ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

HIGH PERFORMANCE POSITION CONTROL OF LINEAR BRUSHLESS DC MOTOR

M.Sc. THESIS

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Department of Electrical Engineering

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AUGUST 2015

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

FIRÇASIZ LINEER DOĞRU AKIM MOTORUNUN YÜKSEK PERFORMANSLI KONUM KONTROLU

YÜKSEK LİSANS TEZİ

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AĞUSTOS 2015

Pooria Norouzi, a **M.Sc.** student of ITU **Graduate School of Science Engineering And Technology** student ID **504121031**, successfully defended the **thesis** entitled **“HIGH PERFORMANCE POSITION CONTROL OF LINEAR BRUSHLESS DC MOTOR”**, which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

Thesis Advisor : **Assoc. Prof. Dr. Ozgur USTUN** ....
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Date of Submission : 4 May 2015
Date of Defense : 5 August 2015

To My Family,

FOREWORD

This thesis describes all the steps to position control of an air core double sided linear brushless d.c. motor. The goal is to design a new control algorithm for mentioned motor to get a precise position control.

By the given chance I would like to thank my supervisor, Assoc. Prof. Dr. Özgür Üstün, for the patient guidance, encouragement and advice he has provided throughout my time as his student. I have been extremely lucky to have a supervisor who cared so much about my work, and who responded to my questions and queries so promptly.

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August 2015

Pooria NOROUZI
(Electrical Engineer)

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ABBREVIATIONS

AC : Alternating Current
ADC : Analog to Digital Converter
APP : Appendix
BLDC : Brushless Direct Current
BLDCM : Brushless Direct Current Motor
BLSR : Brushless Switched – Reluctance
CAN : Controller Area Network
CNC : Computer Numerical Control
CPU : Central Processing Unit
DC : Direct Current
DSP : Digital Signal Processor
DSLM : Double-sided Linear Induction Motor
EM : Electric Machine
EMF : Electromagnetic Force
IC : Integrated Circuit
IEEE : Institute of Electrical and Electronics Engineers
IGBT : Insulated Gate Bipolar Transistor
LED : Light Emitting Diode
LM : Linear Motor
MagLev : Magnetic Levitation
MMF : Magneto motive Force
MOSFET : Metal Oxide Semiconductor Field Effect Transistor
PEC : Power Electronic Circuit
PID : Proportional Integral Derivative
PMBL : Permanent Magnet Brushless
PM : Permanent Magnet
PMLSM : Permanent Magnet Linear Synchronous Motor
PMSM : Permanent Magnet Synchronous Motor
PWM : Pulse Width Modulation
RC : Resistor Capacitor
RMS : Root Mean Square
RPM : Revolutions per Minute
SDI : Shut Down Input
SLIM : Single-sided Linear Induction Motor
SMPS : Switched Mode Power Supply

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HIGH PERFORMANCE POSITION CONTROL OF LINEAR BRUSHLESS DC MOTOR

SUMMARY

The history of linear motor technology can be traced back to the 1840s. The first model made by Charles Wheatstone was inefficient and impractical. The first feasible linear motor was created by a German engineer called Alfred Zehden in 1905 to drive trains and lifts [1]. A more fundamental model was later developed by Herman Kemper. The best example of usage of linear motors today are in Maglev trains in Japan. Less than a decade ago, linear motors were only able to move 5 meters per second with straightness, load capacity and stiffness. This is a positive sign that linear motor technology is growing rapidly and is the focus of a great amount of research and development.

Linear motors are widely used in the industry as they have a simple structure and their cost to produce is becoming much lower. However, linear motors have low power factor and low efficiency. Modern linear motor applications are demanding greater performance. The key demands of a linear motor are high acceleration, long life, low maintenance, few moving parts and precise positioning. Some of the applications include, DNA sequencing, health operations, rocket positioning etc. Therefore, precision of linear motors is becoming significantly more important.

From ideas above, the study involves to control position of linear motor with an interface controller module, it has been create a new algorithm to have precise position control and speed control. The thesis is to demonstrate and explain the position control of a high precision double sided air core linear motor. Linear motor has 22 pole pairs and 6 coils. As the application is having high precision that is applicable to many industrial areas that are listed above. The motor controller is mounted on a platform that is help us to have real time, online control on system. This will be the perfect system that can be mobile and be implemented anywhere is needed.

The studied linear motor can be considered like a BLDC machine. In recent years, Brushless Direct current (BLDC) motors have achieved rapid popularity. BLDC motors are used in industries such as appliances, automotive, consumer, medical, industrial automation equipment and instrumentation. They are more reliable and can be used in poor environmental conditions. Unlike brushed motors as these motors have no chance of sparking, makes them better suited to environments with volatile chemicals and fuels. In a brush DC motor, the motor assembly contains a physical commutator which is moved by means of actual brushes in order to move the rotor. With a BLDC motor, electrical current powers a permanent magnet that causes the motor to move, so no physical commutator is necessary. Brushless DC electric motor (BLDC motors, BL motors) known as electronically commutated motors, are synchronous motors that are powered by a DC electric source via an

integrated inverter/switching power supply, which produces an AC electric signal to drive the motor.

The study has two main research areas: electric powertrain and control unit. This study will focus on both the electric powertrain and control parts of the project.

Electrical machines can be separated into two types. These are AC Alternative Current and DC Direct Current machines. The specification of the AC machines is that alternative current flows into the coils and creates a turning magnetic field in the air gap. Unlikely in DC machines magnetic field that is created is straight. Permanent magnet brushless DC motor can have DC in its name but when this specification is held in the case, it enters to an AC machine type.

For the linear motor a special control method is produced and laboratory tests are made. Motor laboratory tests are made in Mekatro R&D Company with the designed inverter. The project is finished in the second half of 2014-2015.

FIRÇASIZ LINEER DOĞRU AKIM MOTORUNUN YÜKSEK PERFORMANSLI KONUM KONTROLU

ÖZET

Lineer motor teknolojisi 1840'lara dayanmaktadır. Bilinen ilk model bir İngiliz mühendis olan Charles Wheatstone tarafından yapılmıştır, ancak bu model çok kullanışlı ve uygulanabilir olarak hatırlanmamaktadır. Elverişli ilk model, bir Alman mühendis olan Alfred Zehden tarafından 1905'te tasarlanmıştırn [1]. Bu model trenlerde ve asansörlerde kullanılmıştır. Uygulamalar daha da geliştirilerek en ileri şekliyle Herman Kemper tarafından tasarlanmıştır. Yine de herşeye rağmen lineer motorun gelişimine en çok katkıda bulunan ve mucidi olarak tanınan kişi aynı zamanda Imperial College London profösörlerinden biri olan Eric Laithwaite'dir.

Günümüzde elektrik motorlarından beklentiler oldukça fazladır. Bunlardan bazıları hafiflik, kontrol edilebilirlik, doğrudan tahrik, yüksek kuvvet/moment ağırlık oranı ve düşük bakım maliyeti olarak sıralanabilir. Bu saydığımız beklentiler, lineer motorlara olan ilgiyi son zamanlarda fazlasyla arttırmıştır. Lineer motorlar üzerine yapılan çalışmalar asenkron lineer motorlarla başlamış olsa da, lineer fırçasız doğru akım makinaları kontrol edilebilirliklerin çok daha kolay olması nedeniyle asenkron motorlarlara olan bu ilgiyi ikinci plana atmayı başarmıştır.

Lineer motorlar en basit yapılarıyla, dönel bir motorun yarıçapı boyunca kesilip lineer hale getirilmiş durumu olarak tanımlanabilir. Lineer motorda momentden söz edilmez ve bu büyüklük yerini kuvvete bırakır. Lineer motorlar uzunlukları boyunca kuvvet üretirler. Kısa zamanda yüksek kuvvet değerlerine çıkabilmektedirler. Aktarma elemanlarının olmaması ve yapıları gereği bunlara ihtiyaç dahi olmaması döner hareketi lineer harekete çevirirken kaybedilen enerjiyi ortadan kaldırmaktadır. Dolayısıyla motor sürücüleri için daha hassas kontrol sağlamaktadır. Sanayide çeşitli alanlarda kullanılabilirler. Başlıca uygulama alanmaları, CNC tezgahları, robotik ve otomasyon uygulamaları, füze konumlama sistemleri, gen dizimi, konveyör sistemleri, vinç sistemleri ve manyetik levitasyon olarak sıralanabilir. Lineer motor üzerine yapılan çalışmala çoğunlukla Almanya ve Japonya'da yer almaktadır. Lineer motorların bugünkü en ileri teknolojisi, Japonya'da bir manyetik levitasyon uygulaması olan Maglev trenlerinde kullanılmaktadır. Bu tren son zamanlarda ulaştığı 600km/sa hız değeriyle dünya rekorunu kırmıştır. Geçmiş uygulamalara bakıldığında, 10 yıl öncesinde bile lineer motorlar yük altında doğrusal olarak sadece 5m/s gibi bir hızla hareket edebiliyorlardı. Bu düşünüldüğünde Japonya'daki uygulamalar lineer motor teknolojisinde devrim yaratmıştır denilebilir. Böylece pek kullanılmamakta olan lineer motor teknolojisi yeniden dünyanın ilgisini çekmeye başlamıştır.

Lineer motorlar basit yapılarına ve bunun sayesinde imalat maliyetlerinin düşük olması sebebiyle endüstride çok fazla kullanılmaktadırlar. Fakat, lineer motorların düşük güç faktörlü ve düşük verimli olması da göz önünde bulundurulmalıdır. Modern lineer motor uygulamalarında daha üstün performans talep edilmektedir. Bu kavramı açmak gerekirse bu üstün özellikler yüksek ivmeli, uzun ömürlü, az bakım gerektiren, daha az hareket eden parçaların bulunduğu ve hassas pozisyon kontrollü olması olarak sıralanabilir. DNA sekanslama, sağlık operasyonları ve roket konum kontrolü gibi projelerde hassas konum kontrolü diğer taleplere oranla daha da önceliklidir.

Günümüzde lineer motor teknolojisinden beklentiler eskiye göre çok daha ileri düzeydedir. Lineer motor uygulamalarından en dikkat çekenleri gen dizimi, tıp elektroniği ve roket konumlandırma olarak listenebilir. Bu nedenle özellikle hassas konumlandırma, lineer motor teknolojisinde her geçen gün çok daha fazla önem kazanmaktadır. Hassas konumlandırma özellikle belli durumlarda fazlasıyla dikkat edilmesi gereken bir husustur. Özellikle çok yüksek ve çok düşük hız durumu, hızlı ivmelenme ve hızlı yatışma süresi söz konusu olduğunda ön plana çıkar ve verimliliği arttır. Bu durum düzgün hareket ve aşırı hassas ayar gerektiren mekanik ve konumlama elemanlarının başlıca araştırma konusudur. Tüm bu araştırmalar esasında motorun değişken yüke ve uygulanan kontrol sinyaline çabuk cevap verebilmesini amaçlamaktadır.

Bu bilgiler dahilinde, bu çalışmada lineer motorun pozisyon kontrolünü sağlayan bir arayüz programı kullanılmıştır. Bu programla hız kontrolü ve hassas konum kontrolü sağlayan algoritma geliştirilmiştir. Bu tezde yüksek hassasiyetli çift taraflı hava çekirdekli lineer motorun pozisyon kontrolü açıklanacak ve kanıtlanacaktır. Örnek olarak kullanılan lineer motorunun 22 çift kutubu ve 6 adet bobini bulunmaktadır. Hassas konum kontrolü yukarıda da listelendiği gibi endüstrinin bir çok alanında kullanılmaya uygundur. Motor kontrolörü gerçek zamanlı ve çevrimiçi bilgi akışını sağlayacak şekilde bir platform üzerine monte edilmiştir. Bu platform taşınabilir ve uygulanabilir en ideal sistem olarak varsayılmaktadır.

Lineer motorun çalışma ilkesi Lorentz ve Faraday yasasına dayanır. Lorentz kuvvet yasası içinden akım geçirilen bir iletkenin, akıma dik olarak endüklenmiş bir manyetik alana yerleştirilmesi sonucunda bu iletkene bir kuvvet etkiyeceği ve bu kuvvetin iletkeni hareket ettirmeye çalışacağını söylemektedir. Bunun yanında bu kuvvetin iletkendeki sarım sayısı, sargı akımı ve üretilen akı ile doğru orantılı olduğu bilinmektedir. Faraday yasası ise manyetik alan içerisinde bulunan bir iletken, bu alan içerisinde belirli bir hızla haraket ettirilirse bu iletken üzerinde bir gerilim endüklendiğini söyler.

Çalışmanın amacı çift yanlı, hava çekirdekli bir lineer motor için yüksek konum hassasiyetine sahip olan bir kontrol sistemi tasarlamaktır. Uygulama alanları robotik ve otomasyon uygulamaları olarak belirlenmiş ve control sistemi genel olarak tasarlanmıştır.

Elektrik makinaları temel olarak ikiye ayrılmaktadırlar. Bunlardan ilki DA (Doğru Akım) makinaları ve ikincisi de AA (Alternatif Akım) makinalarıdır. Alternatif Akım makinalarını Doğru akım makinalarından ayıran özelliği alternatif akımın bobinlere akması ve hava boşluğunda dönen bir manyetik alan yaratmasıdır. Doğru akım makinalarında ise bu manyetik alan düzgündür. Sürekli mıknatıslı fırçasız doğru akım motorlarının isminin içinde doğru akım geçmesine rağmen teknik özelliklerine bakıldığında alternatif makina sınıfına girmektedir. Buradan hareketle üzerine çalışılmış lineer motorumuz fırçasız doğru akım makinası olarak düşünülebilir.

Tez kapsamında lineer motorlara dair incelemeler, giriş, literatür taraması, lineer fırçasız doğru akım motorları, lineer fırçasız doğru akım motoru modellenmesi, lineer fırçasız doğru akım motor kontrolörünün tasarımı ve tezde incelenen lineer fırçasız doğru akım motoruna dair sonuçlar bulunmaktadır.

Tezin ilk kısmında incelenen konular, lineer motorun tarihçesi, lineer servo motorlar, manyetik levitasyon sistemleri, lineer motorların kontrol yöntemleri, tezle ilgili amaçlar ve araştırma planıdır.

İkinci kısımda lineer motorlara dair literatür taraması yapılmıştır. Bu literatür taraması lineer motorların kontrolü üzerine yazılmış makaleleri kapsamaktadır.

Üçüncü bölümde lineer firçasız doğru akım motorlarının sürücü sistemlerinin incelemesi, lineer fırçasız doğru akım motorlarının matematiksel formülasyonu, tezde kullanılan motorun deneysel sonuçlarının çıkarılması yapılmıştır.

Dördüncü bölümde lineer fırçasız doğru akım motorlarının modellenmesi incelenmiştir. Tezde kullanılan motora uygun blok diyagramı yapılmış, akım kontrol modeli, hız kontrol modeli ve konum kontrol modeli geliştirilmiştir.

Son olarak beşinci bölümde kullanılan motora uygun lineer fırçasız doğru akım motor kontrolörü tasarlanmıştır. PID kontrolör Ziegler- Nichols metoduyla Lineer motor kontrolü için özel bir kontrol yontemi geliştirilmiştir ve tasarlanmış ve bunun doğrultusunda motor pozisyonu ve hız kontrol test sonuçlarına ulaşılmıştır. Konum kontrolünde kullanılan sistemin çözünürlüğü belirtilmiş ve bu doğrultuda akım ve gerilim dalga şekilleri saptanmıştır.

Bütün deneyler Mekatro Ar-Ge şirketinde yapılmış evirici ile gerçeklenmiştir. Bu proje ise 2014-2015 bahar dönemi sonunda başarı ile sonlanmıştır.

1. INTRODUCTION

Linear motors are one of the important machines in industry sector today. The world is rapidly progressing in technology. Among these, one of the important research topic is electric machines and their control methods such as position controlling, speed controlling and etc. see Figure 1.1.

Figure 1.1: Three-phase PM linear motors [2].

Linear motors produce a motion in a straight line directly without any mechanisms such as intermediate gears, screws, or crank shafts to converting rotational motion to linear motion. Linear motor's history goes back as far as the last decade of 19th century. The earliest linear electric motor is emerged before 1838, after discovery of Faraday's induction law in 1831[3]. Then these linear motors were practically forgotten for decades until Professor E.R Laithwaite began work on linear induction motors at Manchester in the 1950s [4]. Figure 1.2 shows the simple body construction of a linear motor.

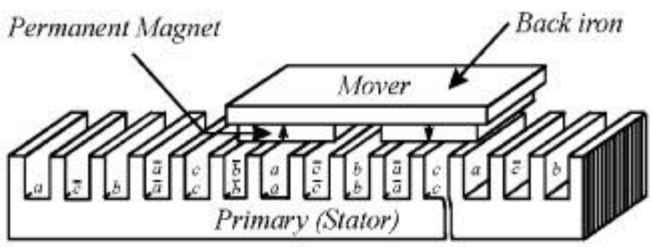

Figure 1.2: Simple linear motor construction [5].

There are many advantages in linear motor driving application, such as low frictional losses, high precision, high efficiency, acceleration and deceleration capability, straight driving, structural flexibility, fast dynamic respond and etc. So they are widely used in modern high-precision industry [6,7]. One of the major use of linear motors is for propelling shuttle in looms. They have been used sliding doors and various similar actuators, even drive large-scale bulk materials transport solutions. They have been implemented in high technologic devices such as aircraft launching and magnetic levitation, CNC machines, robotic applications, machine tools and monorails too. See Figure 1.3.

Figure 1.3: US electromagnetic aircraft carrier launch system [8].

1.1 Brief History of Linear Motor

Linear motor technology goes back to the 1840s. Step motors and brushed linear motor products have been available for quite some time. The brushed system of a DC motor was expensive and application limited. By the time the control technology become more intensive, brush commutator systems were withdrawn and this opened the way to BLDC and furthermore linear motors.

The first linear motor was induction type [4], which was proposed as a shuttle drive in weaving looms; but commercially use of these motors was not profitable, according to comparatively low cost of loom machines compared with electrical machines.
In 1917 the first d.c. linear motor was built [1], it was a reluctance motor in tubular form; it was proposed as a launcher. A steel missile was attracted into a succession of

coils by successively the direct current in coils, this motor was known as Birkeland's Canon and it was never developed beyond the model stage.

In 1957 scientists have done investigations into self-oscillating linear induction motor [9]. Several different types of linear induction pump, which pumped conductive liquid metals, were reported in 1955 [10].

In 1905 Wilson proposed the use, for railway traction section of primary winding (stator) mounted between the rails and the secondary member (rotor) carried on the vehicle. The system was completely expensive because windings had to extend along the whole length of track. Zehden interchanged the roles of the rotor and stator and placed the primary windings, which is the expensive member, on board of vehicle [11].

Figure 1.4: The Birmingham International Maglev shuttle [12].

Throughout the transportation history, there has always been a demand for higher speed. In 1960s a development was done in ground-transportation system, and capability of system improved to very high speeds, typically 400-550 km/h [13]. Laithwaite introduced the transverse-flux high-speed transportation machine in 1973, a path of magnetic flux lies in a railway that transverse to the motion direction [14].

A high-speed d.c. linear motor was built at Royal Aircraft Establishment in Farnborough in 1954, it was a linear form of the conventional rotary motor [15]. It was made and designed as a wind tunnel, and capable of accelerating a mass of 1kg to a speed of 500 m/s. In 1961 an space research programme in an attempt to simulate meteorite effects on space capsules were started [16]. An inventive d.c. accelerators was built for achieving hyper velocities about 15-72 km/h.

Alternating current linear induction motor

Operation principle of Alternating current linear induction motors can be understood by investigation of a rotary induction motor. If it has cut rotary induction motor along a radial plane and unwrapped it, a flat configuration is obtained, which is capable to create a motion in a longitudinal direction.

