DESIGN AND EVALUATION OF SHOCK ABSORBER ELECTRICITY GENERATOR WITH TELESCOPIC COIL SPRING SLEEVES

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I am thankful to my Creator Allah Subhana-Watala to have guided me throughout this work at every step and for every new thought which You setup in my mind to improve it. Indeed I could have done nothing without Your priceless help and guidance. Whosoever helped me throughout the course of my thesis, whether my parents or any other individual, was Your will, so indeed none be worthy of praise but You.

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Abstract

Development and production of Electric Vehicles is now becoming a necessity for automakers across globe due to energy crisis and global warming. This study presents a design concept for vibrational energy harvesting from coil springs of a vehicle using electromagnetic induction. A novel helical magnet spring design is presented that is cost-effective yet sophisticated to fit in any on-going production setup with minimal cost addition per vehicle yet adds to the electrical output. For this purpose an application for Lenz Law is devised using a variance approach in modeling design. 3 design models are simulated in SolidWorks 2017 to analyze the relative motion required for application of N42 series magnets according Lenz Law. A set of USN 12600 winding copper coil sleeves are placed as an outer shell to induce current w.r.t. relative motion of magnets. Design is developed with target of low weight i.e. 10 kg. Various models are developed to meet the targets and evaluated, in EMworks simulation tool for SolidWorks, before any modeling is done. After re-design & evaluation iterations, a final model is selected on ease of assembling and output. Each model is simulated and total current output is measured for a single coil spring. Further, design is optimized for minimal weight of 3.68 kg with an output of 10.843 kW for a total of 1500 oscillations. The practical application for this model is mainly heavy transport vehicles due to their continuous vibrational behavior even on smooth roads in addition to rough traction. Further research avenues for proposed design include simulation on stress analysis, thermal analysis and fatigue cycles.

Key Words: *Electromagnetic Induction, Coil Spring, Battery, Current, Permanent Magnet, Shock Absorber*

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CHAPTER 1: INTRODUCTION

This study presents a helical spring magnet based electricity generator for the application in vehicles to recover energy from shock absorbers of vehicles having auxiliary power storage. Such vehicles are not limited to road cars but also spans to large transport vehicles that run on electrical storage. Proposed design provides a novel approach to designing a linear electrical generator with one of a kind helical magnet spring application. Design strategy for such a test model is set using review of already researched technologies for similar applications.

1.1 Background, Scope and Motivation

Increasing effect of global warming and requirement for zero emissions has lead to a revolution in automobile industry where hybrid and electric vehicles are being developed and produced. Increasing demand in EV require sustainable energy cycle as well as a need for self-charging vehicles. Many methods for self-charging exist and many more are under development including solar, vibrational and regenerative system. This study is focused entirely on vibrational energy harvesting from coil spring system of vehicles as it is the most common part for all kinds of vehicles.

The study aims to compare possible designs that can be considered for electricity generation from coil spring system of vehicle. As a vehicle uses a set of coil springs, hence the output of one coil spring generator can be effectively considered fourfold for a vehicle. Vehicles having more springs will have more of the stacking effect in terms of total output. This is of benefit as to long vehicles which use a lot more springs.

The study concludes with the simulation result of selected model as a proof of concept that with further research a working prototype could be produced after through mechanical behavior study of magnetic spring shell.

1.1.1 Energy Harvesting from Vehicle Shock Absorber

Development of Electric Vehicles has lead to research of ways to harvest different sorts of energies that are associated with vehicle's motion. Many such techniques have evolved over the years including solar, thermal, wind, vibrational energy harvesting. To harvest energy from vibrational motions is under development and many such designs have surfaced with each having some feature to offer. One such design that surfaced in 2012 was by Mossberg J. et. al.[1] to harvest electromagnetic energy from shock absorbers. The design mainly consisted of a copper coiled dampener cylinder with magnetic piston assembly.

Regenerative shock absorbers are not new to the world but their application to automotive industry is limited to only electromagnetic shock absorbers. Kawamoto Y. et. al.[2] presented a simulation based study on the ability of such designs but the cost factor renders such models to be only used in high end machinery.

Many other designs regarding energy harvesting from shock absorbers also came up to spotlight like hydraulic system designed by Deb. P. et. al.[3] as well as a rack & pinion design by Arekar P.. et. al.[4]. Both these designs offered more electrical output as compared to Mossberg J. et. al. but lacked commercialization due to gross weight of assembly, serviceability and manufacturing complexities. So a design that could perform well under these constraints is dire need of Hybrid automotive industry to bring about commercially produced energy harvesting shock absorbers.

1.1.2 Experimental Design for Shock Absorber Generator

Over the last five years, many advanced experimental designs emerged. Research on enabling technologies Sifatul M. et al.[6] also came to sight. A good concept of hybrid technologies for energy harvesting Fathabadi H. et al.[7] refers to use of multiple ways in collaboration with shock absorber assembly to accumulate large amount of current. Similarly Bhatti A. et al.[8] considered addition of piezoelectric technology for the additional output to already modified electromagnetic generator assembly for shock absorber.

Although many of these experimental design were prototyped and tested. Largely the output is not considerably high due to low road roughness index of European roads where most of these design were tested. Competitively, in Pakistan, the road roughness index is considerably high for urban areas and rural areas are mostly offer off-road traction. This is advantageous interms of energy harvesting from vibrations. Although no specific frequency profile for roughness index is provided, a detailed study of road vibrational frequency as suggested by Wei C et al.[9] and Zheng P. et al.[10] could lead to more concrete design of electromagnetic generator.

The biggest efficiency factor for any energy harvesting system for a vehicle largely depends on the support system that allows transformation of raw electrical energy into charging pulses. A suggestion by Mayergoyz I. et al.[11] provides an insight to multiple coil electromagnetic system for such designs that could provide increased voltage with series combination of four electromagnetic generators.

Another issue with Push-to-Market is observed due to lack of space in stock vehicle to house most of the testing designs as the vehicle chassis had to be modified at large scale to enable even one out of four vibrational generators. This is highlighted by Mucka P. et al.[12] and Ahmed K. et al.[13] that suspension design mechanics is one of the limitation for application of such designs.

Eventually, a smaller and less expensive design is required which could be added to a standard road legal vehicle without any structural changes. This can be done both a hybrid system of technologies including thermal, Henry A. et al.[14] as well as solar Fathabadi H. et al[15].

Another challenge that is there in such design engineering is the application of stators for generator. A study on potential of shock absorber assembly to generate electricity presented by Fang Z. et. al. [16] discusses the output possibilities if such technology is developed. Similar studies are also presented by Goldner R. B. et. al.[17], Gupta A. et. al.[18], and Scully B. et. al.[19]. All these aforementioned designs only consisted of shock absorbers with magnet with steel spacers while the coil was either placed inside the dampener case or outside without any stators. A comprehensive study on stator design effects is presented by Lounthavong V. et. al.[20] which provides evidence of drastic improvements in output with variation of stator design. If the stator is added to such a shock absorber, then the output can be marginally improved for researched designs. Cheng, M. et al. [21], Zhu, S. et. al.[22] and Xu, W. et. al.[23] have independently worked on stator simulation of various types and presented the outcomes of stator geometry.

Finally the effect of power circuitry is the crucial one as it can boost the incoming DC output to allow efficient charging cycles to the battery of vehicle. Many such systems exist and a comprehensive study on DC/DC booster specifically for such an application is presented by Fatahbadi H. [24], Mokrani Z.[25] and Rahman A. M. et. al.[26]. A detail output analysis using an experimental prototype is presented by Scully B. et. al.[27] which verifies the potential of such technology for energy harvesting and effects of power boost circuitry. A well-researched design by Goldner R. B. et. al.[28] has also been patented by US Patent Office considering the ability to generate considerable output and possible application to automobile industry.

1.2 Problem Statement

Vibrational Energy from the shock absorbers of market available Hybrid and Electric vehicles is not recovered. Many designs have been researched till date but those require a lot of retrofitting to current market vehicles. The output from such designs is considerable but none of them have been commercialized due to cost to fitting and cost of manufacturing of such designs.[9]

1.3 Core Objectives

The primary objectives of this study are:

- To design and optimize a working model for energy harvesting from shock absorber of a market electric vehicle.
- To compare the relative motion of proposed model and simulate the magnetic field changes.
- To finalize and study the output of modeled assembly for application in electric vehicle.

1.4 Application Areas

- Electric Vehicle Manufacturers
- Auto-Spares manufacturers in Pakistan
- Local Transport Systems
- Energy Sector of Pakistan

1.5 Thesis Overview

Chapter 1 comprises of introduction and description of the problem statement along with the suggested solution design study. It summarizes already researched & published designs with their evaluated in relation with proposed design. This provides direction for design targets that are set to obtain a model that is varied to study magnetic behavior of variable model.

In chapter 2, the modeling has been done as per set targets in SolidWork 2017 to compare and finalize best model to fit proposed solution. Several comparison parameters are chosen to narrow down the prospect of each model for fine tuning of design model. Design parameters are rated with respect to market targets set and final design is selected for further study.

In chapter 3, detailed electromagnetic simulations have been done in EMWorks to evaluate output of modeled assembly. Various changes are brought to studied magnet model to enhance its magnetic flux changes in order to increase it possible output. Final iterated model is analyzed and e.m.f. is calculated for the subject model.

Chapter 4 discusses the results achieved from this study and proposes an application for an electric vehicle for pulse charging. Several aspects of the study relating to magnetostatic behaviors of the magnet are presented and analyzed in detail. And time dependent motion analysis includes magnetic flux density profiles over copper coils and energy flow through the coil.

Chapter 5 concludes this study with calculated values of power generation capacity of proposed design in respect to simulation of magnetostatic motion analysis. It also provides avenues for future studies and possible application areas for local market.

CHAPTER 2: ANALYTICAL MODELS AND EVALUATION

To design such a shock absorber, a generic iterative design methodology is used with quantifiable weighted features to compare. A final design is selected from many plausible concepts and one final design is selected for further concept validation using modeling and simulation. The simulation results showed proof of concept and considerable output that could be claimed commercially applicable. The design is further refined with iterative methods to have an optimized solutions to the required features.

2.1 Design Strategy

As discussed in the introduction, the design that needs to be modeled in study requires following basic components:

- Permanent Magnet with Fixtures
- Copper Coils
- Coil Slide Over Housing
- Power Electronics System

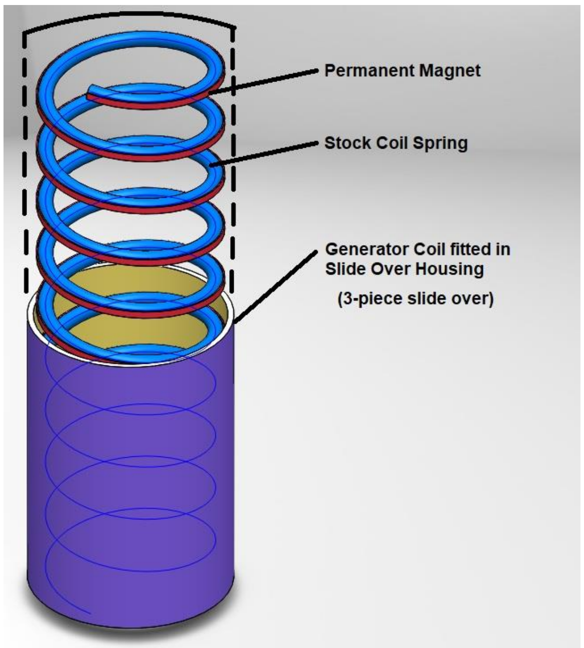

Figure 2.1 – Initial Concept Model

Figure 2.1 represents the initial concept which utilizes a combination of listed components as a movable assembly that can be easily installed in everyday production vehicles in hybrid or electric category.

Following targets are considered as selection criteria for this study.

- Ease of Production
- Ease of Assembling
- Ease of Maintenance
- Cost of Production
- Effective output (Amp/Hr.)

