Statistical and time domain signal analysis of the thermal behaviour of wind turbine drive train components under dynamic operation conditions.

K Nienhaus, M Hilbert, R Baltes and C Bernet

Abstract. Gearboxes and generators are fundamental components of all electrical machines and the backbone of all electricity generation. Since the wind energy represents one of the key energy sources of the future, the number of wind turbines installed worldwide is rapidly increasing. Unlike in the past wind turbines are more often positioned in arctic as well as in desert like regions, and thereby exposed to harsh environmental conditions. Especially the temperature in those regions is a key factor that defines the design and choice of components and materials of the drive train. To optimize the design and health monitoring under varying temperatures it is important to understand the thermal behaviour dependent on environmental and machine parameters. This paper investigates the behaviour of the stator temperature of the double fed induction generator of a wind turbine. Therefore, different scenarios such as start of the turbine after a long period of no load, stop of the turbine after a long period of full load and others are isolated and analysed. For each scenario the dependences of the temperature on multiple wind turbine parameters such as power, speed and torque are studied. With the help of the regression analysis for multiple variables, it is pointed out which parameters have high impact on the thermal behaviour. Furthermore, an analysis was done to study the dependences in the time domain. The research conducted is based on 10 months of data of a 2 MW wind turbine using an adapted data acquisition system for high sampled data. The results appear promising, and lead to a better understanding of the thermal behaviour of a wind turbine drive train. Furthermore, the results represent the base of future research of drive trains under harsh environmental conditions, and it can be used to improve the fault diagnosis and design of electrical machines.

To whom any correspondence should be addressed.
1. Introduction

Wind energy is an energy source that is in the focus of all energy discussions in Europe. Not only the general question if wind energy can be one of the main sources of energy, but also the question if each wind turbine can be designed reliably enough to supply the grid with energy for 20 years. The first question seems to be answered if one looks at the capacity of wind energy project for new wind parks in Europe [1]. The second question is a technical problem and concerns all parts of the wind turbine. Especially the drive train of the wind turbine, including the generator, is one of the focuses of reliability. No other machine is designed to work continuously for such a long period of time with a minimum maintenance. With increase in the number of wind parks more and more remote locations are chosen for the turbines that result very often in harsh condition like extreme cold temperate and ice e.g. the 150 MW wind park in Blaiken, Sweden or extreme hot and dusty e.g. the 63 MW wind park in Zafarana, Egypt.

To increase the reliability and monitor the condition of the drive train components such as the gearbox a lot of research has been done.[2] Most of the approaches are based on vibration analysis or acoustic emission. Therefore the focus is on bearings, gear mesh, imbalance or misalignment. But most of the downtime of a generator is not caused by these components or failures. The main reasons for down time are the generator windings, brushes and other electrical components [3]. As we can see in [4] the generator and the electrical system cause 23.2 % of downtime of a wind turbine, compared to 19.4 % of downtime of the gears. One of the most critical points of the generator and therefore of the entire turbine, is the electrical isolation of generator winding. The problem is that the isolation survives only until a certain temperature. If this temperature is exceeded the life time of the isolation decreases dramatically and a short circuit in the generator is going to become likely.

On this background, this paper analyses the temperature of the stator windings of a doubly fed induction machine of a wind turbine to provide the understanding of condition monitoring of generator components that cannot be analyzed with vibration analysis. The goal of the paper is to understand the temperature behaviour of the generator knowing as little as possible of the machine itself. Even various methods to estimate the temperature of induction machines exists [5-7]; this paper is motivated to understand the thermal behaviour from a more general point of view. There will be no closer look to the design of the generator itself nor its components. In section 2 the data acquisition is presented. The next section focuses on the analysis of the data showing a method to estimate the stator winding temperature and analysis of the temperature curve over time. At the end of the paper, the results and future work are discussed.