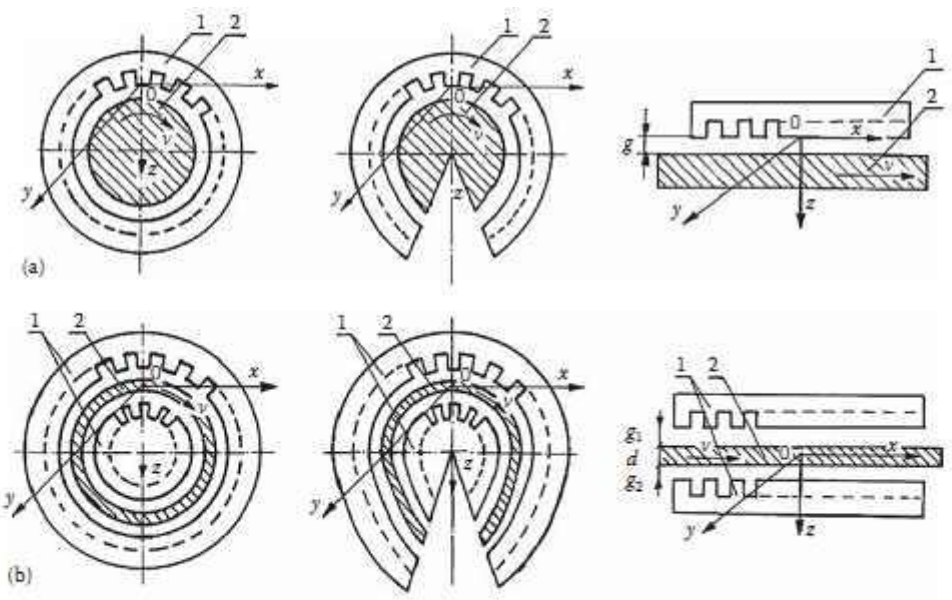

Figure 1.5: Evolution of a rotary induction motor, rotor induction motor into a flat, a) single-sided Linear Induction Motor (LIM). b) double-sided LIM. [17].

Conventional d.c. linear motors are similar to rotational d.c. motors, so they have an armature and a field system, but in the linear case the armature is stationary and the field is moving part. In general, the armature consist of circular bar that is made by ferromagnetic material.

The linear motors can be divided two to types according to whether the rotor or stator is extended to the full length of machines. Short-stator or short primary and short-rotor or short secondary machines, in the former machines the rotor is extended and the moving part is the stator, while in short-rotor machines the stator in extended to the length of the machine and the moving part is the rotor.

Brushless direct-current linear motors

There is several brushless dc motors configurations which provides linear motion. These can be moving-magnet or moving-coil motors. Although there are several differences between these types of motors, they all provide essentially the same basic linear motion.

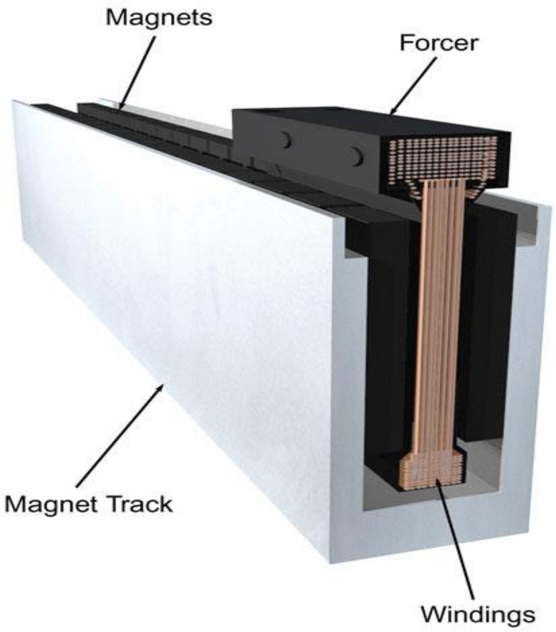

Figure 1.6: Linear motor structure [18].

Linear motor benefits can be listed as:

- High speed
- High precision
- Fast response
- Stiffness
- Zero blacklash (no transmission components)
- Maintenance free operation

The down sides of linear motors will be:

- Cost
- Higher bandwidth drives and controls
- Force per package size (they are not compact force generators)
- Heating
- No (minimal) friction

The main problem with linear motors has always been the cost and difficulty of developing suitable electromagnets. Enormously powerful electromagnets are required to levitate and move big structures, and these typically consume substantial amounts of electric power. Nowadays, often superconducting magnets are used to solve this problem.

Every linear motor type has its own advantage. Below table shows a summary of linear motor attributes and how each type of motor compares to the others.

Table 1.1 : Linear motor types and comparison of their attributes.

Attribute	Iron Core	AirCore	Slotless
Cost	Low	High	Lowest
Attractive Force	Highest	None	Moderate
Cogging	Highest	None	Moderate
Force / Size	Best	Moderate	Good
Thermal Characteristics	Best	Worst	Good
Forcer Weight	Heaviest	Lightest	Moderate
Forcer Strength	Best	Worst	Good

In this thesis, a double sided aircore linear motor will be used. Double sided air core linear motors can work in very high and very low speeds, they can accelerate faster, they are low maintenance and they do not have parts that reduce the efficiency like rollers.

However, they also have disadvantages. For instance, they are not useful in vertical applications, they do not have an emergency break and they are not handy in linear encoder applications when considering the environment.

Despite this disadvantages, double sided aircore linear motors are widely in industry. The most common areas are:

1) Conveyor systems
2) High precision direct drive systems
3) High precision control with higher speeds

For the last two decades many countries such as Japan, Germany and etc. which have been under pressure from high energy prices fluctuations, have implemented variable speed PM motor drives for saving energy [19]. On the other side, the U.S. has continued using cheap induction motor drives, which have lower efficiency than adjustable PM motor drives for energy saving applications. Also, recent rapid proliferation of motor drives into the automobile industry, based on hybrid drives, generates a serious demand for high efficient PM motor drives, and this was the initial of interest in BLDC motors. These motors, also called Permanent Magnet DC Synchronous motors, are one of the motor types that have more rapidly gained popularity, mainly because of their better characteristics and performance [20]. These motors are used in a great amount of industrial sectors because their architecture is suitable for any safety critical applications.

BLDC motors have many advantages over brushed DC motors and induction motors, such as a better speed versus torque or force characteristics, high dynamic response, high efficiency and reliability, long operating life (no brush erosion), noiseless operation, higher speed ranges, and reduction of electromagnetic interference (EMI). In addition, the ratio of delivered force or torque to the size of the motor is higher, making it useful in applications where space and weight are critical factors, especially in aerospace applications.

1.2 Linear Servo Motor

Linear servo motors are permanently actuated synchronous servo motors, with integrated position measurement and overload protection. Permanent magnets in the slider (like a rotor) and windings in the stator are used to generate forces, like in a brushless rotary motor. The configuration and different arrangement of the magnets generate the linear motion directly, using electromagnetic force, without mechanical elements that are subject to wear. The windings, position sensors, temperature monitoring, and bearings are all located in the stator. It consists of a solid metal cylinder in which the motor components are cast, so that they are optimally protected from damage and contamination. The stators are available in two versions, with direct cable exit or a rotating angle connector [21].

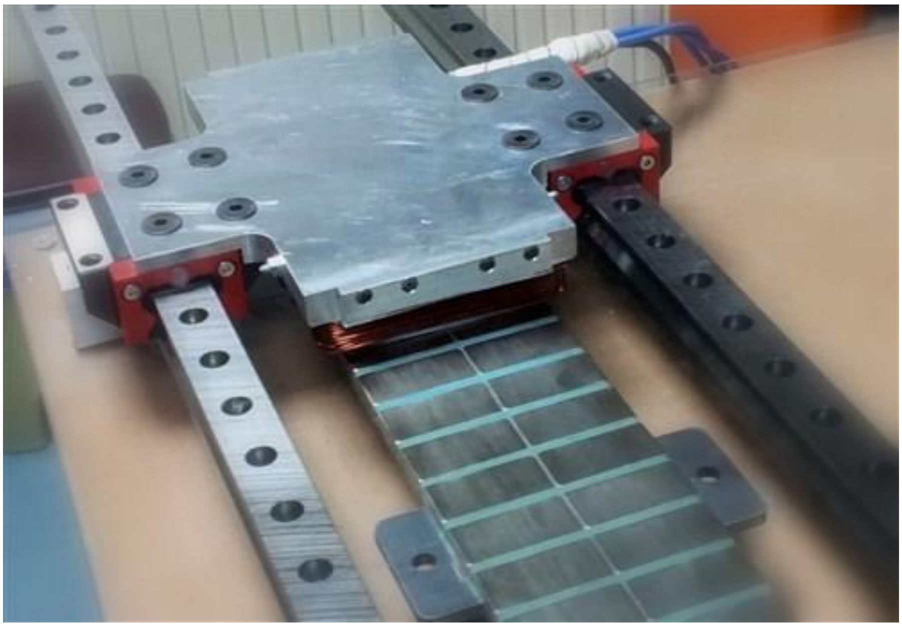

Figure 1.7: Single sided flat type linear servo BLDC motor (courtesy of Mekatro Ar-Ge limited).

The slider consists of a stainless steel tube in which the drive magnets are mounted. During operation, the slider is guided by the plain bearing integrated in the stator. There is no electrical or mechanical connection between the slider and the stator.

Freely positionable with no mechanical end play along the entire stroke.

Adjustable speed within a range of 0.001 - 5.5m/s**.**

Adjustable acceleration for highly dynamic or slower moves.

Synchronization & motion profiling for complicated motions and replacement of cam discs**.**

Adjustable force for totally programmable press and joining operations**.**

Highly dynamic Acceleration values of well over 500 m/s^2 and travel speeds over 5.5 m/s allow cyclical motion sequences of several Hertz.

Controlled dynamics For handling applications with sensitive products, such as transporting wafers in semiconductor production, very gentle, smooth motions with suitable accelerations can be obtained.

Process stability Since not only the end positions, but also speed and acceleration are controlled and monitored, motions that are programmed once are carried out the same way over the entire life of the machine.

Linear servo motor provides industry with the widest range of linear motors, they continually develops advanced products and innovations to meet a variety of linear motion applications.

As mentioned before, Linear servo motors provide unique speed and positioning performance advantages. Linear motors provide direct-coupled motion and eliminate mechanical transmission devices. The rugged mechanical design provides accurate motion and precision positioning for hundreds of millions of cycles. Linear motors and stages are used in thousands of successful applications worldwide [22].

The Benefits of linear servo motors over traditional technologies:

- Direct drive, zero backlash for higher accuracy
- Non-contact, non-wearing for enhanced reliability
- Simplicity, no mechanical linkages provides faster installation
- High acceleration and velocity reduces cycle times
- High accuracy and repeatability provides better quality control
- Low maintenance and long life lowers cost of ownership
- Longer lengths with no performance degradation

Linear Brushless Servo Motors

This type of motors are designed by some Companies for unlimited stroke servo applications that require smooth operation. A large range of motors are available to suit different applications. These motors are supplied in kit form to be integrated into your machine. They are used in closed loop servo systems and provide optimum performance. For higher continuous forces, air and water cooling options are available. Some kind of motors are ideally suited for applications requiring high accuracy (with resolutions down to 0.1µm) and smooth movement. The motors can be controlled from any of linear servo motor's 3 phase brushless drive family. The motors are also compatible with the Next Move range of motion controllers for multi-axis position control.

1.3 Magnetic Levitation Systems

Magnetic levitation systems have long been a sight of railway engineers. Maglev, a combination of superconducting magnets and linear motor technology, realizes super high-speed running, safety, reliability. In 1965 the Department of Commerce established the High Speed Ground Transportation [23]. The earliest research on developing Maglev technology is for that decade. In the United States, work ended in 1975 with the termination of Federal Funding for high-speed ground transportation. It was at that time when the Japanese and German researchers went on their investigations and so derived with the first test tracks. A super high-speed transportation system with a non-adhesive interface that is detached of wheel-and-rail frictional forces low environmental impact and minimum maintenance.

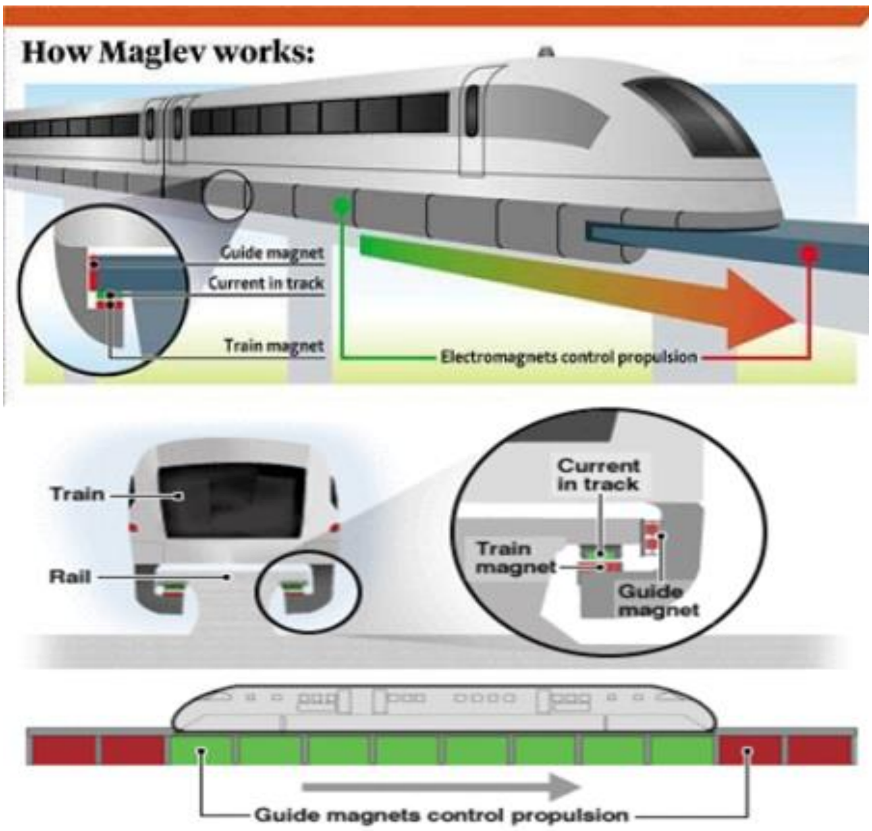

Figure 1.8: Maglev train and railway structure [24].

Superior progressing in the last decades on Maglev technology in transportation, prototype magnetically levitated (maglev) trains cruising at up to 400 kilometers per hour have pointed the way to the future in rail transport. Their compelling advantages include high speeds, negligible air and noise pollution, low energy consumption, and little friction except aerodynamic drag. However, maglev trains also have serious drawbacks in maintenance costs, electronic and mechanical complexity and operational stability.

The following is a general explanation of the principle of Maglev. There are many different moderations of the technology used in levitating train cars for transportation. There are four different development lines of Maglev systems; Figure 1.9.

- Electrodynamic levitation systems with air-core long-stator linear synchronous motors.
- Electromagnetic levitation systems with short stator linear induction motors.
- Electromagnetic levitation systems with iron-core long-stator linear synchronous motors.
- (Controlled) permanent magnetic levitation system with iron-core long-stator linear synchronous motors.

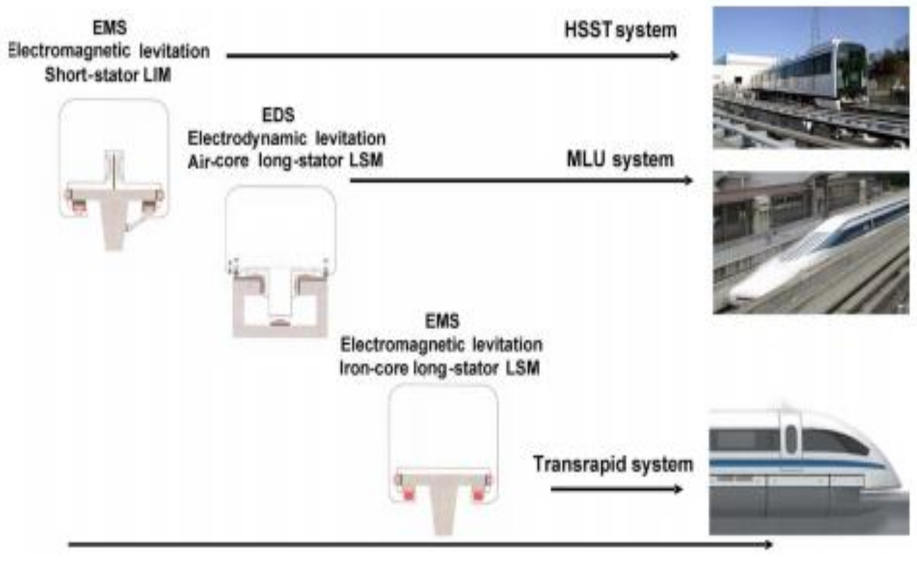

Figure 1.9: Meglav System development in Germany and Japan [25].

Nowadays, there are many new ideas, for instance the utilization of long-stator linear motors in personal rapid transit systems or contactless inductive power supply through the track for ancillary power supply of the vehicles by linear transformers [26,27].

The environmental issues for the quickly developing transportation demand of the future require high-speed high-capacity, and eco-friendly transportation systems. Maglev technology can be a jubilant solution for the upcoming traffic and ecological challenges, because the main advantages of maglev technology are obvious:

1) Short trip times due to high speed and/or high acceleration;

2) Safe and comfortable due to magnetic guidance and levitation systems;

3) Low operating costs due to low maintenance effort (contactless) and high efficiency;

4) Flexible alignment due to high gradients because there is no need for any functional grip between the wheel and the rail;

5) Eco-friendly due to high-efficiency, emission-free system, flexible alignment, low noise, and independence of energy mode.

In particular, countries with large territories or large cities are interested in this technology. Today, there are a lot of number of pending projects all over the world, the future years will show whether or not Maglev or at least linear motor-powered transportation systems will establish themselves.

Linear Electric Motors

In the industrial application point of view, the most common motors used in the hybrid electric vehicles (HEV) and pure electric vehicles (PEV) are: DC motors, induction, permanent magnet synchronous, switched reluctance and brushless DC motors [28].

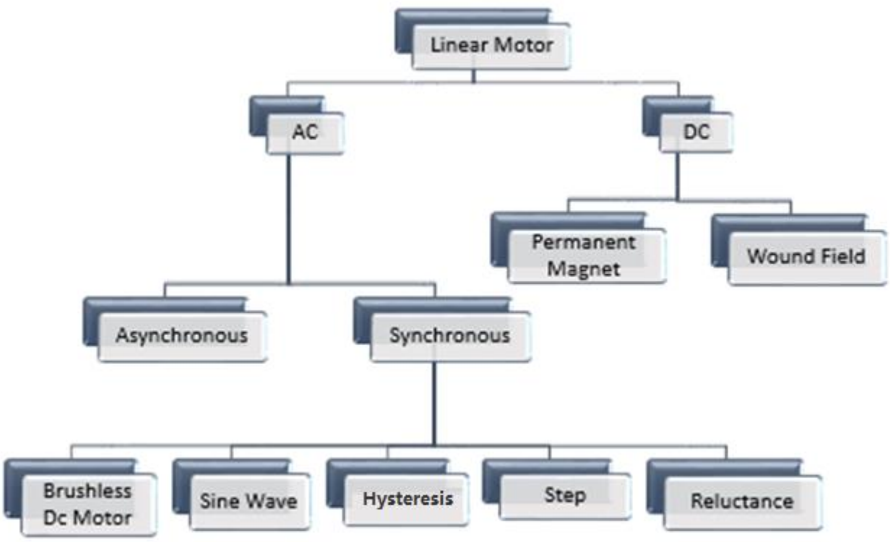

Figure 1.10: Types of linear electric motors used in industry.

The studied linear motor is categorized as a Brushless Synchronous DC Motor, BLDC motor driven by an electrical input, which lacks any form of commutator or slip ring. The motor requires some form of alternating current to turn, either from an AC supply, or an electronic circuit. A brushless DC electric motor contains a synchronous motor and integrated power electronics that operates the motor from a direct current supply.