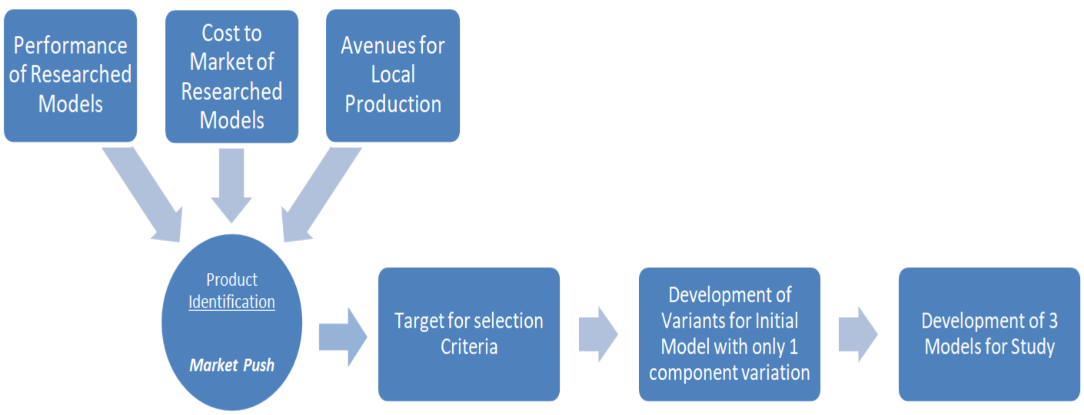

Figure 2.2 – Design Strategy

Figure 2.2 represents how the selection criteria were thought processed in terms of doing research for this study. Initial concept is identified as a market push product.
Following are the factors that were considered mandatory for this study in view of local manufacturing capacity and market:

- **Ease of Production:** Design is simple enough so that issues of local market having high cost of skilled labor and production can be avoided. Design is targeted to be a pre-fabricated magnet along with independent coils.
- **Cost of Production:** Design is able to use stock coil spring and shock absorber assembly so that only cost is of the magnet & coils.

- **Ease of Assembling:** Design is easy to assemble on any market driven hybrid & electric model so that any vehicle can be upgraded with minimal variation in design specifications.
- **Ease of Maintenance:** Design is robust and it can be maintained as it has one moving part.
- **Effective Output:** Design should provide adequate amount of Amperes per Hour so that it could add small charge to battery on high road roughness index.

2.2 Concept Modeling

Three prospect designs were selected according to design thinking process. Three concept models are made to best depict the required physical features of the electromagnetic generator coil spring. **Concept 'A'** tag is assigned to model that is configured as the round profile geometry of permanent magnet as sleeve. **Concept 'B'** is the variant of **'A'** with square profile magnetic sleeve. **Concept 'C'** has array of prefabricated disc magnets.

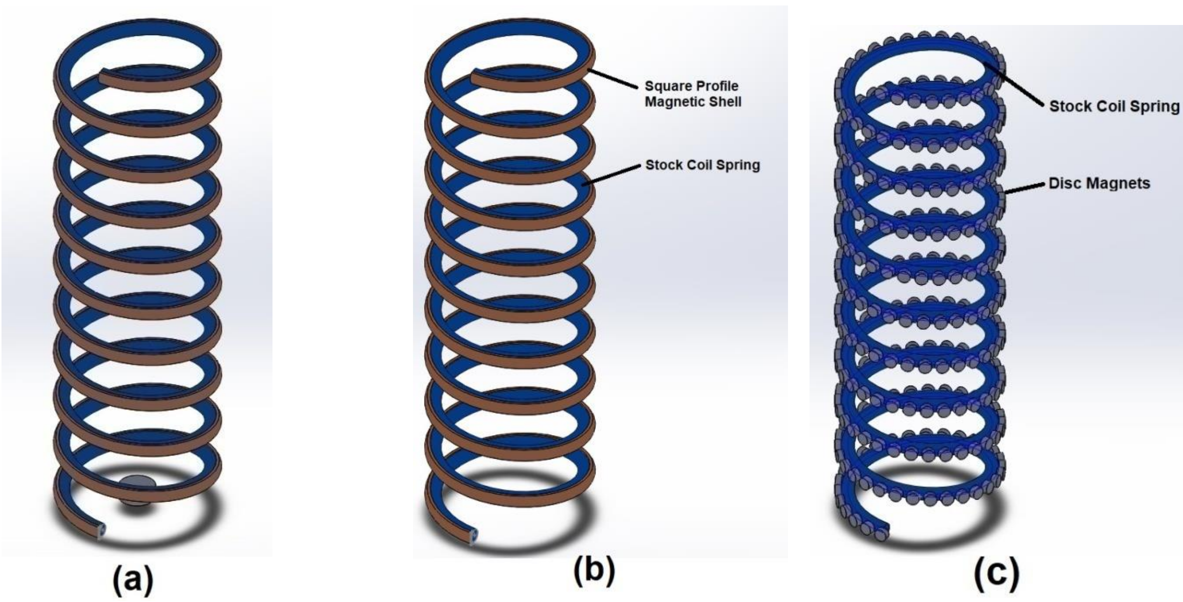

Figure 2.3 – (a) Round Profiled Magnet Concept, (b) Square Profiled Magnet Concept, (c) - Disc Magnet Concept

2.2.1 Component Models

To select the best model for proposed concept, three models were created with distinct magnetic component differences while keeping rest of the assembly same. This way original shock absorber assembly and fitting could be used without need for modification.

The selected stock coil spring is chosen from Toyota Prius 2007 – Cut short in Height for Simulation Ease.

Model A: Round profiled magnetic sleeve is used with direction of magnetic field upward along movement axis of coil spring.

Model B: Square profiled magnetic sleeve is used with direction of magnetic field upward along the movement axis of coil spring.

Model C: An array of prefabricated disc magnets is used with individual field sleeve is used with direction of magnetic field perpendicular to movement axis of coil spring.

Common Components:

1. Multiple Copper Coils with flexible serial connection
2. Stock Coil Spring
3. Sliding soft iron casing for copper coils

Design specifications for components are below:

Stock Coil Spring:

Coil Spring helical height: 100 mm

Coil Spring Cross-Sectional Diameter: 10 mm

Coil Spring Lateral Diameter: 56 mm

Profiled Magnet:

Height& Lateral Diameter: Same as Coil Spring

Outer Arc Section Facing Copper Coils diameter: 10.2 mm

Inner Arc Diameter Facing Spring: 10.2 mm

Cross Sectional Thickness between both Arcs: 2 mm

Square Magnet:

Height& Lateral Diameter: Same as Coil Spring

Section Facing Copper Coils: 10 mm

Inner Arc Diameter Facing Spring: 10.2 mm

Cross Sectional Thickness between Face & Arc Tangent: 3 mm

Disc Magnet:

Disc Diameter: 10 mm (To match thickness of coil spring)

Disc Thickness: 5 mm

Material Chosen: N2414 Magnet

Coercively Direction: Perpendicular to Cross-Sectional Area of Disc

2.2.2 Assembly of Components

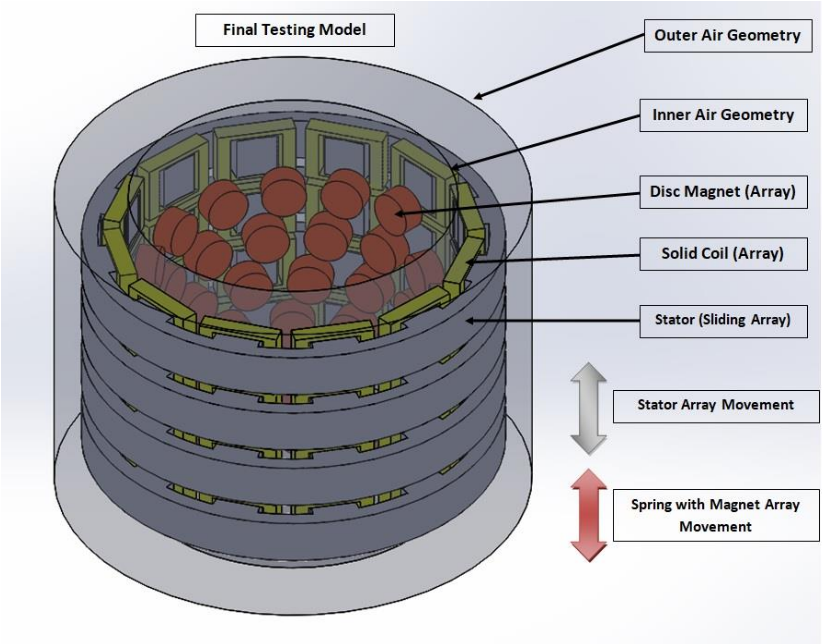

Figure 2.4 – Disc Magnet Array Assembly

Figure 2.4 represents the final assembly of coils, magnets and stator to form a complete generator. The assembly is modified several times to rectify the problems associated with flux direction.

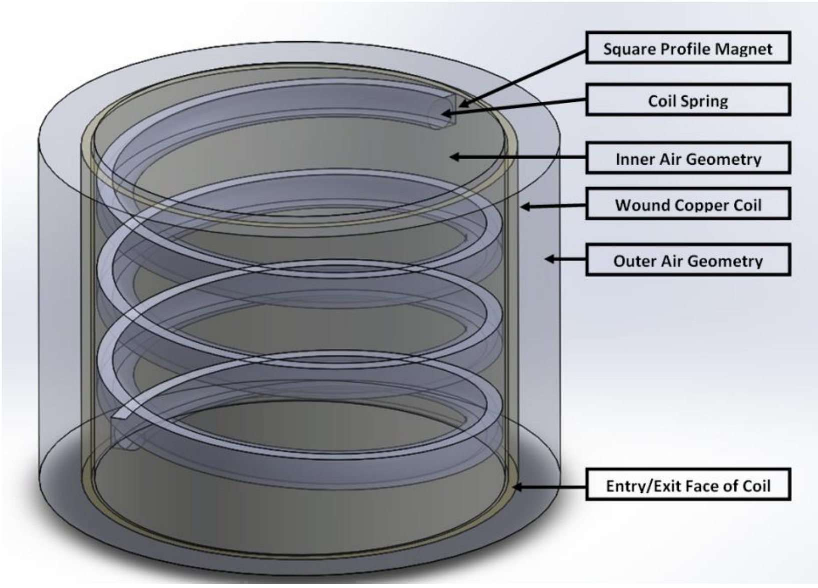

Figure 2.5 – Square Profile Magnet Assembly

On the other hand, figure 2.5 represents the final assembly for simulation testing of Concept B. The assembly is very simple and required little modification for testing in EMWorks.

2.2.3 Magnetic Flux Density Simulation

The two selected model out of three were tested using magnetostatic module (EMWorks) of SolidWorks upon the feasibility of production.

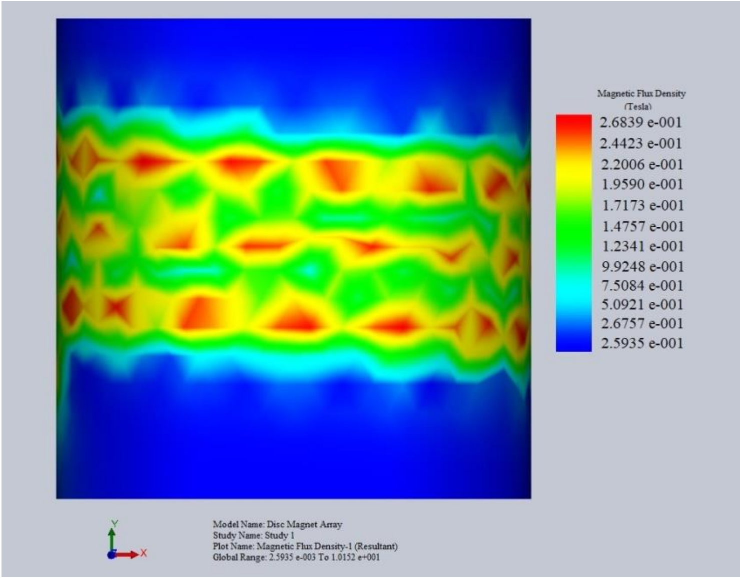

Figure 2.6 – Magnetic Flux Density Simulation Results of Disc Array Magnets

Figure 2.6 shows the magnetostatic distribution of magnetic field. It is clearly visible that the magnetic field is facing destructive interference due to disc array assembly and hence is not a suitable assembly for electricity generation.

