

T.R.
GEBZE TECHNICAL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

**DESIGN AND APPLICATION OF AN AXIAL FLUX PM
GENERATOR WITH FLYWHEEL FOR LINEAR INDUCTION
LAUNCHERS**

CEYHUN SEZENÖĞLU
A THESIS SUBMITTED FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY
DEPARTMENT OF ELECTRONICS ENGINEERING

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PROF. DR. ABDULKADİR BALIKÇI

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JÜRİ

ÜYE

(TEZ DANIŞMANI) : Prof. Dr. Abdulkadir BALIKÇI

ÜYE

: Prof. Dr. M. Hakan HOCAOĞLU

ÜYE

: Doç. Dr. Uğur Savaş SELAMOĞULLARI

ÜYE

: Prof. Dr. Ercan ERTÜRK

ÜYE

: Doç. Dr. Uğur HASIRCI

ONAY

Gebze Teknik Üniversitesi Fen Bilimleri Enstitüsü Yönetim Kurulu'nun
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SUMMARY

In this study, a flywheel energy source is designed for linear induction electromagnetic launchers driven by the generator. In this context, it is determined as the initial condition for a 200 gr projectile to reach 200 m/s speed for an existing launcher. A flywheel energy storage system is also integrated. In principle, the energy in the mains is transferred to the flywheel with the help of a motor, and at a certain time, it is transferred to the launcher with the help of the proposed generator directly connected to the flywheel. The energy required for the specified projectile weight and speed and the flywheel size required for this energy are calculated. Electrical and geometric limits are determined for the design of the generator directly connected to the flywheel shaft. In the generator design, the number of poles, magnet geometry, material and thickness of rotor steel, air gap width, wire cross-section, number of turns and winding type selection are analyzed in detail. Parametric analyses were used when determining the parameters of the generator. In addition, the analyses were supported by the software using the finite element method. The simulations of the designed generator run. As a result of these simulations, magnetic flux density in the air gap, induced voltage, and performance results under load are obtained. In addition, parametric analyses are carried out for various launchers. Finally, the production steps are explained in detail and no-load tests have been carried out.

Keywords: Electromagnetic launchers, Energy storage, Axial flux permanent magnet machines, Flywheel, Energy source.

ÖZET

Bu çalışmada üreteç ile sürülen lineer indüksiyon elektromanyetik fırlatıcılar için volanlı bir enerji kaynağı tasarlanması hedeflenmiştir. Bu kapsamda, mevcut bir fırlatıcı için 200 gramlık bir mermiyi 200 m/s hıza ulaştırılması başlangıç koşulu olarak belirlenmiştir. Ayrıca enerji depolamak için bir volan sistemi entegre edilmiştir. Temel prensip olarak şebekedeki enerji bir motor yardımı ile volanda depolanacak, belirli bir zamanda ise volana direk bağlı önerilen üreteç yardımı ile bu enerji fırlatıcıya aktarılacaktır. Belirtilen mermi ağırlığı ve hızı için gerekli enerji ve bu enerji için gerekli volan büyüklüğü hesaplanmıştır. Volan miline direk bağlı olan üretecın tasarımı için elektriksel ve geometrik sınırlar belirlenmiştir. Üreteç tasarımında kutup sayısı, mıknatıs geometrisi, rotor çeliği malzemesi ve kalınlığı, hava aralığı genişliği, tel kesiti, tur sayısı ve sargı türü seçimi detaylıca analiz edilmiştir. Üretecın parametreleri belirlenirken parametrik analizler kullanılmıştır. Ayrıca analizler sonlu elemanlar yöntemi kullanan bir program ile desteklenmiştir. Tasarımı tamamlanan üretecın benzetimleri koşturulmuştur. Bu benzetimler sonucunda hava aralığındaki manyetik akı yoğunluğu, indüklenen gerilim ve yük altındaki performans sonuçları elde edilmiştir. İlave olarak farklı fırlatıcılar için parametrik analizler gerçekleştirilmiştir. Son olarak üretim adımları detaylıca açıklanmış ve yüksüz testleri gerçekleştirilmiştir.

Anahtar Kelimeler: Elektromanyetik fırlatıcılar, Enerji depolama, Eksenel akılı sürekli mıknatıslı makineler, Volan, Enerji kaynağı.

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TABLE of CONTENTS

	<u>Page</u>
SUMMARY	v
ÖZET	vi
ACKNOWLEDGEMENTS	vii
TABLE of CONTENTS	viii
LIST of ABBREVIATIONS and ACRONYMS	xi
LIST of FIGURES	xiii
LIST of TABLES	xvi
1. INTRODUCTION	1
2. ELECTROMAGNETIC LAUNCHERS	4
3. AXIAL FLUX PERMANENT MAGNET MACHINES	7
3.1. Analytical Model	10
3.1.1. Solution with Magnetic Scalar Potential	11
3.1.1.1. Acquiring Magnetization of Magnet	13
3.1.2. Solution with Magnetic Vector Potential	13
3.2. Magnetic Circuit Model	15
3.2.1. Permanent Magnet Model	15
3.2.2. Leakage Flux Model	16
3.2.3. Rotor Back-Iron Model	18
3.2.4. Air Gap Model	19
3.3. Thermal Analysis	20
3.3.1. Conduction	21
3.3.2. Convection	21
3.3.3. Radiation	22
3.3.4. The Heat Diffusion Equation	22
3.3.5. Heat Generation	25
3.3.6. Temperature Change in Current-Carrying Wire	25
3.4. Winding	27
3.5. Voltage Model and Power	30
3.6. Applications	32

3.6.1.	Aircraft	33
3.6.2.	Electric Vehicles	33
3.6.3.	Marine Applications	34
3.6.4.	Wind Turbines	35
3.6.5.	High-Speed Applications	36
3.6.6.	Other Applications	37
4.	DESIGN OF ENERGY SOURCE	38
4.1.	Linear Induction Launcher	38
4.2.	Motor	40
4.3.	Flywheel System	41
4.4.	Axial-Flux Permanent Magnet Generator	43
5.	DESIGN OF AFPM GENERATOR	44
5.1.	Number of Poles	45
5.2.	Magnet Geometry	45
5.3.	Rotor Yoke Thickness	49
5.4.	Air Gap Distance	49
5.5.	Wire Cross Section Area	51
5.6.	Number of Turns	51
5.7.	Winding	52
5.7.1.	Inductance Analysis of Concentrated and Wave Winding	52
6.	SIMULATIONS	54
6.1.	Magnetic Flux Density	54
6.2.	Induced Voltage	58
6.3.	Comparison of Winding Configurations	59
6.3.1.	Single Stage Same Active Volume	60
6.3.2.	Same Air Gap Distance	62
6.4.	Loaded Simulations	64
6.4.1.	Parametric Analyses	68
6.4.1.1.	$L_L = 1 \mu\text{H}$	70
6.4.1.2.	$L_L = 15 \mu\text{H}$	71
6.4.1.3.	$L_L = 100 \mu\text{H}$	72
6.4.1.4.	$L_L = 400 \mu\text{H}$	73
6.4.1.5.	$L_L = 800 \mu\text{H}$	74
6.4.1.6.	$R_G = 80 \text{ m}\Omega$	75

6.5.	Winding Resistance and Inductance	76
7.	MANUFACTURING AND TESTS	77
7.1.	Generator Test Bench with Flywheel	77
7.2.	Stator Manufacturing	78
7.2.1.	Preparing Coppers of Wave Winding	79
7.2.2.	Soldering	80
7.2.3.	First Mold of the Stator	81
7.2.4.	Arrangement and Soldering of Windings in First Mold	83
7.2.5.	Removing the Stator from the First Mold	84
7.2.6.	Second Mold of the Stator	86
7.2.7.	Arrangement and Soldering of Windings in the Second Mold	87
7.2.8.	Removing the Stator from the Second Mold	88
7.3.	Rotor Manufacturing	89
7.4.	Mounting Generator and Tests	90
7.4.1.	Mounting Generators	90
7.4.2.	No-Load Tests	92
8.	CONCLUSION	94
	REFERENCES	96
	BIOGRAPHY	104
	APPENDICES	105

LIST of ABBREVIATIONS and ACRONYMS

<u>Abbreviations</u>	<u>Explanations</u>
<u>and Acronyms</u>	
A	: Area
A_m	: Area of magnet (m ²)
$\vec{A}$	: Magnetic vector potential
B	: Magnetic flux density
c_p	: Specific heat (J/kg.K)
e	: Induced voltage (V)
E	: Electric field
E_{KA}	: Stored energy on flywheel (J)
E_{KR}	: Required energy on launcher (J)
ER	: Energy recovery from the flywheel
$\dot{E}_g$	: Generated thermal energy
$\dot{E}_{in}$	: Entering thermal energy
$\dot{E}_{out}$	: Leaving thermal energy
$\dot{E}_{st}$	: Stored thermal energy
g	: Distance of air gap (m)
I	: Current (A)
J	: Inertia of flywheel (kg.m ²)
k	: Thermal conductivity
l	: Length (m)
l_m	: Magnet length (m)
m	: Mass of projectile (kg)
M	: Mean magnetization
$\vec{M}$	: Magnetization vector
p	: Number of poles
P_{out}	: Output power (W)
q	: Number of slots per pole and phase
$\dot{q}$	: Heat transfer rate
q_c	: Number of coils per pole and phase

Q_c	:	Number of winding coils
Q_s	:	Number of stator slots
R	:	Resistance (Ω)
R_g	:	Reluctance of air gap
R_{iron}	:	Reluctance of iron
R_m	:	Reluctance of magnet
t	:	Time (s)
T	:	Temperatures (K)
v	:	Volume (m^3)
V	:	Volume (m^3)
y_d	:	Coil pitch
r	:	Distance
ρ	:	Density of the material (kg/m ³)
ρ_c	:	Resistivity
ρ_{cu}	:	Resistivity of copper
φ	:	Electric potential
ψ	:	Flux linkage
Ψ	:	Potential distribution
∇	:	Vector differential operator
μ_0	:	Permeability of free space
μ_r	:	Permeability of material
η	:	Efficiency
AFPM	:	Axial Flux Permanent Magnet
EDM	:	Electric Discharge Machining
EMIL	:	Electromagnetic Induction Launcher
EML	:	Electromagnetic Launcher
GTU	:	Gebze Technical University
LIL	:	Linear Induction Launcher
RFG	:	Rising Frequency Generator
RFPM	:	Radial Flux Permanent Magnet
SEMA	:	Segmented Electromagnetic Array
TFPM	:	Transverse Flux Permanent Magnet
VAWT	:	Vertical Axis Wind Turbine

LIST of FIGURES

<u>Figure No:</u>	<u>Page</u>
2.1: Energy density and power density level for different pulsed power supplies.	6
3.1: Classification of Axial Flux Permanent Magnet Machines.	8
3.2: Cross-section of main topologies of AFPM machines: a) Single rotor single stator, b) single rotor, double stator, c) Multi-disk, d) Single coreless stator and two rotors, e) Single cored-stator and two rotors, f) Single salient pole stator and two rotors.	9
3.3: Current sheet model [47].	14
3.4: Magnetic circuit model of a two-rotor and a coreless stator AFPM machine.	15
3.5: Permanent Magnet Model (a) Thevenin Equivalent Model, (b) Norton Equivalent Model.	16
3.6: PM Flux Leakage Model.	17
3.7: PM Flux Leakage Circuit Model.	17
3.8: Back-Iron Model.	18
3.9: Air gap model.	19
3.10: Air gap model in detail.	20
3.11: Conduction, convection, and radiation heat transfer modes.	21
3.12: Differential control volume for conduction analysis.	23
3.13: Different examples of winding configurations (a), (b), and (c) integral-slot distributed-winding, (d) fractional-slot distributed-winding, (e) and (f) fractional-slot concentrated winding.	28
3.14: Winding classification scheme.	29
3.15: Example wave winding of a single phase [60].	30
3.16: Single-turn coil in sinusoidal field.	31
4.1: Structure of the energy source.	38
4.2: Single section linear induction launcher that 150-turn copper wire (LIL-1).	39
4.3: Single section linear induction launcher that 20-turn aluminum wire (LIL-2).	40

5.1:	Separated winding vs. conventional winding AFPM machine.	45
5.2:	Rotor layouts with circular magnets with (a) 30 mm and (b) 35 mm diameters.	47
5.3:	Rotor layouts with rectangular magnets (a) 40x15 mm, (b) 40x20 mm, (c) 40x10 mm, (d) 50x10 mm, and (e) 25x10 mm.	48
5.4:	Simulation results of the magnetic flux density on the rear surface of the rotor. Rotor yoke thickness: (a) 1 mm (b) 2 mm (c) 3 mm (d) 4 mm (e) 5 mm.	49
5.5:	Magnetic flux densities of the air gap.	50
5.6:	Inductance analysis models of windings: (a) Concentrated and (b) Wave winding.	53
6.1:	Magnetic Flux Density Analysis.	55
6.2:	Magnetic flux density of side air gaps.	56
6.3:	Average magnetic flux density of side air gaps.	56
6.4:	Magnetic flux density of middle air gap.	57
6.5:	Average magnetic flux density of middle air gap.	57
6.6:	Simulation model of proposed machine.	58
6.7:	Induced voltage of the generator.	59
6.8:	Comparison of separated winding with single stage and three stage configurations (a) Separated Winding, (b) Single stage same active volume, and (c) Three-stage same air gap.	60
6.9:	Simulation model of single stage same active volume.	61
6.10:	Induced voltage of single stage same active volume model.	62
6.11:	Simulation model of same air gap distance.	63
6.12:	Induced voltage of same air gap distance model.	64
6.13:	Circuit model of simulation.	66
6.14:	Results of Analysis-1	67
6.15:	Results of Analysis-2.	67
6.16:	Results of Analysis-3.	68
6.17:	Peak power of the generator phase and launcher phase resistance at $LL = 1 \mu H$.	70
6.18:	Peak power of the generator phase and launcher phase resistance at $LL = 15 \mu H$.	71

6.19:	Peak power of the generator phase and launcher phase resistance at $LL = 100 \mu\text{H}$.	72
6.20:	Peak power of the generator phase and launcher phase resistance at $LL = 400 \mu\text{H}$.	73
6.21:	Peak power of the generator phase and launcher phase resistance at $LL = 800 \mu\text{H}$.	74
6.22:	Peak power of the generator phase and launcher phase resistance at $RG = 80 \text{ m}\Omega$.	75
7.1:	Basic drawing of flywheel energy source test bench.	78
7.2:	Manufactured generator test bench with flywheel.	78
7.3:	Preparing coppers of wave winding.	80
7.4:	Soldering winding turns with soldering pot.	81
7.5:	Manufacturing and assembly process of first mold.	82
7.6:	CAD Drawing of first mold.	82
7.7:	Process of arrangement and soldering of windings.	83
7.8:	Removing process of the stator from the mold.	85
7.9:	Finished stator of the one phase.	85
7.10:	Manufacturing and assembly process of second mold.	86
7.11:	Arrangement and soldering of windings in second mold.	87
7.12:	Preparation of mold for epoxy casting.	88
7.13:	Removing process of the stator from the second mold.	89
7.14:	Manufacturing of rotors.	90
7.15:	Mounting the generator to the test bench.	91
7.16:	Mounting the generator to the test bench with new stator spacers.	92
7.17:	Terminal voltages of the generator at no-load.	93
7.18:	Comparison of simulated and measured voltages.	93

LIST of TABLES

<u>Table No:</u>	<u>Page</u>
2.1: Energy Storage Approaches.	5
4.1: Launcher Properties and Performance Requirements.	38
4.2: Parameters of LIL-1 and LIL-2.	40
4.3: Flywheel Dimensions, Efficiency, and Energy.	42
5.1: Initial Parameters of AFPM Generator.	44
5.2: Calculations of Magnet Geometries.	46
5.3: Air Gap Distance Calculation.	50
5.4: Temperature Rise of Copper at 1000 A.	51
6.1: Comparison of Winding Configurations.	60
6.2: Loaded Analyses Parameters.	66
6.3: Values of Parameters Determined for Analysis.	69
6.4: Calculation and Measurement Results of Resistance and Inductance.	76

1. INTRODUCTION

Designing an energy source for generator driven induction-type electromagnetic launchers requires investigation in various fields, i.e. types of electromagnetic launchers, energy storage and driving methods, and kinds of generator drives.

The electromagnetic launchers in the literature are generally grouped under two main topics: the railgun and the coilgun. In the railgun, the energy from the source is transferred directly to the projectile by electrical contact. In the coilgun, the energy is transferred to the projectile by induction. The applications in both launcher families are still under development and have not reached a certain maturity.

Coilguns are usually driven by a capacitor or a generator. The projectile movement is provided by the traveling wave generated in the launching coils. A linear induction launcher is suitable for driving with a generator and basically can be driven by a three-phase generator.

The energy source design of generator driven launchers appears in the literature as a separate study subject called rotating electrical machines. Rising frequency generators (RFG), homopolar generators, pulsed alternators, and compulsators are the main types of rotating generator power sources.

Axial flux permanent magnet (AFPM) machines can be evaluated under pulsed alternators. Specifically, AFPM machines, which can be designed as air-cored, point out due to the low inductance requirement in launcher energy sources. Axial flux permanent magnet machines are used in many applications including electric vehicles and renewable energy sources. Axial flux machines generally differ from radial machines in that the air gap flux is positioned axially. It stands out from other machines with its easy production as air-cored, modular structure and high-power density. Also, a significant improvement can be made when energy is stored mechanically with a flywheel structure to increase the capacity of the launcher energy source.

In this thesis, the energy source design for linear induction launchers is realized through an AFPM generator with flywheel. Considering the requirements of the energy source, an existing linear induction launcher is intended to increase a 200 g projectile to 200 m/s. In this context the content of the thesis was formed under the following headings: electromagnetic launchers, AFPM machines, design of energy source and AFPM generator, simulations, manufacturing, and tests.

In the electromagnetic launchers section, there is the introduction that contains types of electromagnetic launchers, energy storage and driving methods, kinds of generator drives, and a brief history of induction electromagnetic launchers.

In the AFPM machines section, there are an extensive introduction and literature review of coreless AFPM machines. The analytical and magnetic circuit model of coreless AFPM machines are explained based on the literature. Thermal analysis is given for determining the temperature rise of a current-carrying wire. Winding types of the machine are explained and given how to determine the specifications of a winding. The voltage model and power equations are given as well. Finally, applications of AFPM machines in the literature are given.

In the design of the energy source section, system design has been realized and flywheel requirement for energy needs has been determined. The energy requirement and projectile velocity are used as input in the design of the AFPM generator.

In the design of the AFPM machine, the number of poles due to projectile velocity, the geometric boundaries of the flywheel structure and the power of the projectile weight are calculated. However, the topologies of AFPM machines are difficult to meet this power and speed with the traditional approach. Therefore, with a new approach, the AFPM generator is divided into three layers inspired by the modular structure of the three-phase windings and one phase windings are placed in each layer. While designing the winding, the wave winding is selected and a new technique for its production is developed. During the design phase, all parameters of the machine are examined.

Simulations of the proposed machine are realized as a result of the design. First, the magnetic flux density in the air gap is obtained. The induced voltage of the machine was then calculated by transient magnetic analysis. The proposed separated winding structure is compared with conventional topologies. The loaded analyses were performed for different launchers and the forces obtained are calculated. Wherein the structure of the launcher and the electromagnetic generator is very dependent on each other. Finally, inductance analysis of the windings in the simulation is also performed and evaluated.

For the testing of the energy source, a test bench with a flywheel is manufactured first. The production of the generator was carried out in the laboratory and the manufacturing steps are explained in detail. The mold design required to produce the stator is obtained by two iterations. The tools and difficulties in production are also

highlighted in the manufacturing title. Finally, the open circuit tests of the generator were compared with the simulations.

2. ELECTROMAGNETIC LAUNCHERS

In the literature, there are two main types of electromagnetic launchers. The main difference between these types that supply current is directly connected to the armature (railgun) or induced in the armature (coilgun). For the railguns the armature and stator current, relative position and velocity of each other are independent. For the coilguns, the induced armature current is a function of the stator current and its position and velocity [1]. Other kinds of launchers and classifications can be found in the literature [2] [1].

Electromagnetic induction launchers (EMIL) or accelerators have been called with different names in the literature: coaxial, tubular induction or magnetic accelerator. The name “ θ -gun” was coined in 1982 [3] and a more inclusive manner coilgun in 1987 [4] [5].

There are three types of EMIL concepts in the literature [6]: the wound armature pulsed induction accelerator [7], the solid armature (reconnection) pulsed induction coilgun [8] [9], and the traveling wave linear induction launcher (LIL) [10]. In this thesis, a traveling wave linear induction launcher is used.

The basic physics of magnetic accelerators, in other words, electromagnetic launchers (EML) has been well understood since Maxwell’s time late in the 19th century. Then, rotary magnetic motors such as the common induction motors have been more popular for decades. However, EMLs have not received the same attention [11].

A mechanically synchronized discrete coil was built by Northrup in the thirties. A traveling wave accelerator that uses superconducting projectiles was proposed by Winterberg in 1966. In 1972, a brush-commutated helical accelerator was proposed by Thom and Norwood. In 1976, the first actively synchronized mass driver which use discrete coils with solid-state commutation was built by Kolm and O’Neill. In 1978 Bondaletov accelerated 2-gram aluminum rings to 5 km/s in a 1 cm length by pulsed induction. Kemmey, Gora, and Snow invented a self-storing, brush-commutated, double helix launcher in 1981. A tubular launcher driven by flux compression generators that would accelerate hollow projectiles guided and reinforced by an internal mandrel was proposed by Cowan’s group in 1984 [12] [6].

In other words, it is only in the 1970s that they have been seriously investigated. By these years it has had two major difficulties. First, the windings of all motors were wound around a ferromagnetic material such as iron and alloys. But, EMLs must operate above 10 Tesla that iron and its alloys will saturate in this region. Besides, iron-free construction was very difficult because of the presence of extreme structural forces. Second, the extremely high electrical power input needed makes it difficult to operate. For instance, the acceleration energy of over 10 MJ must be stored and then delivered in less than a millisecond [11]. Electromagnetic induction launchers have not yet been a mature technology and similar difficulties remain today.

The main component of an electromagnetic launcher is its power source. Various types of power sources can be found in the literature. The energy storage principle is the main difference among power sources. Capacitors, rotating electrical machines, inductors, batteries, and some chemical materials are energy storage technologies in pulsed power systems as shown in Table 2.1 [13]. McNab noted that despite the illustrative energy densities shown in the right-hand column of Table 2.1, real systems based on these technologies may not demonstrate differences as large as these values.

Table 2.1: Energy Storage Approaches.

Device	Storage mechanism	Defining equation	Assumption	Limiting values	Energy density (MJ/m ³)
Capacitor	Electrostatic	$E = CV^2/2$	Plastic film	$E_{op} = 590 \text{ V}/\mu\text{m}$ $\epsilon_r = 3.2$	2
Rotor	Inertial	$E = I_m \omega^2/2$	High speed rotor	$\rho = 1500 \text{ kg/m}^3$ $v_{periph.} = 400 \text{ m/s}$	60
Inductor	Magnetic	$E = B_{op}^2/2\mu_r\mu_0$	High field air-cored inductor	$\mu_r = 1$ $B_{op} = 10 \text{ T}$	40
Battery	Electrochemical		Li Ion	3.8 V	4000
Propellant/	Chemical		High energy density	Few eV per bond	5000 to 10,000
Diesel fuel	Chemical		Oxygen from atmosphere	More exothermic bonds	40,000

The energy density and the power density levels of different energy sources are shown in Figure 2.1. Rotating electrical machines, i.e., pulsed alternators, point out among power sources with their high energy and power density features [14].

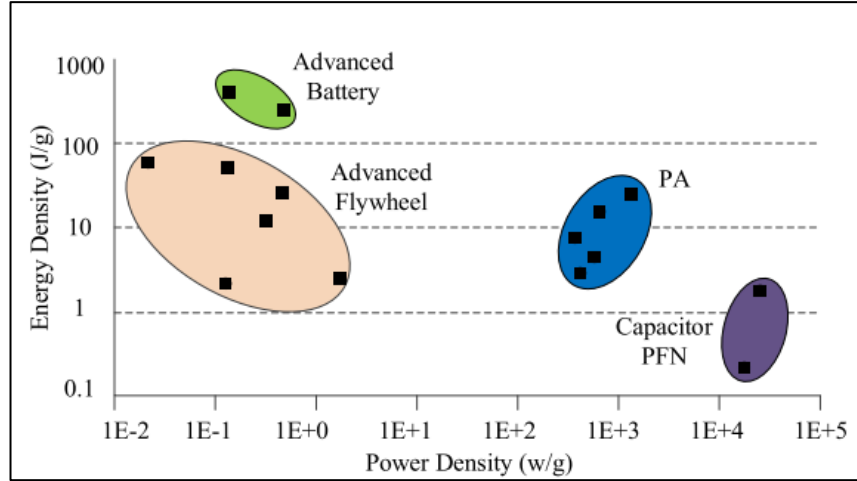


Figure 2.1: Energy density and power density level for different pulsed power supplies.

Rising frequency generators [15], homopolar generators [16], pulsed alternators [17] and compulsators [18] (i.e., compensated pulsed alternators) are the main types of rotating generator power sources. In the future, pulsed alternators are moving towards being hollow, multiphase, rotating field and no compensation structure [14].

In terms of rotary electric generators, axial flux, i.e., disk type, generator is an option with distinct characteristics. Usually, it was combined with a flywheel system in the literature. [19] [20] [21]. Moreover, there are studies of linear induction launchers driven by a flywheel generator system. However, these studies consist of the analysis of the generator driven launchers [22] [23]. A study of axial flux machines has recently been presented, but this includes compensation windings and no experimental work [24].

In this thesis, a power source system was suggested for linear induction launchers. The power source includes a flywheel system and an axial flux (disk type) permanent magnet generator that has no compensation structure [25].

3. AXIAL FLUX PERMANENT MAGNET MACHINES

For the first time in the history of rotary electrical machines, Faraday created two experiments demonstrating electromagnetic rotational motion in 1821 that was a vertically suspended wire moves in a circular movement around a magnet. This was also the first permanent magnet rotary electric machine. Some sources said that this was an axial flux machine [26] [27]. During these years, experiments and studies were carried out on various rotary electrical machines. In the following years, the first real electric motor in Europe was produced by Jacobi in 1834, then in 1837, a motor was produced and patented by Davenport in America [28]. This was also the first patented electric motor [29]. They were also radial flux machines.

Radial flux machines replaced axial flux machines after a relatively short time. The main reason for this was the strong magnetic force that existed between the stator and the rotor. It then became the generally accepted configuration for electrical machines. Radial flux machines have become very popular and are still the most common in the design of electrical machines [26].

After all these developments, especially with the serious development of permanent magnets, the popularity of axial flux machines increased gradually after the 1980s. Axial flux machines are the best solution for many applications due to their outstanding features. Despite the dominance of radial flux machines, axial flux machines have an important place today.

The main characteristic feature of the axial flux permanent magnet machines is that the magnetic flux in the air gap is axially orientated. This feature has given the machine axial name. It is also referred to as disk machines in the literature. The radial length of the stator or rotor from its inner diameter to its outer diameter; it is the effective area of the axial flux machine that generates the torque. Although there are different classifications in the literature, the most common form of classification is as shown in Figure 3.1. Here, the classification is based on the number of rotors and stators. Hereby, the main categories differ with its flux path, and actually, it is based on core machines. After the main division is made between cored and coreless machines, it would be more appropriate to examine each title separately. Because both the main flux path and production are slightly separated.

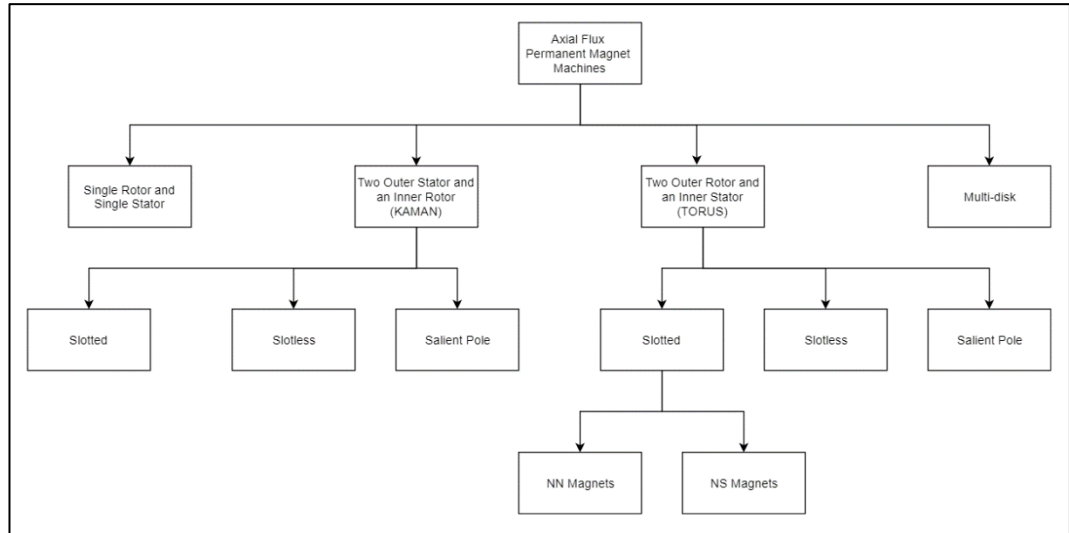


Figure 3.1: Classification of Axial Flux Permanent Magnet Machines.

In addition, various fundamental distinctions or bases for AFPM classification are summarized below. Each distinction is an important feature within certain AFPM topologies. Cross-section views of these AFPM machines are shown in Figure 3.2.

- Single, double or multi air gap
- Cored or coreless stator
- Slotted, slotless or salient pole stator (for cored machines)
- Inner or outer rotor
- Surface mounted or buried magnets

Aydin et al. presented a literature review of AFPM machines in detail. The advantages and disadvantages of various topologies were given. In this paper did not contain any mathematical background of represented works [30].

