DESIGN OF LINEAR GENERATOR

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By

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FINAL PROJECT REPORT

Submitted to the Electrical & Electronics Engineering Programme
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for the Degree
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CERTIFICATION OF APPROVAL

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Approved:

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Assoc. Prof. Dr. Mohd Noh Karsiti
Project Supervisor

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TRONOH, PERAK

JUNE 2010

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

(Ahmad Fuad bin Jamaluddin)

ABSTRACT

This report discusses preliminary research done and basic understanding about the proposed title, '**Design of Linear Generator**'. The objective of this project is to design and develop a prototype of linear motor that could be used to convert mechanical energy into electrical energy and back. In this project, the desired deliverables is a hardware development of linear generator/motor that will produce sufficient electrical energy from a sustained mechanical motion. The challenge of this project is to design a moving iron linear generator that can induce sufficient magnetic flux to produce significant electrical energy. This project will use Finite element method to simulated different construction of moving iron linear generator. After following the methodology, in the end of the project, the designed linear generator is able to produce significant 1-phase sinusoidal electromotive force, emf.

ACKNOWLEDGEMENT

Firstly, I would like to thank my supervisor Assoc. Prof. Mohd Noh Karsiti for the support and assistant during supervising project. He is also being very helpful whenever I have problem in doing my project. Besides that, he always give me courage to not giving up in searching solution in any problems.

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INTRODUCTION

1.1 Background of Study

Recently, the field of linear generator for energy conversion has attracted large attention and becoming one of the rapid growing research areas. The continuous research has unearthed alternative method to produce electrical energy such as wave energy plant [1], energy conversion by ambient vibration [2] etc. This rapid development of linear generator is due to a strong demand of controllable actuator for both traditional and new applications.

The advantage of linear generator is it able to operate at high speed and high acceleration compare to rotary generator that have rotation speed limit. In addition, linear generator is easy to achieve fast and accurate positioning as a result of direct drive. Linear generator has high dynamic stiffness, high servo bandwidth and no stroke limit.

However, because linear generator moves back and forth along two ends, it will produce complicated phenomenon including cogging force, deformation of magnetic field at high speed and others. As a consequence, the design of linear motor should take consideration on suppressing these side effects.

1.2 Problem Statement

Energy consumption has risen in the last few years and the rate of increase appear to be escalating. Economic growth in industrialized countries which is expected to increase significantly in the future will add to the pressure on energy supplies. Moreover, the increase in fossil fuel and gasses price in the market causes an increase in the production cost to generate electricity. Hence, research on an alternative method to produce electrical energy is a necessity.

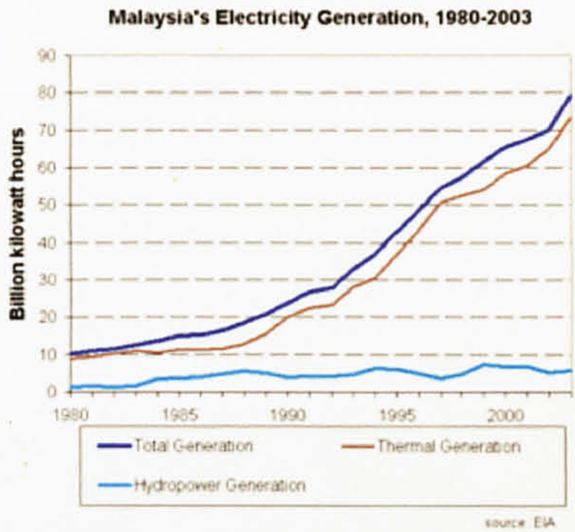

Figure 1: Statistic of Malaysia's electricity generation, 1980-2003 [3]

1.3 Objective

The main objective of this project is to design and develop a prototype of linear motor that could be used to convert mechanical energy into electrical energy and back. At the end of this project, it is expected to achieve these following objectives:

- Understanding the principles of linear generator
- Learn and chose the best topologies for the design which is feasible and able to produce significant result
- Simulating the designed linear generator using **Finite Element Method Magnetic** (FEMM)
- Analyze and optimize the design

1.4 Scope of Studies

Basically, this project will cover a thorough study on electromagnetic and mechanical aspect of linear generator and its properties. The comparison and evaluation of past and existing linear generator will be done as project reference. Upon the completion, the designing process will start concurrently with the design calculation. Then, continue with fabrication and testing of the designed linear generator. This project is conducted in the duration of one year (two semesters) by which in first semester, the project focus will be on literature review and designs for the linear generator should be and simulation. For the second semester, simulation and design calculation should be done and consequently the generator design will be finalized

CHAPTER 2
LITERATURE REVIEW

2.1 Linear Generator Theory

Linear generator is an energy converter which the rotor is moving in a direct drive instead of rotating. Similarly to rotating generator, linear generator has the same operation principle albeit with considerable end effect differences. Linear generator can be realized by cutting one side of the stator of rotary generator and flatten it as shown in the figure 2 below.

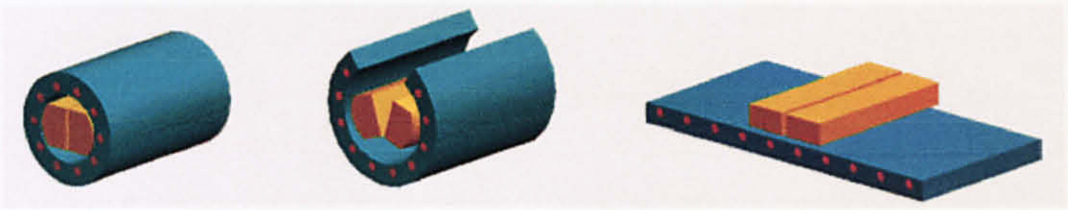

Figure 2: Basic concept [4]

When linear generator operates, its rotor moves along two ends of stator, moving back and forward to which created the changing in magnetic flux thus inducing electromotive force (emf) at the stator.