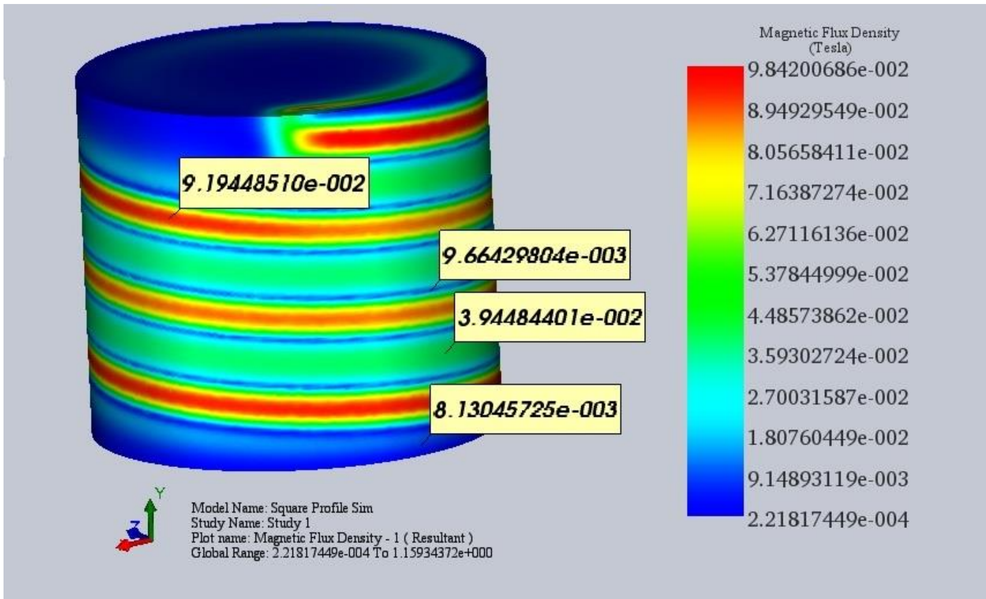

Figure 2.7 – Magnetic Flux Density Simulation Results of Square Magnet

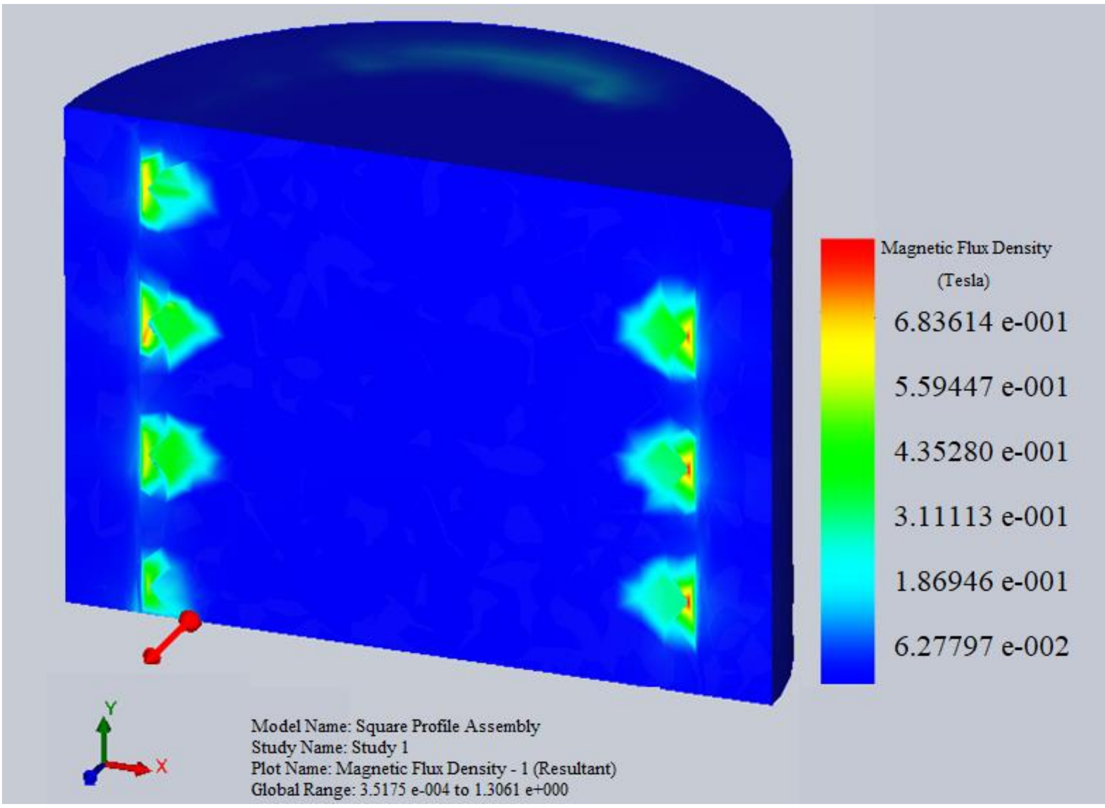

Figure 2.8 – Cross-Sectional Magnetic Flux Density Simulation Results of Square Profile Magnets

Figure 2.7 & 2.8 represent the test simulation of magnetic flux density for the square profiled magnet. It is clearly vissible that field is much more stronger on the coil face adjucent to the magnet while the gaps between each turn of the spriral is not having any flux density due to destructive interference of the magnetic field.

2.2.4 Concept Screening & Scoring

Initial screening of the models is carried out by assigning advantageous, neutral & disadvantageous states of design. A comparison matrix is evaluated with selection criteria ratings. Prospect design is considered for further study.

Table 2.1 – Concept Screening Table

	Concepts		
Selection Criteria	**A** **Round Profile**	**B** **Square Profile**	**C** **Disc Array**
Ease of Production	-	0	+
Cost of Production	0	0	+
Ease of Assembling	0	0	-
Ease of Maintenance	+	+	0
Effective Output (Amp/h)	-	+	+
Sum '+'s	1	2	3
Sum '0's	2	3	1
Sum '-'s	2	0	1
Net Score	-1	2	2
Rank	2	1	1
Continue	No	Yes	Yes

From initial screening of both **Concept B** & **Concept C** showed confidence in terms of further testing and both were considered for concept scoring depending on the results from magnetic flux simulation.

Table 2.2 shows the concept scoring of all three concepts in the study. Specific percentages are given to each criterion according to required application.

Table 2.2 – Concept Scoring Table

		Concepts			
Selection Criteria	**Weight %**	**B Square Profile**		**C Disc Array**	
		Rating	**Weighted Score**	**Rating**	**Weighted Score**
Ease of Production	25	4	1.0	8	2.0
Cost of Production	10	6	0.6	7	0.7
Ease of Assembling	15	7	1.05	4	0.6
Ease of Maintenance	10	7	0.7	5	0.5
Effective Field Intensity	40	9	3.6	6	2.4
Total Score			**6.95**		**6.2**
	Rank		**2**		**1**
	Continue		**Yes**		**Yes**

Total score of each concept is listed in the Table 2.2. Concept **'C'** has scored the highest with the leading factor to be output & ease of production. Concept **'B'** being closer in scoring to **'C'** is also considered for further study. Design is finalized after performing simulation of selected concepts.

2.3 Selection of Final Concept Design

Final design is selected on the basis of concept scoring. Both **Concept B** & **C** are considered for this purpose as both of these design showed potential for generating electricity as per the simulation results. Although **concept C** scored lower than **Concept B** as there is destructive interference of magnetic field which is not there in **Concept B**. Further testing is done using coils in order to study the effective current generation for both designs and comparison is established between the two upon the simulation results to finalize the design.

CHAPTER 3: EXPERIMENTAL MODEL AND SIMULATION

For experimentation, both Concept B & C are selected. Both designs are tested using similar coil design specifications. The results of magnetostatic simulation are discussed in section 3.1.

Following tables represent the Simulation Properties for the experimental design for Concept B shown in figure 2.7.

Table 3.1 – Material Selection for Simulation

Nbr.	Part Name	Material Name	Permeability Type
1	Coil-Assembly	Copper	Isotropic
2	Inner Air	Air	Isotropic
3	Outer Air	Air	Isotropic
4	Square Profile Magnet	N4212	Isotropic
5	Helical Spring	AISI 1010 Steel	Isotropic

Table 3.2 – Coil Properties used for Simulation

Nbr.	Name	Coil Type	Nbr.Of Turns
1	Test Coil 1	Copper AWG 26	150
	Test Coil 2	Copper AWG 26	300
	Test Coil 3	Copper AWG 26	600

Table 3.3 – Mesh Properties for Simulation

Nbr. Of Nodes	Nbr. Of Elements	Element Size (mm)	Tolerance (mm)
7658	41889	10.244983	0.010245

3.1 Simulation of Concept Model

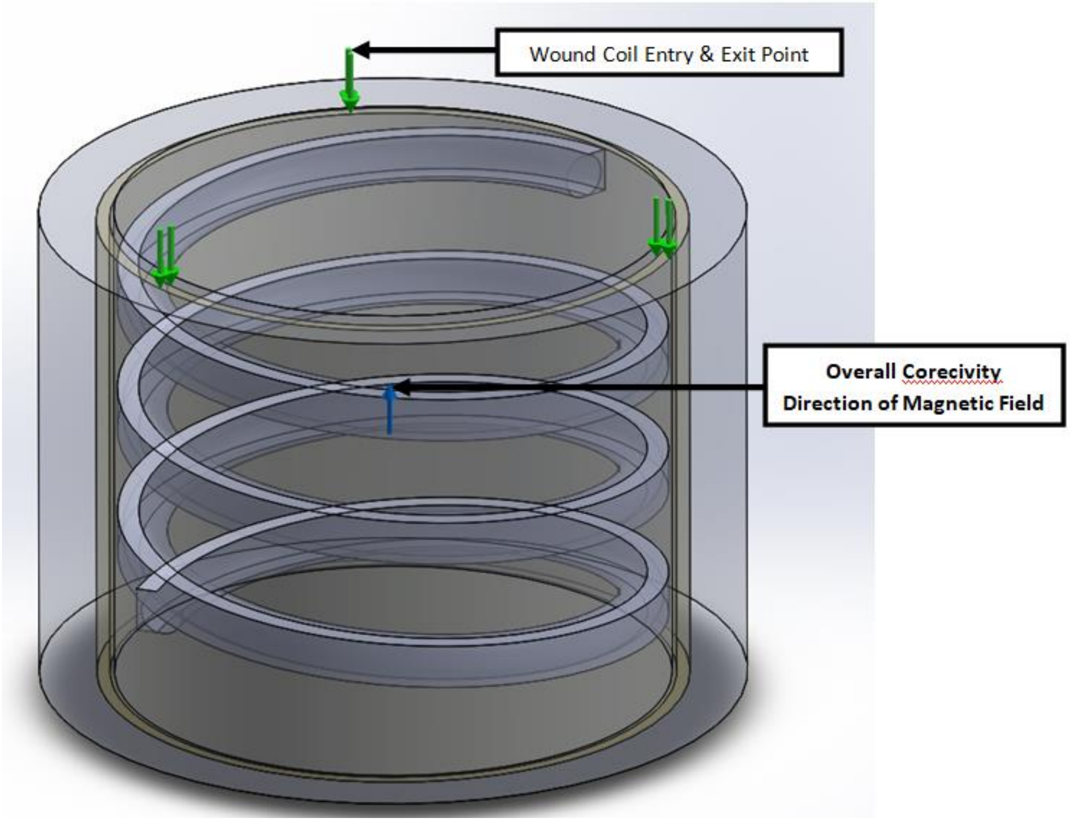

Figure 3.1 – Coil and Magnet Corecivity Direction Representation

Figure 3.1 represents the final configuration of wound copper coil with AWG 19 wire having 300 turns as a testing start. The entry and exit points are kept on top inconsideration to the fact that three individual coils would be coupled in series to effectively increase the potential difference of overall assembly. More over a parallel coupling could be considered in order to increase the current output but at this stage it is not tested as the output is expected to be alternative current. A transformation from higher potential to higher current could be achieved entirely using a power circuitry to best suit the charging ability of the design for application purposes.