Mahmoudi et al. presented another literature review of AFPM machines up to 2010. Topologies investigated in detail. Furthermore, subjects of field weakening, modeling and simulation, analysis, design procedures, and applications were studied [31].

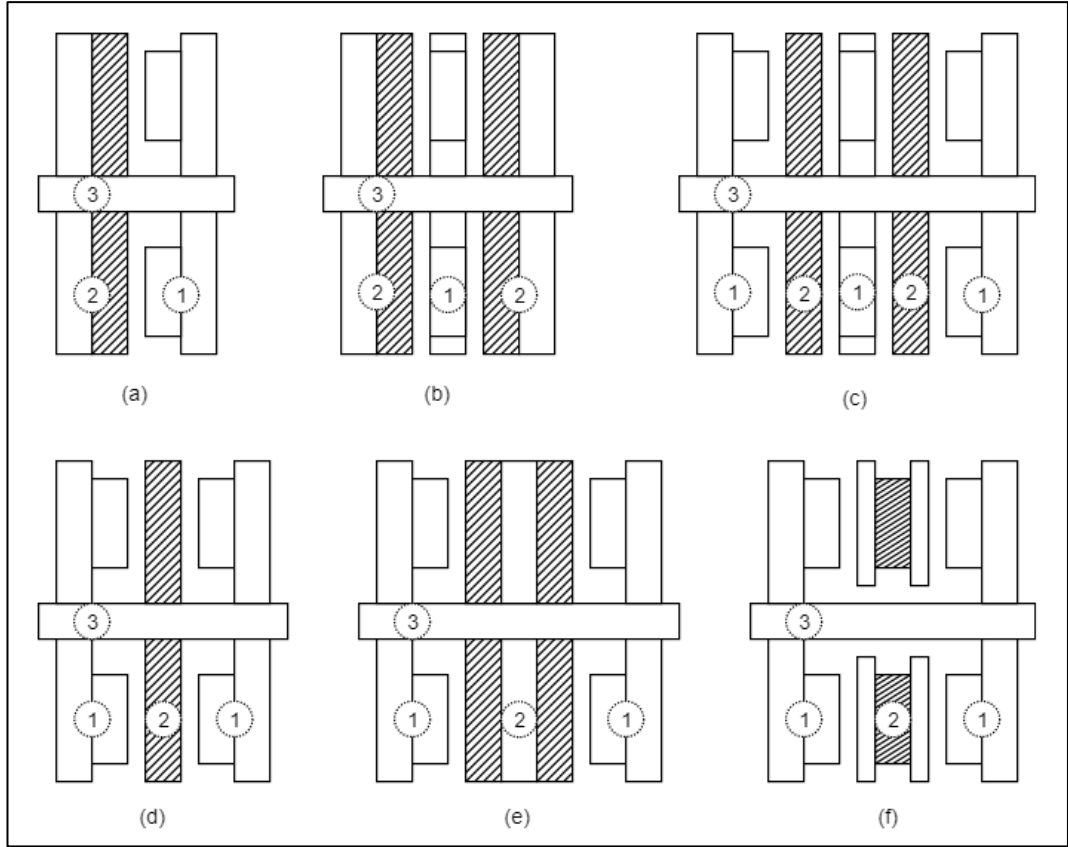


Figure 3.2: Cross-section of main topologies of AFPM machines: a) Single rotor single stator, b) single rotor, double stator, c) Multi-disk, d) Single coreless stator and two rotors, e) Single cored-stator and two rotors, f) Single salient pole stator and two rotors.

Depending on the application, the stators of AFPM machines can be manufactured without cores. If the magnets are positioned with the Halbach arrangement, the rear steel in the rotor is also eliminated and the machine can be completely coreless. In the Halbach sequence, the weight is significantly reduced. As the magnetic material is eliminated in the coreless structures, core losses are eliminated. Thus, coreless machines can be operated at higher efficiency. Also, the inductance of coreless winding can be very low compared to the magnetic core machine. Moreover, the cogging torque is eliminated. Furthermore, in the coreless AFPM machines, it does not generate any pulling force between the stator and the rotor. The first of the two main disadvantages of the coreless configuration is that the magnets need to be larger due to the larger air gap, and the second is that the stator has a lower strength than the iron-cored machine.

AFPM machines can be designed with one or more air gaps with their modular structure [32]. This provides convenience in two respects. The first enables the design

of the machine with the geometry required. Secondly, high power levels can be achieved by increasing the number of layers (i.e., disks). The high inertia of the machine due to the disc structure can also be reduced to suitable levels with the multi-disk design.

The AFPM machines are the highest power and torque density among the existing machines with their compact structure. Due to its axial structure, a large part of the volume can be used effectively. The axially positioned winding and magnet surfaces provide a large effective area. Besides, this area can be easily increased with more than one air gap.

Although the main application of AFPM machines comes first as low-speed high-torque applications, high-speed machines can also be designed. It is widely designed for direct drive small-scale wind turbines [33]. For electric vehicles, the highest power density is available commercially [34]. Applications of AFPM machines will be discussed in detail at the end of this chapter.

3.1. Analytical Model

In principle, torque is generated by the interaction of the coil current with the field of the magnet. In order to calculate the torque, it is necessary to know the magnetic field solution and position of the magnet (with its region), and winding structure. In other words, the magnetic field in the air gap of the machine should be computed accurately. Due to the three-dimensional structure of the AFPM machines, it is difficult to obtain the field solution in a closed-form. Instead, numerical methods such as a two-dimensional approach or a finite element method can be used. However, techniques such as the finite element method make it impossible to make parametric analysis related to existing design [35].

To calculate the magnetic field, B , in the air gap the magnetic scalar potential, ψ , and the magnetic vector potential, A , (often called the vector potential) can be used in classical electromagnetic.

The magnetic scalar potential, ψ , is sometimes used to determine where the magnetic field, H , is not any free currents. Similarly, the electric potential is used to determine the electric field in the electrostatic. A major use of magnetic scalar potential is to determine the magnetic field due to permanent magnet if magnetization is known.

The magnetic vector potential, A , is the most frequently used form $B=\nabla\times A$. The magnetic vector potential along with the electric potential, ϕ , can be used to identify the electric field, E . Therefore, many equations of electromagnetic can be written with both E and B terms and magnetic vector potential, A , and electric potential, ϕ [36].

3.1.1. Solution with Magnetic Scalar Potential

Sommerfeld in 1952 showed the potential expression at a distance of r from a magnet [37]:

$$4\pi\psi = \int \frac{\text{div}\vec{M}}{r} dv + \int \frac{M_s}{r} dA \quad (3.1)$$

For the first time in the literature, Campbell made a study on the analytical expressions of the magnetic field in the air gap of axial flux machines based on this equation in 1974 and 1975. Potential distribution (ψ) in the air gap was given with solving Laplace Equation. In order to find flux distribution in the air gap, potential distribution over the pole surface had to be known [38].

Campbell stated that to optimize the design and performance of the machine, the spatial distribution in the air gap must be known precisely. In this direction, the area in the air gap; calculated from the potential distribution of magnet poles on the surface. By assuming the magnetization as constant, the integral of the potential distribution and calculating this integral numerically. The field in the air gap is found by solving the Laplace equation from the boundary potential distribution and taking the required gradient [39].

$$\psi = \frac{M_s}{4\pi} \int_{-\beta}^{\alpha-\beta} \left[(x^2 + r^2 + s^2 - 2.r.s.\cos\theta)^{1/2} + s.\cos\theta.\sinh^{-1} \frac{r - s.\cos\theta}{(x^2 + s^2.\sin^2\theta)^{1/2}} \right]_{r=R_1}^{R_2} d\theta \quad (3.2)$$

A practical method was introduced by E.P. Furlani in order to make a rapid parametric study on the field strength of the AFPM motor in 1992 [35]. In this method, firstly, the three-dimensional problem reduced a two-dimensional boundary value

problem, then the analytical expression of the field in the air gap was shown. Also, an estimation method of the mean magnetization, M , was presented. An analytical expression of the complete solution for the air gap region was given.

$$\Phi_{gap}(x, y) = -\frac{4}{M} \sum_{n=1,3,5,\dots}^{\infty} \frac{(-1)^{(n-1)/2}}{(n\pi)^2 K(n, h, g, l)} \cdot \sinh\left(\frac{n\pi y}{l}\right) \cos\left(\frac{n\pi x}{l}\right) \quad (3.3)$$

Therefore, the axial or the vertical component of the field in the air gap region was

$$B_{gap,y}(x, y) = -4\mu_0 M \sum_{n=1,3,5,\dots}^{\infty} \frac{(-1)^{(n-1)/2}}{n\pi K(n, h, g, l)} \cdot \cosh\left(\frac{n\pi y}{l}\right) \cos\left(\frac{n\pi x}{l}\right) \quad (3.4)$$

$$K(n, h, g, l) = \cosh\left(\frac{n\pi g}{l}\right) - \sinh\left(\frac{n\pi g}{l}\right) \cdot \coth\left(\frac{n\pi}{l}(g - h)\right) \quad (3.5)$$

where, x equals to the horizontal distance along a circumferential arc at the mean radius of the magnet, and y equals the vertical distance [35].

Again in the same year, J.K. Lee made measurements on three different machines based on the equation of Furlani [40].

Furlani expanded his work in 1994 and introduced a more realistic approach. Compare the results with the Maxwell software using the finite element method [41].

$$\Phi_{gap}(x, y) = \frac{4l\mu_0 M_s}{\mu} \sum_{n=1,3,5,\dots}^{\infty} \frac{(-1)^{(n-1)/2}}{(n\pi)^2 K(n, h, g, l, \mu)} \cdot \sinh\left(\frac{n\pi y}{l}\right) \cos\left(\frac{n\pi x}{l}\right) \quad (3.6)$$

$$B_{gap,y}(x,y) = \frac{4\mu_0^2 M_s}{\mu} \sum_{n=1,3,5,\dots}^{\infty} \frac{(-1)^{(n-1)/2}}{n\pi K(n,h,g,l,\mu)} \quad (3.7)$$

$$\cdot \cosh\left(\frac{n\pi y}{l}\right) \cos\left(\frac{n\pi x}{l}\right)$$

$$K(n,h,g,l,\mu) = -\frac{\mu_0}{\mu} \cosh\left(\frac{n\pi g}{l}\right) + \sinh\left(\frac{n\pi g}{l}\right) \quad (3.8)$$

$$\cdot \coth\left(\frac{n\pi}{l}(g-h)\right)$$

In 2007, Chan et al. investigated the analytical solution of no-load and armature reaction magnetic field distribution using the Fourier series approach for AFPM generators. The magnetic flux density, B, was given for the air gap, within the magnets and produced by the current separately [42].

3.1.1.1. Acquiring Magnetization of Magnet

In order to reach an approximate M value in a magnet, the magnet sample is cut by EDM (electric discharge machining) and after magnetization is magnetized, the corrosion is examined by ultrasonic methods, then the magnetic flux density is measured in the middle of the cylinder. In a cylindrical example, the magnetic flux density can be calculated by the following formula [40]:

$$B_z = \frac{\mu_0 M}{2} \left[\frac{z+L}{\sqrt{(z+L)^2 + a^2}} - \frac{z}{\sqrt{z^2 + a^2}} \right] \quad (3.9)$$

Gu et al. investigated the magnetic field solution with 3D and 2D finite element method. 3D FEM was based on scalar potential function and 2D FEM was based on vector potential function [43].

3.1.2. Solution with Magnetic Vector Potential

Furlani revealed a semi-analytical three-dimensional expression of magnetic flux density in 1994. The vector potential was used, and the numerical integration of the Green function was taken in empty space over a single variable. All three field

components (radial, azimuthal, and axial) are expressed as finite sums of fundamental functions [44]. Then Furlani and Knewton applied this equation to a motor and tested it with the finite element method in 1997 [45] and again applied a motor that had NdFeB magnets [46].

J.R. Bumby et al. obtained the expressions of the magnetic field in the air gap of the cored AFPM by using the vector potential distribution in 2004 [47]. In this method, current sheets were used to model both the magnet and the armature current in 2D as shown in Figure 3.3. By using this method in 2005, they have reached the equations of the magnetic field in the air gap for the coreless AFPM machine [48].

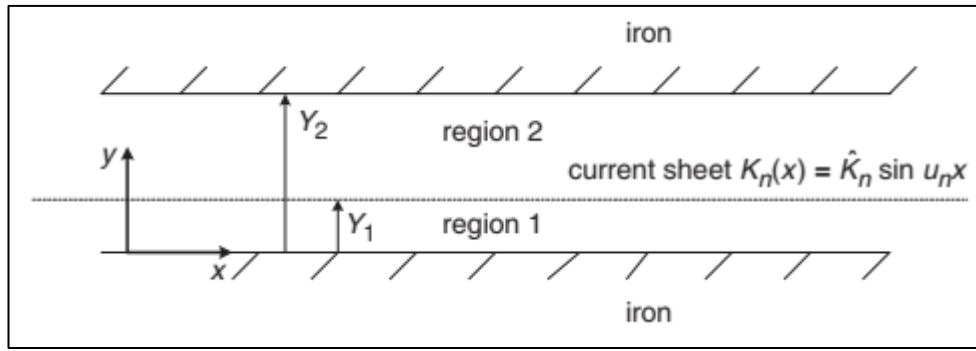


Figure 3.3: Current sheet model [47].

Vector potential and magnetic field were obtained by solving the Laplace equation $\nabla^2 \vec{A} = 0$. The solution of the Laplace equation gives the vector potential and the normal component of the magnetic field as follows [47]

$$A_{zn}(x) = - \frac{\vec{J}_n \mu_0 u_n^2 \frac{\sinh u_n t_m}{\sinh u_n \frac{g}{2}} \cosh u_n \left(\frac{g}{2} - y \right)}{s} \sin u_n x \quad (3.10)$$

$$B_{yn}(x) = \frac{\vec{J}_n \mu_0}{u_n} \frac{\sinh u_n t_m}{\sinh u_n \frac{g}{2}} \cosh u_n \left(\frac{g}{2} - y \right) \cos u_n x \quad (3.11)$$

where

$$u_n = \frac{\pi n}{\tau} \quad (3.12)$$

$$\vec{J}_n = \frac{4}{\tau} \frac{B_{rem}}{\mu_0 \mu_{rec}} \sin \frac{u_n}{2} d_m \quad (3.13)$$

3.2. Magnetic Circuit Model

The analysis of systems with one or more closed magnetic flux path loops can be done with a magnetic circuit. An example of a magnetic circuit model of a two-rotor and a coreless stator AFPM machine is shown in Figure 3.4.

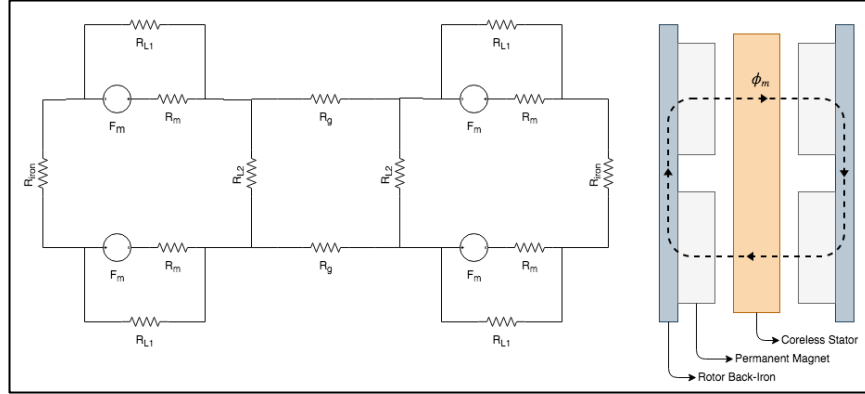


Figure 3.4: Magnetic circuit model of a two-rotor and a coreless stator AFPM machine.

For accurate analysis with the magnetic circuit model, the model of each element should be obtained in detail. Sadeghierad et al. investigated the magnetic circuit model elements of a high-speed AFPM generator [49] [50]. Zheng et al. investigated a one-rotor one-stator AFPM machine using a magnetic circuit model. Then a simplified model was obtained that ignores the back-iron reluctances [51].

3.2.1. Permanent Magnet Model

The permanent magnet model consists of a reluctance (magnetic resistance) and a magnetomotive force (MMF) as shown in Figure 3.5 [50].

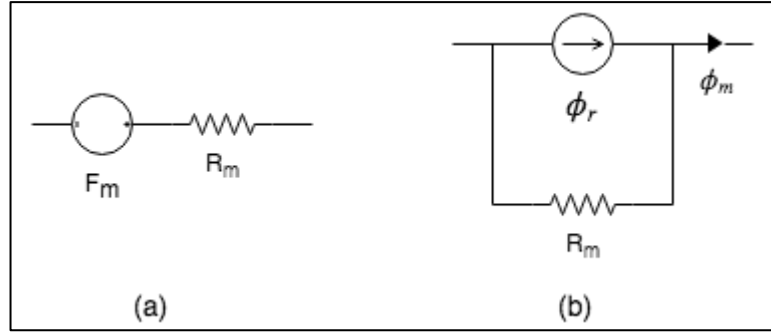


Figure 3.5: Permanent Magnet Model (a) Thevenin Equivalent Model, (b) Norton Equivalent Model.

Formulations for Thevenin Equivalent Model

$$R_m = \frac{l_m}{\mu_0 \mu_{rm} A_m} \quad (3.14)$$

$$F_m = \phi_r R_m \quad (3.15)$$

$$\phi_r = B_r A_m \quad (3.16)$$

Formulation for Norton Equivalent Model

$$\begin{aligned} \phi_m &= B_m A_m \\ &= B_r A_m + \mu_0 \mu_{rm} H_m A_m \\ &= \phi_r + \frac{F_m}{R_m} \end{aligned} \quad (3.17)$$

3.2.2. Leakage Flux Model

In general, leakage flux exists two different fashions in permanent magnet machines. Self-leakage flux exists between permanent magnet and back iron. The other one is seen between two adjacent permanent magnets. In Figure 3.6, (a) and (b) are self-leakage flux paths of the magnet and (c) is the leakage flux path between two magnets.

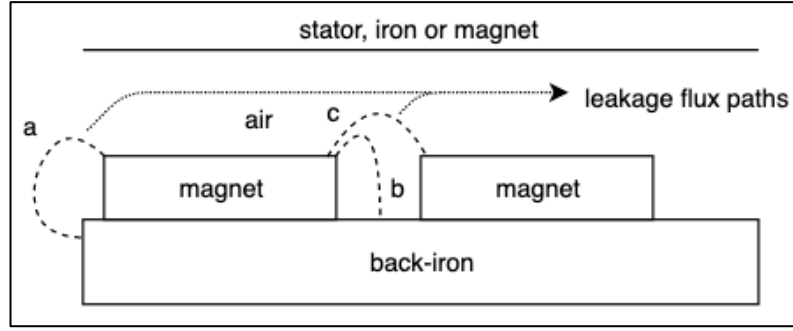


Figure 3.6: PM Flux Leakage Model.

Self-leakage flux and leakage flux between two PMs are shown R_{L1} and R_{L2} respectively in the magnetic circuit model as shown in Figure 3.7.

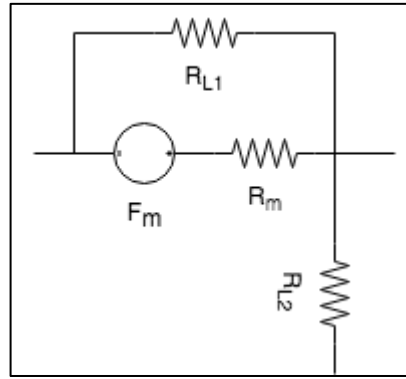


Figure 3.7: PM Flux Leakage Circuit Model.

Self-leakage flux equations [52]:

$$R_{L1} = R_{LA} || R_{LB} \quad (3.18)$$

$$R_{LA} = \frac{p}{\mu_0 k_{pp} \left((D_i - l_m) \ln \left(\frac{l_m + 2g}{l_m} \right) + 2g \right)} \quad (3.19)$$

$$R_{LB} = \frac{9p/2}{\mu_0 k_{pp} \left((3D_o + 2l_m) \ln \left(\frac{l_m + 3g}{l_m} \right) - 6g \right)} \quad (3.20)$$

Leakage flux between two PMs is [50]:

$$R_{L2} = \frac{2\pi(1 - k_{pp})}{\mu_0 l_m p \ln(D_o/D_i)} \quad (3.21)$$

3.2.3. Rotor Back-Iron Model

An important part of the machine is the rotor back-iron. For instance, a two-rotor AFPM machine has back-iron at the end of the PMs. The formula $B(H)$ used in a FEM software to model the back steel is defined as follows [49]:

$$B(H) = \mu_0 H + \frac{2J_s}{\pi} \arctan\left(\frac{\pi(\mu_r - 1)\mu_0 H}{2J_s}\right) \quad (3.22)$$

Coefficient J_s is determined from B-H graphics in Figure 3.8 below:

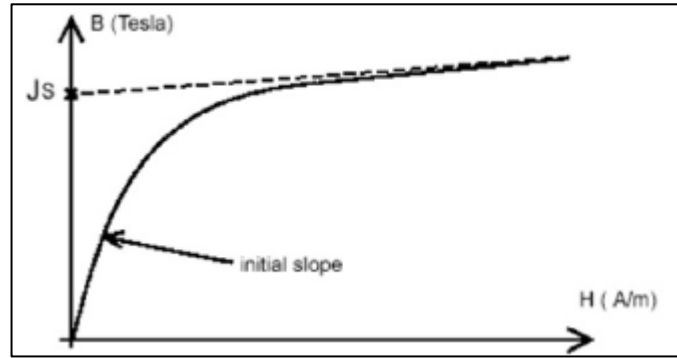


Figure 3.8: Back-Iron Model.

Nonlinear reluctance of back-iron can be calculated by

$$R_{iron} = \frac{F_i}{\Phi_i} = \frac{H_i l_i}{B_i A_i} \quad (3.23)$$

Lombard et al., presented another method for calculating the back iron (yoke) model. In this method, the iron permeability is used to calculate the reluctance of iron. The magnetic permeability of the back-iron is initially calculated as iterative to provide the flux density equation of the back-iron and the B-H curve. The magnetic permeability of the back-iron is used to calculate the reluctance [53].

$$B_g(peak) = \left(\frac{4R_m}{4R_m + 4R_g + R_{iron}} \right) B_r \quad (3.24)$$

3.2.4. Air Gap Model

In electrical machines, the flux generally forms a path between two high magnetic permeable materials. Since the permeability of the air is low, the fringing effect is seen on the edges of the material. To calculate the reluctance of the air gap, this fringing effect should be considered depending on the desired precision. Three different approaches can be used to model the flux path in the air gap as shown in Figure 3.9.

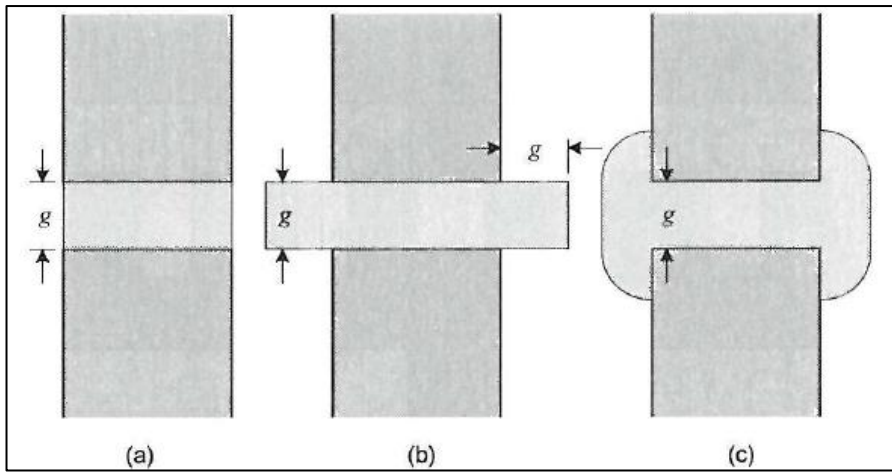


Figure 3.9: Air gap model.

The simplest model is that completely ignores the effect of the fringing as in Figure 3.9a. Here is the reluctance:

$$R_{g1} = \frac{g}{\mu_0 A} \quad (3.25)$$

When the air gap dimensions that the g/A ratio between the two materials is smaller, then, a refined model (Figure 3.9b) exists when the length g is added to the periphery A giving a larger area A' [54].

$$R_{g2} = \frac{g}{\mu_0 A'} \quad (3.26)$$

Finally, it is assumed that the fringe flux follows a circular arc from the edge of a block, travels along a straight line through space, followed by a circular arc to the other block as shown in Figure 3.10. This circular-arc straight-line modeling can compute the flux flow with an analytical expression that is more realistic than any of the first two models [54].

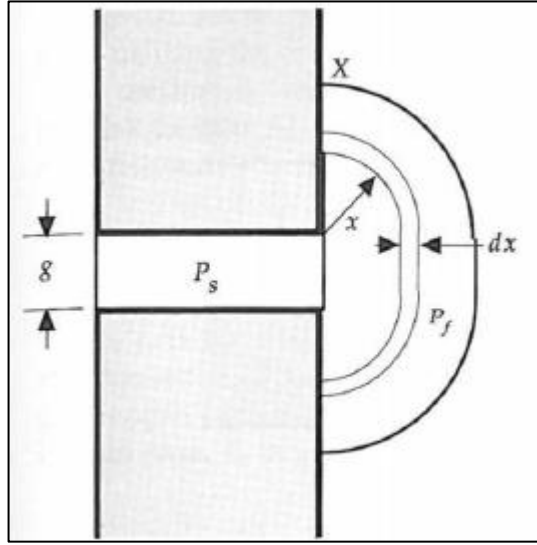


Figure 3.10: Air gap model in detail.

$$P_f = \int_0^X \frac{\mu_0 l}{g + \pi x} dx = \frac{\mu_0 l}{\pi} \ln \left(1 + \frac{\pi X}{g} \right) \quad (3.27)$$

$$R_{g3} = \frac{\pi}{\mu_0 l \ln \left(1 + \frac{\pi X}{g} \right)} \quad (3.28)$$

The unknown variable X is the distance of the fringe effect from the edges and is not dependent on a variable. Generally, a few times the air gap is selected. The total air gap reluctance changes very little if it is increased for $10g$.

3.3. Thermal Analysis

Heat transfer (or heat) is the movement of thermal energy due to the temperature difference in space.

If there is a temperature difference in one environment or between two environments, there must be heat transfer.

As shown in Figure 3.11, there are different types of heat transfer. If it can be solid or liquid in a stable environment, if there is a temperature distribution, the conduction of heat in the environment is called "heat conduction". Conversely, the heat conduction between a surface and a moving fluid is called "convection." The third form of heat transfer is called "thermal radiation". All surfaces with finite temperatures emit energy in the form of electromagnetic waves [55].

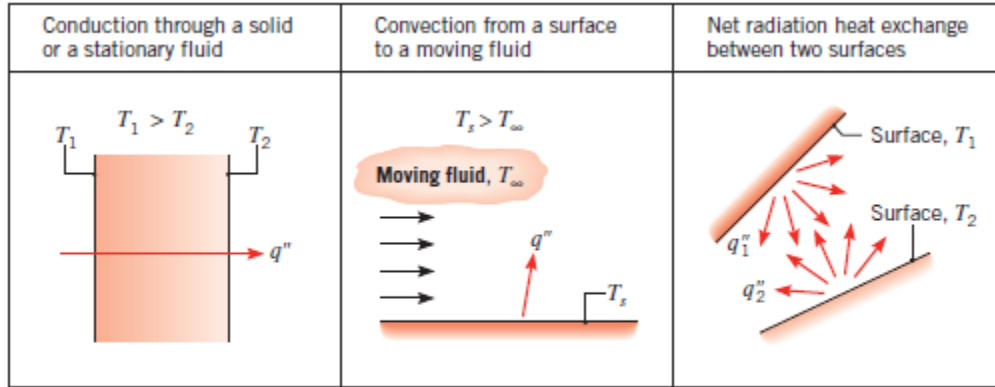


Figure 3.11: Conduction, convection, and radiation heat transfer modes.

3.3.1. Conduction

The heat transfer process can be explained by the corresponding ratio equations. With these equations, the amount of energy transmitted per unit time can be calculated. The current ratio equation for heat conduction is known as Fourier's Law. The uniformity of temperature distribution in one dimension can be shown as follows [55]:

$$q_x'' = -k \frac{dT}{dx} \quad (3.29)$$

where q_x'' is the heat flux (W/m^2), i.e., heat transfer rate, k is thermal conductivity ($\text{W}/\text{m.K}$), and dT/dx is temperature gradient.

3.3.2. Convection

The heat transfer equation for the convection is:

$$q'' = h(T_s - T_\infty) \quad (3.30)$$

where h is convection heat transfer coefficient and is known as Newton's law of cooling ($\text{W/m}^2\cdot\text{K}$), T_s and T_∞ are surface and fluid temperatures (K) respectively.

3.3.3. Radiation

Thermal radiation is energy emitted from anything that does not have a temperature of zero.

The heat radiation rate emitted from the unit surface is as follows [55]:

$$q''_{rad} = \varepsilon\sigma(T_s^4 - T_{sur}^4) \quad (3.31)$$

where σ is the Stefan-Boltzmann constant ($5.67 \times 10^{-8} \text{ W/m}^2\cdot\text{K}^4$), ε is a radiative property of the surface ($0 \leq \varepsilon \leq 1$), T_s and T_{sur} are surface and surroundings temperatures (K) respectively.

3.3.4. The Heat Diffusion Equation

The main purpose of heat conduction analysis is to determine the temperature distribution of the medium as a result of the interactions at its boundaries and within the medium.

Consider a homogeneous and completely immobile environment with a temperature distribution of $T(x, y, z)$. The method will be carried out according to the principle of conservation of energy. First, a very small difference volume is defined as in Figure 3.12, dx, dy, dz .

