

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

**DESIGN AND ANALYSIS OF A LINEAR INDUCTION
LAUNCHER FED BY VARIABLE FREQUENCY POWER
SOURCES**

FEYZULLAH GÜLPINAR
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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2023

T.C.
GEBZE TEKNİK ÜNİVERSİTESİ
FEN BİLİMLERİ ENSTİTÜSÜ

DEĞİŞKEN FREKANS LI GÜÇ
KAYNAKLARIYLA BESLENEN LİNEER
İNDÜKSİYON FIRLATICI TASARIMI VE
ANALİZİ

FEYZULLAH GÜLPINAR
DOKTORA TEZİ
ELEKTRONİK MÜHENDİSLİĞİ ANABİLİM DALI

DANIŞMANI
PROF. DR. ABDULKADİR BALIKÇI

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2023



DOKTORA JÜRİ ONAY FORMU

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JÜRİ

ÜYE

(TEZ DANIŞMANI) : Prof. Dr. Abdulkadir BALIKÇI

ÜYE

: Prof. Dr. Serkan AKSOY

ÜYE

: Dr. Öğr. Üyesi Tuba GÖZEL

ÜYE

: Prof. Dr. M. Hakan HOCAOĞLU

ÜYE

: Doç. Dr. Yunus UZUN

ONAY

Gebze Teknik Üniversitesi Lisansüstü Eğitim Enstitüsü Yönetim Kurulu'nun
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SUMMARY

The structural design and implementation of the asynchronous induction launcher is relatively simple, compared with other linear induction launcher types. Multilevel converter topologies in driving rotating electrical machines have attracted great attention in recent years as a result of their unique advantages. Since linear induction launchers have the same theoretical background as rotary electric machines, there is not any theoretical and practical barrier to drive them by using multilevel power electronics converters. The launcher's stator can be stimulated by a power conditioner constituted of generator/capacitor group which have fixed or variable voltage and frequency. The aim of this thesis is to design and analysis a unique power conditioner using multilevel converter topology for power supplies, fed by variable frequency sources, of asynchronous induction launchers. Multilevel converter structure is designed in PSIM as a cascaded H-Bridge configuration triggered by the scalar level-shifted PWM modulation technique. Since the launcher is assumed as a linear RL model during PSIM simulation and it is expressed by nonlinear mathematical expressions in practical applications, its FEM analysis is executed in JMAG and its electromechanical model is derived too in Simulink for transient analysis in this thesis.

Key Words: Linear induction launchers, multilevel converters, level shifted PWM, electromechanical transient analysis, VVVF.

ÖZET

Diğer lineer indüksiyon fırlatıcı tipleriyle karşılaştırıldığında; sargılı asenkron bobin fırlatıcısının yapısal tasarımı ve uygulaması nispeten daha basittir. Döner elektrik makinelerinin sürülmesinde güç elektroniği uygulamalarından olan çok seviyeli dönüştürücü topolojileri, emsalsiz avantajlarının sonucu olarak son yıllarda büyük bir ilgi görmektedir. Lineer indüksiyon fırlatıcılar, döner elektrik makineleriyle aynı teorik altyapıya sahip olduğu için çok seviyeli güç elektroniği dönüştürücülerini; elektromanyetik fırlatıcıların sürücü uygulamalarına uyarlamasının önünde teorik ve pratik hiçbir engel bulunmamaktadır. Bir fırlatıcının statoru; gerilim ve frekansı sabit veya değişken generatör/kapasitör grubunun oluşturduğu bir güç düzenleyicisi devresi tarafından uyarılabilmektedir. Bu tezin amacı, asenkron indüksiyon fırlatıcıların değişken frekanslı kaynaklarla beslenen güç kaynakları için çok seviyeli dönüştürücü topolojisini kullanan özgün bir güç şartlandırıcısını tasarlamak ve analiz etmektir. Dönüştürücüdeki çok seviyeli yapı; skaler bir modülasyon tekniği olan seviye kaydırmalı PWM yöntemiyle tetiklenen kaskat bağlı H-Köprü konfigürasyonu olarak tasarlanmıştır. Fırlatıcı PSIM simülasyonu boyunca doğrusal bir RL modeli olarak kabul edilmiş, ancak pratik uygulamalarda doğrusal olmayan matematiksel denklemlerle ifade edildiğinden; bu tezde JMAG'de FEM analizi gerçekleştirilmiş ve fırlatıcının geçici analiz çalışması için Simulink'te elektromekanik modeli de türetilmiştir.

Anahtar Kelimeler: Lineer indüksiyon fırlatıcılar, çok seviyeli çeviriciler, seviye kaydırmalı PWM, elektromekanik geçici analiz, VVVF.

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LIST of ABBREVIATIONS and ACRONYMS

Abbreviations **and Acronyms**

Explanations

AC	:	Alternating Current
AICL	:	Asynchronous Induction Coil Launcher
CHB	:	Cascaded H-Bridge
EML	:	Electromagnetic Launcher
FC	:	Flying Capacitor
FEA	:	Finite Element Analysis
FEM	:	The Finite Element
Hz	:	Hertz
JMAG	:	Simulation Technology for Electromechanical Design
LS-PWM	:	Level-Shift Pulse-Width Modulation
NPC	:	Neutral Point Clamped
PSIM	:	Power Electronics Simulation Software of Powersim
PS-PWM	:	Phase-Shift Pulse-Width Modulation
PWM	:	Pulse Width Modulation
RL	:	Resistor-Inductor
SVM	:	Space Vector Modulation
VVVF	:	Variable-Voltage Variable-Frequency

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1. INTRODUCTION

Chemically propelled conventional launch systems are limited by the laws of thermodynamic. Instead, the electromagnetic launch technology was proposed in literature in order to overcome this limitation by employing one of the important rules of electricity: energy or signals propagate as electromagnetic wave in the speed of light in principle [1], [2]. Indeed, it has already found use in various advanced technological applications, which blossomed into high-added-value products in the areas of air/missile defense systems, railway transportation, orbital spaceflight, and high-pressure research [3]. In these applications, cost and speed advantages are observed by substituting electromagnetic force in launching operations for conventional chemical-based propulsion. As an example, only payload is included in cases where a rocket is designed with an electromagnetic launcher. However, conventional rockets should contain rocket engines, power sources, reactive masses, and other auxiliary weights for the same duty [4].

Basically, electromagnetic launchers can be categorized into two main classes: railgun and coilgun [5]. While railgun technology is preferred for the applications in which lighter payload is speeded up to very high velocity, coilgun technology is chosen for accelerating heavier payload with less velocity than railgun [6]. Linear induction launcher, a type of coilguns, is still a nascent field of study which is paid more attention by researchers lately. Also, it has some unique advantages, such as contactless operation between projectile and barrel, longer device lifetime, enabling heavier projectiles to use, and similarity of working principle with AC induction motors which have been well studied for many decades [7].

Linear induction launchers are studied in two different structure as synchronous and asynchronous induction launchers. A series of coils which are driven in sequence by pulsed power supplies constitute the barrel of a synchronous induction launcher, while its armature is only a conductive material [8]. Generally, synchronous coilgun has multistage construction in order to make velocity of the armature higher and the overall performance of the launcher better [9]. Recently, a lot of researchers have focused on improving driver circuit of coilgun by making progress in the area of PPS [10], [11].

An asynchronous induction launcher has the same working principle with a linear induction motor: its stator coils are in multiphase arrangement, and the coils form windings continuously in each phase. The armature, also named projectile, of an asynchronous coilgun is a conductive material as well [12]. When each phase of the stator is excited with sinusoidal voltage in a determined phase angle, the coils generate a travelling magnetic field wave throughout the barrel, and this magnetic field induced a current on the metal projectile [13], [14].

In literature, researchers examined some different type of power sources for linear induction launchers, such as capacitor-based, inductor-based, generator-based, and chemical-based in their experimental setup or simulation study [15]. Similarly, most of the research focused on improving the performance of energy utilization of induction launchers; such as designing a power conditioner for coilgun by utilizing a particular switching array in order to obtain smoother accelerating force [16], [17]. When it comes to driving issues of electrical machines, a lot of technical methods can be utilized for it. Among these methods, multilevel converter topologies have attracted more attention for the last decades due to some of their unique benefits.

Since a linear induction launcher is a subset of electrical machines, and has the same theoretical principles, multilevel topologies can be applied to them as well. Actually, Liu et al. studied three-phase asynchronous induction coil launcher's variable voltage variable frequency control in which improved current filament method is adopted for the usage in two different converter configurations; two level conventional inverter topology and H-bridge cascaded multilevel converter arrangement. Their result stated that projectile speed and force became smoother in cascaded multilevel converter configuration [18].

Since very high power and energy level are being used in these applications, designing the optimum switching construction for their energy storage devices is critical in order to control high energy density and flows of current. Therefore, in this thesis study it is designed and implemented as simulation that a novel conditioner for the power transfer of each phase coil section of barrel in a linear induction launcher. Cascaded H-Bridge multilevel converter configuration is preferred for the conditioner structure with a scalar PWM technique which is less complicated compared with its vector counterpart. Also, varying voltage varying frequency control algorithm, which is an efficient control method for asynchronous electrical machines, is designed and applied to the proposed conditioner. The launcher is modeled as a linear RL load in

PSIM simulations, however it is expressed by nonlinear mathematical formulations in real practical usage. Therefore, its FEM analysis is simulated in JMAG in order to see the impact of nonlinear nature of the launcher on the outcome waveforms, in the course of feeding it by variable frequency sources. Also, its electromechanical model is derived by numerical methods too and it is applied in Simulink for transient analysis.

1.1. Scope and Purpose

In this thesis, a moderately comprehensive literature review on electromagnetic launchers, power converter topologies, modulation techniques and variable voltage variable frequency control is conducted. Electromagnetic launchers, the first applications of which date back to the mid-1800s, have emerged as a discovery that has a potential to overthrow chemical launch technology due to some of the superior advantages they provide. As the people of this age, we owe many technological devices such as modern traction systems, electric vehicles and renewable energy sources that we use in our daily life to the rapid and effective developments in power electronic converters. These advancements triggered the modulation techniques of converters to emerge as well in a wide variety of structures.

The purpose of this thesis study is to design and simulate a novel power conditioner as a multilevel converter topology for the power source of an asynchronous induction coil launcher (AICL). The conditioner structure is designed as multilevel converter which composed of a cascaded H-Bridge (CHB). The level-shifted PWM (LS-PWM) control arrangement is designed for its modulation technique. Furthermore, a variable-voltage variable-frequency (VVVF) control strategy is included in the modulation too. The design of all parts is executed in PSIM which is a strong power electronics simulation software. Also, its transient FEM analysis and electromechanical model is performed in JMAG and Simulink simulation platforms, respectively, for observing the outcomes of an AICL as nonlinear load to the proposed power conditioner.

1.2. Motivation

Despite the fact that power electronics technology has reached higher performances in recent decades, there is still a gap in literature for design and implementation of the cutting-edge switching devices in driving system of linear induction launchers. The primary underlying reason behind this situation is the fact that although the launcher technology was rapidly improving, especially after World War II, the semiconductor technology hadn't developed enough yet. Since the process of firing projectile in a linear launcher occurs in quasi-steady-state, which can be counted as transient, with very high electrical power and current, driving system can include recent power switching devices due to their improved operating frequency and capacity characteristics. The lack of the number of power electronics applications such as simulation or experimental practices for the linear induction launchers has created a gap that needs to be further studied in this area.

In the development process of electromagnetic launchers, many technological limitations, such as material features belonging to barrel and projectile, supplying power sources of launcher, the energy storage equipment, and the switching devices, are majorly eliminated owing to great efforts of the researchers in the area during the recent decades. The current technology of modern power electronics is mature enough to meet the mega-level current and voltage needs of the electromagnetic launching operation in tera-level of power. However, the studies in induction launchers which benefited from modern power electronics are not in a great number yet. Therefore, the motivation behind this thesis study is designing and simulating a novel power conditioner, which is configured as cascaded H-bridge multilevel converter topology with the modulation of LS-PWM method under VVVF control, for the power source of an asynchronous induction launcher.

1.3. Contributions

The main contributions of the research conducted in this thesis is to present a literature review of electromagnetic launchers with their potential power converter applications as driving circuit and to propose a novel power conditioner design for its single- and three-phase models. The proposed power conditioner in this study is built

up with a five-level cascaded H-Bridge multilevel inverter topology due to some of its unique advantages. The scalar level-shift multi-carrier PWM technique is preferred for the modulation of inverter topology because it is much more straightforward and less costly than the space vector PWM method. Furthermore, in order to improve thrust characteristic in the course of launching operation, VVVF control strategy is applied in the modulation process. The inverter simulations are executed in PSIM and its PWM is implemented via analog and digital procedures. Also, the electromechanical model of AICL is derived mathematically and its accuracy is verified in Simulink by comparing the outcomes obtained from JMAG in which FEM analysis of AICL is applied.

1.4. Outline

This thesis study is constructed based on totally five sections. In Section 1, an introduction of the thesis such as scope, purpose, motivation and contributions, is presented briefly. Section 2 introduces a literature review on each topic within the scope of the thesis. Section 3 declares the methods used in this study with presenting outcomes and discussions of the PSIM simulation findings. The FEM analysis and its outcomes are examined in Section 4. The electromechanical model of launcher is developed in Section 5, by verifying it in Simulink too. Section 6 presents conclusion and Section 7 finalizes the thesis by stating potential future works.

2. LITERATURE REVIEW

In this section, a literature review is presented comprehensively in subsections according to the topics that form the theoretical background of this study.

2.1. The Evolution of Electromagnetic Launchers: A Historical Perspective

After the first gunpowder weapon had emerged, there were not breakthrough changes in its technology over the next few centuries. In order to make a gun's effect more severe, the projectile's speed needs to be maximized, which is determined by the quantity and quality of the propellant, the mass of projectile and length of the barrel. However, the dynamism of its acceleration is still dictated by the fact that maximum speed in hot gases is limited by the speed of sound [19].

For almost two centuries, there have been some interests or thoughts for guns in which electricity used. After the great developments happened in the area of electromagnetism, the main motivation behind designing an electric gun is the expectation of releasing pure power of electromagnetism to speed up the projectiles at an acceleration degree which was never before accomplished. While the projectile is pushed by gas molecules in a conventional gunpowder weapon, it is forced by the force of electromagnetic field in an electric gun. That force, theoretically, can be transmitted in the speed of light, so electric guns cause projectiles to accelerate at much higher rates of speed than its conventional counterpart [20].

Verma et al. reviewed some different structures of hypervelocity guns ranging from chemical based to light gas and some other types as well in [21]. They described hypervelocity term within the scope of a few to some tens of kilometers per second. The projectile launchers have been categorized into a few types of guns: Propellant-based, light-gas, electrothermal, electrothermal-chemical, and electromagnetic gun. The first appearance of the electromagnetic gun, SIVA, had begun with an advertisement announcement in 1844. After one year, Dr. Charles G. Page provided a more scientific experiment for it in 1845. The electric gun concept started to be known as electromagnetic gun, because helical coils and batteries are used in that experiment [22].

At the turn of the following century, Norwegian physicist Kristian Birkeland built an electromagnetic cannon which is being counted as the root of today's railgun by some authorities in the area [23]. Actually, there were only handwritten and some lecture notes available from Birkeland's work, but even those papers enlightened the researchers from various countries such as France, Russia, United States, Germany, and Japan. Although Birkeland put a lot of effort for an electromagnetic gun and even he had patent on it, he stopped the project on February 6, 1903 because the power supply had been destroyed by the large short circuit in his official demonstration. In 1930's, Edwin Fitch Northrup constructed the root of today's coilgun named the discrete-coil whose synchronization performed by mechanically for the launching space vehicles ultimately [24].

The efforts to improve electromagnetic guns were interrupted during the World War I, except for studies of Fauchon-Villeplee, who later named as the modern railgun's inventor, in France. However, after it, especially during the World War II, there were great attempts in Germany and Japan. German researcher Hänslér designed and experimented a high velocity anti-aircraft gun [25]. Also, the similar endeavors with Germans in the course of that war were performed by Japanese researchers in Army Research Laboratories without much success. In the middle of 1960's, electromechanical pulsers whose rise time was short and power level was very high were analyzed and studied by Pande and Levi in order to obtain high energy oscillations directly, without using any intermediate storage device [26], [27].

In 1966, a traveling wave accelerator using superconducting projectiles was suggested by Professor Winterberg of the University of Nevada. However, it later became apparent that the proposed design would be longitudinally unstable without synchronization actively. Ten years later, in 1976, the first coaxial launcher which composed of separate coils with active synchronization and semiconductor switching in commutation was constructed by a group of researchers at MIT. A two-gram aluminum projectile was accelerated to 4.9 km/s in a 1 cm length via pulsed power by USSR scientist V. N. Bondaletov in 1978 [28]. Another research group at MIT in 1979 assembled a brush-commutated helical launcher which was invented by NASA staff in 1972.

In the late 1970s, the studies in the area of railgun started to become popular again, especially in the United States, after Richard Marshall's experiment in 1977. He was working in Australian National University, and he designed an electromagnetic

gun whose projectile had reached 5.9 km per second which still stands as one of the highest records even today [29]. Also, he reviewed energy stores and systems for railguns by dividing them into five main categories as homopolar generator, capacitor stores, distributed capacitor stores, distributed homopolar generator stores, and chemical energy stores [30]. In [3], the tumultuous history of electromagnetic launch (EML) systems in the U.S. are explained in details and Dr. Fair stated the major advances and technical developments occurred in the U.S. until 2000s in [31].

In the U.S., researchers have made a lot of study in EMLs so that Dr. Engel proposed to classify them based on the binomial nomenclature method in order to give better understanding of the operation and theoretical relationships between them [32]. Since most of those researchers are holding patents belong to their study, a survey of U.S. patents in this area, between 1980 to 1999, is presented in [33], for illustrating a frame of the broadness of the EML technology. Although it seems that the studies on EMLs performed in the U.S. dominated the research conducted in some other countries, there are a lot of promising ones ongoing in France, Germany, Iran, Israel, Italy, Russia, Sweden, China and U.K. In [34], a review of the electric gun research accomplished in U.K. is introduced. Also, China is one of the most important centers for electromagnetic gun research [35]. Russian researchers concentrated on advancing electric-discharge launchers, railguns, and electrothermal-chemical launchers, especially by examining their physical features in order to make them worked in super higher speeds and longer lifetime [36]. Similar topics were studied in French-German Institute of Saint-Louis too [37].

The research in literature reveals that EML systems hold three following distinctive characters: Higher technology, speedier, and more powerful [38]. Although the EML technology is associated with army researches mostly, there are some cases for transportation applications as presented in [39]. Also, it is studied in the following research areas: Space launch systems, missile defense area, tank armor applications, high-pressure research, and aircraft catapult. In fact, an assisting EML system for a civil aircraft has been proposed in [40], by examining differences between three possible linear motor topologies: Linear induction, linear permanent magnet synchronous, and superconducting linear synchronous motors.

2.2. The Structure of Electromagnetic Launchers

In case the EML system becomes a gun launch technology, the launcher is an electromagnetic accelerator device which employs mutual effect of magnetic fields created by electric currents to increase the speed of a projectile. This accelerator device is an electrical analogue of a conventional gun which utilizes chemical reaction to do it. Actually, these devices are linear electric motors which can be classed in two types: Railguns and coilguns. There has always been rivalry between these two types launcher for many decades. As can be seen from the viewpoint of its performed applications in literature, railgun technology is in the forefront for a long time due to its simple structure. However, this doesn't mean the competition has already resulted because coilgun structure has its unique advantages and more promising performance potentials [41].

In a railgun which is schemed in Figure 2.1, there are two parallel conducting rails which form barrel to generate Lorentz force. In order for those rails to complete electrically each other, an armature carrying projectile is inserted between them. In a coilgun, however, an electrical current which circulates in a coil-or a lot of coils-causes a magnetic field, so it exploits this magnetic force. The projectile is embedded into the center of the barrel of a coilgun which might have one or more such coils. These coils are switched on and off one after the other, and the field due to the generation of each coil's magnetic field either thrust or draw the projectile to the next coil [42].

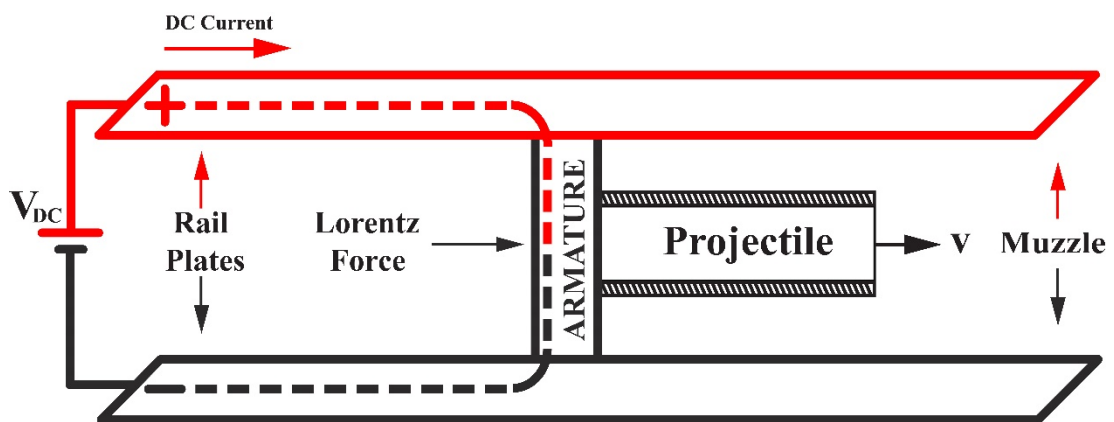


Figure 2.1: Schematic of a railgun.

Coilguns are categorized into two main structural types which are synchronous and asynchronous induction coil launchers [43]. A multi-sectional synchronous configuration is presented in [44] in detail and its schematic representation is shown in Figure 2.2. Basically, a projectile which is constructed by an electrically conductive material and a barrel which is divided into a lot of sections with an array of drive coils form a coilgun. In synchronous type, the drive coils of the barrel in each section can be connected to a power supply through semiconductor switches. Since the barrel has many sections, each section can be fed by a different constant voltage frequency or magnitude from an independent power source.