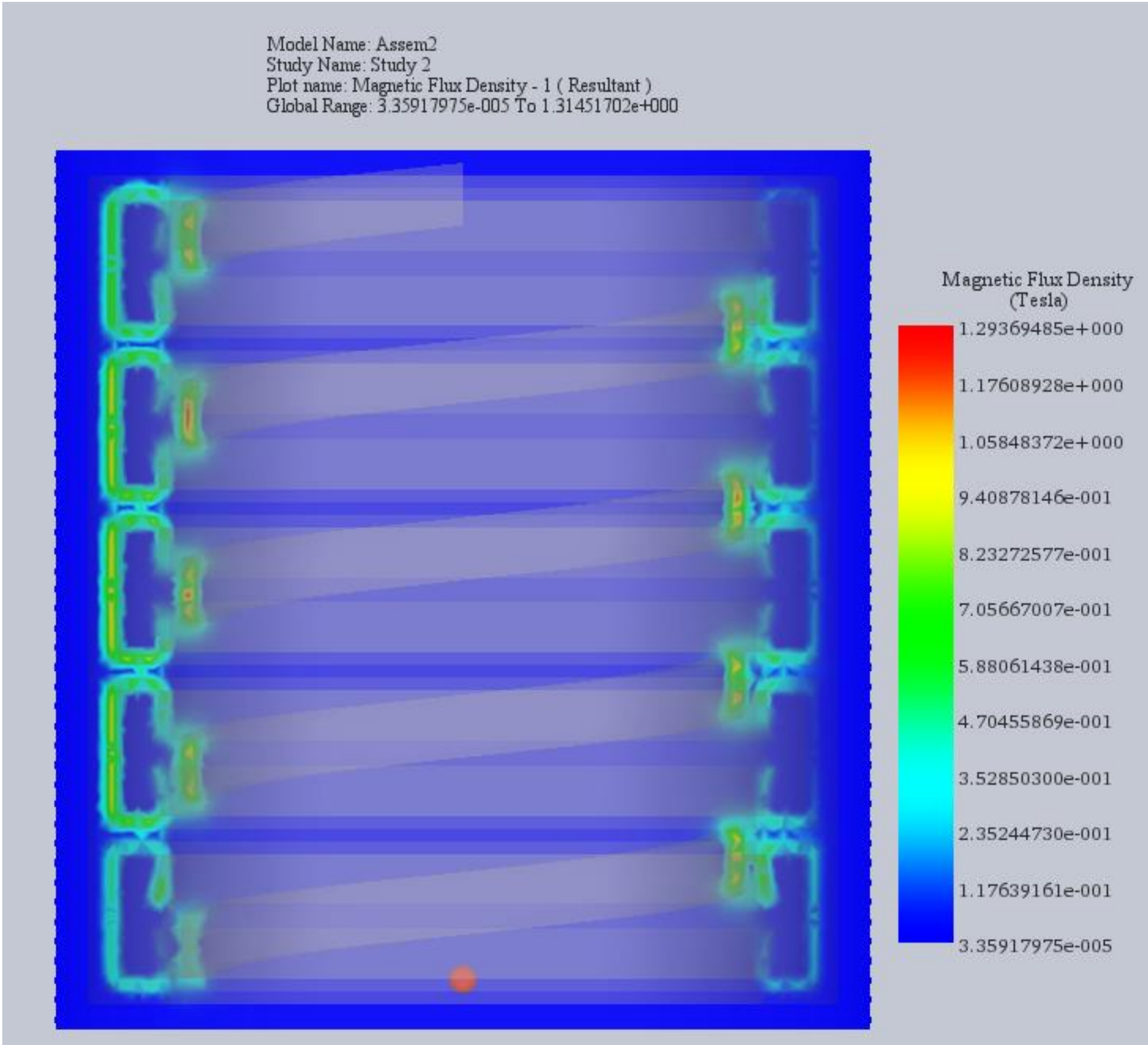

Figure 3.2 – Cross Section of Magnet and Stator Assembly

Simulation results of magnetic field intensity for the addition of stator around the wound copper coil are shown in figure 3.2 which clearly shows the potential of the design to produce electricity. Even though the magnet used is of very thin configuration, the stator has channeled the flux directly over the coil area with magnitude of 0.6 T.

3.2 Simulation of Shock Absorber Assembly

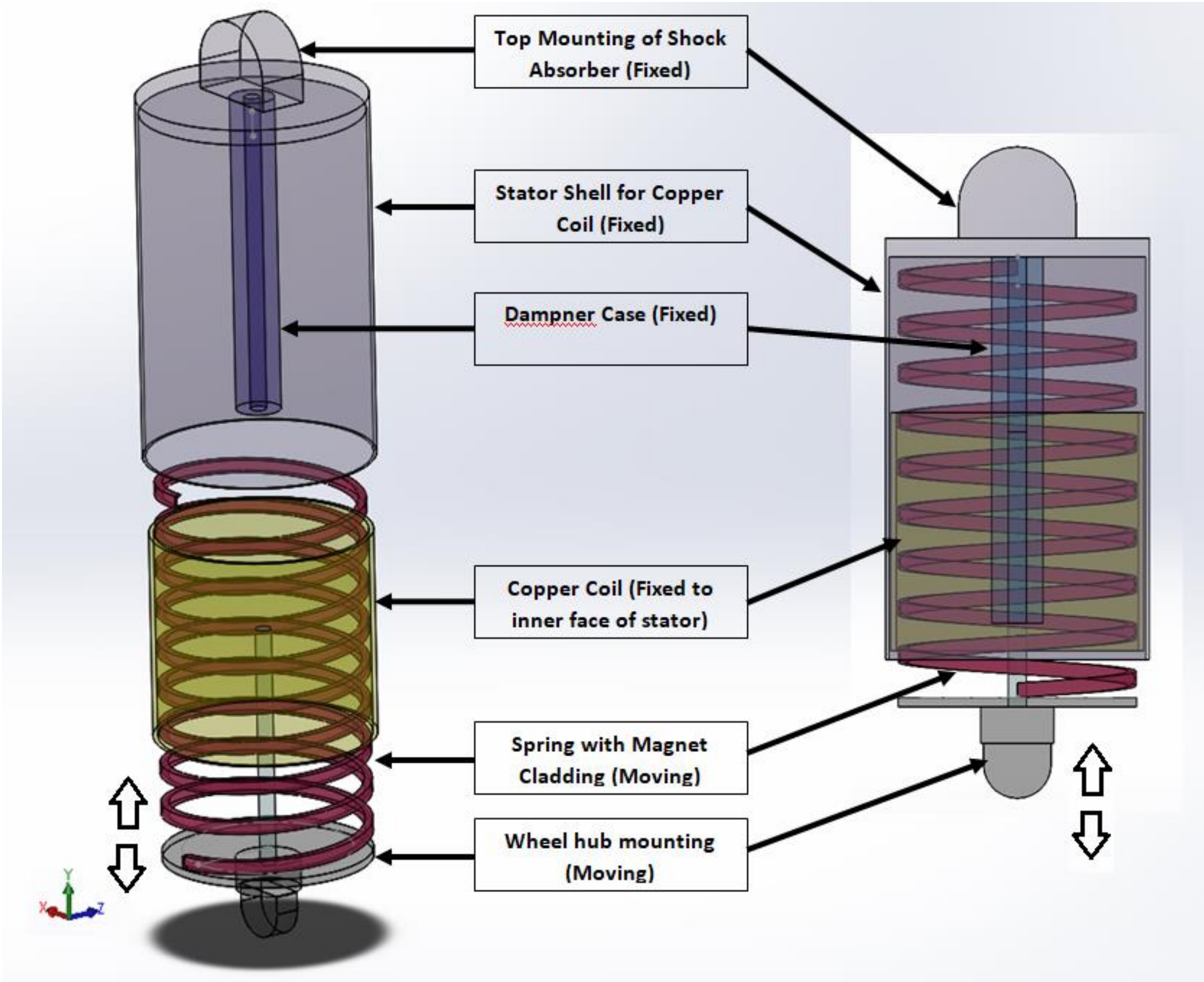

Figure 3.3 – Complete Shock Absorber Assembly

Figure 3.3 represents the complete shock absorber assembly before simulation. For the purpose of simulation, only the coil spring, square profiled magnet, sliding coils and air geometry is considered to form a refined mesh of 1.5 mm to attain accurate results.

3.2.1 Conditions for Test Simulation

To analyze the magnetostatic behavior of the magnet under required design parameters, several variables were assigned to EMS ready model. Simulation results provided magnetic flux density profiles with maxima and minima of flux change over the coil area. Following figures represent the profiles with respective calculations of possible power and e.m.f. capacity of coil array.

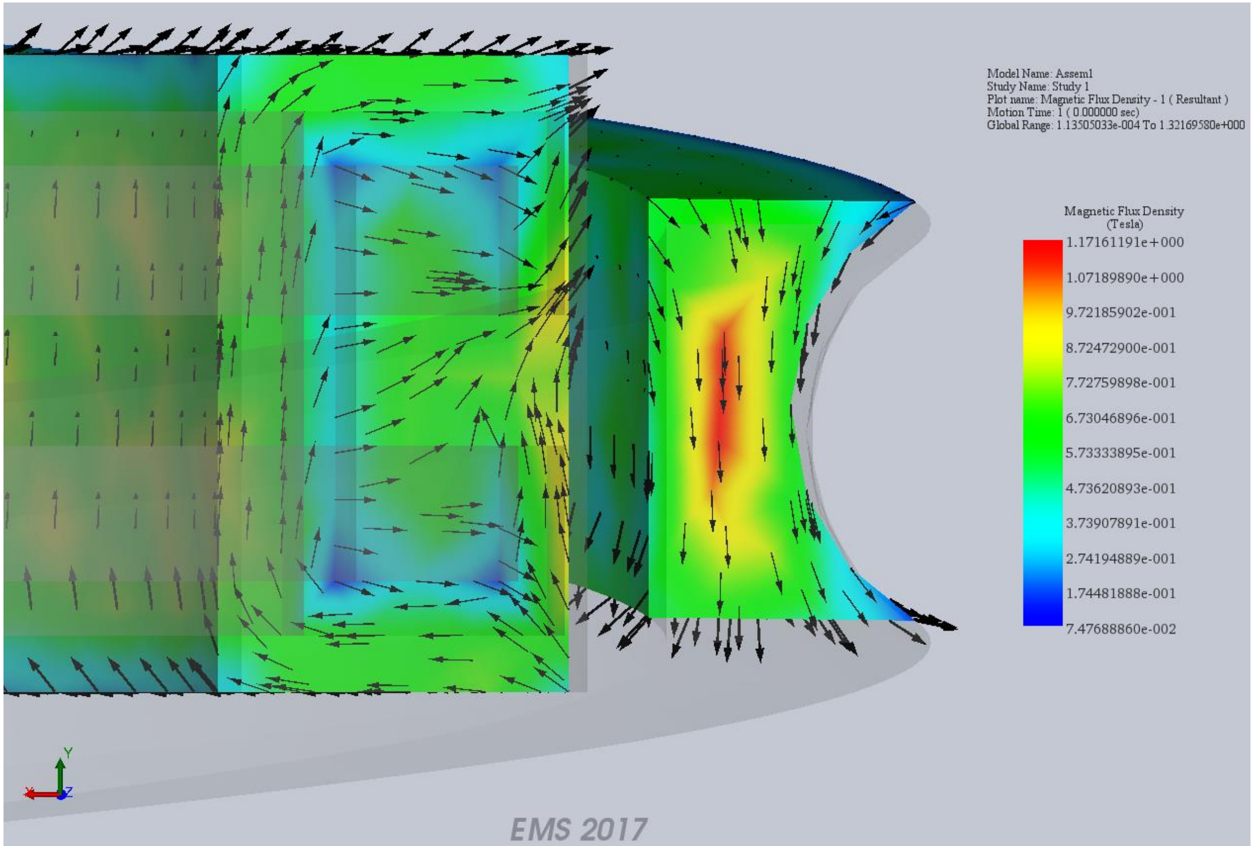

Figure 3.4 – Vectoral Cross-Section of Coil and Stator in Presence of Magnet

Figure 3.4 shows clearly that if there is harmonic movement of the magnet or the coil, there will be flux change perpendicular to winding direction; hence generation of current is possible.

