Linear Induction Motor (LIMO) Modular Test Bed for Various Applications
ECE 4902 – Senior Design II
Spring 2014

Final Project Report

Team 190 Members:
David M. Hackney
Jonathan P. Rarey
Julio C. Yela

Faculty Advisor
Professor A. Bazzi
Office: ITEB 331
Phone: (860) 486-5377
Email: bazzi@engr.uconn.edu

University of Connecticut
Department of Electrical and Computer Engineering
# Table of Contents

I. Introduction

II. Background

III. Statement of Need

IV. Design Procedure

V. Project Design

VI. SOLIDWORKS Model

VII. ANSYS Maxwell Simulation

VIII. LabVIEW Integration

IX. Project Phases and Milestones

X. Budget

XI. Project Collaborators
I. INTRODUCTION

A linear induction machine was designed and fabricated to be used as a modular testing platform for multiple applications. Single or double sided stator configurations can be used in conjunction with two variable frequency drives (VFD). These VFDs supply the flux required to move the rotor of the machine and allow for movement control. The rotor, stators and rotor guides are adjustable so the user can change air gap and other physical parameters of the machine. The user can remove a stator as desired to run the machine as a single sided linear induction motor (SLIM). Rotor material can be removed and replaced easily to allow for testing of different materials and rotor designs. Optical linear encoders and a microcontroller supply feedback to the control loops of the VFDs to allow for accurate speed, position and force control. The two VFDs communicate through Modbus protocol and are controlled through a LabVIEW graphical user interface (GUI) which conveys pertinent information to use and allow for intrinsic control.

II. BACKGROUND

The history of linear motors date back as far as the 19th century with the work of Charles Wheatstone in Great Britain. Charles’s linear reluctance motor and Nikola Tesla’s invention of the induction motor led to the first linear induction motor (LIM) in 1905 by the German inventor Alfred Zehden. The linear induction motor is an AC asynchronous motor which provides a rectilinear motion in contrast to a rotational motion found in conventional motors. A major advantage of linear motors is the capability to produce a direct thrust without the need of converting rotational energy into translational energy [1]. Additionally, the speed of linear motors is completely adjustable and they require lower maintenance cost due to the fact that they do not require bearings like a rotating machine. This results in an increase in reliability as well. A major disadvantage of linear induction motors is they are low efficient as compared to a rotational induction motor [2].

Linear movement is required for many commercial and industrial applications such as industrial robots, liquid metal pumping, machine tools and propulsion systems. An interesting application is the Electromagnetic Aircraft Launch System (EMALS) which is being developed and is currently on its second phase of testing by the United States Navy. EMALS is designed to launch aircraft off aircraft carriers using a linear motor which would replace the conventional system utilizing steam pistons [3]. Another strong example is the use of linear induction motors to drive conveyor belts [4]. They can be found in factories, coal mines, and shipping facilities where movement of merchandise and heavy material is needed. As mentioned previously, they provide economical maintenance cost to owners and have fully adjustable speed. These are a sample of conventional examples, however, there are unlimited applications for linear induction motors.

III. STATEMENT OF NEED

A need was expressed to design, construct and optimize a linear induction motor to be used for a multitude of applications while being highly modular. In essence, the machine would need to be able to perform multiple tasks and be especially useful in machine research applications. To allow for maximum experimental utility the setup would be designed to allow for various rotor
materials, highly accurate sensors to provide for a fast response time, and acceptable motor efficiency. Sensors would be used for the monitoring of the position of the rotor and adjust VFD output to then adjust rotor movement. This modular LIM test bed would allow for significant customization in order to accommodate several applications, designs and machine testing capabilities. LabVIEW would be the interface between the VFDs and the feedback control the system would utilize.