Faraday's law stated, emf produced around a closed path is proportional to the rate of change of the magnetic flux through any surface bounded by that path. This phenomenon is explained as follows (the minus sign is in subsequent of Lenz's law that the direction of the current is the opposite direction of the change in magnetic flux) [5].

$$\varepsilon = -\mu \frac{d\o}{dt}$$

ε is the electromotive force (emf)

ø is the magnetic flux

μ is the permeability of air gap inside the solenoid

2.1.1 Magnetic Flux Lines

Magnet has properties of magnetic field line as show in the figure 3 below. The magnetic field line concentrated near the side of it north and south poles since the electrical energy converted depend on magnetic flux line cut by the windings. Having that said, the linear generator should be designed so that the windings are at the area that has the highest magnetic flux density - which is at the point where the side of the poles, is being set as a focal point of the rotor stroke.

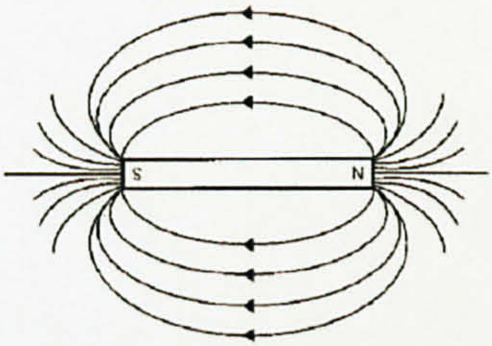

Figure 3: Magnetic Flux Lines [6]

2.1.2 Magnetic Field Area

Magnetic flux denoted by ø is a measure of quantity of magnetism, taking into account the strength and extent product of a magnetic area. In essence, magnetic flux is the dot product of magnetic field force and magnetic field area covered by coil or ø = B.A. Replacing the above equation into Faraday's Law equation will result to an equation as follows:

$$\varepsilon = -\mu B \frac{dA}{dt}$$

ε is the electromotive force (emf)
μ is the permeability of air gap inside the solenoid
B is the magnetic field
A is the area covered by coil

The area of magnetic field covered by a magnet depend on its remanence - the strength of the magnetic field that remains in a magnetic particle after it is exposed to a strong, external magnetic field and the external field is removed.

Table 1: Properties of Magnet [7]

Material	Coercivity (T)	Remanence (T)	$(BB_0/\mu_0)_{max}$ (kJ/m^3)
$BaFe_{12}O_{19}$	0.36	0.36	25
Alnico IV	0.07	0.6	10.3
Alnico V	0.07	1.35	55
Alcomax I	0.05	1.2	27.8
MnBi	0.37	0.48	44
$Ce(CuCo)_5$	0.45	0.7	92
$SmCo_5$	1.0	0.83	160
Sm_2Co_{17}	0.6	1.15	215
$Nd_2Fe_{14}B$	1.2	1.2	260

2.1.3 Number of Turns

The emf induced in one particular point is increase as much as its number of turn of the windings. Therefore, this will result to optimum accumulative magnetic flux changes hence maximizing the emf induced. This can be clarified by the equation as follows:

$$\varepsilon = -\mu N \frac{d\o}{dt}$$

ε is the electromotive force (emf)

ø is the magnetic flux

μ is the permeability of air gap inside the solenoid

N is the number of winding turns

2.1.4 Rotor Speed

Submitting to the equation below, the emf induce is in causal relationship with rotor speed, Hence, the emf produce can be increased by increasing the speed of the rotor

$$C = -\mu B l \frac{dl}{dt}$$
$$= -\mu B l v$$

ε is the electromotive force (emf)

μ is the permeability of air gap inside the solenoid

B is the magnetic field

l is transverse length covered by the rotor

v is rotor speed

2.1.5 Flux Leakage

Flux leakage occur when a portion of magnetic flux generated by the rotor that does not couple to the stator windings. This can be reduced by reducing the distance between rotor and stator or introducing soft steel as a runway for magnetic flux. In the present of soft steel the magnetic flux line is guided back to the opposite poles instead of straying into space hence reducing flux leakage.

Soft steel is a low carbon steel typically with a maximum of 0.25% Carbon and may contain some traces of other elements such as manganese, silicon, phosphorous, lead or sulphur.

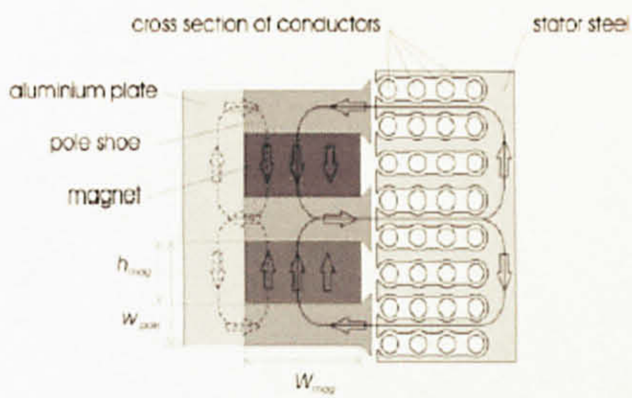

Figure 4: Magnetic flux line in addition of Soft Steel [8]

2.2 Linear Generator Topologies

Basically there is three main topologies for linear generator which is moving magnet, moving coil and moving iron. Basic configuration of these three designs is shown in the figures below (the direction of the arrow is pointing toward north). For moving magnet, the magnet is placed as the rotor and the coil as the stator and vice versa for moving coil.