3.2.2 Output Calculation

Table 3.4 – Ohomic Resistance Calculation for Each coil

Nbr.	AWG Gauge [#]	Area [mm^2]	Nbr. Turns [#]	Central Dia. [m]	Height [m]	Length of Wire [m]	Surface Area [m^2]	Coverage Area [m^2]	*Wire Resist. [ohm]	Resistivity [ohm/m]
1	26	0.129	150	0.0650	0.05	61.23	0.0204	0.0051	8.40E+00	1.770E-08
2	26	0.129	300	0.0650	0.10	122.46	0.0408	0.0102	1.68E+01	1.770E-08
3	26	0.129	600	0.0650	0.15	244.92	0.0612	0.0153	3.36E+01	1.770E-08

In table 3.4, Effective Area represents the only that undergoes constructive flux change compared to the overall area of the coil itself.

Table 3.5 – EMF and Current Approximation for Assembly

Nbr.	Initial velocity [m/s]	Vib. frequency [Hz]	Total Disp. [mm]	Change Flux [T]	**EMF [V]	Current [Amp]	Power [J/s]	Nbr. Vib. [#/Hr.]	Power [W/h]	Charging Eff. [%]
1	0.03	1	30	0.6000	1.1021	0.1322	0.1457	1500	218.56	0.73%
2	0.03	1	60	0.6000	1.8369	0.1322	0.2428	1500	364.27	1.21%
3	0.03	1	90	0.6000	5.5107	0.1322	0.7285	1500	1092.80	3.64%

The high values for the current suggests that the selected gauge for simulation is not compatible but this however does not impact the results of simulation as the temperature study is not done for this simulation. Further research on thermal behaviors of the coil can suggest accurate wire gauge needed to deliver the generated current.

Table 3.4 represents the testing parameters for magnetostatic motion analysis. It shows maxima and minima for Magnetic flux changes attained during simulation for manual calculations of e.m.f. for the coils using Lenz Law.

Table 3.6 – Test Parameters for Magnetostatic Motion Analysis

Flux velocity	**v = 30 mm/s**
Vibrational Frequency of spring	**f = 1 Hz**
Testing Time	**t = 1 s**
No. of time segment for study	**N_t = 5 frames**
Wire Gauge used	**AWG 26 (0.129 mm^2)**
Resistivity of Copper	**ρ = 1.77 x 10-8**
Magnetic Flux change (from simulation)	**ΔB = 0.42 T (Top & Base Coils)**
Mass of the Coils & Stator	**1.263 kg**
Mass of the Magnet	**0.48 kg**

*wire resistance for USN 12600 winding copper 1.77×10^{-8} Ω/m
**EMF calculated as per Lenz Law

3.3 Schematic for Pulse Charging

The simulated design could be used in EV with a very basic power circuitry commonly found. The figure 3.6 shows how the schematic for charging circuitry that could be coupled with the main battery of EV to provide rectified pulse charging.

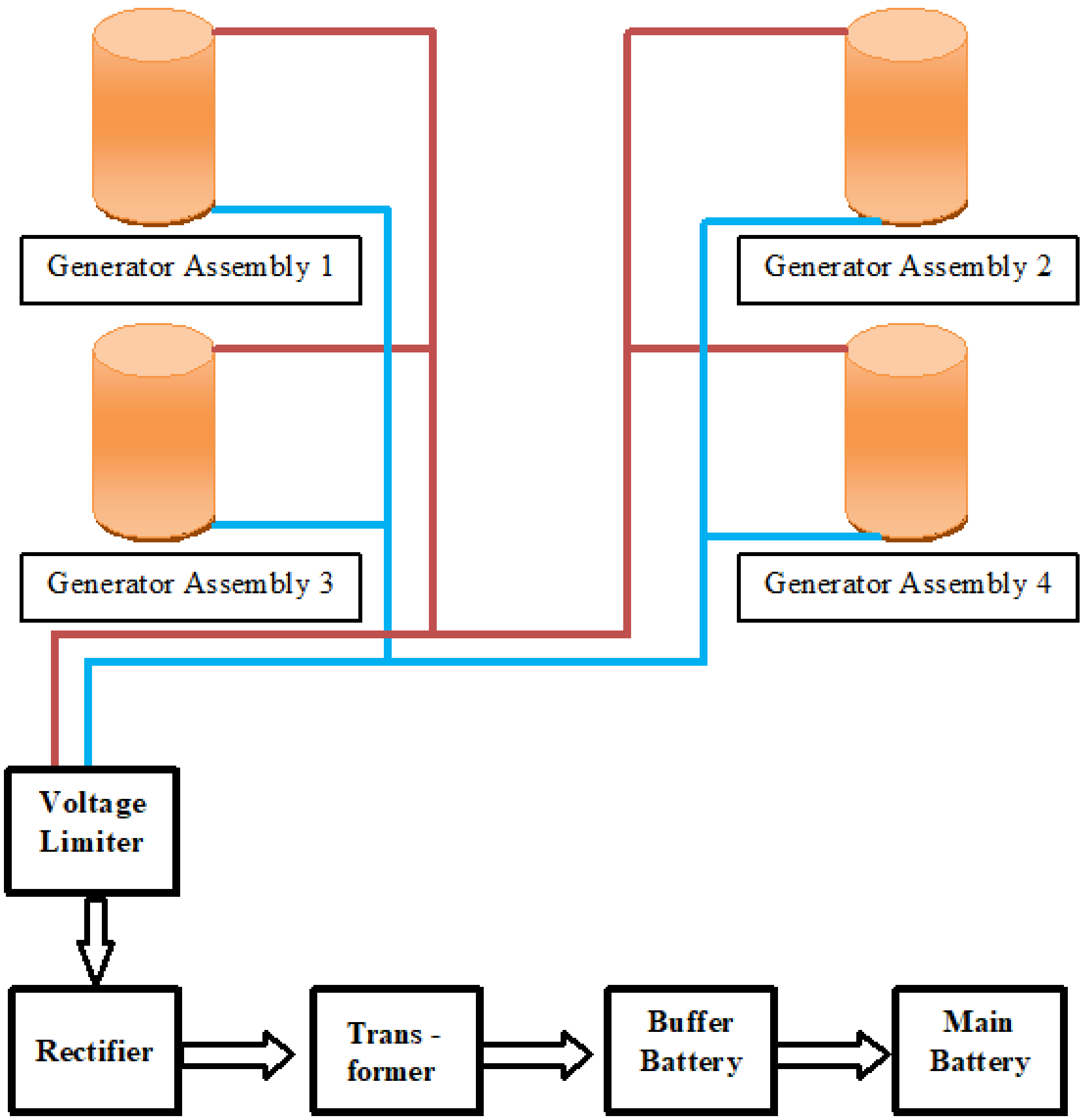

Figure 3.5 – Schematic for Charging Circuitry for Harvesting Energy

The schematic represents the generic circuitry needed to charge the main batter. A voltage limiter is added directly to the output of generators to control the maximum voltage acquired before it could be transformed (step-down transformer) and rectified. Transformer required for this assembly could be adjusted to any required charging value needed for any specific model of vehicle. The rectification is done to ensure that only DC current is collected. The rectified current is stored in a buffer battery to ensure no variable charging cycle damage is done to the main battery. This way the main battery could draw required current from the buffer battery without affecting its own charging cycles from the main engine/charging system.

3.3.1 Output for Each Generator Assembly:

Ohomic approximation of the designed generator is done to find the total output for a total of 1500 oscillations i.e. 3000 pulses for generator including both upward and downward movement.

$$V = vBl$$

$$V = 0.06ms^{-1}\ X\ 0.6T\ X\ 244.92m = 5.5107\ volts$$

Here, '**V**' represents the voltage generated, '**v**' is the relative motion of magnet vs. coil, '**B**' is the magnetic flux change across the coil and '**l**' is the length of the wound copper coil. For the same, the current can be calculated using ohom's law as follows:

$$I = \frac{V}{R}$$

$$I = \frac{5.5107\ V}{33.6\ \Omega} = 0.164\ amp$$

Here, '**I**' is the current generated in the coil due to flux change, 'R' is the resistance across the length of wound coil and '**V**' is generated voltage. For all four generators will be coupled in parallel, hence the total current would be sum of individual current i.e. 0.656 amp.

$$P_t = V\ I$$

$$P_t = 5.5107\ x\ 0.656 = 3.615\ W\ (per\ cycle)$$

For a typical one hour drive, the number of cycles is set to 3000 cycles per hour, which increases the total output generated in one hour i.e. 10.843 kW for all four generators.

3.3.2 Storing Output for Complete Generator Assembly:

Serial output from complete assembly can be assembled using slow charging input system of BMS of electric vehicle. The schematic in figure 3.7 show the layout for BMS upgrade required for this purpose.

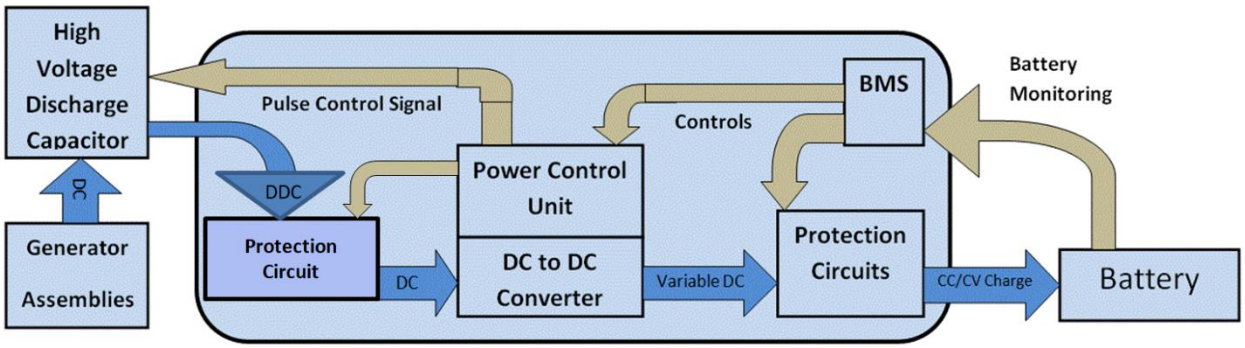

Figure 3.6 – Schematic for Pulse Charging of Main Battery

Here the charging input is controlled by Power Control Unit of BMS. Charging is done as per Level 1 (slow charging input) through 2kW charging line and is directly passed through a protection circuit of its own. However, due to inconsistent charge, the charge is first accumulated in a high voltage capacitor which will discharge upon control signal from PCU to provide pulse charging to the main battery for storing and further use.

