



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

By

**NOR ZAIAZMIN BIN YAHAYA
(1340510952)**

A thesis submitted in fulfillment of the requirements for the degree of
Doctor of Philosophy

**School of Manufacturing Engineering
UNIVERSITI MALAYSIA PERLIS**

2018

ACKNOWLEDGEMENT

Alhamdulillah. Thanks to Almighty ALLAH for nothing good happens except by ALLAH consent.

First and foremost, I would like to express my sincere gratitude to my supervisors Assoc. Prof. Dr. Khairul Azwan Bin Ismail and Assoc. Prof. Dr. Muhamad Saifuldin Bin Abdul Manan for their continuous support, patience, motivation, immense knowledge and experience, time and advice towards the completion of my Ph.D. study. I could not have imagined having a better advisor and mentor for my Ph.D. study other than both of them. Without their support, this research study would not have been possible.

Besides my advisors, I would like to thank the Dean, all my friends and colleagues at School of Manufacturing Engineering, Universiti Malaysia Perlis, particularly Dr. Azuwir Bin Mohd Nor and Ir. Dr. Mohamad Shaiful Ashrul Bin Ishak for all the valuable discussion, support, insightful comments and encouragement which motivated me to widen my research from various perspectives.

Last but not the least, I would like to thank my parents Yahaya Bin Mat Rafar and Siti Hawa Binti Nordin for supporting me spiritually and emotionally throughout the journey in completing this thesis whose love and guidance are always there for me. They are my ultimate role models. Love both of you so much.

Nobody has been more important to me in the pursuit of this research study than the members of my family. I would like to thank my loving and supportive wife, Noraini Binti Othman and my four wonderful children, Farzana Izzati, Fatinah Irdina, Fadhilah Insyirah and Fatimah Intisar, who provide unending inspiration and love.

Once again, thanks to Almighty ALLAH, AR-RAHMAN (The Possessor of Vast Mercy), AR-RAHIM (The Most Merciful).

TABLE OF CONTENTS

	PAGE
THESIS DECLARATION	i
ACKNOWLEDGEMENT	iii
TABLE OF CONTENTS	iv
LIST OF TABLES	x
LIST OF FIGURES	xii
LIST OF SYMBOLS	xvi
ABSTRAK	xviii
ABSTRACT	xix
CHAPTER 1: INTRODUCTION	1
1.1 Permanent Magnet Generator	1
1.2 Thermal Management for Generator	3
1.3 Winding Coil Temperature Models	4
1.4 Problem Statement	6
1.5 Research Objectives	7
1.6 Research Scopes	8
1.7 Research Flow	9
1.8 Outline of Thesis	10
CHAPTER 2: LITERATURE REVIEW	12
2.1 Introduction	12
2.2 Lumped Parameter Modeling	13
2.2.1 Thermal equivalent circuits for one-dimensional (1-D)	15

2.2.2	Thermal equivalent circuits for two dimensional (2-D)	17
2.2.3	Convective: Temperature Passing Method (TPM)	19
2.2.4	Convective: Heat Pickup Method	20
2.2.5	Advantages of the LMP method	22
2.2.6	Shortcomings of the LMP method	24
2.3	Computational Fluid Dynamics (CFD) Modeling Method	25
2.3.1	Discretization Methods	26
2.3.2	Turbulence Models	28
2.3.3	Continuity and Momentum Equations	32
2.3.4	Advantages of the CFD method	33
2.3.5	Shortcomings of the CFD method	34
2.4	Thermal Analysis using coupling method (FEA+CFD)	36
2.4.1	Advantages of the coupling method	38
2.4.2	Shortcomings of the coupling method	39
2.5	Sources of Heat in Permanent Magnet Generator	40
2.5.1	Copper Losses	40
2.5.2	Iron Losses	41
2.5.3	Mechanical Losses	41
2.5.4	Stray Losses	42
2.6	Cooling Methods	42
2.6.1	Air cooling	43

2.6.2	Liquid cooling	44
2.7	Packaging Design	45
2.7.1	Closed type	45
2.7.2	Opened type	46
2.8	Research Gaps	47
CHAPTER 3: EXPERIMENTAL INVESTIGATION		48
3.1	Introduction	48
3.2	Experimental Apparatus	49
3.2.1	Permanent Magnet Wind Generator	49
3.2.2	Servo Motor	51
3.2.3	Servo Driver	52
3.2.4	Resistive load	53
3.3	Temperature Measurement Equipment	54
3.3.1	Thermocouple Amplifier IC	54
3.3.2	Microcontroller	56
3.3.3	Calibration	57
3.3.4	Data Acquisition and Logging	58
3.4	Experimental Procedures	60
3.4.1	Screening	60
3.4.2	Design of Experiment	61
3.5	Temperature Profile	64
3.5.1	Rise Time	64

