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Comprehensive Analysis of Octapole Electromagnetic Launcher

K. Sri Chandan[1], Dr. P. Mallikarjuna Rao
[1]*Research Scholar, Department of Electrical Engineering Andhra University, Visakhapatnam, India*
[2]*Professor, Department of Electrical Engineering, Andhra University, Visakhapatnam, India*

Abstract*: This article presents an analysis of Octapole Electromagnetic Launcher based on catapult acceleration and octupole induction acceleration. The detailed electrical equivalent circuit parameters and dynamic equations of the launch system are presented. An effort is made to derive the mutual inductance and inductance of the octapole coil with respect to the position of the projectile. Analysis of electromagnetic accelerating force is carried out for different configuration parameters.
Keywords: Electromagnetic Launcher, Octapole field, Muzzle velocity, Equivalent Electrical circuit, FEMM.

I. INTRODUCTION

Electromagnetic launchers are attracting more attention as they are an alternative for chemical propulsion with their high muzzle velocities, silent firing and less manufacturing cost. The use of electromagnetic field to produce the propulsive force is beneficial to overcome the velocity and hazardous limitations of chemical launchers [1],[7]-[10].

Multipole Electromagnetic Launchers has the potential of developing huge thrust force, large driven mass, super velocity launch and steady maglev [2]-[6]. For accelerating objects to high speed in a limited space, a high propulsion force is required. In this view, a multiple field system is gaining advantages as this system has high magnetic field strength. In [2]&[3], the basic principles of catapult and multipole field induction acceleration are taken as identical. In this paper, the detailed electrical equivalent circuit of catapult with formula for inductance and mutual inductance with respect to position of the projectile is derived. An electrical equivalent circuit for acceleration coil with formula for inductance and mutual inductance with respect to position of the projectile is proposed. A detailed analysis was expressed by varying the various configuration parameters in the launch system.

II. WORKING PRINCIPLE AND ELECTRICAL EQUIVALENT CIRCUITS

Electromagnetic (coil) Launchers are available in Single stage and Multi stage, designed by the required size and firing range. A single stage launcher consists of a stationary catapult coil energized by a capacitor switching and a moving projectile in a sleeve. The octapole coils are positioned around the sleeve, above the catapult coil. The octapole coils are connected in series energized by capacitor switching. The catapult coil is energized to provide the initial trust on the projectile. The projectile accelerates through the sleeve, enters into the octapole field, where aLorentz force is exerted by the octapole field which will accelerate the projectile with hyper velocities.The pictorial 2D view of the individual structures of the catapult coil, Projectile and Octapole coils are presented in figures 1, 2 & 3 respectively.