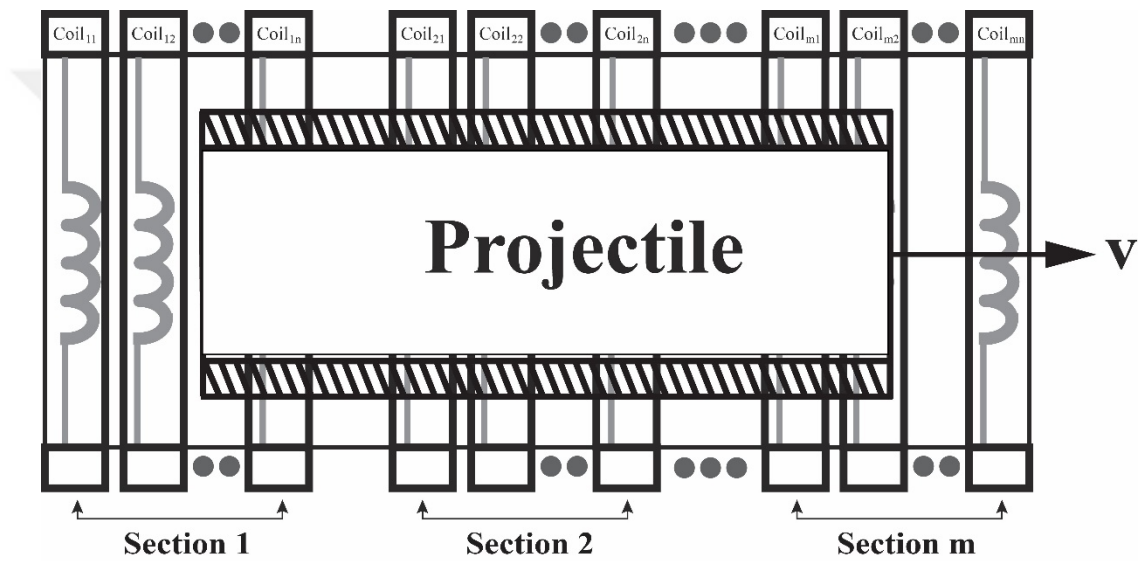


Figure 2.2: Schematic of a multi-sectional synchronous induction coil launcher.

The asynchronous induction launcher structure resembles three phase AC induction motors. In an asynchronous coilgun, the coils in each windings are connected to each other in succession. By the interconnection of corresponding windings in related phase, the multi-phase stator of AICL is formed in order to generate desired electromagnetic force through the barrel. The scheme of a three phase AICL is represented by Figure 2.3. The power sources of induction launchers can be either generator or capacitor banks, so the coilgun's performance is specified with the sort of that power source. For the sake of improving coilgun's performance, a lot of researchers have attempted to make contribution to that by publishing some remarkable papers about this topic.

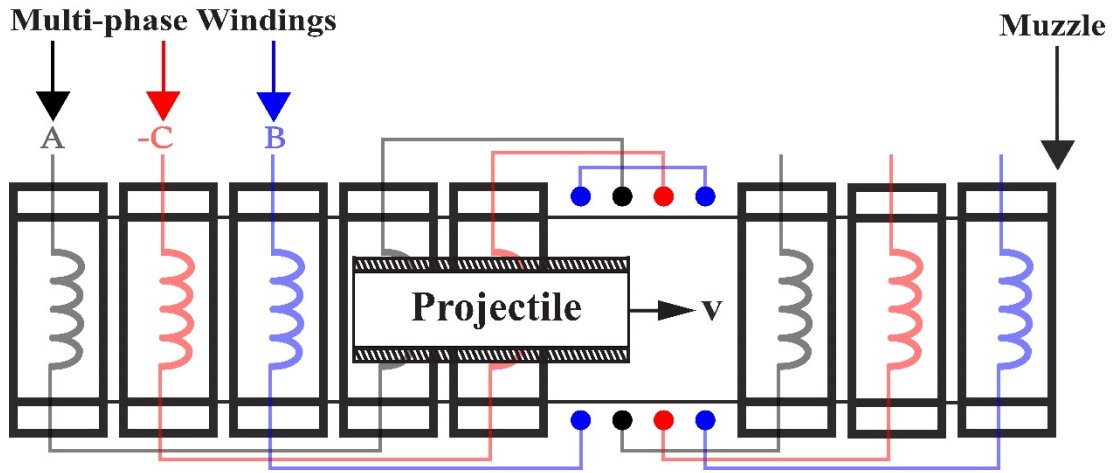


Figure 2.3: Schematic of a multi-phase asynchronous induction coil launcher.

In [45], the performance of generator and capacitor driven linear induction launcher was investigated. It was resulted that two main challenges were faced for generator-driven coilgun: The phase differences of current, induced in projectile while it moves between barrel's sections, and the dc components of coils' current which hinder propulsive force. However, for capacitor-driven the only factor which affects the performance is the total resistance of barrel. In [46], the drawback of generator-driven DC current component increase was overcome by applying energy to the three phases of coils sequentially. This study lighted the way for designing novel energy source types for the hypervelocity linear induction launchers.

As an example for the novel design, flywheel motor/generator set is improved in [47] for driving a coil-gun. This device consists of totally eight sections whose length increases from first to last sections. Also, the frequency of currents supplied to the windings of section is in augmented form. From the muzzle of barrel, a 3 kg projectile at speed of 2 km/sec is obtained as the results of a few simulation executed. Later, Balikci et al. focused on advancing the accelerating force of a linear coil-launcher. In order to have better shaped traveling magnetic wave of barrel, it is concluded that the amount of total phases should be increased from three to five [48]. By this way, the improvement on the waveform of the current which induce in projectile is observed as well.

In addition to the increment number of phases in [48], the connection configuration of coils was changed from series to parallel in [49]. By this way, the outcomes of using input energy more efficiently, smoother acceleration force, and smaller levels of input voltages need are acquired. After some years, Balikci et al.

improved the efficiency of coil launcher in order to take it a step further by suggesting each section of barrel as an individual sub-launcher which is driven by an independent set of shaft-coupled flywheel generator in [50]. In fact, this suggestion gave the freedom for selecting each generator's frequency and voltage separately. By the way, not only efficiency has advanced in the proposed design, but also the projectile's acceleration force results smoother, and its temperature rise become lower as well.

2.3. The Driving Circuit of Electromagnetic Launchers

In the late 1970's, the homopolar generator was utilized as the driving source in a few projects conducted by researchers in The Australian National University in order to apply a large amount of current in a form of electric arc to a railgun type launcher [51]. Later, a magnetically opening switch without using slide contacts was designed and performed to the very high current densities such as 500 MA/m² [52]. An electromagnetic launcher system consists of four basic following units: Prime Power, Pulse Generator, Pulse Conditioner, and Accelerator. Prime power unit is the main energy source of the system such as AC power grid which can be provided from a conventional turbine or diesel engine connected to supply rotary movement for a homopolar generator or a regular generator which charges a group of batteries and capacitors [53]. In order to fire an EML accelerator or launcher device, it needs to be achieved intensification of the electricity power. Therefore, the pulse capacitor will draw battery's energy in a short time such as the rate of seconds. Pulse conditioner will compress a pulse to transfer the high power which requires to fire launcher device in an extremely short time like the rate of milliseconds.

There have been some research, also, on the topic of switches used for electromagnetic launchers. Pawar et al. examined semiconductor switches which can be employed for a railgun in order to lead researchers about selecting the optimal switch type for the nature of their implementation [54]. Singh compared switching devices for a tactical electromagnetic launcher application by discussing attributes of solid and non-solid state technologies regarding operating limits [55]. Among the solid state devices, SCR, GTO SCR, SiC thyristors, and MCT thyristors were counted as recent switching technologies in his study. However, non-solid state devices are old-fashioned technology: Spark gap, triggered vacuum switch, and orientation

independent ignition. In [56], this time Singh studied advanced semiconductor switches such as thyristor and SiC thyristors.

The attempt to advance LIL's performance hasn't been taken focusing only improvement on generator structure, but also there have been some effort to explore some kind of novel driving circuits for linear induction launchers such as using multilevel converter topology in [18]. Multilevel converters have attracted notice a lot in technical literature for last decades [57]. When multilevel converters were first presented in the area, their advantages, such as smaller common-mode (CM) voltage, lower switching frequency, and less distortion in output voltages - input current dominated the usage of classical two-level topologies [58]. The strong motivation behind the endeavor for developing multilevel converter topologies are to bloom modulation methods, balance the DC link's voltage, and make the value of total harmonic distortion (THD) better [59].

As mentioned earlier, a novel driving scheme has been proposed in literature by Liu et al [18]. A current filament approach, which is implemented in variable-voltage/variable-frequency control, is proposed for three-phase asynchronous induction coil launcher. Also, this new approach is applied in two various converter topologies; two level conventional inverter topology and H-bridge cascaded multilevel converter arrangement. It is proven that projectile speed and force became smoother in cascaded multilevel converter configuration with the proposed control algorithm than classical inverter topology [18].

Since there are several more multilevel converter topologies proposed in the literature for almost three decades, in order to design a power conditioner which provides optimum efficiency with a maximum reached projectile speed and smoothest force, there is a need to investigate further about applying these proposed configurations to linear induction launchers. For this purpose, some of the suitable multilevel topologies and their control strategies will be examined in the subsections below.

2.4. Multilevel Converter Configurations

Although some advantages of multilevel converters stated above, there are some disadvantages of them as well. For instance, they need very sophisticated control and

modulation strategies with some complicated switching signals routing. Also, some of topologies demand voltage insulation between each cell. Moreover, balancing DC voltage may cause some difficulties in its implementation for particular converter structures. Much effort in the area has been made to overcome these disadvantages by many researchers to produce excellent results for the multilevel converter applications.

Among several multilevel topologies, the suitable one can be selected based on the type of usage for the research purposes. The popular topologies can be stated as diode-clamped or neutral-point-clamped (NPC), flying capacitor (FC), cascaded H-Bridge (CHB), modular (MMC), and hybrid multilevel converter topologies.

2.4.1 Diode Clamped Topology

This topology is a well-known structure, for almost 40 years, and also commercialized by most of the leading companies in the area, so it is a mature technology. The topology is employed mostly in the variable speed motor drive applications such as conveyors, fans, compressors, and pumps [60]. A three-level diode-clamped multilevel inverter is shown in Figure 2.4. There exist some advantages of diode clamped topology such as its simple configuration as utilizing diodes to make equal blocking voltages of the switches, enabling to implement carrier based PWM method which is known as a less complex modulation technique and zero-sequence injection method to overcome dc voltage imbalances in the circuit.

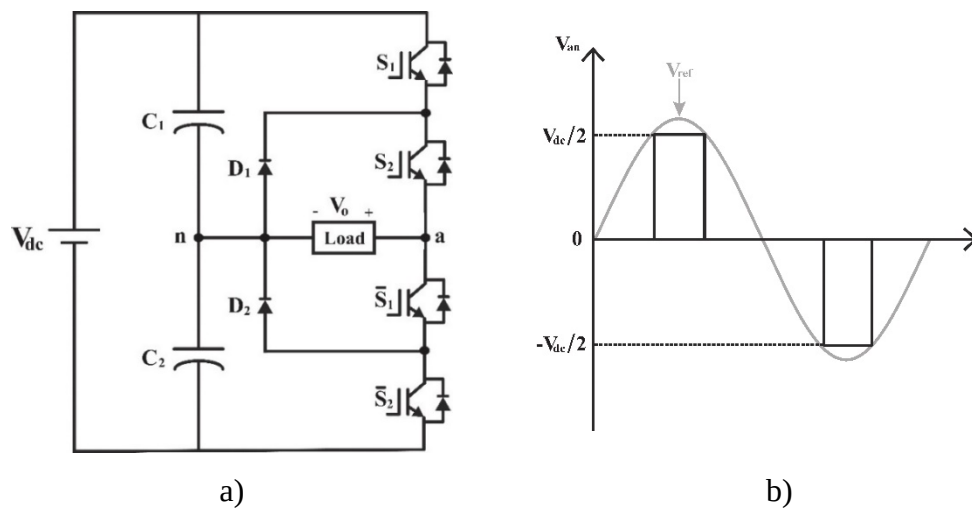


Figure 2.4: a) A single phase leg of a three-level diode-clamped converter topology, b) Its three-level output voltage waveform.

It has some disadvantages too such as inequality in the utilization of power switches; as the inner ones are operated during full period of reference signal, while the outer ones are fulfilled only half of it. Also, due to balancing voltage of dc-link is very hard when it is handled for more than three levels, the implementable topology in real application is limited to only this value of levels. In order to overcome this limitation and make conduction losses of switches less, T-type converter which is very similar to diode clamped topology is improved in [61]. Also, the higher voltage rates can be achieved successfully by using this T-type topology.

2.4.2 Capacitor Clamped Topology

Capacitor clamped inverter is first presented in 1990s [62]. The basic structure of single phase-leg flying capacitor multilevel inverter is illustrated in Figure 2.5. In this type of inverter, the capacitors are used instead of using diode-clamped, which makes flying capacitor inverter differ from the diode-clamped inverter. This topology is used generally for high power motor drive implementations such as traction drives, and for electric power transmission and distribution system [63].

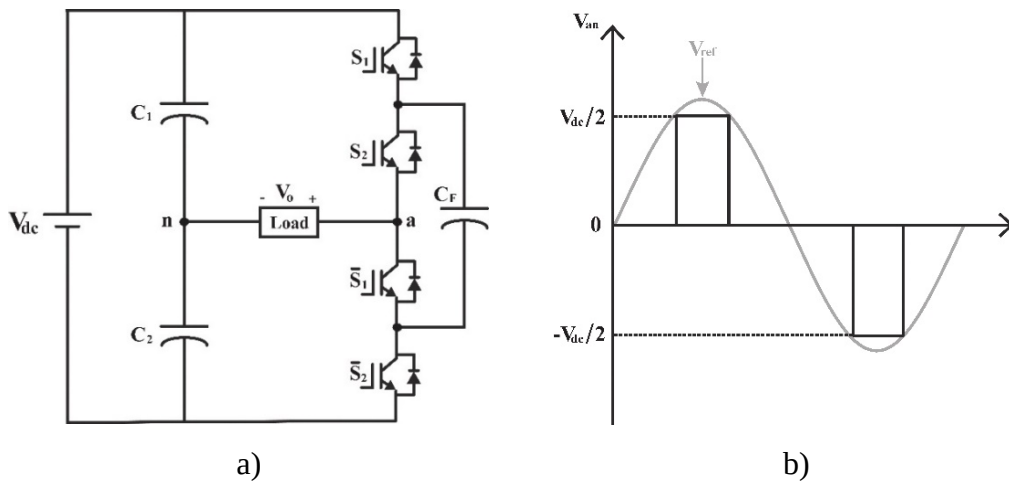


Figure 2.5: a) A single phase leg of a three-level capacitor-clamped converter topology, b) Its three-level output voltage waveform.

The flying capacitor topology is a well-studied arrangement which has been examined for more than thirty years, so its technology is mature enough. Its structure has modularity because simple connected power cells, which consist of two power

switches and one flying capacitor, form the topology. Each power cell means a new level in output voltage waveform. While forming each power cell by inserting an extra bypass switch, the configuration becomes more capable of tolerance to fault circumstances. It uses carrier-based modulation strategy such as phase shifted PWM method, which can be counted as a simple and well-known technique. The phase shifted control strategy provides naturally equal switching losses, balancing floating dc voltages in the circuit, and better THD in output waveforms.

The flying capacitor topology has some drawbacks as well, such as its dynamic response is not satisfied to balance naturally dc voltage during the real-time implementation of the topology with phase shifted PWM approach. Also, when the converter is executed in real applications, averaging time between interruption of its operations is unsatisfactory because of the great number of floating voltages. There are some hybrid topologies in which flying capacitor structure is used as submodule or auxiliary arrangement for the main structure. Therefore, the FCC topology has significant importance to form novel or non-conventional multilevel arrangements.

2.4.3 Cascaded H-Bridge Topology

Its structure was first proposed in the beginning of 1970s, so this topology is a mature technology to implement in industrial and research applications. The CHB topology is formed by the combination of several H-bridge converters and independent DC sources. Figure 2.6 shows a single-phase leg of a nine-level CHB structure and its output voltage waveform. Its structure has modularity because straightforward connected power cells, which consist of H-bridges, form the topology. Each power cell means a new level in output voltage waveform and can make the implementation fault tolerated with adding bypass switches. Also, reaching a high number of levels with the higher nominal voltage values in output waveforms is effortless by making many cells cascaded with each other.

In cascaded H-bridge topology, there is no need for low voltage transformers because the AC output can be directly coupled with medium-voltage grids. It uses carrier-based modulation strategy such as phase shifted PWM method, which is a simple and well-known technique. The phase shifted control strategy provides naturally equal switching losses, balancing floating dc voltages in the circuit, and

better THD in output waveforms. Also, it has a drawback such as demanding a separate DC voltage source for each cell limits the implementation of this topology. The main usage area of this configuration are motor drives and flexible AC transmission systems (FACTS), for instance static synchronous compensators or active filters [64].

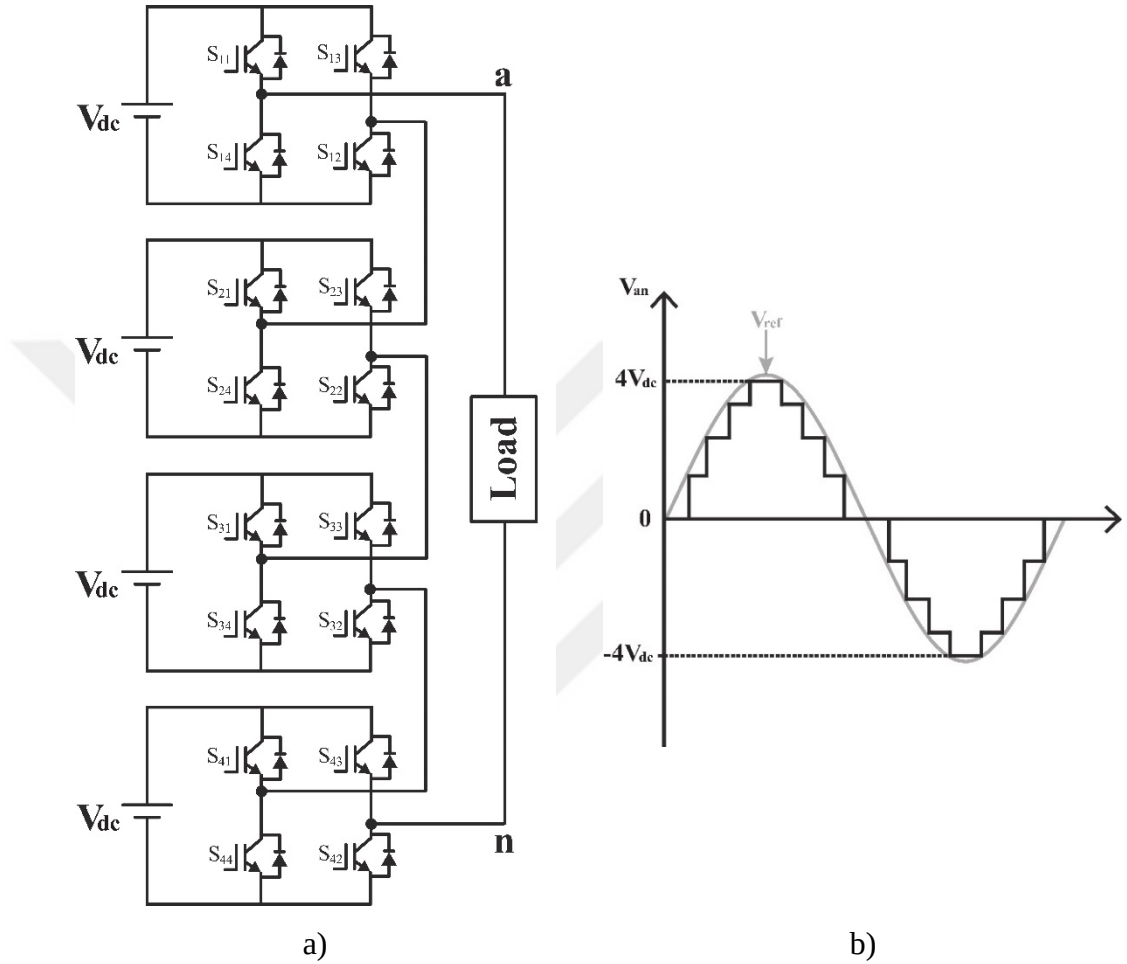


Figure 2.6: a) A single phase leg of a nine-level cascaded H-bridge converter topology, b) Its nine-level output voltage waveform.

2.4.4 Modular Multilevel Converter Topology

It is relatively a novel technology when compared to other topologies. The fundamental employment area of this topology is high voltage DC transmission (HVDC) applications. Also, this structure is utilized in offshore wind farms for converter station applications by implementing it in a back-to-back manner to eliminate the usage of low voltage transformers in the system [65]. It has a modular arrangement shaped by cascade attachment of submodules which may consist of half

bridge, full bridge, flying capacitor, cascaded half bridge, or double clamp structures. The configuration of three-phase modular multilevel converter in which capacitor clamped topology is used for each submodule labeled as “SM” is shown in Figure 2.7.

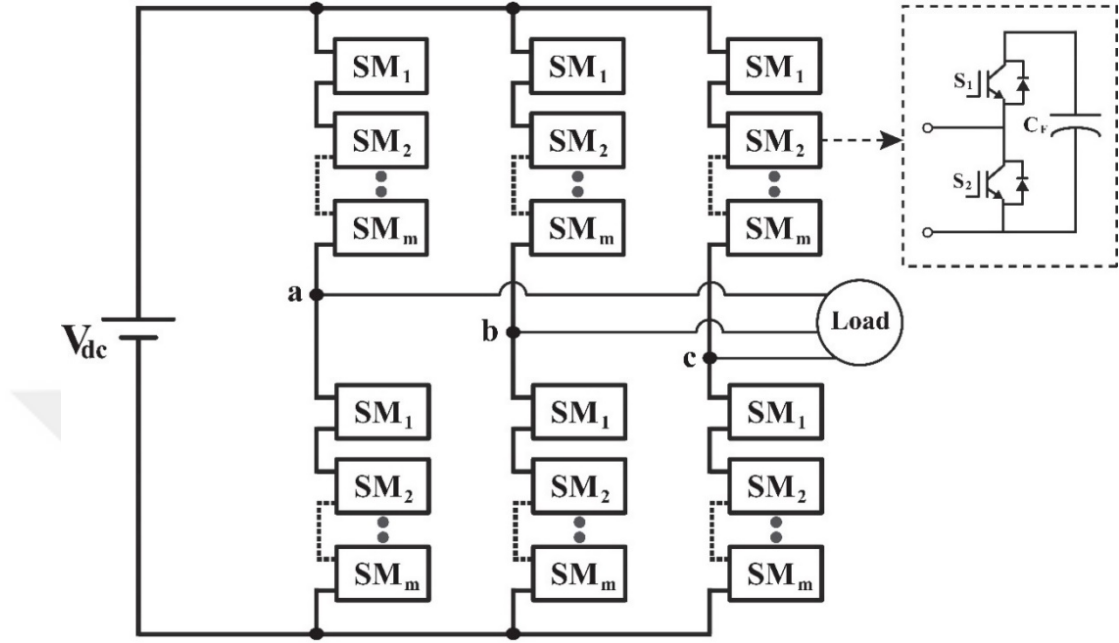


Figure 2.7: The configuration of three-phase modular multilevel converter.