As in case of rotary machines, there are two basic types of linear motor, depending on excitation method:

1) Alternating current (AC)

2) Direct current (DC)

These two type of motors have different positive aspects. Alternating current motors can be categorized into two main group, linear induction and linear reluctance motors, and scientists and researcher are working on both of them during last decade. On the other hand direct current linear motors have been neglected during these years. These machines are classified in three group, reluctance, conventional and recorder.

Moving-armature motors

Moving-armature motors have a moving lamination and windings assembly which is shorter than the stator. The stator consist of a long group of magnets mounted on a magnetically permeable surface. These motors have characteristics which are essentially similar to those in the moving-magnet type, except that all the windings interface with the adjacent magnet. These devices are, therefore, more efficient but they require more magnets. Also note that moving-armature devices require flexible cables for the windings.

Moving-coil Motors

Moving-coil motors, are similar to the moving armature type [29]. The magnet structure is of the balanced type, but a structure with magnets on one side and a flux return path on on the other side also works. These type of motor, which its light-weight armature, has the highest force-to-inertia ratio. It can be designed to feature force levels with an extremely low force ripple due to the absence of any reluctance force. The thermal resistance between the armature and ambient air is higher than in the other models; therefore the coils may require air cooling at high incrementing rates.

Table 1.2: A comparison of three brushless dc linear motor.

LINEAR MOTOR	MOVING-MAGNET	MOVING ARMATURE	MOVING-COIL
WEIGHT OF UNIT	Medium	Heavy	Light
END EFFECTS	Present	Present	Absent
POWER LOSS	High	Medium	Low
VOLUME OF MAGNET	Low	Medium	High
COST	Moderate	Low	High

Figure 1.11 shows a double sided PM linear brushless motor with inner moving coil, a heavy duty conductor wire with high temperature insulation is used. To improve heat removal, it wraps the winding wire during fabrication into a planer surface at the interface with the aluminum attachment bar. The interface between the winding planer surface and the aluminum flat surface maximizes heat transfer. Once heat is transferred into the attachment bar, it is still important to provide adequate surface area in the carriage assembly to reject the heat. The use of thermal grease on the coil mounting surface is recommended. The studied linear motor in this project categorized as a Brushless Synchronous DC Motor, BLDC motor driven by an electrical input, which lacks any form of commutator or slip ring.

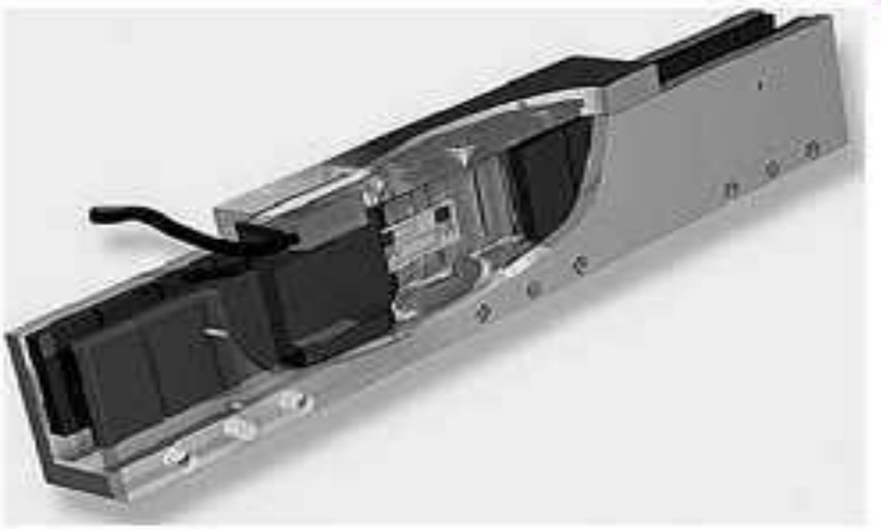

Figure 1.11 : Flat double-sided PM LBM with moving coil [17].

1.4 Control Methods

According to the linear motor model, control variables of this motor are classified to input variables and output variables. Input variable such as input voltage or current, and output variables such as speed or position displacement and etc. there is many control method such as scalar control, vector oriented control method. Scalar control methods are based on conversion of the amplitudes of controlled variables. Vector oriented control method are based on amplitude and phase of the space vectors of control variables.

Standard controllers have constant parameters. Although, the parameters of electric motors are variable, for example windings resistance and windings inductances are dependent on temperature and magnetic saturation, sequencely. So in adaptive controllers variables are modified to adjusting to the variation in parameters of system. Self-tuning adaptive control are tuned to match themselves to drive parameters variations.

Motor drives require a moving part position sensor to properly perform phase commutation and/or current control. For PMAC motors, a constant supply of position information is necessary; thus a position sensor with high resolution, such as a shaft encoder or a resolver, is typically used. For BLDC motors, only the knowledge of six phase-commutation instants per electrical cycle is needed; therefore, low-cost Hall-effect sensors are usually used. Also, electromagnetic variable reluctance (VR) sensors or accelerometers have been extensively applied to measure motor position and speed**.** These kinds of devices are based on Hall-effect theory, which states that if an electric current carrying conductor is kept in a magnetic field, the magnetic field exerts a transverse force on the moving charge carriers that tends to push them to one side of the conductor.

A special semiconductor material can produce a voltage due to magnetic field which is applied on it . Actually, this voltage is somewhat proportional to the applied magnetic field although it has some nonlinearities. However, in brushless DC motor commutation hysteresis latch type Hall sensors are used. The presence of this measurable transverse voltage is called the Hall-effect because it was discovered by Edwin Hall.

Unlike a brushed DC motor, the commutation of a BLDC motor is controlled electronically. To move the BLDC motor the stator windings should be energized in a sequence. It is important to know the position in order to understand which winding will be energized following the energizing sequence. Motor position is sensed using Hall-effect sensors embedded into the stator.

Most BLDC motors have three Hall sensors inside the stator on the non-driving end of the motor such as a motor in this project. Whenever the magnetic poles pass near the Hall sensors they give a high or low signal indicating the N or S pole is passing near the sensors. Based on the combination of these three Hall sensor signals, the exact sequence of commutation can be determined.

Embedding the Hall sensors into the stator is a complex process because any misalignment in these Hall sensors with respect to the rotor magnets will generate an error in determination of the position. To simplify the process of mounting the Hall sensors onto the stator some motors may have the Hall sensor magnets, in addition to the main rotor magnets. Therefore, whenever the moving coil is moved the Hall sensor magnets give the same effect as the main magnets. The Hall sensors are normally mounted on a printed circuit board and fixed to the enclosure cap on the non-driving end. This enables users to adjust the complete assembly of Hall sensors to align with the rotor magnets in order to achieve the best performance.

The process of switching the current to flow through only two phases for every 60 electrical degree, electronic commutation. The motor is supplied from a three-phase inverter, and the switching actions can be simply triggered by the use of signals from position sensors that are mounted at appropriate points in the stator. When mounted at 60 electrical degree intervals and aligned properly with the stator phase windings these Hall switches deliver digital pulses that can be decoded into the desired three-phase switching sequence.

1.5 EMF of Permanent Magnet Brushless Motors

The three phase armature winding with distributed parameters ban be delta or star connected. For the star-connected windings, two phases conduct the armature current at the same time. A.C. synchronous motors equation is general so if it has been put ω=0. For linear d.c. motor, equation becomes [30].

$$V = E_f + RI_a^{(sq)} \qquad \textbf{(1.1)}$$

In this thesis there is rectangular (trapezoidal) waveform in the armature winding of an inverter-fed LBM match to the operation of DC commutator motor. Where R is the sum of two-phase resistances in series for Y-connected phase windings), and E_f is the sum of two phase EMFs in series, V is the d.c. input voltage supplying the inverter and $I_a^{(sq)}$ is the flat-top value of the square-wave current equal to the inverter input current.

1.6 Objectives and Research Plan

A linear direct drive is an excellent choice to meet the requirements of higher speeds, great accuracies and improved reliability due to its mechanical simplicity. Significant advancements have recently been made in technology, in high accuracy and increased productivity.

In order to exploit the advantages of advanced technologies, the requirements on the feed drive in terms of axis speed, acceleration, accuracy and available static and dynamic stuffiness are continuously improving.

In spite of these advantages, linear motors have not been able to replace conventional motors. In order to reduce problems of BLDC linear motor on industrial apparatus. In this extent, it has been created a project to high precision position control and speed control of a linear BLDC motor. High precision is very important for high and low speed, fast acceleration and quick settling times, all of these have effect on industry sector. This is the main problem in mechanical and positioning devices, if extreme accuracy or super smooth motion is of concern. For solving this problem it has been created an algorithm to control this motor by this interface. Drive system development will be taken as subject in this project.

2. LITERATURE REVIEW

Linear motors are used in industry where several attributes such as long or short strokes, high speed, accuracy, or repeatability are required. When the need arises for linear motion or positioning there are many alternative choices. In industry linear motion is used in many sectors as an Acme screw, ball screw, rack & pinion, or belts. Generally, the linear motor solution is more affordable than a rotational motor which is produced linear motion by mechanical equipment, but when one needs highly accurate repeatable high-speed motion then the answer will be a linear motor.
According to reputation of linear motors, some of the popular linear motors are DC Brushless, Hybrid, Synchronous, Stepper, Voice Coil, Induction, and Force Tube. Different specification of this force comprise the stiffness, force speed characteristics, smoothness and continuous and peak force ratings.

As the linear motor technology is getting more and more popular, it has been successfully applied in many different industries, e.g., in health, defense or aerospace. These new applications introduced new challenges in the design, modeling, control and analysis of linear motors. The following articles from IEEE (Institute of Electrical and Electronics Engineers) have been taken into consideration for the literature review.

In 2012, A. Buarse, and W. Subsingha published the paper "*Double-sided linear induction motor control using space vector pulse width modulation technique* ". They presented a DSLIM that has 500W, 300 Vmax, 50 Hz power rating. The used control technique is the average Space Vector Pulse Width Modulation that is applied on a 3 Phase Voltage Source Inverter. A real time control interfacing board (DS1104) was used from dSPACE and utilized by the software development kit Matlab/Simulink. The controller design has been successfully validated by experiments. Both a motor speed and a rotational controller of the DSLIM were tested with the 3 phase voltage source inverter [31].

In the year 2004, the paper "*Position Control of Linear Permanent Magnet BLDC Servo Using Iterative Learning Control*" is done by C.H. Lim, Y.K. Tan, S.K.Panda, J X Xu over position tracking of periodic reference trajectories, such as pick and place assembly operations. For such repetitive control applications, the reference input position tracking and the corresponding tracking error are periodic in nature [32].

In 2006, O. Ustun and N. Tuncay studied development of a linear actuator for an accurate position control with a high force-to-mass ratio and according to this study a novel configuration has been developed which has a double-sided stator and a printed-circuit moving armature. In their work "*Design, Analysis, and Control of a Novel Linear Actuator*". They proposed a design methodology, which is based upon the finite-element method magnetic-circuit analysis, and a simulation software for performance predictions. A hardware-in-the loop control technique is developed and applied to the designed motor. Micrometer position accuracy is achieved experimentally [33].

In the paper "*Sliding-mode Position Controller for Linear Permanent Magnet Brushless DC Servo Motors*". Y.K. Tan and S.K. Panda studied the robust SMC to overcome the problems faced by the linear PID controller and evaluate the performance of the proposed controller. The conventional SMC exhibits chattering, so in order to overcome chattering they introduced a boundary-layer around the switching surface. Furthermore, to enhance the dynamic performance they propose a modified PID-type of switching surface [34].

In the 2013 5th International Conference on Intelligent Networking and Collaborative Systems Li Cailin and Wang Dongmei have discussed "*The permanent magnet synchronous linear motor position control based on fuzzy neural network*". They presented combination of neural network and fuzzy control, PLSLM two-axis control system, in which Backpropagation algorithm is adopted to adjust the network numerical and dynamical structure algorithm is employed to optimize framework of networks, is presented to guarantee a good tracking performance of the system. [35].

In 2006 C.L. Ku, Y.K. Tan and S.K. Panda studied the High-Precision Position Control of Linear Permanent Magnet BLDG in their work "*High-Precision Position Control of Linear Permanent Magnet BLDG Servo Motor for Pick and Place Application*".

They proposed a new control scheme, non-linear sliding mode control (SMC) to improve the performance of pick-and-place application. Sliding mode control is a promising method to control high-order nonlinear dynamic plants operating under uncertain conditions. They discuss the ability to provide fast error convergence and strong robustness for control systems. The robustness come from the insensitivity of nonlinearities, uncertain dynamics, uncertain system parameters and bounded input disturbances in closed loop system of sliding model [36].

The paper "*Fast prototyping of three-phase BLDC motor controller designed on the basis of dynamic contraction method*" which was published in 2008 by Szafranski, G. and Czyba, R. .The main purpose of this paper is to design a speed controller for a brushless dc (BLDC) motor, based on the Dynamic Contraction Method (DCM). The control task is formulated as a tracking problem of a motor speed, where output transients are accomplished in spite of incomplete information about varying parameters of the system and external disturbances. Developed structure allows to connect the software package to physical system, and provide for rapid prototyping and hardware-in-the-loop simulation in real time. To drive this system effectively, a DCM method is applied and implemented to produce the desired dynamic of output. DCM controller and the developed control scheme are theoretically analyzed and the performances are demonstrated by experiments in the HiL structure.].

In 2015, Hsin-Han Chiang and Kou-Cheng Hsu studied the motion control of a LIM drive in their work "Optimized adaptive motion control through an SoPC implementation for linear induction motor drives". They proposed an optimal adaptive tracking control for a LIM drive. They took end effects, payloads and model uncertainties, e.g., friction force, into account. They used a field-oriented control for a LIM and first investigated the primary end effects in the dynamic model. For the basis of the back stepping control design, they embedded a sliding mode controller with a particular fuzzy compensator to deal with the lump uncertainities of the LIM drive. To overcome the obstacle of the unknown bounds of the lumped uncertainities in the total system, an adaptive mechanism is derived to adjust the fuzzy compensator gains. They achieved robust tracking performance in existence of uncertainities and nonlinearities by adopting the soft computing technique and optimizing the controller parameters. Finally, the high performance of the proposed control scheme is validated by hardware experiments [38].

Another paper from X. Jin, M. Weimming, L. Junyong, S. Zhaolong and Z. Yuexing called "*The mathematical model and performance analysis of a novel four-stator double-sided linear induction motor*" was written to design an electromagnetic aircraft launch and the electromagnetic model for this study was presented in this paper. The coupling characteristics of inductive loop on the shuttle inducted by the upper and lower stators, and the coupling characteristics of adjacent windings of the upper and lower stator-ends were analyzed in detail. Based on the advanced equivalent coupling circuit model, the coupling characteristics of relevant physical quantities of the upper and lower stator and lower equivalent windings of shuttle were studied. Moreover, they derived the relationship between the cooling charateristics and motor operation conditions. Experiment results verified the validity of the proposed design and analysis methods [39].

In the paper "*Control strategies for linear synchronous motors*". Dr. Brian M. Perrault discussed advantages and disadvantages of linear motors and their control strategies. He stated that linear motors are superior to the other means of propulsion, as the force is applied directly to the vehicle, does not depend upon friction, is controllable, and the linear motors themselves have no wearing parts. He indicated the unique challenges of linear motors, such as the back-emf, can vary with position as well as speed, the overall thrust constant can vary if there are gaps between the stators, and the stators must be synchronized as a vehicle transition from one to the other. To manage these characteristics the importance of stator length that is energized is indicated. Perrault also discussed methods for operating multiple vehicles safely under the constraints of linear motor block-based control [40].

In the paper "*Performance comparison of control methods for high speed long primary double-sided linear induction motor*" a LIM and long primary DSLIM are investigated for high-speed linear motor application. It was hard to detect the secondary speed with high-accuracy and fast response. The paper compared two control methods for the performance of the long primary DSLIM. The two methods were direct thrust control and secondary field oriented control. The simulation results for both control methods were compared based on motor performance. It was discovered that it is difficult to detect the fast response and high-accuracy secondary speed for the long primary DSLIM in high-speed applications. It was proven that without the high-accuracy and fast response of the secondary speed feedback, the performance requirements can be obtained through the direct thrust control method [41].

"*Precise position control of tubular linear motors with neural networks and composite learning*" is a paper that takes into account uncertinities like friction and electromagnetic phenomena and approximates these with a radial basis function neural network which is trained online using a learning law based on Lyapunov design. This study examines an adaptive control scheme with micro-metric positioning tolerances. The approximator is trained using a composite adaptation law combining the tracking error and the model prediction error. Study shows that a precise control is possible [42].

One of the most important problems in these technologies is precise control. K. Sato in 2014, published a paper called "*High-precision and high-positioning of 100 G linear synchronous motor*" to indicate that linear motors can move with an acceleration above 100G, while also being capable of high-precision and high-speed positioning with a velocity of 12m/s that can provide up to 500nm of position accuracy [43].

3. LINEAR BRUSHLESS DIRECT CURRENT (BLDC) MOTOR

In recent years, Brushless Direct current (BLDC) motors have achieved rapid popularity. BLDC motors are used in industries such as appliances, automotive, consumer, medical, industrial automation equipment and instrumentation. They are more reliable and can be used in poor environmental conditions. Unlike brushed motors as these motors have no chance of sparking, makes them better suited to environments with volatile chemicals and fuels. BLDC motor control can be categorized into three major types:

- Constant load
- Varying loads
- Positioning applications

In constant load applications, variable speed is more important than keeping the accuracy of the speed at a set speed. These applications are fans, pumps and blowers. The load on motor varies over a speed range in varying load application. Home applications like washers and dryers, automotive applications like fuel pump control, electronic steering control, engine control and electric vehicle control are very good examples. Most of the industrial and automation types of application come under positioning applications. Three control loops are simultaneously functioning in these applications. These loops are force or torque control loop, speed control loop and position control loop. Computer Numeric Controlled (CNC) machines are a good example.

The construction of BLDC is very similar to the AC motor, known as the permanent magnet synchronous motor. BLDC motors are a type of synchronous motor.

In practice, the design of the linear BLDC motor drive involves a complex process such as modeling, control scheme selection, simulation and parameters tuning etc. An expert knowledge of the system is required for tuning the controller parameters of servo system to get the optimal performance. Recently, various modern control solutions are proposed for the speed control design of BLDC linear motor. However, Conventional PID controller algorithm is simple, stable, easy adjustment and high reliability, Conventional speed control system used in conventional PID control. But, in fact, most industrial processes with different degrees of nonlinear, parameter variability and uncertainty of mathematical model of the system. Tuning PID control parameters is very difficult, poor robustness; therefore, it's difficult to achieve the optimal state under field conditions in the actual production.

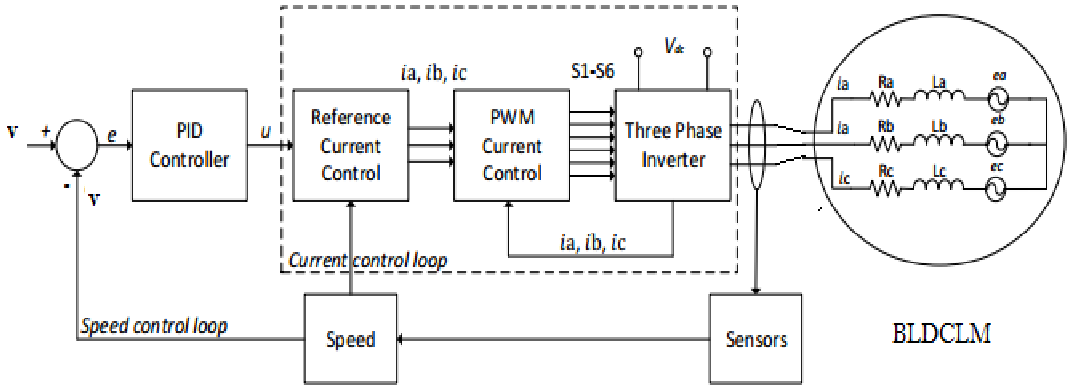

Figure 3.1: Block diagram of Linear BLDC Motor controller [44].