2. Data Acquisition

The data discussed in this paper was acquired on a 2 MW onshore wind turbine in Germany. The turbine is a classical pitch controlled, variable speed, geared horizontal axes turbine with a hub height of 80 m and a rotor diameter of 82 m. The generator is asynchronous doubly fed induction machine. The machine has 4 poles and is air cooled. Because the paper focuses mainly on the generator, the specifications are summarized in table 1.

| Table 1. Generator specifications. |
|-----------------------------------|
| Rated Power | 2 MW |
| Rated Rotational Speed | 1800 rpm |
| Rated Voltage | 690 V |
| Poles | 4 |
| Ingress Protection Rating | IP 65 |
| Frequency | 50 Hz |
The data was acquired during a period of 10 months and includes vibration, shift, torque, electrical current and voltage as well as operational parameters from the PLC (Programmable Logic Controller). This paper's focus is on 4 measurement signals (table 2).

### Table 2. Measurement signals.

| Signal                          | Unit  | Sampling Rate [Hz] |
|---------------------------------|-------|--------------------|
| Power Output \( P_e \)          | kW    | 250                |
| Torque Generator Shaft \( T \)  | kNm   | 500                |
| Rotational Speed \( f_n \)      | Hz    | 100                |
| Stator Winding Generator Temperature \( T \) | °C  | 10                 |

The electrical power output of the generator was measured at the inverter and acquired via a data link from the measurement unit. The torque is measured on the gearbox output shaft towards the generator with strain gauges. The strain gauges are mounted on the shaft surface and joint to Wheatstone bridge. Acquiring the strain on the surface of the shaft, the torque can be calculated. The rotational frequency of the generator shaft is measured with a Hall-Sensor and a toothed wheel on the output shaft of the gearbox. The temperature of the stator winding of the generator is measured with a standard industry PT100. In the following chapters the generator temperature refers to the temperature of the stator winding of the generator. All data is collected in a database and stored for further analysis.

From the data three kinds of scenarios are selected: the start (figure 1 and figure 2), the stop (figure 3 and figure 4) of the turbine and scenarios of steady state (section 3.1.).

![Figure 1. Measurement of start scenario 1.](image-url)
Figure 2. Measurement of start scenario 2.

Figure 3. Measurement of stop scenario 1.
3. Data Analysis

The presented data is used for further analysis of the thermal behaviour of the generator of the wind turbine. In this paper the generator is assumed as a thermal homogenous body. The following chapter will be divided in two main points: the estimation of the stator winding temperature of the generator during steady state operation and the analysis of the temperature curve over time during start and stop scenarios.

3.1. Estimation of the stator winding temperature

The generator, as an electrical machine, converts mechanical power $P_m$ into electrical power $P_e$. During that process a part of the mechanical work is converted into power losses $P_l$. The ratio of mechanical power and electrical power is called energy conversion efficiency $\eta$:

$$\eta = \frac{P_e}{P_m} = \frac{1}{1 + \frac{P_l}{P_e}} \tag{1}$$

Because $\eta$ is known for the machine running at rated power, the power losses at rated power $P_{lR}$ can be calculated using the rated electrical power of the generator.

$$P_{lR} = P_eR \left( \frac{1}{\eta} - 1 \right) \tag{2}$$

Power losses can be divided in two kinds of losses: losses not depending on electrical load of the machine ($P_{l, no-load}$) and losses depending on the electrical load of the machine ($P_{l, load}$). With knowing the proportion of $P_{l, no-load}$ and $P_{l, load}$ during rated power, $P_{l, no-load}$ can be calculated using [8].

$$P_{l, no-load} \approx P_{l, no-load} = P_{lR} \frac{P_{ir, no-load}/P_{lR, load}}{1 + P_{ir, no-load}/P_{lR, load}} \tag{3}$$

During rated power the $P_{lR, load}$ is according to [8]:

$$P_{lR, load} = P_{lR} - P_{l, no-load} \tag{4}$$
To estimate the losses of the generator not only by rated power, but also during load the actual torque $T$ and the torque during rated power $T_R$ is used in [8].

$$P_l = P_{l,\text{load}} \left( \frac{T}{T_R} \right)^2 + P_{l,\text{no-load}}$$ (5)

