Developing an empirical model to predict the winding coil temperature for a compact wind turbine

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Abstract. One of the problems with a compact wind generator is a temperature control. The aim of this research is to establish an empirical model for estimating the winding coil temperature through natural convection cooling. The modeling process began with physical experimentation at different operating conditions while measuring temperature at various positions on the compact wind generator. Later, simulation experiment is divided into two sections: Electromagnetic (EM) simulation and Computational Fluid Dynamic (CFD) simulation. The electromagnetic simulation was applied and tested successfully, with a V_peak discrepancy of less than 4 percent. While the CFD software was then used to replicate the natural convection cooling effects at the compact generator. The CFD results were validated by experimental measurements with a difference in winding coil temperature of less than 9 percent. Then, using Design of Experiment (DOE), various operating conditions were simulated to evaluate the results and Analysis of Variance (ANOVA) was used to develop the empirical model. The empirical model for estimating the winding coil temperature with a difference of less than 10% from experimental data was successfully developed. As a result, the empirical model can be used to estimate the winding coil temperature at different operating conditions with a good accuracy.

Keywords. Empirical model, winding coil temperature, computational fluid dynamics, compact wind generator, natural convection cooling.

1. Introduction
Thermal analysis of electrical machines, particularly generators, has received less attention than electromagnetic analysis in the past. The number of scientific papers published in those fields in the last 20 years demonstrates this. However, due to market globalization and the need for smaller, cheaper, and more powerful generators, the issue of thermal management has begun to attract more attention in recent years. This is because the temperature of the permanent magnet made of Neodymium-Iron-Boron (NdFeB) used in the new generation generators should be kept as low as possible at all times. This is because the remanence flux density of the NdFeB magnet decreases as the magnet temperature rises, thus reducing the performance of the generator [1]. Furthermore, excessive magnet temperature may result in irreversible demagnetization of the permanent magnet material. Magnets may become demagnetized, winding coils may melt, causing a short-circuit, and the binder may lose its bind properties if the temperature exceed the maximum limit. This may cause the generator to fail catastrophically and cause major property damage. According to Baolin and Qingbo [2], since the 1980s,
when wind turbines were first installed, fire has been responsible for 10% to 30% of recorded wind turbine accidents caused by overheated winding coil.

In recent years, the knowledge and technology required to design an efficient wind generator have been increased dramatically. Current offshore wind generators were built up to 8 megawatts [3] of power output. Nonetheless, recent articles on wind turbine thermal studies used either a lump parameter methodology or a numerical method [4]–[6]. Thermal analysis can be divided into three basic methods to model the temperature for internal parts of the generator. The most well-known thermal model methods are the Lump Parameter Model (LMP), Computational Fluid Dynamic (CFD) model and Empirical model. All the three models have their own advantages and disadvantages.

The LMP model can accommodate all three forms of heat transfer processes, including conduction, convection, and radiation [7]. This model, however, is highly reliant on the conduction and convection heat transfer coefficients, which are often difficult to calculate. Furthermore, the Nusselt number, Reynolds number, Prandtl number, and Taylor number are used to determine the convection coefficient values in different positions in the generator, and correctly measuring them is a difficult job [8].

The CFD model on the other hand, used a numerical method to study the fluids and the heat transfer mechanisms. The CFD is widely applied in the thermal analysis of electrical machinery especially in the final design stage. The use of CFD models allows the designer to evaluate and predict detail characteristics such as airflow velocity inside and outside the generator. However, the application is computationally very expensive and time-consuming [8].

Whereas an empirical model refers to any modeling based on measured data rather than depend on describable relationships of the system modeled. One of the advantages of the empirical model is that it requires systematical and well-organized data either experimental data or simulation data. On the other hand, it will never be superior compared to the theoretical model in term of results due to the noise factors [9]. Despite of the disadvantages of the empirical method, Safdar I et al. [10] was able to accurately analyze the efficiency of a turbine and a generator of a hydro system using the method.

The objective of this study is to develop an empirical model that could predict the winding coil temperature by measuring the voltage and current drawn from the wind generator. The empirical model was developed using validated simulation data using CFD. Once the data is validated, the final process in this study was to formulate an empirical model that could estimate the winding coils temperature at various operating conditions.

