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 $620, 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 creates force and movement in a linear direction. Numerous applications of LIMs can be found in industry today, one of the most notable 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 on the side of a 45.72 cm diameter wheel, with the ability to turn the wheel over a specified speed range. Geometric layout and design of the stator core is the most important concept of the proposed project, because the stator design will determine completion of the overall project. Without a functional stator design the LIM would never be operational. Controllability of the LIM is another important aspect of this project, because the wheel in the laboratory cannot exceed 1,100 rotations per minute (rpm) due to vibration problems. 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. 6 [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. *Constraints*

A list of constraints were compiled by the group members. The constraints were determined through extensive research and communication with the project advisor. The first listed constraint is that the LIM must be powered by a three-phase voltage system. Due to power and current limitations, using a three-phase system will be a more feasible option compared to a single phase arrangement. The second constraint is that the motor must not exceed 1,100 rotations per minute (rpm). As the LIM exceeds 1,100 rpm the simulated linear track's wheel will start to vibrate and the LIM will no longer be safe to operate. Constraints were not ranked, and are in top-down order for ease of description.

TABLE I: LIST OF CONTRAINTS

Linear induction motor must be a three-phase system
Linear induction motor cannot exceed 1,100 rpm

D. Scope

The project scope was determined by the project advisor in conjunction with the project team members. 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 II: 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 systems 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.

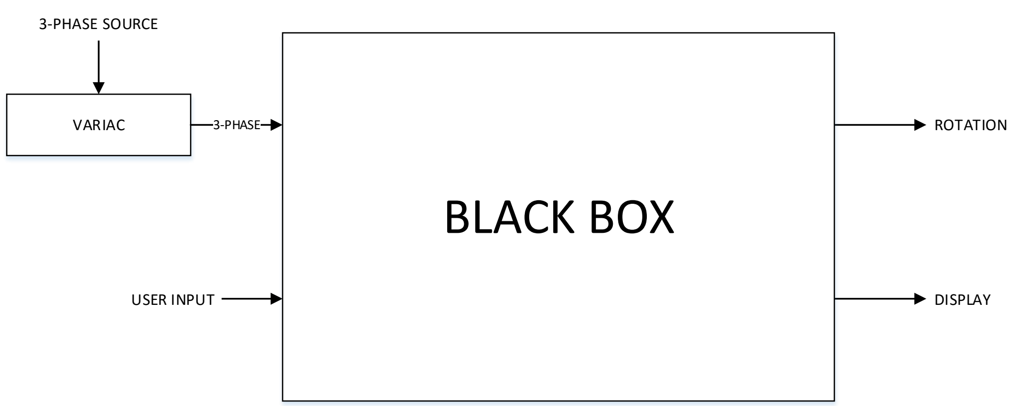

Fig. 1 System Block Diagram showing the necessary inputs and outputs of the system

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. 8 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

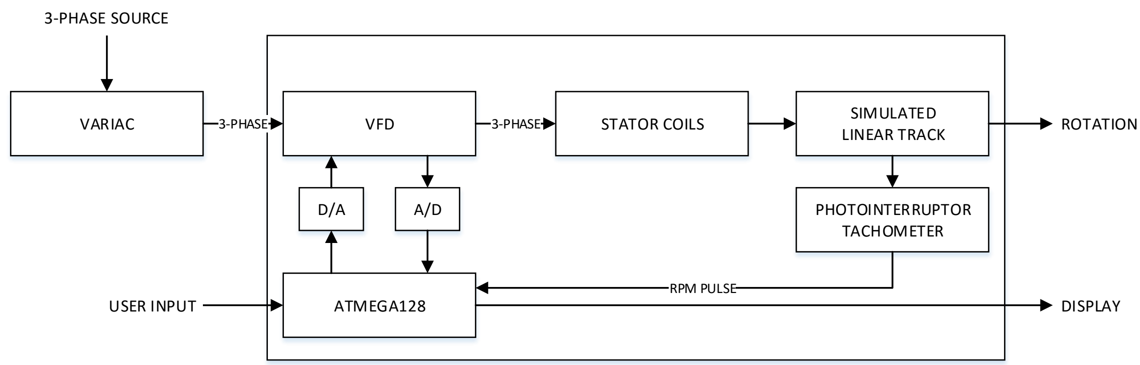

Fig. 2 Subsystem block diagram outlining the various systems and connections for communication to one another.