One of the benefits of MMC is that the modulation technique to control it is not a complex method, which is known as nearest level control strategy. By this way, the power losses between switches can be equalized averagely and the floating capacitor's DC voltages can be stabilized. The main challenges for this type of converter structure is stated in literature too. One of them is oscillating low frequency DC voltages of capacitors used in the topology. This factor causes fluctuation of voltage in capacitors by decreasing the mean time of failures during its operation in real applications. The other one is that it needs complicated management for data acquisition and communication because each MMC is comprised of a huge amount of power cells, especially for HVDC operations.

2.4.5 Hybrid Multilevel Converter Topologies

The hybrid form of the standard multilevel topologies, which are stated until now, can be designed in order to have unique advantages of each of them. A

unidirectional multilevel rectifier arrangement is presented in [66], as being an example of hybrid implementation. In this hybrid topology, the benefits of capacitor clamped and flying capacitor topologies are merged. Also, in [67], active neutral point clamped (ANPC) converter topology is proposed by combining FC with NPC to obtain stepped waveform at output. Actually, designing more novel hybrid topologies for specific purposes in the area of multilevel converter topology is limited only with the creative horizon line of a researcher.

2.5. Modulation Techniques of Multilevel Converters

Since the amount of switching equipment's losses and harmonic performance of the converter in a topology rely on gate signal of power switches, the modulation of a converter to control the on and off conditions of the gates is one of the most significant aspect. Fundamentally, there are three main categories for modulation scheme, which can be classified as carrier signal based PWM, space vector based, and hybrid PWM methods. Actually, the recent researches have showed that carrier- and vector- based methods coincide in a manner which are two different approaches reaching exactly the same outcomes during the modulation process [68], [69], [70].

2.5.1 Scalar (Carrier Signal) Based PWM Technique

In this technique, there are two main signals: a sinusoidal voltage is used for reference signal, and, commonly, triangular waveforms are preferred for carrier signals. By comparing reference voltage with carrier signals, the gate signals of the switches are produced successfully in order to acquire the desired voltage at the output waveform of the converter. The carrier-based modulation strategies can be classified in three groups as level shifted PWM (LS-PWM), phase shifted PWM (PS-PWM), and selective harmonic elimination (SHE-PWM) or preprogrammed PWM methods.

2.5.1.1 Level Shifted PWM Technique

In this method, the triangular carrier signals are equally allocated to contain all values of reference signal based on three different phase states of carrier signals: in

phase disposition, phase opposition disposition, and alternative phase opposition disposition PWM techniques. Figure 2.8 illustrates these techniques respectively [71]. The level of multilevel converter's output waveform is directly related to the total number of carrier signals used in its level shifted control strategies. More explicitly, for designing an N-level converter, the number of N-1 triangular carrier signals are needed to compare with sinusoidal reference signal [72].

LS-PWM method is generally employed in capacitor clamped topology and its derivative or hybrid topologies such as T-type configuration. One attractive feature of LS-PWM technique is its very simple nature to implement in converter topologies. However, an unbalanced distribution occurs in conduction and switching losses of power devices during the practical implementation of this technique.

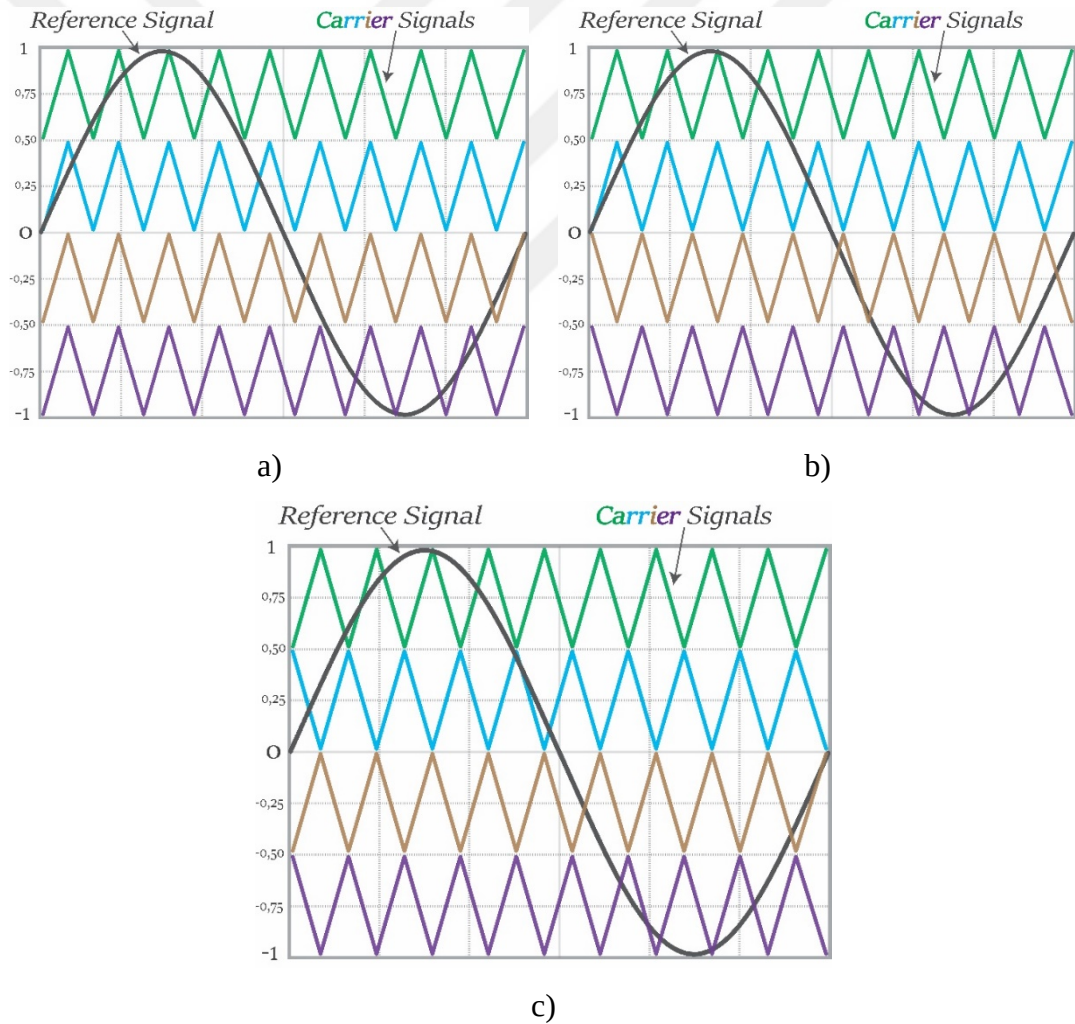


Figure 2.8: a) In phase disposition, b) Phase opposition disposition, c) Alternative phase opposition disposition PWM techniques.

2.5.1.2 Phase Shifted PWM Technique

LS-PWM method is not an effective modulation solution for some of multilevel structures which has modularity, for instance MMC and FC. In this case, the new arrangement of carrier signals is improved and named as phase shifted PWM method. There are particular phase angle differences between carrier signals in this technique. These carriers are compared with sinusoidal reference signals as well. Figure 2.9 depicts a PS-PWM operation for five level cascaded H-bridge multilevel converter topology [73].

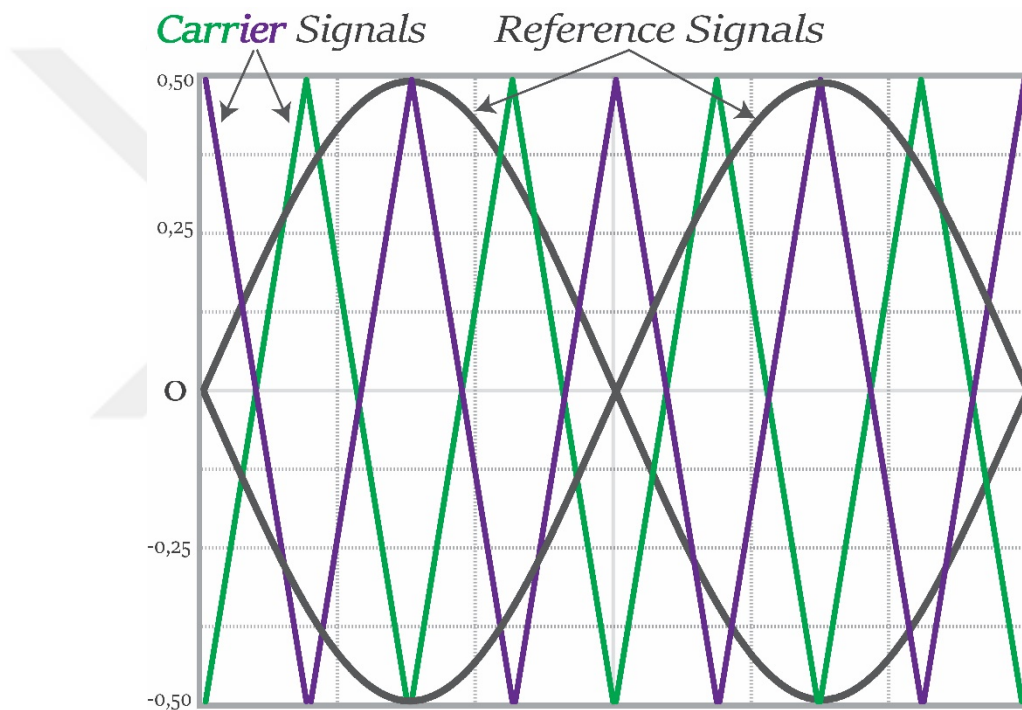


Figure 2.9: PS-PWM implementation for five level CHB topology.

Actually, this strategy is notably applicable for symmetrical modular topologies which has equal DC voltage and identical reference signal for each power cell such as FCC, MMC, and CHB. This symmetry accomplishes allocation of power naturally between each cell of the converter. Also, there is equal distribution in conduction and switching losses of power devices in this strategy.

2.5.1.3 Selective Harmonic Elimination PWM Technique

The gap for the increment of the switching frequency of power devices in order to reduce switching losses is extremely limited in the high power needed applications such as megawatt levels. Additionally, in case carrier based high frequency modulation methods are selected in some implementations in which the low frequency switching requires, the harmonic distortion will be very high. In order to avoid this distortion, selective harmonic elimination PWM strategy is proposed in literature for high power multilevel converters which demands modulated in low frequencies.

In SHE-PWM method, the pre-calculated switching angles are used for eliminating particular harmonic orders from the output voltage waveform. The pre-calculation can be executed by taking advantage of Fourier series analysis which can determine the magnitude of any odd harmonic in output signal. After these calculations, the switching angles are chosen such an exact value that the fundamental harmonic magnitude is set to the value of output voltage, and all the other harmonics' magnitudes are adjusted to zero value [74].

Although this method for high power utilization produces great harmonic performance and less losses during switching of power devices, it doesn't generate good response for transient systems in which enhanced dynamic response is the most important parameter. Also, this method works only during offline periods of the converter operation, it is useless for the applications requiring online procedure.

2.5.2 Space Vector Based PWM Technique

These methods can be applied for multilevel converters whose modulation implementations need high or low switching frequencies. Originally, the space vector control is designed for two-level inverters in three-phase applications. Over the years, it evolved into multilevel modulation strategy too. The basic idea behind this method is using α - β - γ coordinates or dq frame. In unbalanced power systems, γ has a non-zero value, otherwise its value becomes zero. Therefore, a balanced converter's available switching states are schemed in α - β coordinates and the reference voltage can be realized as a weighted array of the closest switching states which are illustrated in Figure 2.10.

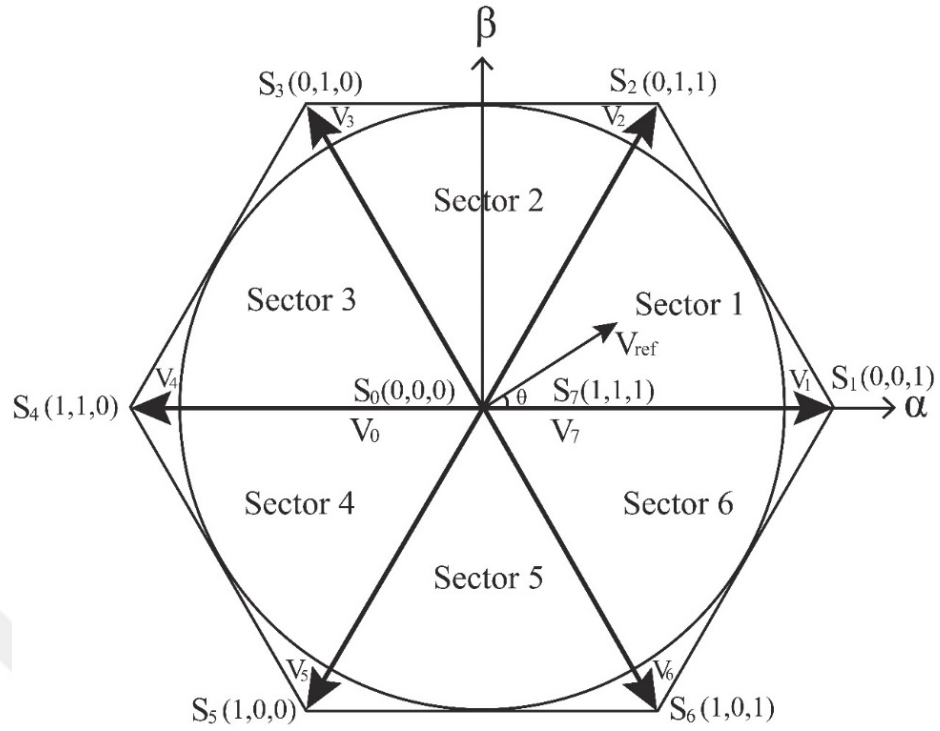


Figure 2.10: Diagram of space vector based PWM technique for two-level converter.

Correspondingly, a space vector modulation technique features a geometrical construction in which the aim is determining the switching combination with suitable duty cycles [75]. As being an advantage of space vector modulation, redundant states can be utilized to balance DC link voltages, to reduce CM voltage, and to minimize switching losses. However, this method is not suitable for the converter which has high number of levels due to complexity of state vector redundancy in those levels.

2.5.3 Hybrid PWM Technique

Although carrier based PWM methods technically can be practiced in any type of multilevel converter topology, it doesn't generate the best performance for that particular form such as an asymmetrical converter arrangement [76]. In these certain circumstances, the hybrid PWM as combination of existing main techniques can be developed in order to obtain better performance with lower switching losses. Actually, based on the novel topology designing, improving the hybrid PWM method for it is an

inevitable duty. In order to do that, a researcher or designer is compelled to strongly comprehend multilevel PWM control concepts.

2.6. Variable-Voltage Variable-Frequency Control

In a power converter circuit, the speed and torque of an induction machine can be controlled by the manipulation of voltage and/or frequency. Changing the stator voltage of an induction machine in a constant frequency leads to speed control only in a limited range. On the other hand, if the stator frequency is adjusted while the stator voltage is constant, the air-gap flux becomes saturated in this case. For this purpose, the variable-voltage variable-frequency technique has attracted broad attention among the various speed and torque control methods in order to make the induction machine's air-gap flux constant.

Additionally, keeping this parameter constant is necessary in order to sustain the torque of the induction machine constant in the course of machine operation. In the VVVF control method, constant air-gap flux is fulfilled by adjusting the magnitude of the stator voltage in proportion to the frequency. Furthermore, any control method in which frequency is variable saves the electricity consumption of induction machines. Since an induction launcher is a type of induction machine, the same advantages can be applied to asynchronous induction coilguns as well.

3. METHODS AND MATERIALS

In this section, the parameters of launcher and inverter are addressed by introducing analog and digital implementations. Also, the schemes of the asynchronous induction launcher and inverter circuit are presented.

3.1. Launcher Parameters

A simple 3D representation of three-phase asynchronous induction coil launcher, which has three primary coils and six coils in each phase, is illustrated in Figure 3.1. Researchers have made a lot of contributions to literature by analyzing linear induction launchers with some types of mathematical models in order to acquire equivalent circuit parameters. The most common numerical models for deriving those parameters are current filament method, current sheet model, wavelet transform, and finite element method.

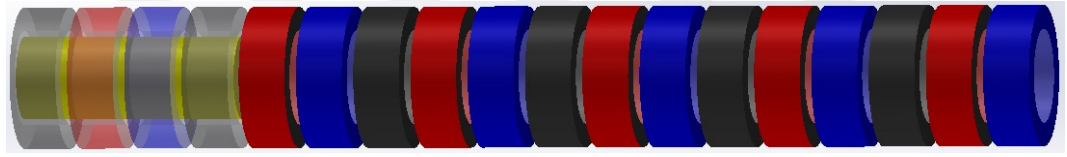


Figure 3.1: 3D representation of three-phase asynchronous induction coil launcher.

Within the scope of this thesis study, however, none of these methods are employed in order to obtain equivalent circuit parameters. Instead, they are calculated by designing the launcher in JMAG. The single-phase equivalent circuit of an asynchronous induction coil launcher, which is driven by 5-level cascaded multilevel inverter, is shown in Figure 3.2.

3.2. Inverter Parameters

The power circuit of the five-level CHB converter consists of two separate DC voltage sources for each phase and six sources for three phase AICL. DC converters, batteries, ultra-capacitors, photovoltaic arrays, or fuel-cells can be used as the DC voltage sources in the applications of cascaded H-Bridge converters.

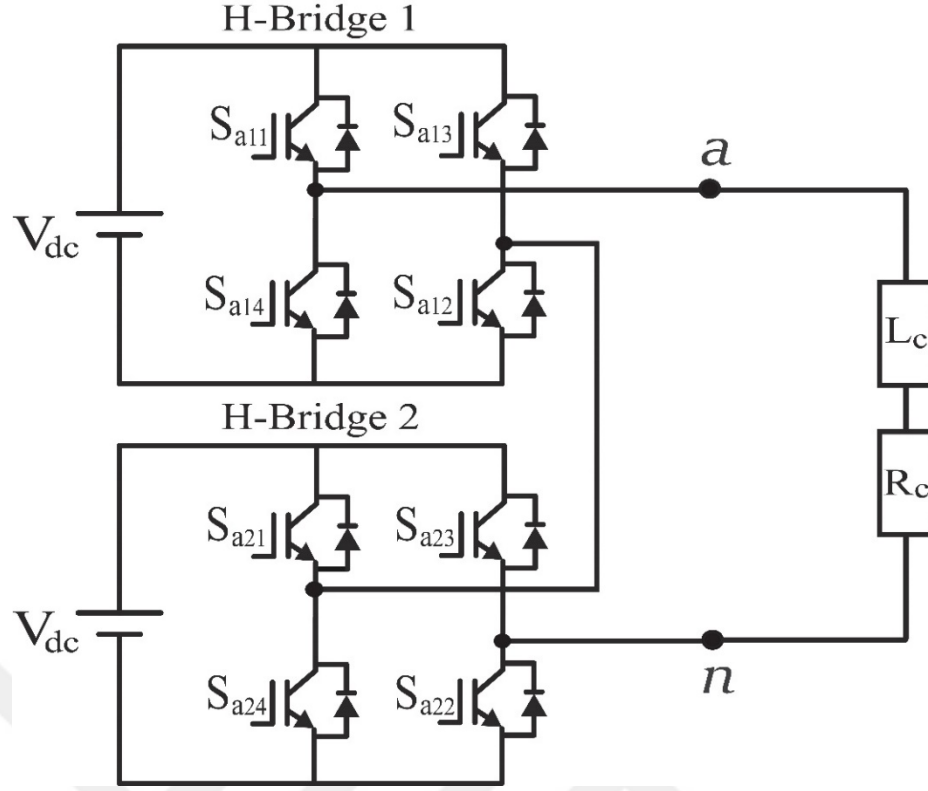


Figure 3.2: 5-level CHB inverter topology with equivalent circuit of AICL load.

The output voltage waveform of the single phase is formed by the augmentation of each DC voltage source of the different cells. During the implementation of modulation in each single-phase H-Bridge unit, one of the three-level voltages is produced at the output of cells: $+V_{dc}$, 0, and $-V_{dc}$. The output voltage and switching sequences for each H-Bridge cell in one phase is tabulated in Table 3.1 as an example for H-Bridge 1 scenario.

The output voltage of each H-Bridge cell, which includes four power switches, links each other consecutively in order to generate AC side of the converter.

Table 3.1: Switching sequence and output voltage.

S_{a11}	S_{a12}	S_{a13}	S_{a14}	V_{a1}
0	1	0	1	0
1	1	0	0	$+V_{dc}$
0	0	1	1	$-V_{dc}$
1	0	1	0	0

The phase output voltage is determined by sum of all output voltages obtained from each H-Bridge, which is given in Equation (3.1).

$$\begin{aligned} V_{an} &= V_{a1} + V_{a2} \\ V_{bn} &= V_{b1} + V_{b2} \\ V_{cn} &= V_{c1} + V_{c2} \end{aligned} \quad (3.1)$$

The obtained staircase output AC waveform fluctuates from $-2V_{dc}$ to $+2V_{dc}$ with five levels, and its shape is approximately sinusoidal, even without any filter. In multilevel converters, modulation and control strategies play a critical role in order to make the overall efficiency of system better by controlling the output waveform of the converter.

3.3. Analog Implementation of LS-PWM Method

In level-shift PWM method, two types of signals play important role for the task of modulation: a sinusoidal reference signal and multiple triangular carrier signals. The gate signals for the switching devices are generated successfully by comparing reference signal with multiple carrier signals based on Equation (3.2) in order to obtain the desired output waveform of the converter.

$$V_{PWM} = \begin{cases} 1, & \text{if } V_{ref} > V_t \\ 0, & \text{if } V_{ref} < V_t \end{cases} \quad (3.2)$$

The analog implementation with comparators and non-gates in PSIM is shown in Figure 3.3.

3.4. Variable-Voltage Variable-Frequency Control Method

Modulation index is the amplitude ratio of the reference signal to carrier signal, whereas frequency index is the frequency ratio of the carrier signal to the reference signal, which are seen by Equation (3.3).