Since there is no movement (mechanical energy), only thermal energy is concerned. In particular, if there is a temperature distribution in the environment, there will be heat conduction between the control surfaces. The heat rates at each control surface are defined as qx, qy and qz along the x, y and z axes. The heat conduction ratio on the opposite surfaces can be shown in the Taylor series expansion as follows [55]:

$$\begin{aligned}
q_{x+dx} &= q_x + \frac{\partial q_x}{\partial x} dx \\
q_{y+dy} &= q_y + \frac{\partial q_y}{\partial y} dy \\
q_{z+dz} &= q_z + \frac{\partial q_z}{\partial z} dz
\end{aligned} \tag{3.32}$$

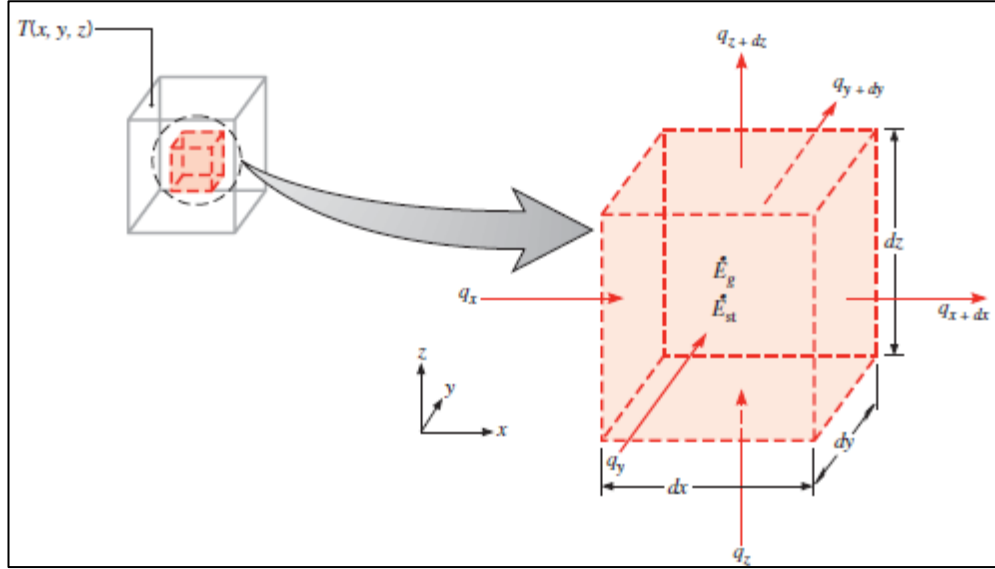


Figure 3.12: Differential control volume for conduction analysis.

There may be a term of energy source that can generate thermal energy in the medium;

$$\dot{E}_g = \dot{q} dx dy dz \tag{3.33}$$

Here $\dot{q}$ refers to the energy produced per unit volume in the medium. (W/m^3)

In addition, there may be variations in the thermal energy stored within the material itself. If the material has not undergone any change at one stage, the term energy storage is:

$$\dot{E}_{st} = \rho c_p \frac{\partial T}{\partial t} dx dy dz \tag{3.34}$$

Here, the term $\rho c_p \frac{\partial T}{\partial t}$ refers to the change in thermal energy per unit volume of the medium over time. Also; ρ is the density of the material (kg/m^3), and c_p is the

specific heat (J/kg.K). It should be noted that $\dot{E}_g$ and $\dot{E}_{st}$ show different physical events.

$\dot{E}_g$; shows some energy cycle operations. These; thermal energy on one side, and other forms of chemical, electrical or nuclear energy on the other. If this term is positive (that is, the source), then it spends other energy sources into thermal energy. If it's negative, it's wasting thermal energy.

$\dot{E}_{st}$; on the contrary, it shows a ratio of the thermal energy change stored in the material.

In the last step, if general equality is written based on the principle of conservation of energy;

$$\dot{E}_{in} + \dot{E}_g - \dot{E}_{out} = \dot{E}_{st} \quad (3.35)$$

Here, the terms $\dot{E}_{in}$ and $\dot{E}_{out}$ refer to the energies entering and leaving the system. From the Figure 3.12 and the previously written equations, the following equation can be obtained:

$$\begin{aligned} q_x + q_y + q_z + \dot{q}dxdydz - q_{x+dx} - q_{y+dy} - q_{z+dz} \\ = \rho c_p \frac{\partial T}{\partial t} dxdydz \end{aligned} \quad (3.36)$$

If the previously obtained equations are written in their place and the equality is simplified.

$$\rho c_p \frac{\partial T}{\partial t} = \dot{q} + \frac{\partial}{\partial x} \left(k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(k \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left(k \frac{\partial T}{\partial z} \right) \quad (3.37)$$

If the transmission is fixed; that is, if there is no permanent change in the amount of energy, the equation can be simplified as follows:

$$\frac{\dot{q}}{k} + \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} = 0 \quad (3.38)$$

The purpose of heat transfer is to determine the temperature distribution. In general, this depends on three dimensions and time. That is, $T = T(x, y, z, t)$. Fourier's fundamental law of heat conduction alone is not sufficient to calculate T [56].

3.3.5. Heat Generation

One of the important conditions of heat generation is the heat produced in the medium. For example, the conversion of electrical energy to heat energy due to ohmic resistance can be demonstrated.

The amount of heat generated per unit volume for the electrical problem is:

$$\dot{q} = \frac{I^2 R}{V} \quad (3.39)$$

where I is current, R is resistance, and V is the volume of material.

If the cross-sectional area of the volume expression is multiplied by the length and the resistance expression is written clearly;

$$R = \rho_c \frac{l}{A} \quad (3.40)$$

$$\dot{q} = \frac{I^2}{lA} \rho_c \frac{l}{A} = \frac{\rho_c I^2}{A^2} \quad (3.41)$$

where ρ_c is resistivity, A is cross-section area, and l is length.

3.3.6. Temperature Change in Current-Carrying Wire

In this case, the time-dependent temperature change in the stator will be obtained.

Assumptions:

- In the stator, the wires are distributed homogeneously and have a whole structure,
- There is no heat input from outside,

- Since there is no permanent situation analysis, there is no heat output to the outside,
- It will be assumed that the temperature is distributed homogeneously throughout the environment. (The temperature difference in the environment is negligible.

Assuming that the system is initially in a steady-state and will generate heat from the moment the current begins to flow, it can be assumed that there will be no heat input.

Heat output is two types. The first is the heat transfer between the surface and the environment, and the second is the heat that the surface will radiate.

The heat generated for ease of account can also be omitted. Equality of conservation of energy becomes:

$$\dot{E}_g = \dot{E}_{st} \quad (3.42)$$

If the statements are written in place;

$$\dot{q}dxdydz = \rho c_p \frac{\partial T}{\partial t} dxdydz \quad (3.43)$$

Since we consider temperature to be spatially homogeneous, the volume-dependent terms of the equation will also disappear.

$$\dot{q} = \rho c_p \frac{\partial T}{\partial t} \quad (3.44)$$

If we take the temperature change;

$$\frac{\partial T}{\partial t} = \frac{\dot{q}}{\rho c_p} \quad (3.45)$$

Starting from the ambient temperature, the temperature that it will reach by rising is integrated with time and becomes as follows:

$$T(t) = \int_{t_0}^t \frac{\dot{q}}{\rho c_p} dt \quad (3.46)$$

The result of the integral is:

$$T(t) = \frac{\dot{q}}{\rho c_p} (t - t_0) \quad (3.47)$$

If this equation is adapted for launcher applications, the amount of energy generated per unit volume is lost and a much simpler equation can be achieved. If the start time is assumed to be zero and the end time is given, the equation to be obtained will depend only on the current and cross-sectional area.

$$\Delta T = \frac{I^2 t \rho_{cu}}{A^2 \rho c_p} \quad (3.48)$$

3.4. Winding

The windings used in three-phase rotating electrical machines can be classified under two main titles: Concentrated and Distributed windings. As the most general definition, if one phase of a winding is placed over more than one slot under a pole, that is said to be distributed, on the other hand, if one phase of a winding is in one slot under a pole, it is called a concentrated winding. Some example winding schemes are shown in Figure 3.13.

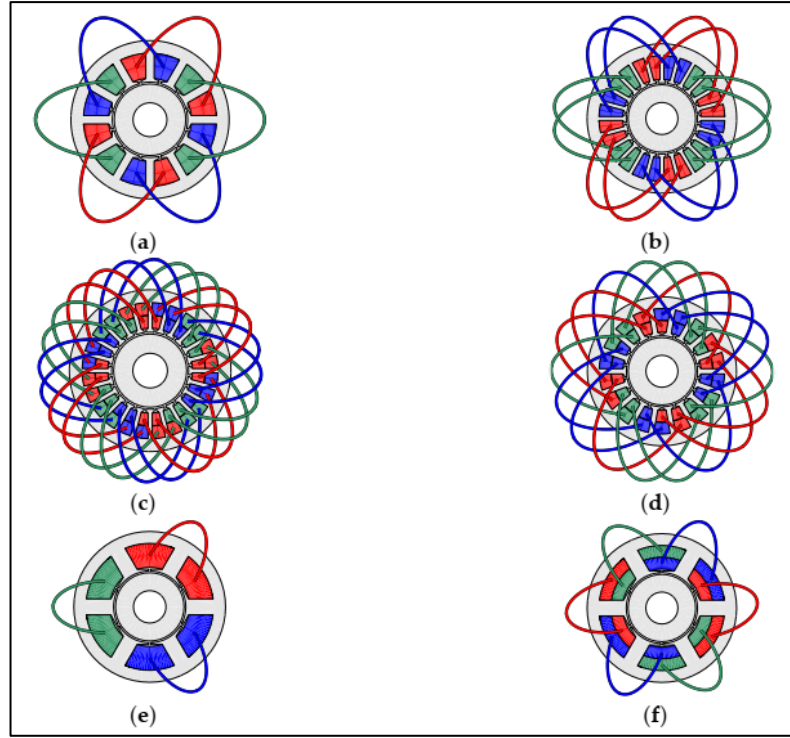


Figure 3.13 Different examples of winding configurations (a), (b), and (c) integral-slot distributed-winding, (d) fractional-slot distributed-winding, (e) and (f) fractional-slot concentrated winding.

Various definitions are used to describe a symmetrical winding scheme using parameters that coil pitch y_d , number of slots per pole and phase q , number of coils per pole and phase q_c , number of winding coils Q_c and stator slots Q_s . Symmetrical winding means that the number of coils used in each phase must be equal. A good classification scheme was presented by Germishuizen and Kamper [57] as shown in Figure 3.14. In this classification, some definitions related to windings are evaluated and the type of winding is indicated by these definitions.

- Overlapping and non-overlapping
- Single and double layer
- Full-pitch and fractional pitch
- Integral and fractional slot
- Distributed and concentrated windings

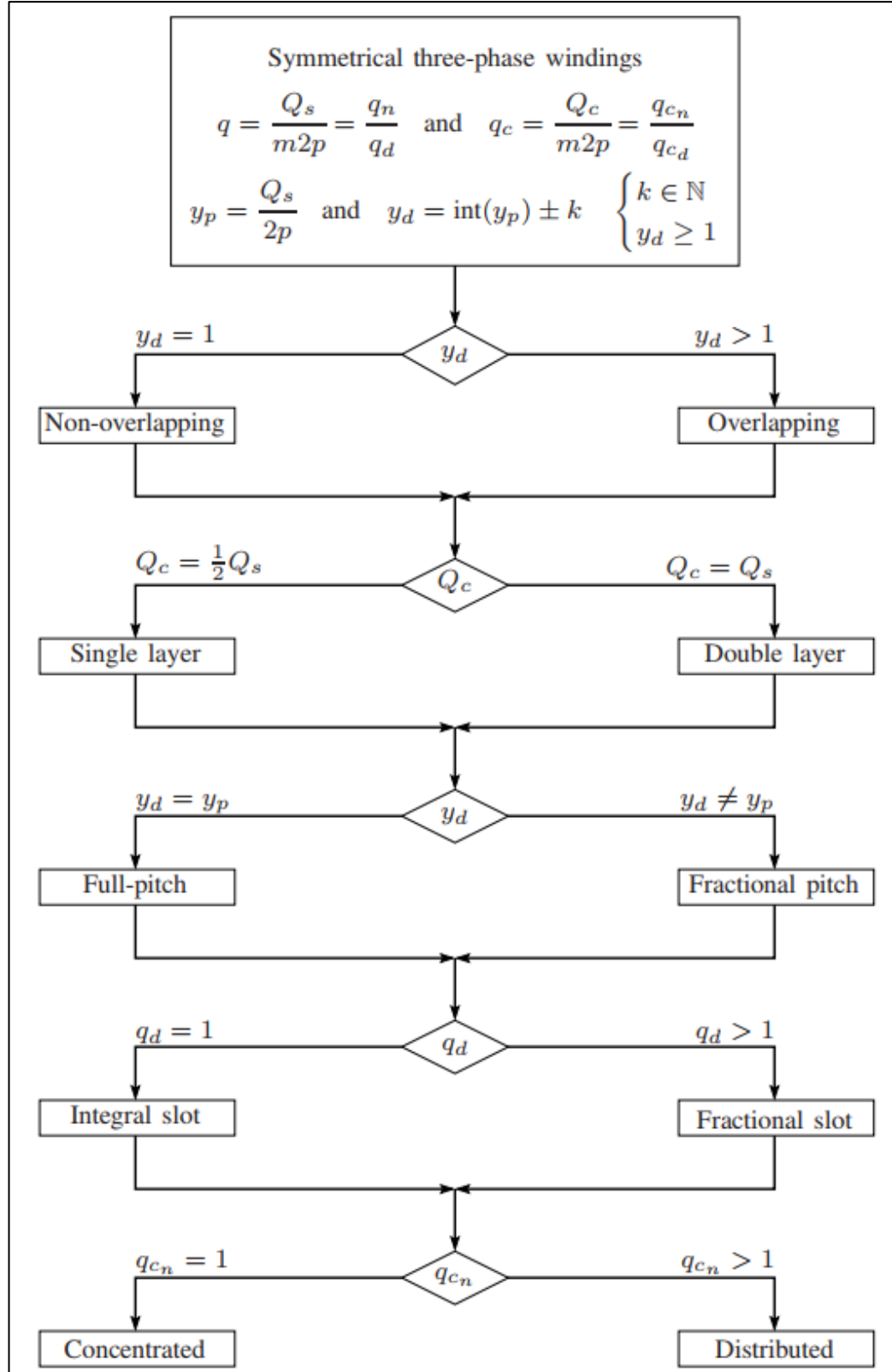


Figure 3.14: Winding classification scheme.

Frequently, identifying the winding of a coreless AFPM machine is complicated by the fact that the machines do not have physical slots due to the lack of core.

However, it is possible to classify a winding scheme of a coreless stator with this classification method in Figure 3.14.

Another classification is lap and wave winding. Although this is mainly used for winding diagrams of DC machines [58], wave winding is used in stator windings of AC machines [59]. An example wave winding diagram is shown in Figure 3.15 [60]. Nowadays, especially in the windings of electric vehicle motors, wave winding in the form of hairpin winding has been used [61]. Although there is no electromagnetic difference, it has advantages such as ease of production [60] and increased efficiency due to the reduction of end-windings [25].

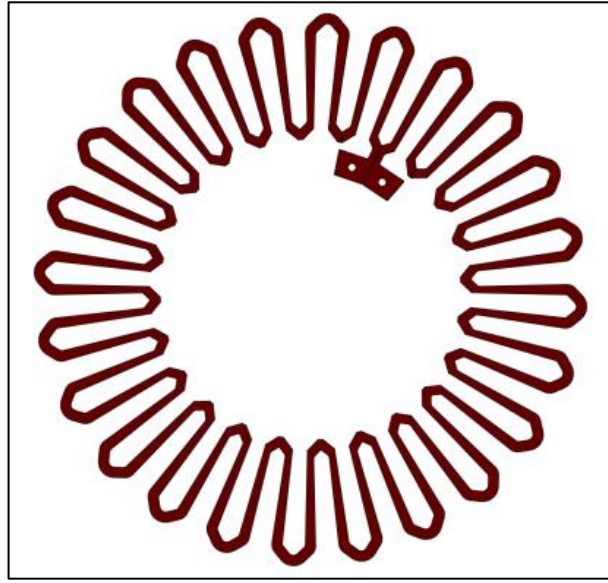


Figure 3.15: Example wave winding of a single phase [60].

3.5. Voltage Model and Power

The voltage induced in winding can be found by derivative of the flux linkage.

$$e = -\frac{d\psi}{dt} \quad (3.49)$$

The flux linkage of a single turn coil that axially positioned in the air gap of AFPM machine can be determined by

$$\psi = \int_{\alpha+\epsilon}^{\alpha+\theta_m-\epsilon} \int_{r_i}^{r_o} B_{peak} \sin \theta \frac{2\pi}{p} r dr d\theta \quad (3.50)$$

where coil pitch is $\theta_m = \pi$ and the coil at position α with respect to the flux density as shown in Figure 3.16, sinusoidal flux density assumed in the air gap as well.

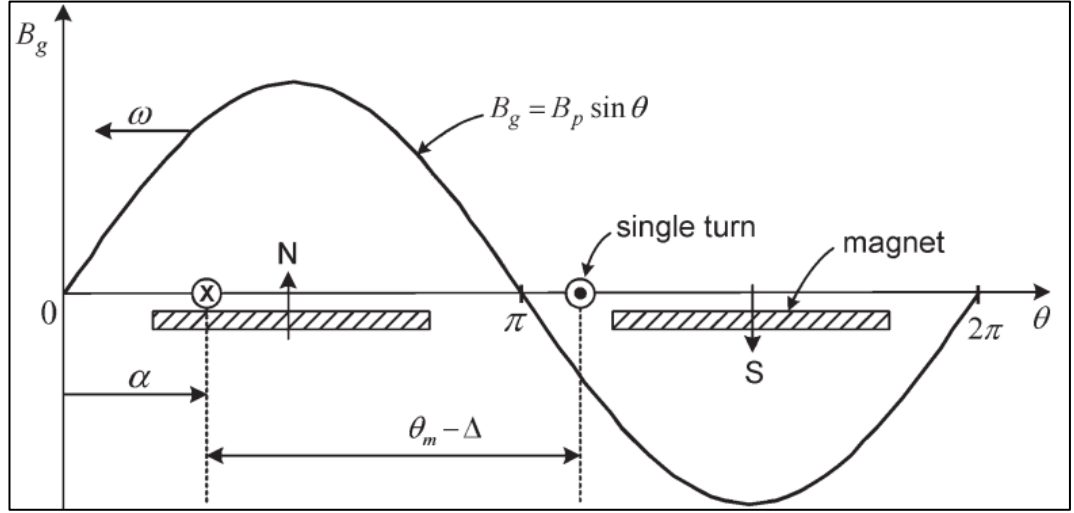


Figure 3.16: Single-turn coil in sinusoidal field.

Executing the integral of flux linkage with $\alpha = \omega t$ and making trigonometric convergence ($\cos \epsilon$) assumptions results in the following form

$$\psi = \frac{4\pi}{p} B_{peak} (r_o^2 - r_i^2) \cos \omega t \quad (3.51)$$

Substituting flux equation (3.52) into induced voltage equation (3.49) for a single turn coil

$$e = -\frac{d\psi}{dt} = \frac{4\pi}{p} \omega_m B_{peak} (r_o^2 - r_i^2) \sin \omega t \quad (3.52)$$

The RMS value of the induced voltage in a phase coil is given by

$$E_{RMS} = 2\sqrt{2}\pi N \omega_m B_{peak} (r_o^2 - r_i^2) \quad (3.53)$$

where pN conductors in a phase coil, B_{peak} peak flux density in the air gap, r_o and r_i outer and inner radius of effective area respectively.

In order to calculate output power of AFPM machine, multiply with three-phase induced RMS voltage and phase RMS current with power factor is assumed unity and voltage drop across the phases is neglected.

$$P_{out} = 3[2\sqrt{2}\pi N\omega_m B_{peak}(r_o^2 - r_i^2)]I_A \quad (3.54)$$

In AFPM machines there is a ratio of inner and outer radius (or diameter) that maximum power output. Therefore, first the electric loading is written, then the output power equation is rearranged. Electric loading is defined as number of ampere conductors per meter of stator periphery at the air gap inner radius.

$$q = \frac{3I_A N}{2\pi r_i} \quad (3.55)$$

Substituting q into output power and rearranging yields

$$P_{out} = 4\sqrt{2}\pi^2 q\omega_m B_g r_o^3 k_r (1 - k_r^2) \quad (3.56)$$

where $k_r = r_i/r_o$. From output power equation $dP_{out}/dk_r = 0$ gives conditions for maximum output power, which is $k_r = 1/\sqrt{3}$. This ratio is important for AFPM machines. Because using such a ratio initially in machine design one of the parameters of inner or outer radius (or diameter) will be reduced.

3.6. Applications

The featured applications in the literature have been examined under main topics according to their application areas.

Al-Badi et al. reviewed the axial flux electrical machines. The topologies were classified by the number and location of the rotor and the stator. Also, the main configurations and applications of machines were presented [62].

3.6.1. Aircraft

Hill-Cottingham et al. presented a multi-disc with plastic structure motor for a solar aircraft. Three types of winding that air-gap concentrated, π spread and concentrated second harmonic winding was analyzed with 2D FEM and winding factor calculation for air gap winding was given. The motor was 2250 W, 1000 rpm, 16 poles, and 96% efficiency. In addition, a design comparison between the radial and the axial machine that three different windings was presented [63].

Hill-Cottingham et al. presented an expanded work with the motor. They used traditional formulation and FEM. 2D and 3D FEM analysis results were compared and a 2D simplification was noted. To increase the winding factor, they used the second harmonic of the MMF waveform rather than concentrated windings. Thus, the winding factor was obtained 0,716. Also, a simplified thermal analysis was carried out [64].

Profumo et al. presented the performance of the AFPM multi-disc plastic structure mentioned above. Experimental tests of prototype motor were taken which phase back emf, torque vs. angular position undercurrent, locked rotor test, and d-axis STR (standstill time response) tests. Compared with computed and experimental results. The experimental motor was 2250 W at 1000 rpm, 4 rotors, 3 stators, 16 poles and it has over 92% efficiency at full load. At the machine air gap was increased 1 mm to 1.5 mm to reduce the uncertainty level due to possible heat deformation. Besides, motor parameters were given [65].

3.6.2. Electric Vehicles

Campbell explained the problems of electric cars in 1972 and proposed an air-cored brushed motor. The motor has about 90% efficiency. He stated that several electric traction motors for electric vehicles those produced by Ford, Toyota and General Motors [66]. After two years he presented test results of the motor. The motor has 1860 W and 78% efficiency. Loaded and unloaded tests about efficiency versus speed were compared. In addition, he noted that the overall efficiency of electric vehicles could be improved by redesigning the transmission system [67].

Caricchi et al. presented an air-cored, water-cooled, three rotors two stators wheel direct-drive motor for a city car. They carried 25 kW motor out with 16 poles, 1100 rpm, and 93% efficiency. They used rhomboidal shaped coils in stator windings.

They also noted that AFPM machines have excellent performance for constant torque applications, but they have not a good performance of constant power operation because of low inductance value. To achieve this, the machine stages were switched between series and parallel [68]. They presented an extended work about it. Parameters of torque formulation were investigated [69].

Profumo et al. reviewed axial flux motors for electric vehicle applications. Two main subjects that were axial flux induction and axial flux permanent magnet motors investigated. Under this subjects wheel AFI, twin-rotor AFI, AF surface PM, AF interior PM motors were described in detail. A comparison of power density between radial and axial flux machines. Also, a formulation was given [70].

Lovatt et al. investigated an air-cored, two rotors one stator, hub motor for a solar-powered electric vehicle. They used a 2D FEM and experimental methods. In the machine, a Halbach magnet array was used. They reached 97.5% efficiency with 1.8 kW, 40 poles, 1000 rpm motor. The motor was compared with competitors and the second design of the motor [71].

Chan et al. investigated an electric bicycle motor with one rotor one. They used 2D FEM model for EMF computation and the circuit equation for terminal voltage calculation. A prototype motor was produced with specifications of 140 W, 200 rpm, 16 poles, and 62% efficiency. Also, the converter design was presented for the motor [72].

Oh et al. tested an AFPM motor for hybrid electric vehicles. Efficiency maps for different operating points were given in detail [73]. Oh and Emadi again presented another work about testing the AFPM motor. Hardware in the loop (HIL) with Japan 10 drive cycle was used and measurements were taken with Labview data acquisition. Measurement results were well prepared about torque, speed, voltage, and efficiency for different air gaps. The air gap of the motor was varied from 1.5 mm to 6 mm and the optimal air gap was found 3.9 mm. Besides, four-quadrant operating modes of the test motor were investigated. System efficiency during motor and regenerative mode were formulated [74].

3.6.3. Marine Applications

Gilbert and Kessinger investigated an air-cored motor. They said to the name of the motor Segmented Electromagnetic Array (SEMA) and theoretically, the name of

the machine is Lorentz Motor. They used the Lorentz principle to design the machine. Air-gap field of the motor calculated by Ampere's Law. In addition, they explained the applications of the machine in detail [75].

3.6.4. Wind Turbines

Dubois et al. presented a comparison of generator topologies for direct-drive wind turbines. Machines were compared with torque density and cost/torque criteria. A comparison of 60 different radial, axial and transverse flux and reluctance machines were shown. Torque density was chosen for comparing machines. Because they were independent of rotational speed. AFPM machines gave twice the torque density of RFPM machines. However, AFPM machines had twice the cost of RFPM machines. Consequently, they noted that prominent machines were TFPM and AFPM generators [76].

Chan and Lai investigated one rotor one stator coreless wind turbine generator. The output power equation and 2D FEA was used. Also, the steady-state performance was studied. A method for determining synchronous reactance was present. In addition, they noted that for a given voltage and output power the number of turns and cross-sectional area of armature conductors may be determined. Double layer full pitch armature winding was used. Generator production was introduced in detail. In conclusion, 230W, 16.7V, 8A, 450 rpm, 16poles generator was produced, tested and results were showed [77].

Bumby et al. presented air-cored, two-rotor, one stator wind turbine generator with two different power rates. The electrical design was analytically calculated. Also, performance calculations were done. Also, output power equations were given. Two power rates that 1 kW and 2.5 kW generators were compared. They compared between particular loads: resistive load, battery charging, and grid-tied. In generators, concentrated armature coils were used. They noted that the main loss mechanism is armature Joule loss. The generators have 16 poles, 12 coils, 250 rpm, and 93-94% efficiency [48].

Bumby et al. investigated two-rotor one stator coreless generator with trapezoidal magnets and coils for VAWT. The circumferential flux density distribution was obtained from a 2D solution of Laplace's equation. To obtain system performance, the generator represented the equivalent circuit model. Also, over-speed control with

dump loads was done. Terminal voltage, power and efficiency graphics of 5 kW, 150 rpm, 16 poles, 12 coils, and over 90% efficiency generator was present [78].

Price et al. investigated air-cored, two-rotor, one stator wind turbine generator. The magnetic field due to the magnets and armature reactions were analytically calculated. The analysis was carried out using radial slices rather than a mean radius approach. They compared the machine with magnetic FEA solutions. The machine specifications are 750 W, 600 rpm, 9 coils, 36 turns and 10 A [79].

Dehghanzadeh and Behjat presented experimental and performance analysis of a coreless AFPM generator for wind turbine applications. 3D FEM was used to reveal the performance parameters. The experimental results of the generator that output voltage under different loads were given. Three-phase R-L load was connected for testing the generator which 300W, 600rpm, 8 poles and 6 coils [80].

3.6.5. High-Speed Applications

Pullen et al. investigated a high-speed multi-disc coreless generator that combination with a gas turbine for electric traction vehicles. The generator was modular, and it had various power rates from 10 kW to 50 kW that two-rotor one stator to six rotors five stators. The generator reached %95 efficiency at 60,000 rpm [81]. After a while, Pullen and Mansir increased the power rate to 100 kW by eight-stage machine [82].

Fei and Luk presented design and performance analysis of high-speed coreless AFPM generator with circular magnets and coils. Analytical formulations and 3D FEA were investigated. Output voltage and power and efficiency graphs were given. In addition, harmonic analysis of line EMF and winding optimization was given. Experiments have been done at 50% of the rated speed because of laboratory regulations and experimental limitations. Comparison among analytical, FEA and experimental results was done. Besides, mechanical holder design was investigated. The experimental machine was 1 kW, 20000 rpm, 8poles, 6 coils generator [83]. Fei et al. presented a shortened work to another journal. The steady-state equivalent circuit was also investigated [84].

3.6.6. Other Applications

Howey proposed a two-rotor one stator air-cored generator for hydropower applications. A flow chart of a Matlab mathematical model for air-cored AFPM performance prediction. 220 V, 500 W at 1000 rpm RFPM machine was tested and was measured about 300 W. Therefore, for AFPM machine, 500 W and 85-90 % efficiency was estimated [85].

Jang and Chang investigated an application of spindle motor with PCB winding. Maxwell stress tensor was used to calculate force and torque. The advantage of Maxwell stress tensor is the direct calculation of force and torque from the magnetic flux distribution. Magnetic flux density, torque variation, axial force and torque due to the variation of air gap length graphs were given. Wave and concentric windings were considered. 8 poles, 12 V, 1 A, 4000 rpm, and 38% efficiency motor was experienced [86].

Jang and Chang continued to investigate a PCB spindle motor. An equivalent magnetic circuit was used to design the model. Torque-speed and torque-current curves were given with a comparison of radial gap motor. Leakage flux was calculated by Roter's method assuming the magnetic flux path of leakage. The experimental motor was up to 10 W, 15000 rpm and 50% efficiency [87].

4. DESIGN OF ENERGY SOURCE

In this thesis, a flywheel system and an axial flux (disk type) permanent magnet generator is preferred among the energy sources used in electromagnetic launchers. The amount of energy that cannot be obtained instantly from the mains can be stored mechanically on the flywheel. With the low stator inductance, the axial flux air-core generator eliminates the need for compensation windings. The structure of the energy source is shown in Figure 4.1.