CHAPTER 4: MOTION STUDY

4.1 Motion Study of Complete Assembly

Figure 3.2, 3.4 & 3.5 clearly shows the potential of the design to generate electricity when used in an electric vehicle. The current density of coils represents ability of shock absorber to generate electricity even with small displacement of shock absorber.

Although, the wound coils were tested for a higher number of turns to generate higher voltage and small currents, depending on the type of battery used in any specific EV. The transformation circuitry and current limiter could provide consider charging pulses to the main battery if coupled with a buffer accumulator.

In general, the design adheres to the set targets of being robust, cost effect and most of all without any modification of original coil spring. Instead, the design could be implemented as an ad-on to the original shock absorber assembly while providing charging pulses.

4.1.1 Magnetic Flux Density Changes W/O Stators

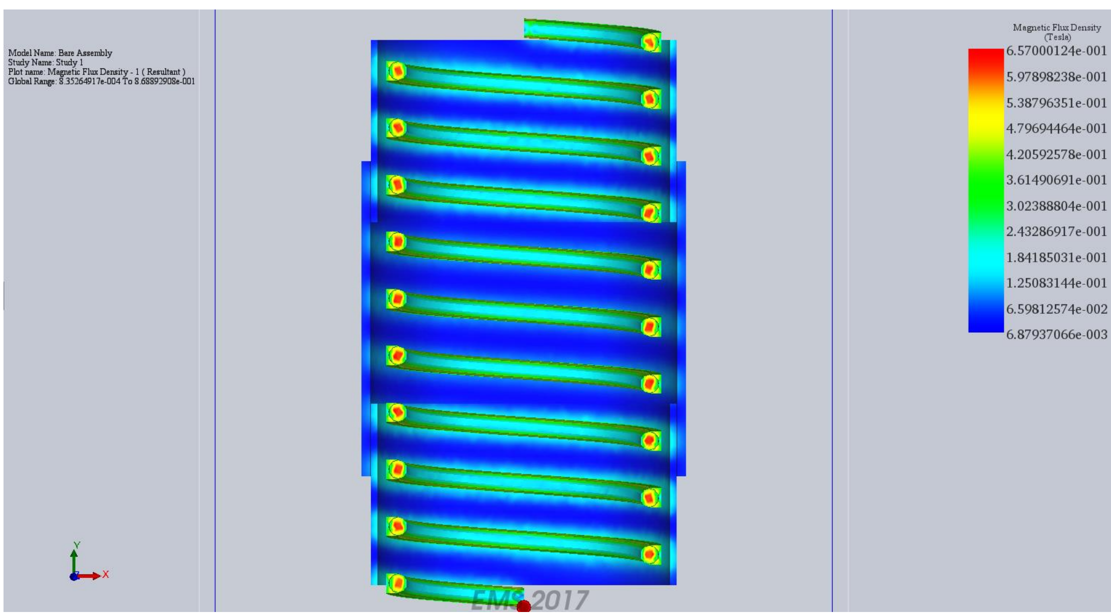

Figure 4.1 – Refined Mesh of Magnetic Flux Density

Figure 4.1 represents the effective area under flux change due to shock movement at a rate of 30 mm/s. Although the coils provide a large area, only ¼ of the actual coil area is generating current.

4.1.2 Magnetic Flux Density Changes with Stators

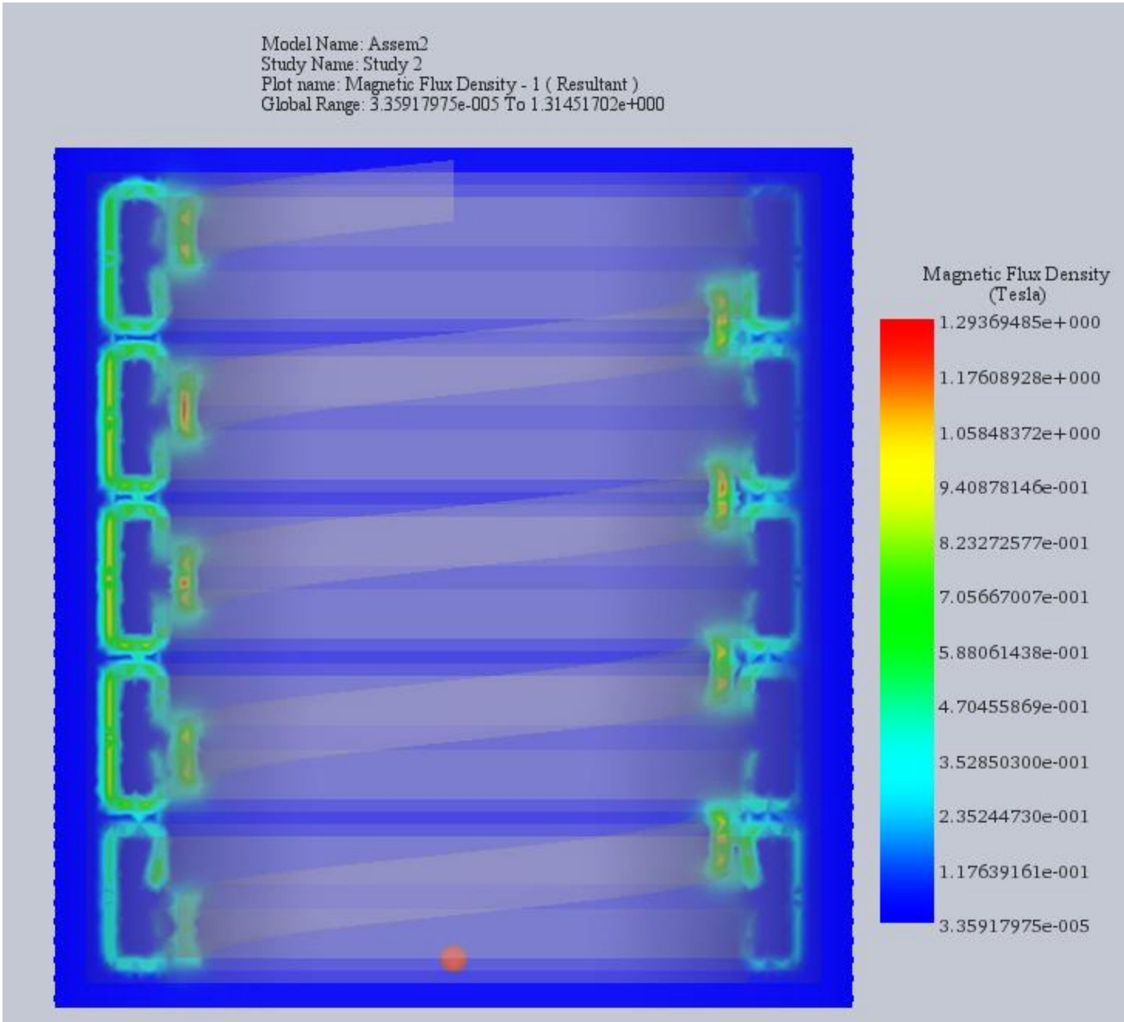

Figure 4.2 – Cross-Section of Shock Absorber Coil section with Stators

Figure 4.2 represents the cross sectional view of assembly at coil region where stators have dramatically improved the flux density across the coils as compared to coils without stators.

4.2 Results and Discussion

Detailed analysis of the simulation and point-wise flux evaluation confirm the output calculations for Table 3.5. Following geometric analysis provides an insight to the flux lines of forces interacting with the coils.

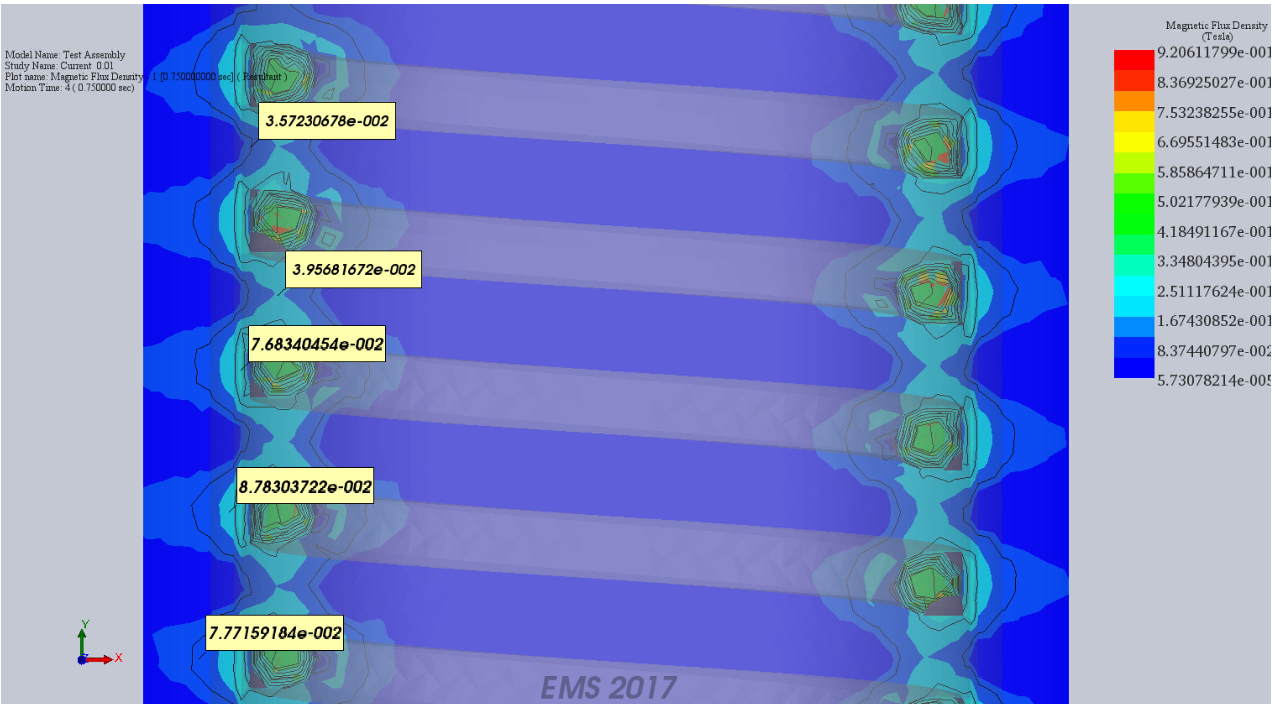

Figure 4.3 – Section View of Flux Density for Test Points

Figure 4.3 represents the magnetic flux lines and relative flux density produced by each turn of the magnetic coil spring. The area facing the coil directly is having large magnetic flux changes (maxima) and the area not adjucent to magnet is under going very little flux change (minima).

It is clearly visible that the magnetic field is not channeled properly without stators hence the use of stators can greatly affect the magnetic flux through coils and hence improving the possible output of generator.

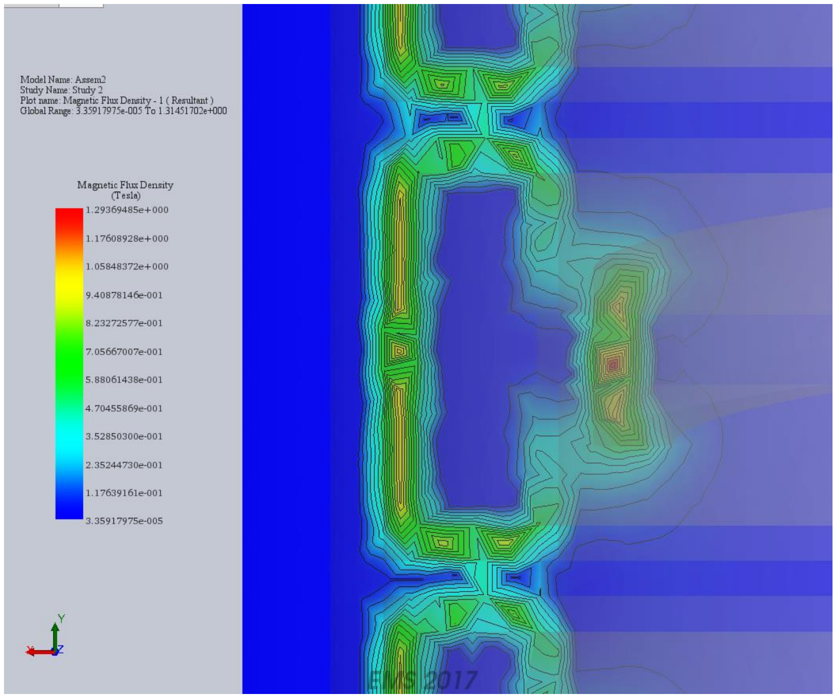

Figure 4.4 – Section View of Flux Density through stators

Figure 4.4 shows the difference of flux changes between coils closer to the magnet and the slide over coil that is adjusted in the middle. The overlaping area between two coil sets represent the minimum flux density due to lower permeability of the magnetic flux top outer coil part.