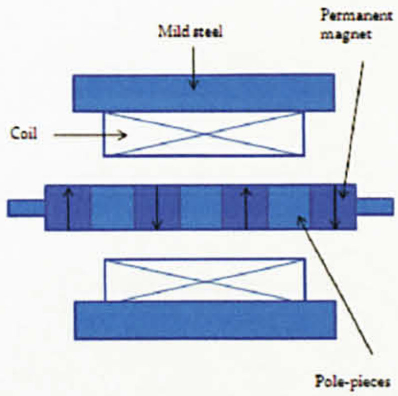

Figure 5: Moving Magnet

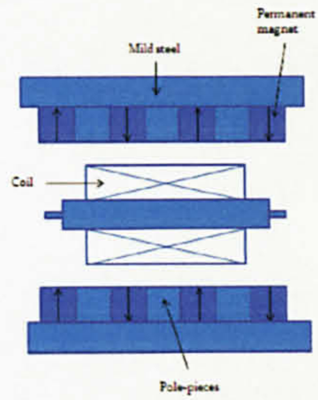

Figure 6: Moving Coil

In this particular project, moving iron linear motor is one of the designs that will be tested and contemplated as the final design aside of moving magnet and moving coil. Moving iron linear generator used slotted iron as a rotor instead of using slotted magnet whereas the permanent magnet is an integral part of the stator. Iron, a material that exhibit detectable magnetic properties, has high magnetization susceptibility expose to a magnetic force is magnetized, hence, acting as temporary magnet. The magnetic properties for ferromagnetic material is shown if Appendix A.

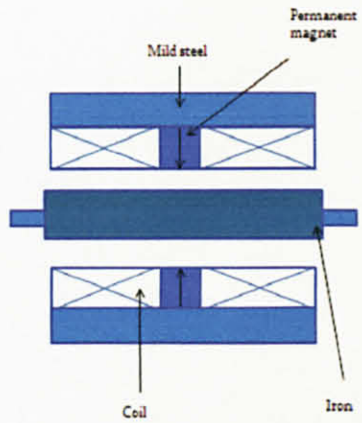

Figure 7: Moving Iron

Table 2: Comparative Studies on Linear Generator Topologies

	Moving Magnet	Moving Coil	Moving Iron
Advantages	- High thrust density - High thrust to moving mass ratio	- High thrust density	- Preserve the magnet from demagnetization due to heat from friction - Flux-linkage reversal are very robust
Disadvantages	- Magnet demagnetization due to exposure of heat from friction	- Low thrust to moving ratio - Relatively large air gap – require significant volume of magnet - Moving cable	- Energy conversion is inferior to moving magnet and coil - Difficult to facilitate resonant application

2.3 Magnetism of Ferromagnetic Materials

Magnetic materials that retain its magnetism when the magnetic force is removed can be classified as ferromagnetic substance. Ferromagnetism occurs in materials in which atoms have permanent magnetic dipole moments. The strong interaction between nearby atomic dipole moments keeps them aligned even when the external magnetic field is removed.

One of the reason moving iron linear generator is being given consideration is because the fault of using permanent magnet as a rotor. The magnetism of a permanent magnet will diminish due to heat exposure because of the friction between the rotor and the solenoid. Iron can be used as a substitute because of it magnetic property.

2.4 Hysteresis Effect

A good permanent magnet should have a strong magnetic field and a low mass relative to its size, and should be stable against the influences which would demagnetize it. The properties as such are typically stated in terms of the remanence and coercivity of the magnet materials

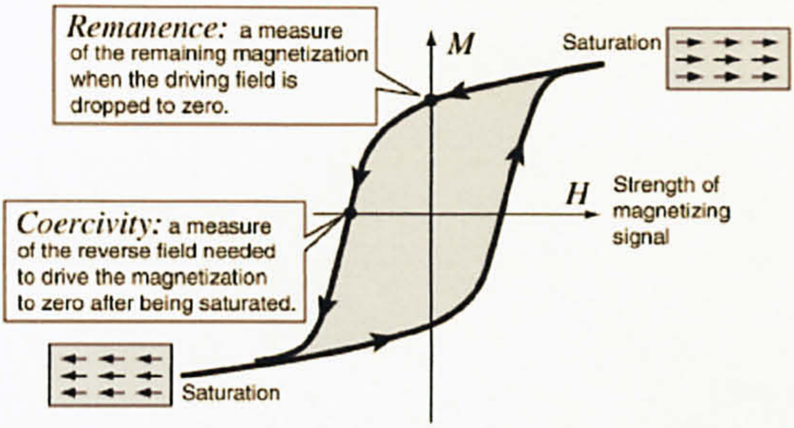

Figure 8: Coercivity and Remanence in Permanent Magnet [9]

When a ferromagnetic material is magnetized in one direction, it will not reduce back to zero magnetization promptly when the imposed magnetizing field is removed. The amount of magnetization it retains at when there is no driving field called remanence. The magnetization will saturate back to zero by a field in the opposite direction - the amount of reverse driving field required to demagnetize it is called its coercivity. The lack of retraceability of the magnetization curve is the property called hysteresis.