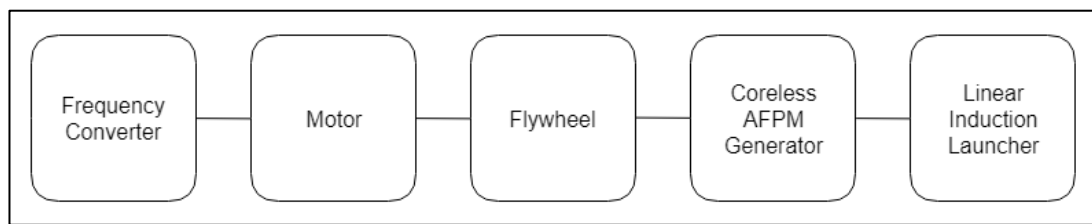


Figure 4.1: Structure of the energy source.

As the initial condition of the design, it was chosen to move a 200 g projectile from the existing single-stage LIL to a velocity of 200 m/s at the muzzle. Based on this condition, the other components of the system are explained respectively. Finally, the design of the AFPM generator is detailed. Launcher properties and performance requirements are given in Table 4.1.

Table 4.1: Launcher Properties and Performance Requirements.

Projectile Weight	200 gr
Muzzle Velocity of Projectile	200 m/s
Coil Pitch of LIL	0,1 m
Frequency	1 kHz

4.1. Linear Induction Launcher

Two laboratory scale, single section, traveling wave, generator-driven LILs were manufactured in Gebze Technical University (GTU) before and they used in this thesis as shown in Figure 4.2 and Figure 4.3. The initial velocity of the projectile is zero, the muzzle velocity v is 200 m/s, and the frequency of barrel can be calculated by

$$f = \frac{v}{2\tau} \quad (4.1)$$

where τ is the coil pitch, which is 0.1 m. Thus, the frequency of supply current, i.e., on the generator terminals, should be 1 kHz.

Inductance and resistance values of the launchers were measured with an LCR meter. Both launchers have 24 coils, but wire material and the number of turns are different. Parameters of launchers are shown in Table 4.2.

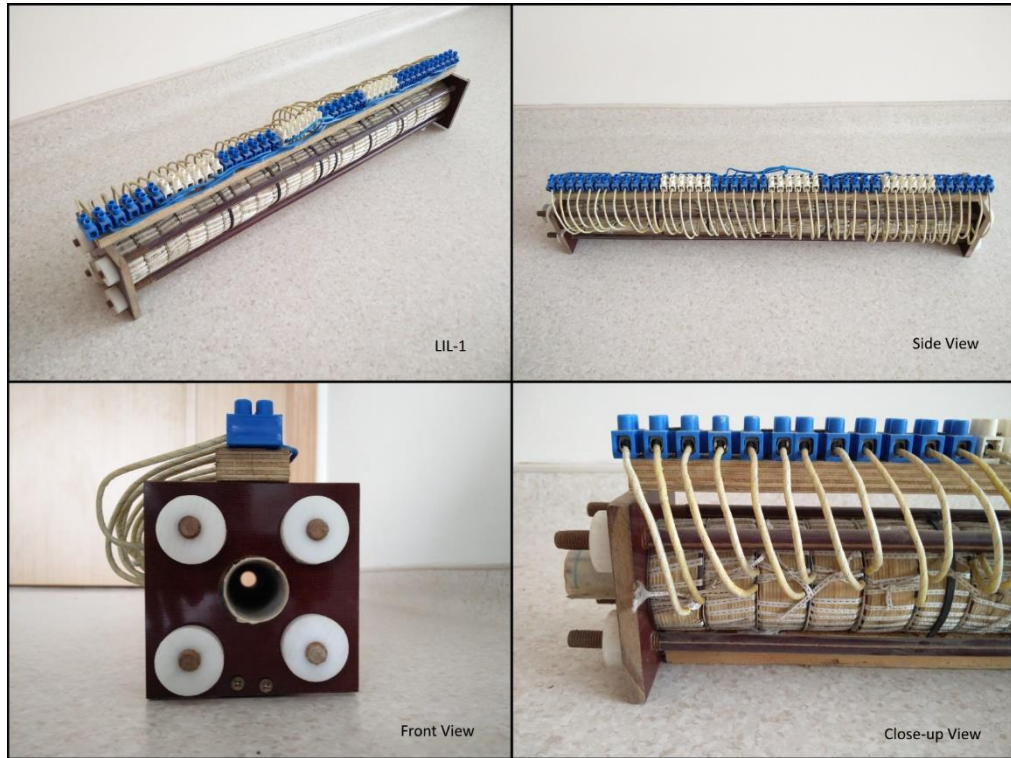


Figure 4.2: Single section linear induction launcher that 150-turn copper wire (LIL-1).

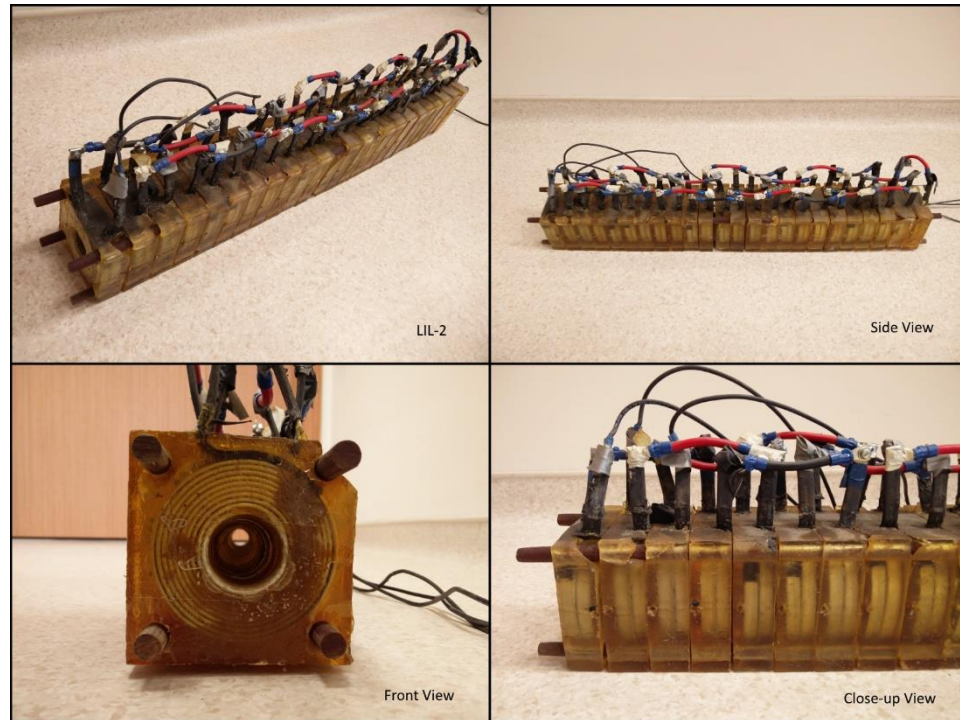


Figure 4.3: Single section linear induction launcher that 20-turn aluminum wire (LIL-2).

Table 4.2: Parameters of LIL-1 and LIL-2.

	LIL-1	LIL-2
Coil Material	Copper	Aluminum
Number of Turns	150	20
Coil Inductance (Average)	780 μH	17.84 μH
Coil Resistance (Average)	322 $\text{m}\Omega$	15 $\text{m}\Omega$
Phase Inductance (Average)	7.45 mH	162.6 μH
Phase Resistance (Average)	2.76 Ω	155 $\text{m}\Omega$

4.2. Motor

There is a conventional induction (asynchronous) motor with a rated power of 18.5 kW in the laboratory. With the mains connection, it can reach a maximum speed of 3000 rpm. Since the required starting torque is too high, the motor is driven by applying a ramp function with a frequency inverter.

4.3. Flywheel System

The flywheel can be used to provide high-energy pulses at power levels that exceed the limit of the available energy source. This is achieved by storing the volatile energy at a rate that is compatible with the low-level energy source and then consuming the energy at a much higher level in a relatively short time when needed. The flywheel/generator system is compact and easy to manufacture, making it a very suitable solution for electromagnetic launcher applications [23].

The simplest flywheel system is a rotating disk that is formed by the high-tensile-strength materials. Feasible flywheel system is a steel disk concerning price and performance ratio. Also, the steel disk can be easily found and manufactured. The design of a flywheel for using in a LIL application is a straightforward process. At first, the required energy to accelerate the projectile is calculated. Then, the kinetic energy of the flywheel is determined. It should be noted that the kinetic energy of the flywheel must be greater than the required energy of the LIL.

Muzzle velocity and the projectile mass must be determined to calculate the required energy to accelerate the projectile. Muzzle velocity was determined to be 200 m/s and the mass of the projectile is measured 0.2 kg, which existed in the laboratory. Required energy storage in the flywheel to accelerate the projectile is calculated by [23]

$$E_{KR} = \frac{0.5mv^2}{\eta \cdot ER} \quad (4.2)$$

where m and v are the mass and velocity of the projectile, respectively, η is the system efficiency, and ER is the energy recovery from the flywheel. From this, the required amount of energy in the launcher was calculated to be 80 kJ in order to increase the projectile to the target speed. From the theory of conventional induction motors, it is known that the energy efficiency for start-up operations is very low. For each energy unit stored kinetically in the rotor, more heat is dissipated by slip losses in the rotor. In the same way, a projectile accelerated from zero to a constant speed will be exposed to the same slip losses. The estimated system efficiency for the electromagnetic launchers is below 30% [88].

Energy recovery from the flywheel should be minimized during operation, which means a reduction in frequency, i.e., projectile speed. It is suitable to use a 20% energy of the flywheel for about a 10% reduction in the rotation speed. Furthermore, the shot can be repeated more frequently. The actual kinetic energy of the disk-shaped flywheel is

$$E_{KA} = \frac{1}{2}J\omega^2 = \frac{1}{2}\frac{\rho\pi r^4 h}{2}\left(\frac{2\pi n}{60}\right)^2 \quad (\text{x.3})$$

where J is the moment of inertia, ω is the angular velocity of the flywheel, ρ is the density of the flywheel material, and r , h , and n are the radius, length, and rotational speed of the flywheel, respectively. The flywheel radius has been selected as 250 mm considering the production possibilities. Then, both energy use and speed reduction were taken as a reference to calculate flywheel height. If energy use (20%) is taken as reference, 80 kJ requires a total flywheel kinetic energy of 400 kJ. For the specified radius, the flywheel height is calculated as 168 mm. About the speed reduction (10%), the flywheel height is 177 mm when the total amount of energy required for a speed falling from 3000 rpm to 2700 rpm at 80 kJ is calculated. The flywheel height is 151 mm in layered structure close to the calculated values. The flywheel dimensions, stored energy in the flywheel at 3000 rpm, and required energy of the LIL are given in Table 4.3.

Table 4.3: Flywheel Dimensions, Efficiency, and Energy.

Radius of Flywheel (r)	250 mm
Length of Flywheel (h)	151 mm
Flywheel Material	Steel 1040
ER	0.2
η	0.25
Stored Energy on Flywheel (E_{KA})	360 kJ
Required Energy on Launcher (E_{KR})	80 kJ

4.4. Axial-Flux Permanent Magnet Generator

The AFPM machines differ from radial machines with an air gap flux path that is axially orientated. Flexible configuration of the AFPM machine allows using it a variety of applications. One of the important features of the AFPM generator is the coreless structure. Lack of the iron core in the stator of the machine results in very low inductance of the stator windings compared to the iron core machines [89]. In addition, it comes through zero cogging torque. The output power of the AFPM generator is related to the outer diameter of the machine. However, it cannot be increased easily because of mechanical constraints. On the other hand, the multi-stage design overcomes this problem [90]. Therefore, the output power can be increased by the number of stages.

5. DESIGN OF AFPM GENERATOR

When starting the generator design, the values obtained and calculated in the previous chapter will be used as the initial parameters as shown in Table 5.1.

Table 5.1: Initial Parameters of AFPM Generator.

Frequency of Stator Current	1 kHz
Maximum Rotation Speed of Generator	3000 rpm
Maximum Rotor Diameter	400 mm
Max. Temperature of Copper Wire	100 °C
Max. Current Flowing Stator	1000 A
Max. Ignition Time	1 s

In the context of these values, the main objective in the generator design is to realize the generator with the lowest inductance within the initial parameters in Table 5.1. Low inductance is required for the rate of current rise at the moment of ignition to be as low as possible.

As mentioned earlier, the design of air-cored AFPM machines reduces the inductance considerably compared to the cored machines. However, additional special conditions are also required in a machine designed for the launchers. The necessity of launching the projectile as heavy and as high as possible the design of a generator which is both high frequency and instantaneous high power, i.e. high current carrying. The frequency can be increased by increasing the number of poles, but when this is the case, the copper cross-section area is reduced by the conventional winding method. As a first solution, a multi-layer AFPM structure is considered suitable. In the multi-layered structure, a new approach is used to design one-phase winding in each stage. Moreover, a new winding technique has been produced with a wave winding for ease of production as shown in Figure 5.1 [25].

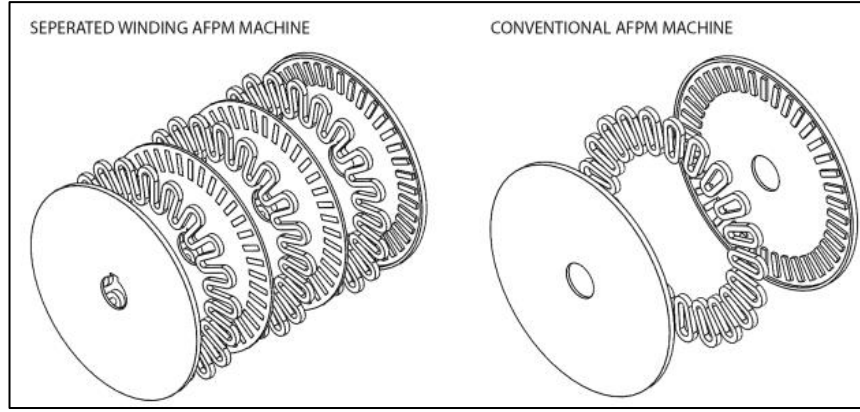


Figure 5.1: Separated winding vs. conventional winding AFPM machine.

5.1. Number of Poles

The first design step is to obtain the required number of poles to ensure the output frequency of the stator current of the generator. With this formula, the required number of poles is found 40.

$$p = \frac{120f}{n_s} \quad (5.1)$$

Increasing pole number is the basic method of raising frequency in electrical machines. Although this is possible with AFPM machines, the rotor diameter increases as the number of poles increases. Rotor diameter is a mechanically limiting factor. On the other hand, when the magnet size is made smaller, three-phase stator windings cannot fit into the one pole.

5.2. Magnet Geometry

After the number of poles was determined, the available magnets were searched in the market. Neodymium-Iron-Boron N35 grade both rectangular and circular magnets were examined because of their rapid availability and cost-effectiveness. Table 5.2 shows magnets of different geometric dimensions.

Table 5.2: Calculations of Magnet Geometries.

Dimensions [mm]	Shape	Do [mm]	Di [mm]	Do/Di	Effective Area [mm ²]	Magnet Area [mm ²]	Magnet Area Percent [%]
30x5	Circ.	476.09	Over Limit				
35x5	Circ.	544.82	Over Limit				
25x10x5	Rect.	304.68	254.52	1.20	220.32	10000	45.39
40x10x5	Rect.	334.67	254.52	1.31	370.88	16000	43.14
40x15x5	Rect.	462.02	Over Limit				
40x20x5	Rect.	462.01	Over Limit				
50x10x5	Rect.	354.66	254.52	1.39	479.12	20000	41.74

Since the flywheel diameter is selected as 500 mm, the generator diameter is selected as the initial condition at most 500 mm. The stator determines the generator diameter and the rotor diameter can be a maximum 400 mm considering the winding ends and connection points. In this direction, the magnets were arranged as 40 poles and analyzed geometrically. For axial flux machines the effective area, i.e. ratio of the outer and inner diameter lengths of the magnets, is best specified as $1/\sqrt{3} = 0.577$ [38]. In addition, space is left between the magnets to obtain a sinusoidal signal (low harmonic) [91]. The rotor layout for each magnet geometry is given in Figure 5.2 and Figure 5.3. The magnet selection was evaluated according to the criteria for total magnet area, percentage of use of magnet area and close to the optimum outer diameter and inner diameter ratio. This evaluation is shown in Table 5.2. As a result, the most suitable magnet geometry was found to be 40x10x5 mm.

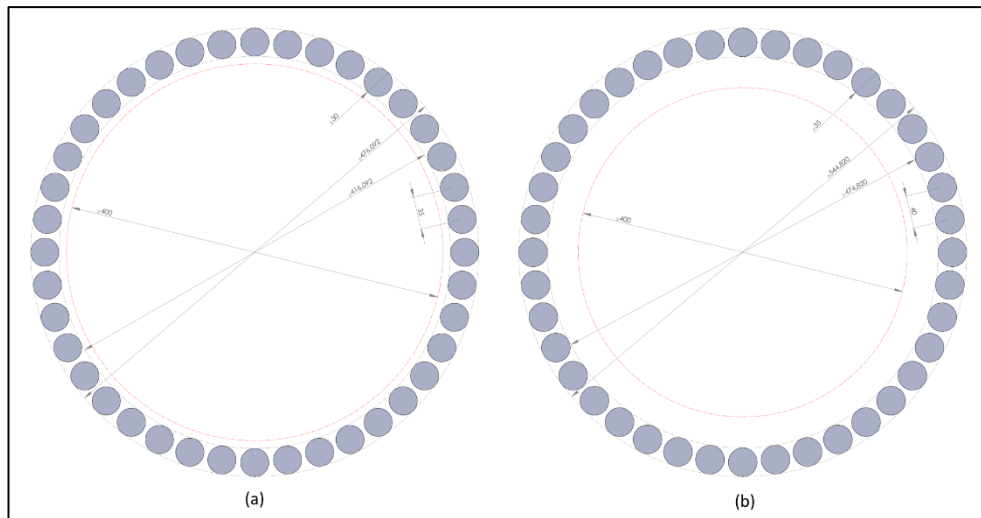


Figure 5.2: Rotor layouts with circular magnets with (a) 30 mm and (b) 35 mm diameters.

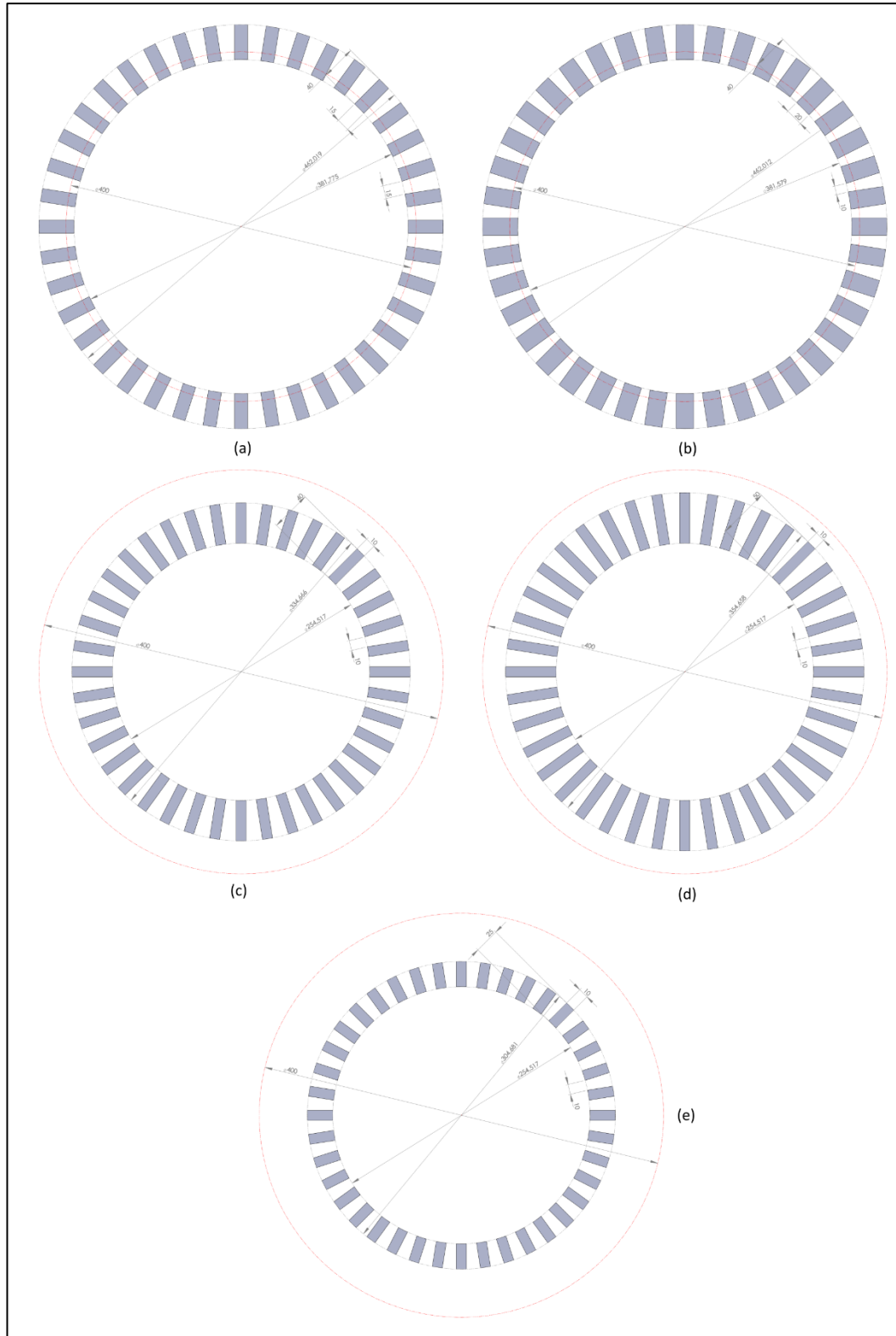


Figure 5.3: Rotor layouts with rectangular magnets (a) 40x15 mm, (b) 40x20 mm, (c) 40x10 mm, (d) 50x10 mm, and (e) 25x10 mm.

5.3. Rotor Yoke Thickness

In order to determine the thickness of the rotor yoke (back-steel), the amount of leakage flux behind the steel is referenced. Thickness was calculated by simulating the magnetic flux density of the magnets in the polarization direction of the component below 0.1 T. Simulation graphs in thicknesses from 1 mm to 5 mm are shown in Figure 5.4. As a result of these analyses, the leakage flux of a 5 mm rotor yoke was decreased below the specified limit.

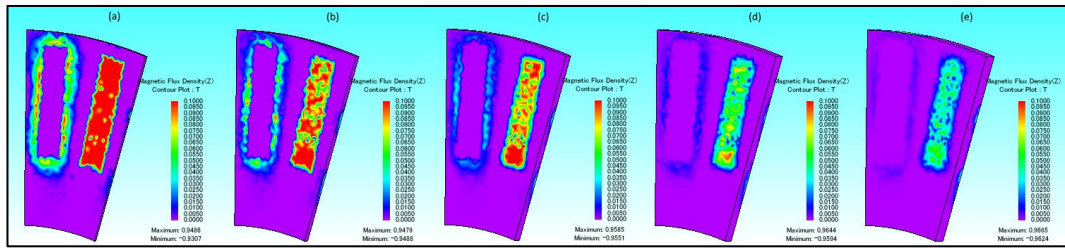


Figure 5.4: Simulation results of the magnetic flux density on the rear surface of the rotor. Rotor yoke thickness: (a) 1 mm (b) 2 mm (c) 3 mm (d) 4 mm (e) 5 mm.

5.4. Air Gap Distance

The induced voltage equation based induced voltage factor parameter was used to determine the distance of the air gap. Air gap flux density at different air gap distances was obtained. The winding number of turns was normalized in the range because of an increasing number of turns with air gap distance. However, peak magnetic flux density decreases while increasing air gap distance. In the end, the induced voltage factor is the product of the normalized number of turns to peak magnetic flux density in the center of the air gap as shown in Figure 5.5. Looking at this coefficient in Table 5.3, the flux density decreases as the distance increases, but the number of unit turns of the stator winding increases. Even if the distance increases after a certain point, the induced voltage does not increase. According to the table, the air gap was selected as 12 mm.

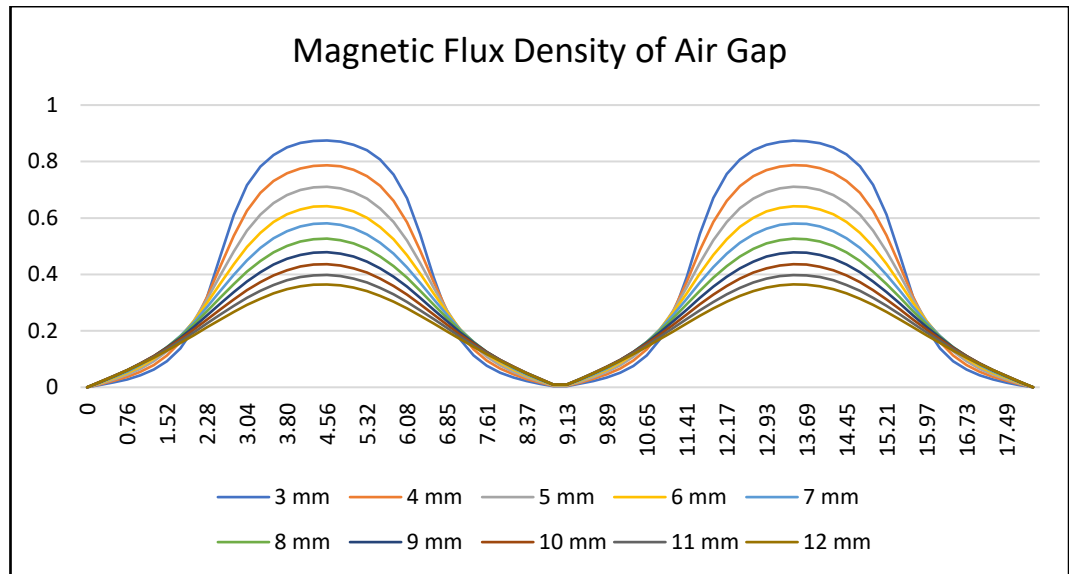


Figure 5.5: Magnetic flux densities of the air gap.

Table 5.3: Air Gap Distance Calculation.

Air Gap Distance [mm]	Normalized Number of Turns	Peak Magnetic Flux Density [T]	Induced Voltage Factor	Increment from Previous [%]
3	1	0.87	0.87	-
4	2	0.78	1.57	79.7
5	3	0.71	2.13	35.4
6	4	0.64	2.56	20.4
7	5	0.58	2.90	13.2
8	6	0.52	3.15	8.7
9	7	0.48	3.34	6.1
10	8	0.43	3.48	4.1
11	9	0.40	3.57	2.7
12	10	0.36	3.63	1.7

5.5. Wire Cross Section Area

In order to determine the cross-sectional area, the temperature rise of the wire is calculated under the following assumptions: The limit value of the copper temperature is 100 °C (i.e., the temperature rise to be 75 °C under normal conditions), the maximum current flow through the wire is 1000 A and the ignition time of the generator is maximum 1 s. Because at high temperatures the winding insulation and the filling of the stator epoxy begin to deteriorate.

Table 5.4: Temperature Rise of Copper at 1000 A.

Cross-section Area [mm ²]	Temperature Rise [°C]
10	48.65
9	60.06
8	76.01
7	99.28
6	135.14
5	194.60

As a result of these calculations, it is understood that the optimal cross-sectional area is 8 mm². Rectangular wire is preferred to use the cross-sectional area of the coil more effectively.

Since the transient situation is considered here, heat conduction and convection are neglected. Calculations were made based on the amount of energy produced only in copper. The actual temperature rise will be below this value. This provides a positive approach to ensure that the design remains in the safe zone.

5.6. Number of Turns

If both air gap distance calculations and cross-sectional area calculations are considered, the fact that the number of turns is too low or too high will not be appropriate. The total cross-sectional area for an effective edge in the wave winding structure can be calculated as 100 mm². Considering the circular cross-section wire,

only nine turns of wire can fit in this area. If a rectangular cross-section wire is selected, 12 wires can fit, but it is understood that a 10-turn winding would be suitable considering the wire insulation material.

5.7. Winding

In the LIL application, a traveling wave must be generated for projectile motion, which requires a symmetrical three-phase winding. When a full pitch concentrated winding is performed, a total of 20 coils are produced. Furthermore, when this number of coils is divided by three for three phases, the induced voltage will not be sufficient for the launcher application. For this reason, the multi-layered structure has been selected and unlike conventional axial flux machines, a structure will be provided as a phase for each air gap. Thus, both the induced voltage level is increased, and the conductor cross-sectional area is increased, allowing high current to pass.

When air-core axial flux machines are examined in the literature, the following three winding types are generally encountered: overlapping and non-overlapping concentrated winding, and wave winding. Overlapping winding is not suitable for this work. Therefore, non-overlapping concentrated and wave winding species were analyzed. These two winding types were compared in terms of internal resistance, inductance, and production techniques.

The properties of symmetrical three-phase windings are described in the AFPM machines section. In terms of these characteristics, both winding types are identical. That is, both windings are a non-overlapping, single layer, full-pitch, integral slot and concentrated. Here, the difference between the results is not analytical but physical. This difference creates a resistance difference and an inductance difference between them. Also, the production method is changing.

5.7.1. Inductance Analysis of Concentrated and Wave Winding

The inductance analysis of both the concentrated and the wave winding was performed on Jmag software. As shown in Figure 5.6, the one-twentieth model was created for both concentrate and wave windings. Then the inductance analysis tool in the software was run. The inductance value for the concentrated winding was 78.2 μH

and the inductance value for the wave winding was 74.5 μH . As a result, the inductance of the wave winding decreases by 4.7%.