3. Nonfunctional Requirements

A list of objectives were compiled by the team members. A compiled list of system objectives (nonfunctional requirements) are itemized in Table III. Each objective has a set of metrics associated with them to rank different options. The value applied with each metric corresponds to a scale system where 10 would be perfect and 0 completely ineffective, seen in Appendix B. The first of the objectives listed below, is that the LIM should be inexpensive. A budget was constructed in order to keep the project in a predetermined window of cost and the group came to an agreement that the amount of available money for expenditure is $1,500. Exceeding this cost is not possible due to the fact that unlimited funds are not available for the completion of the project. Staying in the cost range from $0 to $1,500 is the only solution. The second objective states that the LIM should have electrical efficiency of 50%, or the output power cannot be less than one half of the input power. The purpose of this objective is to ensure the creation of a linear machine that could actually be used, and not a machine that is so terribly inefficient, that it does not function properly. The third objective specifies that the LIM should be controllable via microcontroller. The microcontroller will control the speed of the motor by varying the frequency output of the VFD via a 0-10 V reference signal and a 0-10 V feedback signal from the VFD to the microcontroller. The next listed objective is that the LIM should be safe. The motor should be able to be run safely without causing harm to the operator or anyone within direct vicinity of the machine. The fifth objective is that the LIM should be constructible. The motor should be designed in a way that it can actually be constructed. All materials and internal components should be considered during the design of the motor to prevent oversized and overly expensive parts. The last objective listed is that the LIM should be reliable. The LIM should have the ability to operate for extended periods of time without failures. The least amount of time the motor should run without a single fault, such as overheating or causing destruction to the simulated linear track, will be 30 minutes.

TABLE III: LIST OF OBJECTIVES

Linear Induction Motor should be inexpensive
Linear Induction Motor should be electrically efficient
Linear Induction Motor should be controllable from a microcontroller
Linear Induction Motor should be safe
Linear Induction Motor should be constructible
Linear Induction Motor should be reliable

4. Functional Requirements

The functional requirements for the LIM senior project were divided into four different specifications. The specifications include prescriptive, procedural, performance, and interface performance specifications. The group decided that the prescriptive specifications included the rotation of the simulated linear track at different speeds, the displaying of data, and the LIM will be designed to have minimal power loss. The procedural specifications included slip, rpm, and torque be relayed to the microcontroller and then displayed to a LCD. The VFD output frequency will be sent to the microcontroller via 0-10 V that will be stepped down through an op-amp configuration to function at the 0-5 V so that the microcontroller can handle the data. The 0-10 V signal from the VFD corresponds to a 0-120 Hz range. The tachometer will send pulses to the microcontroller which will then be counted and displayed over the cycle of a 250 ms timer interrupt where it will then be updated and a new count will begin. The slip and output torque of the motor will be calculated internally in the microcontroller using feedback from the tachometer and VFD. The data will then be displayed via LCD in conjunction with the current speed of the simulated linear track. The performance specifications of the LIM are the motor will allow for a variable speed of ± 50 rpm, and the motor will have minimized power loss while running. The interface performance specification is the microcontroller must display the information gathered from the motor to the LCD.

Prescriptive Specifications:

1. The linear induction motor will rotate the simulated linear track at different speeds
2. The linear induction motor will have a data display
3. The motor will be designed for minimal power loss

Procedural Specifications:

1. VFD speed and rpm will be relayed to the microcontroller
2. Slip, rpm, and torque will be displayed

Performance Specifications:

1. The motor will allow for variable speeds between 0-1100 rpm
2. The motor will have at least 50% efficiency

Interface Performance Specifications:

1. The microcontroller must display the information gathered from the motor and refreshed every 250 ms

B. Design Approach and Method of Solution

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. Stator design is the primary focus of the project and will take the majority of the time allotted. Without the stator creation any form of interfacing that has been done with the microcontroller will be useless since there will be no motor to interface with. To combat this problem the group will be focused on the creation of the stator with a smaller focus on the interfacing of subsystems to ensure that the project can meet the given specifications.

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. 10 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. 11 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.

