Linear Induction Motor
Outline of Presentation

• Background and Project Overview
• Microcontroller System
• Final Design
• Economic Analysis
• Hardware
• State of Work Completed
• Conclusion
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Alternating Current Induction Machines

- Most common AC machine in industry
- Produces magnetic fields in an infinite loop of rotary motion
- Current-carrying coils create a rotating magnetic field
- Stator wrapped around rotor
Rotary To Linear

3 PHASE 'SQUIRREL CAGE' INDUCTION MOTOR

MAKE A CUT

OPEN OUT FLAT

3 PHASE LINEAR INDUCTION MOTOR

3 PHASE POWER SUPPLY

SMOOTH THE ROTOR INTO SEPARATE SHEETS

[3]
Linear Induction Motor Background

- Alternating Current (AC) electric motor
- Powered by a three phase voltage scheme
- Force and motion are produced by a linearly moving magnetic field
- Used in industry for linear motion and to turn large diameter wheels
Project Overview

• Design, construct, and test a linear induction motor (LIM)
  • Powered by a three-phase voltage input
  • Rotate a simulated linear track and cannot exceed 1,200 RPM
  • Monitor speed, output power, and input frequency
  • Controllable output speed
Initial Design Process

- Linear to Rotary Model
  - 0.4572 [m] diameter
  - 0.3048 [m] arbitrary stator length
  - Stator contour designed for a small air gap
  - Arc length determined from stator length and diameter
  - Converted arc length from a linear motor to the circumference of a rotary motor
  - Used rotary equations to determine required frequency and verify number of poles

\[ L = \theta r \] (1.1)
Rotational to Linear Speed

\[ v = r \omega \left( \frac{2\pi}{60} \right) \]  

\[ v = \text{Linear Velocity} \left[ \frac{m}{s} \right] \]

\[ r = \text{Radius of Rotor} \ [m] \]

\[ \omega = \frac{120f}{p} \]  

\[ \omega = \text{Rotational Speed of Rotor} \ [\text{rpm}] \]

\[ p = \text{Number of Poles} \]

\[ f = \text{Input Frequency} \ [\text{Hz}] \]
Pole Pitch and Speed

\[ U_s = 2\tau f \]

\[ U_s = \text{Linear Synchronous Speed} \left[ \frac{m}{s} \right] \]
\[ \tau = \text{Pole Pitch} [m] \]

- For fixed length stator \( \tau = \frac{L}{p} \)
- \( L = \text{Arc Length} \)
Linear Synchronous Speed

Ideal Linear Synchronous Speed vs. Frequency

- 2-Pole Machine (stator length 0.3048m)
- 4-Pole Machine (stator length 0.3048m)
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Variable Frequency Drive

- **VFD**
  - 0-10V signal correlates to 0-120 Hz
- **A/D Converter**
  - Onboard the ATmega128
  - 250 ms interrupt service routine
  - Resolution is 0-5V
- **D/A Converter**
  - External chip
  - Provides 0-10V reference signal to VFD to control output frequency
System Block Diagram

Atmega 128 Microcontroller

D/A

A/D

Variable Frequency Drive

Analog 0-10V

Start/Stop 0-10V Signal

0-10V Signal

Analog 0-10V

Analog 0-10V
Tachometer Subsystem

- **Main Components**
  - Photo-interruptor
  - Transparent Disk with Notches

- **External Interrupt**
  - Counts pulses
  - 4 pulses per rotation
  - 250 ms interrupt service routine
LCD Subsystem

• LCD Displayed Values
  • RPM
    • Calculation to obtain RPM
    • Convert to string
    • Input string to LCD
  • Output frequency
    • Calculation to obtain VFD output frequency
    • Convert to string
    • Input string to LCD
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Initial Design

• 3-phase, 2-Pole machine
• Salient pole arrangement
• Operating at a max frequency of 120 [Hz]
• 18” (0.4572 [m]) diameter track
• Desired 12” (0.3048 [m]) length for the stator
• Max rotational speed of 1200 [RPM] corresponding to a max linear speed of 28.72 [m/s]
Rotational to Linear Speed