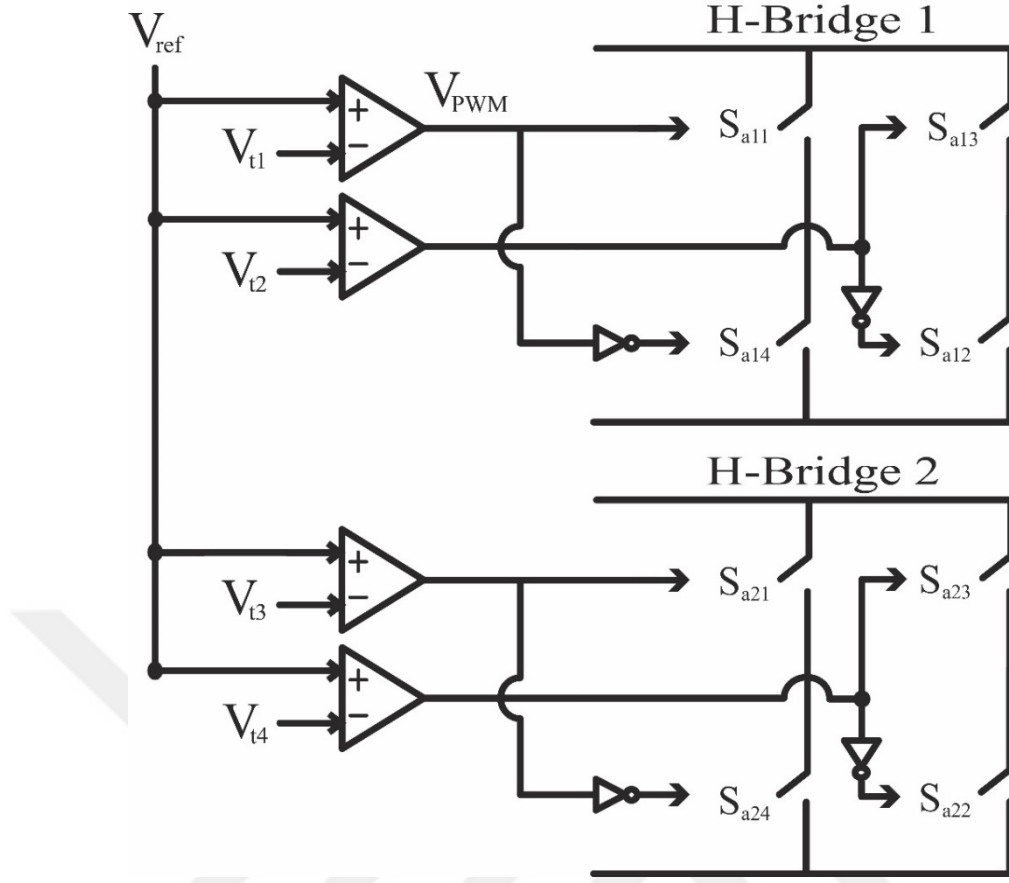


Figure 3.3: Analog implementation of LS-PWM method.

$$\begin{aligned} m_a &= \frac{v_{ref}}{v_t} \\ m_f &= \frac{f_t}{f_{ref}} \end{aligned} \quad (3.3)$$

The output waveform of the inverter forms such a shape that air-gap flux of induction launcher is kept constant by varying m_a and m_f proportionally during the PWM modulation.

3.5. Digital Implementation of LS-PWM Method

Since the experimental setup of this simulation study will be executed as future work, the digital implementation of PWM modulation is performed as well. Additionally, an external DLL block enables users to write codes in C or C++ and link them with PSIM. Furthermore, these codes are extremely useful for the PWM execution on DSP devices. The flow diagram of the algorithm used in digital

implementation of LS-PWM method for creating PWM signals is presented by Figure 3.4.

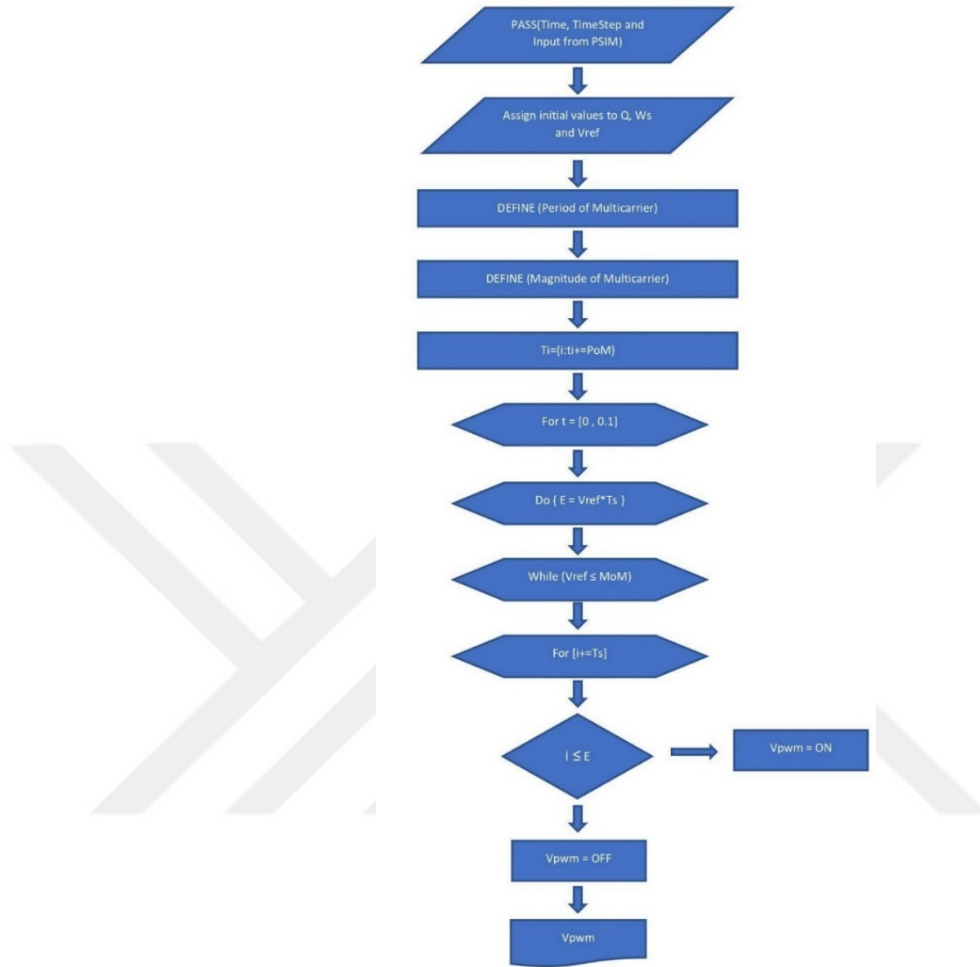


Figure 3.4: Flow diagram of digital implementation to create PWM signals.

The simulation outcomes of the proposed power conditioner in this thesis are obtained via digital implementation of LS-PWM method. VVVF control algorithm is also embedded into the codes.

3.6. Outcomes of PSIM

In PSIM simulation, the parameters of the asynchronous induction coil launcher's equivalent circuit model are determined, based on comparing similar researches in literature, per coil as 250 mΩ for resistance value and 25 μH for inductance value. In total, six coils are designed for each phase; therefore, three phase

launcher parameters per phase are finalized as 1.5Ω for R and $150 \mu\text{H}$ for L. The frequency of carrier and reference signals are set to 10 kHz and 50 Hz, respectively. A DC source with a value of 300V is used for each H-Bridge unit. The amplitude modulation index is adjusted to 0.95 for PWM technique. In VVVF control, m_a and m_r are manipulated in proportion. The simulation of the three-phase version of the proposed power conditioner is performed with the same parameters for the three-phase load as well. The gate PWM signals of the single-phase CHB inverter is illustrated in Figure 3.5.

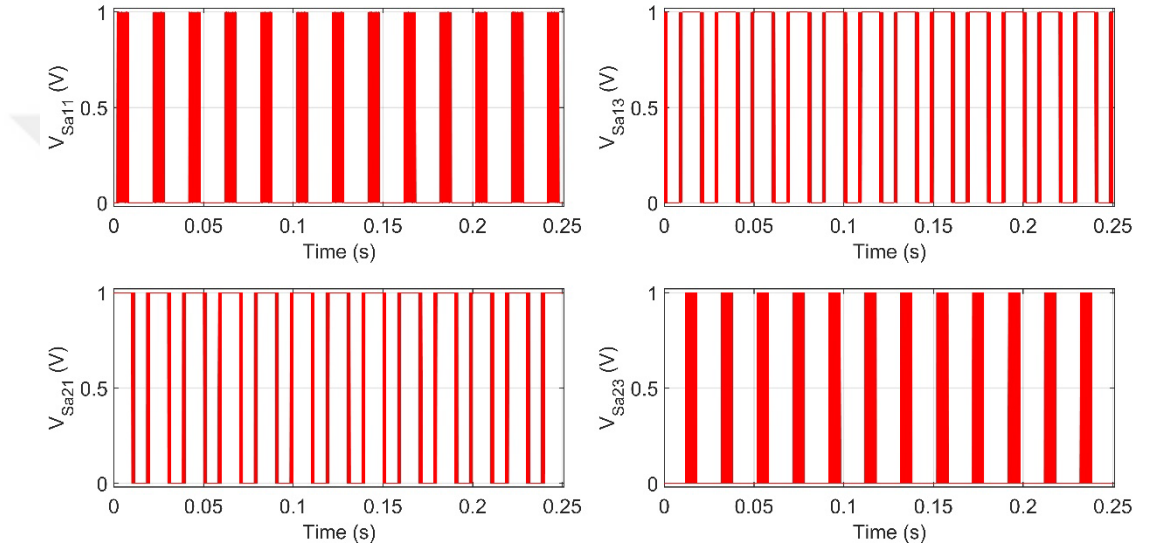


Figure 3.5: The single-phase PWM signals of CHB inverter.

The single-phase output voltage and current of the five-level CHB inverter is shown in Figure 3.6. The analog implementation is used for PWM control in order to acquire gate signals and single-phase results.

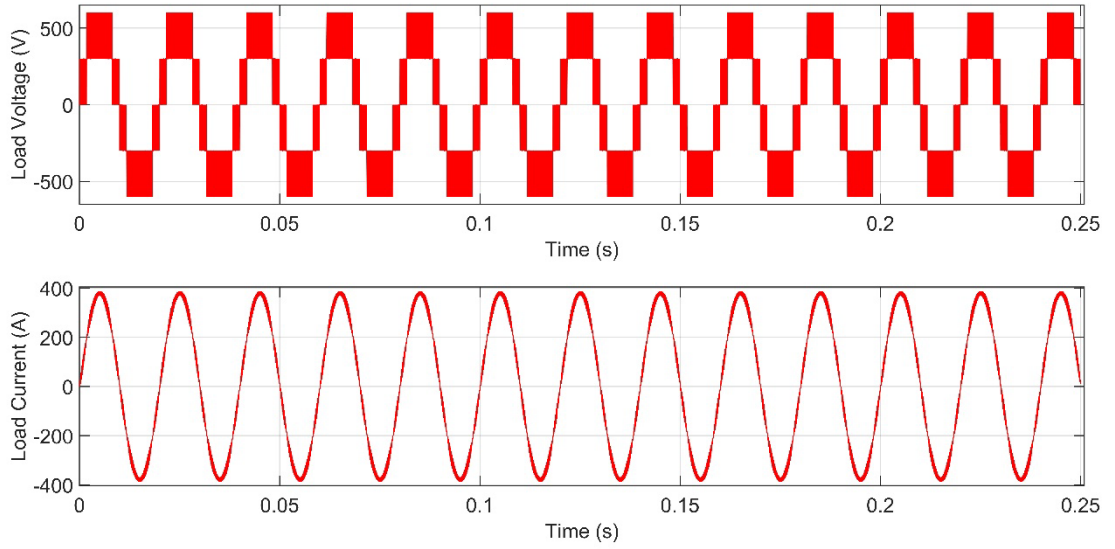


Figure 3.6: The single-phase output voltage and current of 5-level CHB inverter.

Since the VVVF method needs to be performed with an algorithmic approach by its nature, a digital implementation of the PWM technique is utilized in order to obtain the single-phase output voltage and current under VVVF control. Its single-phase outcomes are shown in Figure 3.7.

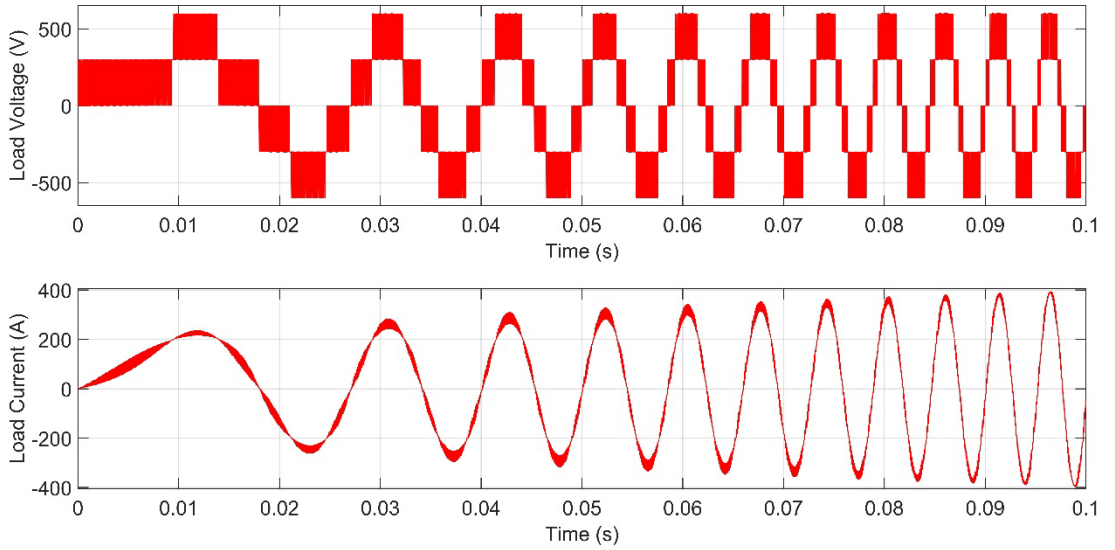


Figure 3.7: The single-phase output voltage and current under VVVF control.

In the waveforms of the single-phase version of the proposed conditioner, the output voltage has a five-level stepped configuration and the current is shaped as an almost-pure sinusoidal signal, which is a desired result in order to effectively drive an

asynchronous induction coil launcher. The analog implementation of the three-phase version of the proposed arrangement is also simulated and the phase-neutral and phase-phase voltage waveforms are demonstrated in Figure 3.8.

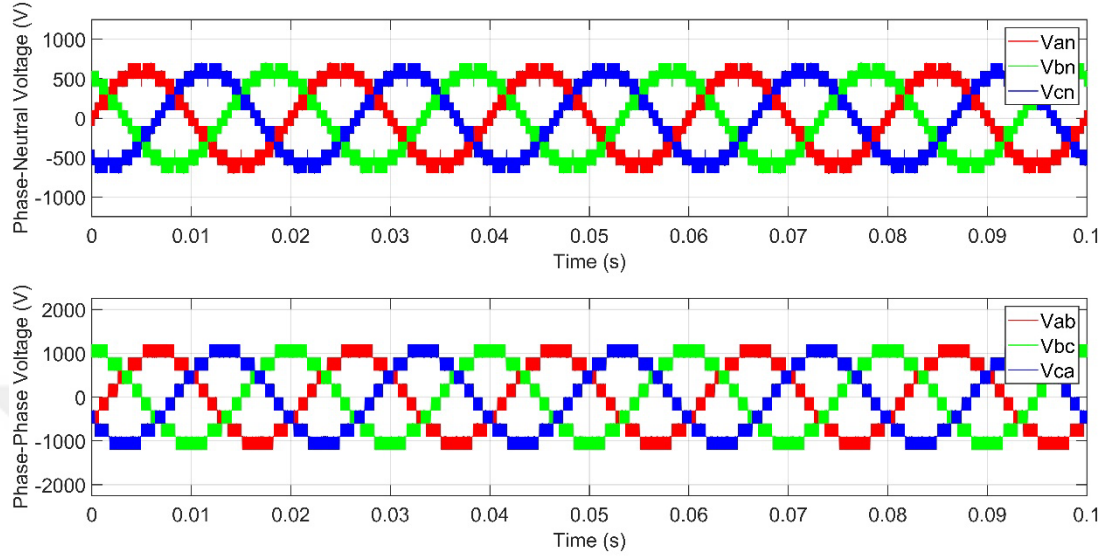


Figure 3.8: Three-phase output voltage waveforms.

The phase current waveforms of three-phase analog implementation are shown in Figure 3.9. The three-phase simulation results show that the current waveform is smoother than its single-phase counterpart. Furthermore, the step level of the voltage waveforms increased two-fold compared with the single-phase voltage output.

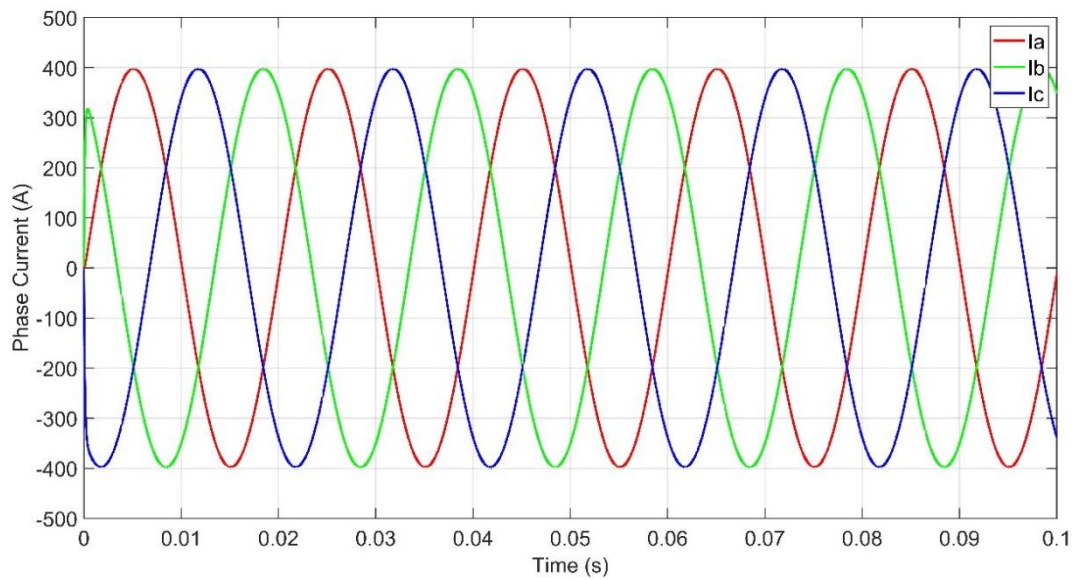


Figure 3.9: Three-phase output current waveforms.

A three-phase power conditioner simulation in PSIM with the digital implementation of PWM under VVVF control is performed as well. The phase-neutral and phase-phase voltage waveforms are illustrated in Figure 3.10 and the phase current waveforms are shown in Figure 3.11, respectively.

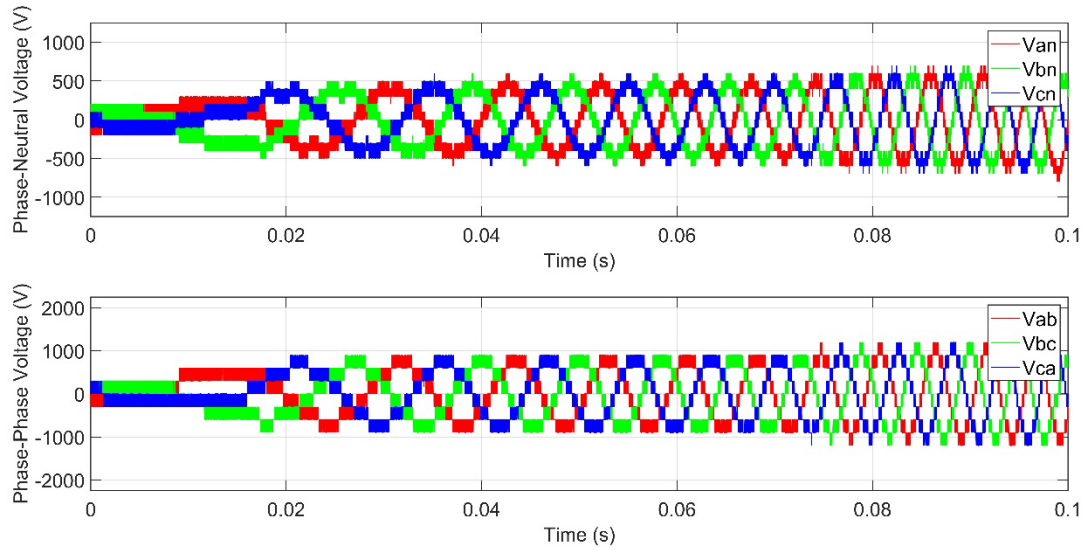


Figure 3.10: Three-phase output voltage waveforms under VVVF control.

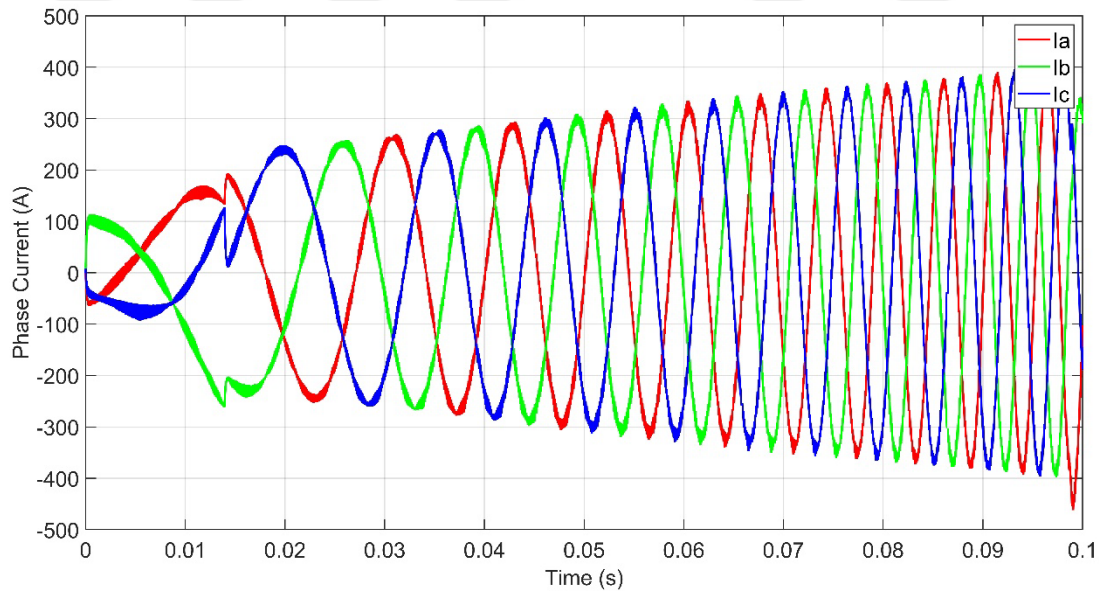


Figure 3.11: Three-phase output current waveforms under VVVF control.

In an electric machine, the air-gap flux is suggested not to become too large or too small because these two cases cause high torque ripple. Therefore, VVVF control

aims at maintaining the air-gap flux constant in an asynchronous induction coil launcher.

The application of VVVF control in industry is generally performed by manipulating frequency in proportion to the voltage of the power supply by using SVPWM in a closed-loop system. The results obtained in this study prove that VVVF control is applicable by using SPWM with an open-loop system as well. Since an asynchronous induction coil launcher is driven as load, the power supplies of each H-Bridge unit are DC sources. The RMS value and the frequency of the output voltage are regulated by changing m_a and m_f , respectively.