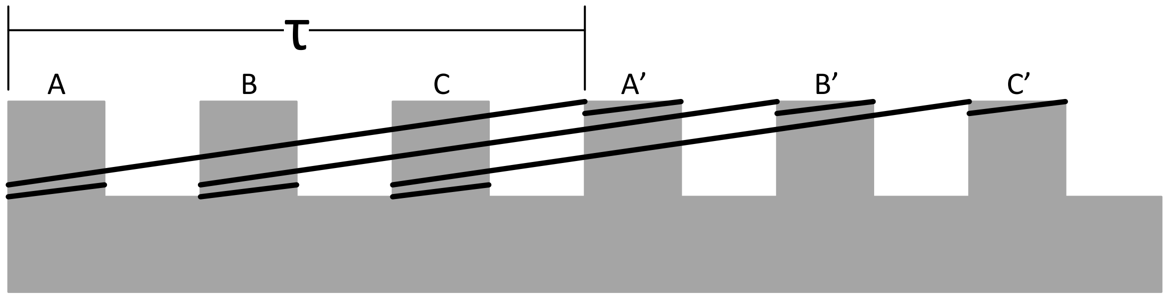

Fig. 3 Pole Pitch, τ, of a Two Pole LIM Created in Visio

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 salient pole arrangement was selected by the team 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.

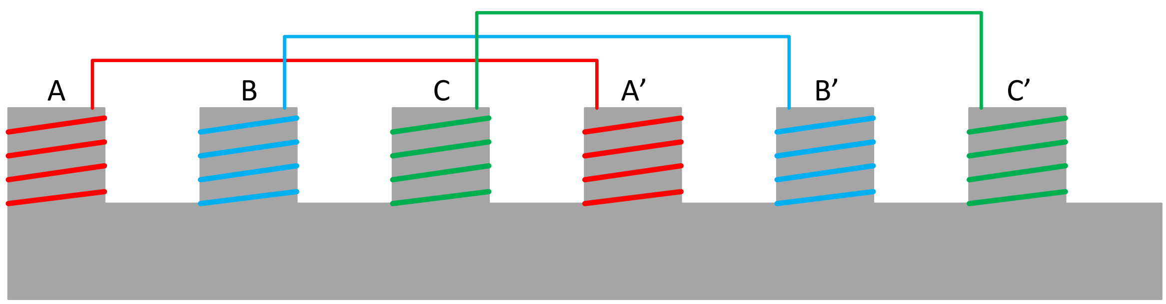

Fig. 4 Salient Pole Arrangement for a Two Pole LIM Created in Visio

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.

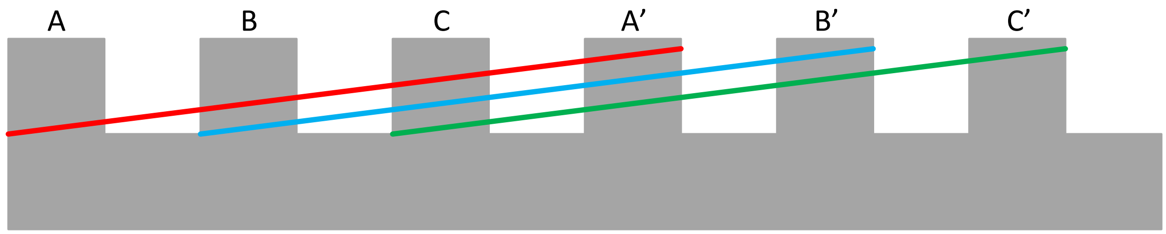

Fig. 5 Non-Salient Pole Arrangement for a Two Pole LIM Created in Visio

The two components of work necessary for the LIM's stator will include the designing and purchasing of stator lamination segments. The stator lamination segments can then be pressed together to the proper width of the LIM. An alternative solution to the stator lamination segments can be water-jetting stator laminations to make stator segments, transformer E-laminations, or a solid manufactured stator core. The water-jet option would be our first alternative option since it would be more economically feasible than the solid manufactured stator core. Another alternative solution for the stator material would be the transformer E-laminations. The transformer E-laminations would be bolted together to achieve the shape of the stator. The bolting of the transformer E-laminations would not provide a smooth curve around the wheel of the simulated linear track and therefore the air gap between the wheel and stator would be greater. With a greater air-gap the LIM would be less efficient and a LIM is already inefficient due to the fact that it is a single-sided machine.

The interfacing using the ATmega128 will be done once the stator design is completed and the stator lamination segments are ordered. 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 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 and sent to the microcontroller via feedback 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 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.

