timeseries data until end of December only, to save the last month for model validation.

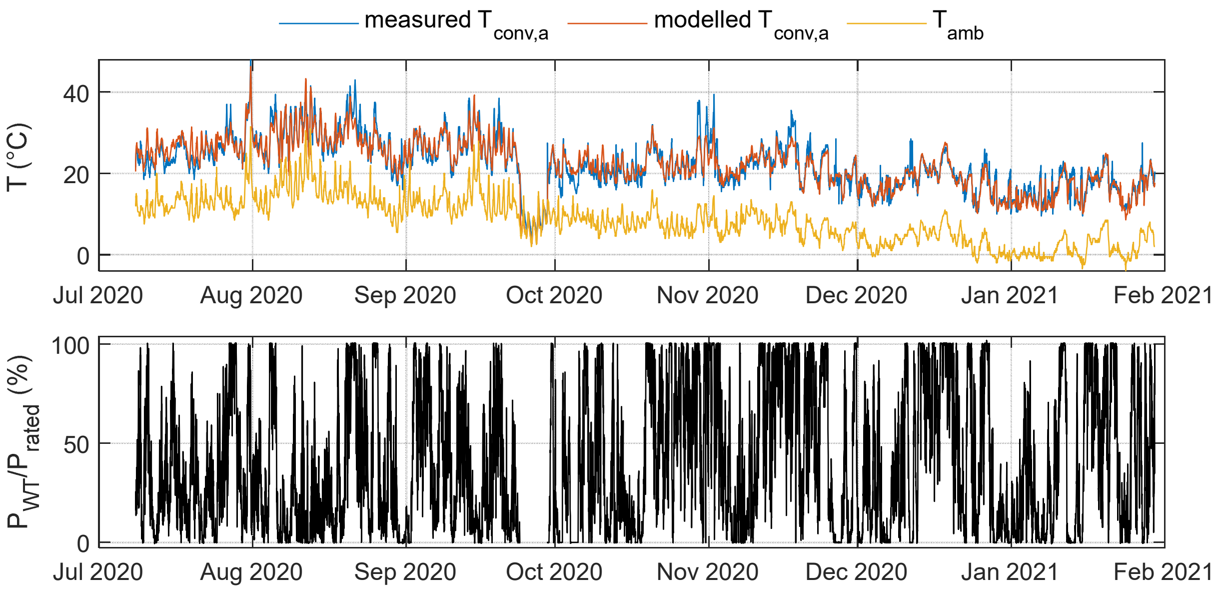


Fig. 6: Results of the identified thermal model of a WT in UK with liquid-cooled, partially rated converter located in the tower base; overall view of the measured and simulated temperature timeseries and the normalized WT active power fed to grid

Excerpts from the full timeseries are presented in Fig. 7, showing how day-night cycles and the WT load conditions influence the WT-internal temperatures. The excerpts cover periods of full-load and part-load operation as well as standstill periods of the turbine.

