Linear Induction Motor

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EXECUTIVE SUMMARY

The main purpose of this project is to design and fabricate a linear induction motor (LIM) that can generate motion and force in a linear direction. The success of the motor will be determined by six different non-functional requirements, and overall by the control of rotation of a large diameter wheel that is being used as a simulated linear track. Research was focused on prior work and low cost alternatives to the many different subsystems that a LIM requires. The majority of the prior work that has been researched is related to this team's project but not specifically limited to a LIM.

The motivation for this project originates from the lack of machines that produce linear force and motion in industry. There are many applications in industry where linear motion is necessary but unobtainable. For instance, when a large radius wheel needs to be continuously rotated and typical rotary induction motors cannot handle the required torque. Another instance where linear motion is required is on specific assembly lines that need to move and control equipment in a flat linear fashion. Providing a solution via linear motors in these instances could increase industrial production, create an ease of control, and generates the possibility to make work environments safer and more efficient.

The physical design of the proposed LIM involves a prefabricated variable frequency drive (VFD) and speed sensor working in conjunction with an ATmega128 microcontroller, and a liquid crystal display (LCD) screen. The additional subsystems required for each component is listed as follows: the VFD controller, speed controller, and speed output via LCD. The prefabricated VFD was chosen because of its rugged build and its accessibility. VFDs are a common component of industrial environments and are all very similar in nature. The VFD that was chosen for our project was the Lenze Tech MCH250B because it meets all of the required needs for the build. The Lenze Tech MCH250B was previously donated by Caterpillar to Bradley University and it provides the needed output frequency range to complete the LIM senior project.

The LIM's stator will be created using copper wires for coils and stator lamination segments for the stator. The stator will be powered by a three-phase voltage scheme and the rotor will be a large radius wheel used as a simulated linear track. The large radius wheel is a component of a past project that consists of a ferrous track mounted on the perimeter of the wheel with a magnetic levitation system mounted above the track. As the wheel spins at certain speeds the magnetic levitation system will provide lift based off of magnetic currents generated from the spinning wheel. The provided simulated linear track will be equipped with a speed sensor that will send data digitally to a microcontroller, which will be displayed via a LCD screen, and will be used as feedback for the desired control scheme. The team's contingency plan involves an array of alternative solutions that will solve any potential problems with our proposed design.

The team is proposing to control the speed of the simulated linear track under magnetic levitation conditions. The total projected cost is $706.87, which includes all materials to build and test the motor. The performance abilities of the motor will be tested in the Department of Electrical and Computer Engineering (EE) Power Laboratory. The EE Power Laboratory offers the simulated linear track along with access to a three phase voltage scheme.

The engineering skills the team has acquired over the past few years along with the research that has been conducted over the past few months, has given us the technical expertise to accomplish all of the goals of this project. The demand and usefulness of this project is apparent, and the only thing required to make it happen is the financial resources.

ABSTRACT
A Linear Induction Motor (LIM) is a specific type of alternating current (AC), multiple-phase machine that provides force and movement in a linear direction. Numerous applications of LIM's can be found in industry today, one of the most interesting being high speed magnetic levitation railway systems. Extensive research has been conducted to find a cost-effective and efficient way to build and test a LIM in the laboratory. The proposed LIM will be mounted underneath a 45.72 [cm] diameter wheel available in the Bradley ECE power laboratory, and will drive the wheel over a specified speed range. Geometric layout and design of the stator core is the most important aspect of the proposed project because the stator design will determine the fundamental operating characteristics of the machine. Controllability of the LIM is another important aspect of this project because without adequate control the machine cannot be used for practical applications. A microcontroller interface with an operator input will be used in conjunction with a speed sensor and a commercially available Variable Frequency Drive (VFD) to control the speed of the wheel.

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I. INTRODUCTION

A. Problem Background

A linear induction motor (LIM) is a specific type of alternating current (AC) motor designed to produce motion in a straight line. A LIM operates under the same principles as its AC rotary motor counterpart, typically powered by a three-phase voltage scheme with a force that is produced by a moving magnetic field [1]. The main difference between a typical rotary motor and a LIM is the way the magnetic field is produced. Inside of an AC rotary motor the magnetic field produced is in an infinite loop rotary motion. A LIM, however, does not operate in an infinite magnetic field loop. A LIM can be imagined as an AC rotary motor with the loop cut down the center and the stator and rotor spread out on a flat line, the induced magnetic field now moves linearly across the flat motor face instead of rotating, see Appendix A Fig. 7 [2]. This idea was what spurred the first development of a LIM. Force is achieved in a linear direction and it is understandable that this would have certain applications in industry, such as rotating large radius wheels and in industrial conveying machines. More recent technological advancements are linear induction machines that have been used in conjunction with high-speed magnetic levitation systems. Very high speeds are obtainable because of minimal friction losses due to the magnetic levitation of the system. The idea behind the LIM senior project was developed in order to further develop the past senior project that consisted closed loop magnetic levitation system completed by Kyle Gavelek, Christopher Smith, and Victor Panek in 2013 [3]. The LIM will implement the simulated linear track developed in the closed loop magnetic levitation system senior project.

B. Problem Statement

Professor Gutschlag is interested in designing and building a LIM that can be mounted on the side of a previous senior project to make a 45.72 [cm] diameter wheel turn. The main focus of this project is to design and implement a LIM that can eventually be used to power and control a magnetic levitation system for future senior design projects. Six main objectives were determined after careful consideration by the team and their advisor. The LIM's objectives include inexpensive cost of materials, electrically efficient, controllable, safe, constructible, and reliable

C. Scope

The project advisor in conjunction with the project team members determined the project scope. The scope of the project was developed to ensure that time would not be wasted on aspects of the project that were not relevant to the overall success of the LIM senior project. Some items that were determined to be outside of the project scope were achieving magnetic levitation and creating a new or improving upon the already existing simulated linear track.

TABLE I: SCOPE OF PROJECT

Within Scope of Project	Outside Scope of Project
Manufacturing a LIM	Magnetic Levitation
Simulated Torque and Speed Analysis	Creating an Improved Simulated Linear Track
Movement of Simulated Linear Track	
Controllable Via Microcontroller	

II. STATEMENT OF WORK

A. System Description

1. System Block Diagram

The system block diagram is shown in Fig. 1. The two inputs of this system are the three-phase power source and user input. The three-phase power source will be regulated using a variac and then power the motor components to create rotation of the simulated linear track. User input consists of the ability to change system settings, such as voltage and frequency levels, to affect the speed of rotation of the wheel. Outputs of this system are rotation of the simulated linear track and a display for information. The rotation output is the force that the motor will generate to turn the simulated linear track. The display portion of the output will show slip and rpm as the system is running.