IV. DESIGN PROCEDURE

The design of the linear induction motor is largely dependent on a combination of two items. First, the team has performed an extensive literature review surveying designs of linear induction motors for a multitude of applications [5]-[10]. The purpose of this literature review is to determine baseline parameters for this design so that they may be optimized. The second determining factor in the design is the testing and optimization of the design using a finite element analysis (FEA) simulation program. The program the team chose to use is ANSYS Maxwell and trial licenses of the program have been granted through the University of Connecticut. These simulations allowed the team to observe different parameters of the proposed linear induction motor such as magnetic fields, current density, ohmic losses and forces. Eventually, the software can be used to optimize our system in order to provide a much more efficient machine and provide simulation results of new topologies.

As shown in Table 1, many of the baseline parameters for the design were chosen and evaluated using ANSYS Maxwell. Preliminary parameters such as stator, rotor and rail system length were chosen from a previous linear induction designed for instructional laboratory development [5]. However, the proposed system designed to provide a power of 2.2kW, LabVIEW integration and position control with a linear encoder. The stator we have designed is a 2 slot per pole phase, with a total of 12 windings. Stator has a total of 24 slots and a pole pitch of 9cm. Pole pitch is an important parameter when it comes to designing LIMs because it plays a role in defining the speed of the motor \( V_s = 2\pi p f_s \) where \( f_s \) is the supply frequency and \( p \) is the pole pitch. Each stator tooth and slot is 0.75cm wide which makes the stator a total length of 36.75cm long. Rectangular teeth shapes were chosen due to their simplicity of manufacturing and literature research.

<table>
<thead>
<tr>
<th>Parameter Type</th>
<th>Parameter</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phases</td>
<td>3</td>
<td>Power and reduce force ripple</td>
</tr>
<tr>
<td>Poles</td>
<td>4</td>
<td>Optimal speed</td>
</tr>
<tr>
<td>Slots</td>
<td>24</td>
<td>Integer winding factor</td>
</tr>
<tr>
<td>Slots per pole per phase</td>
<td>2</td>
<td>Integer winding factor</td>
</tr>
<tr>
<td>Stator length</td>
<td>36.75 cm</td>
<td>Design choice</td>
</tr>
<tr>
<td>Stator width</td>
<td>6 cm</td>
<td>Design choice</td>
</tr>
<tr>
<td>Stator material</td>
<td>M19 steel C5 coated</td>
<td>Low core loss and availability</td>
</tr>
<tr>
<td>Lamination stacking depth</td>
<td>5 cm</td>
<td>Design choice</td>
</tr>
<tr>
<td>Lamination thickness</td>
<td>26 gauge</td>
<td>Standard thickness</td>
</tr>
<tr>
<td>Coil pitch</td>
<td>Full pitch</td>
<td>Ease of winding</td>
</tr>
<tr>
<td>Stator tooth shape</td>
<td>Rectangular slot</td>
<td>Literature research</td>
</tr>
<tr>
<td>Rotor dimensions</td>
<td>36” x 6” x ¼”</td>
<td>Design choice</td>
</tr>
<tr>
<td>Rotor material</td>
<td>Aluminum</td>
<td>Cost effective</td>
</tr>
</tbody>
</table>

Table 1. Technical specifications of the LIM system
The fabrication of the stator windings were initially created with 20 turns, but testing of the motor resulted in low force and current values. ANSYS Maxwell simulations of the stator with different number of turns at 10A showed a magnetic field of around 1 Tesla with 80 turns per winding. The team designed a winding jig to make the windings with the use of a rotary motor. The second set of windings of 80 turns each provided much more force during the second phase of testing the stators. Fig. 1 shows a flowchart summarizing the steps the team took in order to design the LIM test bed.

Fig. 1. Flowchart of designing the LIM test bed
V. PROJECT DESIGN

The proposed project was designed with the main goal of having a high degree of modularity. The linear induction motor test bed has fully interchangeable rotors, application specific rotor guides, variable stator designs and the ability to significantly adjust the air gap. Adjustability of the air gap was designed by having the stators mount movable along 2 T-slotted extrusion bars. These adjustments allow for testing or implementation of various ideas in order to improve efficiency as well as force and speed control. For example, the effect on force and position control when changing from an aluminum rotor to a copper rotor can be observed. Additionally, observing the effect of different stator tooth geometries and sizes could be advantageous for machine research.