To determine the success of this project, experimentation will be completed in the power lab in the Electrical and Computer Engineering Department at Bradley University with Professor Gutschlag supervising the team. In order for the LIM to be considered successful, the measured output power will need be at least 50% of the calculated output power. A LIM is more inefficient compared to a regular AC induction motor due to the fact that it is a single sided machine. The LIM also does not encompass the entirety of the wheel of the simulated linear track adding to the inefficiency of the overall design. The LIM will be tested by varying the voltage and frequency input into the system and taking measurements such as slip, torque, power, current, and speed of the simulated linear track. Slip, speed and torque will be calculated in the microcontroller and displayed via LCD. The displayed values will be observed and compared to pre-calculated values to determine the overall effectiveness of the design. Current will be measured via current probe and will not be interfaced with the overall control system. Current will be used for safety precautions to make sure that the group is not exceeding rated current conditions. Testing will determine the amount of torque and output power that is lost due to the end-effects that occur in LIMs. The design of the LIM will not allow for coil deterioration due to high flowing currents in the stator.

C. *Economic Analysis*

The LIM project is a highly feasible project that is achievable as long as work is divided equally and objective goals are meet. The total component cost is detailed in Table IV and comes in at $1,550. The cost contains all the components that will be used in the project. Components such as the VFD and microcontroller are provided at no cost. The VFD is being provided by Caterpillar and the ATmega128 is being provided by Bradley University. The actual cost expenditures of the project are detailed in Table V and contains the stator, sensors and miscellaneous costs that could arise throughout the project. The miscellaneous costs include additional purchases of copper coil if any winding deterioration occurs, additional sensors, capacitors, resistors, or any additional components. The total cost of expenditure of the LIM project comes out to $620. With the largest cost of the LIM project will be the production of a stator which has been budgeted $500. The funding for the project will be provided by Professor Gutschlag.

TABLE IV: TOTAL COMPONENT BUDGET

Component	Method of Procuring	Cost if Applicable
Stator Steel Laminates	Purchasing	$500.00
Variable Frequency Drive	Provided by Caterpillar	$848.00
Sensors	Purchasing	$20.00
Tachometer EE-SG3	School	$2.00
Microcontroller/ LCD Screen	School	$80.00
Miscellaneous	Purchasing	$100.00

TABLE V: COST EXPENDITURE BUDGET

Component	Method of Procuring	Cost if Applicable
Stator Steel Laminates	Purchasing	$500.00
Sensors	Purchasing	$20.00
Miscellaneous	Purchasing	$100.00

D. *Project Timeline*

The general project timeline for the LIM project can be seen in Fig. 9 of Appendix A. For this project the most important component is the completion of the stator design. The design of the stator was started at the beginning of the semester and will continue to November 17th. With this component of the project completed the purchasing of the stator can occur. The purchasing and delivery of the stator will last from November 17th to the November 30th. After the purchasing of the stator, coding of the microcontroller segments can begin. After the arrival of the designed stator the next priority will be the actual winding of the coils around the stator teeth. Once the coil windings are completed the stator will be mounted onto the side of the simulated linear track and the code implementation and interfacing of the sensors can begin. After the implementation of the code the testing phase will proceed.

E. Division of Labor

The LIM project is divided into design, purchasing, construction, implementation and a testing phase. The design phase is divided into the microcontroller and stator design sections. Design of the microcontroller based control system and sensor interfacing will be worked on by Tyler. The stator design and general LIM design will be handled by Mason and Tim. Purchasing will be handled by the entire group along with the project advisor to insure the proper materials are purchased. During the construction phase Tyler will focus on interfacing the sensors and VFD with the ATmega128 microcontroller, while Mason and Tim work on stator construction. For implementation and testing, the group will come back together and put the stator and microcontroller components together along with troubleshooting any possible issues that arise in the current state of the project.