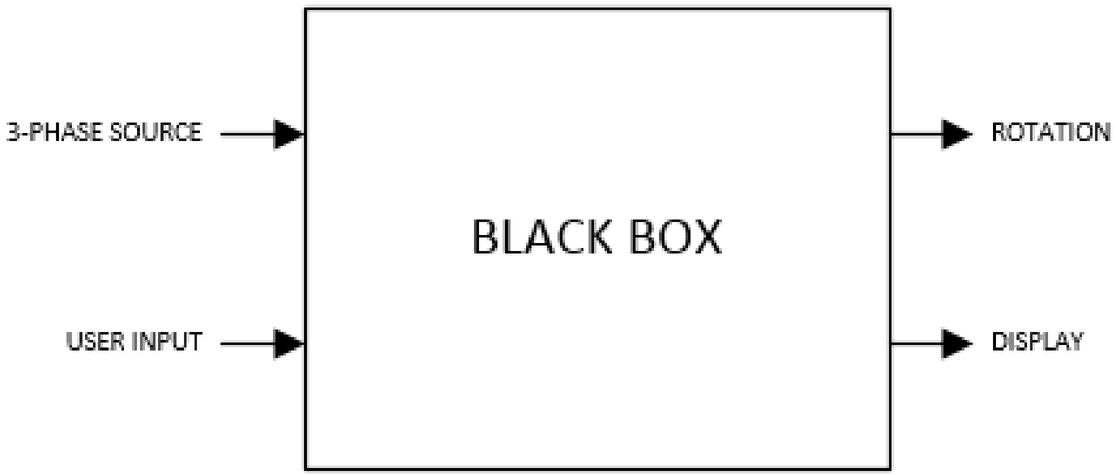

Fig. 1 System Block Diagram showing the necessary inputs and outputs of the system

2. Subsystem Block Diagram

The sub-system block diagram can be seen below in Fig. 2. The three-phase power source will go into a variac that will limit the voltage that enters the variable frequency drive (VFD). The variac will then provide three-phase power to the VFD. The VFD will vary the frequency and voltage provided to the coil windings producing a magnetic field causing linear motion. The linear motion will be used to rotate the rotor of the simulated linear track, causing the wheel to rotate. The VFD user input parameters will be transmitted and displayed via microcontroller and liquid crystal display (LCD). The rotor generated rotation will be measured with a speed sensor that generates pulse via photo-interrupter. Data will be sent to a microcontroller and converted from pulses/second to rotations/minute and then input to the LCD to be displayed to the operator. The microcontroller will compute the torque, speed, and slip of the LIM and send the data to be displayed on a LCD. The overall interfacing design of the system can be seen in Fig. 9 of Appendix A. The VFD requires a 0-10 [V] reference signal that corresponds to a 0-120 [Hz] frequency range. The communication signals will be passed between the devices using a 0-10 [V] signal along with various gain stages. The communication signals will then be converted using analog to digital (A/D) and digital to analog (D/A) converters to bring data in and out of the microcontroller to the various components of the project

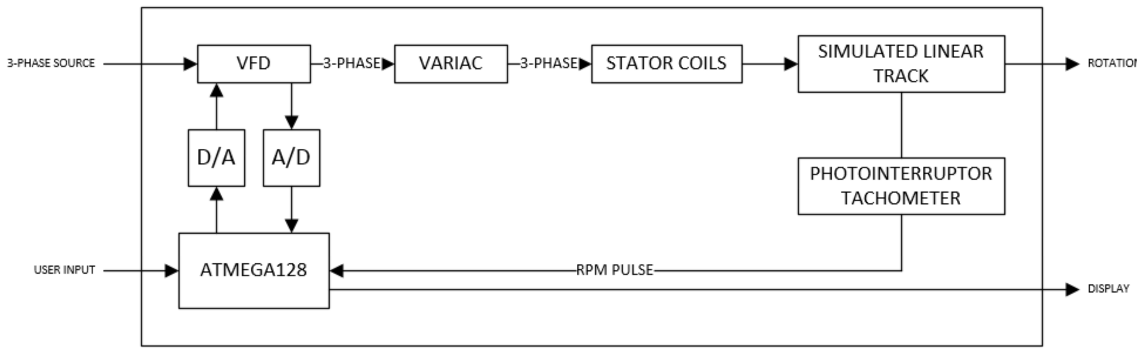

Fig. 2 Subsystem block diagram outlining the various systems and connections for communication to one another.

B. *Design and Solution*

1. Initial Design Approach

This project's goal is to generate linear motion using a LIM to generate a linear force to turn a large diameter wheel under a specified velocity range. The subsystems of this project consist of the motor stator core and interfacing signals with the ATmega128 microcontroller. The stator core has a few options on how it can be designed and constructed. These choices consist of number of poles, pole arrangements, and the material the stator will be made from. The number of poles used in the stator construction can be interchanged between two and four, thus giving the stator different properties to work with. The pole arrangements can be either in a salient pole arrangement or a non-salient pole arrangement, also known as a distributed pole arrangement. The stator core design was the primary focus of the project and took the majority of the allotted time. The main focus of the group was the design of the stator core with a minor focus on the interfacing of the subsystems.

The current design of the LIM stator will contain four poles with 24 stator divisions, broken into 12 teeth and 12 slots. The two-pole machine reaches the desired synchronous maximum speed of 1,100 [rpm] well within the given VFD frequency range of 0-120 [Hz]. With a four pole machine the pole pitch would change, thus the frequency to achieve the synchronous maximum speed would be reached towards the end of the range of the VFD, but when the stator length is increased it reaches the desired speed the same as the two pole machine. Through previous research it was determined that the synchronous speed of a LIM does not depend on the number of poles [2]. This proves to be correct but only for the case of non-static stator length. Without changing the length of the stator the number of poles does determine the synchronous speed of a LIM. The synchronous speed of a LIM is dependent on the pole pitch, seen in Fig. 3, which is the distance between two adjacent poles [4]. When the number of poles is increased while maintaining the length of the stator the pole pitch will decrease, in turn decreasing the synchronous speed. An example of the correlation between the synchronous speed of the LIM and the frequency based on the number of poles can be seen in Fig. 12 of Appendix A. The four pole machine, with an increased stator length, synchronous speed and the frequency of the LIM provided by the VFD correlation can be seen in Fig. 13 of Appendix A. Originally when looking at a two pole to four pole comparison the stator length was held constant and therefore the two pole machine looked to be the ideal solution. When increasing the length of the stator for the four-pole machine the ideal synchronous speed and frequency correlation is the same as the smaller two-pole machine ideal synchronous speed and frequency correlation. The four-pole machine design may be more costly than the two pole machine but it will provide more output power and will require less coil windings per stator tooth making the project more feasible.