Ideal Linear Synchronous Speed vs. Frequency

- 2-Pole Machine (stator length 0.3048m)
- 4-Pole Machine (stator length 0.3048m)
Rotational to Linear Speed

Ideal Linear Synchronous Speed vs. Frequency

- 2-Pole Machine (stator length 0.3048m)
- 4-Pole Machine (stator length 0.4542m)
Turns Per Phase

\[
T_{ph} = \frac{P_{out}}{6.66 \{pn_{ms}B_{ag}A_p k_w I_{ph} \eta(PF)\}}
\]

(1.5)

\( P_{out} =\) Output Power  \\
\( p =\) Number of Poles  \\
\( n_{ms} =\) Mechanical Cycles per Second  \\
\( B_{ag} =\) Average Air – Gap Flux Density per Pole = 1.1 [T]  \\
\( A_p =\) Cross – Sectional Area of Pole Faces = 0.0346 [m]  \\
\( T_{ph} =\) Number of Turns per Phase  \\
\( k_w =\) Coil Winding Factor = 0.86  \\
\( I_{ph} =\) Input Phase Current = 3 [A]  \\
\( \eta =\) Efficiency = 0.6  \\
\( PF =\) Power Factor = 0.7
# Previous Data

## TABLE I: PREVIOUS DATA FROM MAGNETIC LEVITATION SENIOR PROJECT

<table>
<thead>
<tr>
<th>Rotational Speed (RPM)</th>
<th>Output Power [W]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1106</td>
<td>510.78</td>
</tr>
<tr>
<td>1343</td>
<td>619.16</td>
</tr>
</tbody>
</table>

[15] [16]
Final Design

- 4-Pole machine
- Salient pole arrangement
- Laminated stator segments
- Operating at a max frequency of 120 [Hz]
- 16 AWG with current rating of 3.7 [A]
- Stator Tooth Length of 3.5” (0.0889 [m])
- Mounting holes on stator
- Theoretical 213 turns per stator tooth
- Achieved 235 turns per tooth
Wiring Diagram
Insulated Bobbins

- Glass cloth tape used between the stator teeth and coils
- Electrical tape used at ends to secure glass cloth tape
- Necessary to prevent shorting between copper coils and the stator core
- Plastic pieces in stator slots to further prevent shorting
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# Bill of Material

## TABLE II: BILL OF MATERIAL

<table>
<thead>
<tr>
<th>Component</th>
<th>Supplier</th>
<th>Price</th>
<th>Quantity</th>
<th>Total Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laminated Stator Core</td>
<td>Laser Laminations</td>
<td>$375</td>
<td>1</td>
<td>$375</td>
</tr>
<tr>
<td>2,000 ft. Dipped Copper Wire</td>
<td>Illinois Switchboard</td>
<td>$176</td>
<td>1</td>
<td>$176</td>
</tr>
<tr>
<td>Scotch Glass Cloth Tape</td>
<td>Grainger</td>
<td>$11.55</td>
<td>5</td>
<td>$57.75</td>
</tr>
<tr>
<td>Scotch Vinyl Electrical Tape</td>
<td>Grainger</td>
<td>$8.95</td>
<td>3</td>
<td>$26.85</td>
</tr>
<tr>
<td>Power First Cable Tie Bag (100)</td>
<td>Grainger</td>
<td>$13.95</td>
<td>2</td>
<td>$27.90</td>
</tr>
<tr>
<td>3/8&quot; 6&quot; Steel Bolts</td>
<td>Ace Hardware</td>
<td>$3.20</td>
<td>6</td>
<td>$19.20</td>
</tr>
<tr>
<td>3/8&quot; 6&quot; Steel Bolts</td>
<td>Ace Hardware</td>
<td>$1.49</td>
<td>2</td>
<td>$2.98</td>
</tr>
<tr>
<td>3/8&quot; Nuts</td>
<td>Ace Hardware</td>
<td>$0.30</td>
<td>24</td>
<td>$7.20</td>
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<tr>
<td>Angle Irons</td>
<td>Ace Hardware</td>
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<td>1</td>
<td>$13.99</td>
</tr>
<tr>
<td><strong>Total Price</strong></td>
<td></td>
<td>$706.87</td>
<td></td>
<td></td>
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</tbody>
</table>
Outline of Presentation