The power losses are heating the generator including the stator windings and all other parts of the machine. By knowing the $P_l$ the temperature $\theta'$ of the generator can then be estimated using the known temperature during rated power $\theta_R$ according to [8].

$$\theta' = \theta_R \frac{P_l}{P_{lR}}$$ (6)

The estimated temperature $\theta'$ is added with the environmental temperature of the turbine to match the measured temperature $\theta$. The presented method of estimating the generator temperature $\theta'$ is tested with 10 data sets. Each data set presents a short period of time (at least 20 min each) with relatively constant power output of the turbine. Additionally it is ensured that the measured generator temperature $\theta$ reached a steady state. Table 3 shows the mean of measured datasets of the generator temperature $\theta$, the estimated generator temperature $\theta'$ and the absolute error in between them. These results are also plotted in figure 5.

![Figure 5. Correlation of measured and estimated generator temperature.](image)
### Table 3. Comparison of measured and estimated generator temperature.

| Dataset | Generator Temperature | Absolute Error |
|---------|------------------------|----------------|
|         | measured $\Theta$ [$^\circ$C] | estimated $\Theta'$ [$^\circ$C] |                  |
| 1       | 53.37                  | 43.20          | 10.17            |
| 2       | 53.30                  | 43.49          | 9.81             |
| 3       | 63.13                  | 86.34          | 9.39             |
| 4       | 93.96                  | 84.07          | 9.88             |
| 5       | 58.32                  | 54.64          | 3.68             |
| 6       | 38.21                  | 41.88          | 3.68             |
| 7       | 35.80                  | 37.75          | 1.96             |
| 8       | 25.32                  | 31.01          | 5.69             |
| 9       | 30.24                  | 40.37          | 10.12            |
| 10      | 26.50                  | 30.90          | 4.41             |

3.2. Generator temperature curve over time

This section will focus on the behaviour of the generator temperature over time after a step of the system parameters. The step response of the temperature is divided in two cases: the start when the generator heats up and the stop of the turbine when the generator cools down.

Figure 6. Heating and cooling curves for constant power losses. [8]

Figure 6 shows the theoretical behaviour of both cases, assuming that the power losses after the step are constant. It is known that the generator temperature $\Theta$ changes over time during the heating process and it can be estimated by means of equation (7), in its simplest way. $\Theta_0$ is the measured temperature of the generator at the time of the step, $\Delta\Theta_H$ the temperature difference at the end of the heating process and $\tau_H$ the temperature time constant. During the curve fitting $\Theta_0$ and $\Delta\Theta_H$ are known from the measured data. $\tau_H$ represents the variable of the curve fitting. The parameters for both start scenarios are summarized in table 4.

$$\Theta(t) = \Delta\Theta_H \left(1 - e^{-t/\tau_H}\right) + \Theta_0$$  \hspace{1cm} (7)
Table 4. Temperature curve parameters for the introduced start and stop scenarios. The variables of the curve fitting of each scenario are underlined.

| Scenario | \( \tau_H \) [min] | \( \Theta_0 \) [°C] | \( \Theta_H \) [°C] | \( \Delta \Theta_H \) [°C] | \( R^2 \) |
|----------|---------------------|---------------------|---------------------|---------------------|---------|
| Start 1  | 43                  | 24.17               | 54.34               | 30.17               | 0.9812  |
| Start 2  | 170                 | -11.03              | 73.92               | 84.95               | 0.9818  |
| Stop 1   | 383                 | 56.78               | 37.11               | 19.67               | 0.9955  |
| Stop 2   | 383                 | 30.60               | -9.84               | 40.44               | 0.9988  |

Figure 7. Generator heating after a start (start scenario 1).