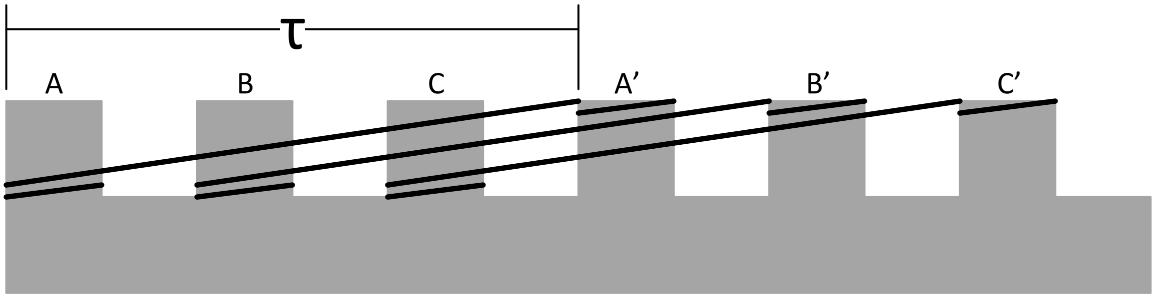

Fig. 3 Pole Pitch, τ, of a Two-Pole LIM Created in Visio

The two options for pole manipulation are the salient pole or non-salient pole arrangements. Salient pole arrangements are most commonly used for large diameter and short axial length wheels. Salient poles are used in lower speed applications and have a large amount of winding losses [5]. The team selected the salient pole arrangement due to the fact that a large diameter wheel is being used to simulate a linear track and due to the fact that a salient pole arrangement is easier to wind the coils in the stator. When winding the coils in a salient arrangement, the coils are wound around a single stator tooth at a time; this can be shown in Fig. 4.

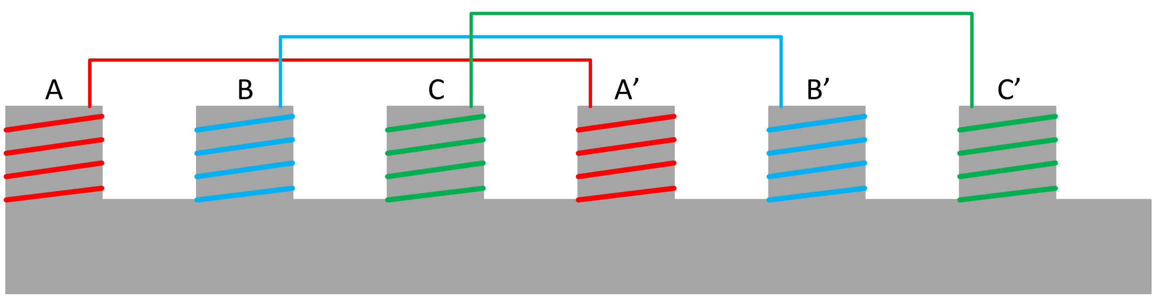

Fig. 4 Salient Pole Arrangement for a Two-Pole LIM Created in Visio

The second option would be to implement a non-salient pole arrangement. Non-salient pole arrangements are normally used in situations with a small diameter and long axial length wheels. The non-salient pole arrangements allows for less winding losses and are better used in dynamic balancing [5]. The non-salient pole arrangement complicates the winding procedure of the coils in the stator. While winding the coils each coil is wrapped around multiple stator teeth, this can be seen in Fig. 5. The non-salient pole arrangement will be an alternative option if the LIM does not have the ability to reach the desired synchronous speed as shown in Fig. 10 of Appendix A.

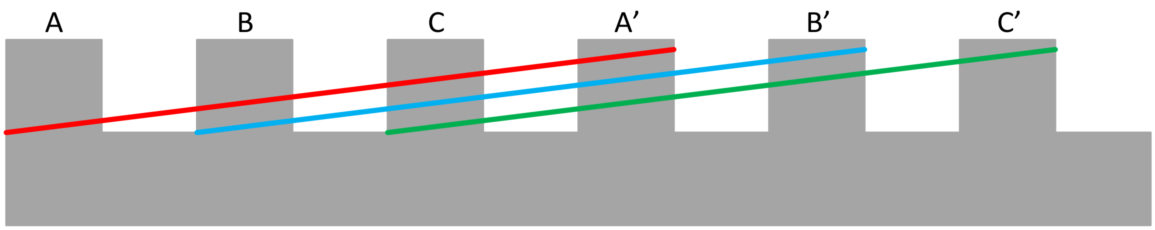

Fig. 5 Non-Salient Pole Arrangement for a Two-Pole LIM Created in Visio

2. Equation Implementation

The first design steps consisted of developing a rotary to linear model so that the designed linear stator could fit within certain specifications that were pre-determined by the group. These specifications originally consisted of creating a stator that was roughly 0.3048 [m] that could move the simulated linear track at a linear velocity of 28.73 [m/s], which corresponds to 1,200 [rpm]. Since the simulated linear track is an infinite circular path, a stator that wrapped around the track was desired. Using the equation Eq. 1.1,

$$L = \theta r \tag{1.1}$$

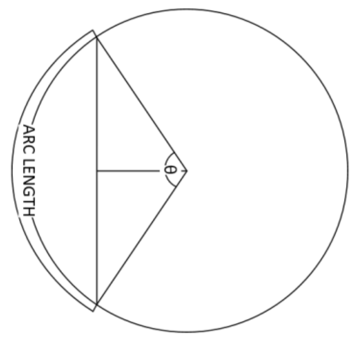

Fig. 6: Visual of Determining the Arc Length of the Stator Core

arc length, L, of the 0.3048 [m] design was determined by using the radius of the simulated linear track, r, along with the angle, Θ, that separates the arc length from the center of the track. The arc length was calculated to be 0.3336 [m] shown in Fig. 6. The arc length was then used to determine an equivalent rotary machine. A rotary to linear model was generated because there are very well developed and researched equations for rotary machines, unlike linear machines, and to also prove the linear model equations that were developed by the team. Using the arc length that was determined, an equivalent rotary machine was then generated by equating the calculated arc length to the circumference of the new rotary machine Fig. 6. With the equivalent rotary machine generated, values can be plugged in to Eq. 1.2

$$\omega = \frac{120f}{p} \tag{1.2}$$

for number of poles, p, and desired rotational speed, ω, to determine the electrical frequency, f, that will be required to generate the desired speed. It was determined that with the static length of 0.3048 [m] as the circumference of the rotary machine, an electrical frequency of 86.2 [Hz] would be required for two poles and an electrical frequency of 172.3 [Hz] would be required for four poles. Anything above 120 [Hz] would be impossible for our group to implement because the upper bound of the variable frequency drive that is being used is 120 [Hz], so two poles was determined as the best option. Turmoil within the group was generated with the pole values that were determined. Multiple sources state that velocity, v, of a linear induction machine is not dictated by how many poles are associated, but rather, the pole pitch, τ, that is associated with the linear machine Eq. 1.3.