2.5 Force Ripple

Force ripple is one important aspect in designing a linear generator. This force is mainly due to the non-perfect sine distribution of the magnetic field causes by cogging force and reluctant force. Cogging force occur as a result of mutual attraction between the stator and stator. Reluctance force is due to the variation of the self-inductance of the windings with respect to the relative position between the stator and rotor. Collectively, these two forces will affect the fast positioning capability and low-speed performance of linear generator.

One of methods to reduce cogging force is to skew the rotor with respect to the winding core. The design can be tested manual by hand to feel the extent of the force ripple. A good design should lead to a smooth movement of a rotor inside the solenoi

CHAPTER 3
METHODOLOGY

3.1 Procedure Indentification

Throughout the entire project, progress of the project should follow the planned methodology to make sure the project can be completed within the time frame. However, author is encouraged to dwell on hand-on work in understanding the principle of linear motor. The materials for experimenting can be borrowed from past project and special laboratory.

At the beginning of the project, author should do scheduling of all activities in order to complete the project within the time frame. The research activities focus on understanding the principle of the linear generator. This can be done through study on the basic theory and several project and research that have been done by other researchers. All the findings should help author to make a good design.

The design process focuses using knowledge acquire during the research to coming up with operational and controllable linear generator. Simulation aim is to help determine if the design tested meet the objective. Rectify or redesign if the design did not meet the requirement. During the analysis activities, all the data gathered from the rest and simulation of different design will be compute and the most effective design of linear generator will be chosen. This process also involving optimization of the design to achieves the objective. The end product is the design that can produce significant electrical energy. All finding should be documented in the report to be sent at the end of the project.

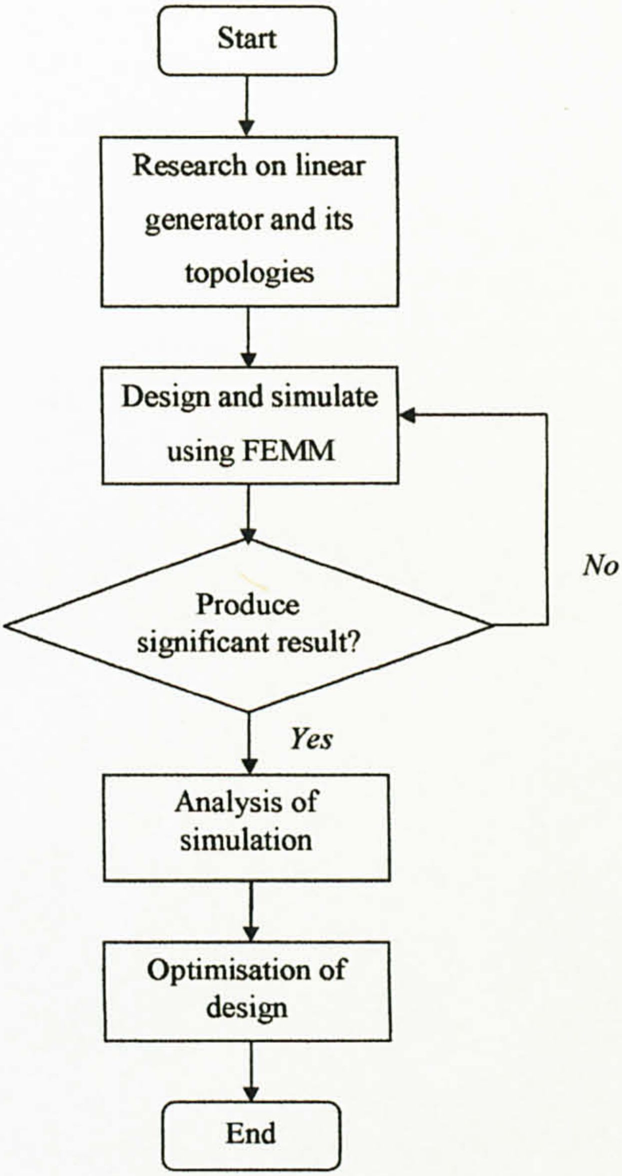

Figure 9: Project Methodology Flow Chart

3.3 Tool and Equipment Required

3.3.1 Finite Element Method Magnetic

The software used for the design and simulation is **Finite Element Method Magnetic®** - A Windows finite element solver for 2D and axisymmetric magnetic, electrostatic, heat flow, and current flow problems with graphical pre and post-processors [10]. Figure 10 below is an example of simulation on rotary generator.

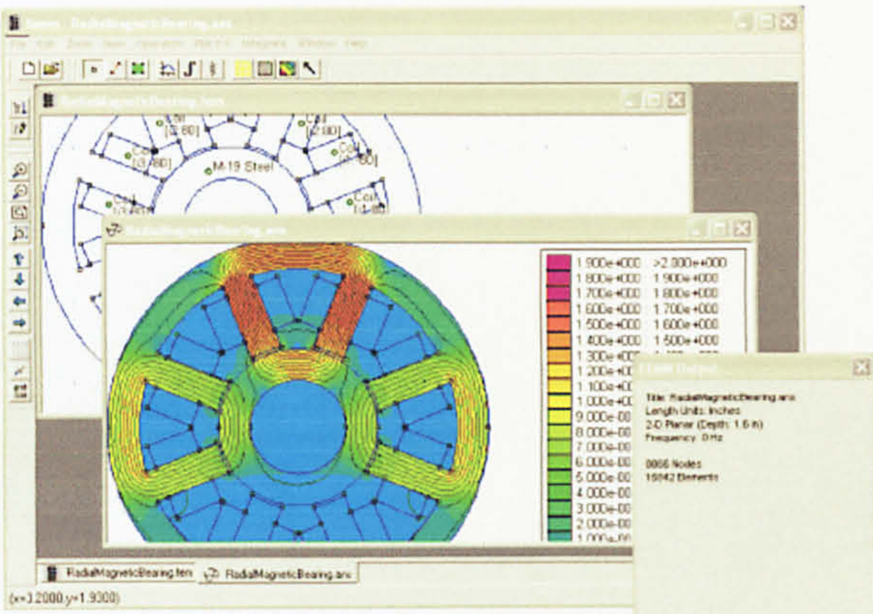

Figure 10: Finite Element Method Magnetic software [14]