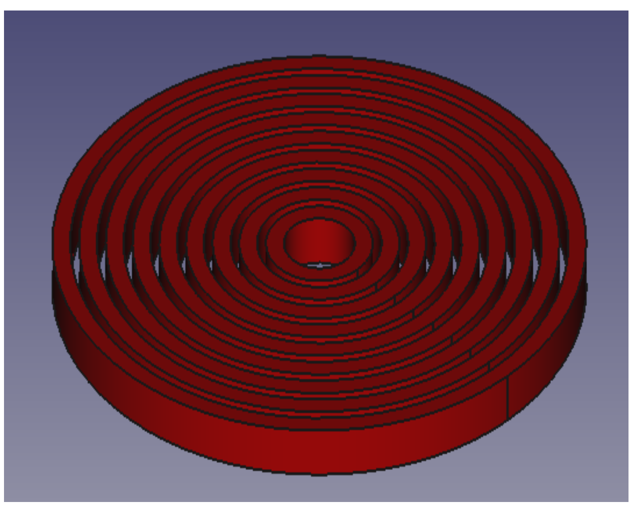

Fig.1. Physical model of the Catapult Coil

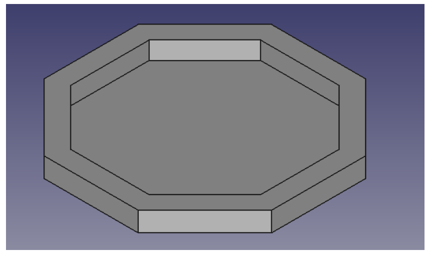

Fig.2. Physical model of the Octashape Projectile

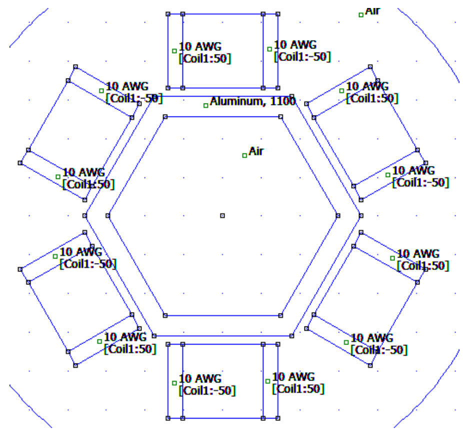

Fig.3. Front view of the Octapolecoil configuration

A. Electrical Equivalent Circuit of Catapult coil

The equivalent circuit of the catapult coil is shown in Fig. 4. The circuit parameters are derived from geometrical dimensions of the catapult and projectile structures.

The resistance of the Catapult coil is calculated by

$$R_{coil} = \frac{\rho l}{A} \quad (1)$$

The inductance of the Catapult coil is given by

$$Lc = \frac{N^2 A^2}{30A - 11D_i} \quad (2)$$

Where

Area of the spiral coil

$$(A) = D_i + N_c \frac{(w+s)}{2} \quad (3)$$

D_i= Inner Diameter of catapult coil ,s= Distance between the coil winding, w=Wire diameter of catapult coil, Nc= Number of turns catapult coil

D_o=Outer Diameter catapult coil

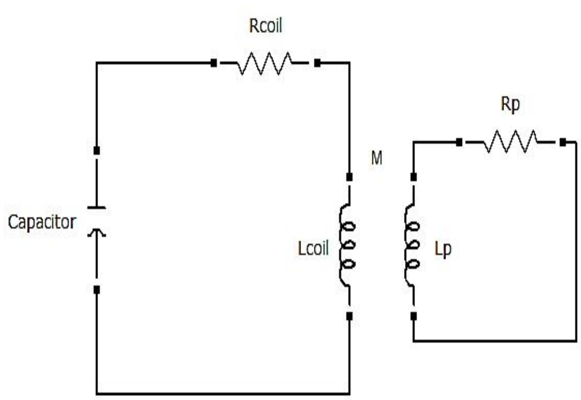

Fig.4. Equivalent circuit of the Catapult Coil

The Mutual inductance of the Catapult coil with respect to projectile position is calculated by

$$M = \frac{\mu\pi N_c N_2 D_O^4}{\sqrt{4D_O^2 x + x^3}} \tag{4}$$

Where

N_x= No. of turns ,x=Position of the projectile

B. Electrical Equivalent Circuit of Acceleration Coil

The equivalent circuit of the octapole accelerating coil is shown in Fig. 5. The parameters are derived from the dimensions of the single octopole coil rectangular in shape and projectile structures.The overall equivalent circuit representation of the launcher is presented in Fig. 6.

The resistance of the Acceleration coil is calculated by

$$R_a = \frac{\rho l}{A} \tag{5}$$

The inductance of the Acceleration coil w.r.t. to the position of the projectile is calculated by

$$L_a = \frac{\mu_o \mu_r N_a^2 l d(1+\frac{x}{d})}{g} \tag{6}$$

Where

N_a= No. of turns in the rectangular coil, l= Width of the rectangular coil, x= Position of the projectile,g=Air gap length

The Mutual inductance of the Acceleration coil w.r.t to projectile position is given as

$$M_a = \sqrt{\frac{\mu_o \mu_r N_a^2 l d(1+\frac{x}{d})}{g}\,(4\pi 10^{-3} a \left(\ln (16\frac{a}{c} - 1.75\right)} \tag{7}$$