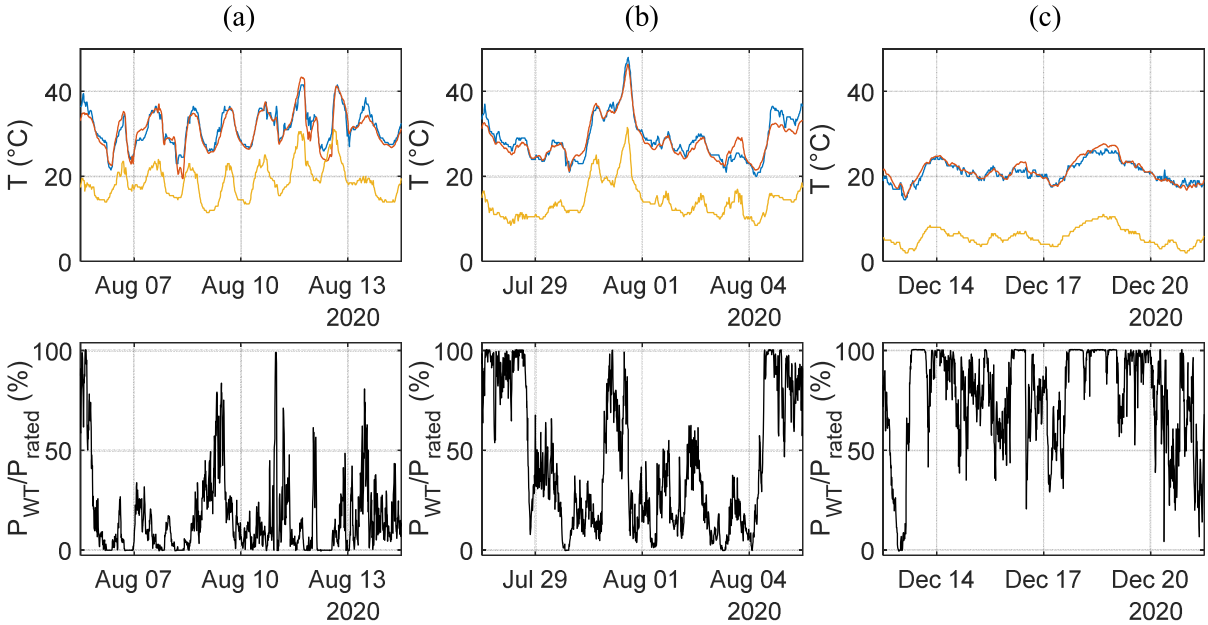


Fig. 7: Results of the identified thermal model of a WT in UK with liquid-cooled, partially rated converter located in the tower base (modelled cabinet-temperature timeseries: red, corresponding measured timeseries: blue; WT-ambient temperature: yellow); periods with (a) part-load operation and pronounced day-night cycles, (b) particularly dynamic variation of temperatures and electrical load, (c) operation close to and at rated power

Figures 6 and 7 show that the derived thermal model can estimate the air temperature inside the converter cabinet with reasonable accuracy. Both the seasonal variation, the day-night cycles and influence of the turbine operation are successfully replicated by the model. Also during a 6-day standstill period with disconnection from the power grid during end of September 2020 (cf. Fig. 6), simulated and measured timeseries are in good agreement. For the data period of the first 5.5 months used for parameter identification, the RMSE of the converter-cabinet temperatures is $RMSE_{T,tot} = 1.95$ K. For the validation period of the last month, it is even lower with $RMSE_{T,tot} = 1.43$ K. In case of the wind turbine considered here, the ambient temperature is found to have a stronger influence on the converter temperature than the operating point, i.e. electrical load of this turbine: At constant ambient temperature, the converter-cabinet temperature varies by no more than approx. 5 K between low part-load and full-load operation.

Fig. 8 presents the results of the hygric model, which are obtained with $T_{conv,a}$ from the thermal model, and their comparison with the measured moisture concentrations. It can be observed that the cabinet-internal and the WT-external absolute humidity are almost identical. This possibly surprising observation is in agreement with our findings from the evaluation of measurement campaigns in >30 WT reported in [7] and appears to be typical of wind turbines without active dehumidification. While at first sight, the internal moisture concentration seems to fully match that in the WT environment, a closer observation makes clear that the temperature difference between the WT-ambient and the converter-cabinet air gives rise to a small shift, i.e. leads to slightly reduced moisture concentrations inside the WT (cf. Equation (5)).

Also in case of the hygric model, the timeseries estimated with the derived model are in good agreement with the measured timeseries most of the time – both during the data period used for parameter identification and during the validation period in the last month. The corresponding RMSE values are $RMSE_{H,tot} = 0.45$ g/m³ in the period used for parameter estimation and $RMSE_{H,tot} = 0.26$ g/m³ in the period used for model validation. An interesting effect, which requires further investigation and is not yet reproduced by the present model, is the short-term peak in moisture concentration observed during the pre-heating routine after the 6-day standstill period end of September 2020 (cf. Fig. 6 and 8), which is likely related to moisture storage in e.g. polymers in the power cabinet.

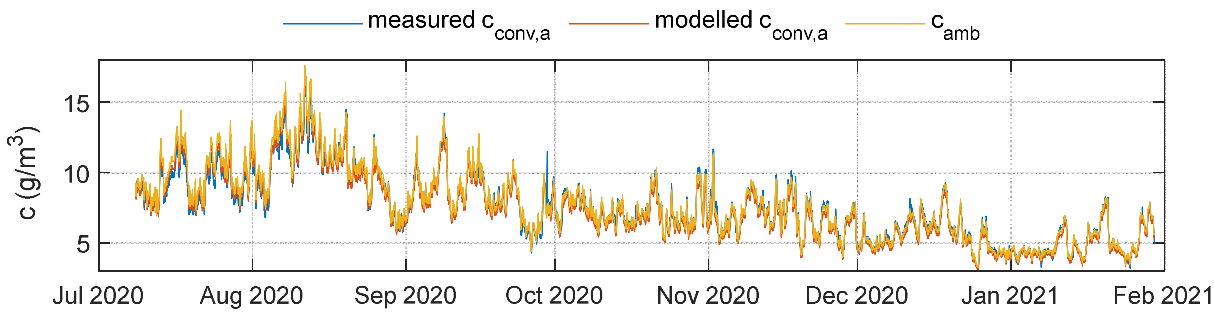


Fig. 8: Results for the moisture concentration (absolute humidity) obtained with the identified hygrothermal model of the same WT (modelled timeseries: red, corresponding measured timeseries: blue; WT-ambient conditions: yellow)