3.3.2 Lua Programming Language

Lua is a powerful, light-weighted, fast, embedded programming language. Lua combines simple procedural syntax with powerful data description constructs based on associative arrays and extensible semantics. Lua run by interpreting the bytecode for a registered-base virtual device, and has automatic memory management with incremental garbage collection, making it ideal for configuration, scripting, and rapid prototyping [11].

CHAPTER 4
RESULT AND DISCUSSION

4.1 Final Design

After research on all the different types and topologies of linear generators, the author has decided on moving magnet topologies. The design contain of permanent magnet, NdFeB, low corbon steel act as a runway to reduce flux leakage, two permanent magnets - with same poles facing each other to increase magnetic flux lines passing through coil and a pole-piece to separate the magnets. The permanent magnet is placed to that the same poles (north) is facing toward one another to flux line is concentrated when passing through the coil. The final design is shown in figure 11 below.

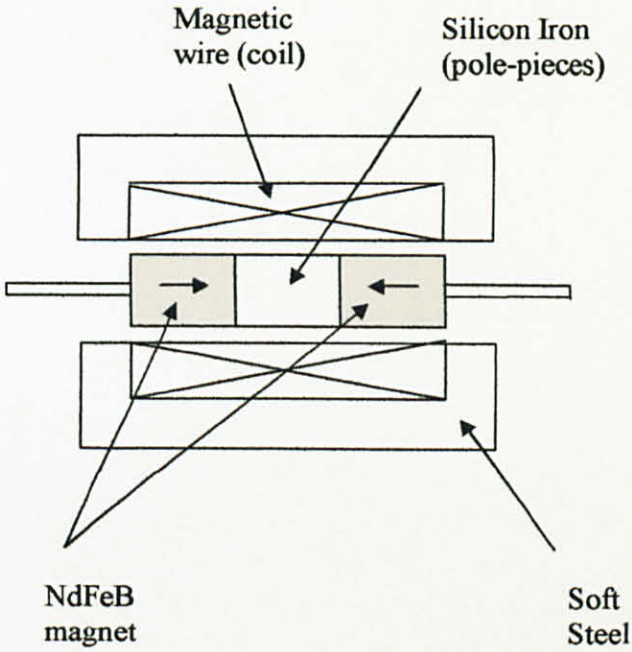

Figure 11: Final design

4.2 Simulation

The final design above is tested using **Finite Element Method Magnetic.** The design shown in figure 12 below is simulate using asymmetric problem definition and periodic boundary condition.

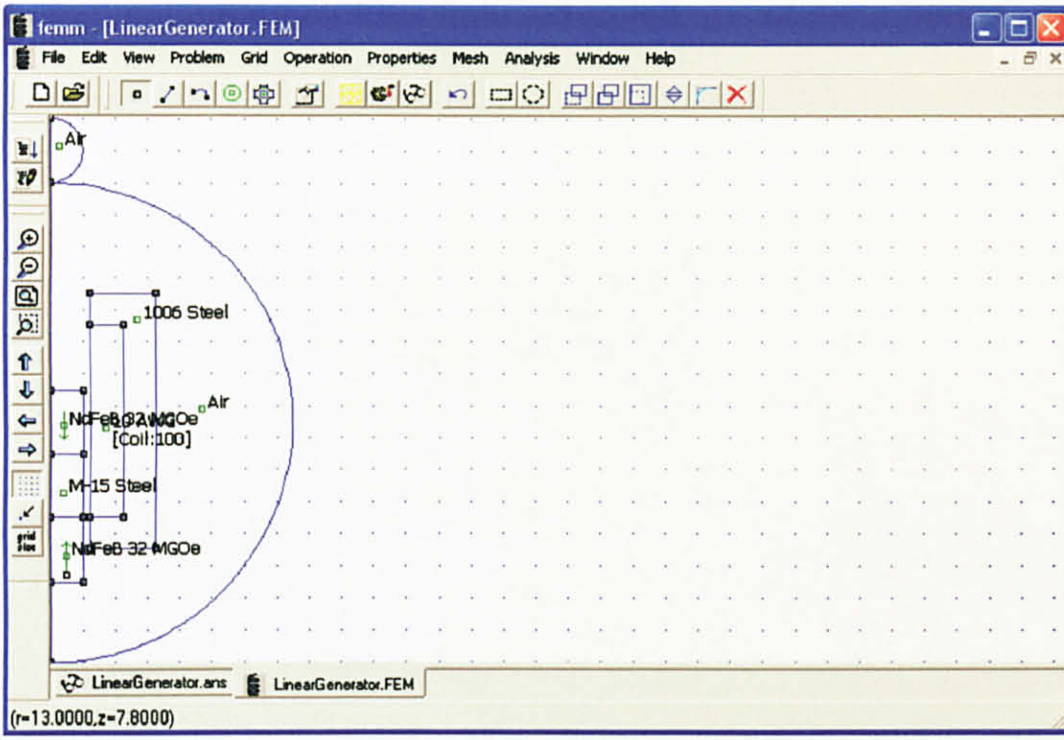

Figure 12: Simulation design

The material used for simulation is labeled inside blue line which separated each block. This drawing is based on the aforementioned final design in figure 11. The material of linear generator used for simulation is as follow:

Permanent magnet	-	NdFeB 52 MGOe
Mild steel	-	1006 Steel (Low Carbon Steel)
Pole-pieces	-	M-15 Steel (Silicon Iron)
Coil	-	10 AWG (Copper AWG magnet wire) (100 turns)

The semi-sphere labeled air represents the region which linear generator operated. By using periodic boundary condition, the big semi-sphere represent the air around the linear generator and the smaller semi-sphere represent the air outside that region.

In this simulation, the unit length used is one centimeter (the length between each dot in the FEMM board). Inference to figure 12, the design specification is shown below in figure 13.

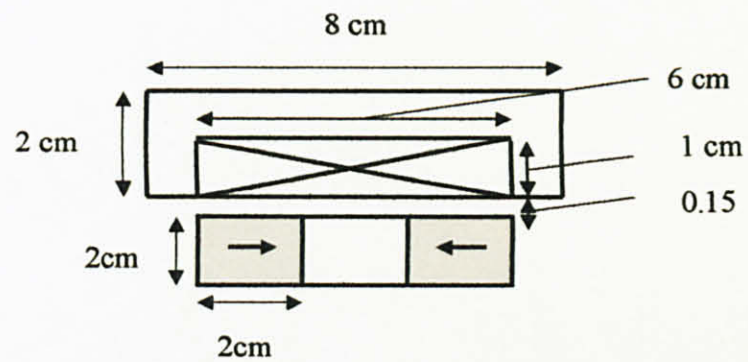

Figure 13: Design specification

4.2.1 Lua Coding

Lua Programming Language can be applied in Finite Element Method Megnetic as a scripting code to perform certain function that is limited in FEMM itself. In this case, the coding below function as to move the permanent magnet in the simulation upward and capture the magnetic density at the coil for each increments.

```
showconsole()
mydir="./"
open("LinearGenerator.FEM")
mi_saveas("temp.fem")
mi_seteditmode("group")
for n=0,20 do
        mi_analyze()
        mi_loadsolution()
        mo_selectblock(1.8,7.4)
        A=mo_blockintegral(8)
        print(A)
        if (n<20) then
                mi_selectgroup(1)
                mi_movetranslate(0,0.2)
        end
end
mo_close()
mi_close()
```

Figure 14: Lua coding

The command used in the coding in figure 14 is described as follows [12]:

showconsole()	-	displays the floating Lua console window.
mydir="./"	-	run and save file in the same directory
open("LinearGenerator.FEM")	-	opens a document specified.
mi saveas("temp.fem")	-	saves the file with name " temp.fem ".
mi seteditmode(editmode)	-	sets the current editmode to "block" (block label)
mi analyze()	-	runs the problem.
mi loadsolution()	-	loads and displays the solution corresponding to the current geometry.
mo selectblock(1.8,7.4)	-	select the block that contains point (1.8,7.4) - in these case the coil
A=mo blockintegral(8)	-	calculated a integral of magnetic flux density, B_r over block blocks is represented as A
print(A)	-	show the result
mi_selectgroup(1)	-	select the group 1 – in these simulation, the rotor (permenant magnets and pole-pieces) has been grouped as group 1.
mi movetranslate(0,0.2)	-	selected objects is shifted 0.2 cm upward.
mi close()	-	closes current magnetics preprocessor document and destroys magnetics preprocessor window.
mo close()	-	closes the current post-processor instance.

4.3 Result

A segment of resulting magnetic flux density in the linear generator is as shown in below. As shown below, the magnetic flux pass through the coil is highest when the rotor is in the center of the linear generator. The magnetic flux leakage also appear less in the when the rotor at the center.