Where

a= Mean radius of a small division on projectile, c= Width of the small division of projectile

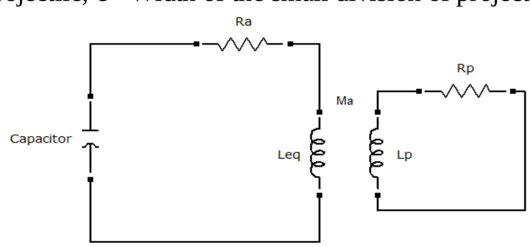

Fig.5. Equivalent circuit of the Acceleration Coil

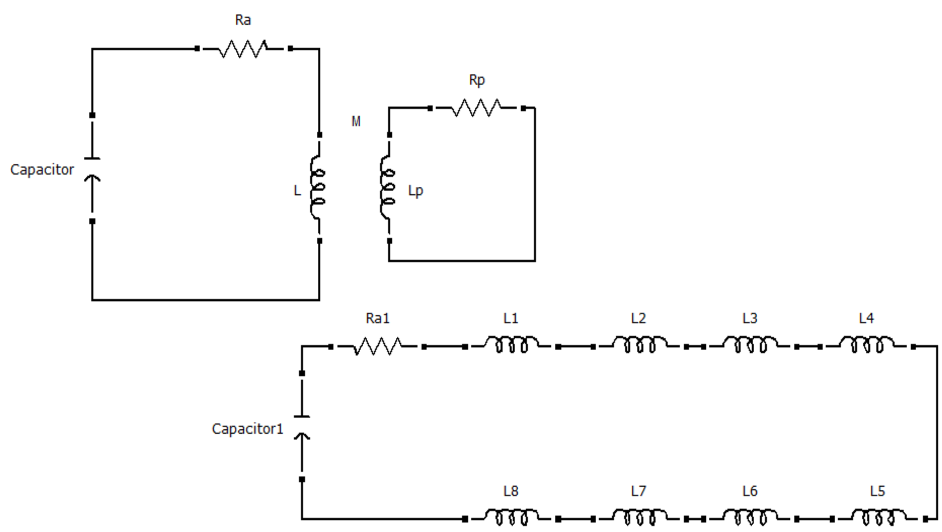

Fig.6. Overall equivalent of the Octapole EML

III. ANALYSIS OF OCTAPOLE ELECTROMAGNETIC LAUNCHER

The performance of any launcher is predicted from its accelerating force acting on the projectile and the final muzzle velocity with which it is propelled. The force generated on the projectile is derived from the electro-mechanical energy conversion principles as,

$$F = i_d^2 \frac{M}{L_p}\frac{dM}{dx} \qquad (8)$$

A physical model of an Octapole EML is developed in MATLAB using the circuit and force equations as shown in figures 7& 8.