3.1. BLDC Motor Drive System

Generally, the BLDC motor drive system can be modeled as an electrical equivalent circuit that consists of a resistance, an inductance and back-EMF per a phase.

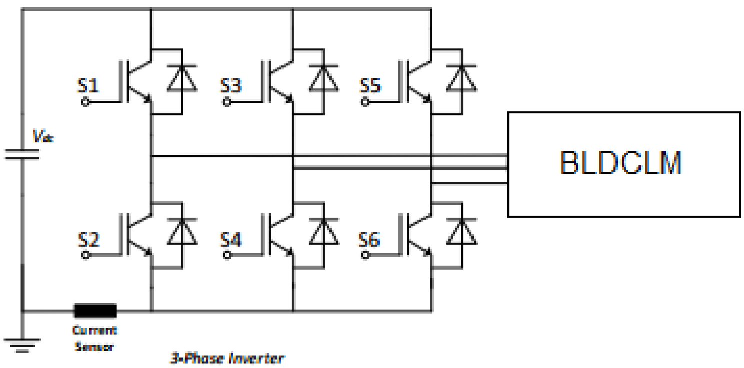

Figure 3.2: The electrical equivalent circuit of BLDC motor drive system [45].

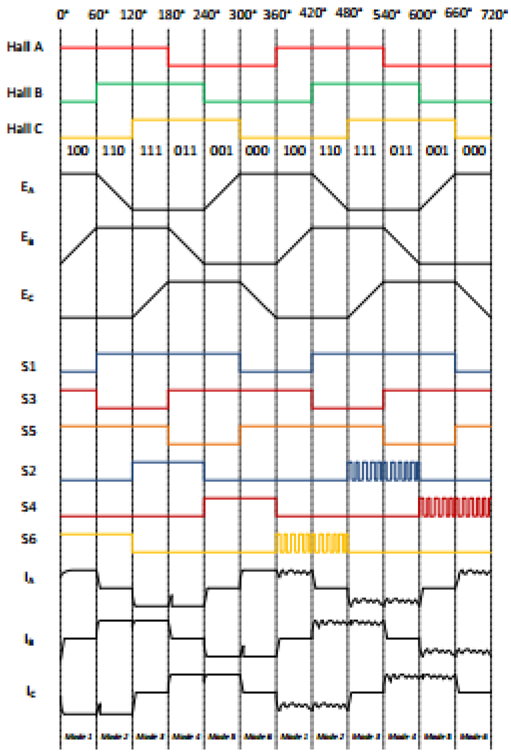

Figure 3.3: Waveforms of Hall sensors, back-EMFs, switches and phase currents [46].

As shown in Figure 3.3 BLDC motor has a trapezoid-shaped back-EMF. Therefore, when back-EMF is constant, square wave current is injected. The studied linear motor circuit is equivalent to a BLDC motor, see Figure 3.4.

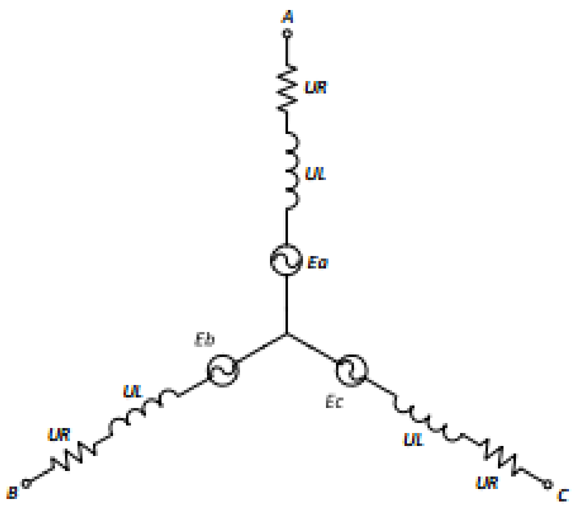

Figure 3.4: Representation of three-phase BLDC motor [37].

Table 3.1: Three phase reference current generation sequence [46].

θ_e (deg)	i_{aref}	i_{aref}	i_{aref}
0_60	i_{ref}	$-i_{ref}$	0
60_120	i_{ref}	0	$-i_{ref}$
120_180	0	i_{ref}	$-i_{ref}$
180_240	$-i_{ref}$	i_{ref}	0
240_300	$-i_{ref}$	0	i_{ref}
300_360	0	$-i_{ref}$	i_{ref}

The BLDC motor drive system is operated by exciting two phases of three phases. Two switches are only operated in one mode.

A BLDC motor is driven by voltage strokes coupled with the moving coil position. These strokes must be properly applied to the active phases of the three-phase winding system so that the distance between the moving coil flux and the permanent magnets flux is kept close to 90° to get the maximum generated force. Therefore, the controller needs some means of determining the moving coil's position, such as Hall-effect sensors, which are mounted in moving coil to detect the magnetic field of the passing permanent magnets. Each sensor outputs a high level for 180° of an electrical rotation, and a low level for the other 180°. The three sensors have a 60° relative offset from each other. This divides a rotation into six phases (3-bit code) [47].

The process of switching the current to flow through only two phases for every 60 electrical degree rotation of the rotor is called *electronic commutation*. The motor is supplied from a three-phase inverter, and the switching actions can be simply triggered by the use of signals from position sensors that are mounted at appropriate points in moving coil. When mounted at 60 electrical degree intervals and aligned properly, Hall switches deliver digital pulses that can be decoded into the desired three-phase switching sequence [31]. Figure 3.3.

The fault tolerant system is achieved by this operating characteristic. Assuming that self and mutual inductances are constant, the voltage equation of three phases is given by;

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} R_a & 0 & 0 \\ 0 & R_b & 0 \\ 0 & 0 & R_c \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L_a & M & M \\ M & L_b & M \\ M & M & L_c \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \qquad \textbf{(3.1)}$$

The mathematical model of the BLDC motor is based on the following assumptions:

- Star winding connection;
- The motor is operated within the rated condition and hence the saturation effect due to current level is neglected;
- Iron losses are negligible;
- Stator resistances of all the windings are equal and self and mutual inductances are constant.

3.2. Mathematical Formulation

Under these assumptions, the BLDC motor can be represented as:

$$u_a - u_0 = R_a.i_a + \frac{d}{dt}(L_a.i_a + M.i_b + M.i_c) + e_a \quad \textbf{(3.2)}$$

$$u_b - u_0 = R_b.i_b + \frac{d}{dt}(M.i_a + L_b.i_b + M.i_c) + e_b \quad \textbf{(3.3)}$$

$$u_c - u_0 = R_c.i_c + \frac{d}{dt}(M.i_a + M.i_b + L_c.i_c) + e_b \quad \textbf{(3.4)}$$

Where: $u_a, u_{b,} u_c$ - phase winding voltages; u_o - differential voltage between the central point of the star connection of motor winding and the power stage natural zero; R_a , R_b and $R_{c,}$-resistance od phase a,b and c; I_a, I_b and I_c- phase currents; L_a , L_b, L_c - self-inductance of phase a, b and c ; M - mutual inductance; e_A, e_B, e_C - trapezoidal shaped Back-EMFs.

The voltage in the central point of the star connection of motor winding is as follows:

$$u_0 = \frac{1}{3}\sum_{j=a,b,c} u_j - \sum_{j=a,b,c} e_j \quad \textbf{(3.5)}$$

Assuming that: $I_a + I_b + I_c = 0$, and considering concentrated winding configuration the mutual inductance is negligibly small, and based on the initial assumptions − the equations (3.2),(3.3),(3.4) can be rewritten in the form:

$$u_a - u_0 = R_a.i_a + L_a\frac{di_a}{dt} + e_a \quad \textbf{(3.6)}$$

$$u_b - u_0 = R_b.i_b + L_b\frac{di_b}{dt} + e_b \quad \textbf{(3.7)}$$

$$u_c - u_0 = R_c.i_c + L_c\frac{di_c}{dt} + e_c \quad \textbf{(3.8)}$$

The electromagnetic force is expressed as:

$$F_e = \frac{e_A . i_A + e_B , i_B + e_C . i_C}{v} \quad \textbf{(3.9)}$$

And, the interaction of F_e with the load force determines how the motor speed builds up:

$$m \frac{dv}{dt} = F_e - F_{load} - D.v \quad \textbf{(3.10)}$$

Where: F_l - load force; m - mass; D - damping coefficient; v - velocity.

Below is the mathematical formulation that describes the motor dynamics of it. The formula is similar to a rotational motor equation. The dynamics of a rotational motor can be written in the following way:

$$T_m = J \frac{d\omega}{dt} + T_{load} + B.\omega \quad \textbf{(3.11)}$$

Modifying the equation *(knowing that T=F x r)* by excluding one dimension *(r)*, the new equation can be obtained and fed to the linear motor. The formulas can be found below;

$$F_m = m \frac{dv}{dt} + F_{load} + D.v \quad \textbf{(3.12)}$$

$$F_m(s) = s.m.v(s) + D\ v(s) + F_{load}(s) \quad \textbf{(3.13)}$$

Equation 3.13 describes the motor dynamics in the frequency domain, where $F_m(s)$, $F_{load}(s)$ and *v(s)* describe the Laplace transform of F_m, F_{Load} and v respectively.

The dynamic equation states that the force acting on the moving unit includes an effect due to mass, a frictional component and a force corresponding to a mechanical load driven by the motor (F_{Load}).

According to electrical formulation the basic equations of the DC motor is the set of equations which are reported here, constitutes a model of the DC motor, which may 6 be represented as a nonlinear dynamic system. The main restrictions of this model, with respect to a real motor are;

1. The assumption that the magnetic circuit is linear (such an assumption is approximate, since the metal parts are not perfectly smooth and there is some flux dispersion inside the motor, moreover, due to saturation of the metal, does not hold for high values of i);
2. The assumption that the mechanical friction is only linear in the motor speed; namely, only viscous friction is assumed to be present in the motor (such an assumption is approximate since Coulomb friction is usually experienced in motors).

In a DC motor, the magnetic flux is generated by windings located on the stator. Although the physical reason why electrical power is transformed in mechanical power, the actual implementations of this result are various, as a matter of fact. In this handout, a simple model, which applies to the above cases (provided proper transformations are performed on the system variables) will be introduced. The stator of the motor will be assumed to have a single coil characterized by an inductance L_e due to the windings and a resistance R_e due to dispersions in the conductor. The equation associated with such an electric circuit is given by;

$$V_e(t) = L_e \frac{di_e}{dt} + R_e i_e + e \tag{3.14}$$

Since relation (3.10) is linear, by transforming in the Laplace domain the signals, it can be written,

$$\frac{i_e(t)}{v_e(t) - e} = \frac{K_e}{1 + T_e s} \tag{3.15}$$

Where $K_e = \frac{1}{R_e}$ is the stator gain and $T_e = \frac{L_e}{Re}$ is the stator time constant.

3.3. Experiments of the Study

All experiments are conducted at the ITU Electrical Machines Laboratory with the motor fixed in a stable position as shown in Figure 3.5.

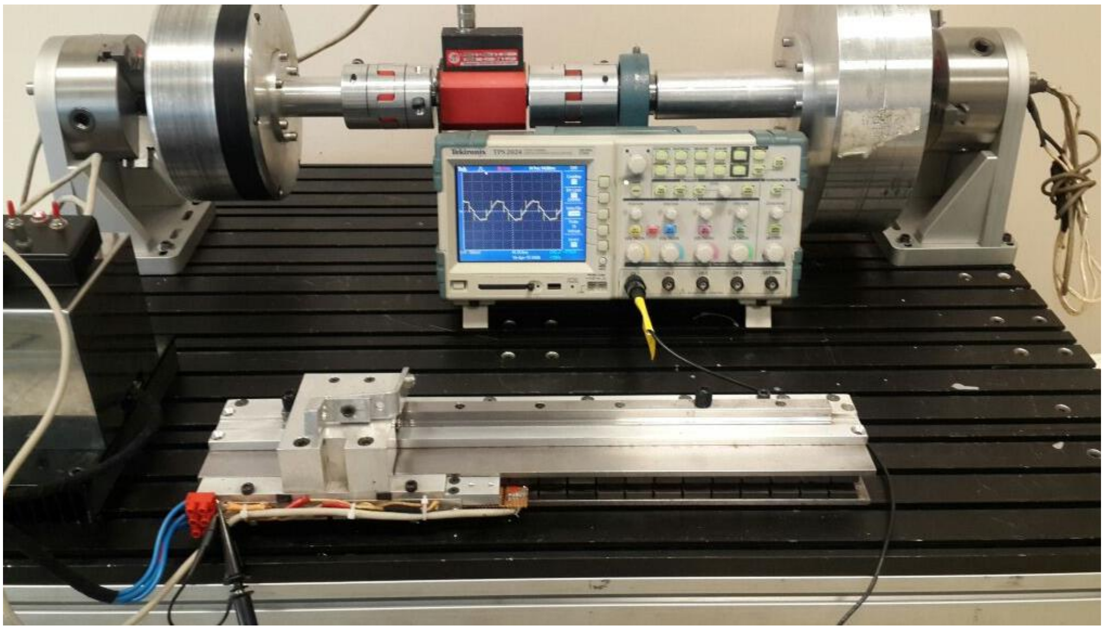

Figure 3.5: Motor test bench (Mekatro Lab.).

The initial testing aimed at estimating the current force relation of the motor to obtain accurate measurements of the force for a given current, the test was repeated three times for each different coil position. Then the motor current and voltage curves were gathered from an oscilloscope in no-load and loaded conditions of the motor. Based on the measured current force relation, the $k\emptyset$ value of the motor can be calculated. Further experiments were performed to identify the wire resistance and inductance.

Testing Force - Current Relation

The first test was to get the current–force curve of the motor under load. For these test runs the motor operated at fixed current values ranging from 1A to 20A in 1A steps. For each current input the corresponding motor force is measured. It shall be emphasized that the tests needed to be conducted in a timely fashion, as the motor heats up quickly under higher loads. The nominal friction of the system and the pull-out force are estimated to be 5N and 5.6N, respectively. This test was repeated three times, each time at a different coil position to ensure consistent measurements and reduce the chance of procedural errors.

After performing the tests for different positions of the motor, the mean of the three curves is calculated.

Table 3.2: Moving force - current graph, calculated for the average values of the three tests.

Test No.	Average Current Value (A)	Average Force Value (N)
1	1	11,13
2	2	13,80
3	3	21,00
4	4	29,40
5	5	37,87
6	6	46,33
7	7	54,53
8	8	63,00
9	9	71,67
10	10	79,87
11	11	87,57
12	12	97,00
13	13	104,73
14	14	113,00
15	15	121,47
16	16	129,93
17	17	138,20
18	18	146,80
19	19	156,07
20	20	163,80

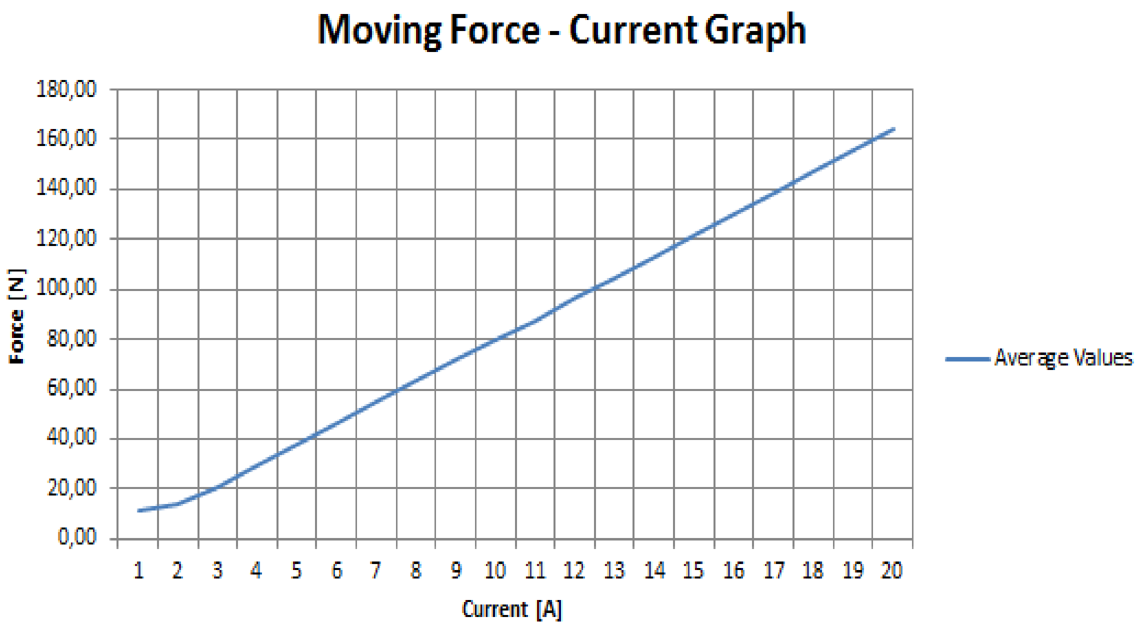

Figure 3.6: Moving force - current graph, plotted for the average values of the three tests.

The experiments show that test runs produce consistent measurements within the expected tolerance limit.

From the curve, it is visible that force is directly proportional and linear outside the very low current regime.

3.4. Motor Free Running Tests (Constant PWM)

The next set of experiments consists of motor free running tests. No mechanical load is applied to the motor during the experiment. In this section the measured moving coil voltage and current waveforms will be shown and investigated. The results are captured using an oscilloscope. Only signals in one phase are captured from the oscilloscope. The inverter of the motor drive has a 3V DC source and the switching frequency of the inverter is 10 kHz. The reason to select 3V is to find a reasonable speed for the motor, so that the results are visible in the oscilloscope. The results are shown in the following figures.

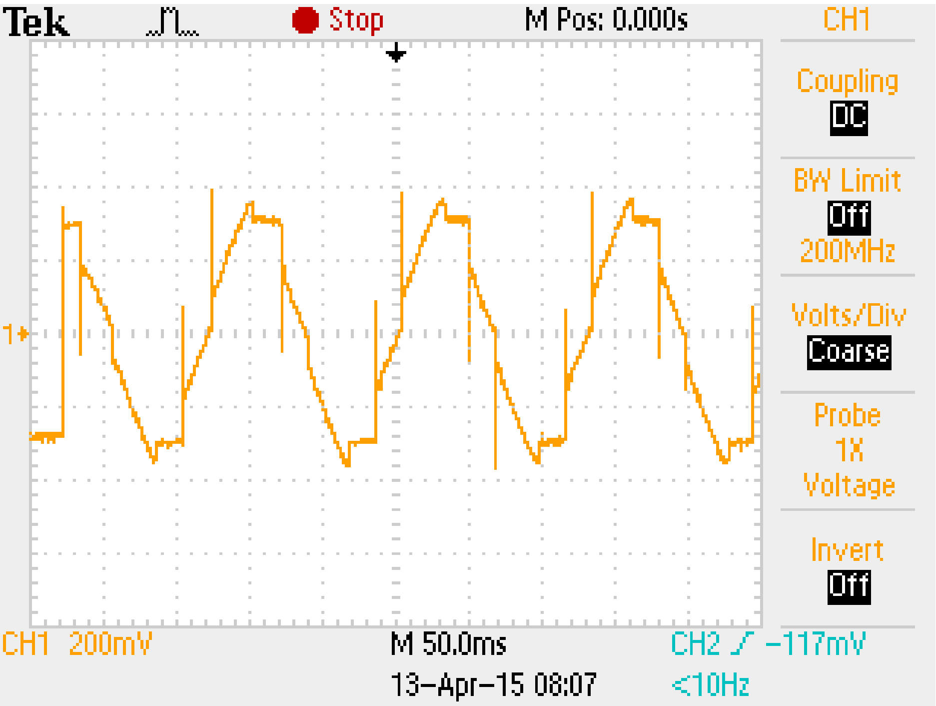

Figure 3.7: Rotor voltage waveform on free running.