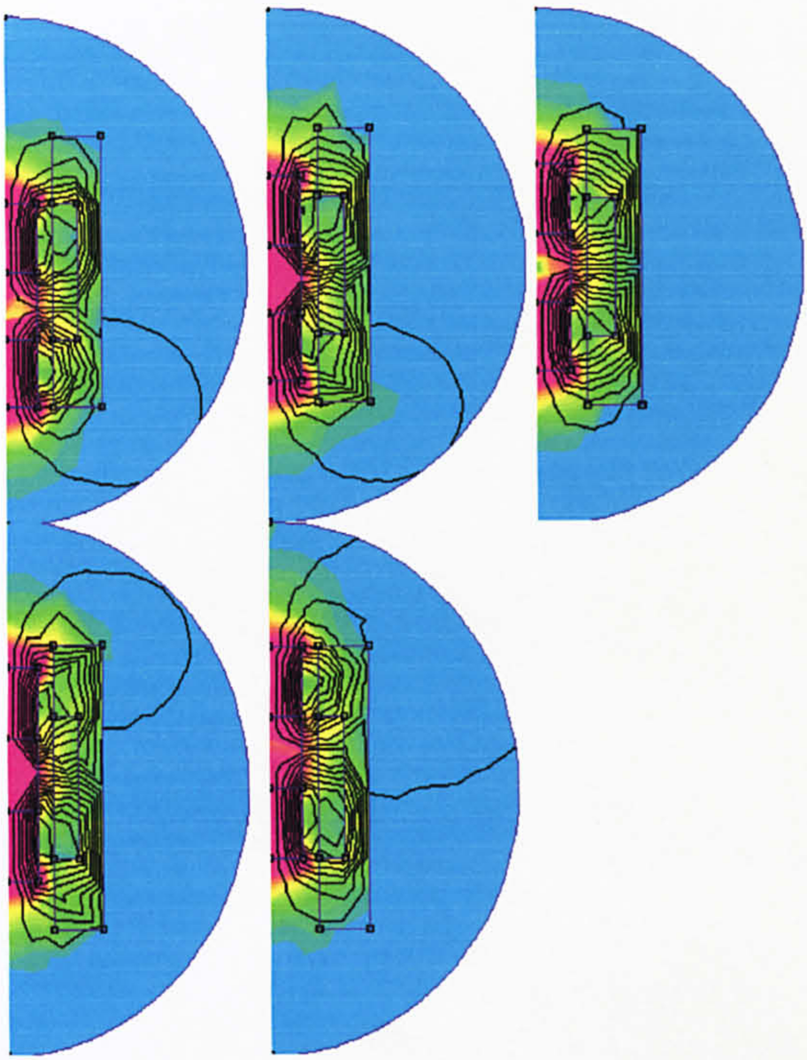

Figure 15: Flux Density images (displacement 1.0, 1.6, 2.0, 2.4, 3.0 cm from starting point)

From the simulation done in the aforementioned linear generator, the resulting magnetic flux density for every displacement from starting point is as shown below in table 3. Referring to the table below, the resulting magnetic flux density pass though the coil increase as the rotor moves toward the linear generator and reduce as it move away.

Table 3: Magnetic flux density

Displacement, cm	**Magnetic Flux Density, B**
0	1.08617e-3
0.2	1.82387e-3
0.4	2.38817e-3
0.6	2.79926e-3
0.8	3.19185e-3
1.0	3.49210e-3
1.2	3.81076e-3
1.4	4.160545e-3
1.6	4.28857e-3
1.8	4.40336e-3
2.0	4.55459e-3
2.2	4.31589e-3
2.4	4.17843e-3
2.6	3.94226e-3
2.8	3.76790e-3
3.0	3.44552e-3
3.2	3.08599e-3
3.4	2.72887e-3
3.6	2.30950e-3
3.8	1.84382e-3
4.0	1.00176e-3

4.4 Calculation

Since FEMM only deal with magneto-static, it cannot calculate the resulting emf produce by moving the permanent magnet using lua scripting language. However by taking data gathered for each translation of 0.2 cm, emf produce could be calculated by using formula as follows:

$$\varepsilon = \frac{dB}{dt} \times A \times N$$

$$\varepsilon = \frac{dB}{dx} \times \frac{dx}{dt} \times A \times N$$

$$\varepsilon = \frac{dB}{dx} \times v \times A \times N$$

ε is the electromotive force (emf)

B is the magnetic flux density

A is the effective area of the winding perpendicular to the magnetic field

N is the number of turns

v is velocity if the moving permanent magnet

From the equation, v is assumed to be 5 ms^{-1}. Since the design using tubular magnets, the effective area for the circumference of the windings to the transverse length travel by the magnets which is $2\pi \times r \times l$ where r is the radius of the solenoid and l is the length cover by the coil along the solenoid.

Calculating the emf using the formula described above, the emf produce for each displacement is as shown below in Table 4. Referring to the table below, emf produced by the linear generator changes from positive to negative value as it move along the linear generator.

Table 4: Emf produced, V

Displacement, cm	Emf produced, V
0.2	8.69
0.4	6.64
0.6	4.84
0.8	4.63
1.0	3.53
1.2	3.76
1.4	4.12
1.6	1.51
1.8	1.34
2.0	1.79
2.2	-2.82
2.4	-1.63
2.6	-2.78
2.8	-2.05
3.0	-3.79
3.2	-4.23
3.4	-4.21
3.6	-4.94
3.8	-5.49
4.0	-9.92

Plotting the emf produced in a graft resulting a figured as below in figure 16.