2. Experimental Setup

The experiment apparatus used in this study was a customized design for the purpose of investigating the winding coils temperature (Figure 1). The apparatus is fitted with a 1000 watts wind generator and it is driven by a servo motor mounted on a rigid table-top workbench. Besides the main equipment, several support components were also required for acquiring measurement values. A digital ammeter and voltmeter panels were used to measure and display the current and the voltage output from the wind generator, respectively. A MATLAB software was used to receive and store the temperature data. The wind generator used in this study has 36 slots of Y-type configuration for its winding coils and 12 poles of strong permanent magnets attached to the rotor.

Figure 1. Experimental equipment used in this study.
3. Design of Experiment

For this study, a Design of Experiment (DOE) method was employed to establish a relationship between input variables and output responses [11]. Only two input variables/factors were chosen for this study because of the limitation in the experimental apparatus (Table 1). This approach results in improved statistical interpretation of the results. It requires less time for analysis and requires fewer experiments. Experimental runs were determined using an orthogonal array based on the Response Surface Methodology with Central Composite Design variation (RSM-CCD) method.

Table 1. Factors and range used in this study.

| No. | Factors       | Range  | Unit |
|-----|---------------|--------|------|
| 1   | Rotational Speed | 100-550 | RPM  |
| 2   | Load          | 3.5-11.5 | Ohm  |

Table 2 shows experimental results after performing experiments using RSM-CCD approach. While conducting the experiment, several limitations were observed. The servo motor that attached to the rotor used in the experiment was automatically stop when the servo motor temperature exceeded 180 °C. The higher the current drawn out from the generator, the higher torque requirement to rotate the rotor.

Table 2. Experimental results.

| Run | Factor 1 (RPM) | Factor 2 (Ohm) | Response 1 (V<sub>DC</sub>) | Response 2 (A<sub>DC</sub>) | Response 3 (°C) |
|-----|----------------|----------------|----------------------------|----------------------------|-----------------|
| 1   | 100.00         | 7.50           | 9.75                       | 0.39                       | 30.7            |
| 2   | 165.90         | 4.67           | 16.75                      | 0.85                       | 32.2            |
| 3   | 165.90         | 10.33          | 18.75                      | 0.55                       | 32.1            |
| 4   | 325.00         | 3.50           | 34.00                      | 1.56                       | 40.5            |
| 5   | 325.00         | 7.50           | 38.75                      | 1.30                       | 34.3            |
| 6   | 325.00         | 7.50           | 38.75                      | 1.30                       | 35.1            |
| 7   | 325.00         | 7.50           | 38.75                      | 1.30                       | 34.9            |
| 8   | 325.00         | 7.50           | 39.00                      | 1.30                       | 34.7            |
| 9   | 325.00         | 7.50           | 38.75                      | 1.24                       | 35.5            |
| 10  | 325.00         | 11.50          | 40.75                      | 1.17                       | 35.3            |
| 11  | 484.10         | 4.67           | 55.50                      | 1.72                       | 40.9            |
| 12  | 484.10         | 10.33          | 62.00                      | 1.50                       | 37.7            |
| 13  | 550.00         | 7.50           | 68.00                      | 1.76                       | 43.6            |

4. Electromagnetic Simulation

The simulation experiments consist of two parts. First is the electromagnetic simulation and second is the computational fluid dynamic simulation. An electromagnetic simulation is an analysis of electromagnetic field. The results of the electromagnetic analysis can be in the form of induced voltage, current output, total losses, torque and back electromagnetic force (EMF). The strongest magnitude of magnetic flux density (B) measured in tesla was found at the winding coils and was evenly distributed around the stator and rotor cores, as shown in Figure 2.
Figure 2. Example of magnetic flux distribution inside the wind generator.

Transient analysis is another important aspect of electromagnetic simulation to investigate. For this study, 180 timesteps per one complete sinusoidal waveform were used. Two output parameters were observed which are the induced voltage output and the induced current output as shown in Figure 3. These two parameters were chosen because they can be compared to the experimental data.