The linear induction motor test bed uses a rail system to support the rotor and provide for smooth movement. Actual rail system parts used are shown in Fig. 2. Two 2000 mm rails and four linear bearings were used to construct the rail system. The rail system slides forward and aft based on the forces applied to the rotor by the stator or stators. Either long or short rotors can be utilized with this rail system. The rotor platform was designed to secure different rotor thickness for experiments. Fabrication of the rotor platform consist mainly of steel, and inside the gap there is a piece of delrin that insulates the rotor from the platform itself. The team created a rail system with a total length of 6 ft. and 7 inches.

Fig. 3 shows the rail system with the rotor platform on top of the rails. The linear bearings allow full movement of the platform. Holes were created in the base plate in order to facilitate the movement of the LIM system. Four T-slotted extrusions were secured onto the platform to allow adjustable stator mounts. Fig. 4 and 5 shows the rail system with the encoder PCB and one stator mounted. Three-phase banana plug connectors were used to supply a voltage source from the VFDs. The encoder PCB board was designed to send feedback to the computer by using a linear encoder. The linear encoder was positioned below the rotor mount where a linear strip was placed adjacent to it. This linear strip slides through the linear encoder of the PCB and provides a position feedback. Finally, Fig. 6 shows the completed platform with the two stator mounts and rotor mount.

Fig. 2. Rails, linear bearings and T-slotted extrusion used in rail system
Fig. 3. Base plate with the rotor platform

Fig. 4. Platform with one stator and encoder PCB mounted

Fig. 5. Different view of the platform with stator (left) and the platform with an aluminum rotor (right)
VI. SolidWorks Model

Each individual part in the final machine was designed in SolidWorks and send to Tech Services for fabrication. The only exceptions to this would be the rail system parts purchased through Amazon.com seen in Fig. 2 above. The finished assembly can be seen in Fig. 7 below. All parts in the rendered photo below with a polished silver finish are constructed of aluminum. The red insulators in direct contact with the stators are made of a nylon based material and the black inserts insulating the rotor and its platform are made of delrin.

SolidWorks was crucial to the development and production of the stator laminations for the machine. Polaris Laser Laminations LLC provided the fastest manufacturing time and lowest cost of all manufacturers contacted and were the choice for the lamination order. 440 laminations were ordered so that 4 individual stators could be built. Each stator consists of 102 laminations for a total stacking depth of 5cm. A SolidWorks model of a stator is shown in Fig. 8 below.
Each individual part contained in the system assembly designed in SolidWorks are true to life dimensions and are as follows. The baseplate of the system can be seen in Fig. 9 below and has an overall footprint of 25” long x 18” wide x $\frac{5}{8}”$ thick. Each of the four t-slot extruded bars which mount the stator platforms to the baseplate are 1” wide x 1” tall x 6” long and is made of anodized aluminum. The t-slot bars are recessed into the baseplate by $\frac{1}{8}”$ as are the rails for extra rigidity.

Fig. 8. Rendered SolidWorks photo of an individual stator

Fig. 9. Rendered SolidWorks photo of baseplate

Fig. 10 below shows a SolidWorks rendering of the rotor assembly. The rotor platform itself is constructed of aluminum and has a footprint of 15” long x 5 $\frac{3}{8}”$ wide x 1” thick. The rotor is also made of aluminum and is 36” long x 6” tall x $\frac{1}{4}”$ thick. The two black rotor inserts shown are made of delrin and are $\frac{7}{8}”$ wide x 15” long x $\frac{3}{4}”$ tall. The rotor and rotor inserts sit in a $\frac{1}{4}”$ recess in the rotor platform for extra strength and stability and each piece of the assembly is bolted in place.