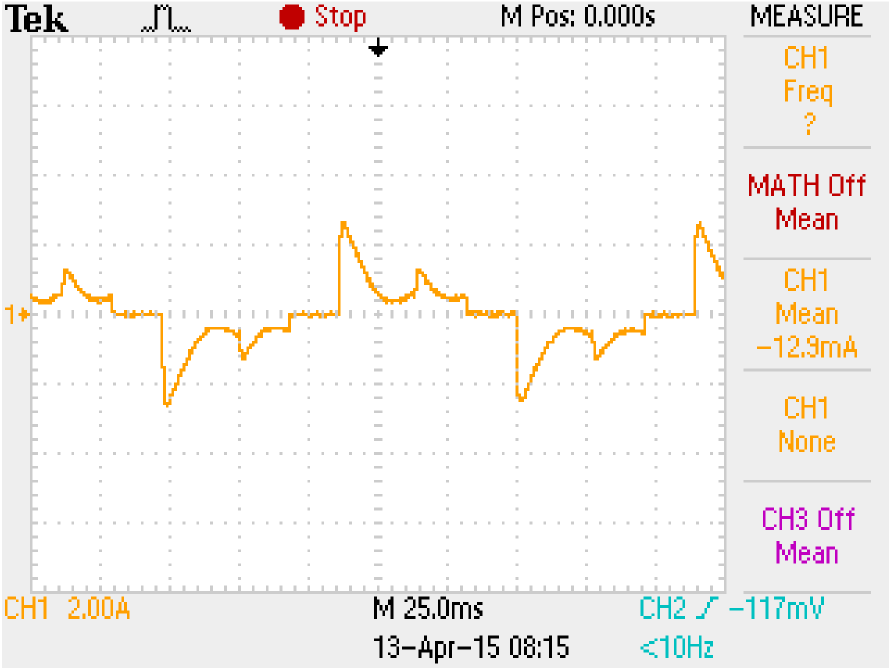

Figure 3.8: Rotor current waveform on free running.

The measured peak value of the current is 2.64A.

Chopped tests were also performed. First the PWM signal with the duty cycle of 70% is used to get the current curve without load. Then the PWM duty cycle is increased to 80% to get the voltage waveform for the same condition in free running mode of the motor.

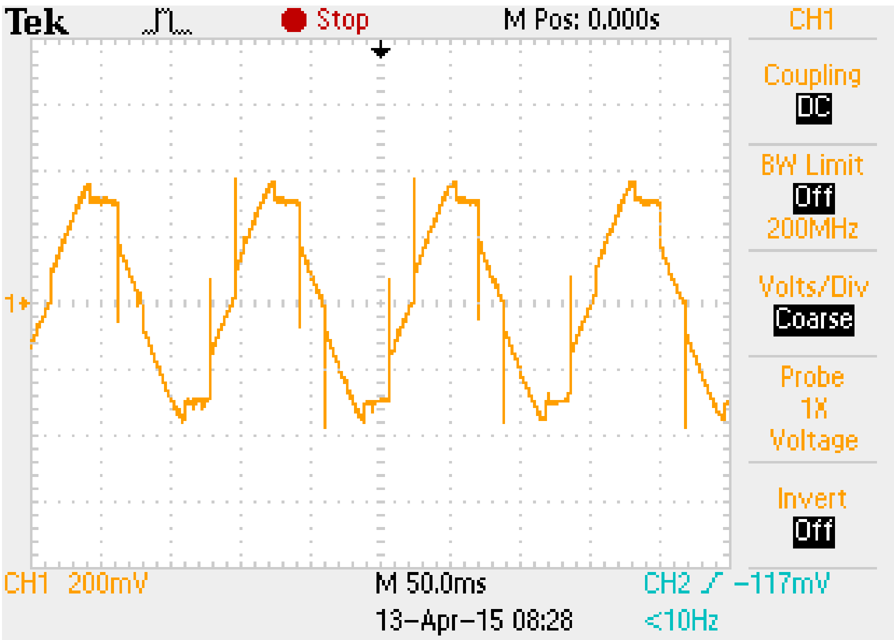

Figure 3.9: Rotor voltage waveform by 80% PWM duty cycle on free running.

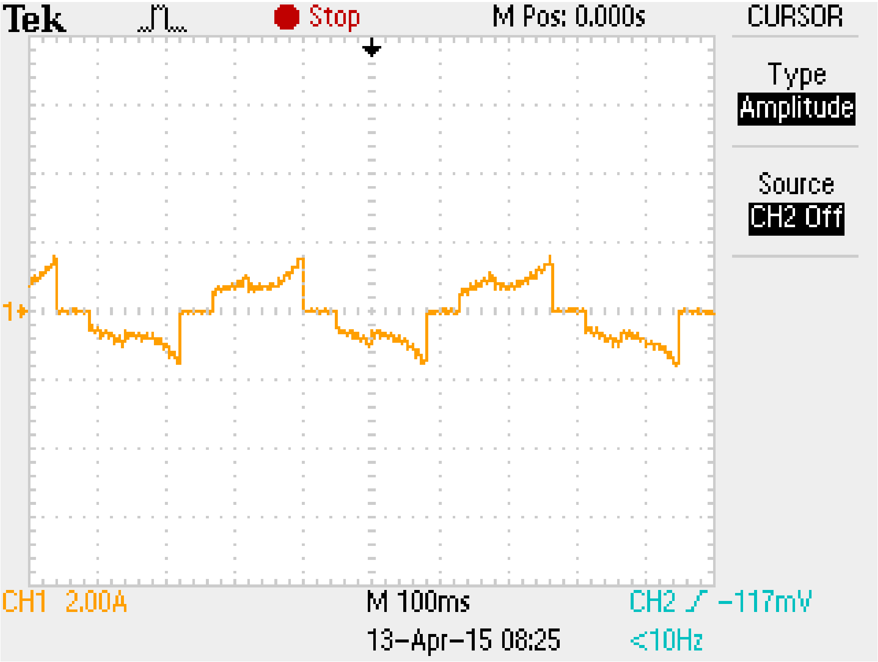

Figure 3.10: Rotor current waveform by 70% PWM duty cycle on free running.

3.5. Motor Tests Under Load (Constant PWM)

. After increasing the inverter DC link voltage up to 5V and changing the PWM duty cycle to 100%, the rotor voltage and current waveforms are captured by an oscilloscope. 120 degrees commutation pattern is used to control the motor drive. The spikes occur during the switching of the other two phases.

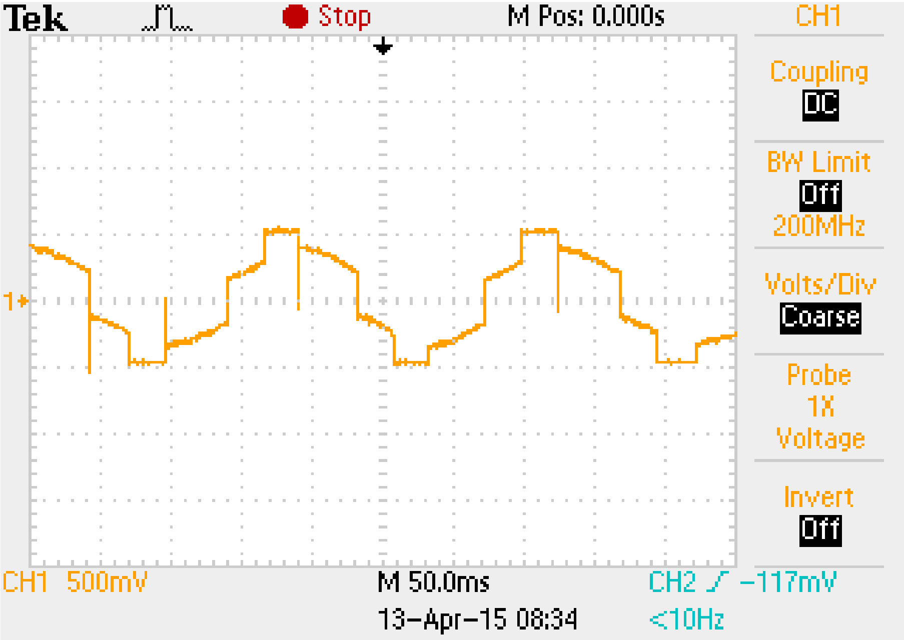

Figure 3.11: Rotor voltage waveform by 100% PWM duty cycle.

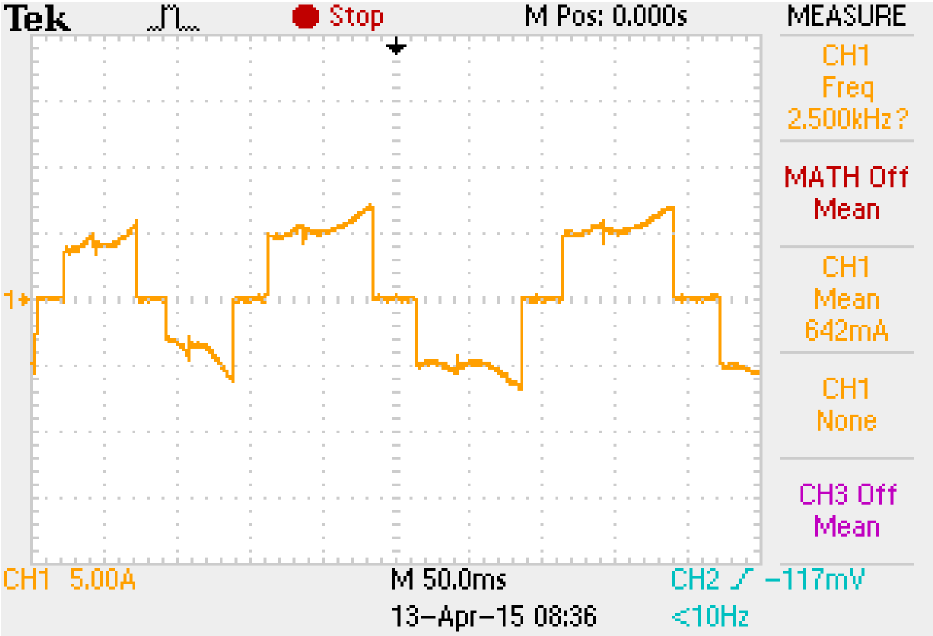

Figure 3.12: Rotor current waveform by 100% PWM duty cycle.

The motor under investigation is a PM linear motor with sinusoidal back-emf. To prove this the back-emf wavefrom is measured during the open circuit voltage test. The fact that rotor voltage waveform by 100% PWM duty cycle under load is not sinusoidal, is due to the effect of excitations provided by the inverter circuit (120 degrees trapezoidal commutation pattern).

Further tests were conducted to measure the inductance and the resistance of the coils. The wire resistance values of the three phases were also measured at 26 degrees Celcius room temperature.

The inductances and the resistance values of the coils for three phases are listed in Table 3.3.

Table 3.3: Measured inductance and the resistance values of the coils.

Phase	**Inductance Value (mH)**	**Resistance Value (mΩ)**
A	144.5	310
B	131.8	290
C	144.4	304

3.6. Calculating the kØ Value by Using Current-Force Plots

The relationship between the force and the current is given by the following equation:

$$F_e = k.\emptyset.i \tag{3.16}$$

The output force is the difference between electrical force and the pull-out force.

$$F_{out} = F_e - F_{pull-out} \tag{3.17}$$

It has been calculated the pull-out force as 5.6N as stated previously in this chapter. Starting from 10A, the $k\emptyset$ values are calculated for each current-force result pair. The average value of the $k\emptyset$'s from the 10 results were calculated again. The average value of $k\emptyset$ was 8.48.

4. LINEAR BRUSHLESS DC MOTOR MODEL

4.1. Block Diagram of Linear BLDC Motor

By implementing chapter III equations in a nonlinear block diagram, the result shown in Figure 4.1 is obtained. In the block diagram, the variable x represents the moving coil position.

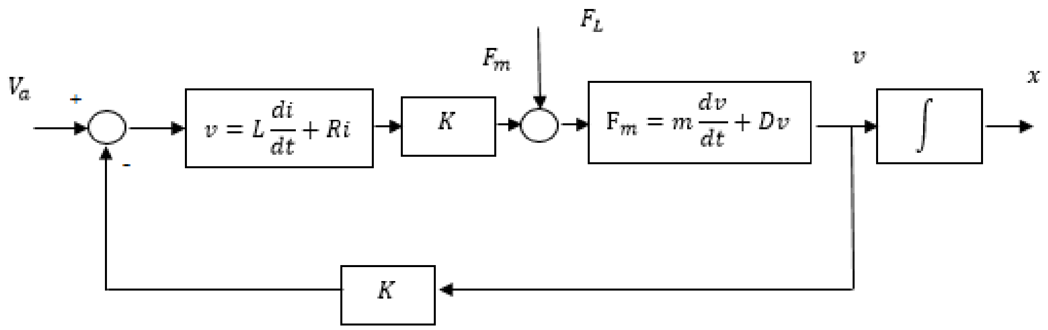

Figure 4.1: Nonlinear block diagram of a linear BLDC motor.

Transfer Function

The linear block diagram of the system can be easily computed by specializing the block diagram.

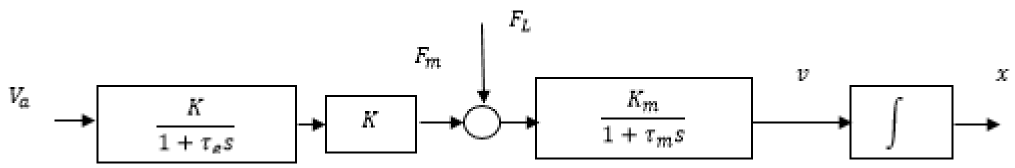

Figure 4.2: Block diagram of the DC motor with constant current.

$$X(s) = [W_1(s) \quad W_2(s)] \begin{bmatrix} v(s) \\ F_l(s) \end{bmatrix} \tag{4.1}$$

Where

$$W_1(s) = \frac{K_{AC}}{s(1+\tau_e s)(1+\tau_m s)}, \qquad K_{AC} = K_e K K_m i_a. \tag{4.2}$$

$$W_2(s) = \frac{K_m}{s(1+\tau_m s)}, \tag{4.3}$$

As remarked above, the motor damping may, in many cases, be negligible. So that the mechanical time constant approaches infinity. In such a case, it has been noticed that there is no steady state value for the speed v. This can be here motivated by the fact that the transfer function related to the speed $\frac{\omega(s)}{v_e(s)} = \frac{K_{AC}}{s(1+T_e s)}$ has a pole at the origin.

The current control renders linear the nonlinear block diagram in Figure 4.1, it is of interest to compute the transfer function of the motor between the input v and the output V (or, equivalently, x) and the transfer function between the disturbance input F_L and the same output. It is once more stressed that, due to the feedback action of the back EMF, the system is a velocity control system, as a matter of fact, besides the action of the disturbance F_L, the speed V, at the steady state, is proportional to the input signal v with a steady-state error depending on the R resistance between two phase.

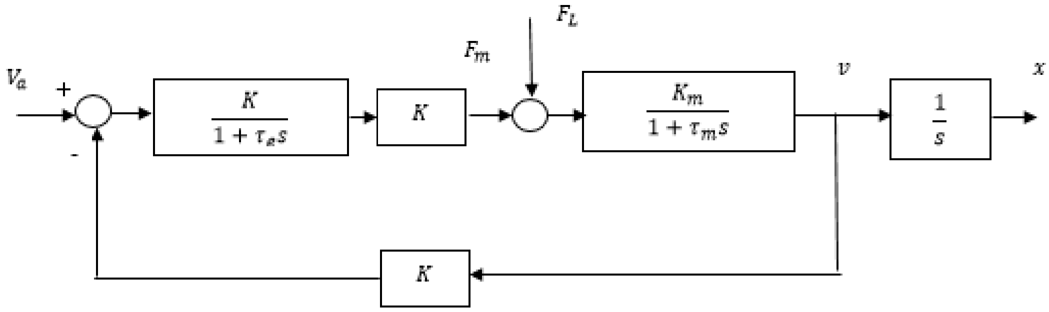

Figure 4.3: Block diagram of the linearization of the DC motor under current control.

The transfer matrix of the system may be written as;

$$V(s) = \begin{bmatrix} W_1(s) & W_2(s) \end{bmatrix} \begin{bmatrix} v(s) \\ F_l(s) \end{bmatrix} \tag{4.4}$$

Where

$$W_1(s) = \frac{K \,.\, K_\emptyset .\, \emptyset .\, K_m}{(1+\tau_e s)(1+\tau_m s) + K \,.\, K_m (K_\emptyset \emptyset)^2} \tag{4.5}$$

$$W_2(s) = \frac{K_m(1+\tau_e s)}{(1+\tau_e s)(1+\tau_m s) + K \,.\, K_m (K_\emptyset \emptyset)^2} \tag{4.6}$$

4.2. Current Control System

The most common control technique for DC motors is the current control. Such control is performed by keeping the flux constant inside the motor. To this aim, either the stator voltage is constant or the stator coils are replaced by a permanent magnet. In the latter case, the motor is said to be a permanent magnet DC motor and is driven by means of the only moving coils [48].

Permanent magnet DC motors are totally equivalent to current-controlled DC motors; as a matter of fact, in both of them the flux Φ is constant. It can be seen that, with standard DC motors, the desired force may be obtained by increasing i (namely, the flux), or both of them. Conversely, permanent magnet motors may be controlled by means of the only available current i. This is bad from the heating point of view; as a matter of fact, the moving coils are hard to be cooled (since they are inside the motor) and, indeed, in the permanent magnet motors, are the only power source of the motor itself. Referring to Figure 4.1, note that keeping the flux constant, the block diagram becomes linear. In addition, the motor has an intrinsic negative feedback structure, when at the steady state, the speed V is proportional to the reference input v. However, several disadvantages arise from this control technique.

- Although the flux is constant (hence the back EMF never goes to zero when the motor is running), the current could take, in several cases, high values, thus bringing the motor into dangerous operating conditions. In particular, the speed of the motor could decrease to zero due to an equilibrium between the load and the motor force, or, equivalently, the current could take high values during the transient, after a step has been applied at the input. In this latter case, the mechanical time constant will delay the increase of speed Δv corresponding to the increase of voltage Δv and during this delay the current will raise at high values.
- The reference input and the power input of the motor are the same. This often leads to a trade off, between accuracy with respect to a desired reference value and maximum power exerted. As a matter of fact, the fidelity of a linear power amplifier is inversely proportional to the maximum power exerted by such power amplifier.

4.3. Speed Control System

The current controlled DC motor is intrinsically a velocity control scheme. In particular, consider the steady-state equations and the dependence of the speed v upon the values of the inputs V and F_L.

As it is considered in this study, if the load force F_L is different from zero, a steady state error will be experienced on the system. it can be shown in next chapter, the less the steady state error is large. Whence, it seems obvious to perform a control technique in which an additional speed feedback is performed. By means of a tachometer (i.e., a sensor for the measurement of the speed of the motor), an additional feedback loop is closed over the block diagram in Figure 4.3.

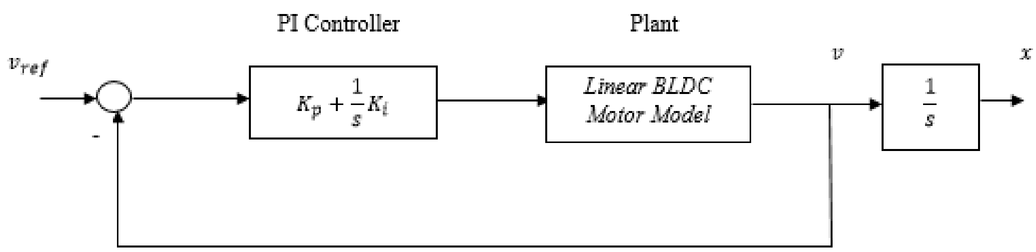

Figure 4.4: Block diagram of the speed control system for a BLDC motor**.**

It should be noticed that, with this control scheme, a steady state error is always found, although this error may be decreased as much as necessary by the choice of the best coefficient for PI controller [48].