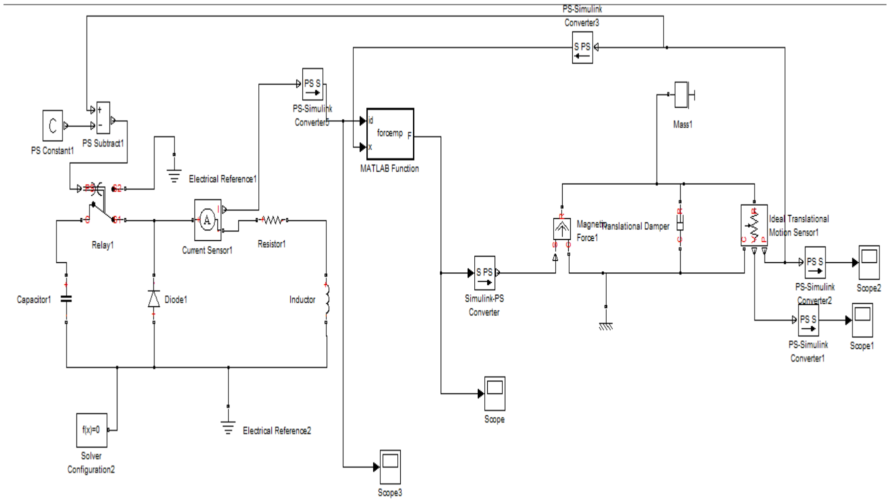

Fig.7. MATLAB model of the Catapult Coil

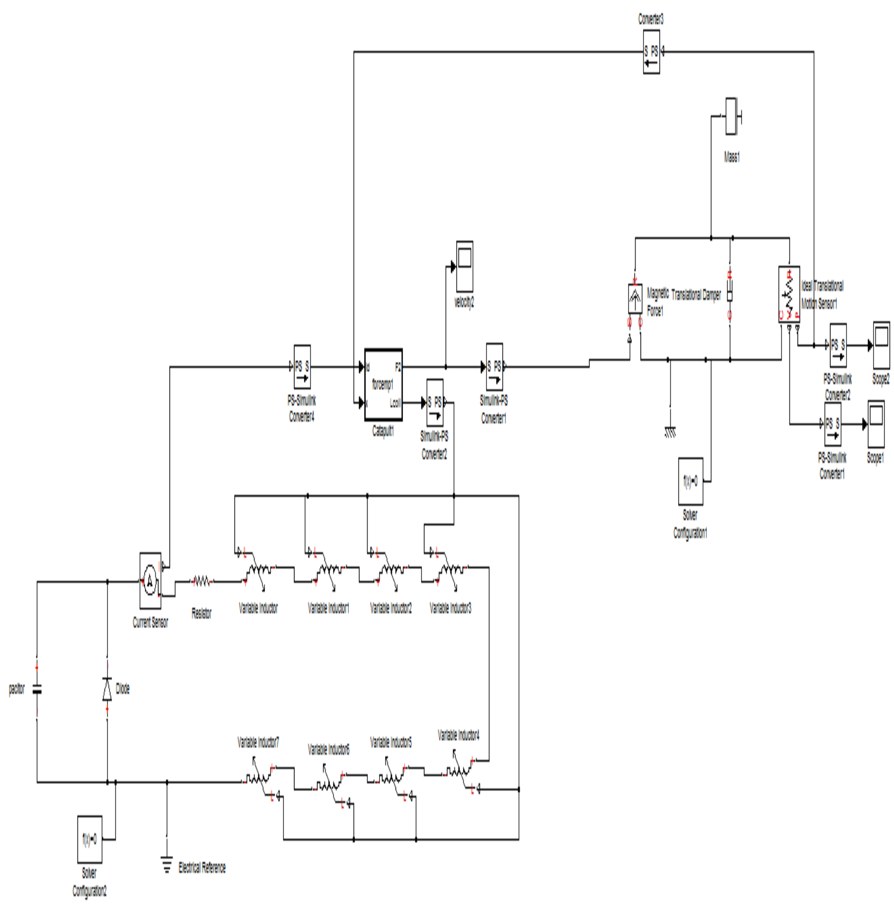

Fig.8. Simulation model of the Octapole Coils

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IV. RESULT ANALYSIS

The single stage model of anoctapole electromagnetic launcher is simulated to analyze itsperformance. Thespecifications to simulate the acceleration coil and catapult coil models shown in Fig. 7 & 8 are

Catapult Coil Material used: Copper Dimension: 2 mm X 16 mm Number of Turns: 30	Induction Acceleration Coil Number of Coils: 8 Material used: Copper Inner Rectangle: 18mm X 18.1 mm Outer Rectangle: 28.4 mm X 28.5 mm Number of Turns: 50	Projectile: Material used: Aluminum Mass: 0.25 kg Inner Radius: 29 mm Outer Radius: 37mm

A capacitor of 200µF is initially charged to a voltage of 40KVfor catapult switching, and a capacitor of 400µF charged with 50 kV for accelerating coil switching. The circuit switches are triggered by the sensor detecting the projectile position. The two coil currents, force acted on the projectile and velocity curves of the launch system are shown in Figures 9,10&11 respectively.