Using the modelling and parameter-identification approach described above does not provide the exact value of each single model parameter, but of their products ($R \cdot C$) and ($R_D^* \cdot V^*$), respectively. These can be used to determine the time constants of the heat and the moisture transfer between the WT-ambient air and the converter. For the turbine considered above, the overall thermal time constant ($R_{AT} + R_{IC}) \cdot C_{conv}$ is approx. 1.5 h. The hygric time constant ($R_D^* \cdot V^*$) is influenced by the temperature levels. For the temperature conditions encountered inside and around the above WT, the hygric time constant is approx. 0.3 h and thus considerably shorter than the thermal time constant.

## Dependence of model accuracy on environmental input data

In the case presented above, measured temperature and humidity timeseries are available from both the converter cabinet and from outside the wind turbine. In many other cases, measured data are available only from inside the turbine. In that case, ERA5 reanalysis data are used instead to include the site-specific ambient conditions of the WT. An interesting question is to which extent this influences the accuracy of the derived hygrothermal models, i.e. of the WT-internal timeseries calculated with these models. This is investigated for the same wind turbine as above.
The temperature and humidity timeseries obtained based on ERA5 data are shown in Fig. 9. The RMSE values for the entire measurement period in case of measured vs. ERA5 data for the environmental conditions are summarized in Table III.

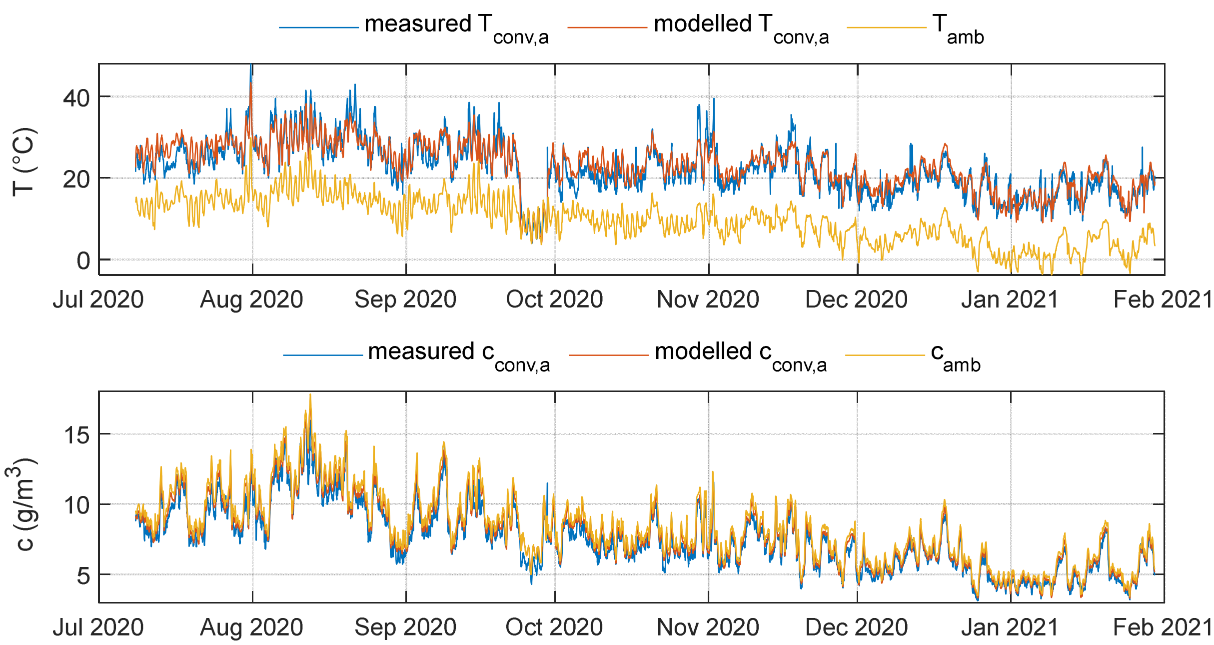


Fig. 9: Temperature and moisture-concentration timeseries based on site-specific ERA5 data for the ambient conditions

A comparison of the timeseries in Fig. 6, 8 and 9 makes clear that the differences are small: The ERA5 reanalysis data are in good agreement with the data measured on site. In consequence, also the modelled timeseries show little differences between the scenario using measured ambient data (Fig. 6 and 8) and the one using ERA5 ambient data (Fig. 9).