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Completed Stator

- Manufactured by Laser Laminations
Simulated Linear Track Mounting Solution

- Using previous mounting hardware used with new base mounting
- Smaller air-gap then anticipated was achieved
  - Under 1/8” air-gap
Simulated Linear Track Mounting Solution Con’t

• 6 Inch fully threaded steel hex bolts
  • Allow for fine adjustment of wheel height
• Wheel mounting was raised 1-9/16”
• Put bolts through all linear track mounting parts to prevent bending of bolts on angled components
Stator Mounting Solution

• Angle irons used to hold bottom mounting holes of stator to base
• 11/32” bolts used in both base and stator mounting

[22]
General Mounting

• All parts sand blasted to remove rust and previous paints
• Spray painted grey for uniform color and rust prevention
• Washers used with mounting hardware
Issues with Mounting

• Initial stator mounting holes from stator to base were off
• Required re-drilling of mounting holes
• Simulated linear track is not perfectly balanced
• Changed the screws holding the copper on simulated linear track to prevent coil interference
## Linear Track Run-off

**TABLE III: Total Run-off of Simulated Linear Track**

<table>
<thead>
<tr>
<th>Side</th>
<th>(+) Run-off</th>
<th>(-) Run-off</th>
<th>Total Run-off</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right</td>
<td>+ 0.015”</td>
<td>- 0.015”</td>
<td>0.03”</td>
</tr>
<tr>
<td>Middle</td>
<td>+ 0.016”</td>
<td>- 0.013”</td>
<td>0.029”</td>
</tr>
<tr>
<td>Left</td>
<td>+ 0.018</td>
<td>- 0.012”</td>
<td>0.03”</td>
</tr>
</tbody>
</table>
Coil Materials Used

- 16 AWG Wire
- GP/MR-200 Magnet Wire/ Winding Wire
- Heat is rated at 210°C by wire
- Wire diameter calculated when determining turns per phase and stator tooth width
- 0.418” of gap between adjacent coils

[26]
Mock Stator Tooth

- Created a mock wood stator tooth
- Grooves in base to hold zip-ties
- Wrapped brass around tooth
  - Increase size
- Allows for coil to be moved on stator easier
Winding Coils

• Created a replica stator tooth for winding coil on
• Initially used a slow lathe for windings coils
• Approximately 2 hours to create one coil
• Issues with layer quality

[28]
Winding Coils

- Changed to a different lathe
- Benefits included higher quality wraps
- Increase in speed
  - Only 30 Minutes to complete a coil
Winding Methods and Changes

• Drilled a hole into base of wooden tooth for more secure winding start
• Added a layer of Teflon on each coil layer
• Wrapped outsides of coils with glass cloth tape for protection and extra support

[30] [31]
Issues with Winding and Coils

• Wires crossing back accidently in layers
• Losing tension in wrapping
  • Results in slinky effect
• Coils when tightened down collapse
Mounting Coils

- Wire ends were sanded down to remove the varnish insulation
- Wires are labeled with inner and outer wire for connecting coils together
- Zip-ties are used on each side of the coil to secure the wires together to prevent
- Additional zip-ties were used to secure the coils to the stator to prevent movement when the wheel is in motion
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Completed Work

• Stator Built and Designed
• Frequency vs. Speed simulation
• Coils designed and created
• Mounting solution built for simulated linear track and stator
• A/D convertor
• Tachometer and LCD interfacing
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Conclusion