$$v = 2\tau f \tag{1.3}$$

Turmoil was generated by this realization, because why would the number of poles affect the output velocity of the track, if the pole pitch is the only value that will affect the output? The realization then came, that the pole pitch will change with the number of poles associated, if the length of the stator stays static, shown by Fig. 12. What this means, is that, if the length of the stator stays at 0.3048 [m], as poles are added, the pole pitch will shrink, because more poles will require more space. This is the exact reason why number of poles affects the speed of a rotary motor, because the stator of a rotary motor is set to a static circumference. This means that as the number of poles increases, the pole pitch of the rotary machine decreases which causes a lower output velocity. The sources that state that the number of poles of a linear machine does not dictate the output velocity of the linear machine, do not take into account a static length for the stator of the linear machine. If a static length for stator is used, there would be an equation relating number of poles to the required electrical frequency, f, and desired output velocity, v, derived and shown in Eq. 1.4 and 1.5. was determined by the group.

$$\tau = \frac{L}{p} \tag{1.4}$$

$$v = \frac{2Lf}{p} \tag{1.5}$$

The major equation that was used to design the stator was the turns per phase, T_{ph}, equation. Deriving the equation was a major breakthrough in the design procedure. There were many assumptions that had to be made in order to determine the number of turns per phase. The equation derivation started with the two simple equations for power efficiency, η, Eq. 1.6, and power factor, PF, Eq. 1.7.

$$\eta = \frac{P_{out}}{P_{in}} \tag{1.6}$$

$$PF = \frac{P_{in}}{3V_{ph}I_{ph}} \tag{1.7}$$

The power factor equation is used when computing three-phase power factor by measuring a voltage, V_{ph}, and current, I_{ph}, from a single phase. Solving for output power the equation becomes Eq. 1.8.

$$P_{out} = \eta 3V_{ph}I_{ph}(PF) \tag{1.8}$$

The group knows the output power, current, and voltage needed to spin the wheel at 1,100 [rpm] from the data provided by a previous senior project. Assuming ideal coil windings with no losses or leakage flux, the induced phase coil voltages are equal to the applied phase voltages, Eq. 1.9 [8].

$$V_{ph} = 4.44 f_s \Phi_{ag} T_{ph} k_w \tag{1.9}$$

Where f_s is the synchronous electrical frequency, Φ_{ag} is the average air-gap flux per pole, and k_w is the coil winding factor. The voltage at one phase can be substituted into Eq. 1.8. Also known is the equation for synchronous electrical frequency, Eq. 1.11.

$$f_s = \frac{p n_{ms}}{2} \tag{1.10}$$

$$\Phi_{ag} = B_{ag} A_p \tag{1.11}$$

Where p is the total number of poles of the system and n_{ms} is the mechanical cycles per second. The equation for synchronous electrical frequency can also be substituted into Eq. 1.9. Also the equation for the average air-gap flux per pole, Eq. 1.11, can be substituted into Eq. 1.9. B_{ag} is the average air-gap flux density per pole and A_p is the cross-sectional area of the pole faces. The final equation for the turns per phase can be seen below in Eq. 1.12.

$$T_{ph} = \frac{P_{out}}{6.66\{pn_{ms}B_{ag}A_p k_w I_{ph}\eta(PF)\}} \quad (1.12)$$

To determine the turns per phase many initial assumptions had to be made. The group made initial assumptions when determining the turns per phase. Worst-case scenarios were assumed for the coil winding factor, power factor, and power efficiency. LIM's are inefficient due to the fact that there is a larger air-gap, compared to rotary motors. LIM's are not continuous thus losing magnetic flux due to end-effects. Therefore, assuming high efficiencies, power factors, and winding factors would be impractical.

3. Interfacing

Interfacing between operator and systems will be done using the ATmega128. Interfacing will consist of the communication of the various subsystems. The ATmega128 will send and receive a 0-10 [V] signal to and from the VFD. The 0-10 [V] signals will be ran through simple gain stages and converters so the signals can be processed at a proper level. The 0-10 [V] signal being sent to the VFD will be generated in the ATmega128 in conjunction with a digital to analog converter and controlled via keypad. The digital to analog converter will generate a 0-5 [V] signal, which will then need to be amplified to a usable 0-10 [V] signal. The 0-10 [V] signal sent to the VFD will be used as a reference voltage to change the frequency being output to the stator core. The VFD will then generate a 0-10 [V] reference voltage, which will be sent to the microcontroller via feedback loop to the ATmega128 to determine what the operating frequency is at that current moment in time. The 0-10 [V] signal back to the microcontroller will need to be ran through a voltage divider to drop to the voltage level from 0-10 [V] to a usable 0-5 [V] signal. The feedback signal will then be input into the ATmega128 onboard analog to digital converter, so that the microcontroller can properly analyze the signal. Along with the signals generated for the VFD, there will also be a feedback signal from a tachometer system to measure the speed of the simulated linear track. The signal from the tachometer system will create pulses when the simulated linear track is moved. A photo-interrupter will be used as the pulse generator along with a transparent disc with opaque notches overlaid on it. As the transparent disc rotates, light will flow through, depending on the position of the opaque slots, and will generate a pulse when light is allowed to shine through. The pulses will then be counted and analyzed via microcontroller to determine the speed that the track is moving. The feedback signal from the tachometer will then be processed and used as a set point for the 0-10 [V] signal that is being sent to the VFD. As the speed of the frequency output from the VFD increases the linear velocity of the simulated linear track will also increase.

4. Final Design

The final design of the LIM is a three-phase, four pole machine. The LIM has 12 teeth on the stator core, each tooth having its own coil winding energized by a three-phase 0-120 [Hz] VFD. Originally it was calculated that the total number of coil winding layers on a single tooth would have to be five, providing 213 turns per coil, in order to produce enough magnetic flux to reach the desired speed of 1,100 [rpm]. Once the group started the coil winding process, it was determined that five layers produced 275 turns, so a decision was made to reduce the number of coil layers from five to four. With four coil layers 235 turns were able to fit onto a single stator tooth. The overall coil winding process consumed a majority of the project time. Initially, to wind one coil, it took two hours of lab work. The group was originally using a CNC lathe to wind the coil on a wooden replica of a single tooth from the stator core. This process was extremely time consuming, as the lathe did not rotate at a fast speed. After 10 hours of winding coils on the CNC lathe, the wooden replica tooth was modified to fit into a different, faster, lathe. The winding process was then cut down to about 30 minutes per coil. When a coil was finished on the lathe, it was then quickly wrapped in insulated tape and zip-tied together to ensure that it would not break apart when transferring to the stator core.