Total harmonic distortion (THD) is a waveform's distortion factor, which is defined as the ratio of the effective (rms) value of harmonic components to its counterpart of the fundamental component. In other words, THD is the degree of relatedness of the output waveform shape to its fundamental component. On the other hand, fast Fourier transform (FFT) is an algorithm that analyzes a distorted waveform to acquire its discrete sinusoids. Since an inverter deals with switching processes and their gate signals in order to generate an output waveform, it will be useful when examining THD and FFT concepts as well. Therefore, an FFT analysis of three-phase output voltages and current waveforms under VVVF control is carried out in PSIM and they are shown in Figure 3.12. The fundamental frequency for THD analysis is 50 Hz and the final calculated values of the phase-neutral voltage and phase current are, respectively, %13.38 and %15.28.

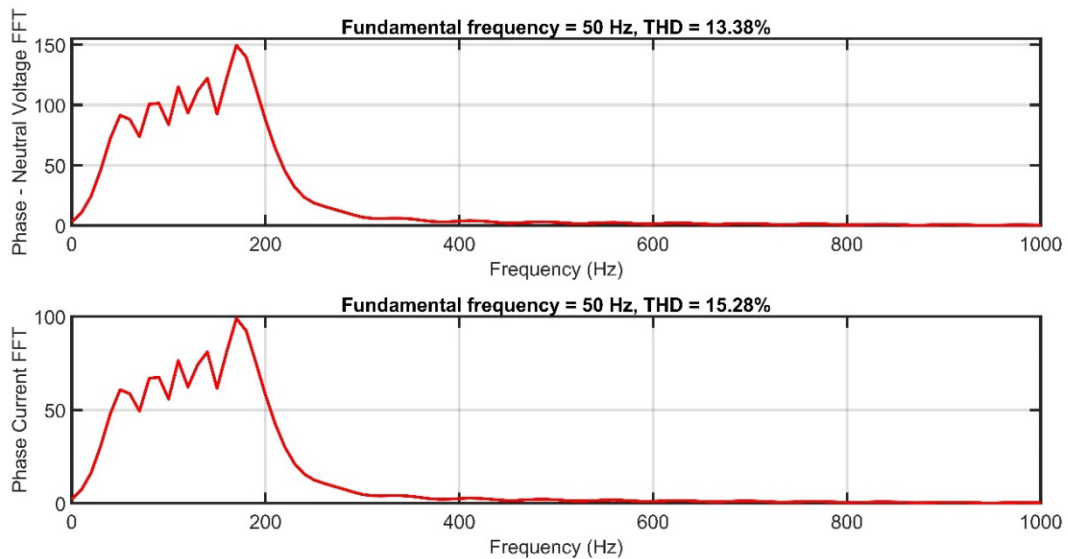


Figure 3.12: FFT analysis of 3-phase output voltage and current waveforms.

4. FEM ANALYSIS OF LINEAR INDUCTION LAUNCHER IN JMAG

In the previous chapter, the asynchronous induction coil launcher is assumed having a linear RL model during PSIM simulations. However, the dynamics of rotary or linear electric machines in practical applications are expressed by nonlinear mathematical expressions in which time dependent circuit components and parameters should be considered for transient analysis. Since the proposed AICL in this research operates in a time period which can be counted as transient, some of the simulation tools such as JMAG based on finite element (FEM) analysis needs to be used in order to include these considerations while its design process. AICL is represented by FEM coils in JMAG simulation as it is shown in Figure 4.1.

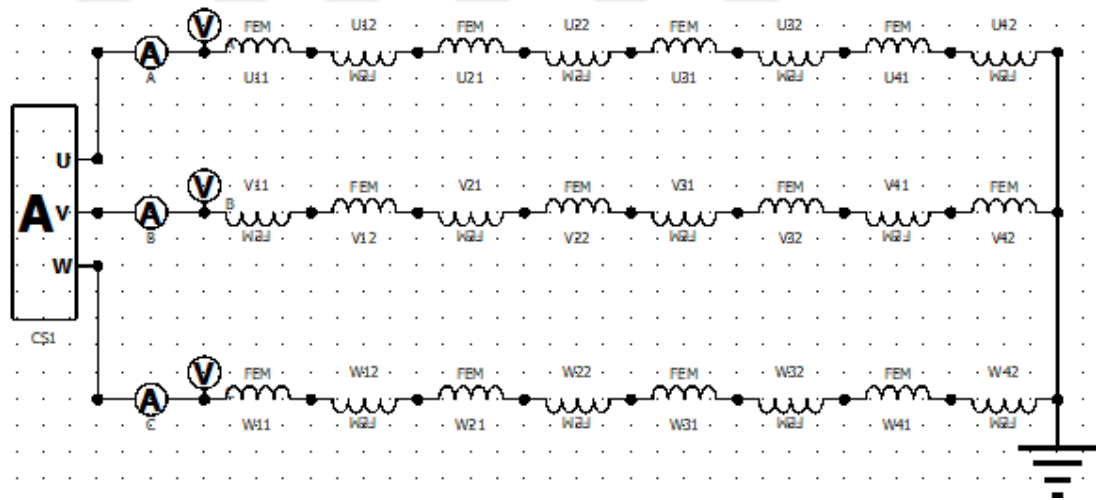


Figure 4.1: The FEM coils representation of AICL in JMAG.

They are grouped respectively as the U_{mn} , V_{mn} and W_{mn} in each phase to avoid consuming time to associate components one by one due to a lot of FEM coils in an electrical machine. JMAG presents a lot of options in order to develop geometry of machine models in the fulfilment process of the finite element calculations comprehensively. Some of the 3-D views of AICL designed in JMAG is depicted in Figure 4.2.

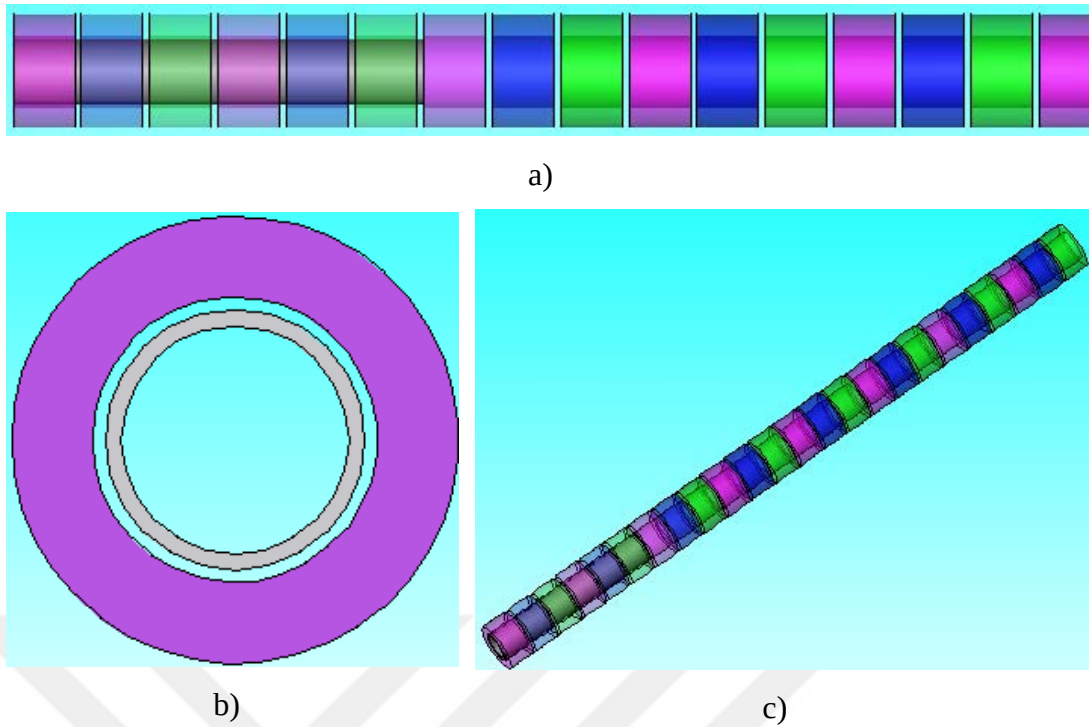


Figure 4.2: a) Longitudinal view of AIOL, b) Latitudinal view of AIOL, c) Diagonal view of AIOL in JMAG.

There are various modules available for transient and static states in JMAG such as magnetic field, electric field, transformer and thermal analysis which are modeled uniquely by optimal mesh generations. A few mesh model examples of the AIOL designed for this section is presented in Figure 4.3.

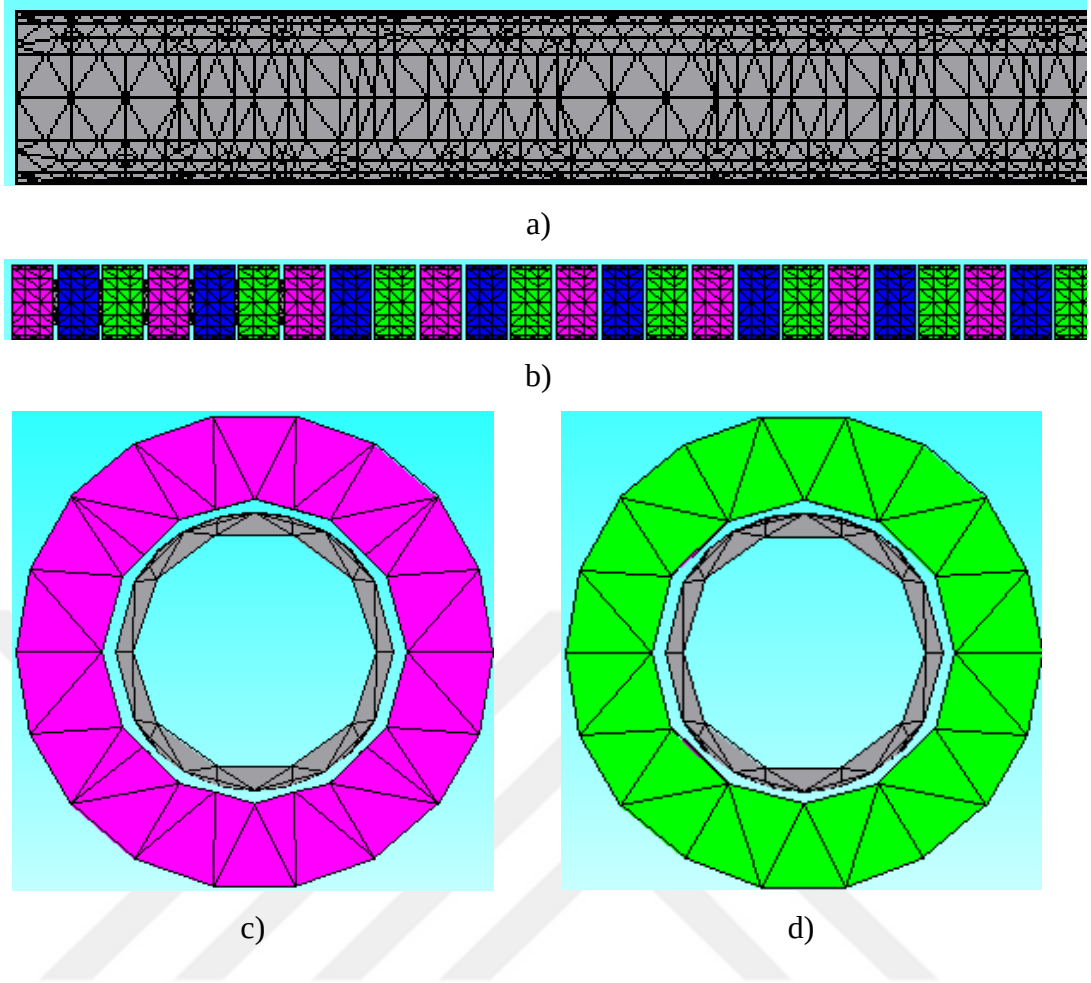


Figure 4.3: a) Mesh view of the projectile, b) Mesh view in each phase, c) Mesh view in a specific phase, d) Mesh view in another phase.

4.1. Constant Values of Voltage or Frequency Condition

The proposed asynchronous induction coil launcher is designed in JMAG for finite element analysis in order to acquire some outcome waveforms such as phase voltages, projectile velocity inside muzzle, the slip which is defined as the difference between AICL's synchronous and asynchronous speed, force generated by travelling wave on the projectile, and displacement. For this reason, a balanced three phase current is applied by increasing its magnitude and frequency discretely in order to analyze the effect of increase of voltage and frequency values on the operating characteristics. All the time units in this section are given in millisecond.

The provided graphs illustrate the temporal evolution of thrust forces produced by the launcher. These forces are generated by applying currents of different

amplitudes and frequencies to the suggested Finite Element Method (FEM) model. The velocity of projectiles in linear induction launchers is primarily influenced by two key factors. The parameters under discussion are the pole pitch length of the launcher and the frequency of the applied voltage. Once the launcher is completed, it will be unable of modifying the pole pitch length. However, it is possible to alter the speed at which the projectile is launched by controlling the frequency, which is the main goal of this thesis. The magnitude of the applied current has no effect on the velocity at which the projectile is expelled. Nevertheless, it does impact the duration required for the projectile to reach synchronous speed as a result of its influence on the magnetomotive force produced in the stator coils.

The figures 4.4 and 4.5 display the relationship between the applied frequency and amplitude of 500 Ampere on the stator coils, and the resulting voltage, force, projectile speed, and position information of the projectile over time. The frequencies tested were 100 Hz, 300 Hz, 500 Hz, 700 Hz, and 900 Hz. The graphs in Figure 4.4 depict the correlation between the force applied to the projectile and the frequency, while keeping the current constant at 500 amperes, and showing the associated voltage needed to achieve that current. Empirical evidence suggests that when the frequency increases, the voltage magnitude required to energize the stator coils must correspondingly rise in order to sustain a consistent current of 500 Amperes.

Moreover, as the projectile reaches the end of the launcher and starts to move away, a fluctuation in voltage is observed. The distortion occurs due to the end effect, where the magnetic field produced in the projectile and the magnetic flux generated in the launcher coils interact with each other. The ultimate consequence also results in a reduction in the applied force on the projectile and the presence of opposing forces acting on the projectile. Figure 4.6 illustrates that this behavior becomes more pronounced as the amplitude of the current passing through the stator coils increases. In order to mitigate the negative consequences of the end effect, it is crucial to immediately stop the flow of electric current in the stator as soon as the projectile starts to leave the launcher. The force imparted on the projectile is enhanced by raising the frequency while keeping a constant current of 500 amperes.

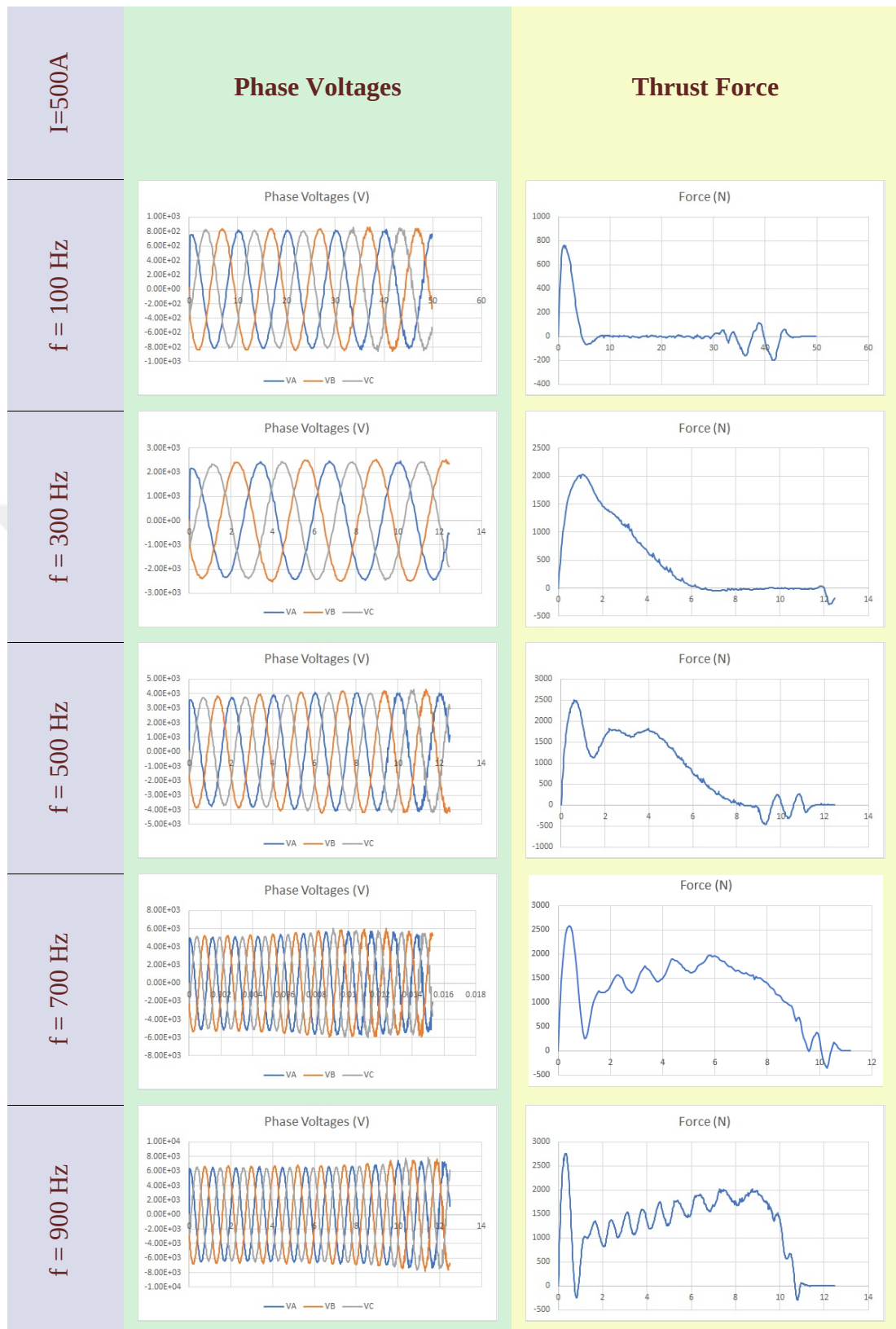


Figure 4.4: The phase voltages and thrust force under different frequency values.

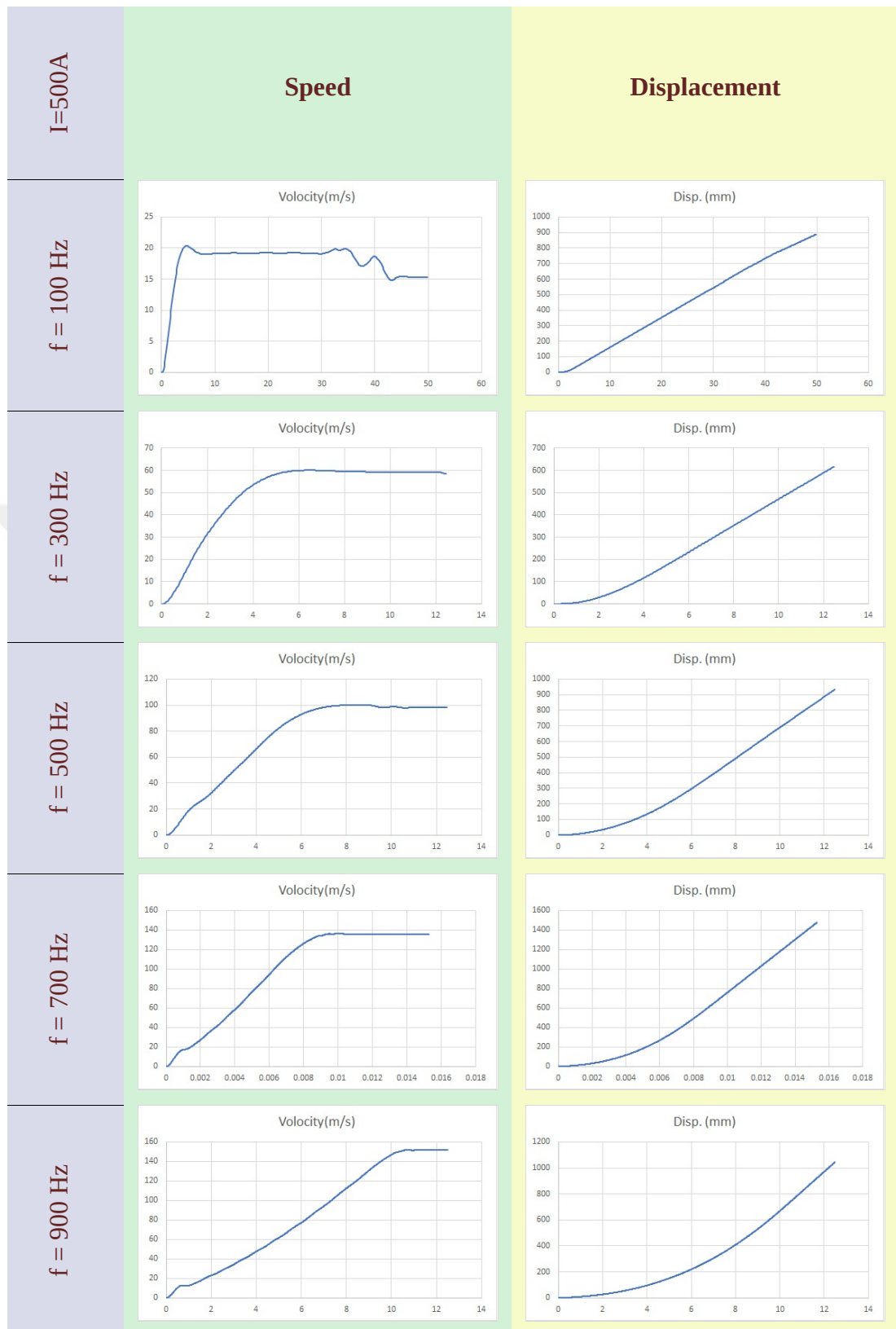


Figure 4.5: The speed and displacement under different frequency values.

Figure 4.5 illustrates that the velocity at which the projectile exits rises. At a current of 500 amperes and a frequency of 100 Hz, the projectile undergoes a maximum force of 764 Newton. This force is exerted for a period of 1,125 milliseconds (ms). The velocity of 20 m/s is attained in a duration of 4 ms, known as the synchronous speed. However, when exceeding this speed for a certain period of time, the applied force becomes overly powerful, leading to a decrease in the synchronous speed. As the projectile exits the barrel, its velocity decreases to 15 m/s due to the end effect. The maximum force of 2026 Newton is achieved at a frequency of 300 Hz, with a time period of 1.0833 ms.