3.5.2	Settling Time	66
3.5.3	Winding Coil Temperature Profile	66
3.5.4	Room Temperature Profile	68
3.5.5	Coil Temperature Profile Validation	72
3.6	Data analysis using ANOVA	74
3.6.1	Effect Analysis	76
3.6.2	Empirical Model	79
3.7	Experiment Limitation	79
3.8	Summary	80
CHAPTER 4: ELECTROMAGNETIC MODELING		81
4.1	Introduction	81
4.2	Dimension Acquiring Method	82
4.2.1	Acquiring Dimensions Using Image Processing Technique	83
4.3	Creating Generator Parts in Ansys Maxwell	85
4.3.1	Rotor	85
4.3.2	Stator	86
4.3.3	Winding Coils	87
4.4	Electromagnetic Meshing	88
4.4.1	Automatic Meshing	88
4.4.2	Adaptive Meshing	90
4.5	Electromagnetic Analysis	92
4.5.1	Transient Analysis	93

4.5.2	Total Loss Analysis	95
4.5.3	Volumetric Heat Source	95
4.6	Validating the Electromagnetic Simulation	97
4.7	Summary	99
CHAPTER 5: COMPUTATIONAL FLUID DYNAMIC MODELING		101
5.1	Introduction	101
5.2	Winding Coils Non-Contact Issue	103
5.3	Meshing Process	107
5.3.1	Mesh Dependent Study	112
5.3.2	Mesh Visualization	115
5.4	CFD Simulation Parameters Setup	117
5.4.1	Turbulence Model	117
5.4.2	Boundary Conditions	120
5.4.3	Solver Setting Parameters	123
5.5	Validation of CFD simulation	124
5.6	Design of Experiment for 3D CFD simulation	126
5.7	CFD Data analysis using ANOVA	129
5.7.1	Natural Convection Cooling	129
5.7.2	Forced Convection Cooling	134
5.8	Empirical Model	138
5.8.1	Natural Convection Cooling Model	139
5.8.2	Forced Convection Cooling	144

5.9	Estimating the Winding Coils Temperature using the Empirical Models	149
5.9.1	Winding Coil Temperature under Natural Convection Cooling	149
5.9.2	Winding Coil Temperature under Forced Convection Cooling	150
5.10	Summary	153
CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS		154
6.1	Summary of Present Work	154
6.2	Suggestion for Future Work	156
REFERENCES		157
LIST OF PUBLICATION		165
APPENDIX A		166

©This item is protected by original copyright

LIST OF TABLES

NO.	PAGE
Table 2.1: Strength and weaknesses of several types of discretization methods.	26
Table 2.2: Comparison of the three cooling methods	45
Table 3.1: 3-phase 1000 Watts Synchronous Permanent Magnet Wind Generator Specification.	51
Table 3.2: Servo motor specification.	52
Table 3.3: Servo Driver Specification.	53
Table 3.4: Thermocouple amplifier specification.	55
Table 3.5: Microcontroller specification.	56
Table 3.6: Temperature Calibration Results.	58
Table 3.7: Sample data logged by Matlab package software.	59
Table 3.8: Selected Input Variables and their Ranges.	61
Table 3.9: Number of experiment run per input variables using RSM-CCD method.	62
Table 3.10: Input variables and their ranges	63
Table 3.11: Experiment runs with 2 factors and 5 center points.	63
Table 3.12: The effect of the Room Temperature and Winding Coil Temperature.	72
Table 3.13: Winding coil temperature validation.	73
Table 3.14: RSM-CCD Experimental Data.	75
Table 4.1: Comparison between Catia and Vernier Caliper measurements.	84
Table 4.2: Validation on the dimension measurement of hole done by Catia.	84
Table 4.3: Rotor and magnets dimensions used in the Ansys Maxwell.	85
Table 4.4: Stator dimension used in the Ansys Maxwell.	86
Table 4.5: Winding coil dimension used in the Ansys Maxwell.	87
Table 4.6: Automatic and adaptive meshing methods comparison.	91

Table 4.7: Comparison between experimental results and simulation results.	99
Table 5.1: Mesh quality rubric based on ANSYS Mesh manual.	113
Table 5.2: Mesh dependent study for 3D model wind generator.	114
Table 5.3: Meshing quality.	115
Table 5.4: Minimum Reynolds number required for turbulent to develop.	118
Table 5.5: Temperature dependent air properties.	122
Table 5.6: ANSYS Fluent parameters setting.	124
Table 5.7: Validation of the CFD simulation.	124
Table 5.8: List of simulation runs for natural convection cooling.	127
Table 5.9: List of simulation runs for forced convection cooling.	128
Table 5.10: Simulation results for natural convection cooling.	130
Table 5.11: ANOVA analysis for natural convection results.	131
Table 5.12 : Simulation results for forced convection cooling.	135
Table 5.13: ANOVA analysis for forced convection cooling.	136
Table 5.14: ANOVA for simplified empirical model for natural convection.	140
Table 5.15: Evaluating the simplified empirical model vs. simulation data.	141
Table 5.16: Evaluating the simplified empirical model vs. experimental data.	143
Table 5.17: ANOVA for simplified empirical model for forced convection.	146
Table 5.18: Simplified empirical model regression results for forced convection.	147
Table 5.19: Temperature Estimation at 30°C Environment Temperature.	149
Table 5.20: Temperature Estimation at 30°C with 1 m/s air velocity.	150
Table 5.21: Temperature Estimation at 30°C with 10 m/s air velocity.	151

