MODELING OF THE WINDING COIL TEMPERATURE IN A COMPACT PERMANENT MAGNET WIND GENERATOR

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LIST OF ABBREVIATIONS

ADC	Analog to Digital Converter
ANOVA	Analysis of Variance
CAD	Computer Aided Design
CCD	Centre Composite Design
CFD	Computational Fluid Dynamic
DAQ	Data Acquisition
DOE	Design of Experiment
EMF	Electromagnetic Force
FDM	Finite Difference Method
FEA	Finite Element Analysis
FEM	Finite Element Method
FVM	Finite Volume Method
HPM	Heat Pick-Up Method
IC	Integrated Circuit
LES	Large Eddy Simulation
LMP	Lumped Parameter Modeling
NdFeB	Neodymium Iron Boron
PIC	Peripheral Interface Controller
RAM	Random Access Memory
RPM	Rotational Speed
RSM	Response Surface Method
SA	Spalart-Allmaras
$SmCo_5$	Samarium Cobalt
TEFC	Totally Enclosed Fan Cooled
TO	Topology Optimization
TPM	Temperature Passing Method

LIST OF SYMBOLS

$\dot{m}$	Mass flow rate
P_{copper}	Copper Losses
P_{iron}	Iron Losses
x_1	Voltage
x_2	Current
x_3	Environment Temperature
x_4	Air Flow
∂x	Small change in x-axis
∂y	Small change in y-axis
∂z	Small change in z-axis
A_d	Surface area of conduction heat transfer
A_r	Surface area of radiation heat transfer
A_v	Surface area of convection heat transfer
c_p	Specific heat capacity
C_T	Thermal capacitance
dP	Small change in pressure
dt	Small change in time
G	Gap between the two surfaces
h_d	Radiation heat transfer coefficient
h_v	Convection heat transfer coefficient
I	Current
k	Thermal conductivity coefficients for conduction
k_a	Thermal conductivity coefficients for axial material
k_d	Conduction heat transfer coefficient
k_p	Proportional constant
k_r	Thermal conductivity coefficients for radial material
L	Length
m	Mass
$q_{convection}$	Convection heat transfer

R	Resistance
R_d	Conduction thermal resistance
Re_θ	Reynolds number.
R_r	Radiation thermal resistance
R_v	Convection thermal resistances
R_v	Convection thermal resistance
t	Time
T_1	Temperatures of surfaces 1
T_2	Temperatures of surfaces 2
T_{in}	Temperature at inlet
T_o	Initial winding coils temperature
T_{out}	Temperature at outlet
T_p	Peak time
T_{surf}	Temperature at surface
V	Volume
v	Velocity vector field
ε	Emissivity of the surface
ρ	Density
σ	Stefan-Boltzmann constant