Figure 8. Generator heating after a start (start scenario 2).
It is also known that the temperature changes $\theta$ over time during the cooling process and it can be estimated using the equation (8) in its simplest way.

$$\theta(t) = \Delta \theta_c e^{-t/\tau_c} + \theta_c$$  \hspace{1cm} (8)

The generator temperature $\theta_0$ is the measured at the time of the step, $\theta_c$ the final temperature of the cooling process and $\tau_c$ the temperature time constant. With (8) the generator temperature could be fitted using the environmental temperature of the wind turbine as $\theta_c$ and the difference between generator temperature at the moment of the stop and $\theta_c$ as $\Delta \theta_H$. $\tau_H$ represents the variable of the curve fitting and results in $\tau_H = 383$ min for stop scenario 1 (table 4). For stop scenario 2 (figure 10) $\theta_c$ and $\Delta \theta_H$ are changed to the scenario specific values and $\tau_H = 383$ min was used from stop scenario 1.

Figure 9. Generator cooling after a stop (stop scenario 1).

Figure 10. Generator cooling after a stop (stop scenario 2).
4. Discussion

4.1. Estimation of the stator winding temperature

The applied method (in section 3.1) shows that even with that relatively simple method it is possible to predict the stator winding temperature and therefore provide an estimate of the normal temperature with a maximum absolute error of around 10 °C. In case of a failure, that estimation could help to save the isolation of the winding before it gets destroyed. Compared with thermal models that are based on neuronal networks [7], the introduced method does not need any training data or training time. As well as complex thermal models [9] the method of this paper suffers from the disadvantage that the accuracy of the results is highly depended of the algorithm parameters. Only with the correct parameters the result will lead to a usable estimate of the temperature. Not like neuronal networks this method and complex thermal models are based on the physical context of the machine. It is clear that such a general method, like the one presented in this paper, will result always in a larger error than methods that are developed analysing the generator in detail [5, 6, and 9]. But in a lot of applications (e.g. machine protection) the error has to be in balance with computing cost and the data used to build the model. Taking this into account, the method presents an effective solution for the temperature estimate.

4.2. Generator temperature curve over time

The curve fitting in section 3.2 shows that even with a simple function the temperature can be estimated about a long period of time. At the start scenario 1 with a relative constant power output over the heating time, the estimate temperature has a maximum absolute error of 2.32 °C compared to the measured temperature. This represents a very accurate fit. The temperature time constant $\tau_H$, with a value of 43 min, matches the machine parameter given by the manufacture. At the start scenario 2 with a very variable power output over the heating time, the estimate temperature has a maximum absolute error of 5.86 °C compared to the measured temperature and a less smooth rise of the temperature. The temperature time constant $\tau_H$ has a value of 170 min. It is shown that with a varying power output, in start scenario 2, the fitting of the temperature curve using equation (7) has a bigger error than in start scenario 1. The reason is that the equation assumes constant power losses over the time of the curve fitting. This is not given with a variable power output. With a constant power output, (7) can lead to an accurate curve fitting of the generator temperature. Stop Scenario 1 and 2 could show that a precise curve fitting is possible using the same time constant $\tau_C$ for both stop scenarios. Because $\Theta_C$ and $\Delta \Theta_H$ are known at anytime of the operation of the wind turbine, equation (8) can be used to estimated the generator temperature curve. Therefore with (8) the cooling of the stator windings of the generator can be predicted until the next start of the turbine. The results of the curve fitting will be used to develop a more accurate temperature estimate with thermal models in the future, and contribute to a better understanding of the thermal behavior of wind turbine generators.

5. Conclusion

In this paper methods for temperature estimation while constant power output, as well as for start and stop scenarios are presented. Measured data and the method of estimation are introduced. The temperature estimation is based on machine parameter supplied by the manufacturer. The estimation is tested with real data, but only for constant power output of the wind turbine generator. Furthermore, for start and stop scenario the temperature over time is fitted with curves to study the behavior. The results lead to a better understanding of the thermal behavior of the wind turbine drive train, especially with very little information about the machine parameters. To obtain a better estimate the method has to be extended to take more machine parameters into account. Nevertheless, the results represent the base of future research of drive trains under harsh environmental conditions, and can be used to improve the fault diagnosis and design of electrical machines.
6. References

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