LIST OF FIGURES

NO.	PAGE
Figure 1.1: Examples of burned generators	3
Figure 1.2: Research Flow.	10
Figure 2.1: 2-D Thermal circuit of annulus or ring solid	17
Figure 2.2: Control volume for TPM thermal circuit.	19
Figure 2.3: Temperature passing method	20
Figure 2.4: Convection heat transfer modeling by HPM	21
Figure 2.5: Types of meshing element commonly used.	27
Figure 2.6: Couple Analysis	36
Figure 2.7: Steady-state thermal analysis of 2-D using FEA.	37
Figure 2.8: Types of Losses in electrical machine.	40
Figure 3.1: A 1000 watts wind generator and apparatus for experiment.	49
Figure 3.2: 3-phase 1000 watts synchronous permanent magnet wind generator.	50
Figure 3.3: Servo motor and flexible coupler.	51
Figure 3.4: Servo driver.	52
Figure 3.5: Thermocouple IC	55
Figure 3.6: PIC microcontroller.	56
Figure 3.7: Temperature calibration device.	57
Figure 3.8: Location of the thermocouples.	60
Figure 3.9: 1 st order response curve.	65
Figure 3.10: Winding coil temperature recorded during an experiment.	65
Figure 3.11: Extrapolation of experimental data.	67
Figure 3.12: Room Temperature vs. Extrapolated Curve.	69
Figure 3.13: Coils & Room Temperature Curves (Uncontrolled Room Temperature).	70

Figure 3.14: Coils & Room Temperature Curves (Controlled Room Temperature).	71
Figure 3.15: Winding Coil Temperature between Controlled and Uncontrolled Room Temperature.	71
Figure 3.16: Winding coil temperature validation for 24 hours.	73
Figure 3.17: Surface plot for voltage response.	76
Figure 3.18: Surface plot for current response.	77
Figure 3.19: Surface plot for coil temperature.	78
Figure 4.1: The concept of multiphysics analysis	82
Figure 4.2: Interior of the wind generator (a) Captured photo and	83
Figure 4.3: Wind generator model in Ansys Maxwell.	88
Figure 4.4: Automatic meshing of the electromagnetic modeling.	89
Figure 4.5: Adaptive meshing process.	90
Figure 4.6: Adaptive meshing of the electromagnetic modeling.	92
Figure 4.7: Example of induced voltage output result.	94
Figure 4.8: Example of induced current output result.	94
Figure 4.9: Example of the total loss result.	95
Figure 4.10: Common losses in the generator.	96
Figure 4.11: Volumetric heat source (W/m^3).	96
Figure 4.12: Raw induced voltage data and traced sinusoidal waveform.	97
Figure 4.13: Filtered experimental induced voltage waveform.	98
Figure 4.14: Electromagnetic simulation induced voltage waveform.	98
Figure 5.1: CFD Flowchart	102
Figure 5.2: Winding coils are not in contact with the stator body in ANSYS Maxwell.	104
Figure 5.3: Large gap at stator slot in ANSYS Maxwell.	104
Figure 5.4: Adding contact pad at the stator slot in CAD software.	105

Figure 5.5: Winding coils contact with stator slot.	106
Figure 5.6: Wind generator 3D model with casing.	106
Figure 5.7: Wind generator cross section view before meshing.	108
Figure 5.8: Meshing result using automatic meshing method.	109
Figure 5.9: ANSYS Fluent energy residual graph for non-converges energy term.	109
Figure 5.10: Improved meshing result view at stator from YX Plane.	110
Figure 5.11: Improved meshing result views.	111
Figure 5.12: Automatic meshing with surface contact method.	116
Figure 5.13: Final meshing using 35% element size reduction with surface contact method.	116
Figure 5.14: Overall picture after the final meshing at the YZ plane view.	117
Figure 5.15: Air flow inside and outside of the wind generator.	118
Figure 5.16: Mean flow velocity profile	119
Figure 5.17: Inlet and outlet boundary condition.	121
Figure 5.18: Solution procedures.	123
Figure 5.19: Simulation results for Case 2 (XY Plane).	126
Figure 5.20: Residual graph for converging indication.	126
Figure 5.21: Contour plot for natural convection cooling at (a) 20°C, (b) 40°C and (c) 50°C.	133
Figure 5.22: Contour plots for forced convection cooling at air flow of 5m/s for (a) 20°C, (b) 40°C and (c) 50°C.	137
Figure 5.23: Predicted temperature vs. simulation results.	142
Figure 5.24: Predicted temperature vs. experimental results.	144
Figure 5.25: Predicted temperatures vs simulation temperatures.	148
Figure 5.26: Winding Coils Temperature vs Current Output at Various Environment Temperature.	152
Figure 5.27: Winding Coils Temperature vs Current Output at Various Air Velocity.	152

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
$Q_{\text{convection}}$	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 Gegeleung 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