Permodelan Suhu Gegelung Dawai Di Penjana Angin Magnet Kekal Padat

ABSTRAK

Penggunaan tenaga angin telah wujud sejak tamadun purba lagi. Pada masa kini, tenaga angin digunakan untuk menjana tenaga elektrik dengan menggunakan penjana angin. Dengan penurunan harga bagi magnet kekal berprestasi tinggi pada masa kini, memungkinkan pembinaan penjana angin yang lebih kompak dan berkecekapan tinggi. Permasalahan yang timbul dengan penjana bersaiz ini ialah pengurusan suhu. Oleh itu, kajian ini bertujuan membangunkan model empirikal yang akan menganggar suhu gegelung dawai di bawah pengaruh penyejukan secara perolakan semula jadi dan paksaan. Proses permodelan ini dimulakan dengan menjalankan eksperimen di pelbagai keadaan operasi sambil memerhatikan suhu di beberapa lokasi pada penjana angin. Cabaran dalam menjalankan eksperimen adalah ia memerlukan masa yang panjang bagi membolehkan suhu untuk mencapai keadaan yang stabil. Maka, kajian ini mencadangkan satu kaedah untuk mengurangkan masa eksperimen dengan menganggarkan masa stabil dengan memodelkan sistem kejuruteraan kawalan. Dengan menggunakan kaedah ini, penjimatan masa eksperimen ialah 55% dengan ralat sebanyak 1% antara suhu yang diramalkan dan suhu pada keadaan stabil. Oleh kerana beberapa kekangan pada peralatan eksperimen, eksperimen yang menjana arus tinggi (melebihi 1 amp) tidak dapat dijalankan, ini membawa kepada alternatif secara penyelakuan. Cabaran penyelakuan bermula dengan kesukaran untuk mengukur parameter fizikal pada penjana angin. Dengan itu kaedah yang dicadangkan untuk mengatasi masalah ini dengan menggunakan teknik pemprosesan imej. Cabaran seterusnya ialah untuk menjana jejaring yang berkualiti semasa proses permodelan elektromagnet. Penyelesaiannya melalui kaedah mudah suai yang menyebabkan nilai fluks magnet meningkat sebanyak 5.3% berbanding dengan menggunakan kaedah automatik yang membawa kepada keputusan elektromagnet yang lebih baik. Permodelan elektromagnet telah berjaya dilaksanakan dan disahkan dengan perbezaan kurang daripada 4.0% bagi V_{rms} (volt) antara keputusan penyelakuan dan keputusan eksperimen. Keputusan elektromagnet kemudiannya dipindahkan ke perisian pakej Ansys Fluent untuk analisis dinamik bendalir. Perisian ini digunakan untuk menyelakukan proses pemanasan dan kesan penyejukan melalui perolakan semula jadi dan paksaan di penjana angin. Dua model empirikal telah dibangunkan untuk meramal suhu gegelung dawai dengan perbezaan kurang daripada 10.7% ketika penyejukan perolakan semula jadi berbanding dengan keputusan eksperimen. Sementara itu, bagi perolakan model empirikal paksaan, ia telah digunakan untuk menganggarkan arus elektrik dan suhu maksimum di pelbagai keadaan operasi. Kajian ini telah membuktikan bahawa model empirikal boleh digunakan sebagai kaedah alternatif untuk meramal suhu gegelung dawai di pelbagai keadaan operasi dengan lebih tepat.

Modeling of the Winding Coil Temperature In a Compact Permanent Magnet Wind Generator

ABSTRACT

Wind energy harvesting has existed since ancient civilization. Nowadays, wind energy is harvested to generate electricity using a wind generator. With the recent reduction in the price of high-performance permanent magnet, it is made possible to construct a high-efficiency compact generator. One of the problems with the compact generator is temperature management. Hence, this study aims to develop empirical models in estimating the winding coil temperature for natural and forced convection cooling. The modeling process was started with conducting experiments at various operating conditions while observing temperatures at several locations on the wind generator. One of the challenges in conducting the experiment is that it consumed a lot of time for the temperature to reach its steady state condition. Thus, this study proposes a method to reduce the experimental time by estimating the settling time using a control system engineering modeling technique. By using the method, the experimental time reduces by 55% with the difference of 1% between the predicted temperature and the steady state temperature. Due to several limitations of the experimental equipment, experiments with high current output (more than 1 amp) cannot be conducted, this leads to the alternative of simulation experiments. The challenges of simulation experiments started with the difficulty to acquire parts dimension. A method is proposed to acquire the dimension by using an image processing technique. The next challenge is to generate a quality mesh during the electromagnetic modeling process. To tackle this problem, an adaptive meshing technique is used which resulted in magnetic flux value increases by 5.3% compared to an automatic meshing method. The electromagnetic modeling was successfully implemented and validated with the difference of less than 4.0% in V_{rms} (volt) between simulation and experimental results. The electromagnetic results were then transferred to Ansys Fluent for computational fluid dynamic analysis. The Ansys Fluent software was used to simulate heating and cooling effects via natural and forced convection at the wind generator. Two empirical models were developed to predict the winding coil temperature with the difference of less than 10.7% in the natural convection cooling results compared to the experimental results. As for the forced convection empirical model, it was used to estimate the maximum current output and temperature at various operating conditions. This study has proven that an empirical model can be used to predict the winding coil temperature at various operating condition with a good accuracy.