4.4. Position Control System

With reference to the linear block diagram in Figure 4.3**,** if a feedback loop is closed between the input and the position output x, then a position regulation is performed on the system. By virtue of the fact that, as remarked above, the back-EMF effect is equivalent to a velocity feedback, the feedback gain from V which refers to the back EMF. In addition, the diagram depicted in Figure 4.6 correctly represents the behavior of the system having two feedback loops: one with respect to the motor speed and one with respect to its position.

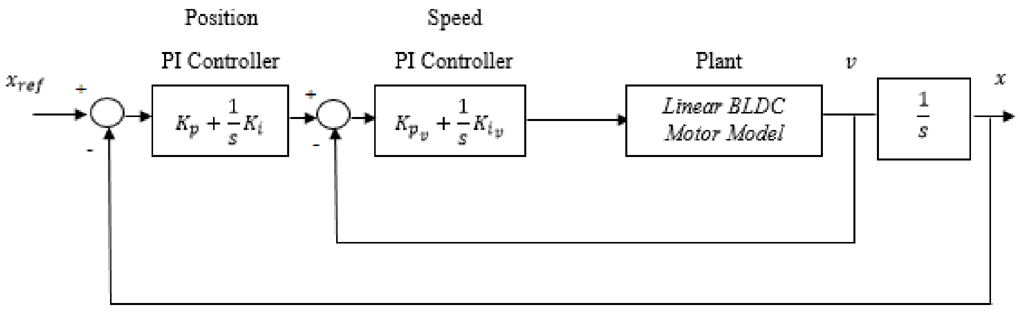

Figure 4.5: Block diagram of the position control and speed control system for a linear BLDC motor.

5. LINEAR BLDC MOTOR CONTROLLER DESIGN

This chapter covers the linear motor control part of the thesis. It aims to describe co-simulation, its procedure, advantages and drawbacks. A review of control algorithms developed for linear machines have been included in the study. The chapter also includes characteristic equations of linear machines.

The characteristics of system components can influence the overall performance and behavior of the system when integrated together. For example cogging force can cause undesired motion control and speed response. On the other hand, harmonics due to non-sinusoidal supply of a PWM inverter can increase motors losses, reducing efficiency [49].

As presented before, motion control of linear motors is a widely researched topic. A study of different control strategies for linear motors is presented here to give reader insight into the topic.

ECM-0554-112-0904-C/F Controller

As a control system it is used the ECM-5554-112-0904-C/F control module. This rugged controller is capable of operating in harsh automotive, marine, and off-highway applications, but in this thesis it is decided to use that to control the linear BLDC motor, because of the intensive ability of this controller. The module and its connector system are environmentally sealed and suitable for motor mounting in many applications. This unit provides 112 connector pins with inputs, outputs, and communications interfaces that support a wide variety of applications. The ECM-5554-112-0904 is part of the ControlCore family of embedded control systems. The rapid development of complex control systems is one of the advantages of this controller. Each controller is available in ‘F’ (Flash) or ‘C’ (Calibratible) versions. Flash modules are typically used for production purposes. Calibratible modules are typically for prototyping/development only; they can be calibrated in real time using MotoTune (Program for online calibration and tuning the control system) [50].

The system Microprocessor is Freescale MPC5554, 80 MHz. this module have 2MB Flash Memory, 64K RAM, + 32K Cache, 32K EEPROM. its Calibratible Memory is 512K (256K x2) RAM. it works at 9–16 dc voltage.

Benefits of this controller are generally;

- Simpler, faster development.
- Better testing using real ECM hardware.
- Quickly develop and enhance software features.
- Analyze and control real-time Operating System.
- Direct access to the production controller‘s I/O from software.
- Lower cost for fleet testing; outfit an entire test fleet with rapid prototyping capability.

Figure 5.1:. Motohawk controller (Mekatro Ar-Ge limited).

5.1. PID Controller

Feedback control is a control mechanism that uses information from measurements. In a feedback control system, the output is sensed. There are two main types of feedback control systems: 1) positive feedback 2) negative feedback. The positive feedback is used to increase the size of the input but in a negative feedback, the feedback is used to decrease the size of the input. The negative systems are usually stable. A PID is widely used in feedback control of industrial processes on the market in 1939 and has remained the most widely used controller in process control until today [51]. Thus, the PID controller can be understood as a controller that takes the present, the past, and the future of the error into consideration. After digital implementation was introduced, a certain change of the structure of the control system was proposed and has been adopted in many applications. But that change does not influence the essential part of the analysis and design of PID controllers. A proportional– integral–derivative controller (PID controller) is a method of the control loop feedback. This method is composing of three controllers:

1. Proportional controller (PC)
2. Integral controller (IC)
3. Derivative controller (DC)

Role of a Proportional Controller (PC)

The role of a proportional depends on the present error, I on the accumulation of past error and D on prediction of future error. The weighted sum of these three actions is used to adjust Proportional control is a simple and widely used method of control for many kinds of systems. In a proportional controller, steady state error tends to depend inversely upon the proportional gain (ie: if the gain is made larger the error goes down).

The proportional response can be adjusted by multiplying the error by a constant K_p, called the proportional gain. The proportional term is given by;

$$P = K_p.Error \quad \textbf{(5.1)}$$

A high proportional gain results in a large change in the output for a given change in the error. If the proportional gain is very high, the system can become unstable. In contrast, a small gain results in a small output response to a large input error. If the proportional gain is very low, the control action may be too small when responding to system disturbances. Consequently, a proportional controller (K_p) will have the effect of reducing the rise time and will reduce, but never eliminate, the steady-state error.

Role of an Integral Controller (IC)

An Integral controller (IC) is proportional to both the magnitude of the error and the duration of the error. The integral in a PID controller is the sum of the instantaneous error over time and gives the accumulated offset that should have been corrected previously. Consequently, an integral control (K_i) will have the effect of eliminating the steady-state error, but it may make the transient response worse.
The integral term is given by:

$$I = K_I \int_0^t Error(t)dt \tag{5.2}$$

Role of a Derivative Controller (DC)

The derivative of the process error is calculated by determining the slope of the error over time and multiplying this rate of change by the derivative gain K_D. The derivative term slows the rate of change of the controller output. A derivative control (K_D) will have the effect of increasing the stability of the system, reducing and improving the transient response. The derivative term is given by:

$$D = K_D.\frac{dError(t)}{dt} \tag{5.3}$$

Effects of each of controllers K_p, K_I and K_D on a closed-loop system are summarized in the table shown below in tableau 1.
A typical structure of a PID control system is shown in Figure 5.1. it shows a structure of a PID control system. The error signal $e(t)$ is used to generate the proportional, integral, and derivative actions, with the resulting signals weighted and summed to form the control signal $u(t)$ applied to the plant model.

Table 5.1: A PID controller in a closed-loop system [51].

Parameter	Rise Time	Overshoot	Settling Time	Steady-state error
K_p	Decrease	Increase	Small change	Decrease
K_I	Decrease	Increase	Increase	Decrease significantly
K_D	Minor decrease	Minor decrease	Minor decrease	No effect in theory

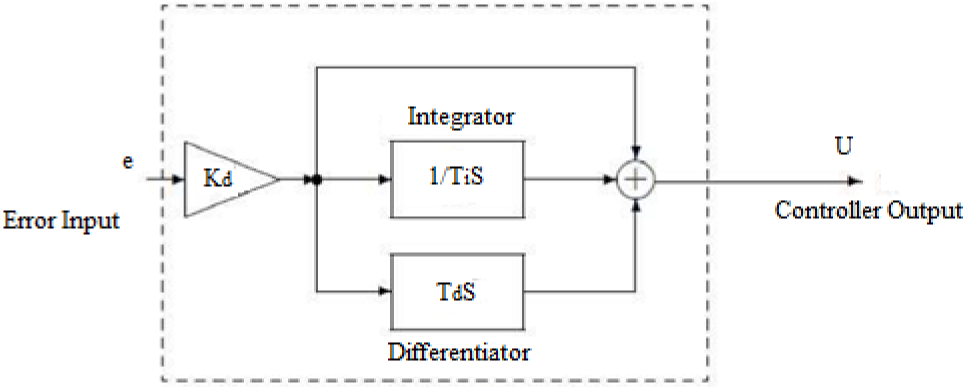

Figure 5.2:. A PID control system.

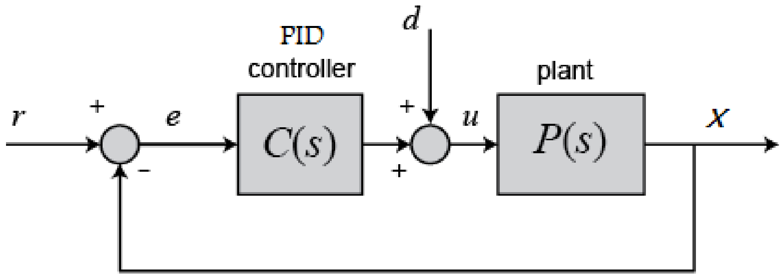

Figure 5.3: A structure of a PID control system.

Where u(t) is the input signal to the multivariable processes, the error signal e(t) is defined as e(t) = r(t) – X(t), and r(t) is the reference input signal.

A standard PID controller structure is also known as the ''three-term'' controller. This principle mode of action of the PID controller can be explained by the parallel connection of the P, I and D elements shown in Figure 5.3.

$$G(s) = K_{p.}\left(1 + \frac{1 + T_{I.}.T_D.S^2}{T_I.S}\right) = K_p(1 + \frac{1}{T_I.S} + T_D.S) \quad \textbf{(5.4)}$$

Where K_P is the proportional gain, T_I is the integral time constant, T_D is the derivative time constant, $K_I = K_P / T_I$ is the integral gain and $K_D = K_P T_D$ is the derivative gain. The ''three-term'' functionalities are highlighted below. The terms K_P , T_I and T_D definitions are:

- The proportional term: providing an overall control action proportional to the error signal through the all pass gain factor.
- The integral term: reducing steady state errors through low frequency compensation by an integrator.

- The derivative term: improving transient response through high frequency compensation by a differentiator.

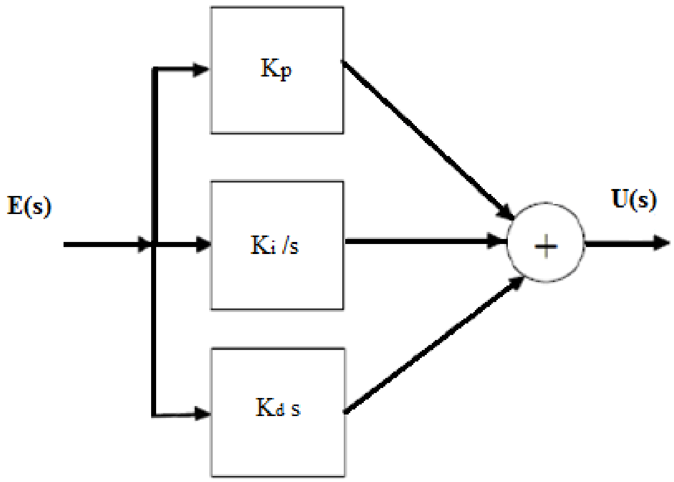

Figure 5.4: Parallel Form of the PID Compensator.

These three variables K_p, $T_I$and T_D are usually tuned within given ranges. Therefore, they are often called the *tuning parameters* of the controller. By proper choice of these tuning parameters a controller can be adapted for a specific plant to obtain a good behaviour of the controlled system.

The time response of the controller output is;

$$U(t) = K_p(e(t) + \frac{\int_0^t e(t)\,dt}{T_I} + T_d\frac{de(t)}{dt}) \quad \textbf{(5.5)}$$

Using this relationship for a step input of $e(t)$, i.e. $e(t) = \delta(t)$, the step response r(t) of the PID controller can be easily determined.

5.2. The Ziegler-Nichols Tuning Method

The Ziegler–Nichols tuning method is a heuristic method of tuning a PID controller. It was proposed by John G. Ziegler and Nichols in the 1940's [52]. It is performed by setting I (integral) and D (derivative) gains to zero. The P (proportional) gain, K_p is then increased (from zero) until it reaches the ultimate gain K_u, at which the output of the control loop oscillates with a constant amplitude. K_u and the oscillation period T_u are used to set the P, I, and D gains depending on the type of controller used [51,53].

Table 5.2 : Ziegler-Nichols Method [51].

Control Type	K_p	K_I	K_D
P	$K_u/2$	-	-
PI	$K_u/2.2$	$1.2\,K_p/T_u$	-
PID	$0.6K_u$	$2\,K_p/T_u$	$K_pT_u/8$
Overshoot	$0.33K_u$	$2\,K_p/T_u$	$K_pT_u/3$
No overshoot	$0.2K_u$	$2\,K_p/T_u$	$K_pT_u/3$

5.3. Position Control System Resolution

For reading motor position data, a displacement encoder is used, Festo MLO-POT-225-TLF (152625) with analog output (0-5V) and an A/D converter is used. Motor length is 295mm.

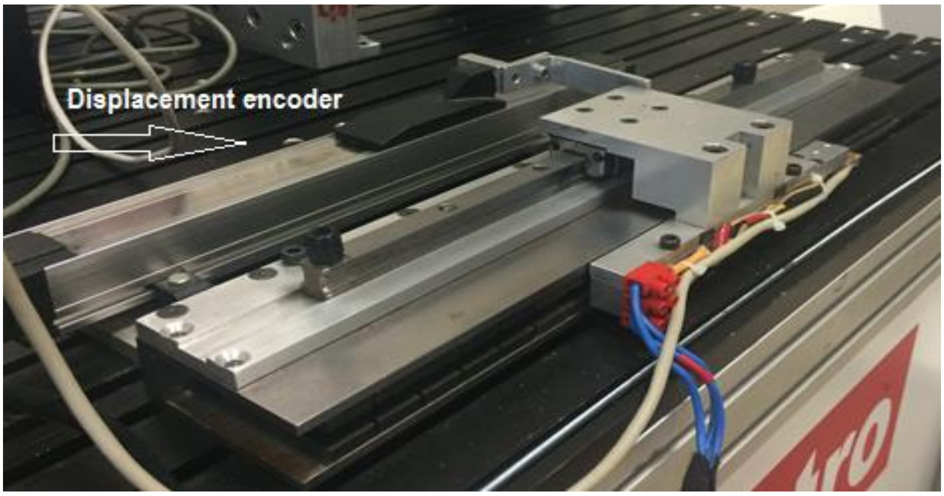

Figure 5.5: Mounted displacement encoder to the motor on test bench.

The A/D converter features which is used, with 2^{10} bit digital output. The smallest change in analog signal that will result in a change in the digital output is called resolution.

$$\Delta V_r = \frac{V_r}{2^N} \tag{5.6}$$

V_r = Reference voltage range

N = Number of bits in digital output

2^N = Number of states

ΔV = Resolution

The resolution represents the quantization error inherent in the conversion of the signal to digital form.

As you know it has seen displacement here such as voltage, that with handheld computing can be seen that the resolution is about .00488 V, which if convert this amount to meter, it means A/D resolution in terms of meter is about .288 mm, so the maximum steady state error will be about 288 micron in this study program.

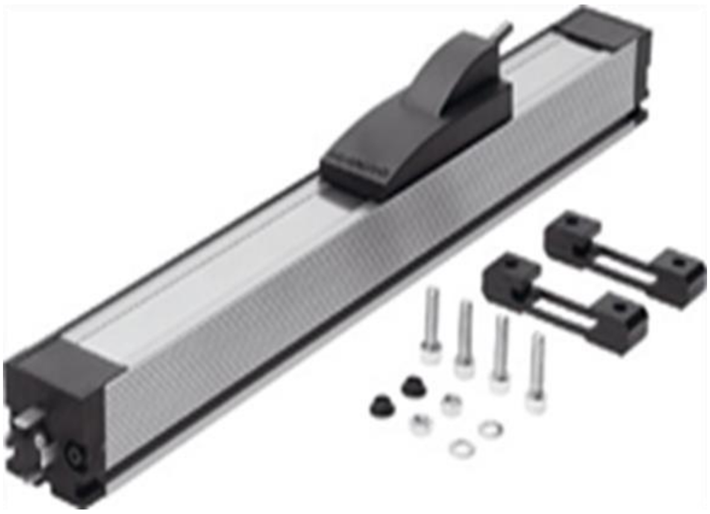

Figure 5.6: Potentiometer [54].

5.4. Control System Simulation Results

System simulation is done by VISSIM software. According to measurments in Chapter III they are used to in the simulation to get the best result in VISSIM program as simulator.

VISSIM is widely used in control system design and digital signal processing for multidomain simulation and design. It includes blocks for arithmetic, Boolean, and transcendental functions, as well as digital filters, transfer functions, numerical integration and interactive plotting. The most commonly modeled systems are aeronautical, biological/medical, digital power, electric motor, electrical, hydraulic, mechanical, process, thermal/HVAC and econometric.

VISSIM Simulation is used for plant model to optimize common operating parameters such as PID values with off-line tuning. Just insert parameter unknown blocks for the parameters that it is desired to optimize; then construct the objective function to be minimized using standard VISSIM blocks.

Typical objective functions consist of integrating the square of the set point error with an overshoot penalty factor to ensure system stability.

When it has been simulated with optimization enabled, VISSIM iterates the diagram over the specified operating region, trying different values of the parameters. Using sophisticated, tunable, nonlinear, gradient descent search methods, VISSIM determines the combination of parameter values that minimize the objective function. VISSIM's fast computational engine is well-suited to speeding up the compute intensive nature of iterative solvers.

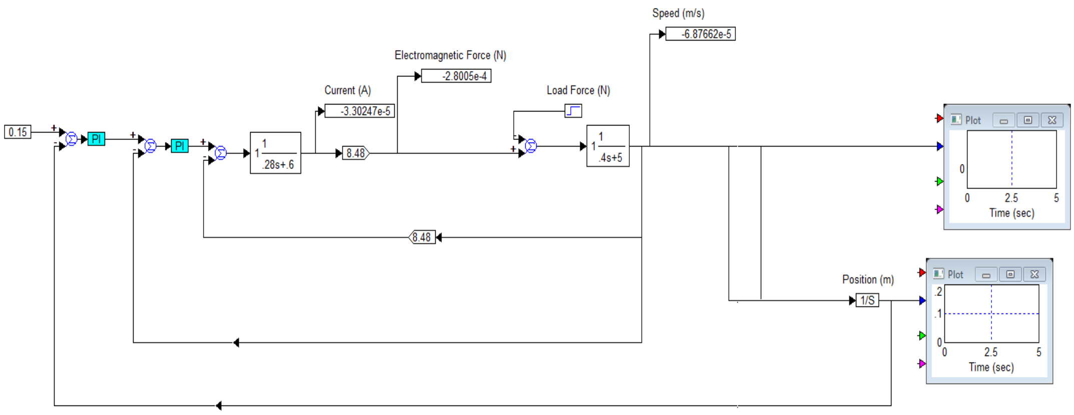

Figure 5.7: Schematic of simulation block diagram in Vissim program.

Below Figures are shown the speed diagram and position diagram of the system (Figure 5.8, 5.9 and 5.10.).

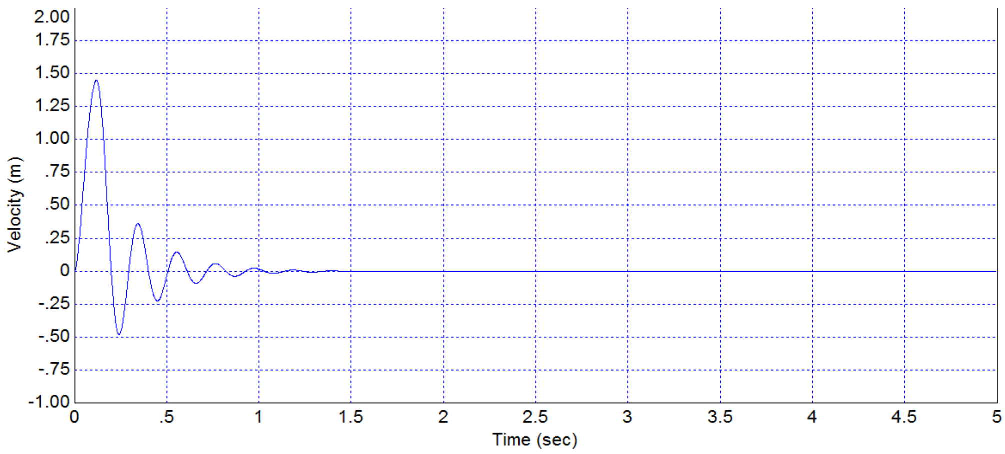

Figure 5.8: System's speed diagram with Position controller.