The projectile achieves a velocity of 60 m/s within a time period of 6.1667 ms at a frequency of 300 Hz. Afterward, it continues to maintain a constant velocity until the projectile leaves the barrel. The maximum force of 2512 Newton is achieved at a frequency of 500 Hz, over a time frame of 0.6 ms. Similarly, the synchronous speed of 100 m/s is attained within 8 ms. The peak force of 2669 Newton was attained at a frequency of 700 Hz within a time interval of 0.4866 ms. Although reaching the synchronous speed of 140 m/s was not possible, a speed of 136 m/s was successfully attained at a time period of 9.6 ms. The velocity reached a peak of 2761 Newton in a time span of 0.333 ms, with a frequency of 900 Hz. However, it fell short of the target synchronous speed of 180 m/s. The velocity reached its maximum value of 151 m/s during a duration of 10.5 ms at a frequency of 900 Hertz. The synchronous speed was successfully reached at frequencies of 100 Hz, 300 Hz, and 500 Hz, but it was not possible to do it at 700 Hz and 900 Hz. This is because the launcher lacks adequate length.

Specifically, when the frequency is set to 900 Hz, the launcher has reached its furthest elongation prior to the completion of the projectile's acceleration. Another observed feature is that, even when having the same current value, the maximum force achieved rose in direct proportion to the frequency. In addition, the time required to generate the highest level of force decreases as the frequency increases. However, when the frequency grows, the force's fluctuation rate also escalates. At a frequency of 900 Hz, the force undergoes a sudden and significant rise, reaching its maximum value. However, it then experiences a swift decrease, briefly becomes negative, and then fluctuates. The varied force applied to the projectile has the potential to damage the electrical and mechanical components used for guidance within the projectile. Therefore, the fluctuation in the force applied to the projectile is an unfavorable

situation. An optimal frequency for a current value of 500 Ampere would be 300 Hz. As the projectile has reached synchronous speed, which is the maximum attainable speed at this frequency, and the force applied to the projectile has stayed consistent.

The force exerted on the projectile, its velocity and displacement, and the voltage profiles necessary to supply the necessary current to the coils are illustrated in Figures 4.6 and 4.7. The stator coils are energized at currents of 200 A, 400 A, 600 A, 800 A, and 1000 A at a constant frequency of 100 Hz. Given a frequency of 100 Hz, the maximum attainable speed of the projectile is 20 m/s, which is the synchronous speed. It is observed that varying current values have an impact on the magnitude of force exerted on the projectile and the time it takes to reach the maximum attainable force.

When a current of 200 A is applied, it achieves a peak force of 165 Newton in a time span of 2.75 milliseconds. The synchronous speed was achieved within a time frame of 36.25 milliseconds. Achieving a value of 532 Newton took 1.65 milliseconds at 400 A, while reaching synchronous speed took 6.625 milliseconds. When a current of 600 A was applied, the stator coils generated a force of 1029 Newton in 1.0 ms and achieved synchronous speed in 2.75 ms. Due to the strong force on the projectile, the synchronous speed was temporarily surpassed.

When the synchronous speed was surpassed, a counteracting force acted against the projectile, causing it to decelerate and return to the synchronous speed. The projectile once again achieved synchronous speed over a time span of 5 milliseconds, and it continued to proceed at this velocity inside the barrel. The maximum power value was rapidly attained at both 800 A and 1000 A, similar to the achievement of synchronous speed in a brief duration as observed at 600 A. Similarly, due to excessive force, the projectile speed surpassed the synchronous speed, resulting in an exceeding of the synchronous speed. The induction machine cannot operate at a speed higher than the synchronous speed without the application of an external force. Hence, the projectile experienced a negative force, causing its velocity to decrease to the synchronous speed. An important observation is that as the current value grows, the amplitude of the force fluctuation on the projectile also increases. This is caused by the end effect that occurs at the end of the barrel. At a coil current of 1000 A, the projectile speed reached synchronous speed due to the end effect. However, by the end of the barrel, the speed had reduced to 6 m/s. At a frequency of 100 Hz, it is seen that the ideal current value is 400 A. This ensures that the force on the projectile reaches synchronous speed promptly and without exceeding the desired limit.

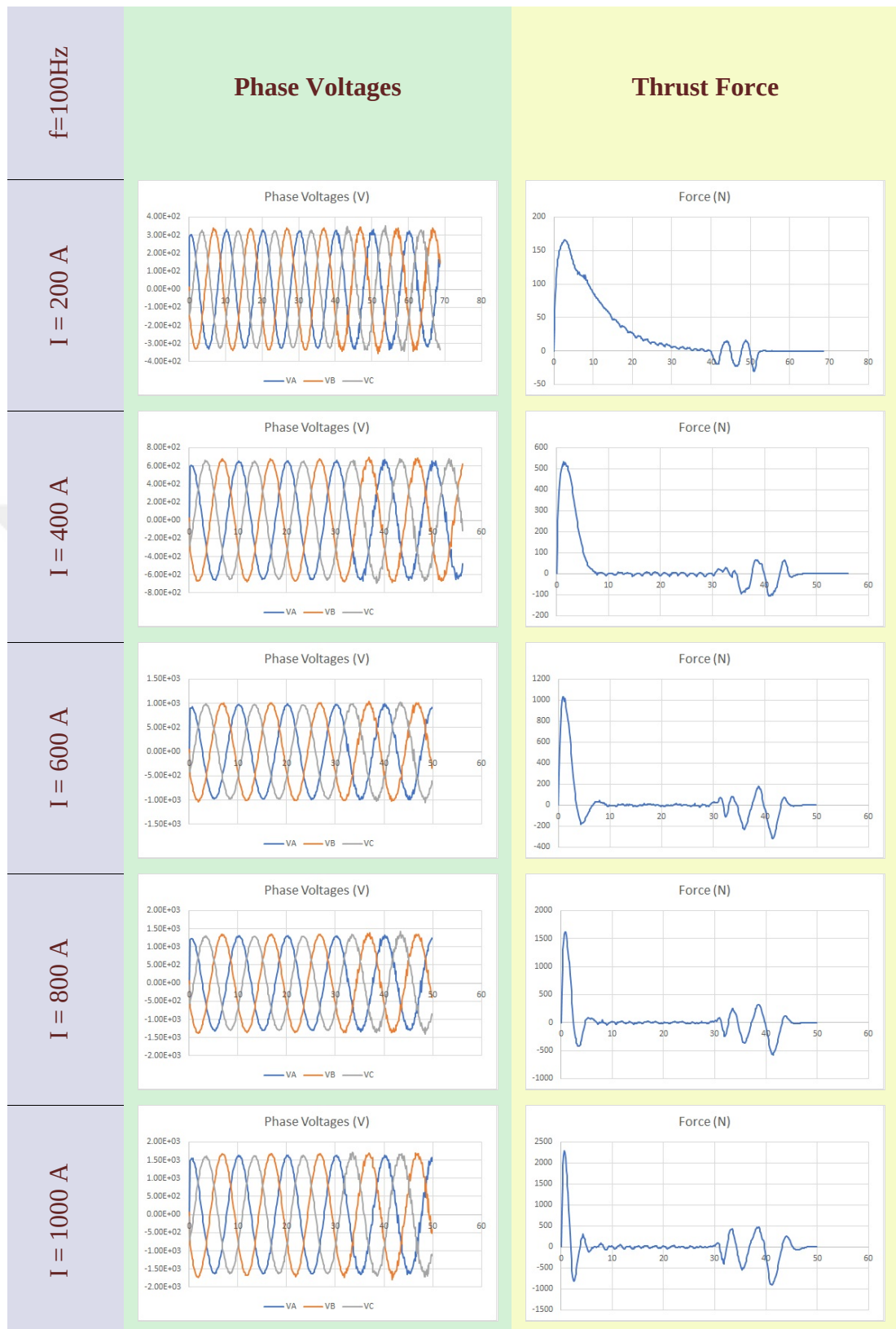


Figure 4.6: The phase voltages and thrust force under different voltage values.

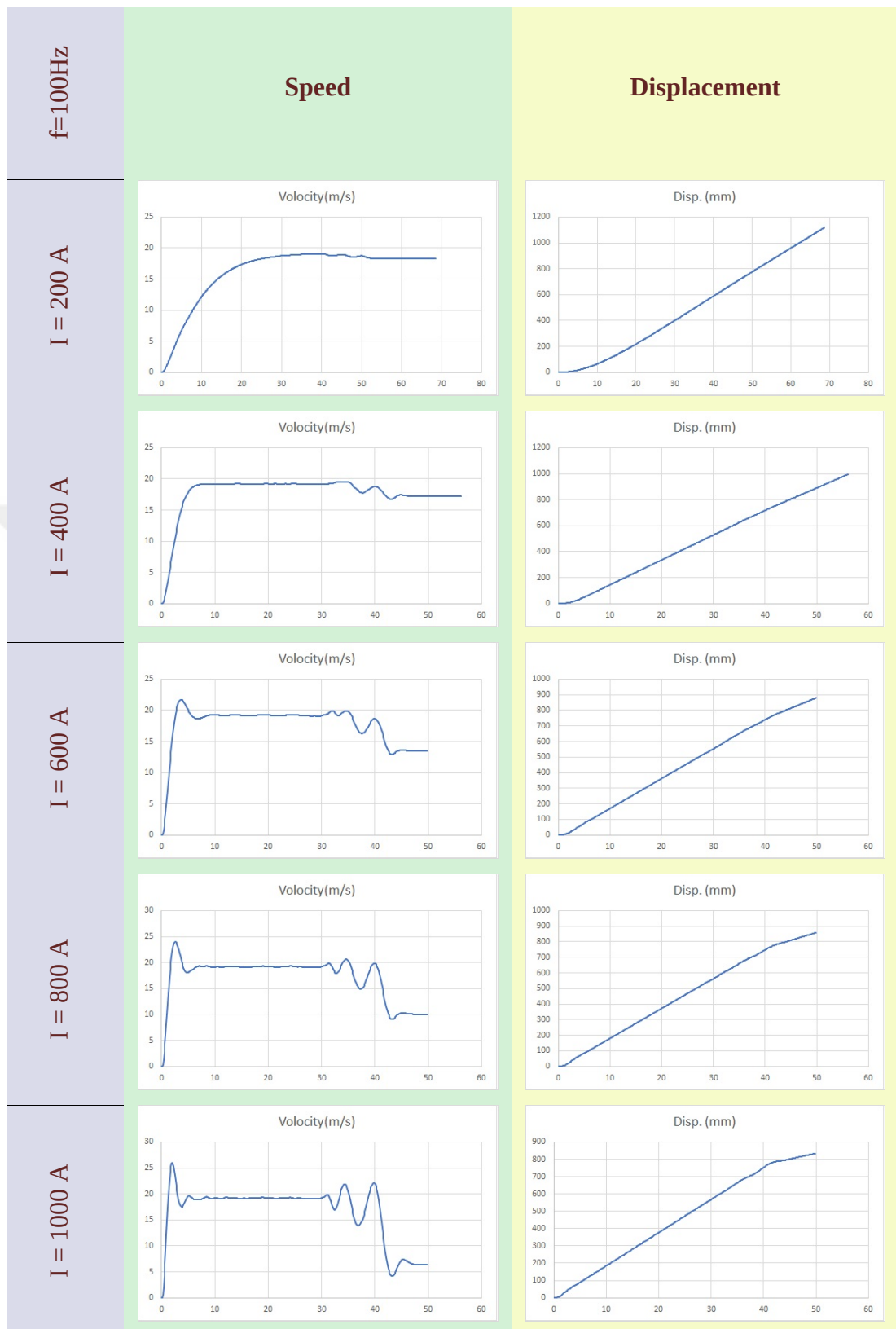


Figure 4.7: The speed and displacement under different voltage values.

4.2. Varying Values of Voltage or/and Frequency Condition

To achieve a consistent force in induction machines, it is necessary to maintain a constant magnetomotive force. In order to guarantee this, it is necessary to maintain a consistent magnitude of the current flowing through the stator coils. Linear induction launchers are machines that function in the transient regime. The object within the barrel is designed to undergo uniform acceleration. To ensure that the projectile experiences uniform acceleration, it is necessary for the force acting on the projectile to remain constant. As the projectile inside the barrel reaches synchronous speed, the discrepancy between its own speed and synchronous speed diminishes. Consequently, the voltage induced on the projectile reduces, leading to a decrease in the current flowing through it. The reduction in electrical current results in a corresponding decrease in the force exerted on the projectile.

As the velocity of the projectile rises, the synchronous speed must also be augmented. In order to accomplish this, it is necessary to augment the frequency of the electrical current that is supplied to the stator coils. To maintain a steady current amplitude and increase its frequency, the amplitude and frequency of the voltage source powering the stator coils need to be raised. The term used to refer to this procedure in the literature is Variable Voltage Variable Frequency (VVVF). The thesis explores the application of current to the simulated launcher using the VVVF method at different rates of frequency rise and subsequently analyzes the resulting impacts.

The rate of increase of the frequency must be related to the acceleration of the projectile. For this reason, situations at various frequency increases are evaluated.

$$f(t) = f_0 + \frac{\Delta f}{\Delta t} t \quad (4.1)$$

The equation 4.1 is used for the frequency increase rate. Here f_0 is the initial frequency, Δf is the frequency change with time and Δt is the time change.

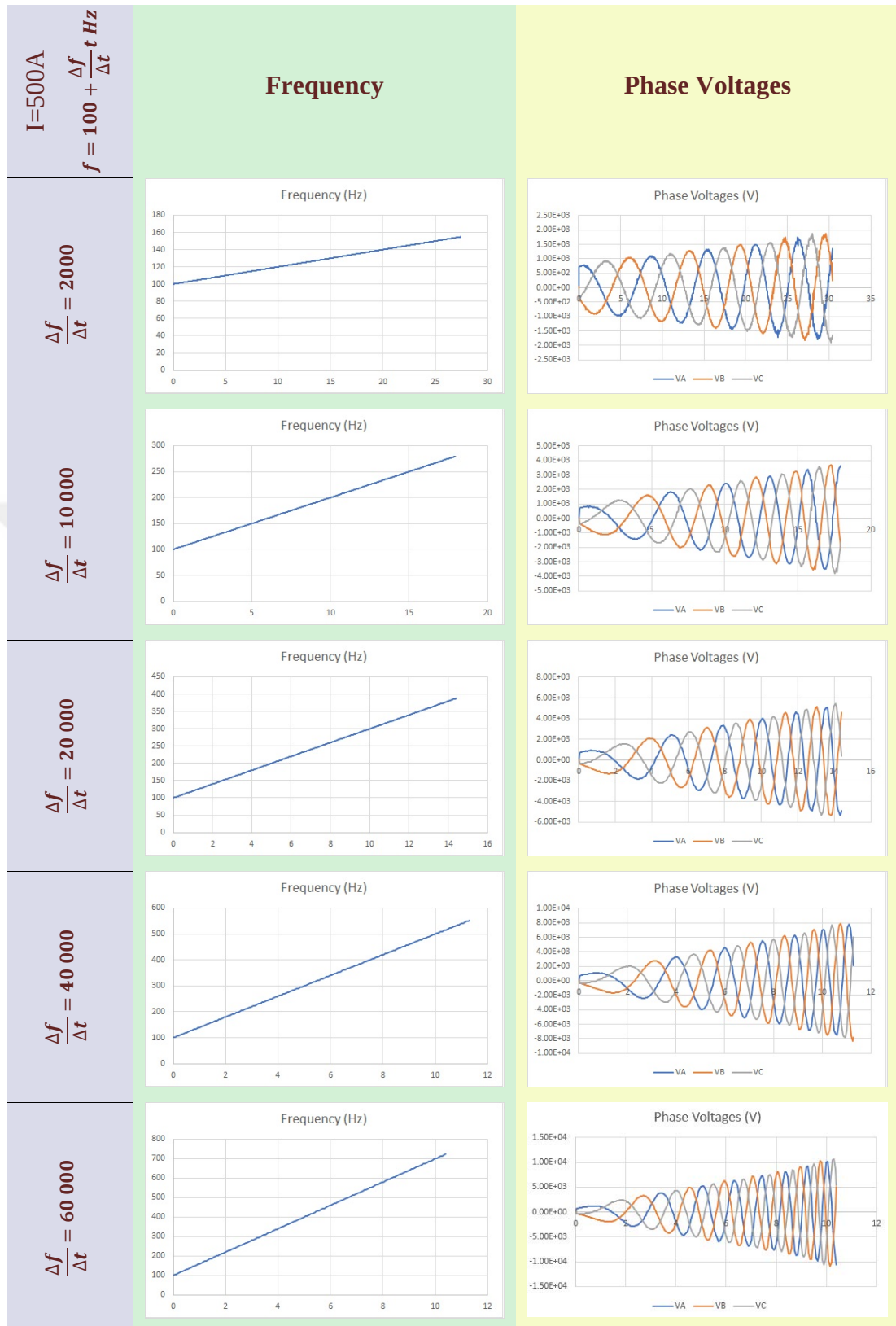


Figure 4.8: The frequency and phase voltages under constant current and varying frequency values.

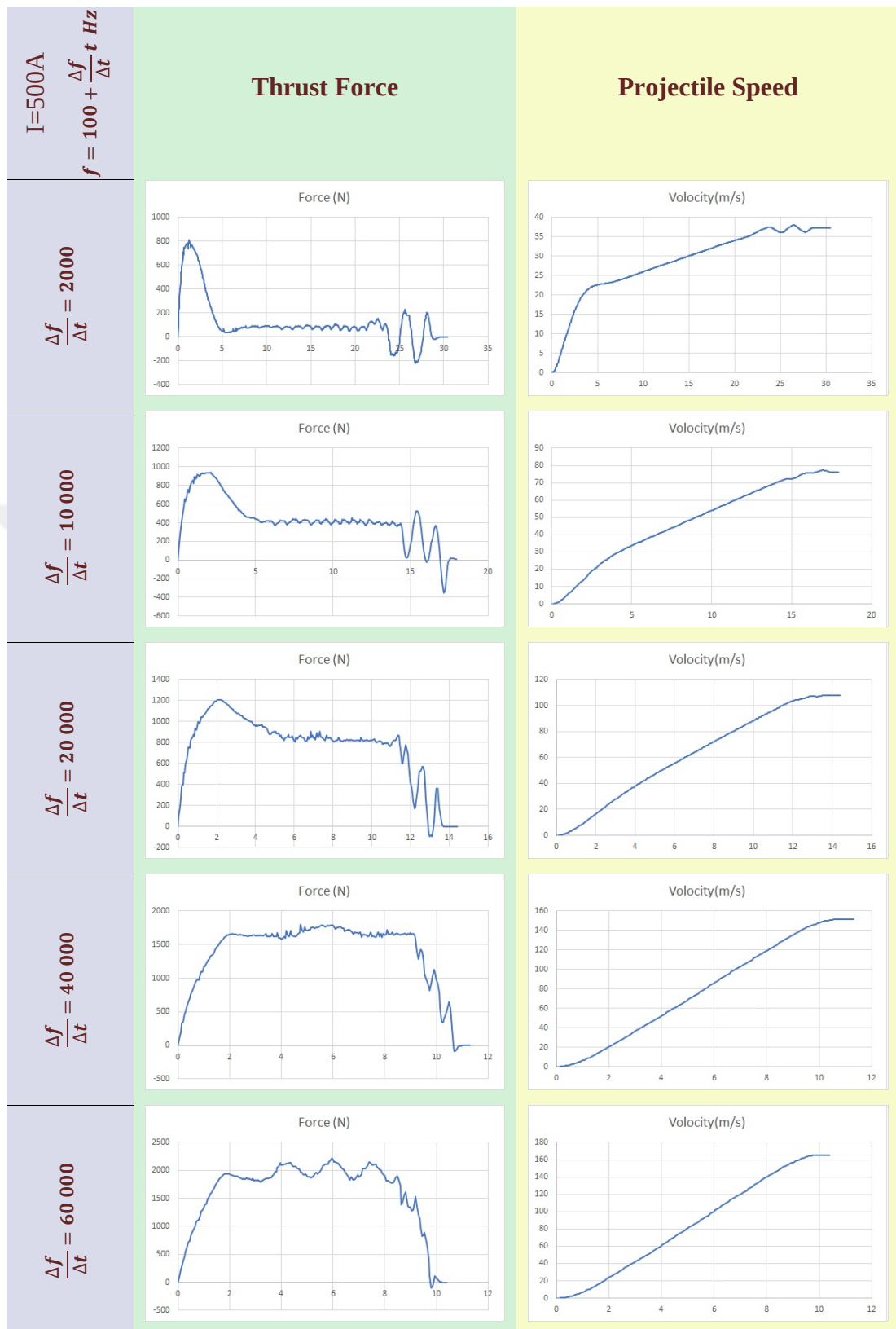


Figure 4.9: The force and speed of projectile under constant current and varying frequency values.

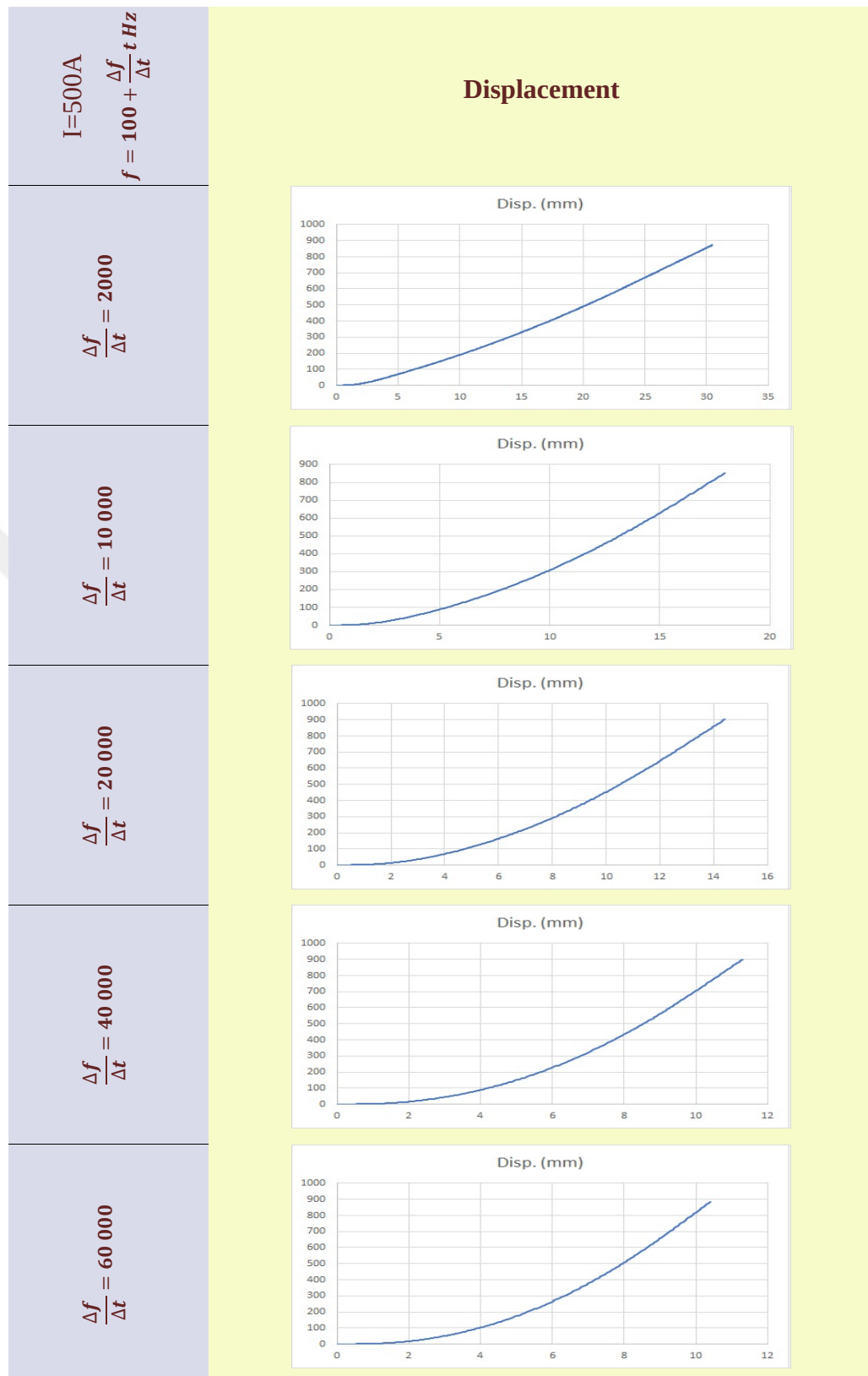


Figure 4.10: The displacement of projectile under constant current varying frequency values.