Minor modifications were made to the previously made simulated linear track. The track needed to be raised in order for the stator to be mounted underneath. Additional mounts were cut and used to raise the linear track 7.62 [cm] in height. The additional 7.62 [cm] mounts did not add enough height to allow for the stator core to fit underneath, so adjustable screws and bolts were used to raise the track enough to ensure a tight fit of the stator core underneath. The entire height of the mounting solution was 31.75 [cm] and the linear track has a radius of 22.86 [cm], therefore the linear track sits 8.89 [cm] from the ground. The stator core has a height of 12.7 [cm] at the center, so the linear track would need to be raised an extra 3.81 [cm]. The group decided on purchasing 15.24 [cm] bolts and to be used as a height adjustment solution in order to achieve minimal air gap between the copper track and the stator. With this mounting solution, the air-gap was 0.32 [cm]. This air-gap was smaller than the expected air gap of 0.64 [cm]. With a smaller air-gap the LIM will have a greater efficiency. There are already a large amount of losses when operating a LIM due to the open air between stator the stator and track, and also end-effect losses that occur when dealing with machines that do not carry and infinite loop of magnetic flux, like rotary motors.

The simulated linear track shaft will be coupled to an outside AC motor, which will be used as an AC generator. The AC generator will be powered by the motion of the linear track and will allow for an accurate output power measurement. The speed of the linear track will be measured via a tachometer subsystem with the output speed being sent to the ATMega128 microcontroller board and will displayed on a LCD. The current of the overall system will be measured using a current probe. Power to the LIM will be achieved using a VFD, with the output of the VFD going through a three-phase variac. The three-phase variac will control the output voltage from the VFD. VFD's have internal voltage to frequency ratio, meaning that as the frequency is increased the voltage is also increased. The variac will be used as a safety barrier when operating the LIM to allow for current and voltage through the stator coils to be better maintained. A wattmeter will be used at the input of the LIM to measure the input power of the LIM.

5. Results and Conclusions

The group members began testing with the VFD connected to the LIM system. The LIM was connected in a star-connection, shown in Fig. 10, where the A''', B''', and C''' are tied together to form a floating neutral or star point. Assuming that the LIM system is balanced, allowed for the three phases to be tied together without having to be tied to a line neutral. A balanced system assumes that each coil has the same number of turns. For the case of the LIM the standard deviation of turns per coil is around ±5 turns. The group placed the coils in a North to South arrangement using the right hand rule to determine the polarity of the coils.

When the VFD was initially powered on, a fault occurred. It was determined by performing a continuity test that there was a short between the stator coils and the stator core. It seems, the stator teeth edges cut through the bobbin solution as well as the lamination on three coils, and therefore three coils had to be re-wound. Plastic pieces were also added onto the stator teeth edges to further prevent any shorting. The VFD no longer displayed the fault error message, but the current per phase was up at 5 [A] when the group estimated to only operate around 3.7 [A].

Group members went out and purchased a compass to determine the polarity of each individual stator tooth. A constant DC current of 3 [A] was applied to the LIM to energize the coils. Using the compass, it was found that the A' was set as a North and not a South. Changing the polarity of the A' coil and re-applying the VFD the LIM was able to rotate the simulated linear track. The current per phase was 3.8 [A] and the wheel began rotation around 30-40 [Hz] with a steady rotation occurring at 60 [Hz].

The expected linear synchronous speed at 60 [Hz] was 20 [m/s], that, unfortunately was not the case for current operation. Many inefficiencies of the LIM system have to do with the wheel of the simulated linear track. The plastic wheel has a copper track with no steel backing. The steel backing behind the copper track will close the loop for the magnetic fields produced by the LIM. With the current wheel design there are flux leakage losses into the plastic of the wheel. The group was able to slide thin (0.3175 [cm]) steel sheets underneath a portion of the copper track. When the wheel rotates and the portion of the wheel with the steel backing enters into the LIMs produced magnetic fields, the wheel does in fact increase in speed. Placing a thicker steel backing behind the copper track would indeed increase the efficiency of the system and increase the speed of the simulated linear track. Another major inefficiency with the wheel design is the wheel bearings. Using a frictionless wheel design will increase the efficiency of the overall system, and possibly lead to generating the expected speeds that were used in design.

C. Economic Analysis

TABLE II: BILL OF MATERIAL

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

The overall total project cost was $706.87. The prices included in the bill of material were costs incurred during the year of work, not including the cost of the materials that were readily available from the previous senior project. The project cost was above our expected cost for the overall project. Initially the team estimated the price of the stator core construction to be around $200 more than the amount we were able to purchase from Laser Laminations. The group ordered extra wire in the case that there were any mishaps when winding the coils and a coil would need to be re-wound. The glass cloth tape and the vinyl electrical tape were used in creating the bobbins for the stator core. Originally the group intended to order premade plastic bobbins, but the price of the bobbins were outside of the project price range. We contacted two separate companies and both companies quoted the bobbins to be over $1,000 for 12 stator bobbins. Using the high temperature glass cloth tape and the high temperature vinyl electrical tape allowed the group to maintain an economical price point for the LIM. The high temperature cable ties were also used in the bobbin creation, while the angle irons were used for stator core mounting. The high cost of the glass cloth tape put the group over our expected total price of materials of $620. Overall the group was able to stay within reason to the original estimated total price.

D. Project Timeline

The Gantt chart in Fig. 11 the LIM team was behind overall for the implementation and testing of the project. The time delay was due mainly to the delays in final approval for purchasing the stator and a solution for wrapping the coils for the stator. Once the stator was purchased it arrived in under a weeks' time along with the magnetic coil winding wire. The next delay that occurred was with the methodology used to create the coils and the best solution for bobbin creation. A perfect solution would have been premade or custom-made bobbins, but they would have taken months and thousands of dollars to create. The project picked up steam, during the final assembly of the LIM system. The remaining work to complete the project in full was to implement the microcontroller onto the control bus of the VFD.

E. Division of Labor

The theoretical design work for the LIM senior project was handled by Mason and Tyler with Tim contributing feedback into the design. Mason focused on simulations for the output synchronous speed of the LIM as well as the equation derivation for the turns per phase. Tyler concentrated on the initial theory behind the rotary to linear motion and how to relate a rotary motor to a linear motor. The microcontroller code and additional sensors was handled fully by Tyler. Mason handled paperwork and researching for the final paper along with presentation materials with Tyler and Tim also providing material for consideration into the final documentation and presentation materials. Tim completed AutoCAD drawing design of the LIM stator core with consultation from Mason and Tyler. Tyler created the wooden replica of the stator tooth that was used for the coils with the full group giving input on the design. Tim with Mason mainly handled the winding of the coils and Tyler providing a hand when scheduling permitted it. Tim handled the mounting hardware work that was required to mount the wheel and stator. Mason and Tyler completed the wiring and testing of the VFD while the mounting hardware was being painted and assembled by Tim. Tim handled the fine-tuning of the mounting of solution. The whole team will take part in the final assembly and testing of this project.

TABLE III: DIVISION OF LABOUR

Tasks	Group Member
Stator Design	Mason and Tyler
Equation Derivations	Mason and Tyler
Simulations	Mason
Purchasing	Tim and Tyler
Coil Windings	Tim and Mason
Stator Mounting	Tim
Microcontroller System	Tyler
VFD Testing	Mason and Tyler
Implementation	All
Testing	All
Deliverables	All

III. CONCLUSION

The main objective of the LIM project is to create an AC linear machine that can be used for future projects in the field of power electronics. The prototype LIM that is being designed will be used as a base for future senior projects as well as generate useful knowledge to future students.