TABLE VI: DIVISION OF LABOUR

Tasks	Group Member
Stator Design	All
Purchasing	All
Construction – Stator	Mason and Tim
Construction – Microcontroller System	Tyler
Implementation	All
Testing	All
Deliverables	All

F. Societal and Environmental Impacts

The project affects the project team and project advisor along with suppliers of components due to the small scale of this project. The LIM uses natural resources such as copper and steel in its construction. To reduce the amount of natural resources consumed by this project accurate calculations and reusing existing equipment will allow for the conservation of natural resources. The development of the LIM project will follow stringent safety policies to ensure no injuries occur during the construction and testing of the LIM. The safety procedures will include the following: working in pairs, wearing safety glasses, checking all power connections, observing the motor for possible issues, monitoring sensor outputs on the LCD screen and turning off power to the motor when it is not in use. Issues that could arise from not following safety procedures could be stator meltdown, explosions, fire, electrocution, microcontroller and sensor destruction, injury and the simulated linear track becoming damaged. The LIM and the simulated linear track will be in an enclosure to ensure the safety of the individuals operating the motor. With this said individuals that are not on the project team or are the project advisor should not attempt to operate the LIM for safety and liability concerns. Liability concerns of the project can come from damage to the lab area, damage to the project, and injuries of individuals on the project team. To minimize the possible concerns following the aforementioned safety procedures will reduce such risks. Ethically this project does not violate human rights law and will not be used to create a weapon.

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. After analyzing the problem thoroughly, it was determined that building the base linear motor for a future magnetic levitation system would be the most feasible option for the time frame allotted. The team has developed a tentative timeline and division of labor to aid in the timely completion of the proposed project. The entire system will consist 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 will be sending power to the stator along with a control signal back to the control application. Speed will be 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 will consist of generating models from a power and control theory background. The background information regarding the construction of a LIM has been completed and will follow all of the ethical, societal and environmental impacts that are related when completed.

IV. REFERENCES

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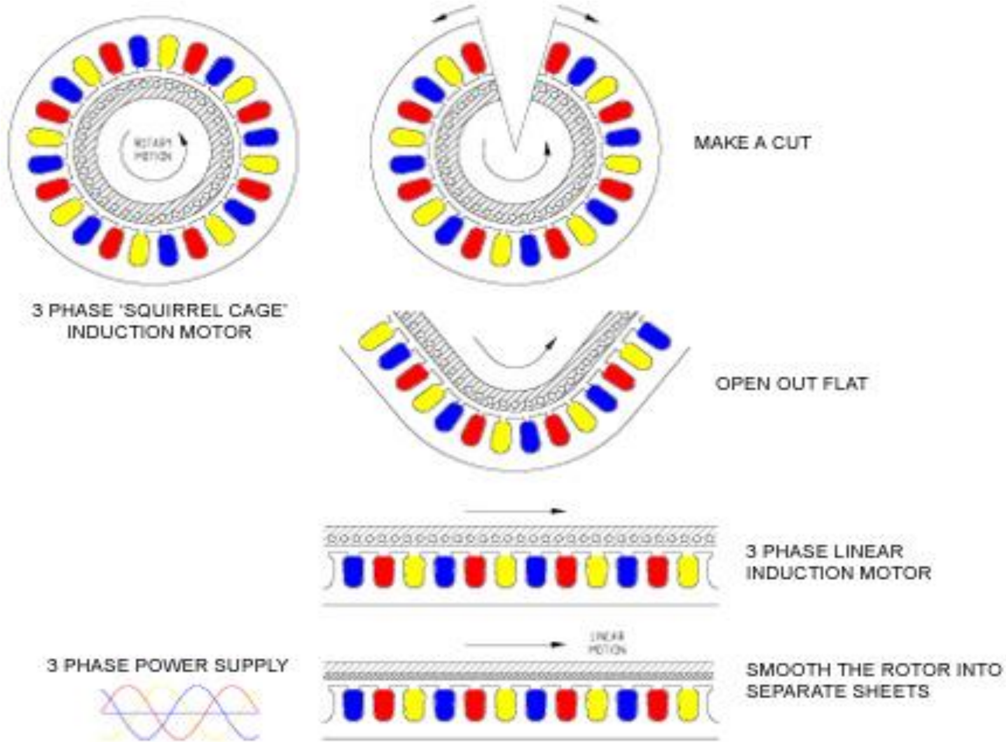
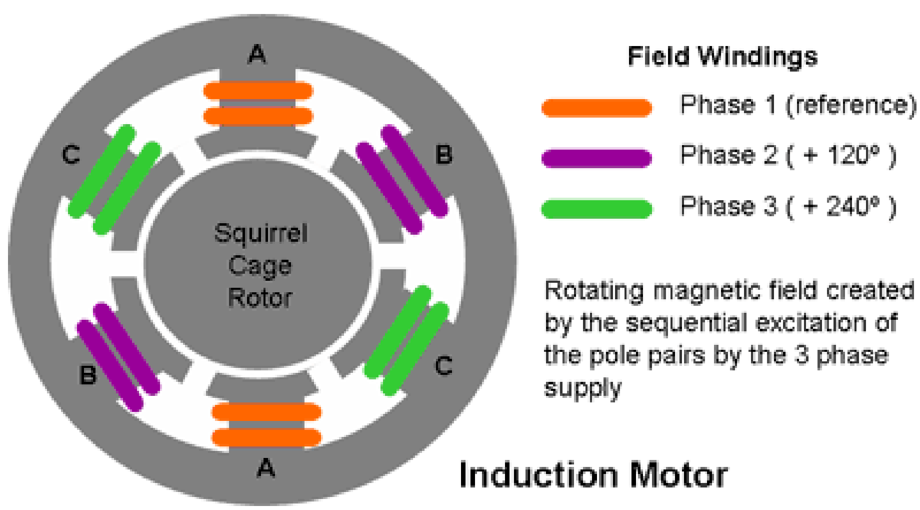
V. APPENDIX A