Figures 4.8, 4.9, and 4.10 illustrate the voltage that must be applied to the stator coils in order to allow the desired current to flow through them, the thrust force that develops in the projectile, and the speed and displacement graphs under the conditions where the current value in the stator coil is held constant at 500 A and the $\frac{\Delta f}{\Delta t}$ values are 2000, 10 000, 20 000, 40 000, and 60 000 respectively. The force exerted on the projectile achieves its maximum value of 811 Newton in 1.25 milliseconds when $\frac{\Delta f}{\Delta t}$ is equal to 2000, and then it gradually decreases to 60 Newton somewhere about 5 milliseconds later. Up until it reaches the end of the barrel, the projectile maintains a constant acceleration of around 60 Newton. In this scenario, the velocity of the projectile climbs to 38 meters per second as it exits the barrel.

The force exerted on the projectile reaches its highest value of 937 Newton in 1.95 milliseconds and then declines to 400 Newton in 5.4 milliseconds when the value of $\frac{\Delta f}{\Delta t}$ is set to 10 000. The force exerted on the projectile remains at this value until it reaches the end of the barrel. The projectile travels at a speed of 77 meters per second when it exits the muzzle of the gun. When the ratio $\frac{\Delta f}{\Delta t}$ is increased to 20 000, the force exerted on the projectile falls to 800 Newton somewhere around 6 milliseconds, after reaching its maximum value of 1208 Newton in only 2.15 milliseconds. The velocity of the projectile increases to 108 meters per second as it nears the end of the barrel.

The force exerted on the projectile reaches 1660 Newton in 2.1 milliseconds when the value of $\frac{\Delta f}{\Delta t}$ is set to 40 000. The force then oscillates around this value and remains constant up until the projectile hits the end of the barrel. At the very end of the barrel, the projectile travels at a speed of 151 meters per second. If $\frac{\Delta f}{\Delta t}$ is calculated to be 60 000, then the force exerted on the projectile will have increased to 1900 Newton in just 1.7 milliseconds. The force that is exerted on the projectile varies from 2211 Newton all the way down to 1718 Newton as it makes its way along the barrel. At the point as the projectile begins to emerge from the barrel, it has reached a speed of 165 meters per second.

When looking at the various frequency change rates, it is possible to say that the value of $\frac{\Delta f}{\Delta t}$ of 40 000 is the optimal value when the force on the projectile achieves its highest value and continues at that maximum value without fluctuating much while

the projectile is in the barrel. This occurs when the force on the projectile reaches its maximum value and continues at that maximum value without changing significantly



Figure 4.11: The output waveforms under varying current varying frequency values.

In Figure 4.11, not only the frequency but also the amplitude of the current applied to the stator coil is changed. The initial values of frequency and current were determined as 500 Amperes and 100 Hz, and the rates of change were determined as 100 000 and 200 000.

When the rate of change of frequency and current amplitude was determined as 100 000, the speed of the bullet at the end of the barrel was 268 m/s, but when it was 200 000, the bullet speed reached 377 m/s. Although the rate of change of frequency and current amplitude increased by 2 times, the bullet speed increased by approximately 1.4. When the rate of change was determined as 200 000, the impulse force on the bullet fluctuated more than in the other case. The frequency and amplitude change rates of the current should be selected so that the force fluctuation is minimum. In addition, since the amplitude of the current is also changed, it is clearly seen from the voltage graphs that the amplitude of the voltage that should be applied to the stator coils should be increased exponentially, not linearly. In this case, it will not be possible for the V/F ratio to remain constant.

5. ELECTROMECHANICAL MODEL OF AN AICL FOR TRANSIENT ANALYSIS

In order to make overall performance of a launcher better, the system should be designed by taking into account transient and steady-state models. While the former is preferred for evaluating design parameters of the machine and assisting in controller scheme, the latter is practiced for obtaining the rms values of voltage and current with the average power to calculate the consumption of total energy. In literature, the transient analysis of rotary induction machines and their drives have been studied sufficiently [77], [78]. However, there is a gap on studying numerical transient analysis of a whole asynchronous induction launcher system under power supply. In its transient model, electromagnetic force of projectile is analyzed and simulated in [79]. A transient model of linear induction machines is improved in [80], to make simulations more rapidly in an accurate form.

The reference frame theory, or direct-quadrature (DQ) transformation, is one of the methods used in the process of deriving transient model of the AC machines. This transformation has some superiority such as eliminating rotor position dependence on passive elements, rotating reference frames of AC waveforms to make them become DC quantities which simplify all calculations in development of equivalent circuit parameters, and aid in designing controllers for electrical machines. Also, adopting the DQ model in simulations make computations more efficiently than time-varying phasor models by enabling controller design and analysis of machine behavior to be implemented in the uniform environment. Therefore, the DQ models are applied for the AICL's transient analysis in this thesis. While deriving the transient model of the presented AICL in the previous sections of this thesis, it is benefited from the contents for the transient analysis of rotary electric machines as provided in the books of [81] and [82]. In addition, the created equations from the transient analysis are implemented in MATLAB based on the simulation method and Simulink models performed by Kapinski in [83].

Supply voltage is applied to all windings of the stator simultaneously for creating torque on the rotor in rotary electric machines. As a unique feature of linear electric machines, yet only the stator windings close to the rotor can be excited locally by requiring less voltage and current which minimize power consumption. Since the corresponding coils are interconnected in each phase of AICL's stator windings, its

transient model is very similar to an induction motor. However, its rotor model contains some differences from induction motor's, because it acts as a projectile which is not rotational but coaxial. One of the most important differences is that the rotor is designed and implemented as much shorter than the length of its stator. The others are absence of ferromagnetic material in its structure and its extremely short transit time in stator which is similar to the time constant of transient currents in whole system. This situation causes the DC components in current of stator coils by creating a large retarding force which may even stimulate acceleration of projectile in negative direction. Since all stator windings are excited at the same time and projectile is much shorter than barrel, some parts of stator should be residual while projectile pass through. Thus, the transient model of AICL's stator must contain these inactive parts which helps to minimize DC current offsets generated in coils.

5.1. Electromechanical Model of AICL

In this paper, the design of an AICL's electromechanical model in dq reference frame is mostly rooted in studies of transient analysis for rotary and linear electrical machines in literature. All the mathematical expressions are based on the theory of electromechanical energy conversion which is established by the electrical parameters, commonly the currents, and the replacement of a mechanical structure. Since energy transfer in electrical machines is carried out through magnetically connected circuits, it is also very important to arrange the equations explaining their behavior. Also, some of the inductances which are functions of the rotor position makes voltage equations complicated. Reference frame theory as changing variables to the quantities of dq model reduces that difficulty by eliminating the values of inductances depend on rotor position. The winding parameters of the proposed AICL configuration are determined for modeling transient analysis and its simulation in MATLAB as follow: two slots for each phase and pole, 105 turns for each slot, 200 mm pole pitch, poles are serial connected each other, and 2 poles adjacent to the projectile.

In the differential equations which represent electromechanical model of an electric machine, some of the coefficients have values which are depend on rotor position. The dq0 transform which is product of Clark and Park transforms used during the derivation of the dynamic model parameters in order to reduce the complexity of

position or time dependent quantities. The visually relationship and waveform differences between dq0, Clarke and Park transformations is schemed in Figure 5.1.

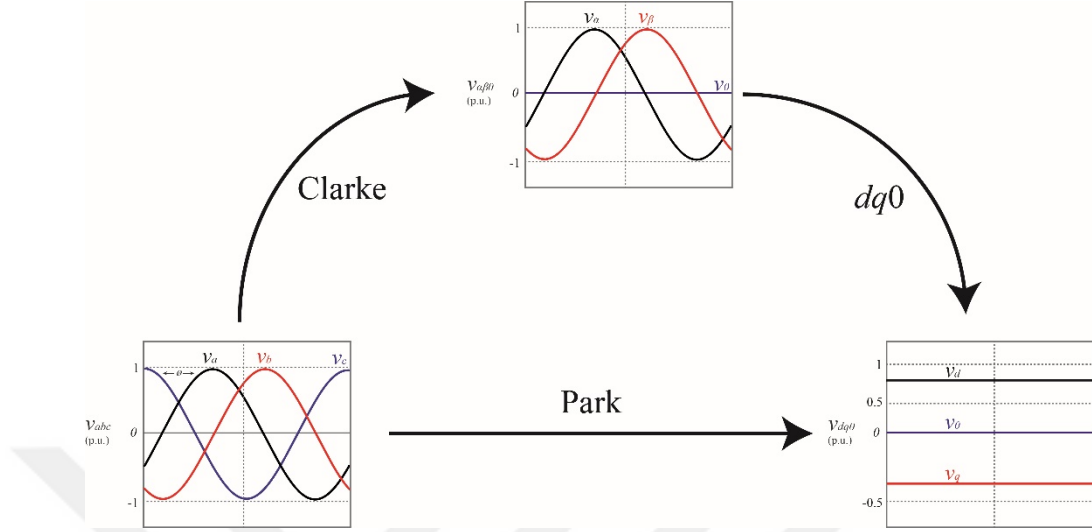


Figure 5.1: The visually relationship between transformations.

The transformation of three phase variables to the reference frame can be formulated in general form as following equation:

$$\mathbf{f}_{qd0} = \mathbf{K} \mathbf{f}_{abc} \quad (5.1)$$

where K is Park transformation matrix and expressed as:

$$\mathbf{K} = \frac{2}{3} \begin{bmatrix} \cos\theta & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ \sin\theta & \sin(\theta - \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \quad (5.2)$$

and the relation between angular position θ and frame velocity ω is given by:

$$\frac{d\theta}{dt} = \omega \quad (5.3)$$

in case the dq0 variables need to be transformed back into phase variables, the following inverse Park transformation is used:

$$K^{-1} = \begin{bmatrix} \cos\theta & \sin\theta & 1 \\ \cos(\theta - \frac{2\pi}{3}) & \sin(\theta - \frac{2\pi}{3}) & 1 \\ \cos(\theta + \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) & 1 \end{bmatrix} \quad (5.4)$$

In Equation 5.1, the variable f serves as one of the electrical circuit parameters such as voltage, current, flux linkage, or electric charge. Since elaboration on the transformation of circuit elements in abc frame into dq0 frame is widely available in literature, in this study the three-phase circuit variables are directly derived in dq0 frame to avoid repetition.

5.2. Expressions of the Electromagnetic Parameters

In electric machines, electrical circuits in relative motion are magnetically connected to its mechanical counterpart in order to achieve converting electrical energy. Each coil in the stator windings of the AICL yields its own flux which composed of two different elements as leakage and magnetizing components, shown in l and m subscripts respectively. Its lumped-parameter basic equivalent circuit model in dq0 frame with referred to the stator is shown in Figure 5.2.

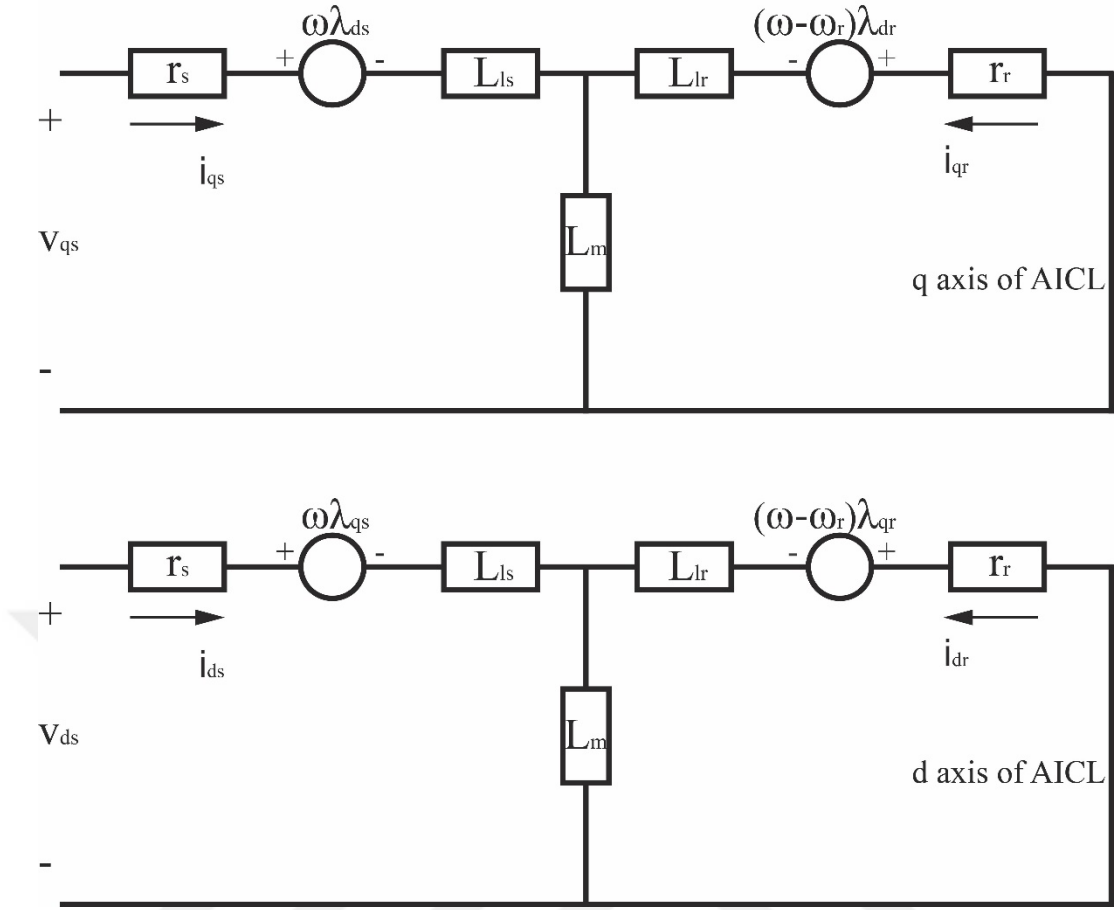


Figure 5.2: Equivalent circuit model in dq0 frame with referred to the stator.

The voltage, flux and current equations of stator in the equivalent and transformed DQ variables circuit of an AI CL become as follows:

$$v_{qs} = r_s i_{qs} + \omega \lambda_{ds} + \frac{d\lambda_{qs}}{dt} \quad (5.5)$$

$$v_{ds} = r_s i_{ds} + \omega \lambda_{qs} + \frac{d\lambda_{ds}}{dt} \quad (5.6)$$

$$\lambda_{qs} = L_{ls} i_{qs} + \frac{3}{2} L_m (i_{qs} + i_{qr}) \quad (5.7)$$

$$\lambda_{ds} = L_{ls} i_{ds} + \frac{3}{2} L_m (i_{ds} + i_{dr}) \quad (5.8)$$

$$i_{qs} = \frac{1}{L_{ls}} (\lambda_{qs} - \lambda_{mq}) \quad (5.9)$$

$$i_{ds} = \frac{1}{L_{ls}} (\lambda_{ds} - \lambda_{md}) \quad (5.10)$$

$$\frac{d\lambda_{qs}}{dt} = v_{qs} - r_s i_{qs} - \omega \lambda_{ds} \quad (5.11)$$

$$\frac{d\lambda_{ds}}{dt} = v_{ds} - r_s i_{ds} + \omega \lambda_{qs} \quad (5.12)$$

rotor voltage, flux and current equations become:

$$0 = r_r i_{qr} + (\omega - \omega_r) \lambda_{dr} + \frac{d\lambda_{qr}}{dt} \quad (5.13)$$

$$0 = r_r i_{dr} - (\omega - \omega_r) \lambda_{qr} + \frac{d\lambda_{dr}}{dt} \quad (5.14)$$

$$\lambda_{qr} = L_{lr} i_{qr} + \frac{3}{2} L_m (i_{qs} + i_{qr}) \quad (5.15)$$

$$\lambda_{dr} = L_{lr} i_{dr} + \frac{3}{2} L_m (i_{ds} + i_{dr}) \quad (5.16)$$

$$i_{qr} = \frac{1}{L_{lr}} (\lambda_{qr} - \lambda_{mq}) \quad (5.17)$$

$$i_{dr} = \frac{1}{L_{lr}} (\lambda_{dr} - \lambda_{md}) \quad (5.18)$$

$$\frac{d\lambda_{qr}}{dt} = -(\omega - \omega_r) \lambda_{dr} - r_r i_{qr} \quad (5.19)$$

$$\frac{d\lambda_{dr}}{dt} = (\omega - \omega_r) \lambda_{qr} - r_r i_{dr} \quad (5.20)$$

$$\omega_r = \frac{\pi P}{2\tau} \frac{dx}{dt} \quad (5.21)$$

The abbreviations in the equations above are referred as following: flux linkages to λ , voltages to v , resistances to r , and inductances to L . The subscripts q , d , and 0 are associated with the axes of quadrature, direct and zero. Also, ω is electrical frequency, ω_r is angular frequency of rotor, P is number of poles of machine, and τ is pole pitch.

5.3. Expressions of the Electromechanical Parameters

Since an electromechanical system includes mechanical system, the linear force equations need to be derived too. The most important phenomenon for this derivation

is defining the instantaneous energy stored in the coupling field as W_f . The linear force effective on the projectile is stated as:

$$F_e = \frac{dW_f}{dx} = \frac{3\pi P}{4\tau} (\lambda_{ds} i_{qs} - \lambda_{qs} i_{ds}) \quad (5.22)$$

Since the rotor is an aluminum projectile, the mechanical model of the load can be considered as passive load associated only with mass and damping effects. The force on projectile which has linear direction is defined by summing those effects as follow:

$$\vec{F} = m\ddot{x} + B\dot{x} \quad (5.23)$$

The abbreviations of m and B are defined respectively as mass of projectile and viscous friction coefficient of machine. In order to simulate linear mechanical load in SIMULINK, the state-space form of Equation 6.15 is needed to state clearly as follow:

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & -\frac{B}{m} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ -\frac{1}{m} \end{bmatrix} F_e \quad (5.24)$$

This state-space representation of the linear load equation is necessary not only for convenience in simulation, but also because it includes components caused by the disruptive forces and harmonics generated in machine slots.

5.4. Simulation Process

The dynamic model of an AICL is formed by the equations of electromagnetic parameters between equations 5.5 – 5.12, and electromechanical parameters between equations 5.14 and 5.16 in previous section. In this section, this model is simulated in Simulink which is a MATLAB-based graphical programming environment for dynamic analysis of systems. Firstly, the reference frame transformation model from

abc phase variables to their dq counterparts via Clarke transformation is performed in Simulink as shown in Figure 5.3.

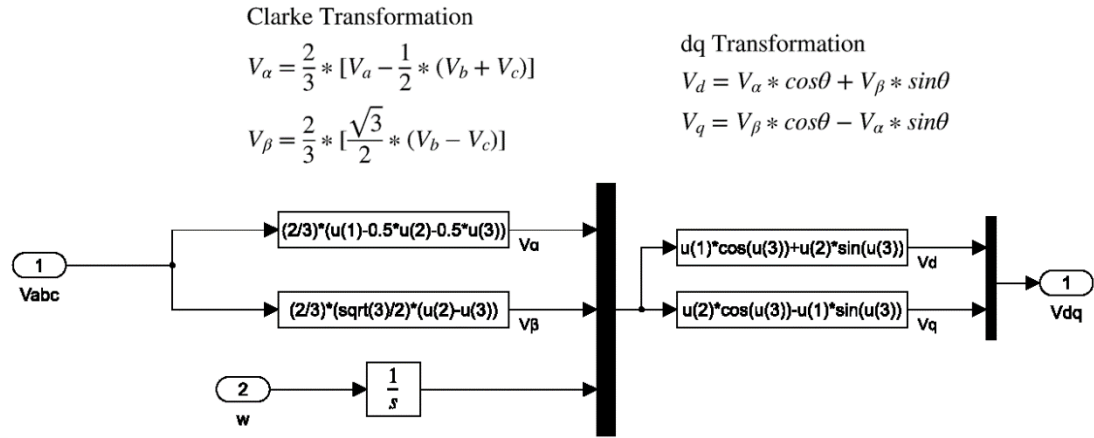


Figure 5.3: The reference frame transformation in Simulink.

The current and flux equations of the stator are designed in Simulink as shown in Figure 5.4 and 5.5 respectively. Equations 5.9 and 5.10 are used for stator current model, while equations 5.11 and 5.12 form the stator flux model.