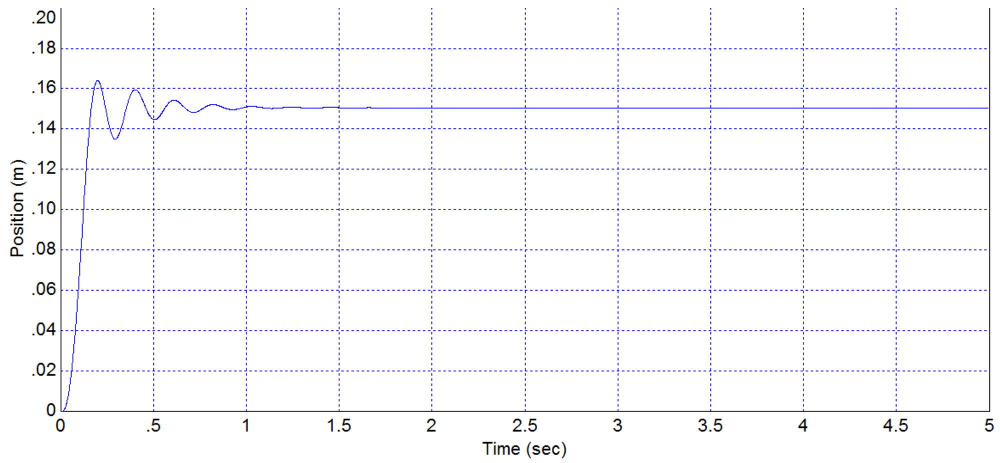

Figure 5.9: System's Position diagram with Position controller.

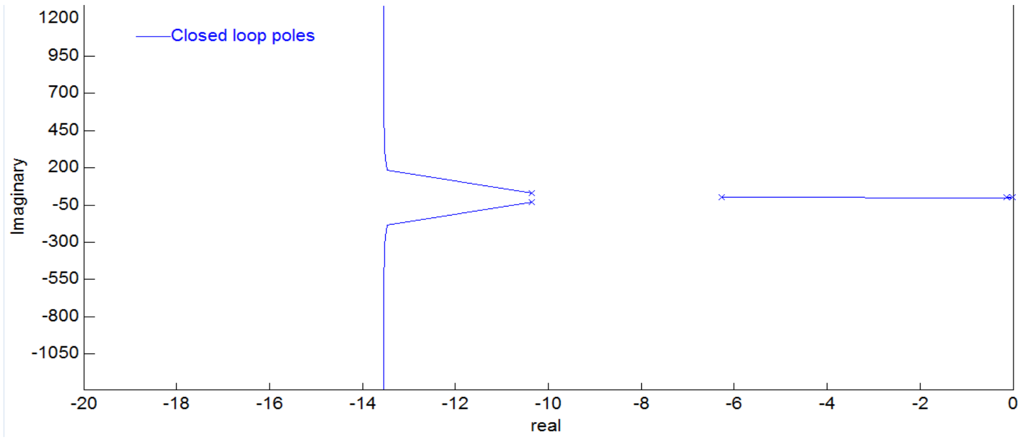

Figure 5.10: System root locus diagram with position controller.

It is considered that the diagrams according to position and speed diagrams system have completely logical answer. System is stable with good precision. It has been desired to have current control and speed control in the system, to have more controllable, more accurate, applicable and faster system. The results can be improved by using an inner current control loop.

As it can be seen the oscillatiory behaviour of controlled position is quite remarkable due to the interaction of mass and friction coefficient. But real behaviour of frictional nature of used linear bearing is much complicated. A more comprehensive modeling effort is needed to simulate the system including nonlinear behaviour of mechanical system.

In second step, simulation result of system with designed speed controller and position controller, is shown below.

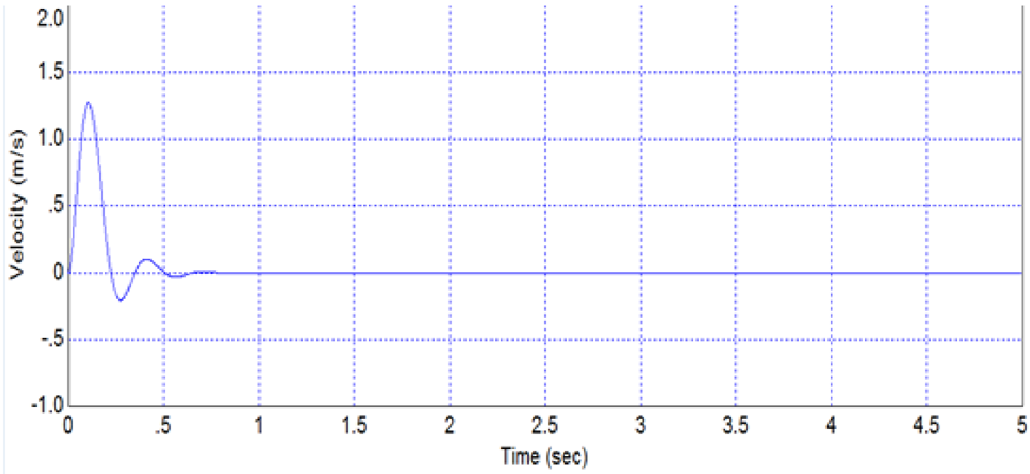

Figure 5.11: System's speed diagram with speed controller.

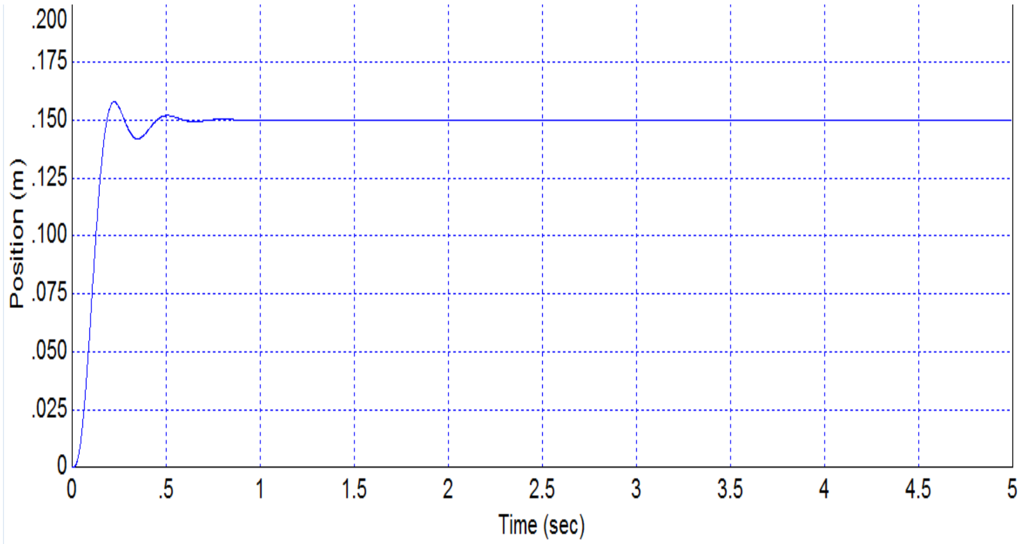

Figure 5.12: System's Position diagram with speed controller.

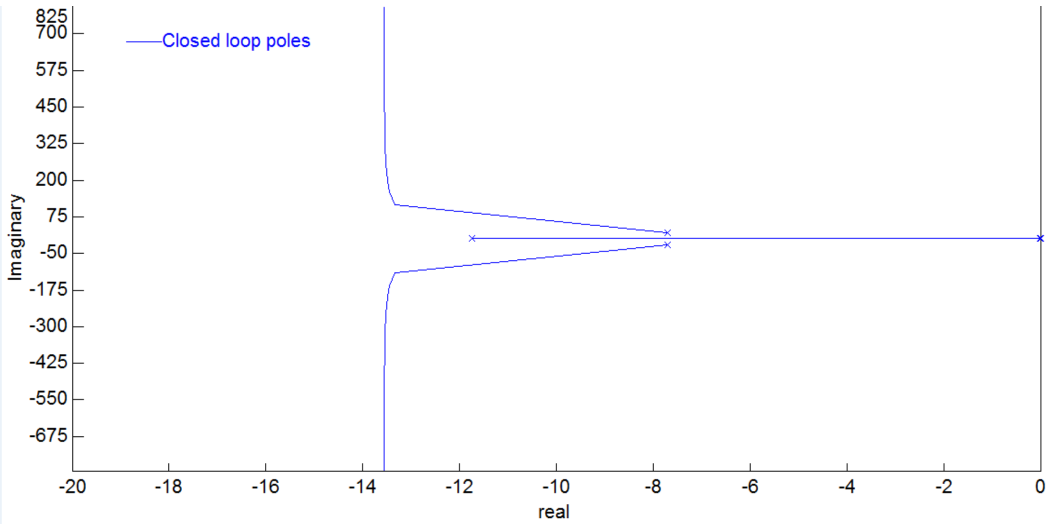

Figure 5.13: System root locus diagram with speed controller.

According to above diagrams it can be seen that the system is faster than before with speed and position control, so as simulation illustrate us speed steady state error is negligible and position steady state error is below 288 micron.

5.5. Motor Position and Speed Precision Test Results

The tests are done to get the result of simulation, so mechanical load is applied to the motor during the experiment, 98 N (10 kg). Below diagrams show three test results, each time from set point (x=0) to a different position, such as long distance, medium distance and short distance, to ensure measurement of motor precision position control, with consistency of the experimental data and it is compared between the simulation model and the experimental data.

Tests are done for examine speed controller, it was repeated three times, each time from set point (x=0) to a different position, such as long distance, medium distance and short distance, to ensure measurement of motor speed.

The first tests are done for a long distance as you see in Figure 5.14 ,Figure 5.15 and Figure 5.16.

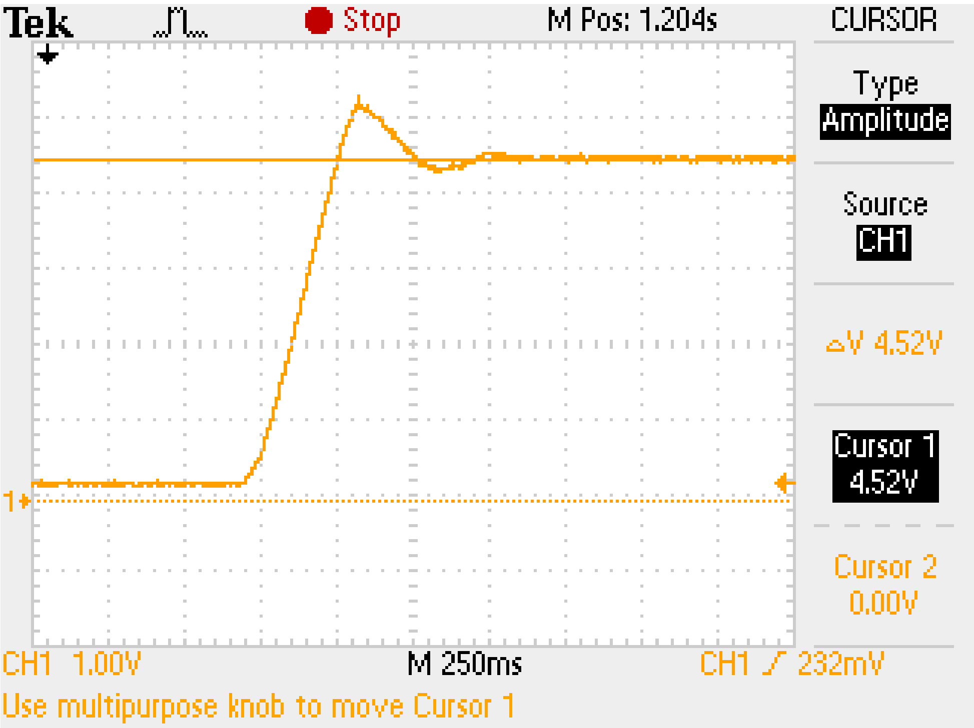

Figure 5.14: System Position Test for Long Distance_ Oscilloscope screen (from x = 0 to x = 268 mm).

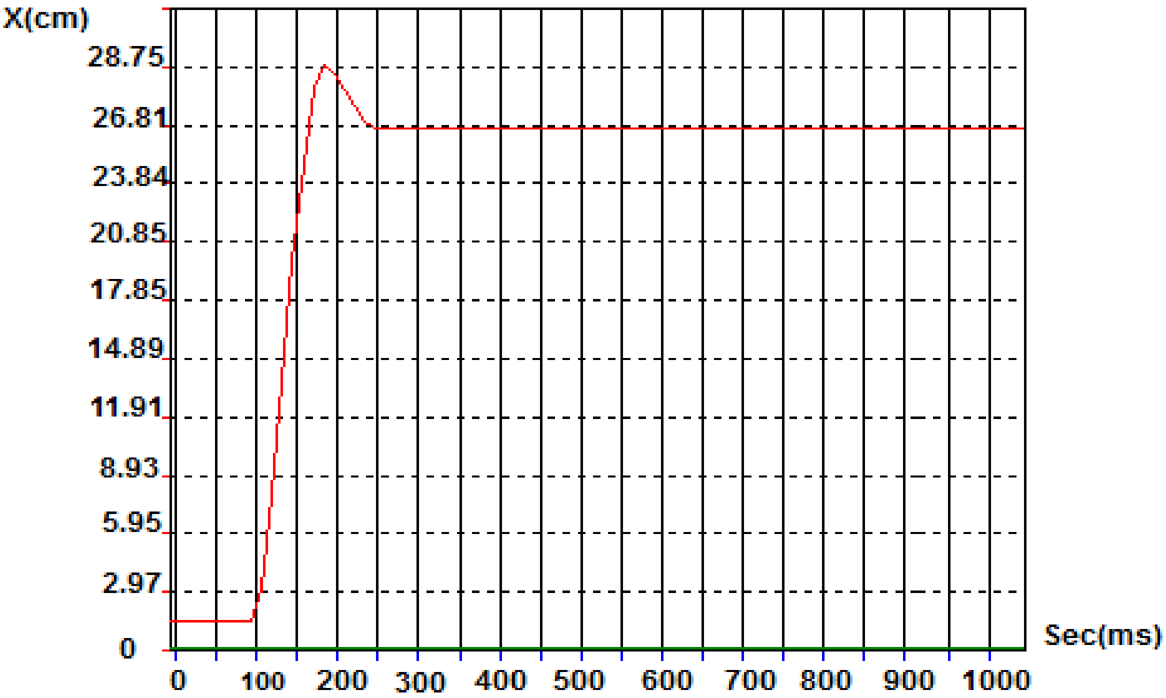

Figure 5.15: System Position Test for Long Distance (from x = 0 to x = 268 mm).

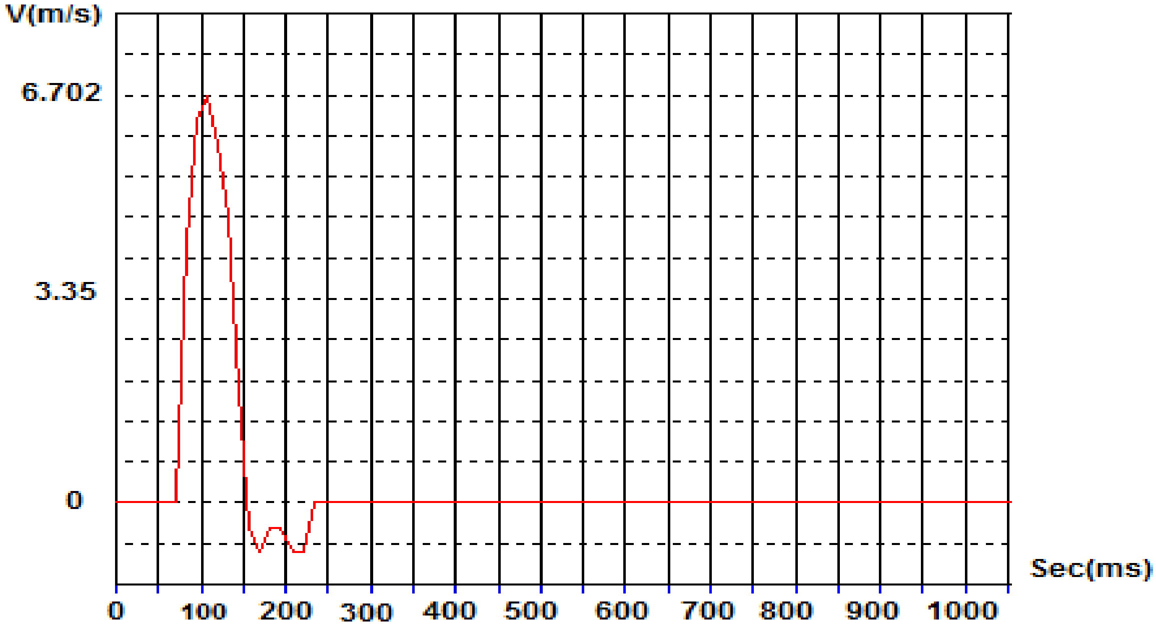

Figure 5.16: System Speed Test for Long Distance (from x = 0 to x = 268 mm).

The same tests are performed for the medium distance mode. The results can be seen in Figure 5.17, Figure 5.18 and Figure 5.19.

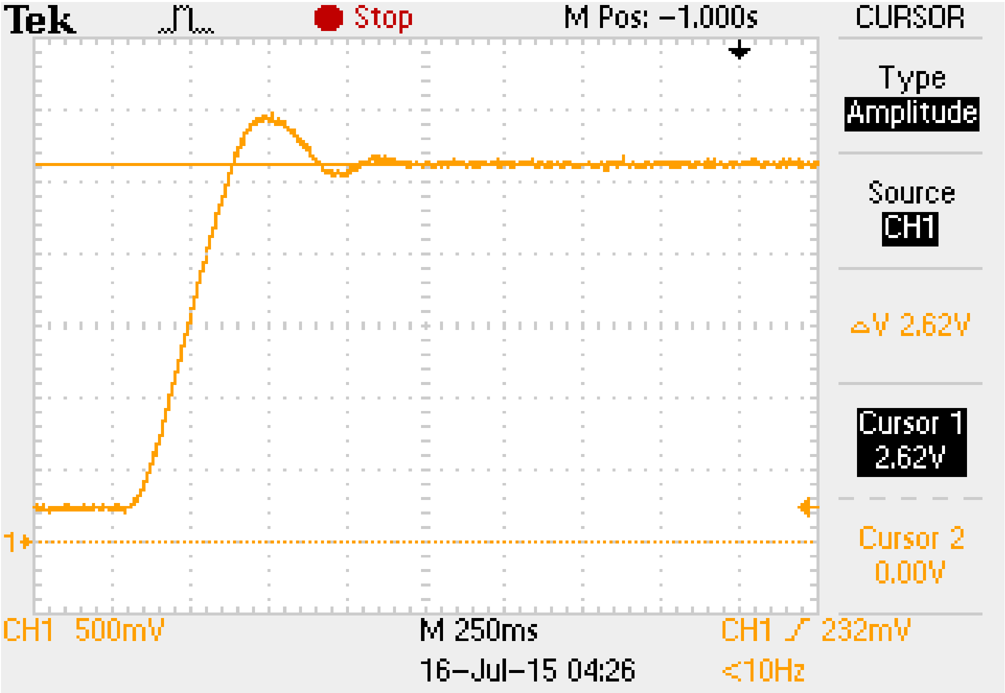

Figure 5.17: System Position Test for Medium Distance_ Oscilloscope screen (from x = 0 to x = 153 mm).