Some such projects would be interfacing our core motor design with a newly designed magnetic levitation system. The original proposal of this project was to get to the designing stage of a small-scale magnetic levitation system. The entire system consists of a control application that will be varying the frequency of a VFD along with providing necessary information to the operator via LCD screen, a stator core that houses multiple wound coils, and a VFD that sends power to the stator along with a control signal back to the control application. Speed is measured via tachometer mounted on the simulated linear track to control a set point that is sent to the control system. Designing the stator core and the control system consisted of generating equations from a power and control theory background.

A. Future Senior Projects

Multiple improvements can be made to the current LIM system, to allow for more efficiency. The main improvements deal with updating the simulated linear track. Currently the copper track associated with the simulated linear track has no steel backing, therefore causing large losses of magnetic flux inside of the wheel. The operation of the LIM could be greatly increased if steel plating were to be added on, behind the current copper track, on the simulated linear track. The LIM team designed the mounting solution to allow for the height of the linear track to be adjustable, in the hopes that a steel backing could be added with no interference with the stator mounted underneath. The wheel currently can only operate up to 1,100 [rpm] without major vibrations, limiting the frequency that the LIM can be operated at. The wheel could also be dynamically balanced to allow for higher speed applications. The LIM team designed the stator coils to be easily slid on and off of the stator core. The coils could be redone in order to achieve a higher power output if the need ever arises. The next iteration of the LIM system could focus on operating the LIM under magnetic levitation conditions. There are many opportunities to evolve this project into future senior projects.

IV. REFERENCES

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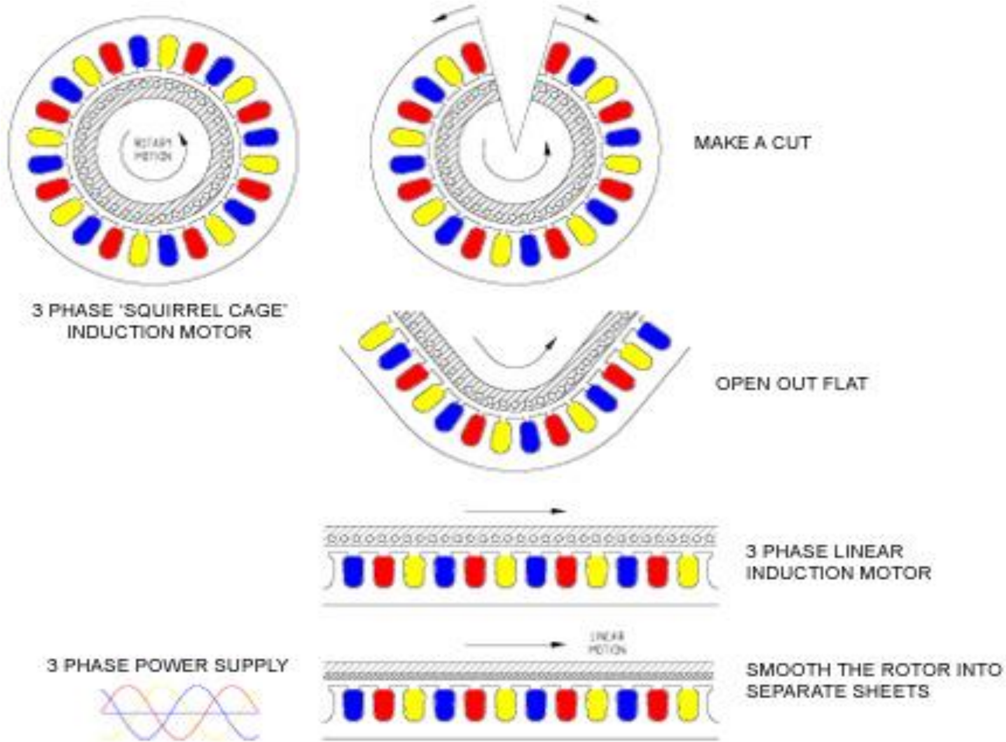
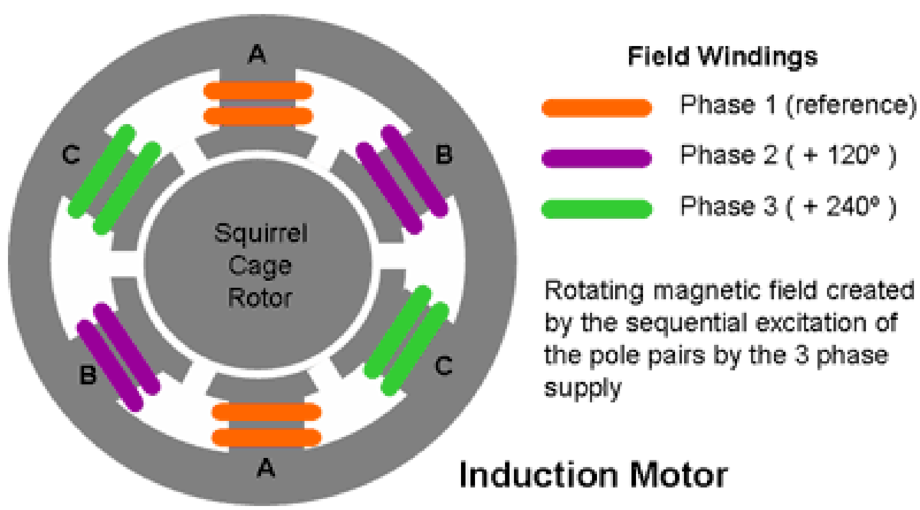
V. APPENDIX A

FIGURES



[1]

Fig. 7 Visual Representation of an AC Induction Motor Being Cut and Laid Flat to Become a LIM



[2]