**Table III: Comparison of model qualities by means of root-mean squared errors**

| Scenario | Thermal model | | | Hygric model | | |
|---|---|---|---|---|---|---|
| | $RMSE_{T,op}$ | $RMSE_{T,st}$ | $RMSE_{T,tot}$ | $RMSE_{H,op}$ | $RMSE_{H,st}$ | $RMSE_{H,tot}$ |
| Model based on measured $T_{amb}$ and $c_{amb}$ | 1.80 K | 2.36 K | 1.87 K | 0.42 g/m³ | 0.50 g/m³ | 0.43 g/m³ |
| Model based on $T_{amb}$ and $c_{amb}$ from ERA5 reanalysis | 2.31 K | 2.56 K | 2.34 K | 0.56 g/m³ | 0.80 g/m³ | 0.60 g/m³ |

This is confirmed by the RMSE values in Table III: While the model accuracy is – expectedly – higher (i.e. RMSE values are lower) when measured timeseries are used, the RMSE values are increased by no more than 0.51 K and 0.3 g/m³ in the case based on ERA5 data. Taking into consideration that the accuracy of the temperature and humidity loggers used in the measurement campaign is 0.3 K and 2% relative humidity [7], this is considered a very limited loss in model accuracy – a result that encourages the use of ERA5 data for the purpose of modelling, simulating, and investigating the site-specific climatic conditions in wind turbines.

## Model transfer to identical turbines at different sites

Another important question is if the model parameters derived from a measurement campaign at a certain site may be transferred to a turbine of the same type operating in another region. We investigate this for the above case of DFIG-based turbine type for which measurement and operating data are available not only from a site in the UK but also from a site in Germany.

Fig. 10 shows the temperature and humidity timeseries calculated using the transferred model parameters of the previous WT in UK in combination with environmental data (here: ERA5 data) and the active-power timeseries of the turbine in Germany. The visual impression that the transferred model can describe the climatic conditions with similar accuracy as those in the original WT for which its model parameters were identified is confirmed by the corresponding RMSE values: With a value of $RMSE_{T,tot}$ = 2.53 K for the temperature timeseries in the WT in Germany, the measured temperatures and those simulated with the transferred thermal model show only a slightly higher deviation compared with the original WT in the UK (with $RMSE_{T,tot}$ = 2.34 K, see Table III). In case of the humidity timeseries, the value of $RMSE_{H}$ = 0.32 g/m³ indicates that the timeseries simulated with the transferred hygric model match the humidity data measured on this turbine even better than on the original WT located in the UK (with $RMSE_{H}$ = 0.60 g/m³, see Table III).

Similarly successful transfers of hygrothermal models between WT of identical type could also be observed in the cases of further turbines not presented here. This is an important finding as it confirms that the derivation of application-typical requirement specifications and test procedures is not limited to sites at which field-measurement campaigns have been carried out. Instead, the hygrothermal models derived from the field-measurement data can be combined with ambient climatic data from any site in the world (including e.g. challenging climates in tropical regions) to obtain region-specific test profiles or requirement specifications.