CHAPTER 1

INTRODUCTION

This chapter starts with the introduction of a permanent magnet generator as a clean power production, followed by the importance of a thermal management for a generator and several winding coil temperature models are presented in general. Furthermore, the objectives and outlines of this research are also explained in details.

1.1 Permanent Magnet Generator

A permanent magnet generator is a generator where the magnetic field in the rotor winding is produced by permanent magnets instead of electromagnets. Permanent magnet generators are the primary source of commercial electrical energy for low rated power output. They are commonly used to convert mechanical power output of steam turbines, gas turbines, hydro turbines and wind turbines into electrical energy.

There are several types of commonly used permanent magnet generator nowadays. Most of the permanent magnet generator use either a direct transmission or a gear mechanism to rotate the rotor that acts as the prime mover. Based on the internal design of the generator, it can be either radial or axial type depending on the axis of the magnetic field that cut the winding wire. The axial type is simple and inexpensive, but the drawback is, it is less efficient compared to the radial type that is more complex and expensive but rather high efficient based on its performance on energy conversion (Grauers, 1996).

To maximize the energy conversion from wind energy to electrical energy, a highly efficient generator needs to be developed. Several improvements on the generator design have been studied to make it compact and the used of rare earth material as permanent magnet such as Samarium Cobalt ($SmCo_5$) and Neodymium Iron Boron (NdFeB) have significantly increased the efficiency of the permanent magnet generator. The development of rare earth magnetic materials and the recent reduction in their prices made the construction of high-efficiency permanent magnet generator possible.

However, the problem with the high-efficiency and compact generator is its temperature management. It is essential to control the temperature of the magnets, winding coils and binder so that the magnets will not be demagnetized, winding coils will not melt causing short-circuit and the binder will not lose its binding properties. If the stator windings are wound with epoxy resin, when the temperature exceeds the binder or the epoxy resin critical limits, the magnet and winding start loosening and eventually detach from the rotor and stator (Hong, 2010). The detachment of magnet and winding coils could lead to the catastrophic failure of the generator. According to Baolin and Qingbo (2009), since 1980s, when wind farms were first constructed, it is found that fire has accounted for 10% to 30% of reported wind turbine accidents. Figure 1.1(a) shows the burned petrol generator at open space, whereas Figure 1.1(b) shows the burned wind generator at the wind farm near Jackson, Minnesota, USA. Therefore, the need of thermal management for all types of power generator is compulsory to ensure the safety of the generator and its user.

(a) (b)

Figure 1.1: Examples of burned generators (Baolin & Qingbo, 2009)
(a) Petrol generator and (b) Wind generator.

1.2 Thermal Management for Generator

The publication activity in the field of permanent magnet generator cooling has been very intense over the past few years. This is mainly because the temperature of the new Neodymium-Iron-Boron (NdFeB) permanent magnet should be kept as low as possible at all operating conditions. As magnet temperature increases, the remanence flux density of the NdFeB magnet decreases, thus reducing the performance of the generator (Slemon, 1994). Furthermore, too high magnet temperature could lead to irreversible demagnetization of the permanent magnet material.

There are three main sources of heat produced inside the permanent magnet generator. First, in the winding coil itself where the current and the copper resistance causes the Joule Losses. Second in the laminated core where the variation of the magnet field causes Eddy Current thus leads to Iron losses. Third is Stray Losses that came from the bearings where the mechanical friction results in heat generation (Wenming, Shengnan, Zhongliang, Hongyang, & Renyuan, 2010).

The heat from the winding coils dissipated to the stator laminated plates causes the stator temperature to rise and heat is transmitted to other generator components, such as magnets, rotor and casing, by means of conduction and convection heat transfer. Due to the relatively low-temperature differences between components in the generator, the radiation heat transfer inside the generator can be neglected (Giovanni, 2010).