Fig. 8 AC Induction Motor Visual Explanation

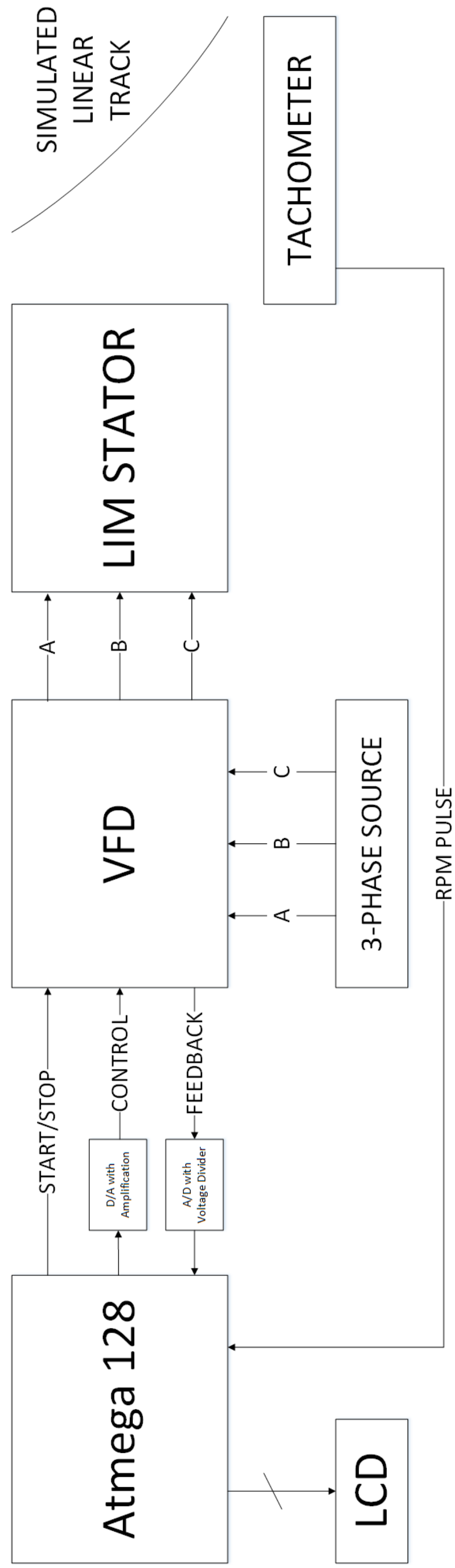


Fig. 9 Entire System Block Diagram of Entire LIM Interfacing System

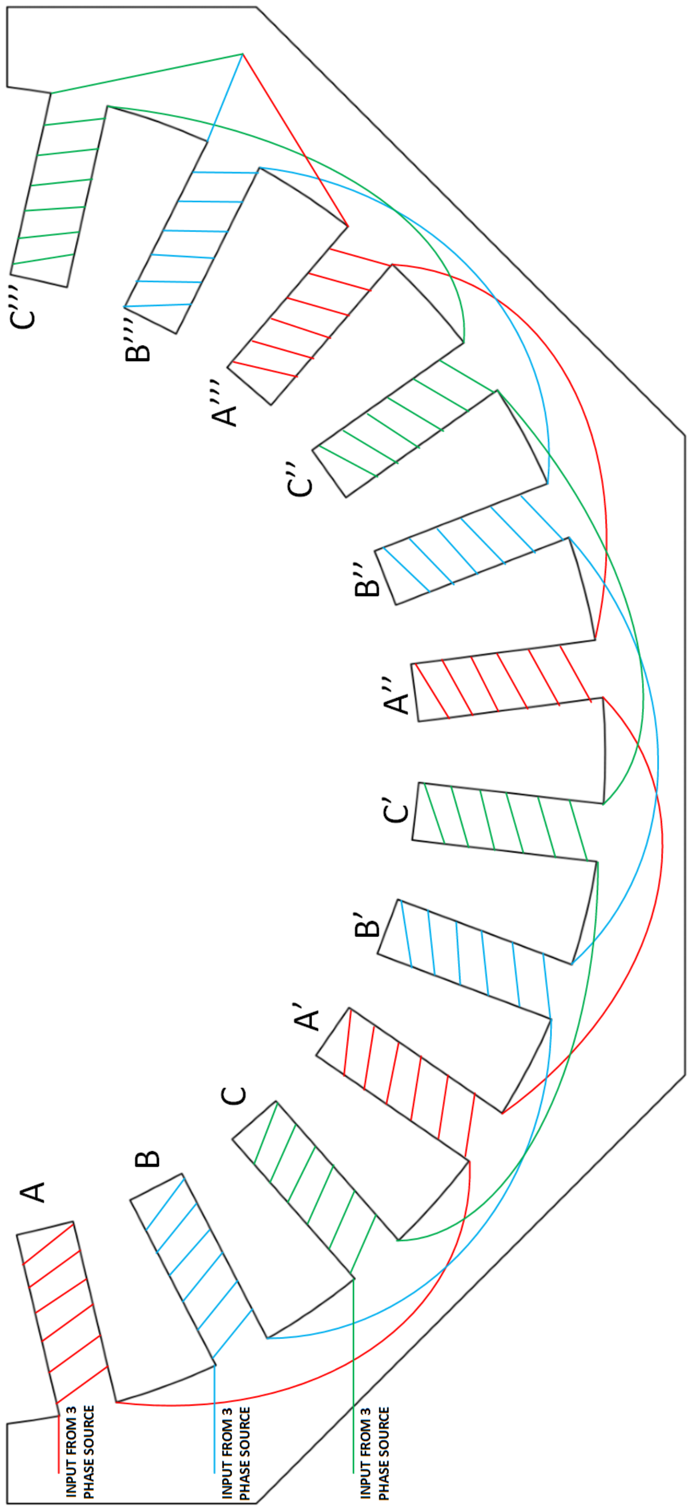


Fig. 10 System Wiring Diagram (Star-Connection)