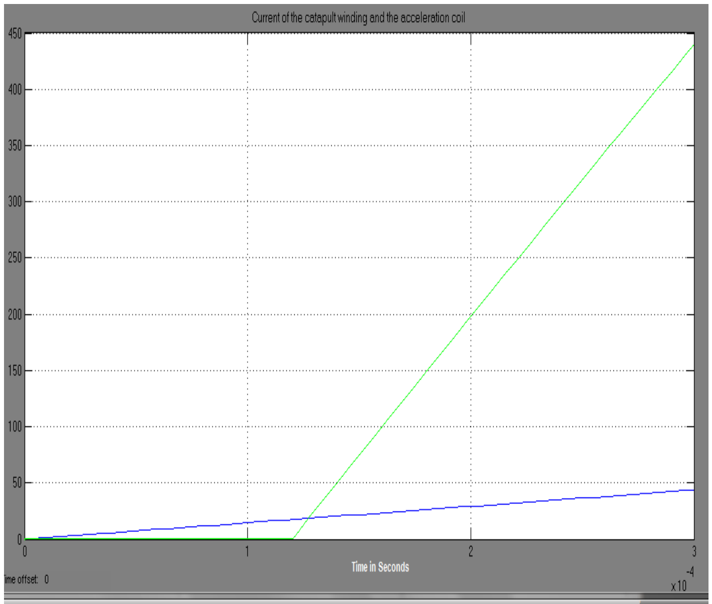

Fig.9. Current of the catapult winding and the acceleration coil

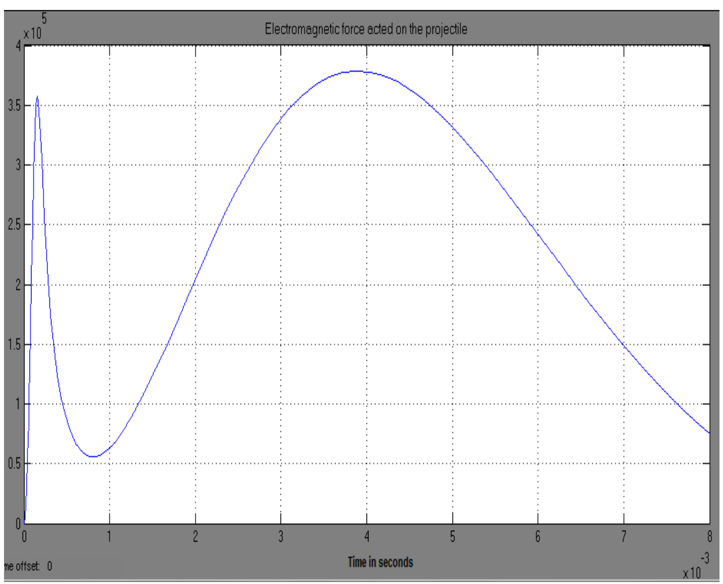

Fig.10. Electromagnetic force acted on the projectile

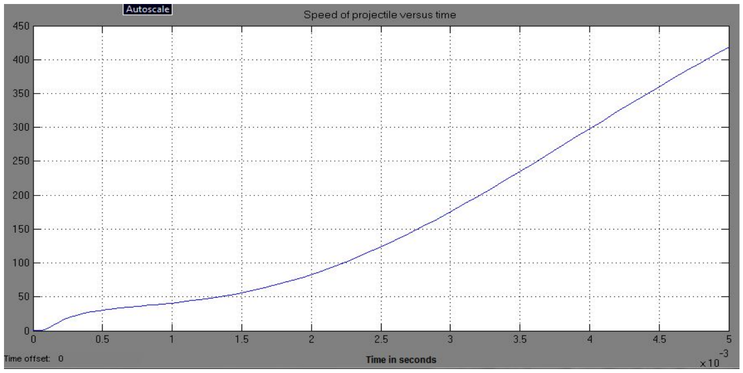

Fig.11. Speed of projectile versus time

The curves in figures 12,13&14 shows the comprehensive analysis in coil currents, force and velocity in the launch system when the catapult coil turns are increased from 30 to 50and accelerating coil turns are changed from 50 to 80. As the turns are incremented the current in the coils decreases as the inductance and resistance of the coils are increasing. Hence the force and velocity on the projectile improves.

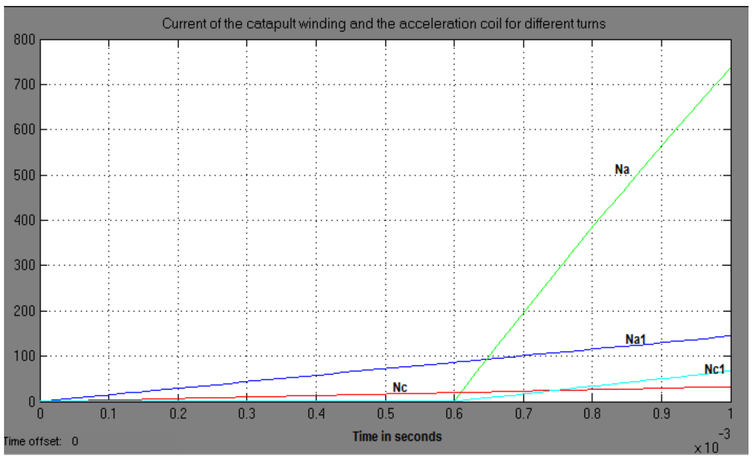

Fig.12. Current of the catapult winding and the acceleration coil with change in turns