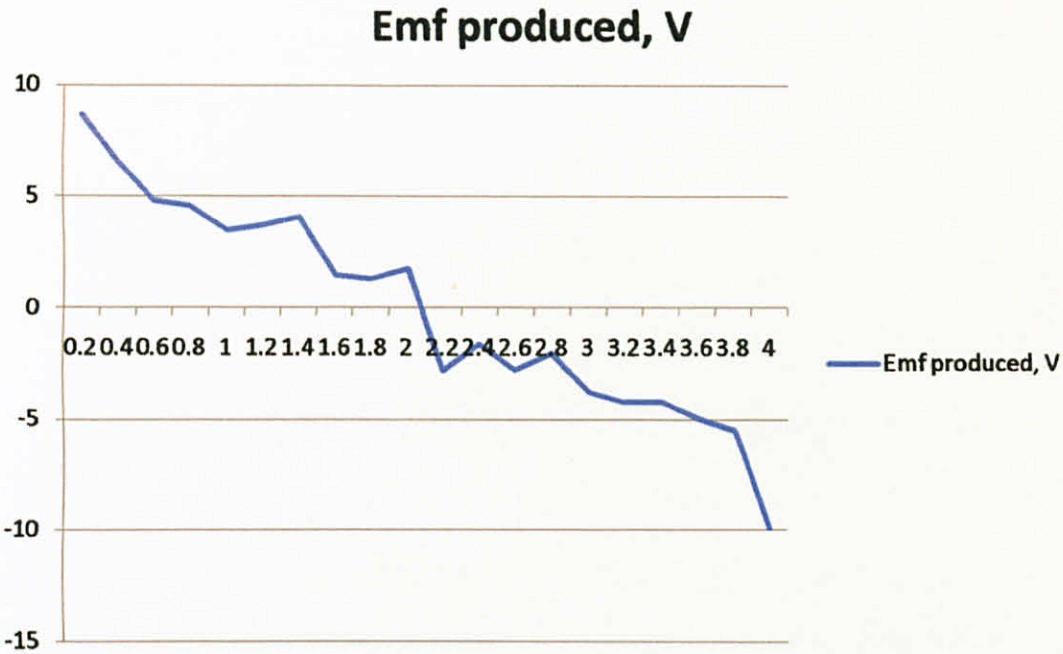

Figure 16: Emf produced, V (Graph)

4.4 Discussion

Referring to figure 15, it can be concluded that the magnetic flux leakage are minimum as the rotor move along the linear generator. The inclusion of soft-iron reduces the magnetic flux leakage.

The graph in figure 16 shown that as the permanent magnet move along the solenoid it produce positive emf and then as it move away from the middle of the solenoid it produce negative emf. This is because when it move toward the center the a larger cumulative magnetic flux density is minus a lower magnetic flux density to produce the emf produce positive value and vice versa as the rotor move away from the center of the solenoid.

Consequently, if the permanent magnet is to move back and forth the design linear generator will produce a 1-phase sinusoidal output emf. The designed linear generator also able to produces significant electrical energy conversion.

CHAPTER 5
RECOMMENDATION AND CONCLUSION

5.1 Recommendation

The emf produce by the linear generator above is not very accurate as it is taken from point to point basic. Therefore, the in upcoming research it is advices that the author use more intricate software to capture the emf produce as it move along the linear generator. The author should proceed to the fabrication of the linear magnet to validate the theory and the result as per produce on the simulation.

5.2 Conclusion

For the conclusion, the methodology which is used in this project can support the objectives in the project which is to design and develop a prototype of linear generator that could be used to convert mechanical energy into electrical energy and back. In the duration of two semesters, this project give the opportunity for the author to develop skills such as project managing, problem solving, data gathering, designing prototype by using software. Furthermore, the findings from this project can be a reference for future research on improving the design of linear generator. Finally, this project will enhance author knowledge which is crucial to become a successful e

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APPENDICES

Appendix A
Magnetic Properties of Ferromagnetic Materials [15]

Material	Treatment	Initial Relative Permeability	Maximum Relative Permeability	Coercive Force (oersteds)	Remanent Flux Density (gauss)
Iron, 99.8% pure	Annealed	150	5000	1.0	13,000
Iron, 99.95% pure	Annealed in hydrogen	10,000	200,000	0.05	13,000
78 Permalloy	Annealed, quenched	8,000	100,000	.05	7,000
Superpermalloy	Annealed in hydrogen, controlled cooling	100,000	1,000,000	0.002	7,000
Cobalt, 99% pure	Annealed	70	250	10	5,000
Nickel, 99% pure	Annealed	110	600	0.7	4,000
Steel, 0.9% C	Quenched	50	100	70	10,300
Steel, 30% Co	Quenched	...	...	240	9,500
Alnico 5	Cooled in magnetic field	4	...	575	12,500
Silmanal	Baked	...	...	6,000	550
Iron, fine powder	Pressed	...	...	470	6,000

Appendix B
Gantt chart for the Project

	Task Name	Duration	Start	Finish
1	**Semester One**	**110 days**	**Mon 7/20/09**	**Fri 11/6/09**
2	Selection of Project Topic	12 days	Mon 7/20/09	Fri 7/31/09
3	Preliminary Research	26 days	Mon 7/27/09	Fri 8/21/09
4	Submission of Preliminary Report	1 day	Fri 8/21/09	Fri 8/21/09
5	Research	28 days	Sat 8/22/09	Fri 9/18/09
6	Submission of Progress Report	1 day	Fri 9/18/09	Fri 9/18/09
7	Seminar I	26 days	Mon 9/28/09	Fri 10/23/09
8	Design and Simulation	29 days	Sun 9/27/09	Sun 10/25/09
9	Submission of Interim Report Final Draft	1 day	Fri 10/30/09	Fri 10/30/09
10	Oral Presentation	5 days	Mon 11/2/09	Fri 11/6/09
11	**Semester Two**	**103 days**	**Mon 1/25/10**	**Fri 5/7/10**
12	Fabrication	82 days	Mon 1/25/10	Fri 4/16/10
13	Submission of Progress Report I	1 day	Fri 2/19/10	Fri 2/19/10
14	Submission of Progress Report II	1 day	Sat 2/20/10	Sat 2/20/10
15	Seminar II	19 days	Sun 2/21/10	Thu 3/11/10
16	Poster Exhibition	1 day	Wed 4/7/10	Wed 4/7/10
17	Submission of Dissertation (soft bound)	1 day	Fri 4/23/10	Fri 4/23/10
18	Oral Presentation	5 days	Mon 4/26/10	Fri 4/30/10
19	Submission of Project Dissertation (hard bound)	1 day	Fri 5/7/10	Fri 5/7/10