There are two configurations of air cooling system for generators, first is the self-ventilated and another is externally ventilated. For the self-ventilated air cooling, a special feature of rotor disk has used that act as a pump impeller to draw the ambient air through the gaps between stator and rotor disk (Hong, 2010). Most of the self-ventilated cooling system are air cooled.

For the high power generator, self-ventilated air cooling may not be sufficient to reduce the temperature. Therefore, an externally ventilated cooling system like external fans is required. For extreme temperature, the generator may need an external fluid cooling system like water cooling system embedded into the stator core to bring down the temperature (Hong, 2010). Hence, the need of temperature model to design a cooling system of generators especially for the winding coils is necessary to ensure that the thermal cooling system is efficient in lowering the temperature.

1.3 Winding Coil Temperature Models

There are three types of thermal model used to model the temperature for internal parts of the generator especially the winding coils. The most well-known thermal model methods are Lump Parameter Model (LMP), Computational Fluid Dynamic (CFD) model and Empirical Model. All the three models have their own advantages and disadvantages.

In the LMP model, the generator is divided into a number of lumped components and each lumped component is represented by a collection of thermal impedances and capacitances. The construction of thermal equivalent circuit is done by connecting the collection of thermal impedances and capacitances based on the heat flow paths in the generator (Hong, 2010). Besides the thermal impedances and capacitances, the heating and the cooling elements are also modeled in terms of thermal resistances in the thermal equivalent circuit as presented by Nerg, Rilla, and Pyrhonen (2008).

The LMP model can be used to handle all three types of heat transfer mechanisms such as conduction, convection and radiation heat transfer (Nerg & Ruuskanen, 2013). However, this model heavily depends on the conduction and convection heat transfer coefficients that are often difficult to determine. Furthermore, the Nusselt number, Reynolds number, Prandtl number and Taylor number are required to calculate the convection coefficient values in various locations in the generator and to measure them accurately is a tough task (Nerg & Ruuskanen, 2013).

In the CFD model, a numerical method is used 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. It is a common practice in CFD to have all the part dimensions and properties for all solids and fluids involved in the simulation to be as accurate as possible to acquire good simulation results.

The use of CFD models allows the designer to evaluate and predict several characteristics such as airflow velocity inside and outside the generator in details. Once the airflow velocity has been determined, the convection heat transfer coefficient can be calculated (Boglietti et al., 2009). However, the disadvantage of using the CFD model is that the application is computationally very expensive (require a high-end computer) and time-consuming and it is not suitable for preliminary design stage where there are many redesigns taking place that requires certain aspects to be analyzed in a short period of time (Nerg & Ruuskanen, 2013).

On the other hand, empirical model refers to any modeling based on observations data (experimental data or simulation data) rather than depend on mathematically describable relationships of the system modeled. When the theoretical model cannot be formulated due to the complexity of the problem, an empirical model is an excellent alternative. Kravtsov, Tilinina, Zyulyaeva, and Gulev (2016), Tan and Can (2004) and Storkey, Cussans, Lutman, and Blair (2003) have formulated empirical models using validated simulation data in their studies.

One of the advantages of the empirical model is that it required systematical and well-organized data either experimental data or simulation data that can be obtained for example, using Design of Experiments method (DOE) such as Response Surface Methodology (RSM) instead of struggling with complex physical laws to formulate a theoretical model. On the other hand, the disadvantage of empirical model is that it will never be superior compared to the theoretical model in term of results due to the noise factors when conducting the experiment. This noise factors will cause the empirical model to be less accurate compared to the theoretical model.

Basically, formulated models are only useful if they help to solve problems. The best model whether it is theoretical or empirical, is where the model can predict the best solution thus finally able to solve the problem.

1.4 Problem Statement

As mentioned earlier in this chapter, the problem with the high-efficiency and compact generator is the temperature management. It is essential to control the temperature of the magnets and winding coils to avoid overheating. If the temperature exceeds the maximum limit, magnets could be demagnetized and winding coils could