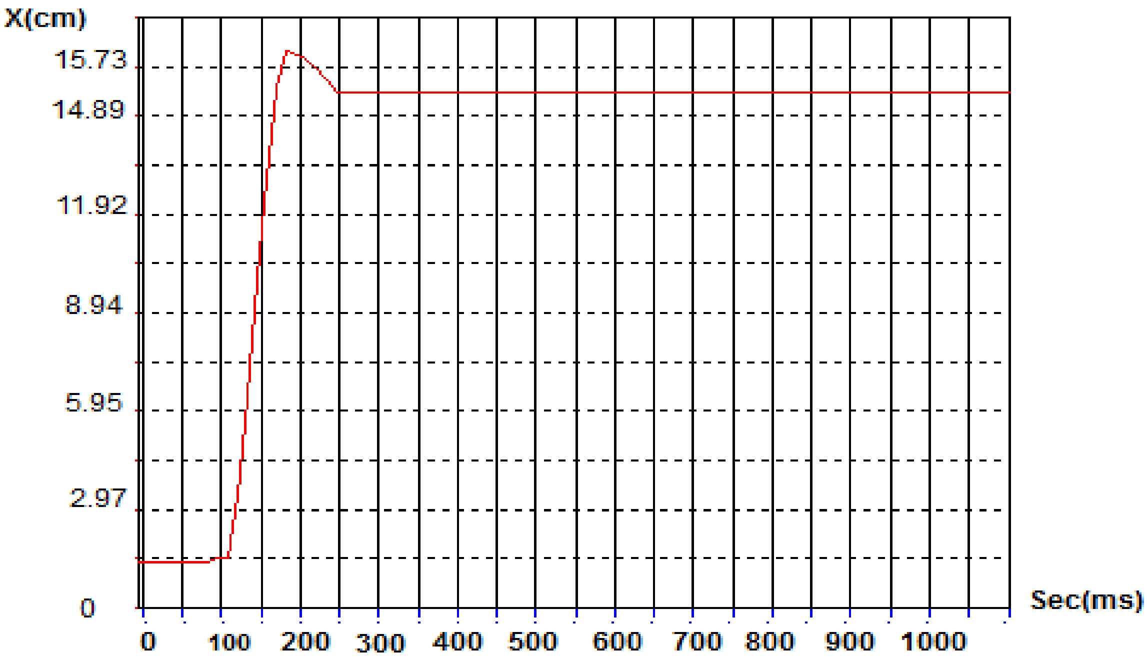

Figure 5.18: System Position Test for Medium Distance (from x = 0 to x = 153 mm).

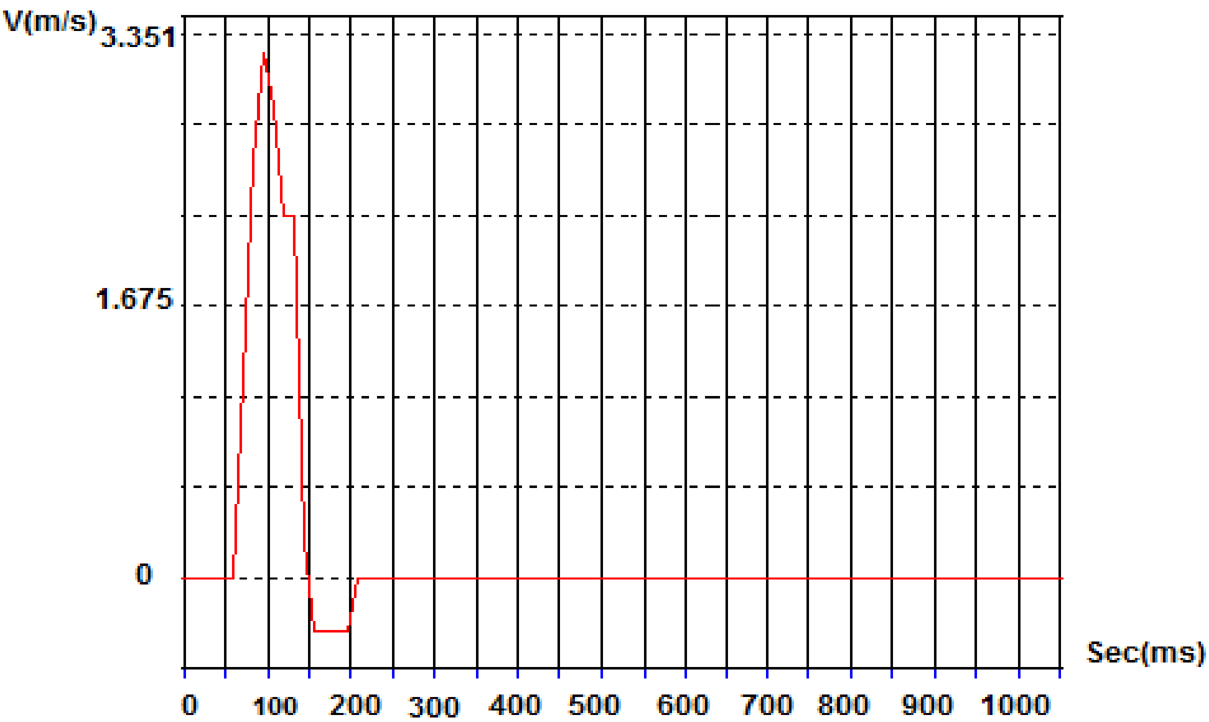

Figure 5.19: System Speed Test for Medium Distance (from x = 0 to x = 153 mm).

For a third position and speed tests are performed once again to validate the first two test results.

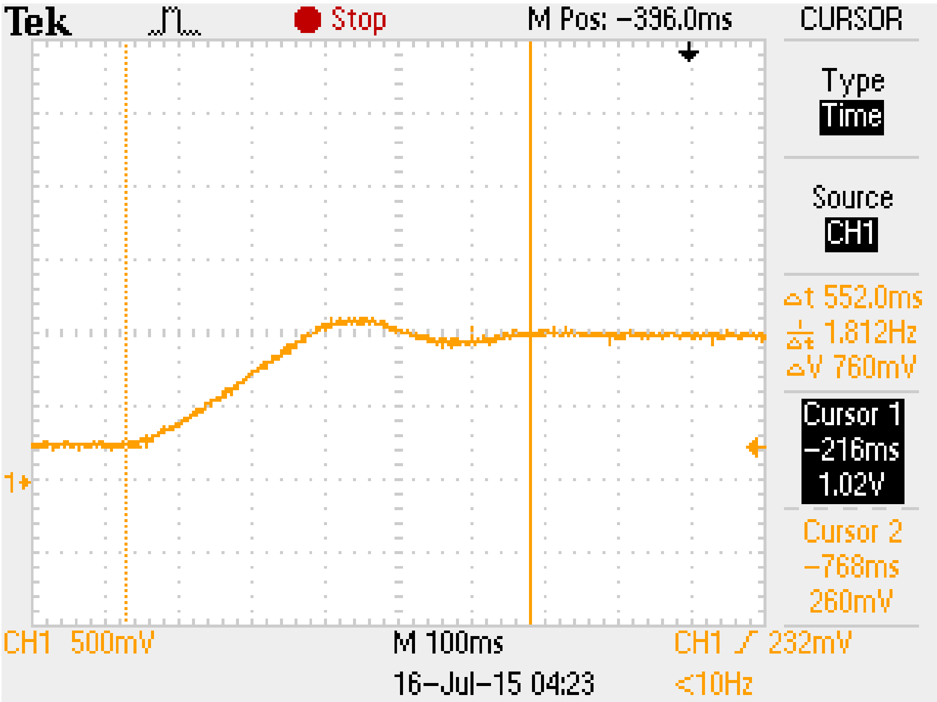

Figure 5.20: System Position Test for short Distance_ Oscilloscope screen (from x = 0 to x = 58.1 mm).

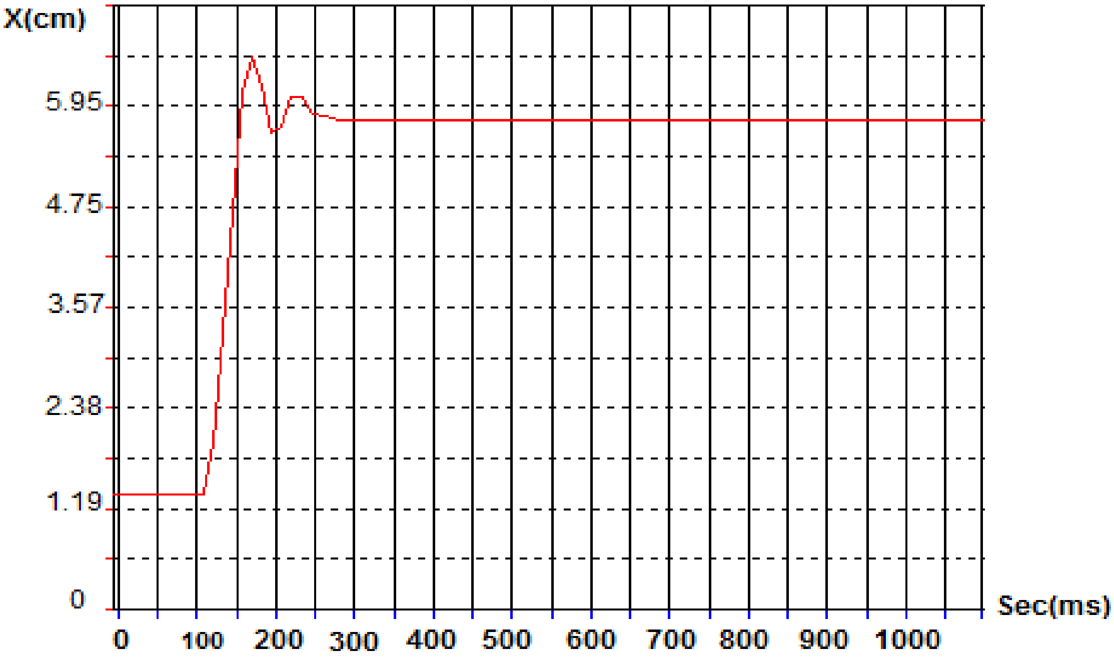

Figure 5.21: System Position Test for Short Distance (from x = 0 to x = 58.1 mm).

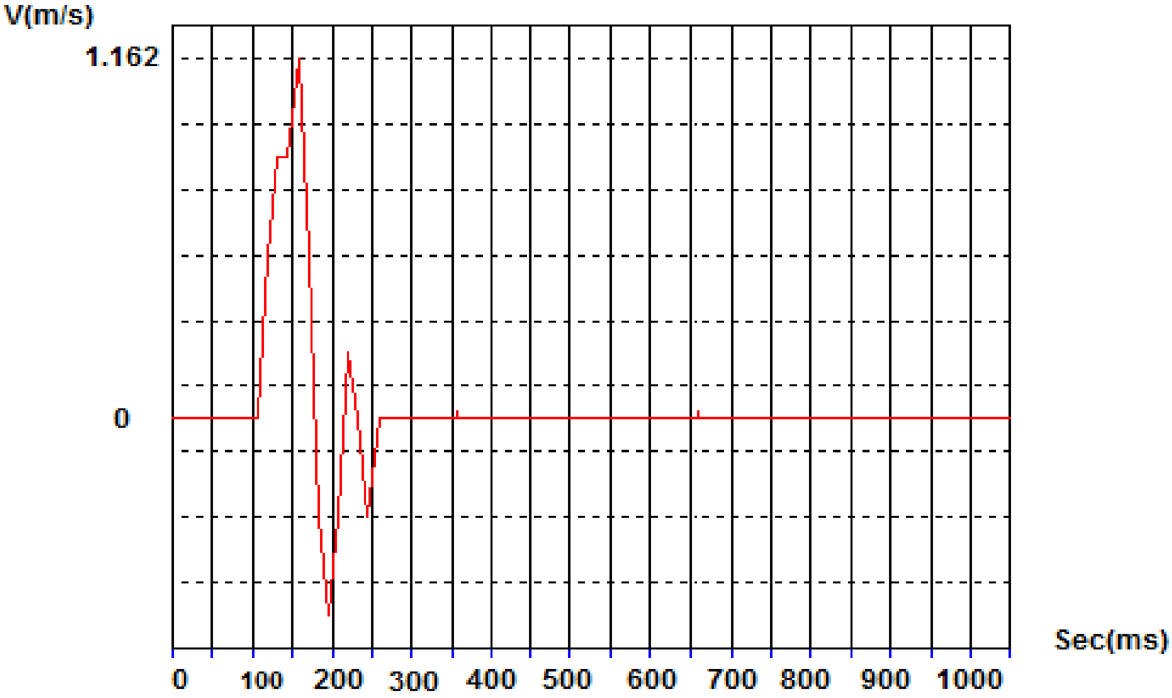

Figure 5.22: System Speed Test for Short Distance (from x = 0 to x = 58.1 mm).

The experiments show that all three test runs produce consistent measurements within the expected tolerance limit.

Finally, comparison between practical tests and simulation results is clarified, both are so close to each other, of course there will be some differences in practical tests becauase of mechanical and electrical constructions of them and non ideal nature of components, but result are acceptable. In the simulation results, overshoot is about 8%, settling time is approximatelly 600 ms, rising time is about 300ms and steady state error is elemicated. while position controller and speed controller are in the close loop system (Figure 5.11 and Figure 5.12). On the other hand, In practical tests, average overshoot is about 10%, settling time is approximatelly 800 ms, rising time is about 300ms and maximum steady state error is 288 micron.

According to Motor Position result, system's position control and speed control tests are matched to the system's simulations. Having fast operation below milliseconds for some applications is important, This is the main problem in mechanical and positioning devices, if extreme accuracy or super smooth motion is of concern. The controller is high performance since it is achieved high precision and smouth motion alongside fast moving coil motion of motor.

5.6. Current and Voltage Waveforms During Position Control

The next set of experiments consists of voltage and current tests. Mechanical load is applied to the motor during the experiment, 98 N (10 kg). In this section the measured moving coil voltage and current waveforms will be shown and investigated (Figure 5.23 and Figure 5.24). The results are captured using an oscilloscope. The inverter of the motor drive has a 10V DC source and the switching frequency of the inverter is 10 kHz. The results are shown in the following figures.

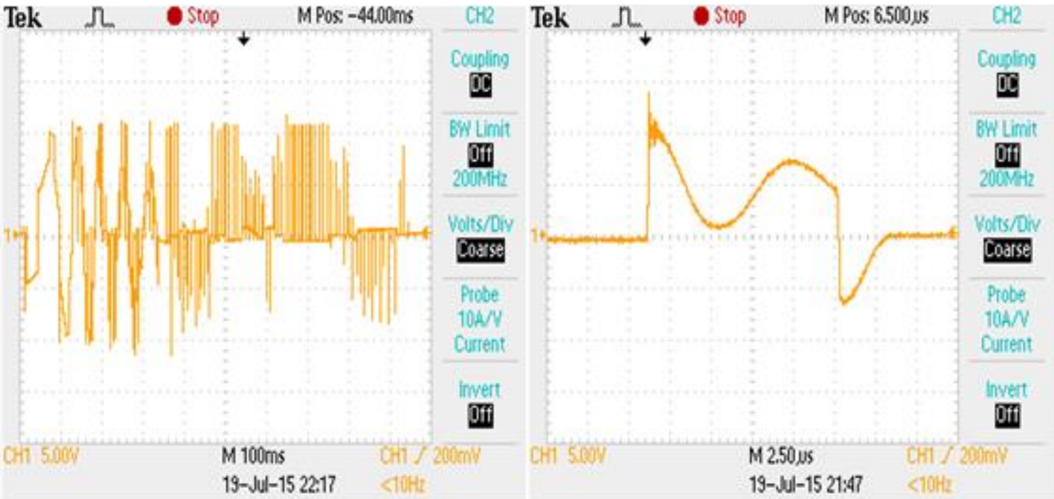

Figure 5.23: Moving coil voltage waveform.

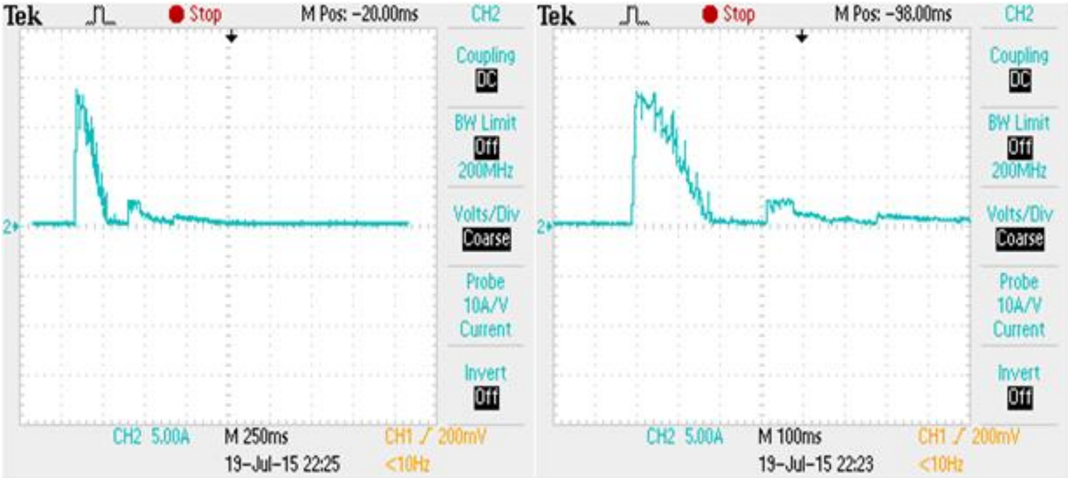

Figure 5.24: DC bus current waveform.

As it is shown in above figures, moving coil voltage wave is such as rectangular, but because of short travel distance of linear motor it is not so clear here, another point in this waveform is seen, while motor pass the reference position, voltage changes polarity for an instant to goes back to reference position. In the Figure 5.23, short travel distance of the motor causes to bus current damped so fast while the motor reach to reference position , some oscillations are seen in waveforms since, till moving coil settle on considered position.

6. CONCLUSIONS

In this study, a position controller and speed controller are designed. Position controller has been proposed for position control of linear BLDC Motor drive system. However, the transient performance can be improved far beyond the ability of linear position controller. Overall, compared with other advanced control schemes, this position controller holds its advantages such as relatively simpler linear design principle and easily application to other linear BLDC Motor position control drive systems. Due to that the uncertainties caused by parametric variations and external load force disturbances are unavoidable, a two pieces cascaded coupled loops proposed for the uncertainties feed-back compensation. Since it can easily be ensured by tests the designs, the overall linear BLDC Motor position control system stability is guaranteed easily.

As it has been achieved in simulation and practical results position rise time is and steady-state error reduce significantly.

The simulation results have shown control system's performance and the practical tests validate these simulation results. It is clear that the position control performance of Linear BLDC Motor have to be precise and accurate, and have achieved to acceptable accuracy (below 288 micron). Having fast operation below milliseconds for some applications is important, This is the main problem in mechanical and positioning devices, if extreme accuracy or super smooth motion is of concern. The designed controller provides high performance results since both accuracy and setlling time are rather small. This is a much desirable performance for specific applications in industial positioning systems. Also the controller achieves high precision and smooth motion alongside fast moving coil motion.

In the thesis the functionality of the design has been experimentally validated. The next step shall be to modify the system to achieve better results. The motor performance can be improved in many areas, e.g., noise. Noise prevents the motor from being useful for applications that require precise positioning when the amplitude is high. To overcome this problem another sensor can be introduced that has a finer position resolution. This step should greatly increase the motor's usefulness to precision positioning applications too.

Another significant problem in the system is the heating of the motor under load. By controlling the current it has been overcome this problem significantly, it could allow significantly faster, better performance and will allow the motor to run longer.

As future study, also the periodic errors with an iterative learning algorithm in addition to an adaptive controller can be used to improve controller performance for different applications.

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