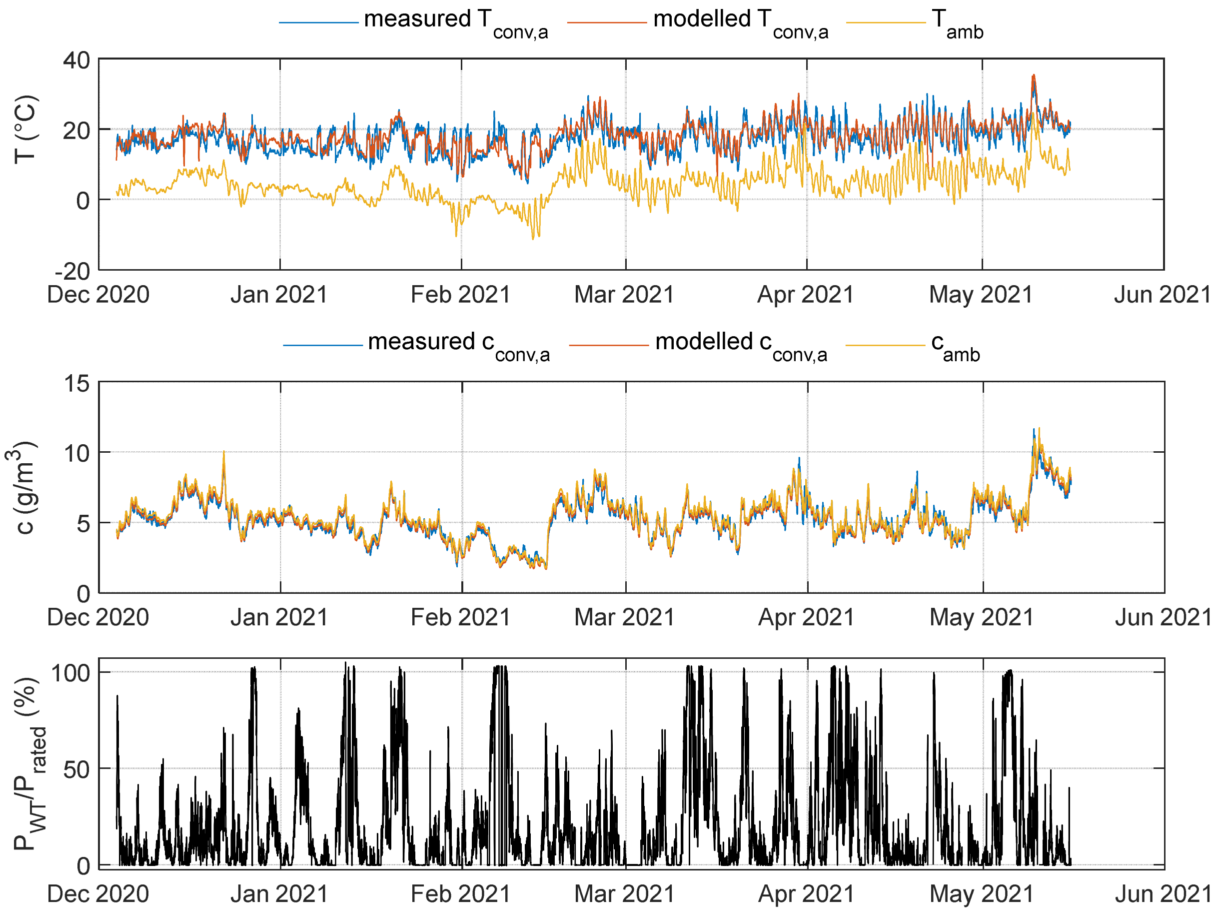


Fig. 10: Results of model transfer from the WT in UK to a WT of identical type in Northern Germany (Note that the simulated strong temperature drops in mid of December 2020, are caused by gaps in the active-power timeseries and therefore not attributable to the model quality.)

## Conclusion

Using a lumped-parameter modelling approach, we have been able to derive hygrothermal models of low complexity that are capable of describing the climatic conditions in power converters of wind turbines. The field-data based models successfully replicate the seasonal variation of the climatic conditions experienced by the power converter throughout the year as well as the variations on a shorter timescale related to day-night cycles and load fluctuations. For the wind turbine with water-cooled power converter in the tower base considered in the present work, model qualities with an average root mean squared error of 1.4-2.5 K for the cabinet-air temperature and 0.3-0.6 g/m³ for the cabinet-internal moisture concentration have been achieved. The models describe periods with turbine operation slightly more accurately than standstill periods. For the considered turbine, the identified time constants for heat and moisture transport are in the range of 1.5 h and 0.3 h, respectively, indicating thermal balancing to be much slower than the hygric balancing processes.

We have demonstrated that it is not necessary to have measured temperature and humidity timeseries from the environment of the wind turbine. Global ERA5 reanalysis data for the site of interest can be used instead with only a slight reduction in model accuracy. In addition, we could show that it is possible to transfer the model parameters identified from measurement data from a certain site to turbines of identical type located at other sites.

In contrast to Schuster et al. [13] who investigated and modeled the climatic conditions in railway traction converters and reported massively increased moisture concentration inside the converter cabinets, we found the absolute humidity in the converter cabinets of wind turbines to be mostly very similar to the ambient conditions of the turbine. However, an interesting effect in wind turbines requiring further investigation and model refinement are short-term peaks in absolute humidity during the pre-heating routines applied after longer standstill periods of wind turbines, which could be related to moisture storage in polymers.

Field-data based hygrothermal models make it possible to simulate the temperature and humidity conditions in wind turbines at any possible location in the world based on the ambient environmental conditions at this site. Thus, they play an important role for the adjustment of requirement specifications as well as for the derivation of application-specific test procedures for power converters and their components.

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