FIGURES



[1]

Fig. 6 Visual Representation of an AC Induction Motor Being Cut and Laid Flat to Become a LIM



[2]

Fig. 7 AC Induction Motor Visual Explanation

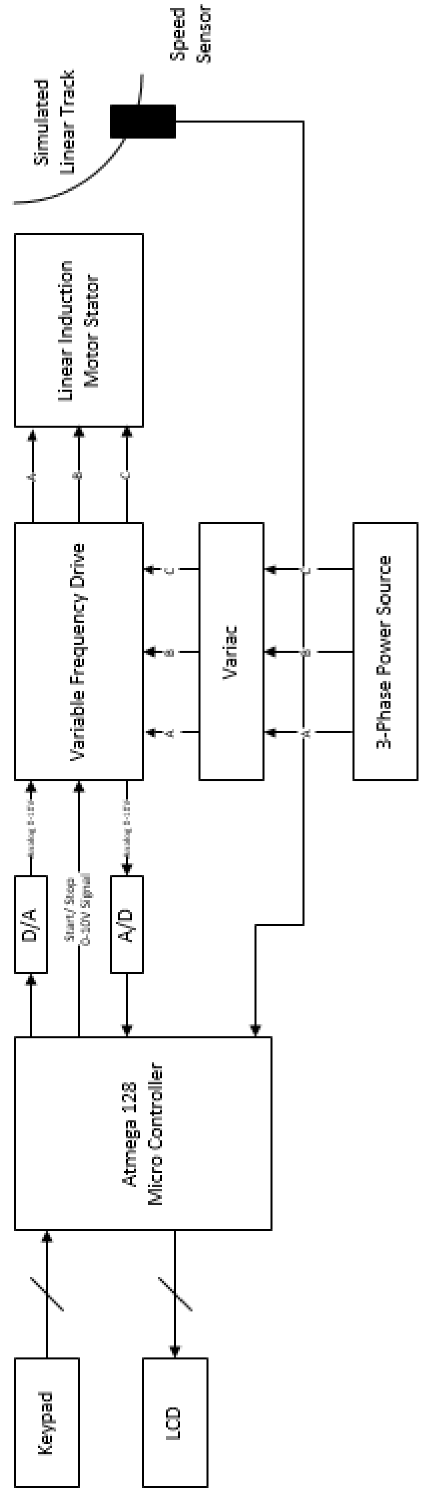