Fig. 10. Rendered SolidWorks photo of the rotor assembly

Finally, an example of one of the stator assemblies is shown in Fig. 11 below. It consists of two views of the same assembly. The base of the stator platform is aluminum and is 15” long x 4” wide x 1 $\frac{3}{8}”$ thick. Each of the four uprights are constructed of aluminum and consist of two
parts, and upper and a lower part which act as a vice when bolted together to clamp down on the stator. To electrically isolate the stator from the aluminum structure, red nylon inserts were installed which measure 1 ¼” wide x 1 ¼” tall x 15” long. This are in direct contact with the stator as shown in the figures below.

Fig. 11. Rendered SolidWorks photo of the stator assembly

VII. ANSYS MAXWELL SIMULATION

FEA analysis of the proposed double sided linear induction motor (DSLIM) was designed and created using ANSYS Maxwell. A solution type of Eddy Current analysis was chosen to observe the magnetic field of the LIM as a locked-rotor situation. Fig. 12 shows a single stator with a total of 12 windings designed in ANSYS. This design followed the preliminary parameters as shown in Table 1. The windings were designed as separate coils and currents were assigned to each phase separately. Material of the windings were defined as copper, and the stator material as iron with zero conductivity in order to ignore eddy currents induced in the stator. The through holes in the stator showed no significant effect in simulation results. Fig. 13 shows the DSLIM with two stators and the aluminum rotor in between. The air gap between the stator and the rotor was defined as 2mm. This value was chosen from literature review of linear induction machine design.

Fig. 12. Stator design with windings in ANSYS
Fig. 14 shows the configuration of the currents and poles of the windings. As stated previously, the LIM is a 2 slot per pole per phase motor, and each phase creates two poles (north and south). The first two slots were assigned phase A with a current of 0 degrees (current going in), and four slots down the stator the return path for phase A was placed. Note that the two windings in the first two slots are the same phase. Phase B was created with -120 degrees (current going out) and similarly these phases were repeated on the second half of the stator. The current assigned to these phases are defined as Amps-turns, therefore each phase was assigned 200A if the estimated current was 10A and 20 turns per winding.

Fig. 16 and 17 shows the magnetic field distribution of the proposed system with a current assigned of 800A and 200A, respectively. Originally the team created the windings with 20 turns each, but not enough force and power was experienced. This is due to the low magnetic field as shown in Fig. 17. Simulating a higher winding-turns as shown in Fig. 16 resulted in a value close to 1 Tesla which is what the team was aiming for. With this result, the next set of windings were created with 80 turns each. Actual values of force and efficiency are yet to be calculated of the physical LIM system. Fig. 18 shows the ohmic loss across the rotor. Ohmic loss is the heat generated by passing current through a conductor. The total ohmic loss calculated in ANSYS was around 4W at 800A turns.
Fig. 16. Magnetic field distribution with 800A assigned current

Fig. 17. Magnetic field distribution with 200A assigned current

Fig. 18. Ohmic loss across the stator
Lastly, different materials of rotor were experimented in ANSYS. The forces are summarized in Table 2. Silver rotor showed a force of 6.84 pounds force compared to aluminum which was 4.28 pounds force. Further research in these different of rotors can be done utilizing ANSYS and performed in the lab by the use of the test bed. Efficiency of the whole system can be obtained in ANSYS such as core losses and total voltage induced. These values can be obtained using the Transient analysis, but due to limited time throughout this semester the team was only able to simulate the system using Eddy Current analysis. As shown in Fig.1, future work involves optimizing the preliminary test bed by simulation results using the Transient analysis. For example, some parameters that can be optimized are the number of turns, tooth shape, stator back iron size and rotor materials. All these materials can lead to an optimized LIM test bed.