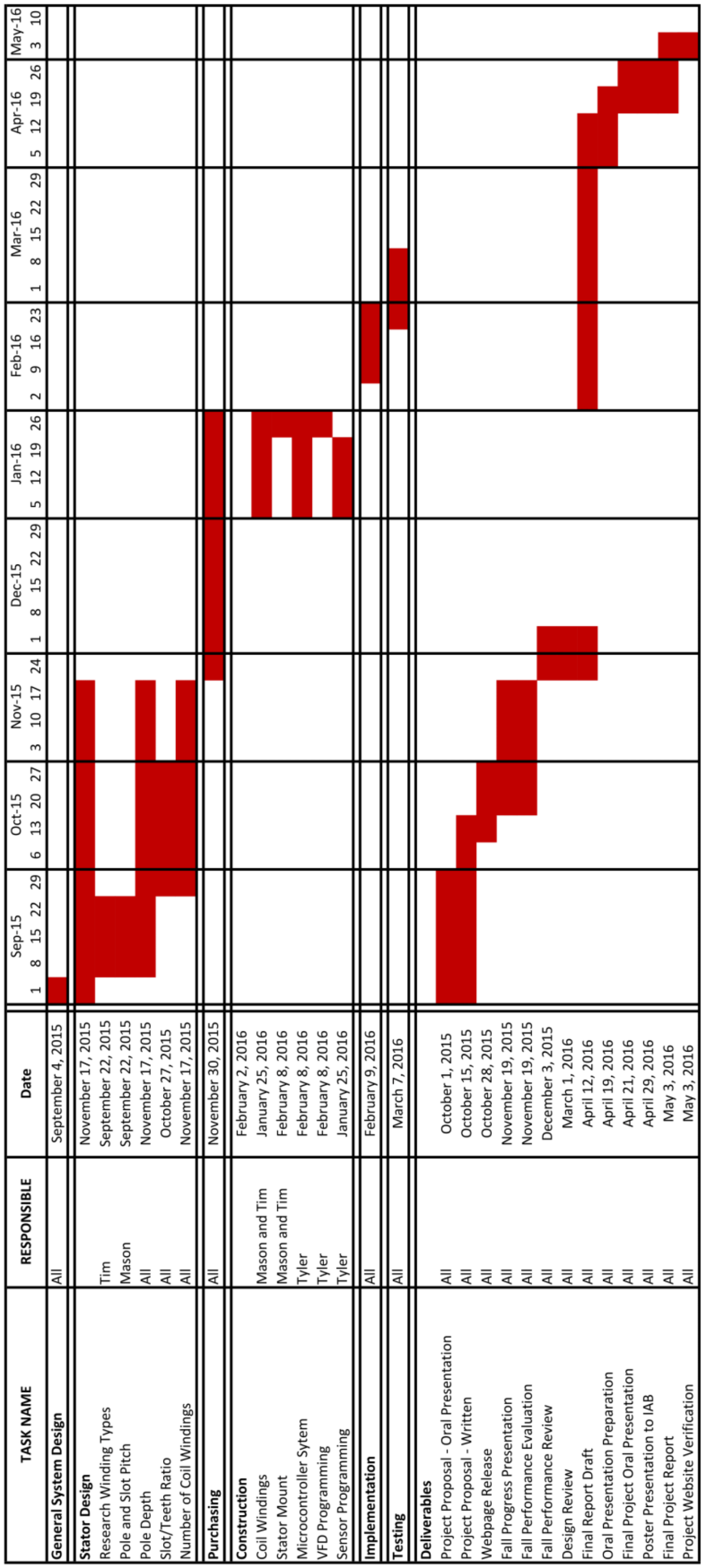


Fig. 11 Overall Gantt Chart of the LIM Senior Project

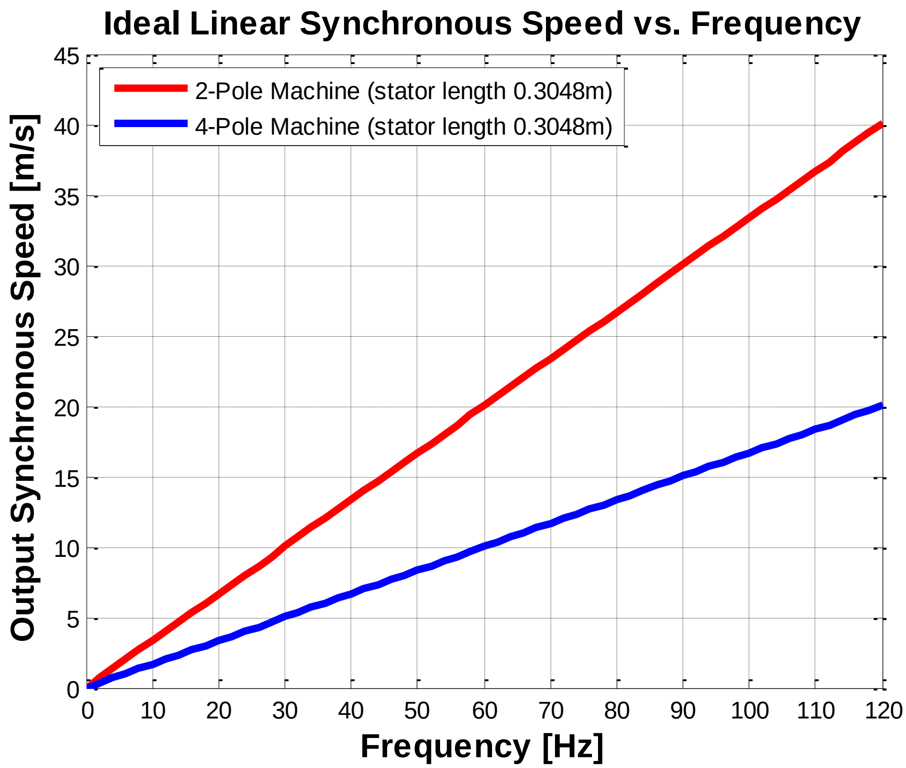


Fig. 12 Ideal Linear Synchronous Speed vs. Frequency with a Constant Stator Length

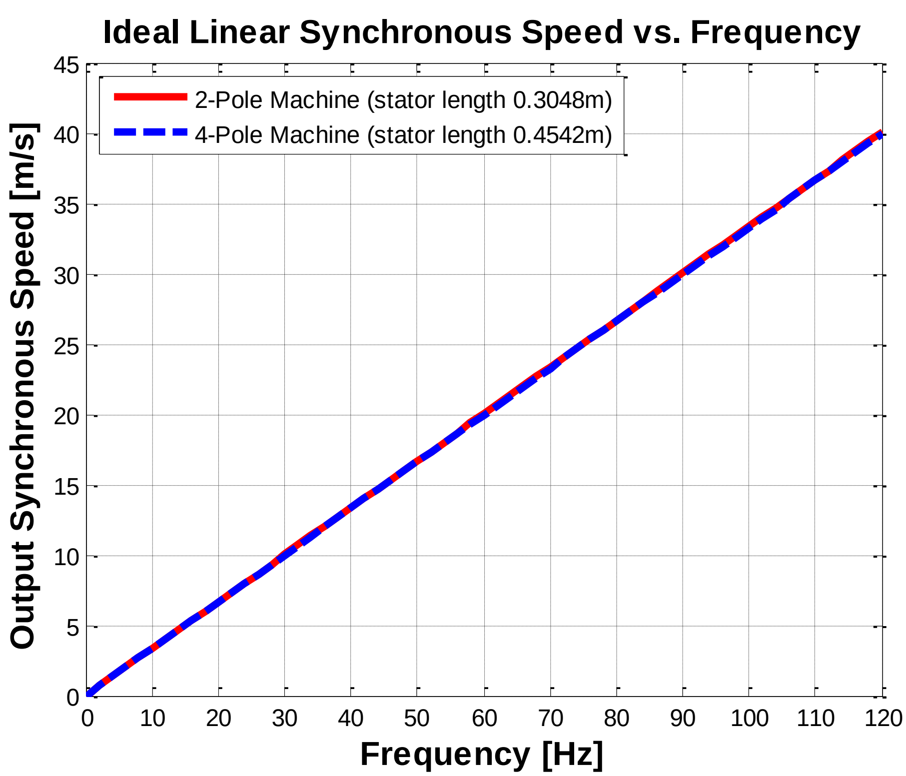


Fig. 13 Ideal Synchronous Speed and Frequency with Varying Stator Lengths

CITATIONS FOR FIGURES USED IN APPENDIX A

[1] Force Engineering. *How Linear Induction Motors Work.* [Photograph]. Retrieved from http://www.force.co.uk/linear-motors/how-linear.php

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