Fig. 8 Entire System Block Diagram of Entire LIM Interfacing System

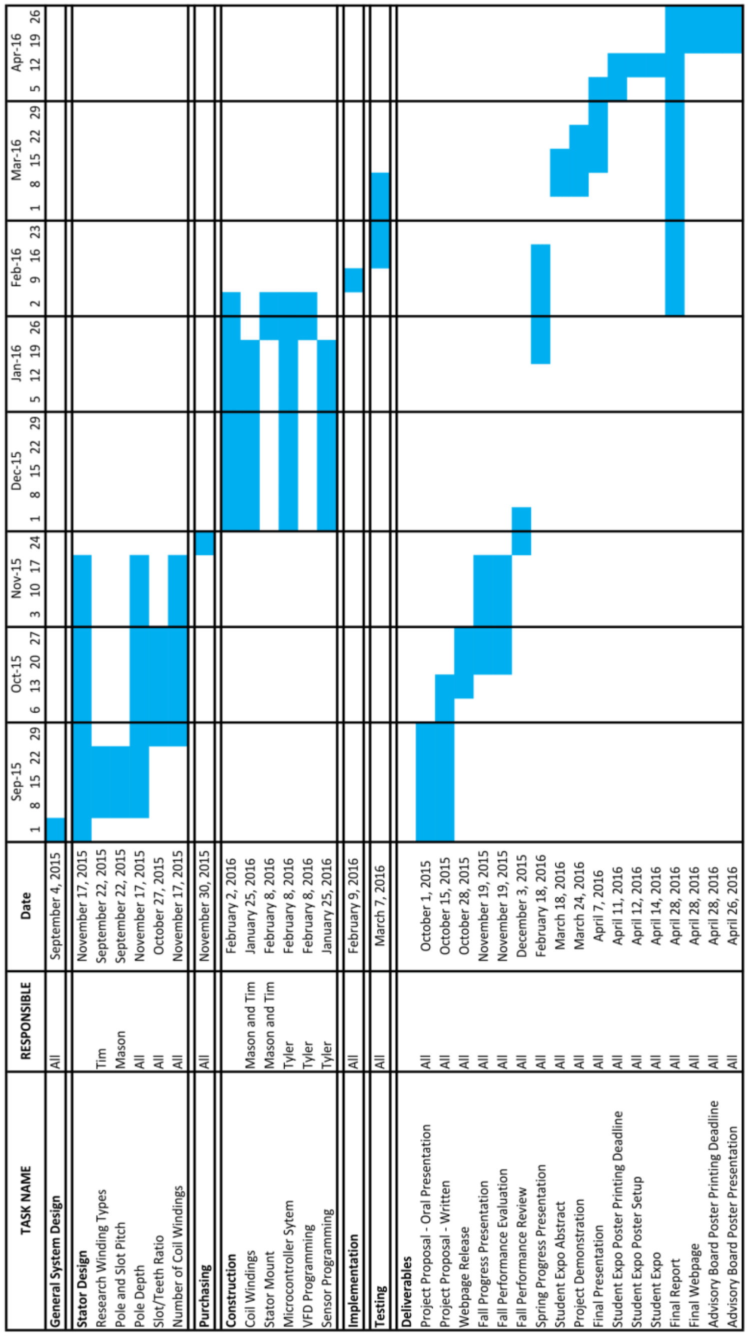


Fig. 9 Detailed Gantt Chart

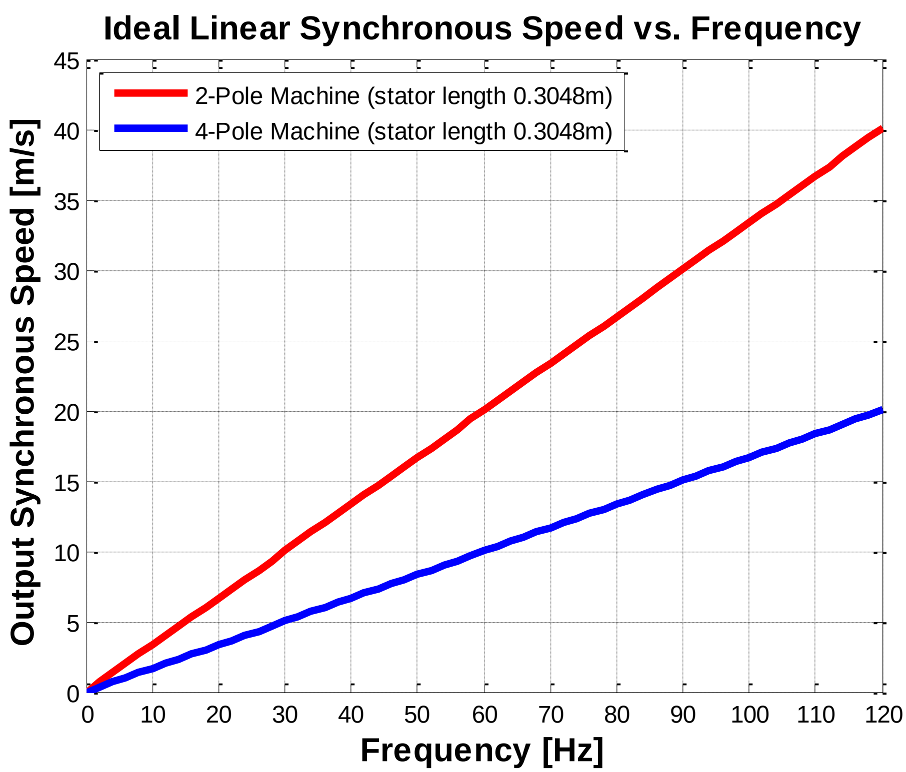


Fig. 10 Ideal Linear Synchronous Speed vs. Frequency with a Constant Stator Length