<table>
<thead>
<tr>
<th>Rotor Material</th>
<th>Aluminum (Al)</th>
<th>Copper (Cu)</th>
<th>Silver (Ag)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Force (Pounds Force)</td>
<td>4.28</td>
<td>6.51</td>
<td>6.84</td>
</tr>
</tbody>
</table>

**VIII. LabVIEW Integration**

The control aspect of the design is another important piece of the project. As mentioned previously, the linear induction motor will be controlled via one or two Yaskawa A1000 VFDs. Each VFD is capable of controlling two stators and in the case of a quad-stator design, two VFDs will be necessary. The VFDs will communicate through Modbus protocol from a LabVIEW GUI. Optical linear encoders will supply feedback to the control loops of the VFDs to allow for precise speed, position and force control. The team has decided to use a US Digital linear encoder and encoder scale for this project as shown in Figures 20 and 21.
The LabVIEW interface allows the user to connect to all relevant devices individually. This was done to increase program stability and functionality if there were problems with one or more devices or if the user simply did not wish to activate the entire system. As shown in figure 22 the user has separate connection panels for each device and the status for each device is shown top use user in real time, allowing the user to monitor device connections that could help in debugging and troubleshooting.

Device parameters for all relevant devices are shown to the user in real time. All parameters are monitored at a minimum of 100 Hz update rate with a maximum of 1000 Hz for the encoder resolver. Bus voltage, rotor position, line voltage and current all shown to the user via large meters on the front panel as they are some of the most important parameters of the system to monitor, as shown in figure 22. Shown in figures 23 are the full list of device parameters shown in digital displays. Most of these parameters are shown on the mail indicators although there are a few that are not. Here the user can view all parameters of devices connected.
The current program only runs in an open loop setup, such that the user can set the output frequency and direction of either of the two VFD’s individually to control the machine, shown in figure 25. This control allows the user to easily test the machine perform simple motion tasks by changing the direction of the motor. Other control parameters are set in the Program Options tab of the GUI. As shown in figure 24. Here the user is able to control settings on the encoder module attached or the Magna-Power DC supply if it is in use. The user can turn on and off power going to the encoder sensor, zero the position count of the encoder, enable or disable the transmission of data from the encoder, enable or disable the auto transmit (1000 Hz update signal), and request a single update from the device. The user also has full open loop control over the Magna-Power supply if it is attached, allowing the user to turn off and on the supply, as well as set the desired output voltage and current limits, and the overvoltage and overcurrent limits.
The linear encoder is used to observe the speed of the rotor and determine its position. The encoder scale was affixed to the rotor so that the linear encoder can "see" the position change of the rotor. An example of a linear encoder tape is shown in Figure 4. The encoder tape has precisely marked divisions which will allow for precise position and speed control of the linear induction motor. The ends of the stators will also have LEDs and sensors to ensure the rotor is not ejected from the stator. The encoder resolver unit designed to convey positional information to the computer was designed around a microcontroller to count the number of pulses from the linear encoder setup and send them over serial to the computer. The finished design of this resolver is shown in figure 26, the PCB design follows in figure 27. Using this device the LabVIEW code is able to interpret the position information and show the user this data in real time.

Figure 29 shows a block diagram of the control setup of the proposed linear induction test bed. The three-phase AC source is connected to a bus which connects to two of the VFD. The VFDs are then interfaced with LabVIEW for control operations. The output of the VFDs are connected to the stator pair (in this setup) to provide a controllable voltage and frequency value. An encoder is connected to the rotor and back to the two VFDs to provide position control.
The LabVIEW control was built with constant control, safety, stability and overall functionality in mind allowing the user complete control over all relevant parameters and device settings. The queue structure used in constructing the code behind the GUI function like a separate operating system, taking inputs from the user on interrupts, adding those function to a queue, and handling them one at a time, running thousands of functions per seconds in real time.