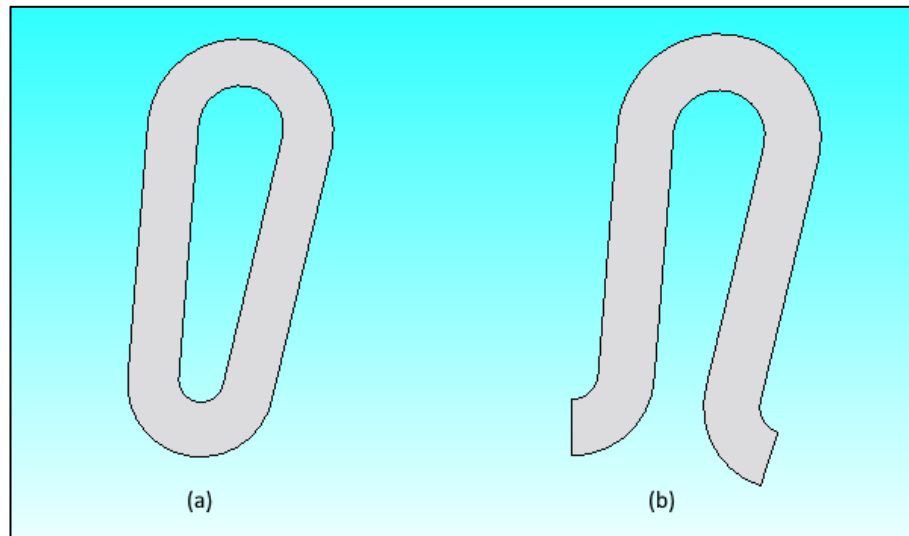


Figure 5.6: Inductance analysis models of windings: (a) Concentrated and (b) Wave winding.

6. SIMULATIONS

Simulations of the designed AFPM generator were performed. Firstly, the distribution of the magnetic flux density in the air gap is obtained. Then phase windings were added by using the same model and transient magnetic analysis was run and the graph of induced voltage was obtained. Subsequently, the proposed separated winding is compared with the conventional AFPM configuration those single-stage 3-phase winding that contains the same volume active material and three-stage 3-phase winding that has the same air gap distance.

In order to find the energy to be transferred to the launcher, an inductor and a resistor are connected to the phase ends of the generator and the launcher equivalent model is added. Thus, voltage, current, and power values of the launcher model were obtained. Thus, loaded simulations of the generator are realized. Finally, inductance analysis was performed and evaluated with Jmag software.

6.1. Magnetic Flux Density

In order to determine the performance characteristics of a permanent magnet machine, the priority is to determine the magnetic flux density in the air gap. The only source of magnetic flux in the air gap is permanent magnets. For this purpose, the machine model was created and the flux density in the air gap was obtained at different distances. Because the flux density decreases as we move away from the magnet. This distance plays a critical role, especially in air-core machines. However, considering the analysis in the previous sections, the flux density between the two magnets decreases slightly after a certain point as the distance increases. Also, the measurement taken at the midpoint of the air gap will give the lowest value of the flux density. Therefore, the average of the measurements taken at different cross-sections in the air gap will provide more accurate flux density.

To achieve a balanced three-phase voltage in the proposed system, the magnetic flux density in each air gap must be equal. In the proposed system, since all magnets are of equal height, equal flux density will not be obtained in all three air gaps. For this reason, it is necessary to measure the side air gaps and the middle air gap separately. Here, the measurements for the side air gaps and the middle air gaps were

made separately and the mean flux density of the air gaps was obtained by taking the mean values.

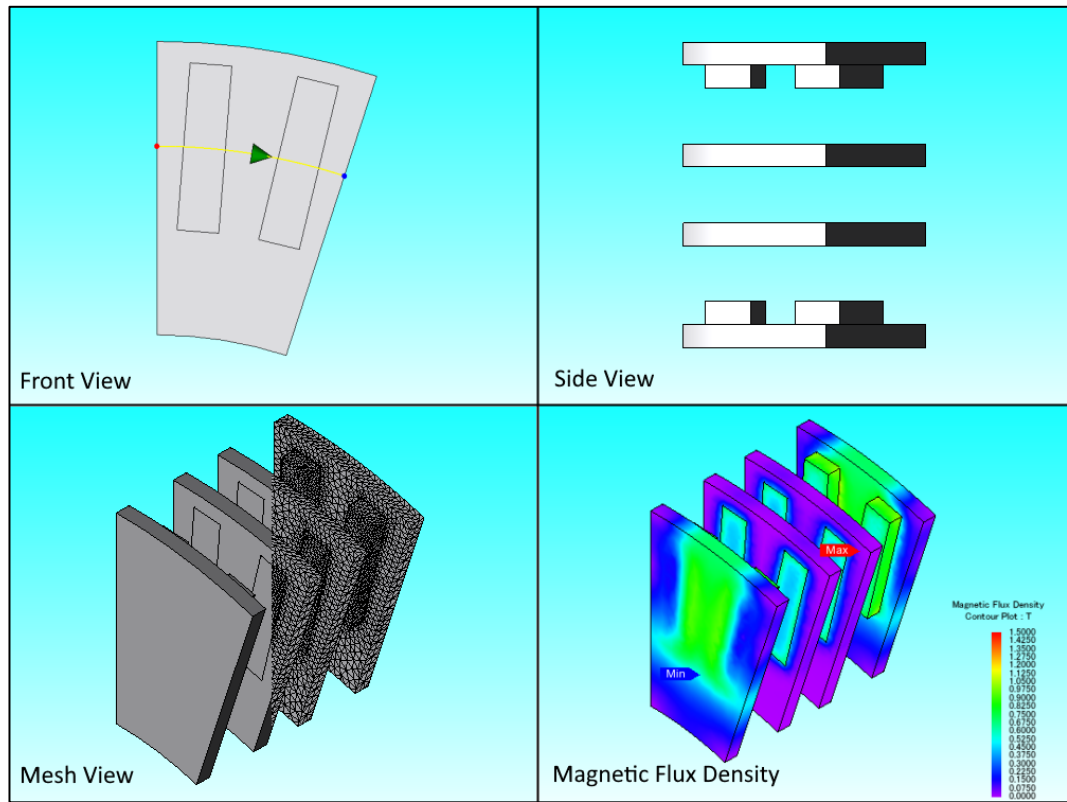


Figure 6.1: Magnetic Flux Density Analysis.

For the simulation, the magnetic model in Figure 6.1 is created. A periodic flux density graph was obtained by selecting only two poles. An arc is taken from the midpoint of the outer and inner radius where the magnets are located. The mesh element length of the magnets was chosen as 1 mm to ensure the obtained graphics to be precise. There are two different flux paths: a side air gap and a middle air gap. Graphs were obtained at 1 mm intervals over these two air gaps, then averaged. The side air gaps flux density graphs are shown in Figure 6.2 and Figure 6.3. The middle air gap flux density graphs are shown in Figure 6.4 and Figure 6.5.

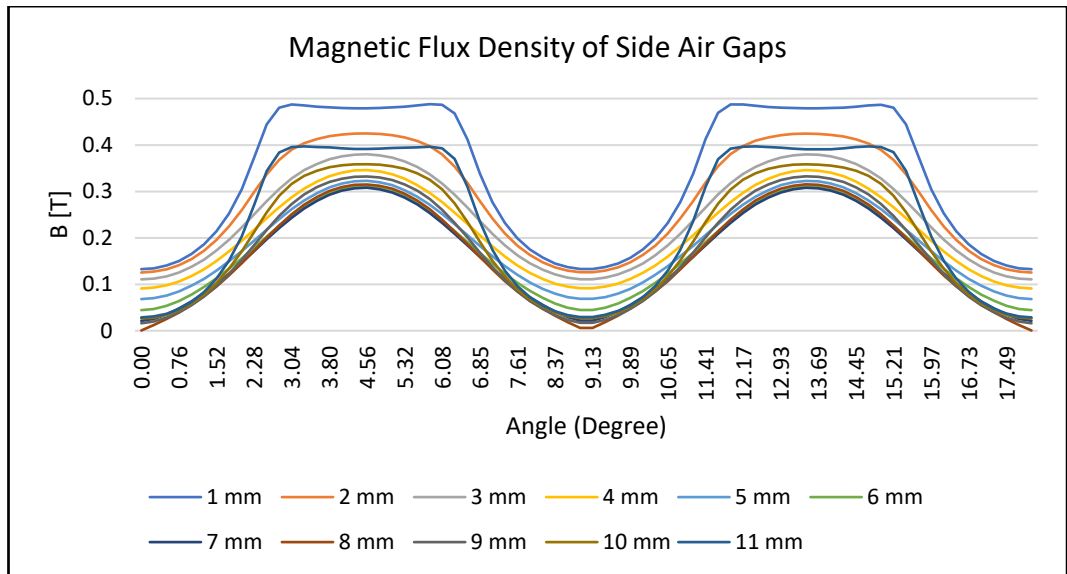


Figure 6.2: Magnetic flux density of side air gaps.

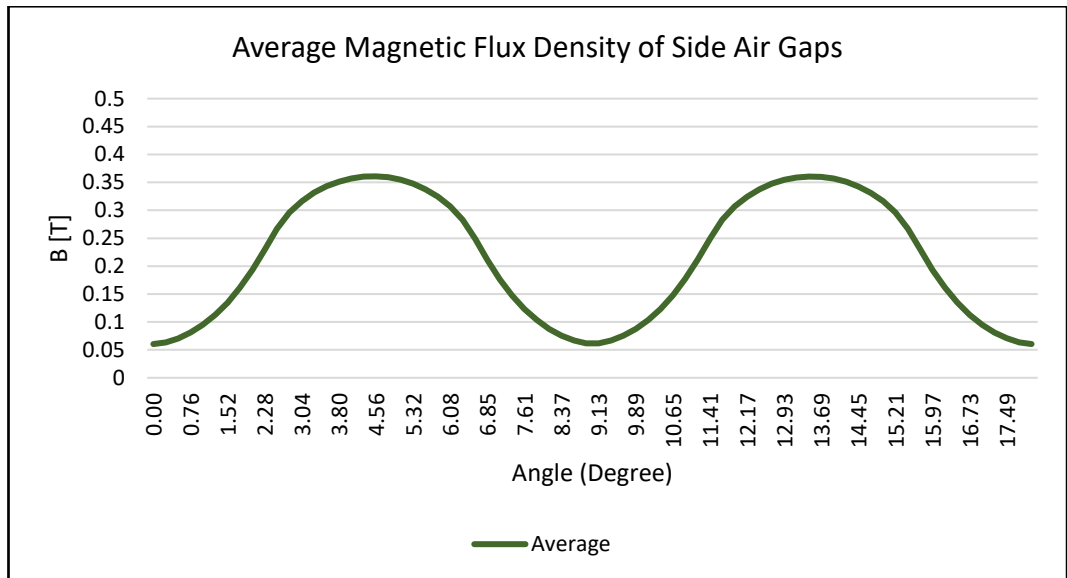


Figure 6.3: Average magnetic flux density of side air gaps.

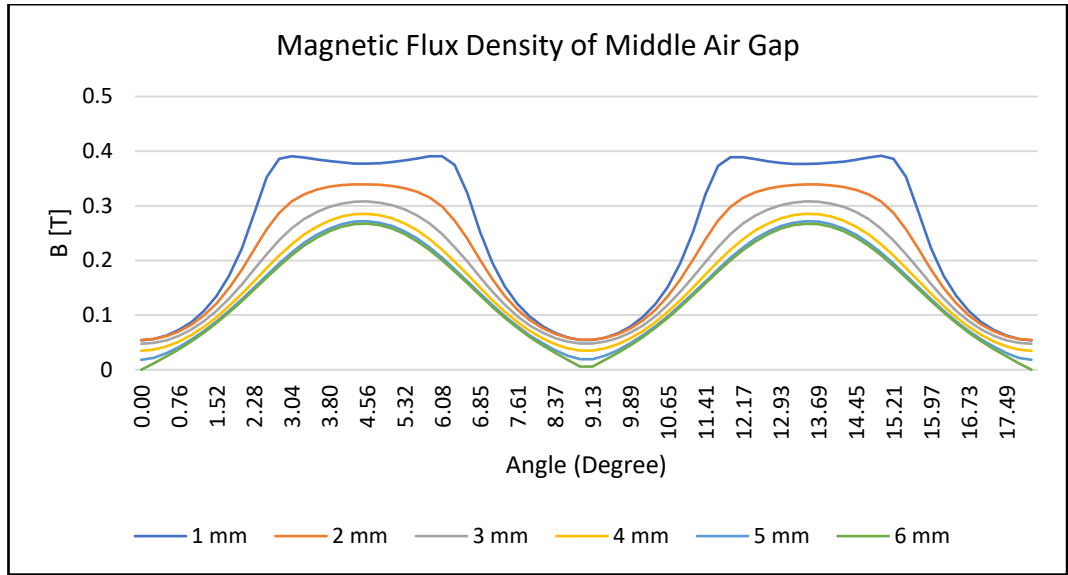


Figure 6.4: Magnetic flux density of middle air gap.

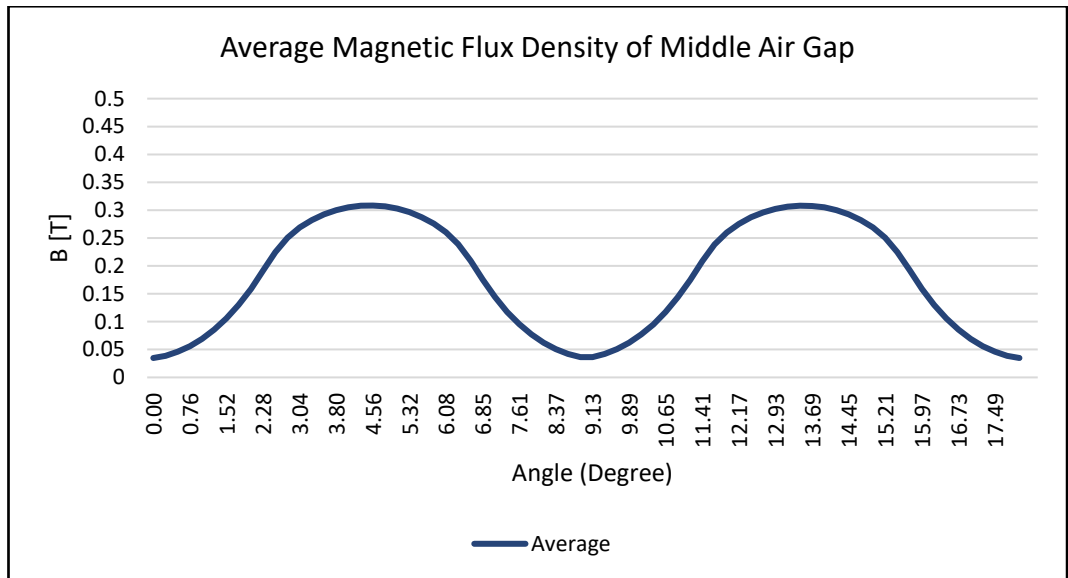


Figure 6.5: Average magnetic flux density of middle air gap.

As shown in Figure 6.3 and Figure 6.5, the peak value of the magnetic flux density is different from each other. The side air gap flux density is higher than the middle air gap flux density due to rotor yoke. Because leakage flux is more in the middle air gap. This can be overcome by increasing the height of the magnets in the middle rotor.

6.2. Induced Voltage

The induced voltage is obtained by constructing the model in Figure 6.6. To calculate the induced voltage, it is necessary to run transient magnetic analysis on Jmag. A precise solution can be achieved by adjusting the pitch and mesh resolution appropriately. However, reducing the pitch and mesh resolution greatly simplifies the simulation time. Furthermore, since there are moving parts (rotor), a sliding surface is formed between the fixed parts and the moving parts. On radial machines, the software automatically adjusts this. In axial flux machines, more than one surface usually occurs, and surfaces need to be defined. Particularly in multi-stage structures such as the work in this thesis, more than two surfaces are formed. Also, as a requirement of the software, fixed parts and moving parts must not be separated. According to this requirement, the rotors are connected to the shaft by an additional part, and the stator parts are connected with a virtual part. Thus, the simulation could be run.

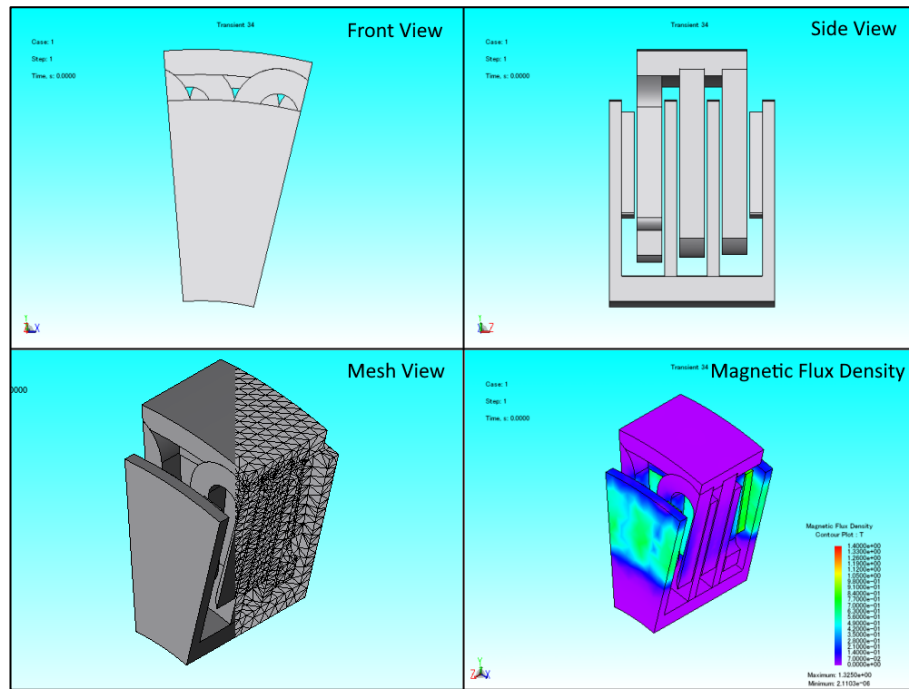


Figure 6.6: Simulation model of proposed machine.

The voltage expression obtained as a result of the simulation is shown in Figure 6.7. Approximately 13% of the voltage difference occurs between the side phases and the middle phase.

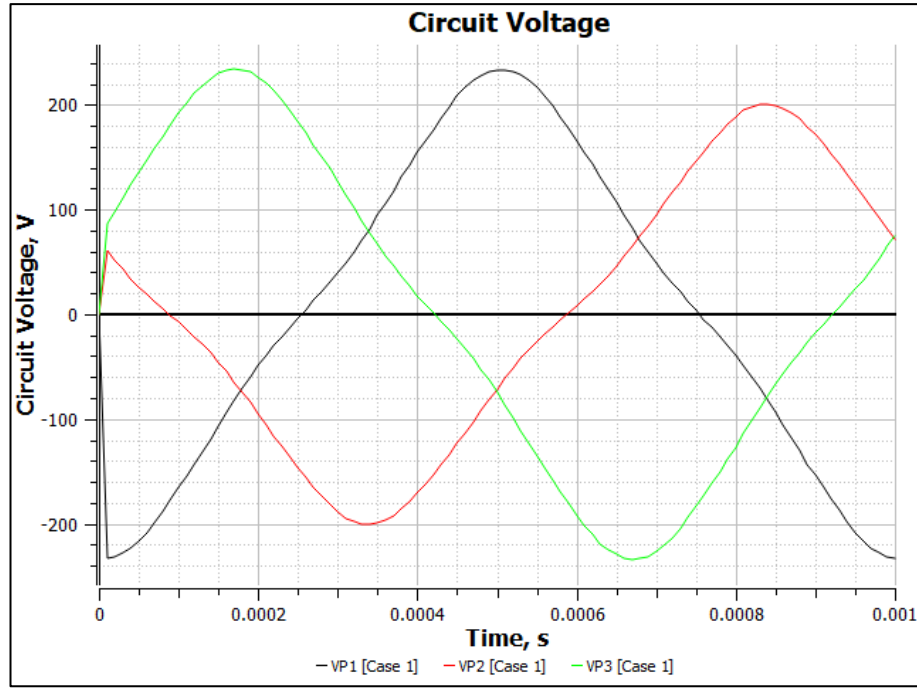


Figure 6.7 Induced voltage of the generator.

6.3. Comparison of Winding Configurations

The realization of the machine by dividing the three-phase windings into three separate layers named as separated windings provides some advantages. Although production may seem complex, it is advantageous for applications with multipole (i.e. high frequency) and high-power applications. Also, compared with the conventional same power AFPM machine, it is less complex. The separated winding configuration is compared with conventional AFPM machines in two different views. The first one is to keep the volume of active material constant and to form a single layer structure. In other words, the volume of the magnet and copper is kept constant, and the three-phase windings of the machine are positioned in a single air gap. In this case, the voltage induced in the phases was substantially different as the air gap increased three times compared to one. In another structure, the air gap was kept constant, again three-phase windings were placed in this air gap and it was made of three stages. In other words, a three-layer structure of stator having three-phase windings is realized. Close results are obtained to the existing separated winding, but it is more complex when evaluated in terms of production and assembly. Cross-section views of compared machines are shown in Figure 6.8.

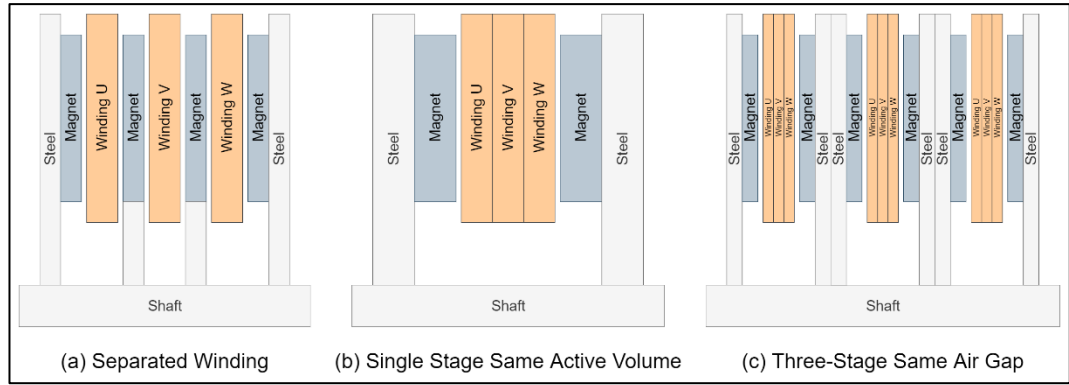


Figure 6.8: Comparison of separated winding with single stage and three stage configurations (a) Separated Winding, (b) Single stage same active volume, and (c) Three-stage same air gap.

The data obtained from the simulations are compared in Table 6.1.

Table 6.1: Comparison of Winding Configurations.

	Separated Winding	Single Stage Same Active Volume	Three Stage Same Air Gap Distance
Peak Induced Voltage	238 V	172 V	242 V
Voltage Difference	%13	%56	%15
Difficulty of Manufacturing and Assembly	Easy	Very easy	Difficult

6.3.1. Single Stage Same Active Volume

In this analysis, the magnet and copper volume were kept constant. In the proposed generator, windings distributed in three separate air gaps are collected in a single air gauge. Similarly, the magnets in four different rotors are positioned in two separate rotors by increasing their heights. The simulation model is shown in Figure 6.9.

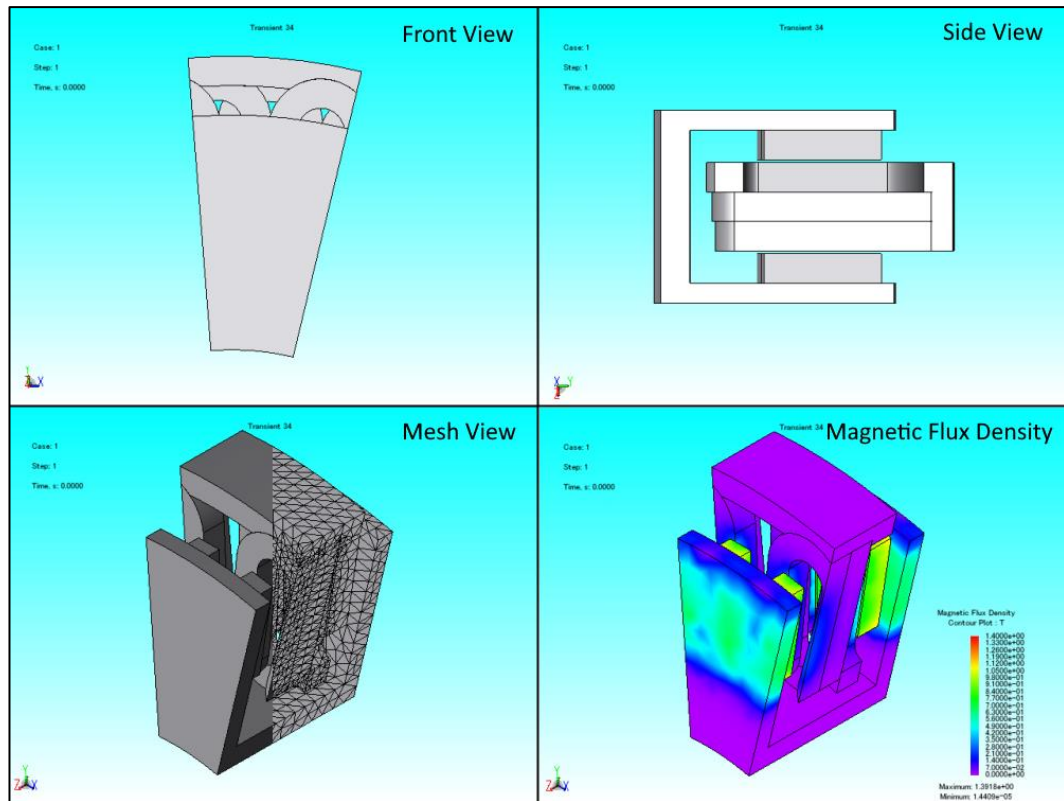


Figure 6.9: Simulation model of single stage same active volume.

In this structure, the air gap has increased almost three times. As a result, the magnetic flux density in the air gap is reduced, thereby reducing the induced voltage. In addition, the induced voltage is very low, since the middle phase winding is very low compared to the flux density of the other windings. In other words, the induced voltage difference between the phases is very high. Since the copper cross-sectional area does not change, the maximum current flow is the same. That is, the power to be obtained in this configuration will be reduced by the same rate as the induced voltage. Figure 6.10 shows the induced voltage graph. As shown in the graph, the induced voltage difference between the phases is over 50%.

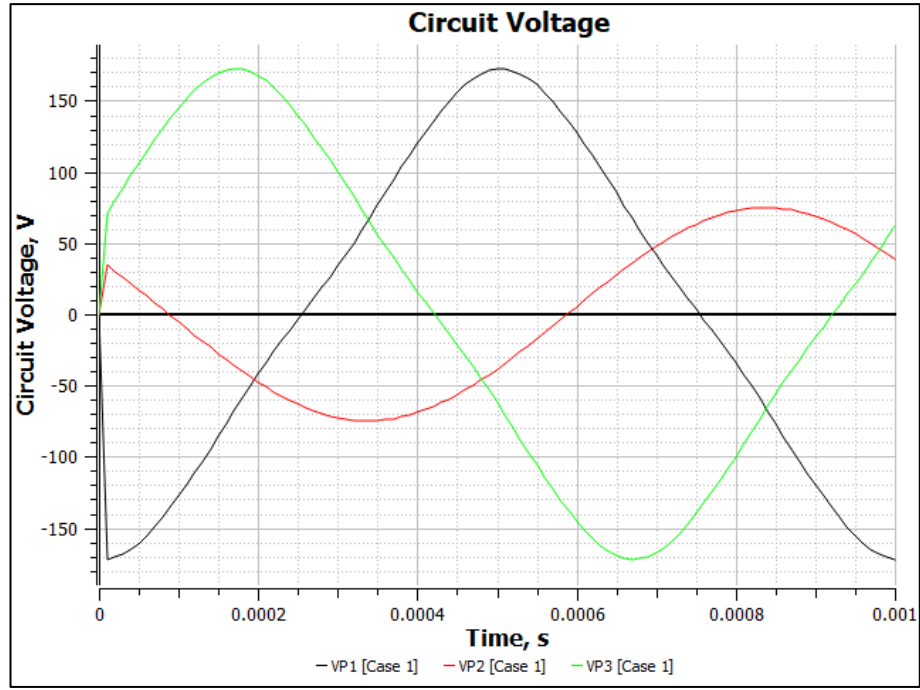


Figure 6.10: Induced voltage of single stage same active volume model.

6.3.2. Same Air Gap Distance

In this analysis, the decrease in magnetic flux density which occurs when the air gap is increased is aimed to be higher and the difference between the induced voltages is lower. However, when three-phase windings are positioned in the same air gap, the cross-sectional area of the phase windings will be reduced by one-third. To increase the power level to a comparable level, three machines were placed on the same shaft by the conventional method. So, the multi-stage machine structure was applied. Thus, the current-carrying capacity of each phase was increased by paralleling the three-phase windings. As it is a three-stage machine, the results were evaluated by simulating the single-stage as shown in Figure 6.11. This configuration is more difficult to manufacture and assembly.