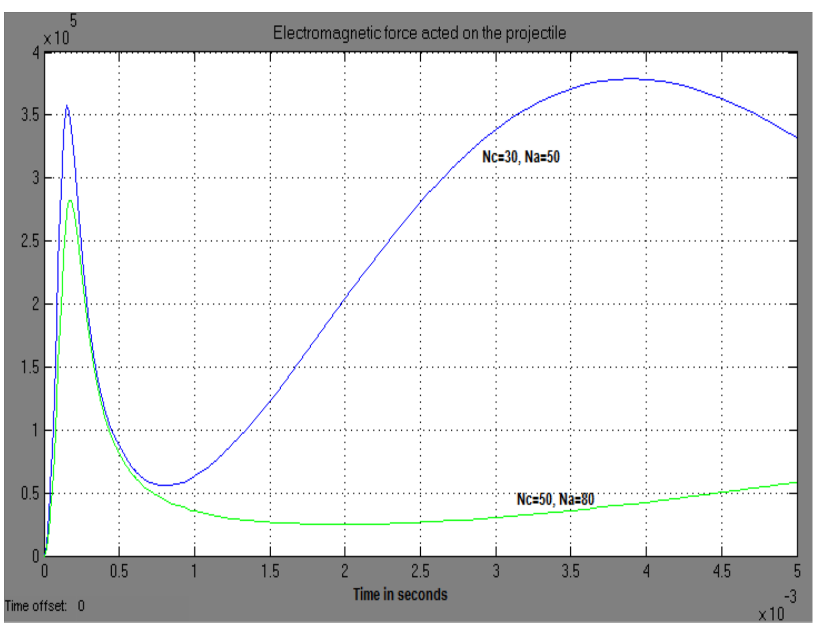

Fig.13. Electromagnetic force acted on the projectile with change in turns

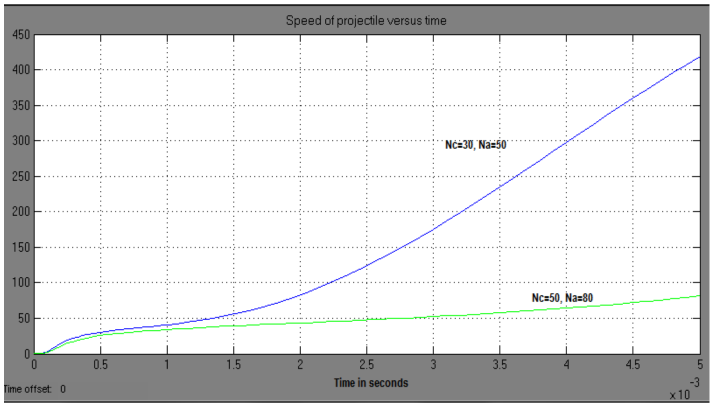

Fig.14. Speed of projectile versus time with change in turns

The power supply to any system will definably play a role in the launcher operation. The performance of the launch system are compared by incrementing the charging voltages of the two capacitors in the system by 