IX. Project Phases and Milestones

As mentioned above, the project was divided into multiple stages of development. The two main delineation points were the fall and spring semester. The timeline shown below was followed as closely as possible, but in the spring semester the work became rigorous and the team fell behind the timeline. The main focus of September and October of the fall semester was an extensive literature review. This was in conjunction with a review of commercial linear induction machines as well as a search for potential VFDs and the corresponding system control. The two Yaskawa A1000 VFDs used in this project were ordered in early November and the team looked to obtain simulation software through ANSYS Maxwell. ANSYS simulation and SolidWorks construction of the system started later than intended in December and the order date for the stator laminations was made in mid March.

SolidWorks CAD updates and ANSYS simulation continued through most of the spring semester as designs changed. Sensor research and purchase came at the end of the fall semester. Graphical user interface (GUI) work integrating LabVIEW with the system controls came later than expected due to time constraints in stator assembly and overall machine assembly. This also lead to a significant decrease in time available to optimize the machine and finish control work ahead of schedule. This project work was in parallel to written assignments and presentations which were all completed on time. Even with the extreme time constraints this project presented, the team was able to adapt and thrive. The project produced a working production design by senior design day on May 2, 2014. Not only was the project a success in respect to the team’s graded requirements, the team also was awarded first prize of all electrical engineering projects.
X. BUDGET

The budget was provided through the team’s advisor Professor Bazzi and his lab APEDL. Table 2 below shows a breakdown of the approximate cost to construct the linear induction motor. A large portion of the budget was spent on the two Yaskawa A1000 VFDs necessary to power each stator. Each VFD cost approximately $1,000 for a total of $2,000. The largest portion of the order would be Tech Services which machined the SolidWorks designs for the machine assembly. This estimate is in the $3,500 range, but is a flexible number and may be misleading in the end. Next largest would be the 440 M19 silicon steel laminations provided by Polaris Laser Laminations LLC at approximated $900. Most other items were under $500 except for the rail system parts obtained online through Amazon.com. These other items include the Magnet wire used to wind the coils installed in the stators, sensors and electronics for system feedback as well as interface boards. The total project cost is estimated at $7,654.27 but this again could be somewhat less depending on the Tech Services payment arrangements.

Table 2. Approximate cost of the linear induction motor modular test bed

<table>
<thead>
<tr>
<th>Name</th>
<th>Approx. Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 Yaskawa A1000 VFDs</td>
<td>~ $2,000.00</td>
</tr>
<tr>
<td>Stator Laminations (Polaris)</td>
<td>$888.80</td>
</tr>
<tr>
<td>TufQUIN TFT Insulation Paper</td>
<td>$46</td>
</tr>
<tr>
<td>4000 ft 18 AWG Magnet Wire</td>
<td>$205.58</td>
</tr>
<tr>
<td>Rail System Parts</td>
<td>$568.49</td>
</tr>
<tr>
<td>Sensors and Electronics</td>
<td>$245.40</td>
</tr>
<tr>
<td>Interface Boards</td>
<td>$200.00</td>
</tr>
<tr>
<td>Tech Services Order</td>
<td>~ $3,500</td>
</tr>
<tr>
<td>Total</td>
<td>$7,654.27</td>
</tr>
</tbody>
</table>

XI. Project Collaborators
University of Connecticut Electrical and Computer Engineering
- David Hackney
  - Senior Design Team Member
  - Electrical Engineering Major
  - david.hackney@uconn.edu
- Jonathan Rarey
  - Senior Design Team Member
  - Electrical Engineering Major
  - jonathan.rarey@uconn.edu
- Julio Yela
  - Senior Design Team Member
  - Electrical Engineering Major
  - julio.yela@uconn.edu
- Professor Ali Bazzi
  - Faculty Advisor
  - bazzi@engr.uconn.edu

Illinois Institute of Technology (IIT) Electrical and Computer Engineering
- Professor Ian Brown
  - ibrown1@iit.edu

Technical Services Center at the University of Connecticut
- Mark Drobney
  - Senior Machine Shop Engineer
  - mark.drobney@uconn.edu
- Joseph Csiki, III
  - Machine Shop Engineer
  - j.csiki@uconn.edu

Sources