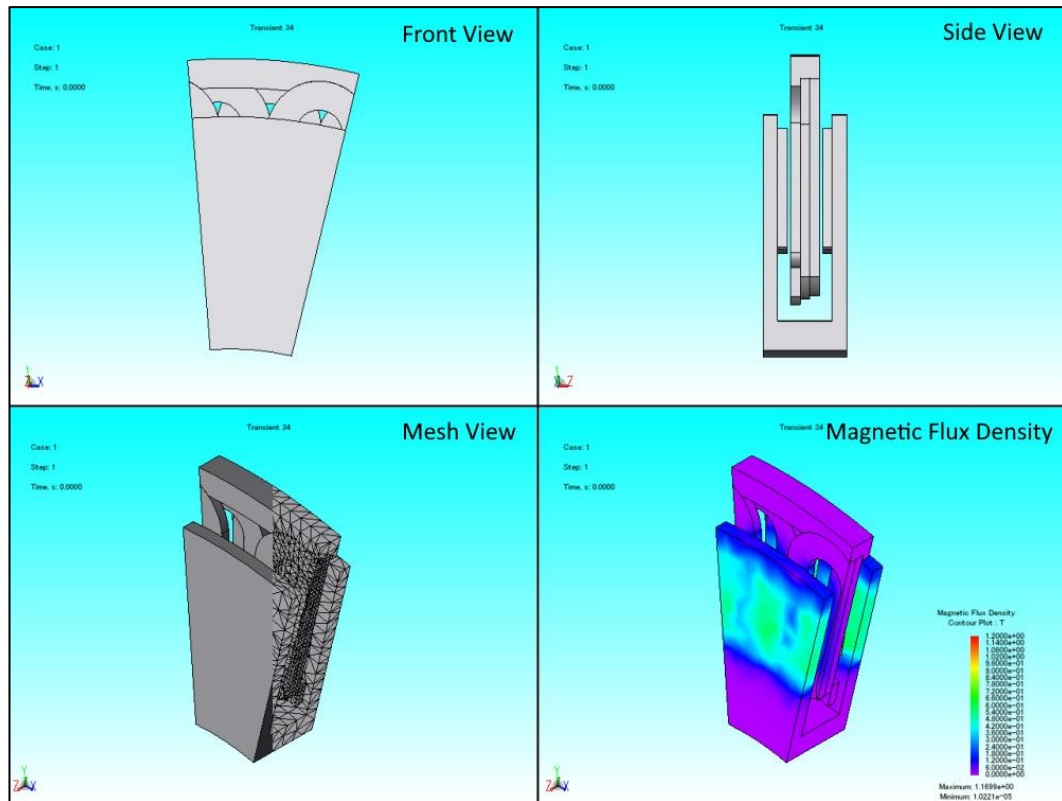


Figure 6.11: Simulation model of same air gap distance.

The voltage graph induced according to the simulation results of this model is shown in Figure 6.12. The peak value of the induced voltage is higher than the recommended machine, but the ratio is less than 2%. However, the difference between phase voltages has increased to 15%. Furthermore, this structure is more difficult to manufacture and assemble than the proposed machine.

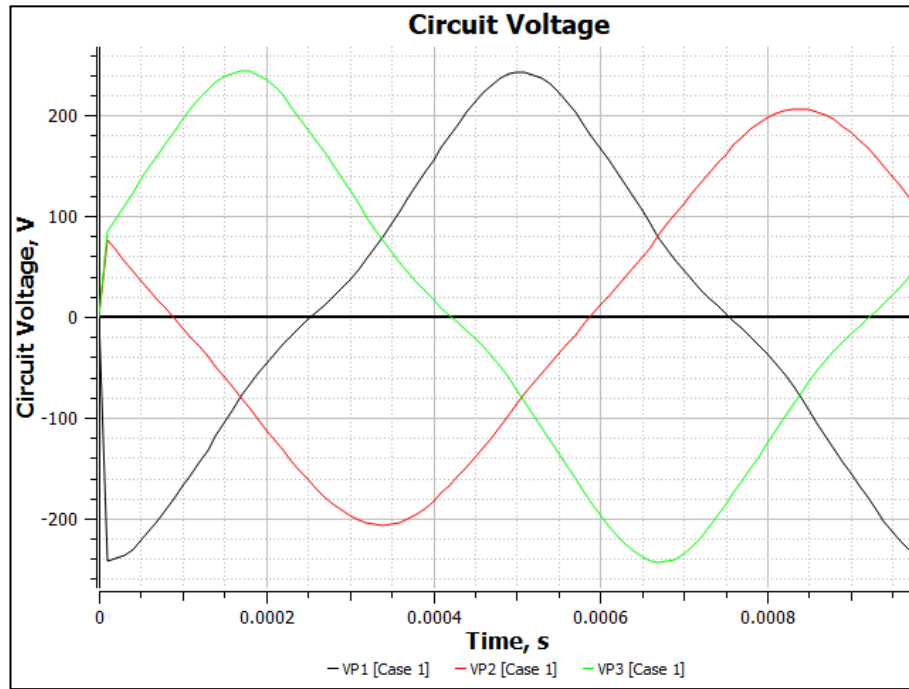


Figure 6.12: Induced voltage of same air gap distance model.

6.4. Loaded Simulations

The biggest difficulty encountered in performing simulations under load is to connect the launcher model to the generator system as a load. In the simulation program, simple circuit elements can be connected as load. However, the equivalent circuit model of the launcher is not that simple. Coilgun-type launchers equivalent circuit model studies are available in the literature. Although it is quite complicated to determine the values of equivalent circuit elements, the general tendency is to model the launcher coils and the projectile separately and is represented by an inductor and a series-connected resistor in the model. Besides, the structure is complicated by the fact that the launcher itself is a dynamic system in the transient state.

Zabar et.al. designed a capacitor driven linear induction launcher in 1989. The coils of the launcher are modeled as an inductor and a series-connected resistor that represent the kinetic energy of the system and the total ohmic loss. There was no equation to calculate the values of these elements in this work [10].

In 1993, He et.al. created the equivalent circuit model of induction type launcher by using the electromagnetic field transmission line approach. The model created here was quite complex [92].

Balikci et.al. investigated a generator driven LIL in their study in 2005. The model of the launcher was given with launcher coils and the projectile, but the analysis mostly focused on the analysis of the connection of the launcher coils. Similarly, both the launcher coil and the projectile are modeled here as inductors and resistors in series [93].

Polzin et.al. gave a model in their article in 2012 that was quite simple. It is modeled as only a transformer and a series resistor connected to the secondary terminal. The launcher coils represent the transformer's primary windings and the projectile represents the transformer's secondary windings and an equivalent series of resistors connected thereto [94].

Based on these approaches, and at least to perform the generator's performance analysis, it would not be wrong to model the launcher as an inductor and a series connected resistor. In this thesis, different inductance and resistance values are analyzed in order to investigate the performance of the generator. The inductance and resistance values of the current launchers are taken as reference.

For accurately analyzing the performance of the generator and the launcher together, the simulation model of both the generator and the launcher should be created and run in coupled. This analysis is another subject of study.

The model in Figure 6.11 was used to perform the loaded analyses. Also, the circuit diagram of Figure 6.13 is formed and the launcher is represented by an inductor and a series-connected resistor. Resistors R1, R2, and R3 represent the ohmic losses of the launcher and the kinetic energy of the projectile, L6, L7, and L8 coils represent the launcher's equivalent inductance, Coil1, Coil2 and Coil3 represent the phases of the generator. The simulation values of these elements are shown in Table 6.2. After a certain time, the switches are switched off, and current starts to flow through the induced voltage in the generator phases and the launcher inductance and resistance. VP and CP are voltage and current probes respectively. Each condition of loaded simulations finishes more than 12 hours. All three analyses results are seen in Figure 6.14, Figure 6.15, and Figure 6.16.

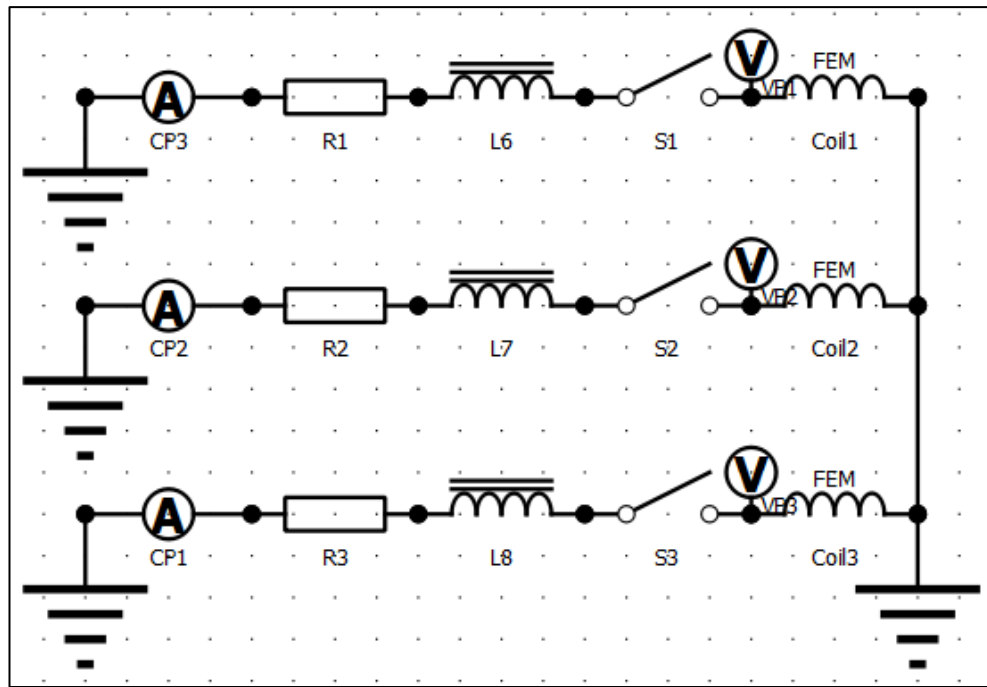


Figure 6.13: Circuit model of simulation.

Table 6.2: Loaded Analyses Parameters.

	L6, L7, L8 (μH)	R1, R2, R3 ($\text{m}\Omega$)	R (Coil1, Coil2, Coil3) ($\text{m}\Omega$)
Analysis-1	800	180	4
Analysis-2	80	180	4
Analysis-3	15	4.74	4

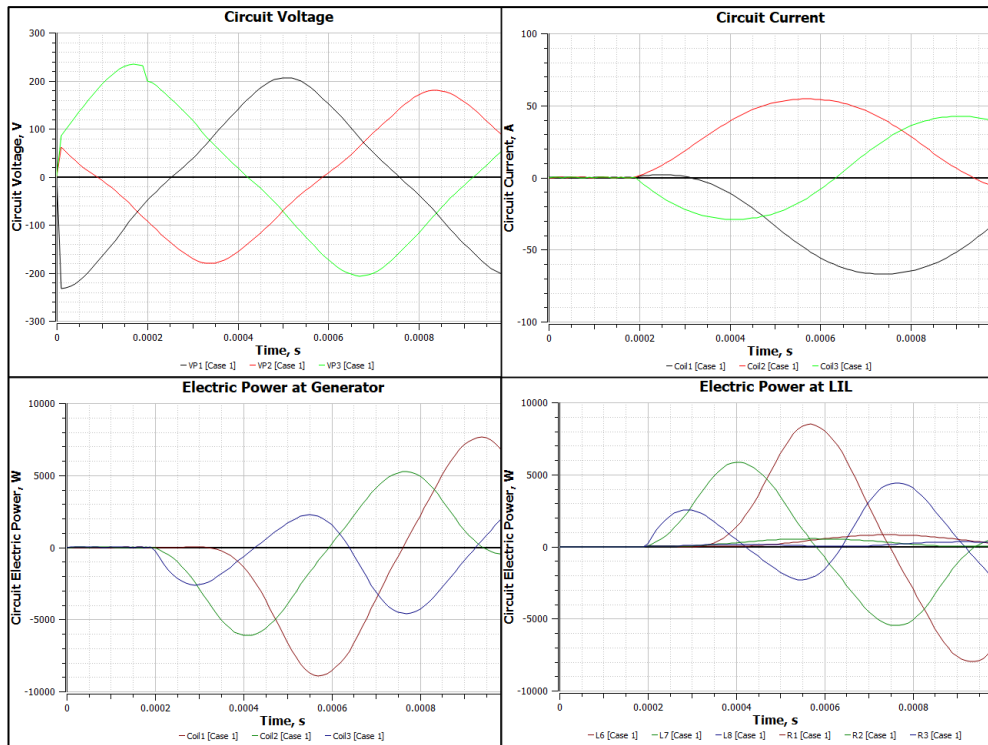


Figure 6.14: Results of Analysis-1

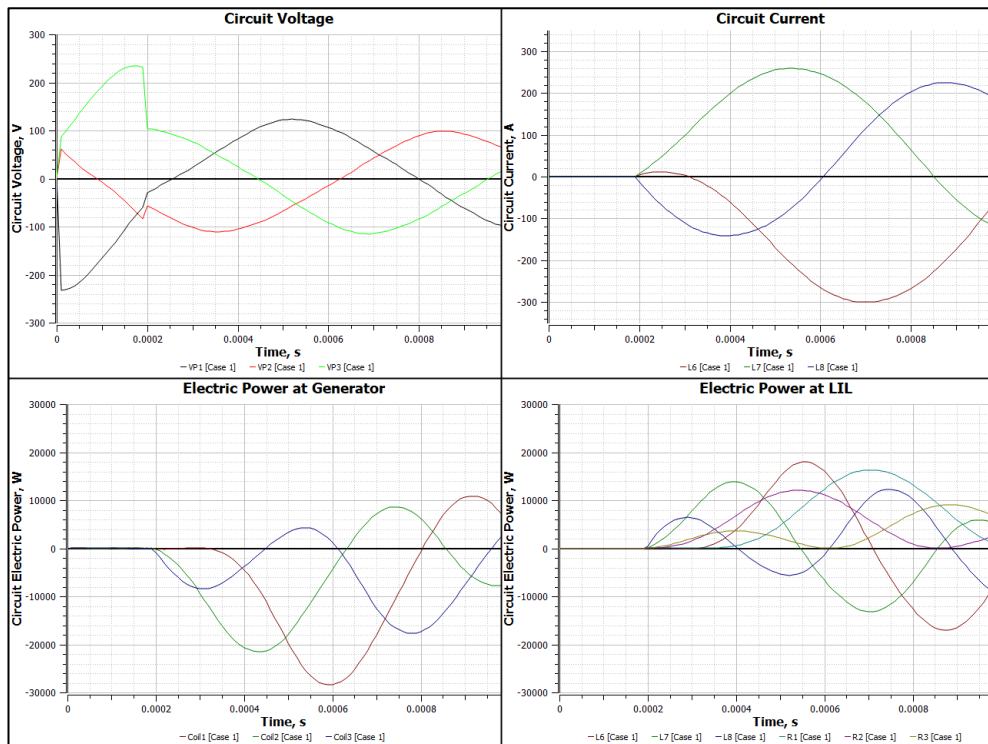


Figure 6.15: Results of Analysis-2.

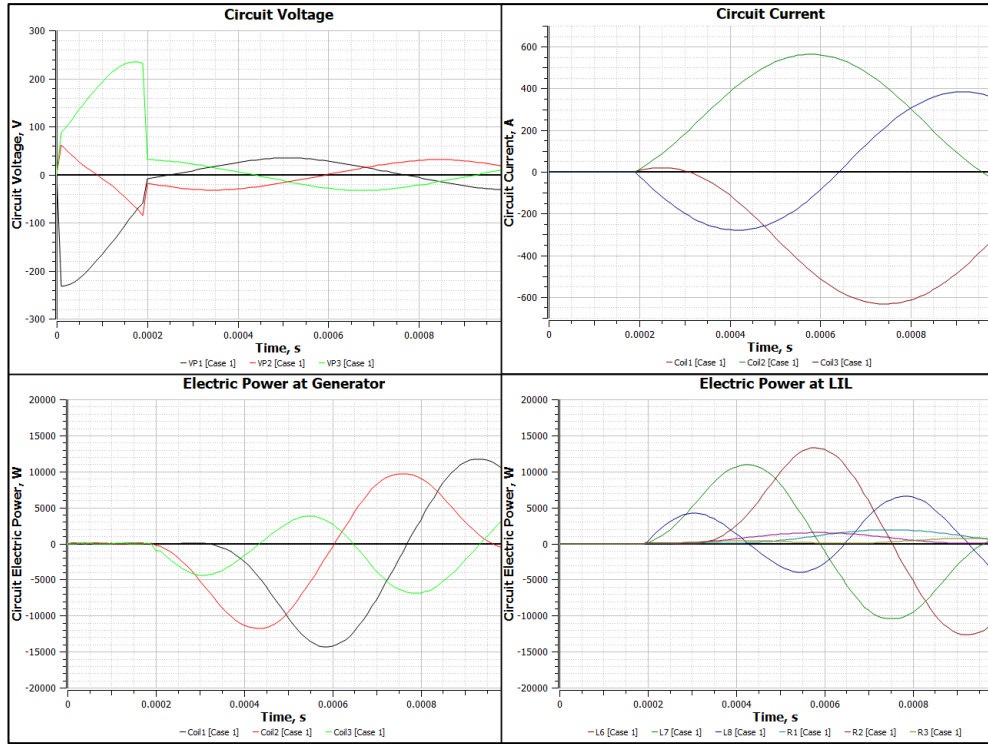


Figure 6.16: Results of Analysis-3.

6.4.1. Parametric Analyses

As a result of these analyses above, more detailed analyses were needed. Because the analysis here does not shed light on how to improve the generator or how to design the launcher for a specific generator. Therefore, more detailed analyses of the parameters herein will help both the generator and the launcher design.

Four detailed parameters were determined for detailed analysis: Launcher inductance and resistance and generator inductance and resistance. However, the inductance of the generator cannot be entered the simulation program. That is, the inductance is calculated by the program based on the existing geometry of the generator (approximately 80 μH). However, the resistance is required to be entered the program. Similarly, when the launcher is modeled as an inductor and a resistor, it is desirable to enter these values. Thus, five different values for the three main parameters were determined. Thus, 125 different simulation models were created.

Table 6.3: Values of Parameters Determined for Analysis.

LIL Inductance (L_L)	LIL Resistance (R_L)	Generator Resistance (R_G)
1 μH	1 $\text{m}\Omega$	1 $\text{m}\Omega$
15 μH	4 $\text{m}\Omega$	10 $\text{m}\Omega$
100 μH	10 $\text{m}\Omega$	80 $\text{m}\Omega$
400 μH	100 $\text{m}\Omega$	100 $\text{m}\Omega$
800 μH	500 $\text{m}\Omega$	500 $\text{m}\Omega$

One of the challenges here is the simulation time. For each model in twenty, the duration of each simulation is over 12 hours. Therefore, the total simulation period exceeds 60 days. Here, a single-phase model of the generator is created by approaching such that some simulations are performed to achieve a simulation time of just over 30 minutes. Thus, the total simulation time was less than 70 hours.

When the graphs obtained as a result of the analyses are examined, the following comments can be made. The highest power was obtained when the inductance of the launcher was lowest. Again, the highest power transmission occurred when the generator resistance was the lowest and the launcher resistance was the highest. In the inductance values, 1 μH and 15 μH , the power in the generator is almost the same as in the launcher resistance, but when it reaches 800 μH , it is below 20%.

The overall results are best achieved with a launcher with low inductance and high resistance. In practice this is unlikely. Because the inductance value is proportional to the square of the round number. Increasing the number of turns to increase the inductance naturally increases its resistance. However, since the inductance is proportional to the square, an optimization can be made.

The more fundamental problem in this analysis is that the launcher model is represented by a simple equivalent circuit model. Because, as mentioned before, the circuit element indicating the resistance of the launcher includes the kinetic energy of the projectile, i.e. the armature reaction. This is a value that cannot be obtained with simple measurements. Here, load analysis using a more sensitive dynamic model can give more realistic results.

6.4.1.1. $L_L = 1 \mu\text{H}$

The power at the generator phase and launcher phase resistance is shown in Figure 6.17 in the case where the launcher inductance is $1 \mu\text{H}$.

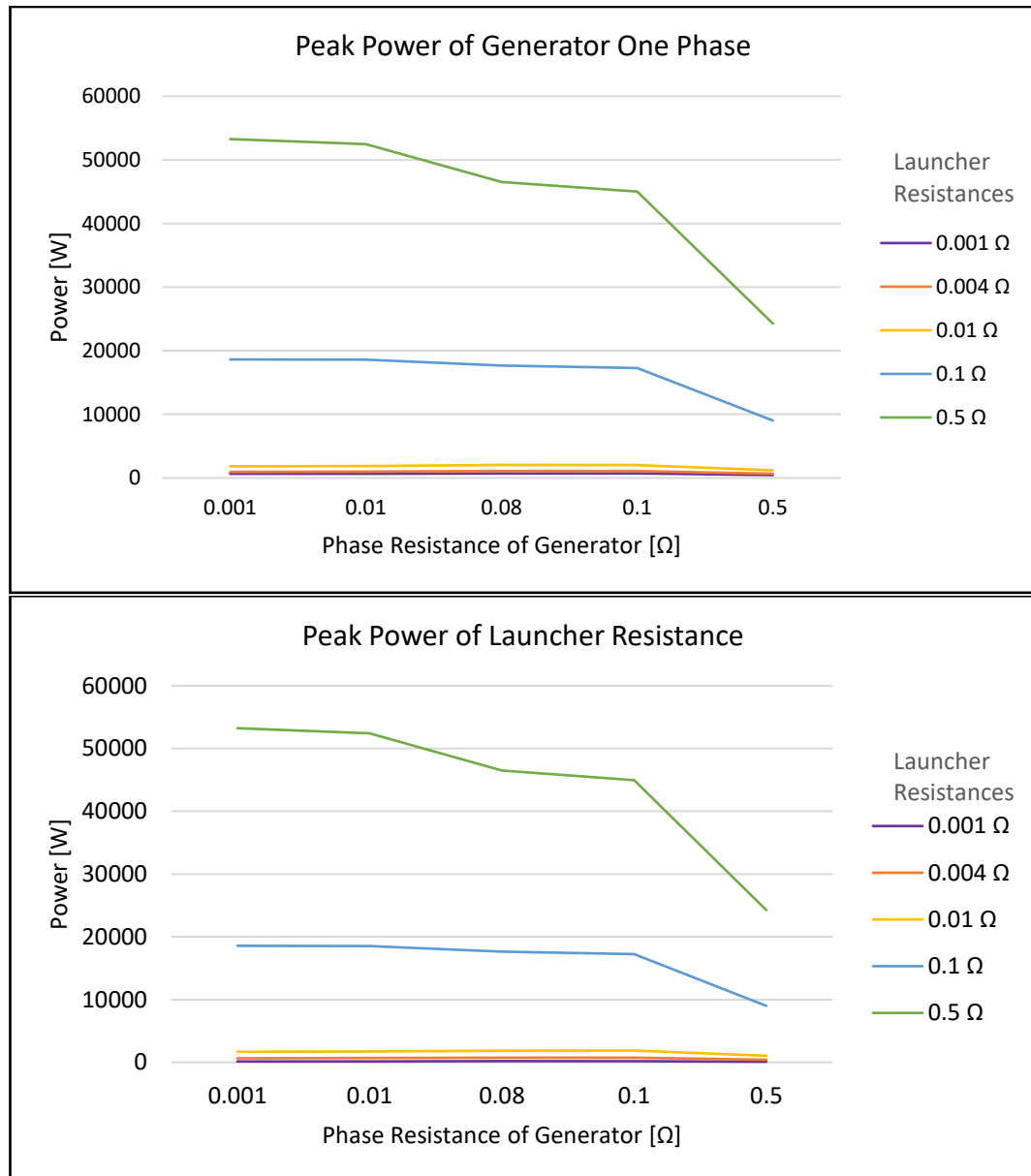


Figure 6.17: Peak power of the generator phase and launcher phase resistance at $L_L = 1 \mu\text{H}$.

6.4.1.2. $L_L = 15 \mu\text{H}$

The power at the generator phase and launcher phase resistance is shown in Figure 6.18 in the case where the launcher inductance is $15 \mu\text{H}$.

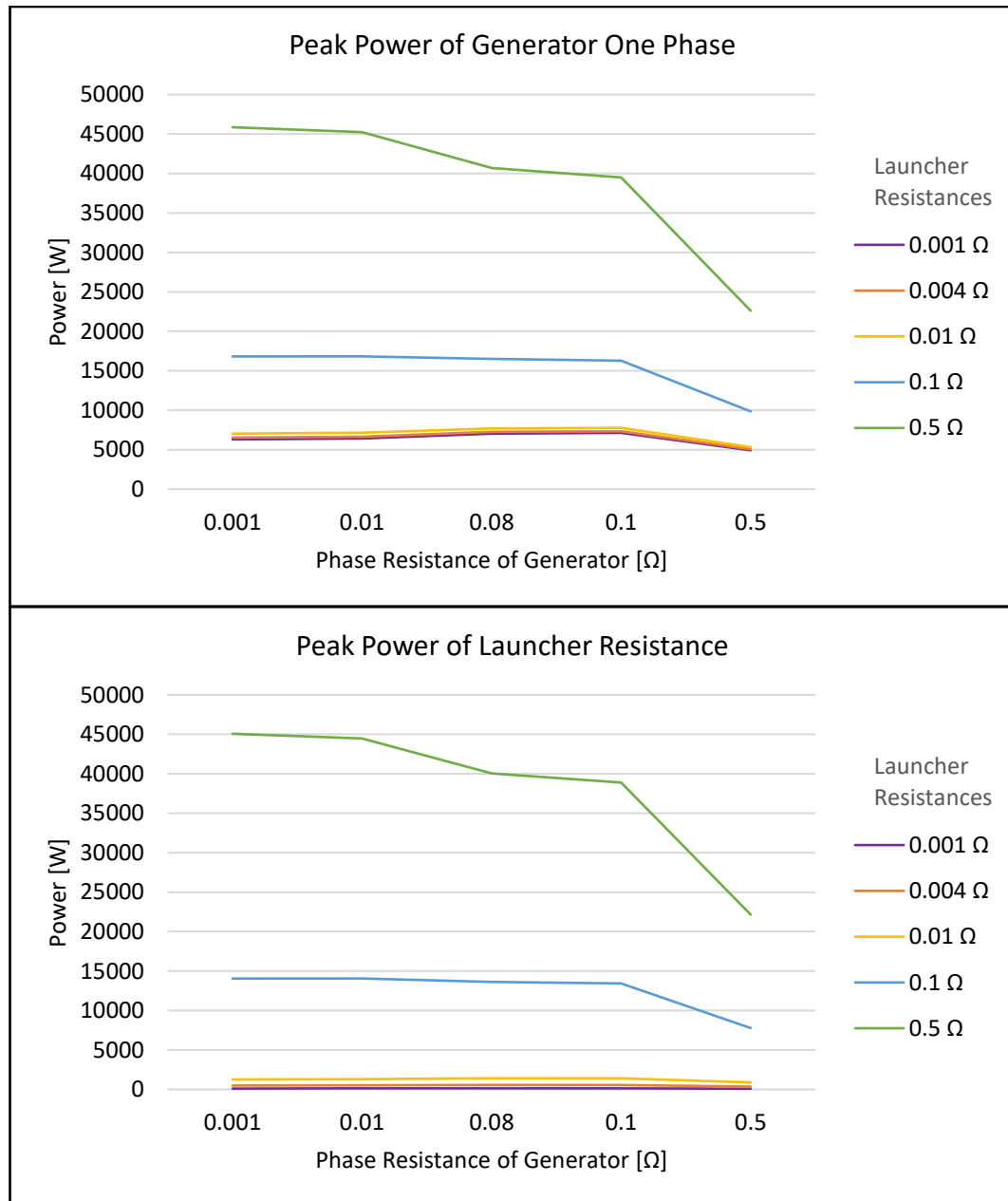


Figure 6.18: Peak power of the generator phase and launcher phase resistance at $L_L = 15 \mu\text{H}$.

6.4.1.3. $L_L = 100 \mu\text{H}$

The power at the generator phase and launcher phase resistance is shown in Figure 6.19 in the case where the launcher inductance is $100 \mu\text{H}$.

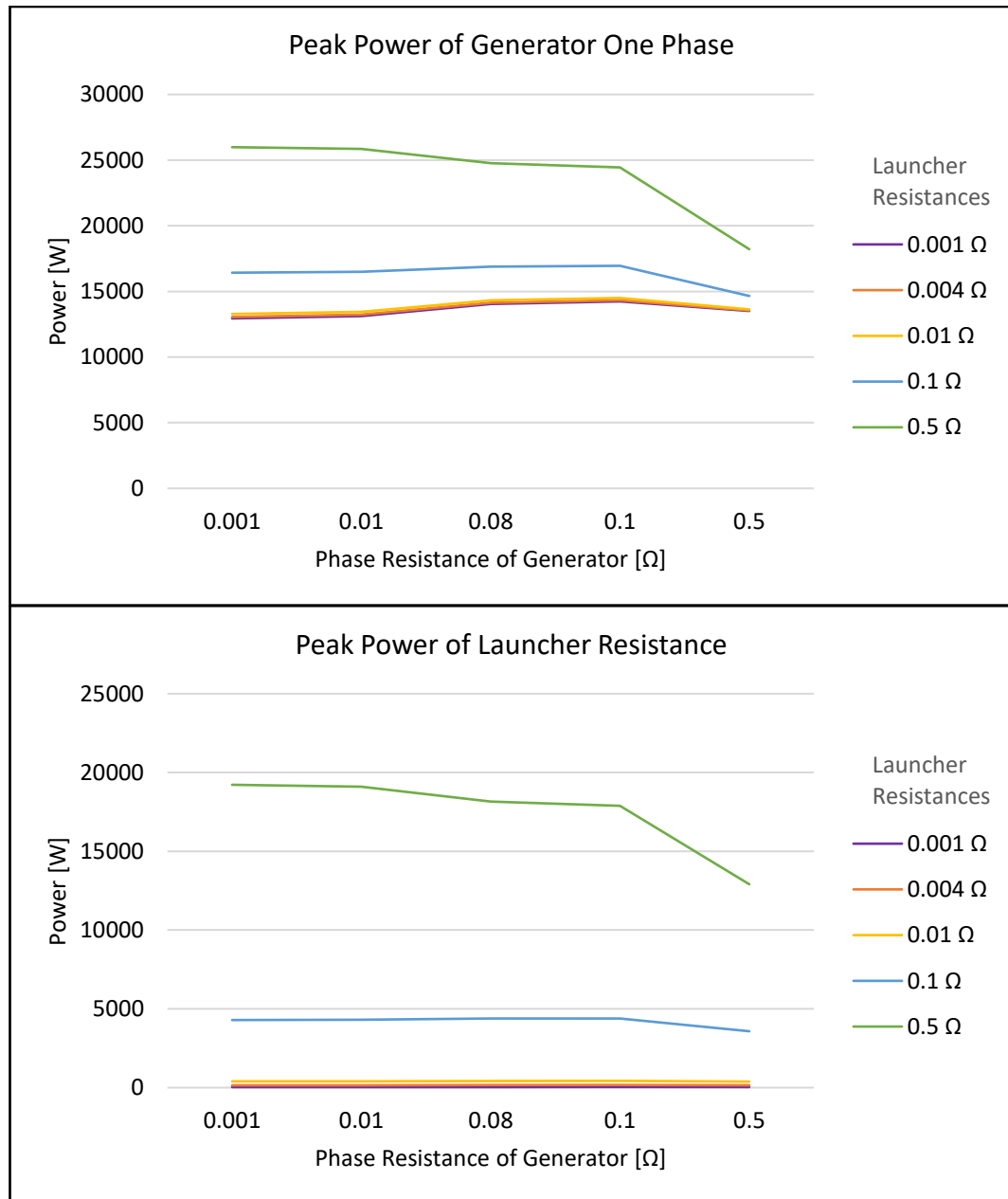


Figure 6.19: Peak power of the generator phase and launcher phase resistance at $L_L = 100 \mu\text{H}$.