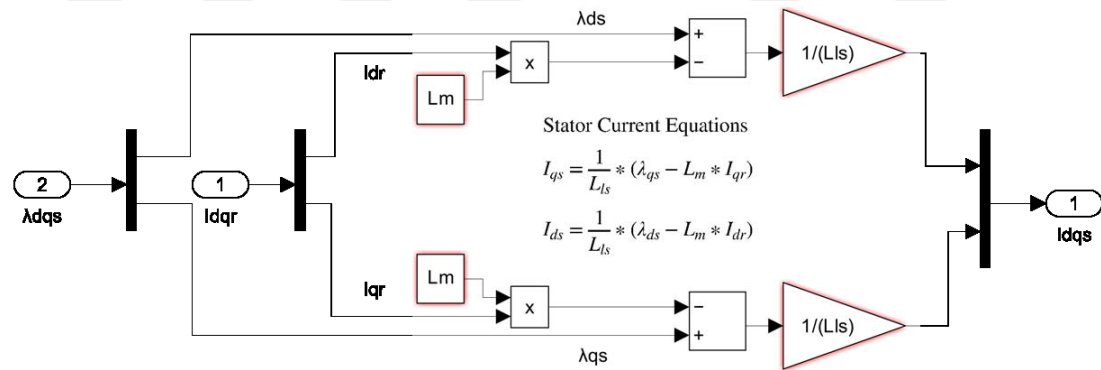


Figure 5.4: Simulink model of stator current equations

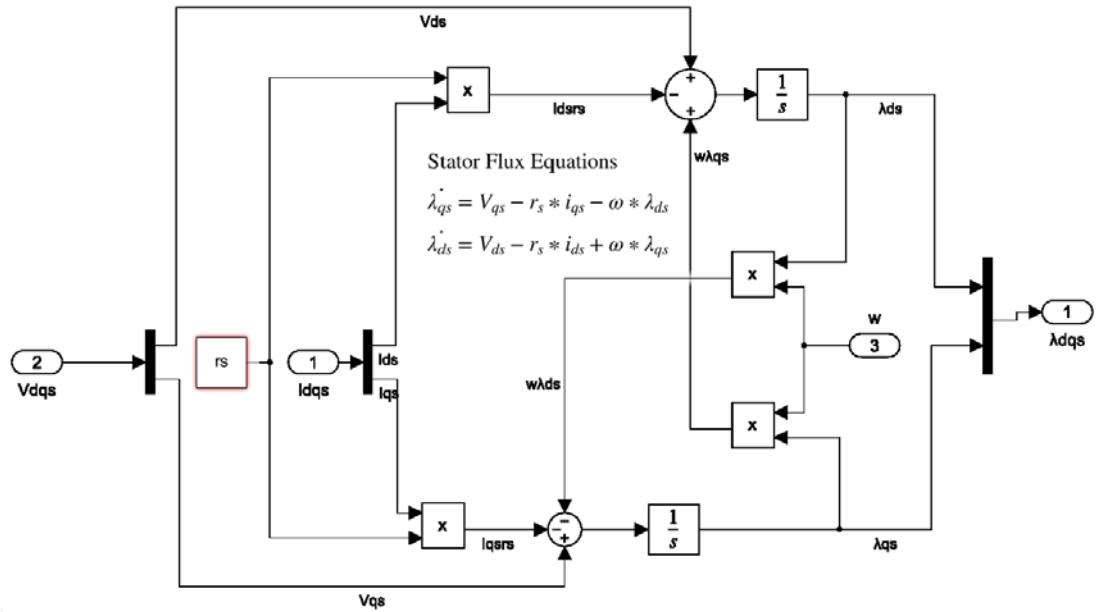


Figure 5.5: Simulink model of stator flux equations.

The current and flux equations of rotor (projectile) are modeled in Simulink as shown in Figure 5. 6 and 5.7 respectively. Equations 5.17 and 5.18 are employed for the current of rotor in model, while equations 5.19 and 5.20 construct the rotor flux model.

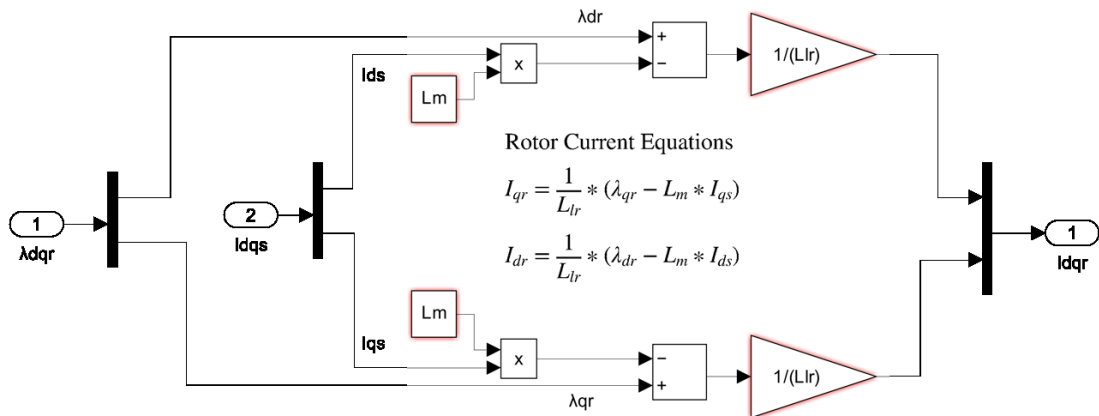


Figure 5.6: Simulink model of rotor current equations.

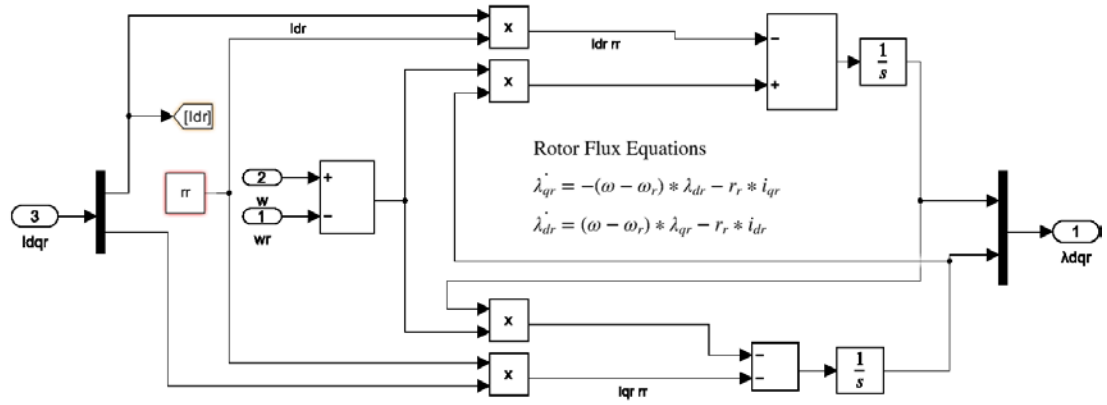


Figure 5.7: Simulink model of rotor flux equations.

The linear force F_e is modeled in Simulink based on Equation 5.22 as illustrated in Figure 5.8.

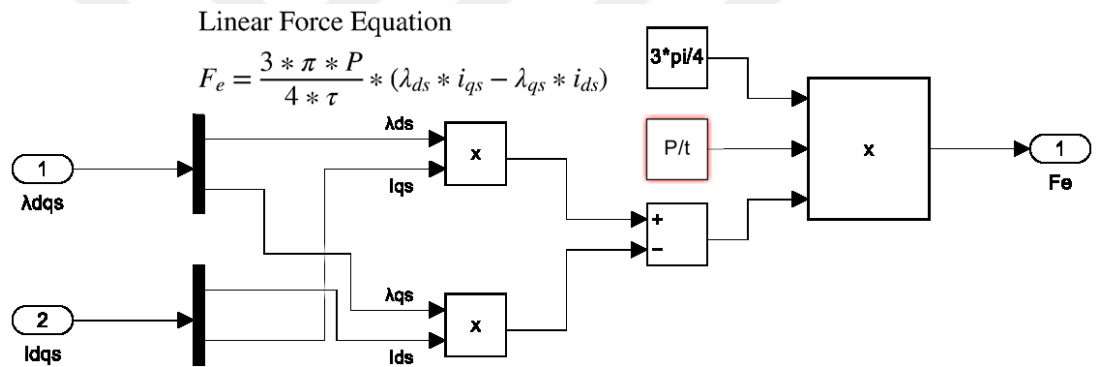


Figure 5.8: Simulink model of linear force equations.

The linear mechanical load system which is stated in Equation 5.24 is modeled in Simulink as depicted in Figure 5.9.

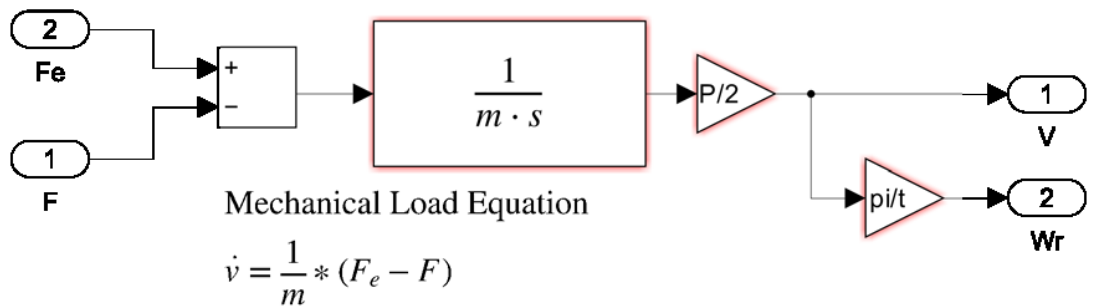


Figure 5.9: Simulink model of mechanical load equation.

The scheme of the all sub-systems which are connected with corresponding models is depicted in Figure 5.10.

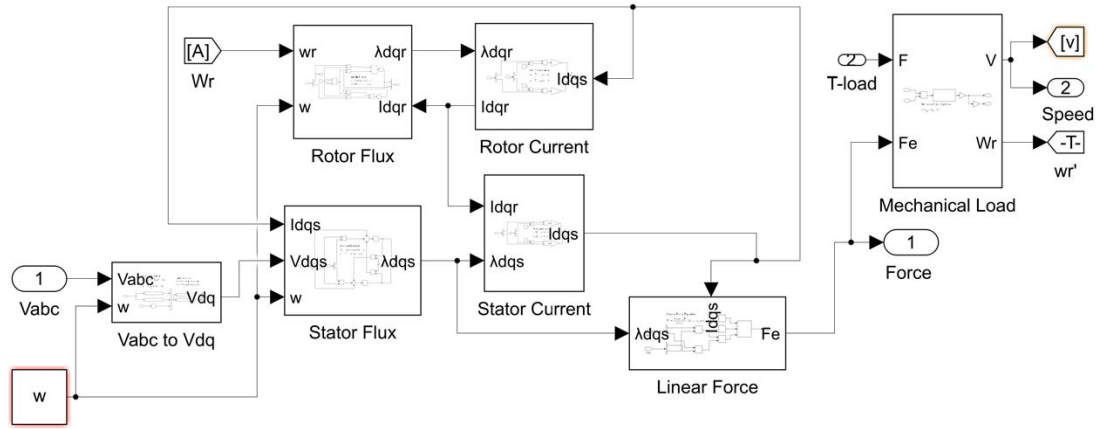


Figure 5.10: The scheme of the all sub-systems are connected in relevance.

Finally, the simulation is completed by adding AICL model as a whole system as schemed in Figure 5.11, with scopes and displays in order to obtain desired output waveforms such as force and speed. All variables are entered easily via one of the great properties of Simulink called as Model Callback Initialization Parameters Function.

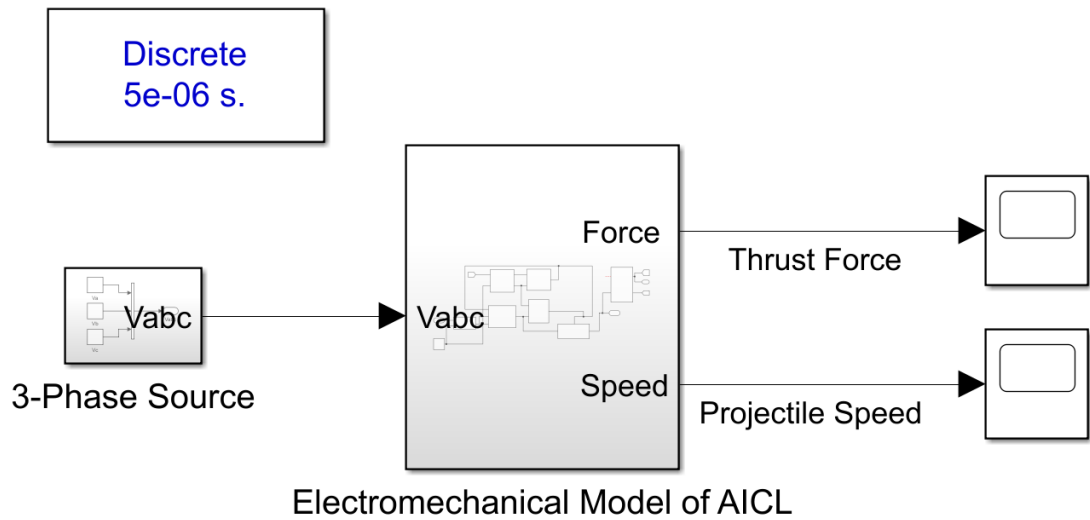


Figure 5.11: The Simulink model of whole system with scopes and displays.

5.5. Simulink Model Verification and Outcomes

At this stage, the transient electromechanical model of proposed asynchronous induction coil launcher is derived mathematically and executed in Simulink, without considering end effect which appears due to inactive coils in stator while projectile pass through. The parameters of the launcher Simulink model presented in Table 5.1 are obtained by reviewing similar machine transient analysis researches in literature.

Table 5.1: The launcher parameters for Simulink model.

Parameter Name	Abbreviation	Value
Synchronous Frequency	ω	$2*\pi*(100 \sim 1000 \text{ Hz}) \text{ rad/s}$
Line to Neutral Voltage	Vabc	170V ~ 1700V
Number of Phases	ph	3
Number of Poles	P	2
Number of Turns per Slot	Ns	105
Pole Pitch Measurement	τ	0.2 m
Stator Resistance	rs	1.4 Ω
Stator Leakage Inductance	Lls	0.0027 H
Rotor Resistance	rr	0.1 Ω
Rotor Leakage Inductance	Llr	0.000026 H
Magnetizing Inductance	Lm	0.0032 H
Mass of Projectile	m	0.113 kg

The parameters for asynchronous induction coil launcher are applied in Simulink model. Thrust force waveforms in frequency value of 100 Hz for some of the current values between 100A and 1000A are obtained as illustrated in Figure 5.12. The waveforms from JMAG are also included for visual comparison purpose.

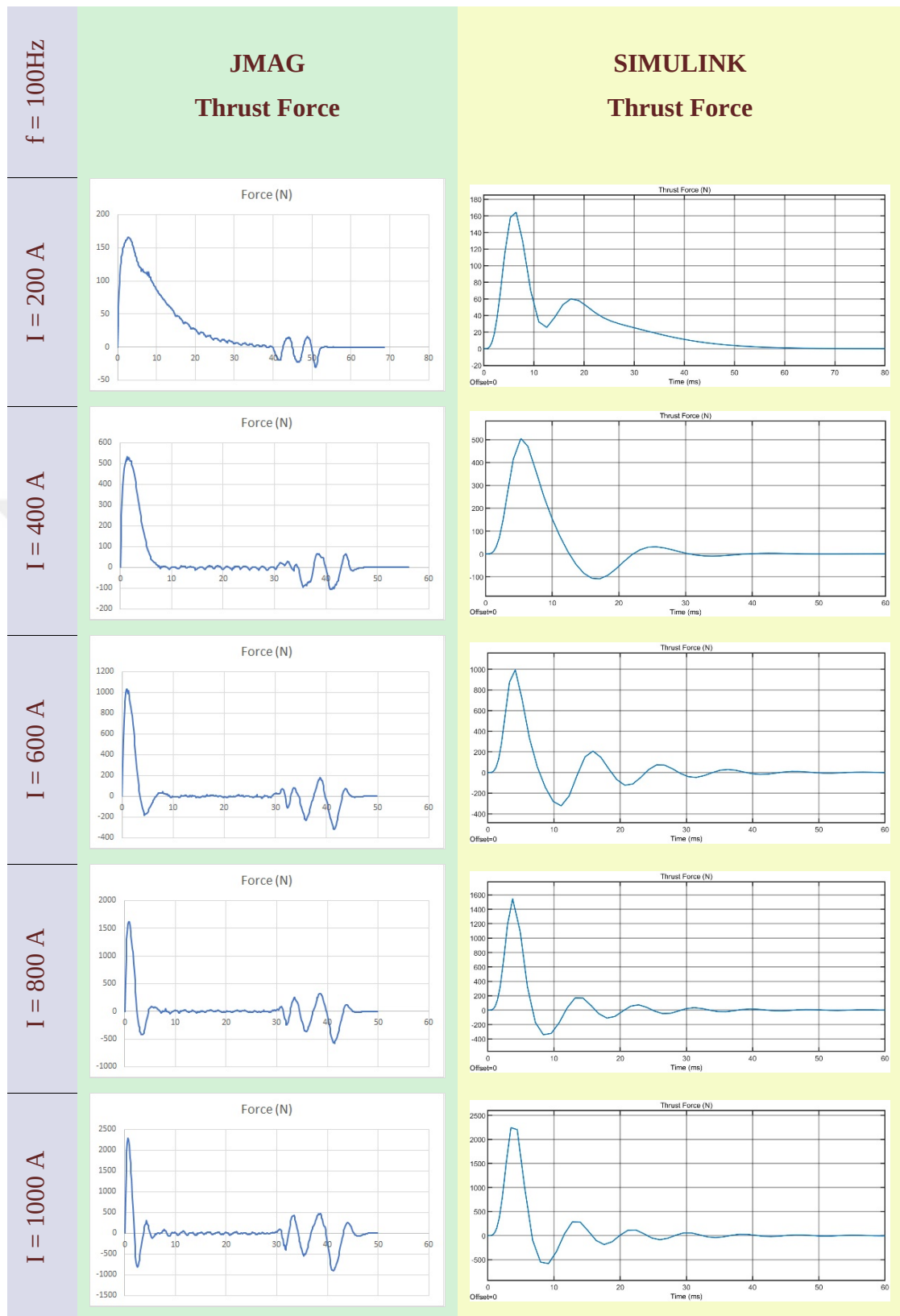


Figure 5.12: Thrust force waveforms, for 100 Hz between 100A and 1000A, obtained from JMAG and Simulink model.

The percentage error rates of the peak and average values between the outcome waveforms presented in Figure 5.12 are shown in the Table 5.2 below. Since the end effect of the AICL is not taken into account in Simulink model design, the average values in this section are calculated based on this fact by limiting JMAG outcomes to that value.

Table 5.2: The percentage error rates between peak and average values of thrust force waveforms in Figure 5.12.

f = 100 Hz	The Peak Value	The Average Value
Current	Error Rate (%)	Error Rate (%)
100A	0.20	10.71
200A	3.62	5.35
300A	2.42	5.94
400A	0.75	3.49
500A	0.11	4.12
600A	2.04	5.47
700A	0.69	2.56
800A	0.50	3.89
900A	1.03	1.22
1000A	0.17	1.01

Similar outcome waveforms are obtained for the current value of 500A between some of the frequency values between 100 Hz and 900 Hz in Figure 5.13 as well.



Figure 5.13: Thrust force waveforms, for 500A between 100 Hz and 900 Hz, obtained from JMAG and Simulink model.

The percentage error rates of the peak and average values between the outcome waveforms presented in Figure 5.13 are shown in the Table 5.3.

Table 5.3: The percentage error rates between peak and average values of thrust force waveforms in Figure 5.13.

I = 500 A	The Peak Value	The Average Value
Frequency	Error Rate (%)	Error Rate (%)
100 Hz	0.11	4.12
200 Hz	1.40	1.64
300 Hz	2.81	1.06
400 Hz	1.92	1.23
500 Hz	1.51	4.26
600 Hz	1.83	21.27
700 Hz	5.79	12.10
800 Hz	1.58	40.52
900 Hz	0.98	33.00
1000 Hz	0.97	16.83

As it can be seen from the Table 5.2 and 5.3 above, the error rates are in an acceptable range even without including end effect. Hence, Simulink model of the proposed asynchronous induction launcher in this thesis is verified successfully by comparing its outcome waveforms with the ones obtained in JMAG simulation in Section 4.

6. CONCLUSIONS

While many advances have been achieved in power-electronics applications over the past 30 years, it has not been applied much in linear induction launchers whose structures theoretically resemble asynchronous motors. The main objective of the research conducted in this thesis is to present a brief review of the driving technologies of AICL, propose a novel power-conditioner design for its three-phase model, and the effects of variable frequency power sources on its characteristics. The proposed power conditioner in this study is built up with a five-level cascaded H-Bridge multilevel topology in PSIM. Scalar level-shift multi-carrier PWM technique with VVVF control, which is the fundamental novelty and innovation, is preferred for the modulation of inverter topology because it is much more straightforward and less costly than the space vector PWM method.

In PSIM simulations, the proposed conditioner is applied to the launcher which is represented by a linear RL load, however it behaves as having nonlinear mathematical characteristics in its practical implementations. In order to understand the effect of AICL's nonlinear dynamics on the output waveforms, hence, its FEM analysis is performed in JMAG fed by variable frequency sources. In addition, electromechanical transient model of AICL is improved by using numerical methods. For its transient analysis, this model is applied in Simulink too and the outcomes have proved its accuracy which are consistent with the ones obtained from JMAG.

Similar researches conducted without power-electronics converters in literature show that when the output voltage and current waveforms converge sine form, projectile speed and thrust force become smoother, the thrust ripple decreases, and overall performance of machine increases. Indeed, the simulation outcomes obtained in this thesis affirm that the results of similar researches in literature. The single- and three-phase output voltage waveforms of proposed conditioner exhibit multilevel stepped structures. Furthermore, the current waveforms are formed in pure sinusoidal shapes, even without any filters used. Also, varying frequency power sources are applied to a whole AICL in JMAG. Finally, its transient model is derived mathematically by designing in Simulink. It proves that all outcome waveforms and results obtained in this thesis are consistent with each other and similar researches in literature.

7. FUTURE WORKS

Due to lack of time for experimental studies during this thesis process, the power conditioner proposed in this paper can be implemented in an experimental setup by future researchers in this area. As switching devices, IGBTs can be preferred when using a multilevel cascaded H-Bridge inverter topology. Additionally, DC capacitor banks can be included as DC sources to the input of inverter. Similarly, VVVF control can be applied during experimental realization based on the algorithm in this study to obtain some of the measurements, such as the temperature increase of launcher, thrust force, thrust ripples and the projectile speed waveforms.

Some other researches can be conducted in future based on this thesis such as an integration of JMAG finite element analysis model of asynchronous induction launcher to PSIM platform. The model can be connected as load via the MagCoupler module of PSIM in very close accuracy of its real time practical implementation. Also, due to its much faster nature than FEA model, the electromechanical transient Simulink model of AICL can be used in the researches for timesaving applications. Moreover, Simulink model of asynchronous induction coil launcher can be connected as load in PSIM via SimCoupler module.

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BIOGRAPHY

Feyzullah Gulpinar received the B.S. degree in electrical and electronics engineering department of Ondokuz Mayıs University, Samsun, Türkiye, in 2010 and the M.S. degree in electrical and computer engineering department of Purdue School of Engineering & Technology in 2014. He is currently studying in Ph.D. program of electronics engineering department of Gebze Technical University, Kocaeli, Türkiye. His area of expertise is electric machinery, drive systems, power electronics, and power systems.



APPENDICES

Appendix A: Publications in the Scope of Thesis

Gulpinar, F., Balikci, A., (2022), “Driving Asynchronous Induction Launchers: Design and Simulation of a Novel Power Conditioner with a Brief Review”, *Energies*, 15, (24), 9360.

Gulpinar, F., Balikci, A., (2020), “Design and implementation of a novel power conditioner for linear induction launchers”, In *Proceedings of the 2020 International Conference on Electrical, Communication, and Computer Engineering (ICECCE)*, 1-4, Istanbul, Turkey, 12-13 June.