![Example of induced voltage output result.](image)

Table 3 shows the comparison between experimental results and electromagnetic simulation results. $V_{\text{peak}}$ was measured by the maximum peak of the induced voltage, and frequency was measured in time laps between the two peaks. The difference for both measurements is less than 4%.

| No. | Experiment result | Simulation result | Difference (%) |
|-----|-------------------|-------------------|----------------|
| $V_{\text{peak}}$ (Volt) | 20.0 | 19.2 | 4.0 |
| Frequency (Hz) | 13.0 | 12.8 | 1.5 |

5. Computer Fluid Dynamic Simulation

The Realizable $k-\varepsilon$ turbulence model was used as the turbulence model in the CFD analysis. This model is an improvement over the standard $k-w$ turbulence model. It contains a new formulation for the turbulent viscosity and a new transport equation. Advantages of using the Realizable $k-\varepsilon$ turbulence model is that it provides improved predictions for the spreading rate of both planar and round jets. It exhibits superior performance for flows involving rotation, boundary layers under strong adverse pressure gradients.
6. Result and Discussion

Figure 4 and 5 show the temperature distribution inside and outside the wind generator from the cross-section view of XY and YZ planes. The temperature is distributed evenly throughout the generator body once the temperature reaches the steady state condition. Because the air around the generator body has a lower density due to the heating effect, buoyancy effect forces the air upward and act as a natural cooling effect to the generator.

**Figure 4.** Heat distribution at XY cross-sectional.

**Figure 5.** Heat distribution at YZ cross-sectional.

The temperature differences between the CFD simulation data and the experimental results are less than 10% as shown in Table 4. The 10% difference is acceptable based on several previous research works. Three experimental runs were chosen for the validation process because they represent lower, middle and upper value of RPM speed.

| No. | Winding Coil Temp (°C) | Difference (%) |
|-----|------------------------|----------------|
|     | Experiment | Simulation |               |
| Run 2 | 32.2       | 29.35       | -8.85         |
| Run 4 | 40.5       | 43.05       | +6.30         |
| Run 12 | 37.7      | 40.62       | +7.75         |

Once the simulation results have been validated, the RSM-CCD is used to design CFD simulation runs to simulate the situation in which the experimental work cannot be completed due to safety concerns. The simulation results are then analyzed using Analysis of Variance (ANOVA). As a result, the complete quadratic empirical model (Eq. 1) is developed.

\[
\text{CoilTemp} = -6.9110 - 0.3258x_1 + 13.9962x_2 + 1.2064x_3 + 0.2388x_1x_2 \\
+ 0.0012x_1x_3 + 0.0164x_2x_3 - 0.0045x_1^2 + 2.3646x_2^2 - 0.0029x_3^2
\]  

(1)

where

- \(x_1\) = Voltage (Volt)
- \(x_2\) = Current (A)
- \(x_3\) = Environment Temperature (°C)

The empirical model is then used to predict the winding coil temperatures, which are then compared to simulation results, as shown in Table 5 below.
Table 5. Comparison between predicted winding coils temperatures using the full quadratic empirical model and experimental results.

| No. | Coil Temperature (°C) | Differences (°C) | (%) |
|-----|------------------------|-----------------|-----|
|     | Experiment             | Empirical Model |     |
| 1   | 30.7                   | 29.2            | -1.5| 4.7 |
| 2   | 32.2                   | 36.4            | 4.2 | 13.1|
| 3   | 32.1                   | 25.9            | -6.2| 19.4|
| 4   | 40.5                   | 48.9            | 8.4 | 20.8|
| 5   | 34.3                   | 36.7            | 2.4 | 6.9 |
| 6   | 35.1                   | 36.7            | 1.6 | 4.4 |
| 7   | 34.9                   | 36.7            | 1.8 | 5.0 |
| 8   | 34.7                   | 36.5            | 1.8 | 5.2 |
| 9   | 35.5                   | 34.2            | -1.3| 3.6 |
| 10  | 35.3                   | 30.4            | -4.9| 13.8|
| 11  | 40.9                   | 44.8            | 3.9 | 9.7 |
| 12  | 37.7                   | 31.4            | -6.3| 16.7|
| 13  | 43.6                   | 40.6            | -3.0| 6.8 |

The average temperature difference between the predicted temperatures using the full quadratic empirical model (Eq. 1) and experimental results is 3.6°C or 10.1%. This comparison demonstrates that the empirical model can accurately predict the winding coil temperature of a compact wind generator. This can be concluded that the full quadratic empirical model can be used to predict the winding coils temperature accurately.

7. Conclusion

Due to the limitations of the experimental apparatus, there is insufficient data to develop an empirical model using the results of physical experiments; thus, simulation experiments are required to acquire the data. An empirical model was successfully developed in this study to estimate the winding coil temperature with a difference of less than 10%.

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