6.4.1.4. $L_L = 400 \mu\text{H}$

The power at the generator phase and launcher phase resistance is shown in Figure 6.20 in the case where the launcher inductance is $400 \mu\text{H}$.

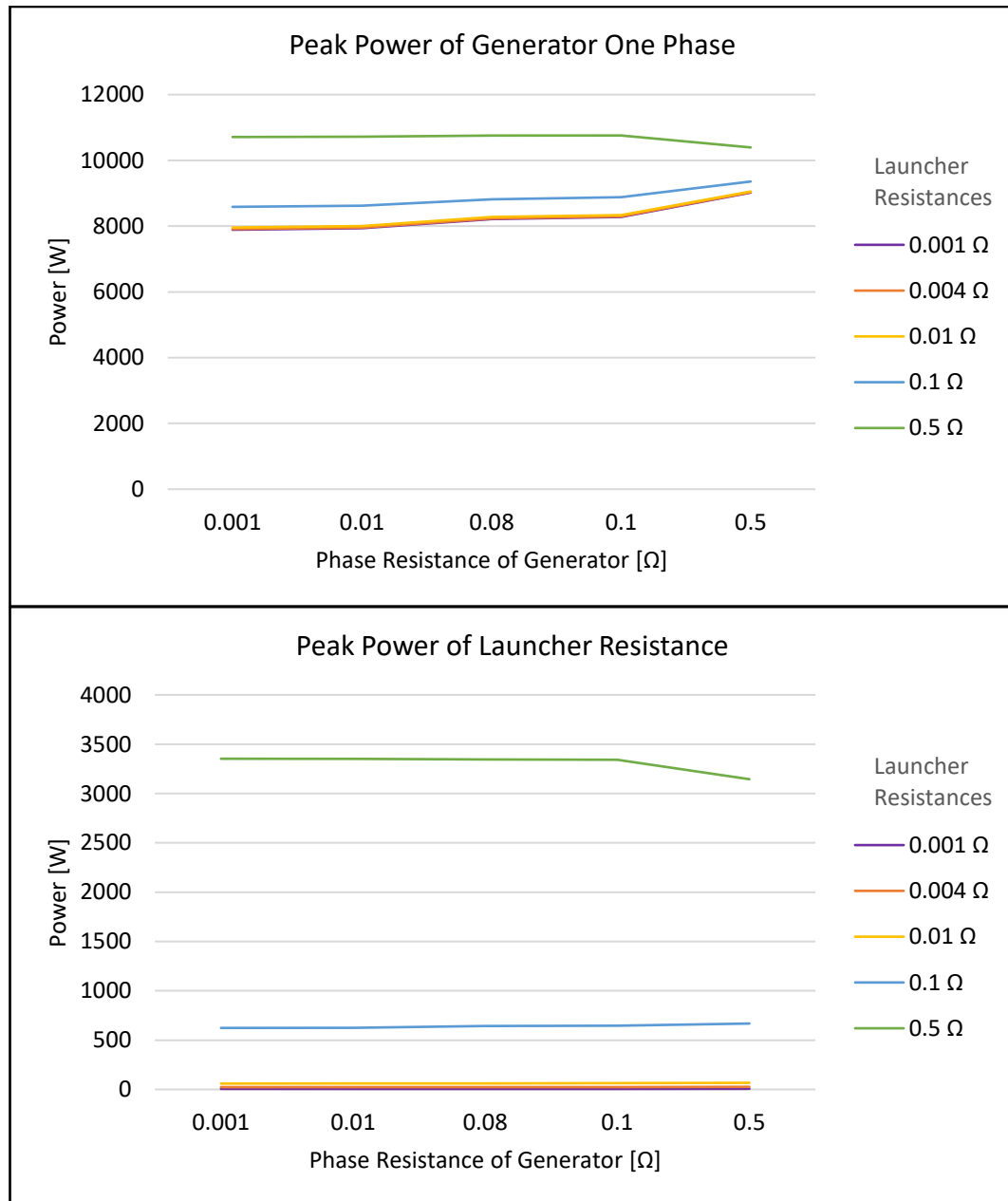


Figure 6.20: Peak power of the generator phase and launcher phase resistance at $L_L = 400 \mu\text{H}$.

6.4.1.5. $L_L = 800 \mu\text{H}$

The power at the generator phase and launcher phase resistance is shown in Figure 6.21 in the case where the launcher inductance is $800 \mu\text{H}$.

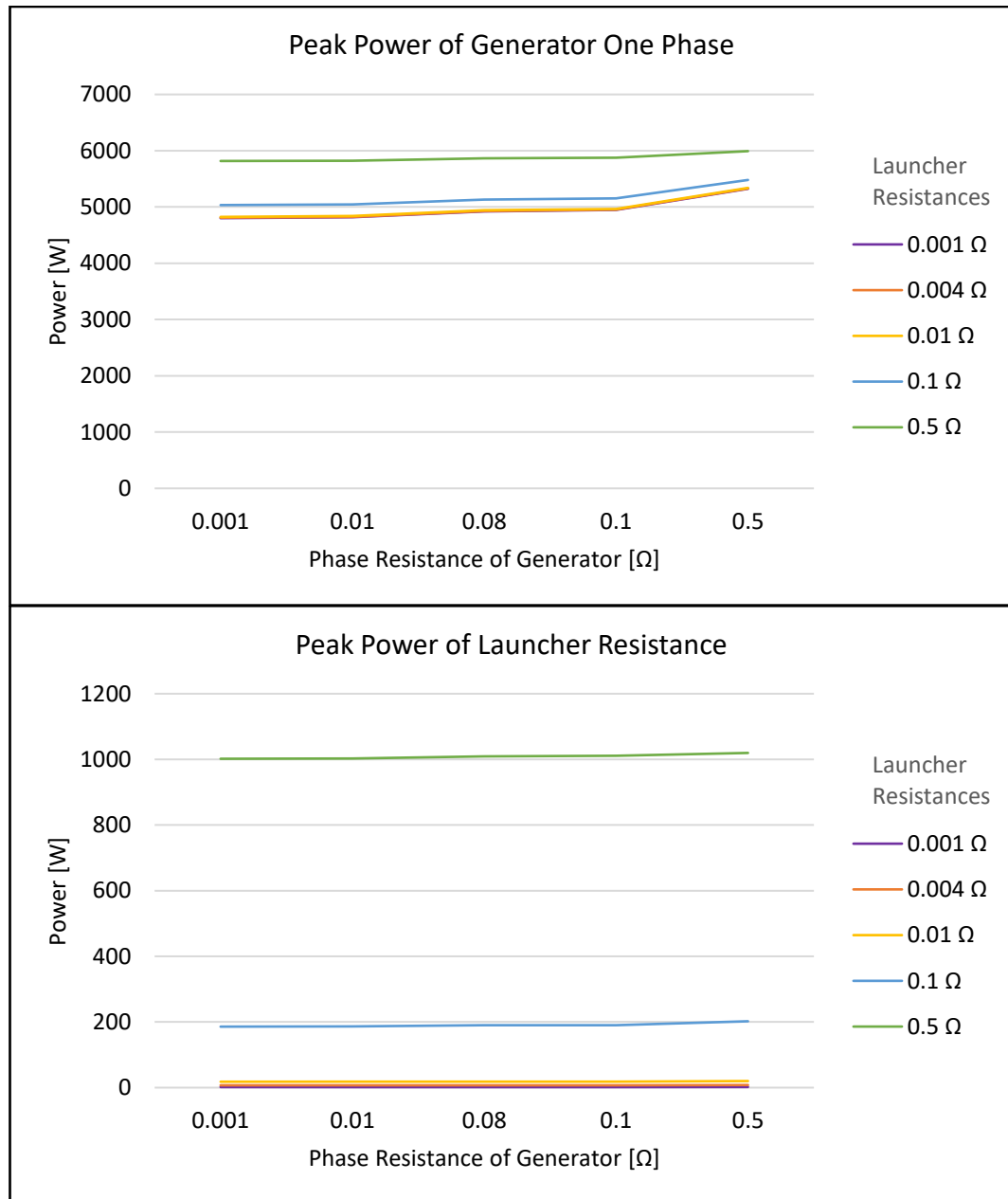


Figure 6.21: Peak power of the generator phase and launcher phase resistance at $L_L = 800 \mu\text{H}$.

6.4.1.6. $R_G = 80 \text{ m}\Omega$

The power at the generator phase and launcher phase resistance is shown in Figure 6.22 in the case where the generator resistance is $80 \text{ m}\Omega$.

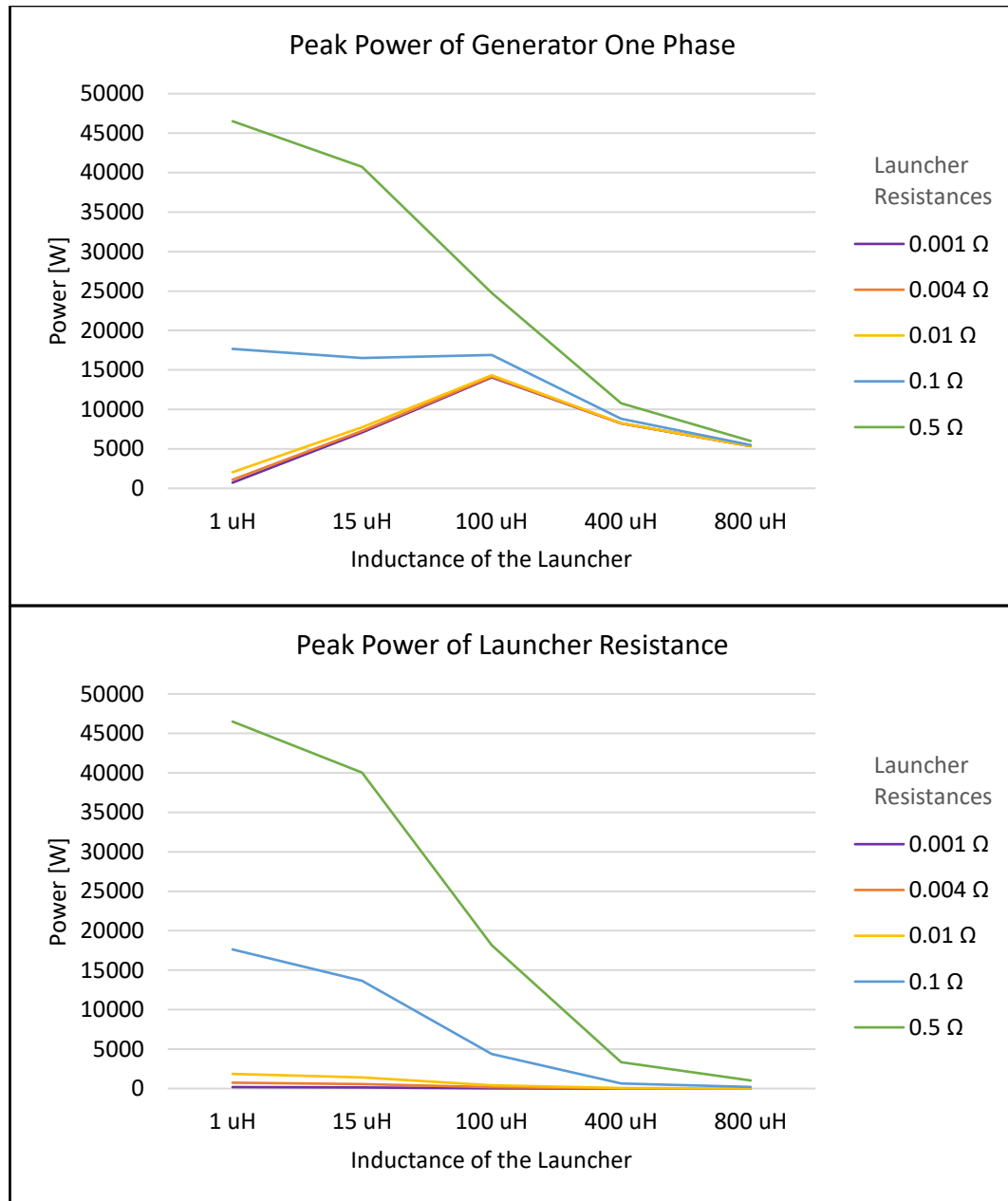


Figure 6.22: Peak power of the generator phase and launcher phase resistance at $R_G = 80 \text{ m}\Omega$.

6.5. Winding Resistance and Inductance

The winding resistance of the proposed machine was calculated analytically and equation (6.1) was used for calculation. The cross-sectional area of the copper used is 8 mm^2 and the resistivity of the copper is known as $1.72 \times 10^{-8} \text{ } \Omega\text{m}$. After the winding length is calculated, the resistance value can be obtained. The winding length of a phase is calculated as 34.24 m by taking the average line of the wave winding and taking into account that there are 10 turns of winding in each phase. As a result, the resistance of a phase was obtained as 73.61 m Ω . The winding was then measured by LCR meter and the results are given in Table 6.4.

$$R = \rho \frac{l}{A} \quad (6.1)$$

The inductance of a coreless machine is difficult to formulate clearly [89], and it is noted that the coreless axial-flux machines have very low inductance (below 100 μH) due to lack of iron in the stator [95]. Furthermore, there are no published works about the determination of the inductance of wave windings. Accordingly, the inductance of the wave winding is calculated by Jmag software. Then, the inductance of every phase measured by LCR meter at 1 kHz is shown in Table 6.4.

Table 6.4: Calculation and Measurement Results of Resistance and Inductance.

Resistance	Phase 1	Phase 2	Phase 3
Measured	82.15 m Ω	82.46 m Ω	82.51 m Ω
Calculated	73.61 m Ω		
Inductance	Phase 1	Phase 2	Phase 3
Measured	90.02 μH	84.56 μH	91.02 μH
Calculated	74.5 μH		

7. MANUFACTURING AND TESTS

In this section, the energy source designed, and the production of the proposed generator are detailed. The requirements of the flywheel test bench for the energy supply system have been determined and manufactured by a manufacturer on the market. The production of the AFPM generator was largely carried out in the laboratory. Laser cutting works of copper used in windings and steel production of rotors were done outside the university. Two different molds were made for stator production. Problems of the first mold were solved, and the second mold was produced. Then the assembly of the produced generator is explained. Finally, no-load tests were performed. Loaded tests could be unperformed because of the high eddy currents in the windings, which could be unextended to full speed.

7.1. Generator Test Bench with Flywheel

At first, a flywheel test device to connect the generator was produced. In production, it is paid attention that the test apparatus is a laboratory scale.

In this direction, the flywheel diameter was determined as 500 mm. It was planned to be modular for allowing the possibility for future applications in flywheel production. In this respect, the flywheel system was manufactured with interconnectable discs. Since the flywheel will constitute the main weight of the system, it is provided that the flywheel disc is mounted between two main legs and with suitable bearings.

To store energy on the flywheel, it is necessary to turn the flywheel using a motor. For this purpose, an 18.5 kW asynchronous motor was used. The motor is connected to the flywheel by coupling and can be removed and replaced if necessary.

The generator is on the same shaft as the flywheel. Connection with coupling is unrequired. Because the generator is smaller in weight and volume than the flywheel. Furthermore, if coupled by coupling, the generator will need to be further supported and positioned on the appropriate feet. It is placed on the same shaft to avoid complexity. Thus, the test device in Figure 7.1 is produced. The produced bench is seen in Figure 7.2.

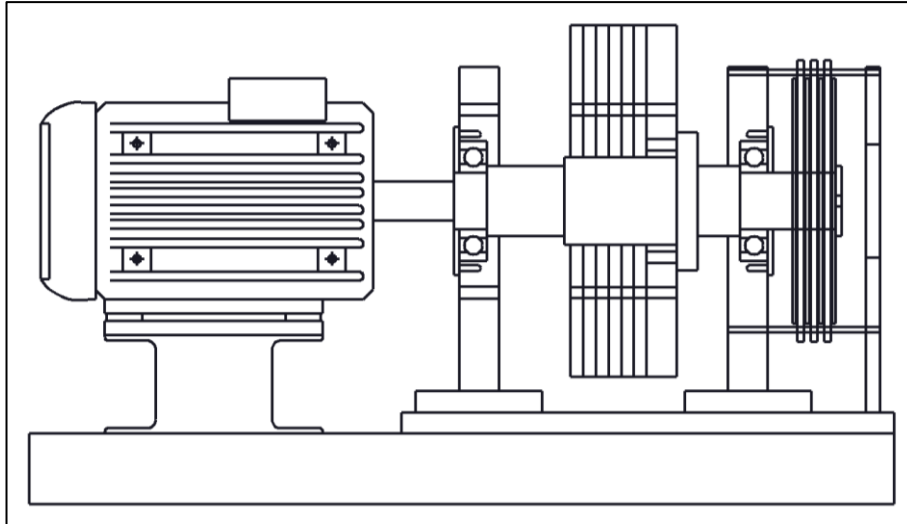


Figure 7.1: Basic drawing of flywheel energy source test bench.

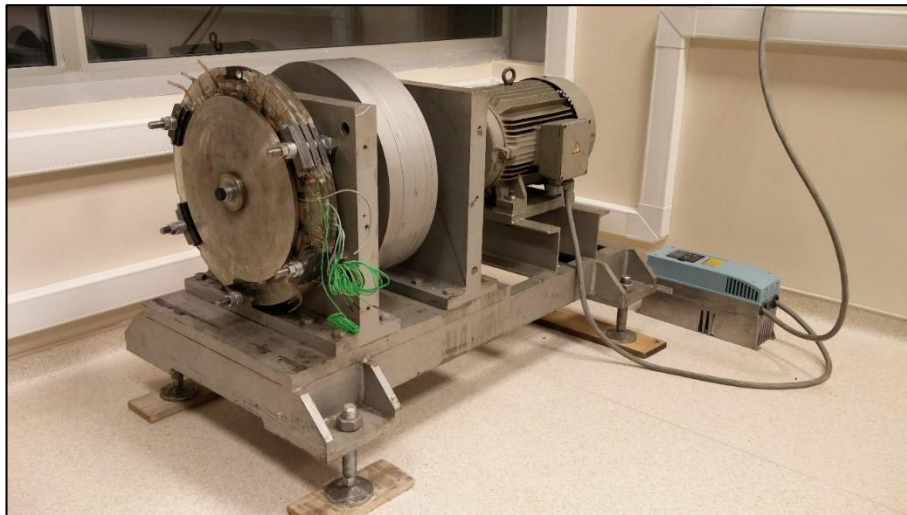


Figure 7.2: Manufactured generator test bench with flywheel.

7.2. Stator Manufacturing

Technical drawings of the copper to be used in windings were made. It has been deemed appropriate to cut the windings from the copper plate and cutting methods have been investigated to be able to cut them the most properly. Then, wave cuts were obtained by cutting with laser cutting. Two different molds were produced for the stator. In the first mold, the problem of removing from the mold was encountered. For that reason, the second mold was manufactured. After the copper winding turns were placed in the mold, the soldering process was performed, and the mold was closed,

then epoxy casting was performed. Finally, after the curing of the epoxy, the stator was removed from the mold and made ready for installation.

7.2.1. Preparing Coppers of Wave Winding

Copper sheets of appropriate thickness were purchased after designing technical drawings of copper. Methods of cutting were investigated to be able to estimate the most appropriately. The four most commonly used cutting methods were examined. The most precise method is die-cutting, but the price is extremely expensive. It makes sense only in mass production. Cutting by wire erosion (or EDM) and waterjet methods is also given very good results, but the usage rate for both devices is low in the market, also service price is high. The laser cutting offers the most suitable solution. It gives good results if appropriate adjustments are made for the material to be cut. If it is not properly set, burrs usually occur on the cutting edges. However, it is quite common, and the price is reasonable.

Then the wave winding copper was cut from the plates by the laser cutting method. Due to the material's reflective nature, a laser beam can bounce back off it and damage the laser cutter. Because of this, many manufacturers cannot cut copper plates or do not want to cut, the cutting place was investigated for a while. Production was done with Hake Metal which has a machine that can cut copper plate.

Due to the temperature rise in the plate during cutting, bending was observed on the plate. As a result of this, the focal point of the laser is moving, resulting in burrs in the cutting edges of many of the windings. These burrs are eliminated with sanding or grinding tools. Preparing steps of the copper wires is shown as in Figure 7.3.



Figure 7.3: Preparing coppers of wave winding.

7.2.2. Soldering

Each phase of the winding obtained by laser cutting from the copper plate is placed one on top of the other to obtain a phase winding. Method research related to the joining of windings was conducted. Theoretically, the most reasonable joining technique is to melt two joins together. This coupling process is carried out by different techniques. The simplest of these is the passing of high current between the two ends, known as spot welding, to ensure the melting of that point. Commercially available spot welds are often used to assemble battery packs, thus failing to connect 0.8 mm thick winding ends. Another process is to weld with the laser but any manufacturer that could apply this technique could not be found.

Soldering technique was used to combine the winding rounds. Because of the high thickness and total surface of the copper plate, the copper could be unreachable to the temperature to be soldered with the high-power soldering iron. For that reason, a solder pot was used. The soldering process was applied to the ends of the winding turns to ensure better soldering. The Figure 7.4 shows the soldering process and the result of the soldering pot of the winding ends.

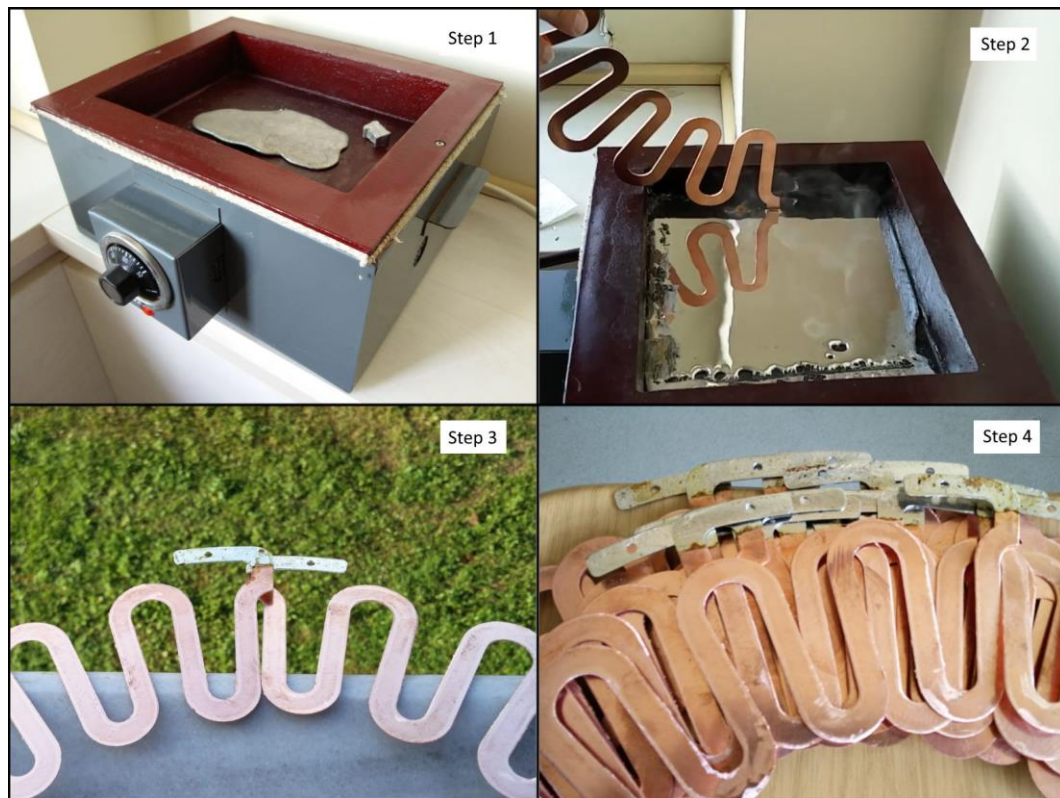


Figure 7.4: Soldering winding turns with soldering pot.

7.2.3. First Mold of the Stator

Three points have been considered when forming the stator mold. The first one, not to protrude when epoxy is poured. The second is that the windings stay inside properly. The last one, the height is constant throughout the entire surface after casting. When the stator is positioned as a disc parallel to the ground, it will have upper and lower plates and internal and external heights. There are no holes in the bottom plate and inner height. There are gaps in the outer height where only the phase terminals and temperature sensors will exit. In the upper plate, holes were drilled so that the epoxy can be distributed homogeneously. CAD drawing of the first mold is shown as in Figure 7.6.

The phase windings deformed due to the high temperature in the laser cutting. Therefore, the windings do not stand flush when placed in the mold. The inner height of the mold is produced as shown in Figure 7.5, and it is aimed to maintain the shape of the windings.

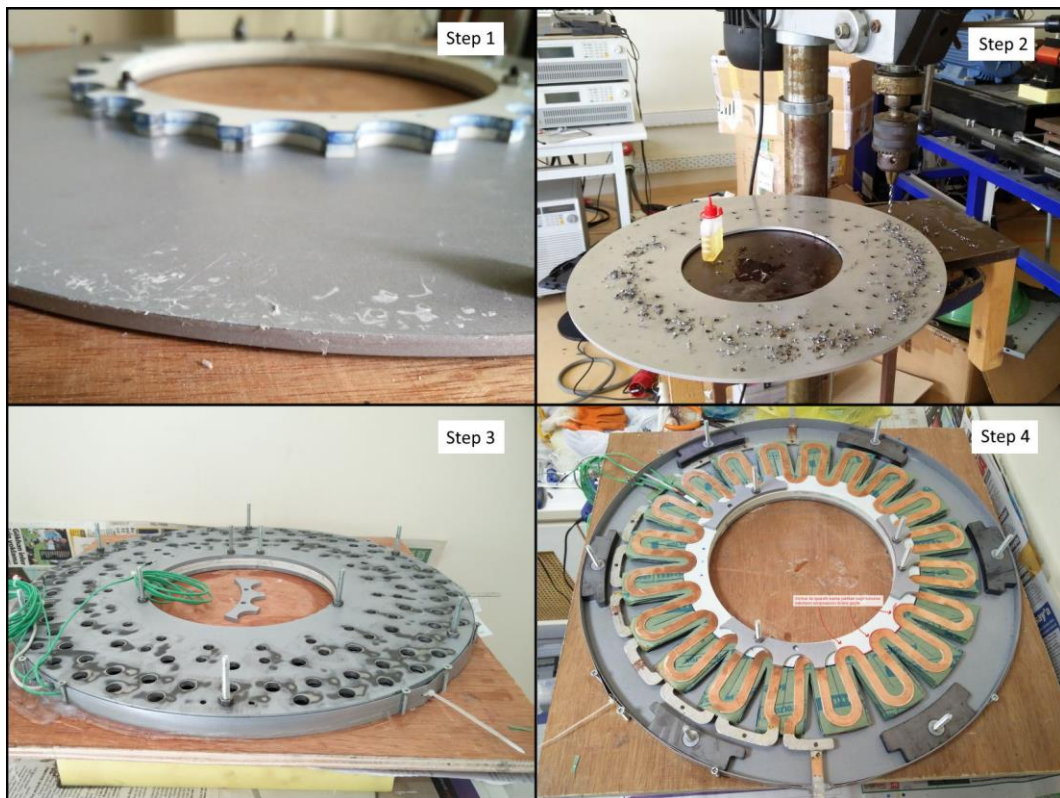


Figure 7.5: Manufacturing and assembly process of first mold.

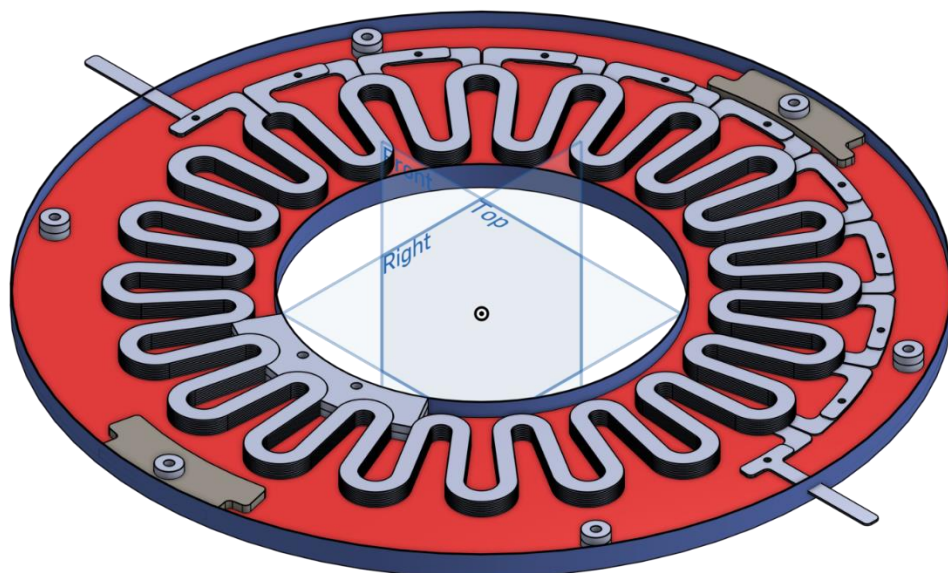


Figure 7.6: CAD Drawing of first mold.