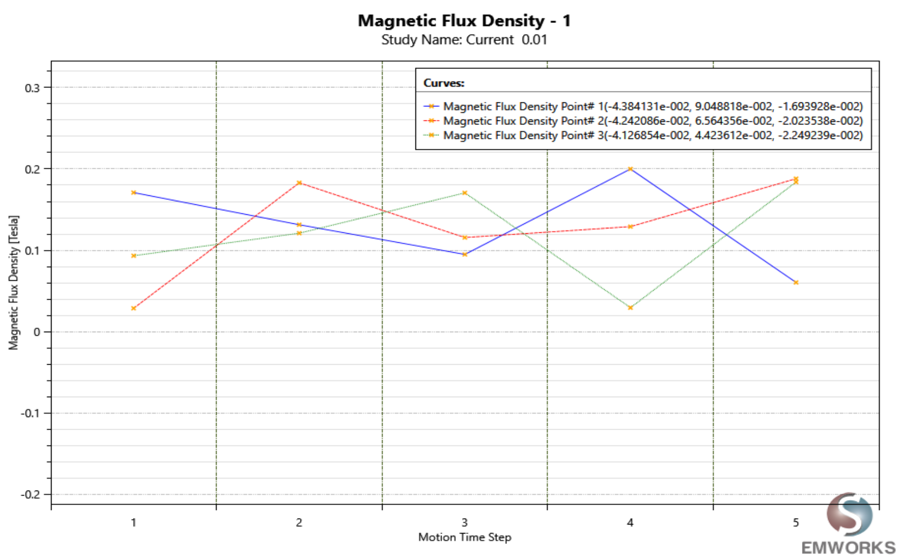

Figure 4.5 – Magnetic Flux Density vs. Time (5 FPS)

Figure 4.5 represents the plot of flux density on three randomly chosen points on the middle coil to study the minimalistic flux accros its area. The curves are due to the gap between the magnetic turn of the shock absorber spring that induces changes in the flux on coil area.

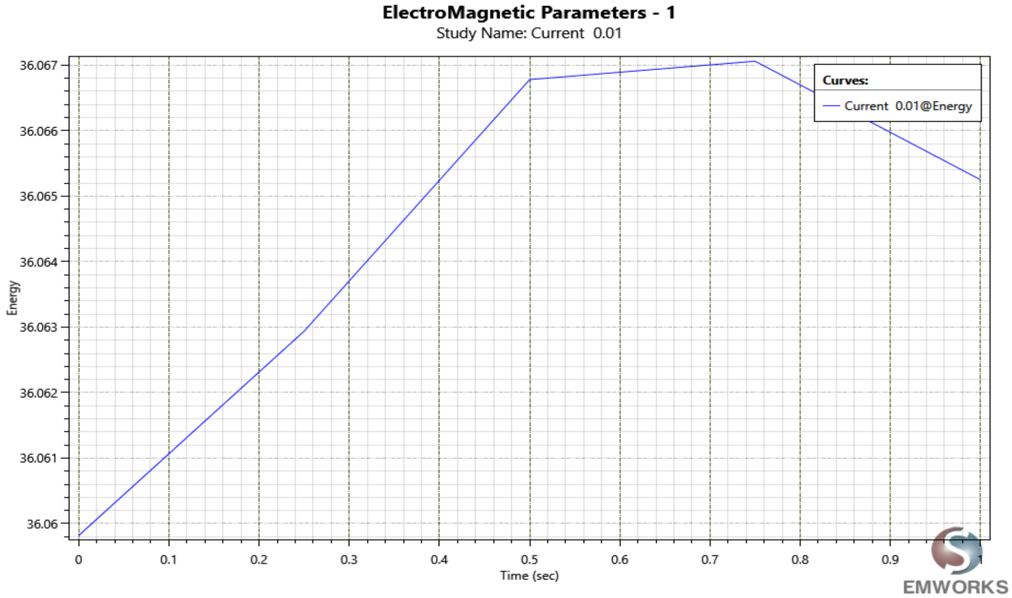

Figure 4.6 – Electrical Energy-Time Plot (5 FPS)

Figure 4.6 shows the electrical energy generated over the period of one shock cycle for the middle coil during compression. This plot is comparable to the calculated value of 21.84 J as per the table 3.5. The simulation value is higher as impedance for the coils is selected at ideal case of 0 ohms while the calculations done manually were inclusive of wire resistance over length and inductive impedance.

4.3 Scale Model Testing

To test the concept model as well as benchmark the difference between helical design magnet and disc type magnet, a simple scale model was built with two identical magnetics to be employed. One magnet was fixed to a plunger to simulate the disc type configuration for experimental data. The other magnet was split in 4 equal quadrants. Each quadrant was attached to the plunger in order to replicate the helical shape of proposed magnet. The following figure shows the details of the assembly that was built to test the proposed concept. The coil however was kept same along with same testing conditions for vibration frequency

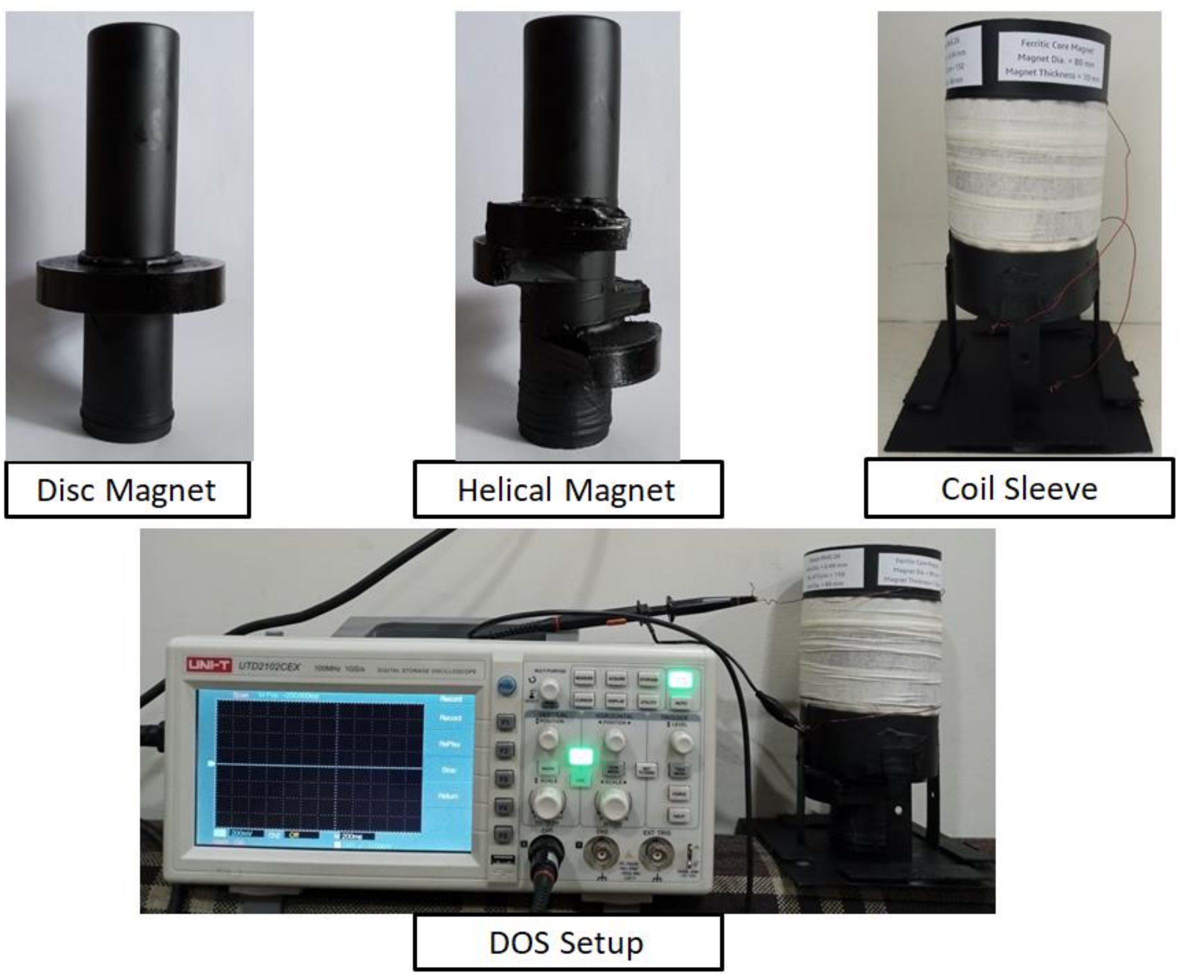

Figure 4.7 – Scale Model Testing Setup

4.3.1 Output Analysis of Scale Model

To test the output of both configuration, a digital oscilloscope was connected across the coil the measure the voltage generated by the coil when the magnets were moved back and forth in vertical direction.

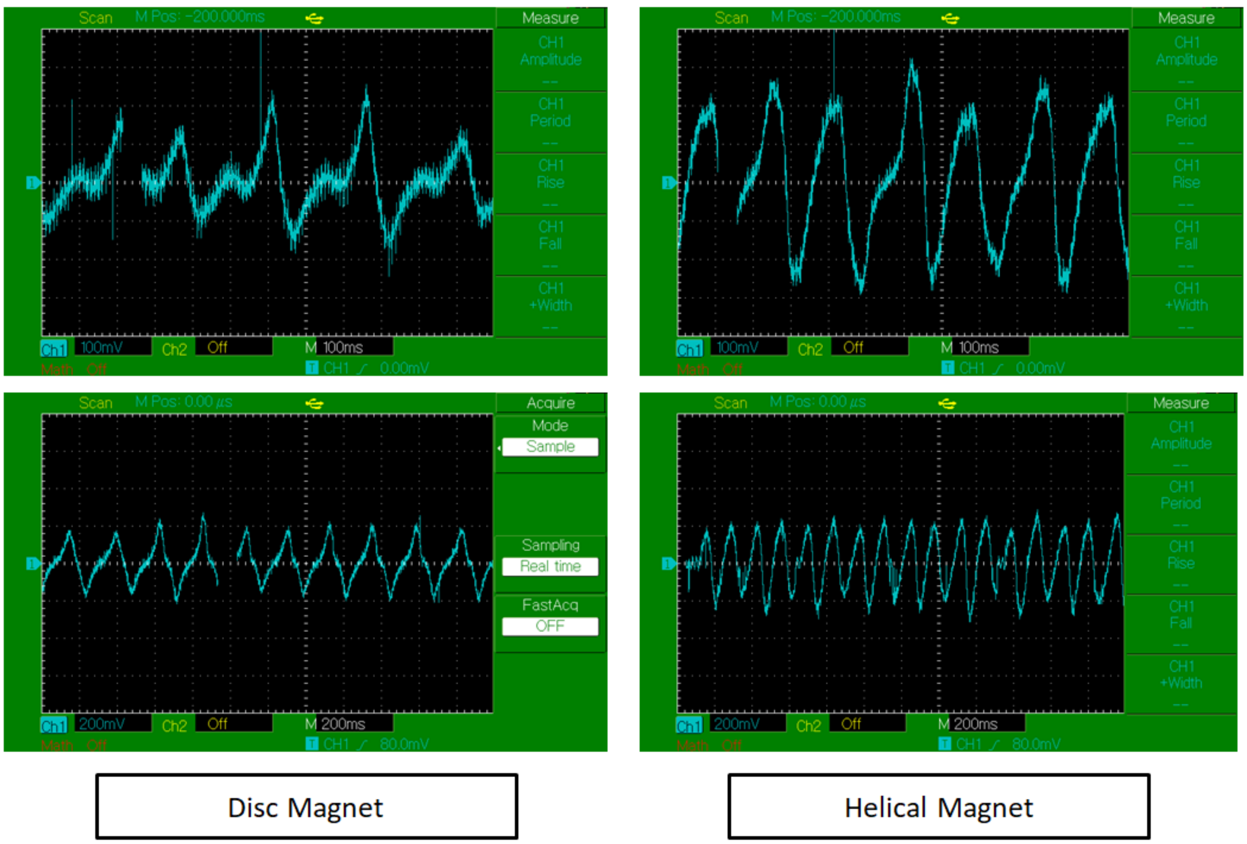

Figure 4.8 – Output Displace of Digital Oscilloscope for both magnet configurations

Figure 4.8 shows comparative results of voltage generation for both disc magnet and helical shape magnet over a span of 200ms and 100ms scaling. The results show clear advantage of helical design over disc magnet as the voltage if slightly higher as well the area under the curve (current produced) is also greater. This proves that helical design can harness energy from linear generator more efficiently compared to a disc magnet of same weight and size.