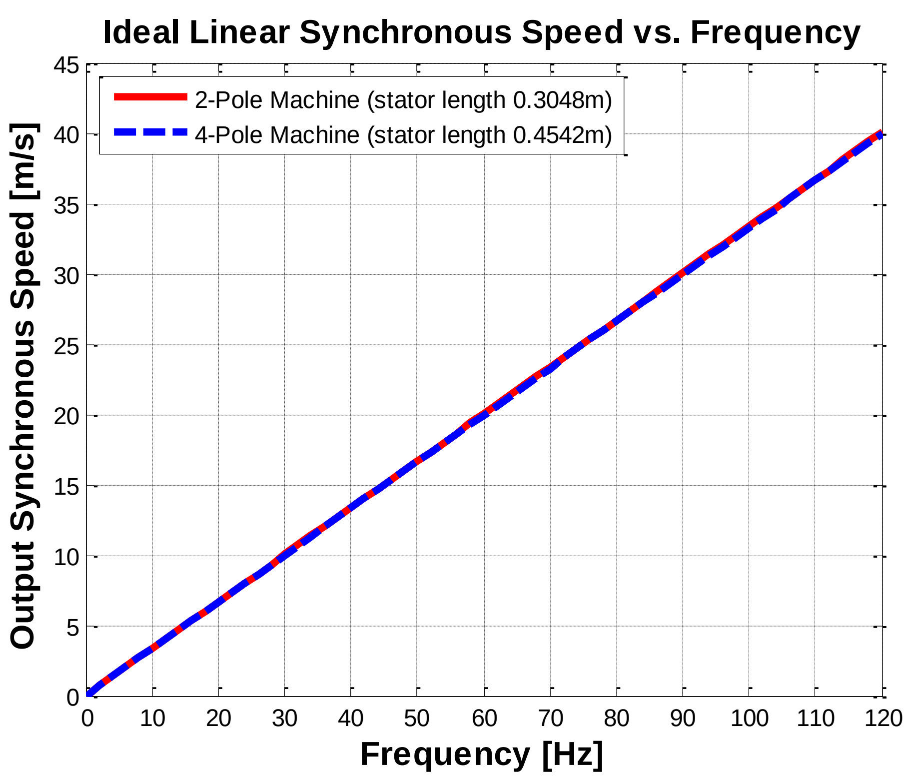


Fig. 11 Ideal Synchronous Speed and Frequency with Varying Stator Lengths

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

[2] *Linear Induction Motor.* [Photograph]. Retrieved from http://www.mpoweruk.com/motorsac.htm

VI. APPENDIX B

METRICS

Inexpensive

Able to build entire motor at low cost	10
Able to build entire motor at reasonable cost	7.5
Able to build entire motor at higher cost	5
Able to build entire motor at extremely high cost	2.5
Cost is too great to build	0

Electrical Efficiency

High efficiency	10
Medium efficiency	7.5
Low efficiency	5
Very low efficiency	2.5
Does not work, completely inefficient	0

Controllable

Control and display speed and power	10
Control and display speed	7.5
Control speed but speed is not displayed	5
Control speed but data is incorrect	2.5
Uncontrollable	0

Safety

Safe to use at high power levels	10
Safe to use at medium power levels	7.5
Safe to use at low power levels	5
Safe to use at very low power levels	2.5
Unsafe to use	0

Constructible

Design is feasible, can be built in a short time period	10
Design is feasible, can be built in given time	7.5
Design is complex, can be built in given time	5
Design is complex, will take longer than given time to	2.5
Cannot be built in given time period	0

Reliable

Can run for indefinite period	10
Can run for 10 hours	7.5
Can run for 3 hours	5
Can run for 1 hour	2.5
Does not run for any length of time	0