7.2.4. Arrangement and Soldering of Windings in First Mold

The windings were placed in the mold respectively. Between each layer was placed 0.1 mm thick insulating paper. The opposite ends of the windings previously soldered in the soldering pot were soldered. Specially predicted parts for the terminals were connected to the phase input and output points. Attachment parts were placed on the bench leg of the stator. Temperature sensors were located close to the windings, and cable outlets were provided. Then, the top cover, where epoxy was poured, was closed, tightened with screws and the edges were covered with a thin sheet. Finally, the parts where the epoxy can be leaked were covered with hot silicon and made ready for epoxy pouring. Figure 7.7 shows some steps. After the mold was prepared, the epoxy casting process was performed.



Figure 7.7: Process of arrangement and soldering of windings.

7.2.5. Removing the Stator from the First Mold

After the epoxy application, all mold surfaces in contact with epoxy are carefully coated with mold release of the mold. After the mold was properly closed and ready for casting, the epoxy casting was performed. For such applications, the thermal conductivity of the epoxy should be very high. However, this information could be unreached in market research. Therefore, high strength epoxy is provided. The epoxy should be applied within 30 minutes after preparation. It slowly loses its fluidity after 30 minutes. Due to the structure of the mold and the stator, epoxy is applied in many points in order to distribute homogeneously. However, the application was carried out without losing the epoxy viscosity. The specific epoxy could cure for 48 hours. If the epoxy is heated, curing can be performed in a shorter time. However, this period waited since curing was carried out at room temperature.

In order to separate the mold, the height around the outer circumference was first removed. The top cover is then separated. Finally, the lower surface is easily separated from the mold as shown in Figure 7.8. It is a problem that the inner height part is not easily separated. Since the inner height ensures the shape of the copper, it touches the copper at many points. Subsequent application of epoxy, this congestion was very strong, and the internal height was not easily separated. This was dismantled by long efforts, but short circuits were formed in the winding as it deformed the copper when leaving the stator. These short circuits were eliminated as a result of long efforts. However, it is not possible to prepare other phases by using this mold. For this reason, new mold work has started.



Figure 7.8: Removing process of the stator from the mold.

After the inner height is removed, the stator including the phase windings is shown in the Figure 7.9.

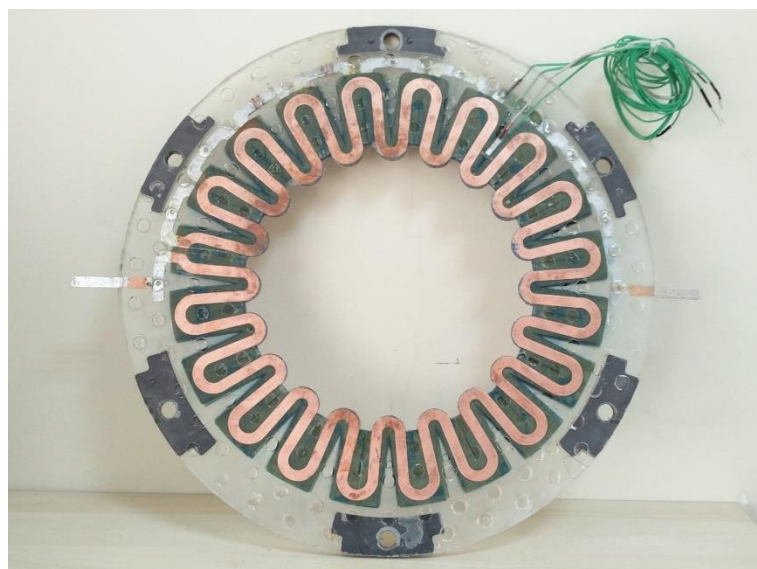


Figure 7.9: Finished stator of the one phase.

7.2.6. Second Mold of the Stator

Considering the difficulties experienced in the production of the first stator, the second stator mold was prepared. The biggest difficulty encountered in the first mold is that the inner height of the mold was contact with the stator copper to a large extent and as a result of this it is both difficult to dismantle and short circuit after stator copper removal. For that purpose, the inner height is made in the form of a flat ring. However, there is no part to align the stator windings in that case. To align that, ring-shaped parts are produced in the rotation portions of the stator windings. In this way, it is aimed to prevent the compression problem due to the copper. Also, the top cover has been completely redesigned to make epoxy easier to apply.

Another feature of the new mold is that each of the three-phase windings accommodates connection points which can be electrically different from each other by 120 degrees. Thus, it is possible to cast three different phase windings by changing only the connection points with this mold. Manufacturing and assembly process of second mold is shown in Figure 7.10.

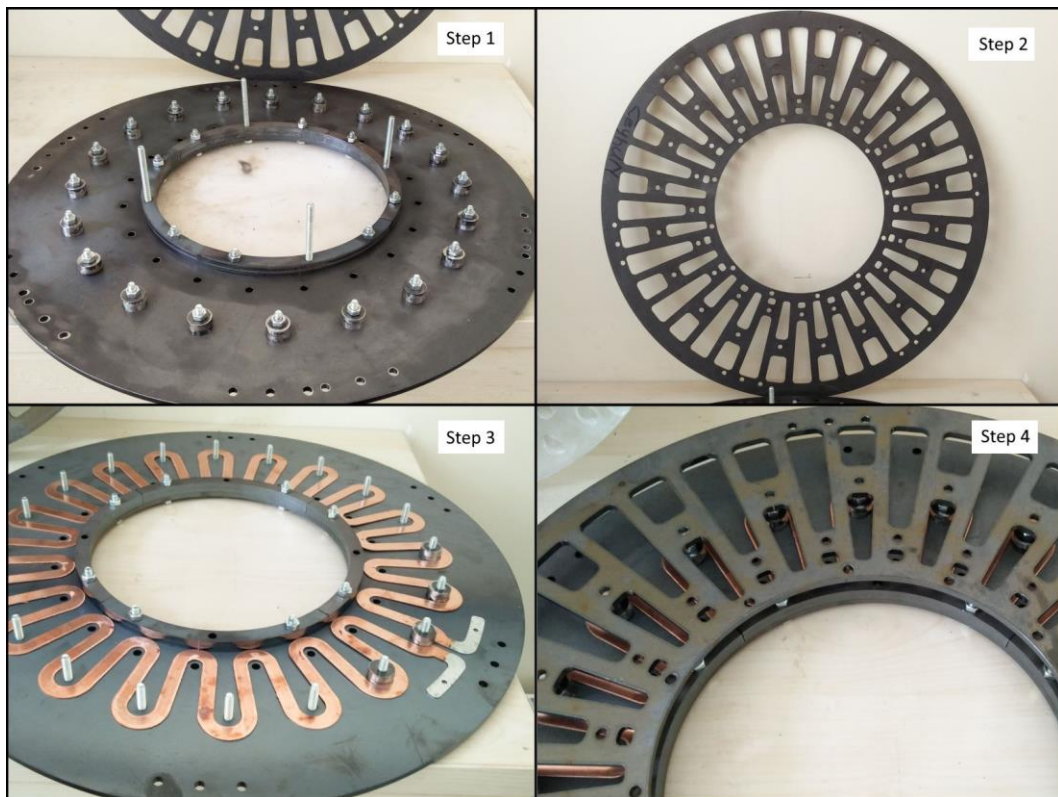


Figure 7.10: Manufacturing and assembly process of second mold.

7.2.7. Arrangement and Soldering of Windings in the Second Mold

The holes that are not needed in the floor plate are covered with duct tape. The insulation papers were then cut according to the new mold. The windings were then ordered appropriately. The winding ends are soldered after the whole process, and the terminals are prepared. Figure 7.11 shows the process steps.

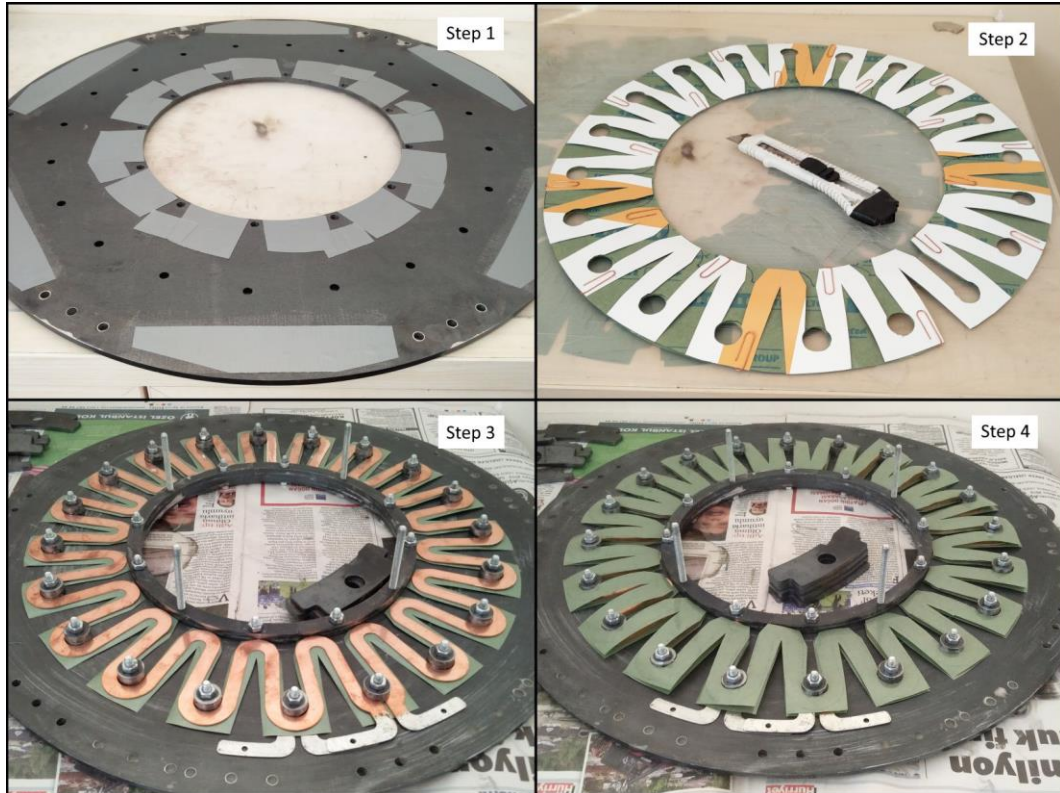


Figure 7.11: Arrangement and soldering of windings in second mold.

After the windings were placed, the cover was closed and fastened with screws. In the previous mold, the edges are covered with a thin sheet. Because this sheet is not a single piece and is not very flexible, there are gaps in the joints and at some points. Although these gaps were covered with hot silicone, epoxy leakage occurred at some points. In order to prevent this, the outer circumference of this mold is covered with duct tape. It was incredibly easy to apply and did not leak at all. Figure 7.12 shows the steps of closing the mold with duct tape.



Figure 7.12: Preparation of mold for epoxy casting.

7.2.8. Removing the Stator from the Second Mold

The epoxy casting was performed after the whole system was shut down. The epoxy application was quite easy as the sections where the epoxy would be poured were quite large. First, the edge strips were removed. The upper and lower covers were then removed. Disassembling the mold was relatively easy compared to the previous mold. Finally, the alignment parts in the middle of the windings have been removed. The steps of separating the stator from this mold are shown in the Figure 7.13.

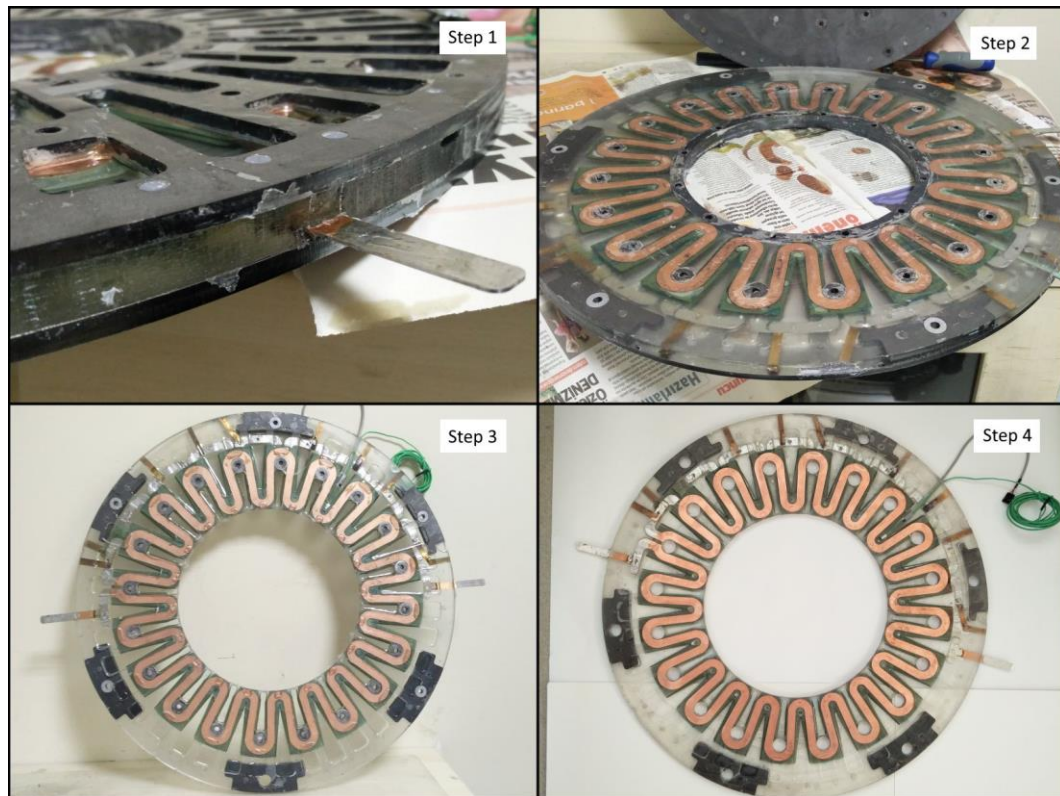


Figure 7.13: Removing process of the stator from the second mold.

7.3. Rotor Manufacturing

There are two kinds of rotors in the machine and a total of four rotors. The two rotors in the middle are made of AISI 304 stainless steel with no magnetic properties. The two external rotors are AISI 1040 carbon steel.

The rotors in the middle are made by laser-cut and have slots to hold the magnets. Here, the corners could not be produced very sharp in laser cutting. For that reason, the corners are rasped for easy insertion of the magnets.

The external rotors are manufactured on the lathe. Since the magnets adhere to the surface, they are produced in such a way that they protrude around the outer area so that they cannot be thrown at high speed. In order to guide the magnets to their exact points, the template was cut from the most suitable plexy material as shown in Figure 7.14. Finally, all magnets are bonded with a strong adhesive.



Figure 7.14: Manufacturing of rotors.

7.4. Mounting Generator and Tests

After entire parts were manufactured, it was assembled to the test bench with the flywheel. In axial flux machines, assembly is usually carried out respectively in the rotor and the stator order. Particularly in multilayer structures like this thesis, the assembly process is carried out as much as the number of rotor and stator. Then, idle tests were performed.

7.4.1. Mounting Generators

The stator of the first phase is first placed after the rotor is placed on the shaft. Afterward, the other rotor is placed, but it is important to note that after certain proximity, a gravitational force is generated due to the magnets in the rotors. Failure to observe this issue during installation may result in serious injury. After assembly of each part, the rotor must be rotated to check whether it touches the stator. There is a possibility of stretching according to the mold of the stator and the compression of the internal windings. Due to the large diameter compared to general axial flux machines,

depending on production accuracy, contact between stator and rotor may occur. In this case, the distance between the rotors and the stator can be adjusted utilizing spacers smaller than 1 mm. Figure 7.15 shows the mounting steps.

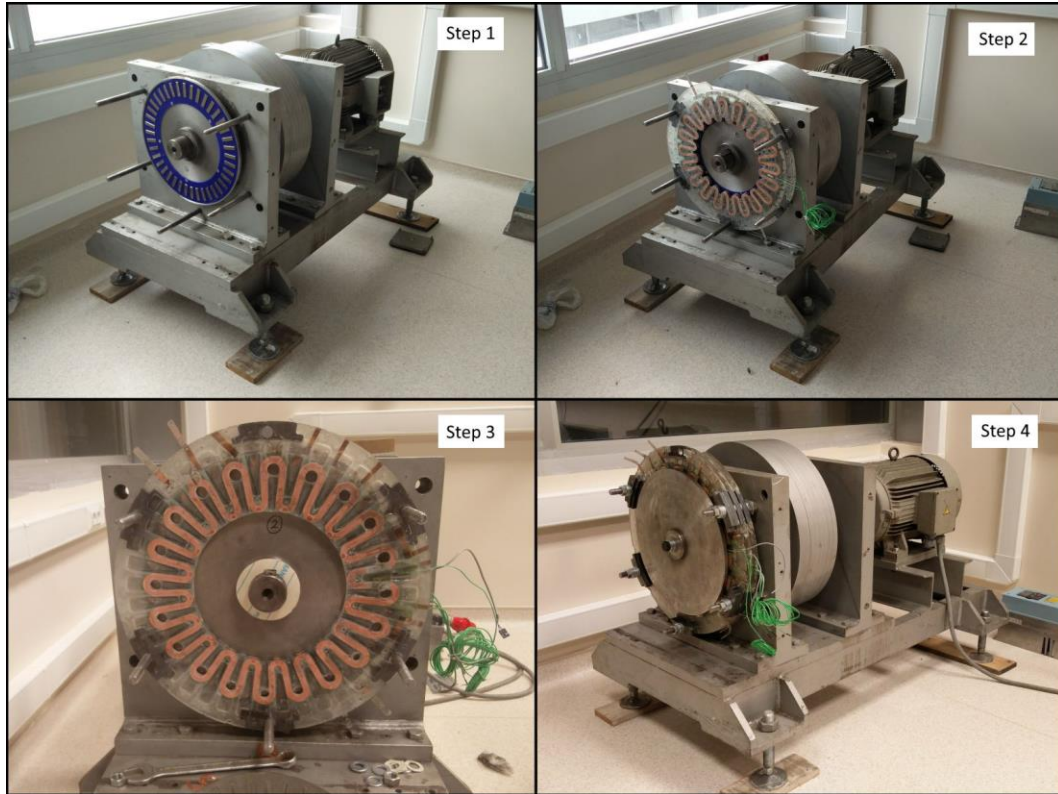


Figure 7.15: Mounting the generator to the test bench.

After the initial assembly, stator connection points were not enough to keep the stators rigid. Then, ring-shaped fastening parts between two stators were produced to better adjust the distance between the stators and provide a more rigid assembly. Installation with new parts is shown in Figure 7.16.

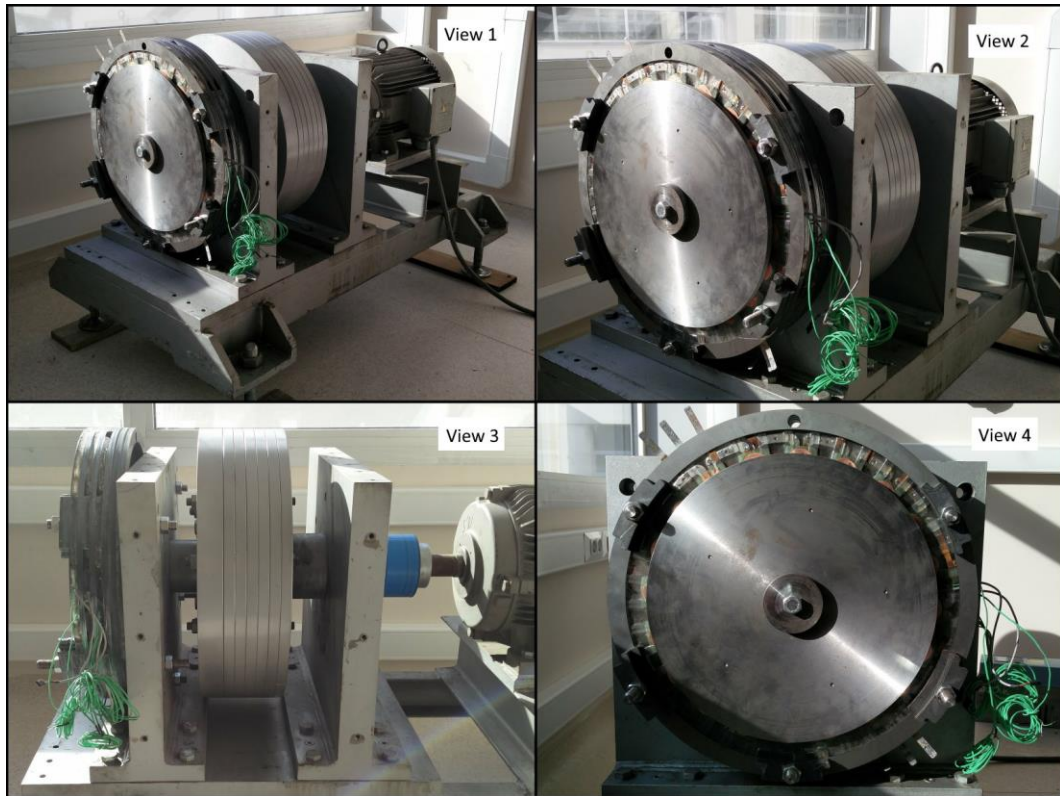


Figure 7.16: Mounting the generator to the test bench with new stator spacers.

7.4.2. No-Load Tests

In order to carry out the tests of the generator, the first flywheel energy storage is performed. However, when the engine is directly supplied from the mains, it cannot overcome the inertia of the flywheel and does not take off. Therefore, the ramp function is applied to the motor with a frequency inverter. Thus, it can reach the desired speed level.

The engine does not accelerate any further after reaching a certain speed. When the reason was investigated, it was found that it was caused by high eddy currents in the windings. It brakes after a certain speed and the temperature of the windings rises.

For that reason, no-load tests were performed. The terminal voltages at the maximum speed at which it rises are measured. Terminal voltages are shown in Figure 7.17.

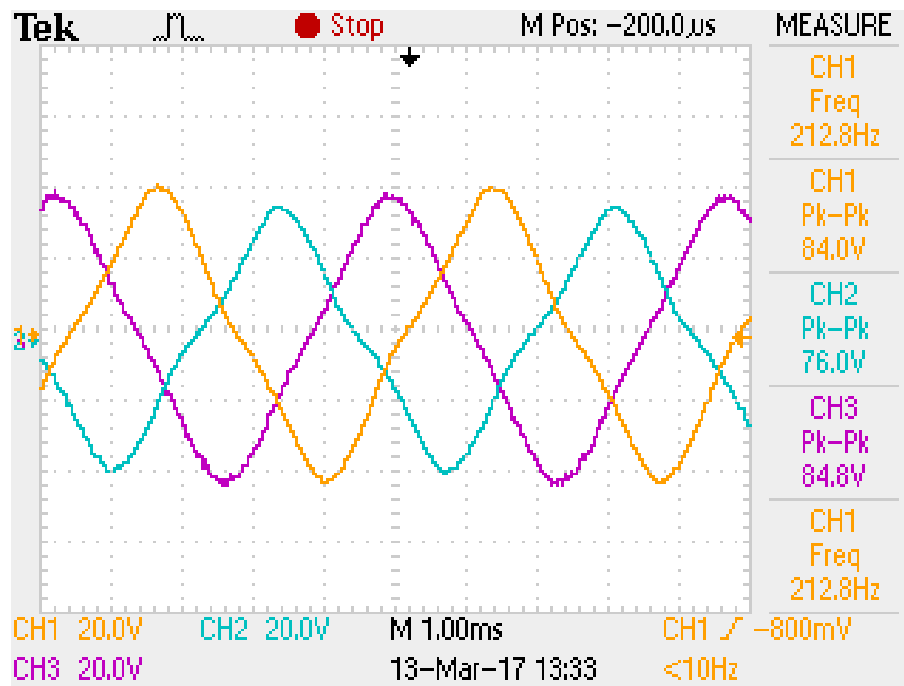


Figure 7.17: Terminal voltages of the generator at no-load.

Since the actual tests could not reach full speed due to eddy currents, JMAG simulations were run according to the obtained test data. The induced voltage graphs obtained from the simulation are compared with the measured values and shown in Figure 7.18. A good agreement is achieved between simulation and measured results.

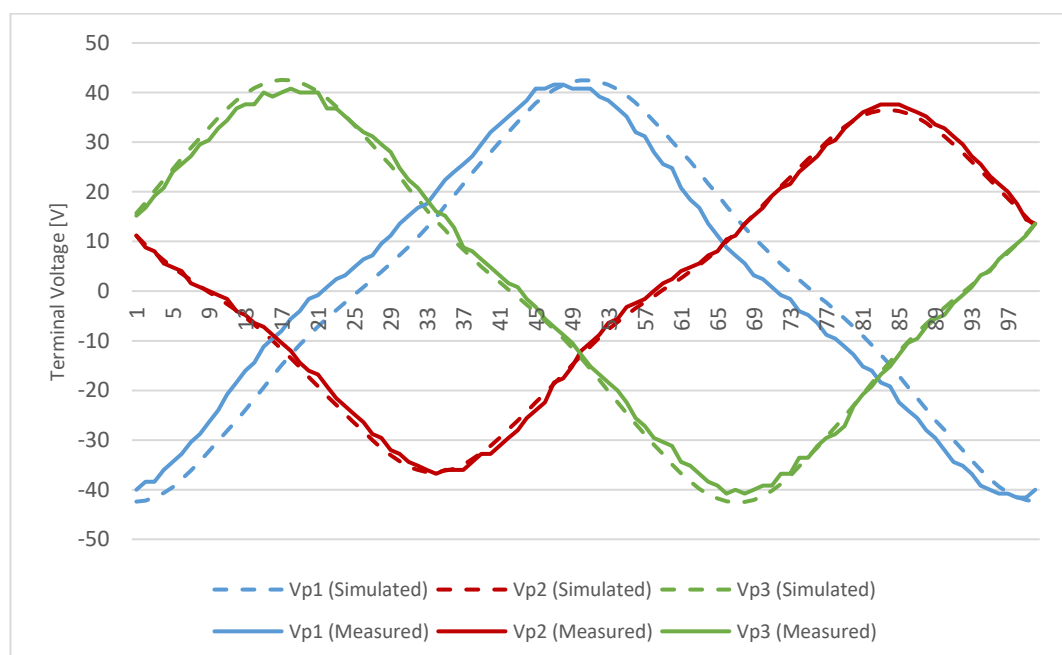


Figure 7.18: Comparison of simulated and measured voltages.

8. CONCLUSION

In this thesis, an energy source for linear induction launchers is designed. It has been ensured that the energy source is in a laboratory-scale and it is ensured that it can store energy from the mains. Energy is stored mechanically on the flywheel. The AFPM generator design, which transfers this energy to the launcher, has been realized in detail. The results of this thesis can be summarized as follows.

The suitability of the axial flux PM machines for launching applications was evaluated. Especially due to the low inductance demand, it is seen that the air-core structure stands out.

The axial flux machines are suitable for low-speed high torque applications due to their structure. Using the modularity of its structure, a new topology is named separated winding has been proposed and compared to traditional AFPM machines. As a result, the separated winding is found to be suitable for launcher applications.

A wave winding is proposed for stator windings of axial flux machine. Despite the superior properties of the wave winding, the use of it in conventional AFPM machines has some disadvantages. However, the use of the wave winding has become advantageous with the separated winding topology proposed in this thesis.

Moreover, within the scope of this thesis, a new technique related to the production of the wave winding has been put forward and this production technique has been patented. With this technique, each round of the wave winding is cut from the plates, and stator is formed between them by supporting with insulation papers. This method significantly simplifies stator production.

Finally, the analysis of the generator with different loads in the simulation environment was carried out to determine how electrically the launcher and the generator are connected. Although the launcher is modeled only as resistance and inductance, it has been shown that the variations in these values affect the transmitted power. The result of this analysis is the importance of designing the launcher and the generator together.

The generator does not achieve the desired performance due to the formation of a very large eddy current through the formation of windings from the plates. Here, the classical eddy current formula and the effect of the skin are examined, and it is seen that the copper used is suitable. In addition, when the windings are selected as coils in

the simulation environment, even if the eddy currents option is included, there is no negative effect of eddy currents. As a result, the necessity of examining the surface widths of rectangular windings used in axial flux machines in terms of eddy currents emerged.

Compared with the simulation results performed at the design stage, the no-load measurements made at the point where the generated generator can reach are very close.

The existing machine can also be used at very low speed and high torque applications. Since eddy currents are related to frequency, these losses can be omitted if the frequency is too low. Due to the large cross-section, it can carry high current and thus achieving high torque. It can be used as a motor in milling and mixer machines.

In future studies, eddy current losses on the winding surfaces of axial flux machines should be examined. Also, the eddy current forces on the surface of non-circular wires should be investigated. The wave winding proposed in this thesis can also be produced with the surface of the rectangular wires positioned perpendicular to the magnets. The production method of such a winding may be studied. Finally, windings can be manufactured with circular cross-section wires or Litz wire and full performance tests of the generator can be performed.

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BIOGRAPHY

Ceyhun Sezenoglu was born in Erbaa, Turkey in 1983. He received B.Sc. and M.Sc. degrees in Electronics Engineering from Gebze Institute of Technology, Gebze, Turkey in 2006 and 2009. He had worked as a research assistant with the Electronics Engineering Department, Gebze Technical university for 10 years. He is currently working as an R&D engineer in CADEM A.S. on motors and drivers for electrical vehicles. He is also the founder of AFPM Technology with the support of the TUBITAK entrepreneurship program. His areas of interest are axial flux pm machines, motors and drivers of electric vehicles, small scale wind turbines, and battery management systems.

APPENDICES

Appendix A: Publications in the Scope of the Thesis

Sezenoglu, C., Balikci, A., (2018), “Coreless AFPM Pulsed Alternator with Low Internal Inductance”, IEEE Transactions on Plasma Science, 46, (8), 3120-3125.