• Future Work
  • Update wheel for an improved simulated linear track
  • Update mounting solution for a more balanced wheel and smaller air-gap
  • Test thoroughly and generate model for simulations
  • Implement more advanced control scheme
  • Reinstall magnetic levitation system
Questions?
Derivation of Eq. (1.5)

\[ P_{out} = \eta P_{in} \]

\[ P_{in} = 3V_{ph}I_{ph}(PF) \]

\[ P_{out} = \eta 3V_{ph}I_{ph}(PF) \]

\[ V_{ph} = 4.44f_s \Phi_{ag} T_{ph} k_w \]

\[ P_{out} = 3 \{ 4.44f_s \Phi_{ag} T_{ph} k_w \} I_{ph} \eta(PF) \]

\[ f_s = \frac{p n_{ms}}{2} \]

\[ P_{out} = 3 \{ 4.44 \frac{p n_{ms}}{2} \Phi_{ag} T_{ph} k_w \} I_{ph} \eta(PF) \]

\[ \Phi_{ag} = B_{ag} A_p \]

\[ P_{out} = 3 \{ 2.22 p n_{ms} B_{ag} A_p T_{ph} k_w \} I_{ph} \eta(PF) \]

WHERE:

\[ f_s = \text{Synchronous Electrical Frequency} \]

\[ \Phi_{ag} = \text{Air Gap Flux per Pole (Average)} \]

\[ V_{ph} = \text{Input Phase Voltage} \]
Salient and Non-Salient

Salient Pole Arrangement

Non-Salient Pole Arrangement
Final Stator Design
# Gantt Chart

<table>
<thead>
<tr>
<th>TASK NAME</th>
<th>RESPONSIBLE</th>
<th>Date</th>
</tr>
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<tbody>
<tr>
<td>General System Design</td>
<td>All</td>
<td>September 4, 2015</td>
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<tr>
<td>Stator Design</td>
<td>All</td>
<td>November 17, 2015</td>
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<tr>
<td>Research Winding Types</td>
<td>Tim</td>
<td>November 17, 2015</td>
</tr>
<tr>
<td>Pole and Slot Pitch</td>
<td>Mason</td>
<td>September 22, 2015</td>
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<tr>
<td>Pole Depth</td>
<td>All</td>
<td>November 17, 2015</td>
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<tr>
<td>Slot/Teeth Ratio</td>
<td>All</td>
<td>October 27, 2015</td>
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<tr>
<td>Number of Coil Windings</td>
<td>All</td>
<td>November 17, 2015</td>
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<tr>
<td>Purchasing</td>
<td>All</td>
<td>November 30, 2015</td>
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<tr>
<td>Construction</td>
<td>All</td>
<td>February 2, 2016</td>
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<tr>
<td>Coil Windings</td>
<td>Mason and Tim</td>
<td>January 25, 2016</td>
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<tr>
<td>Stator Mount</td>
<td>Mason and Tim</td>
<td>February 8, 2016</td>
</tr>
<tr>
<td>Microcontroller Sytem</td>
<td>Tyler</td>
<td>February 8, 2016</td>
</tr>
<tr>
<td>VFD Programming</td>
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<tr>
<td>Sensor Programming</td>
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<td>Implementation</td>
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<td>Fall Performance Review</td>
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<td>Project Website Verification</td>
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<td>May 3, 2016</td>
</tr>
</tbody>
</table>

[37]
Coil Inductance

$$L = \frac{31.6\mu_r N^2 r_1^2}{6r_1 + 9l + 10(r_1 - r_2)}$$  \hspace{1cm} (1.6)

$L = \text{Inductance of Multiple Winding Coil} \ [\mu H]$

$\mu_r = \text{Permeability of Material} \ [Hm^{-1}]$

$N = \text{Number of Turns}$

$r_1 = \text{Inner Diameter of Coil} \ [m]$

$l = \text{Length of Stator Teeth} \ [m]$

$r_2 = \text{Outer Diameter of Coil} \ [m]$

2-Pole:  $L = 2.55 \ [\mu H]$  \hspace{1cm} 4-Pole:  $L = 0.30 \ [\mu H]$
Star Connection
Overall System Block Diagram
4-Pole Machine Wiring Diagram


References #8-16


References #17-27


References #28-37


[34] T. Zastawny. *Salient Pole Arrangement*. [Diagram].


[37] T. Zastawny. *Final Presentation Gantt Chart*. [Diagram].
References #38-40

[38] Star Connection Configuration [Photograph].
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[40] 4-Pole Machine Wiring Diagram [Photograph].
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https://www.ibiblio.org/kuphaldt/electricCircuits/AC/02428.png