4.4 Application of Simulated Design

The possible application for discussed study could be to drive the electrically driven A/C compressor. The selected model is ES14 eCompressor by DENSO, Europe, which is available for Toyota Prius-Hybrid retrofitting. The air conditioning unit has a power rating of 5 kWh. The total power generated by all four generators is 10.845 kWh.

ES18 DCP50502 model has a voltage and current rating of 150 V and 34 A respectively. For the same, the output from the generators must be transformed to required voltage for an accumulator to support such electrical device. For this a step-up transformer is required to provide the same. Here the calculation is made using for collective one hour pulse cycles:

V_i = 5.5107 volts, I_i = 1968 amp and the required output voltage is V_o = 150 volts

$$P_i = P_o$$

$$V_i I_i = V_o I_o$$

$$I_o = \frac{V_i I_i}{V_o} = \frac{4.179 \times 1968}{150} = 54.82\ amp$$

The lack of current can be adjusted by using an accumulator battery of required amperages i.e. at least a 40A multi-cell battery is placed with total of 150+ volts. Only then the generated pulse charges can be utilized for A/C operations.

With 5% transformation losses, the usable output will be:

Useable energy from generators = $10.845 - \frac{10.845 \times 5\%}{100} = 10.3\ kWh$

Duty Cycle for A/C = $\frac{energy\ available}{energy\ required} \times 60\ mins. = 123.6\ mins.$

So for every one hour of bumpy road, the generators should be able to support the A/C compression operation for nearly 123.6 mins. This however is still an ideal case where only transformation conversion losses are considered. Line losses, coil impedance and temperature based induction losses are not considered. Here, research on thermal and electrical simulation is suggested for future studies.

CHAPTER 5: CONCLUSION

5.1 Conclusion

1. A novel design is presented, studied and evaluated in this study for generating electricity using vibrational energy from shock absorbers of a vehicle.
2. The design requires minimal modification to automobile and easily maintainable due to complex part geometry.
3. Experimental data shows that helical design of magnet offers slightly more voltage and considerably more current for the same test conditions compared to disc magnet design.
4. Calculated output of the helical spring in concept model is 2.7 kW for a total of 1500 oscillations with less than ~0.92 kg of weight for each generator. Total output for all four generators would be a sum of 10.843 kW with ~3.68 kg of weight.
5. As the design has less weight and volume, it can be added onto any vehicle without issues of space confinement.

5.2 Future Recommendations

1. Stress analysis of neodymium magnet can be simulated to fine tune the countours of model.
2. Fatigue cycle simulations can provide detailed analysis of material behavior over span of several years to adjust the model to be maintenance free.
3. Research into stator design of proposed novel helical magnet generator can lead to improvements in output of the model with little addition to net weight of assembly.
4. Application design for energy harvesting from industrial machinery having spring based vibration dampening system.

APPENDIX A

Induced EMF (Lenz Law)

The formula needed to calculate the EMF generated in each coil is taken as the ideal case of Lenz law. The calculations for impedance are not done as the temperature study is needed to actually study the change in impedance during current generation.

$$\boldsymbol{\varepsilon = N\frac{\Delta B . A}{t}}$$

Resistance Calculation

The resistance for each coil is calculated for ideal **temperature @ 25C**.
For calculation, Ohom's law is used. Where the value for **$\rho = 1.77x10^{-8}$ 'Ω/m** of **USN 12600 Winding copper** is used.

$$\boldsymbol{\varepsilon = \rho\frac{L}{A}}$$

Toyota Prius 2007 Battery Datasheet*

Hybrid System Specifications

Battery Specifications
Manufacturer: Panasonic EV Energy
Battery Type: Nickel Metal Hydride
Rated Capacity: 6.5 Ahr (C/3 Rate)
Rated Power: Not Available
Nominal Pack Voltage: 201.6 VDC
Nominal Cell Voltage: 1.2 V
Number of Cells: 168

Vehicle Specifications
Manufacturer: Toyota
Model: Prius
Year: 2004
Number of Motors[1]: 1
Motor Power Rating[2]: 50 kW
VIN #: JTDKB20U740011052

Battery Lab Test Results

HPPC Test
Peak Pulse Discharge Power @ 10s[3]: 21.2 kW
Peak Pulse Discharge Power @ 1s[3]: 30.0 kW
Peak Pulse Charge Power @ 10s[3]: 21.2 kW
Peak Pulse Charge Power @ 1s[3]: 30.3 kW
Maximum Cell Charge Voltage: 1.5 V
Minimum Cell Discharge Voltage: 1.0 V

Static Capacity Test
Measured Average Capacity: 5.34 Ah
Measured Average Energy Capacity: 1130 Wh

Vehicle Mileage and Testing Date
Vehicle Odometer: 159,697 mi
Date of Test: March 31, 2008

Analysis Notes:
1. Motor refers to any motor capable of supplying traction power.
2. Motor power rating refers to the manufacturer's peak power rating for the motor(s) supplying traction power.
3. Calculated value based on selected battery voltage limits and at 50% SOC.

*HEV America, U.S. Department of Energy Advanced Vehicle Testing Activity[?]

Datasheet for ES14 eCompressor [?]

A/C Components | Application Tables - Compressors

Application Tables

T

				TYPE	GAS	DENSO PN	OE
TOYOTA *Continued*							
LAND CRUISER (J80) (90-98)							
4.2 D	1H-Z		01/90-05/93	10PA15C	R12 (Retrofit to R134a necessary!)	DCP50070	88310-60460
4.2 D	1H-Z		01/90-12/97	10PA15L	R134a	DCP50071	88310-60770
4.2 TD	1HD-T		01/90-12/97	10PA15L	R134a	DCP50071	88310-60770
4.2 TD 24V	1HD-FT		03/95-12/97	10PA15L	R134a	DCP50071	88310-60770
LAND CRUISER (J100) (98-08)							
4.2 TD	1HD-FTE		01/98-07/08	10PA15L	R134a	DCP50073	88310-6A010
4.2 TD	1HD-FTE	For vehicles with front and rear A/C	01/98-07/08	10PA17C	R134a	DCP50074	88310-6A100
4.2 TDi 24V	1HD-FTE	For vehicles with automatic climate control	01/98-07/08	10PA15L	R134a	DCP50073	88310-6A010
4.2 TDi 24V	1HD-FTE	For vehicles with front and rear A/C	01/98-07/08	10PA17C	R134a	DCP50074	88310-6A100
4.7	2UZ-FE	For vehicles with A/C	01/98-12/08	10PA20C	R134a	DCP50087	88320-6068*
4.7	2UZ-FE	For vehicles with automatic climate control	02/02-12/08	10PA20C	R134a	DCP50087	88320-6068*
LAND CRUISER (J200) (07-)							
4.5 D V8	1VD-FTV		01/08-	10SR19C	R134a	DCP50088	88310-6A350
4.5 D-4D	1VD-FTV		01/08-	10SR19C	R134a	DCP50088	88310-6A350
4.5 D4-D	1VD-FTV		08/07-	10SR19C	R134a	DCP50088	88310-6A350
LAND CRUISER / PRADO (J70) (84-06)							
3.0 TD	1KZ-T		05/93-05/96	10PA15C	R134a	DCP50021	
4.2 TD	1H-Z		04/96-08/01	10PA15C	R12 (Retrofit to R134a necessary!)	DCP50070	88310-60460
LAND CRUISER / PRADO (J120) (02-10)							
3.0 D-4D	1KD-FTV	For rear air conditioning	01/03-08/04	10S17C	R134a	DCP50085	88320-6A081
3.0 D-4D	1KD-FTV	For vehicles with automatic climate control	08/04-08/06	10S17C	R134a	DCP50085	88320-6A081
LAND CRUISER / PRADO / COLORADO (J90) (95-)							
4.7	2UZ-FE		08/02-	10PA20C	R134a	DCP50087	
PICNIC (96-01)							
2.2 D	3C-TE		08/98-04/01	10S15L	R134a	DCP50090	88310-44140
PREVIA II (00-06)							
2.0 D-4D	1CD-FTV		04/03-01/06	10S17C	R134a	DCP50226	88310-28540
2.4	2AZ-FE		08/00-07/03	10S17C	R134a	DCP50081	88310-28450
2.4	2AZ-FE		08/03-01/06	10S17C	R134a	DCP50080	88310-28550
PRIUS (W2) (03-09)							
1.5	1NZ-FXE		08/03-03/09	ES18	R134a	DCP50503	88370-47010
PRIUS (W3) (09-)							
1.8 Hybrid	2ZR-FXE		04/09-12/12	ES14	R134a	DCP50502	
PRIUS Plus (W4) (11-)							
1.8 Hybrid	2ZR-FXE		05/11-	ES27	R134a	DCP51011	
[illegible]							
2.0 16V 4WD	3S-FE		12/97-06/00	10PA15L	R134a	DCP50031	88310-42070
2.0 4WD	3S-FE		09/97-06/00	10PA15L	R134a	DCP50031	88320-42050
RAV 4 II (00-05)							
1.8 VVTi	1ZZ-FE		08/00-11/05	10S15L	R134a	DCP50030	88310-42200
2.0 D-4D 4WD	1CD-FTV		09/01-11/05	10S15L	R134a	DCP50032	88310-42210
2.0 VVTi 4WD	1AZ-FE		06/00-07/03	10S15C	R134a	DCP50033	88310-42180
RAV 4 III (05-)							
2.0 VVT-i 4WD	1AZ-FE		03/06-12/08	5SE12C	R134a	DCP50035	88310-42260
2.2 D-4D	2AD-FTV		12/08-02/10	5SE12C	R134a	DCP50301	88310-42250
2.2 D-4D 4WD	2AD-FHV;2AD-FTV		03/06-02/10	5SE12C	R134a	DCP50301	88310-42250
2.2 D-CAT 4WD	2AD-FHV		03/06-12/08	5SE12C	R134a	DCP50301	88310-42250
RAV 4 IV (12-)							
2.0 D4-D	1AD-FTV		12/12-	6SES14C	R134a	DCP50311	
2.0 D4-D 4WD	1AD-FTV		11/13-	6SES14C	R134a	DCP50311	
2.2 D4-D 4WD	2AD-FHV; 2AD-FTV		12/12-	6SES14C	R134a	DCP50311	
URBAN CRUISER (07-)							
1.33	1NR-FE		04/09-	5SER09C	R134a	DCP50304	

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