10KV as shown in figures 15, 16&17. With the increment in supply voltages, the current supplied to the coils increases, resulting in an improved force and velocity.

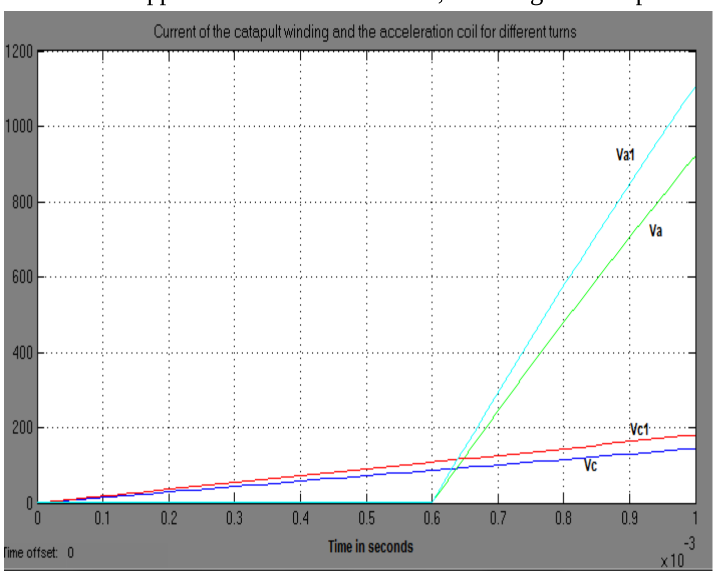

Fig.15. Current of the catapult winding and the acceleration coil with improved system voltages.

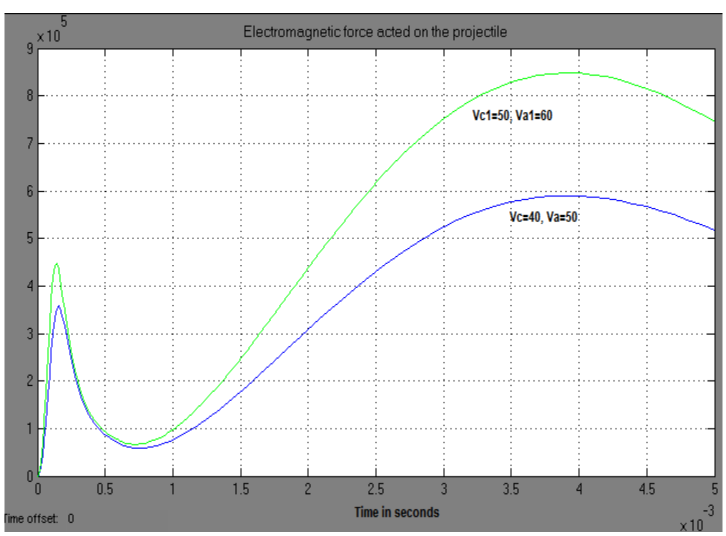

Fig.16. Electromagnetic force acted on the projectile with improved system voltages.

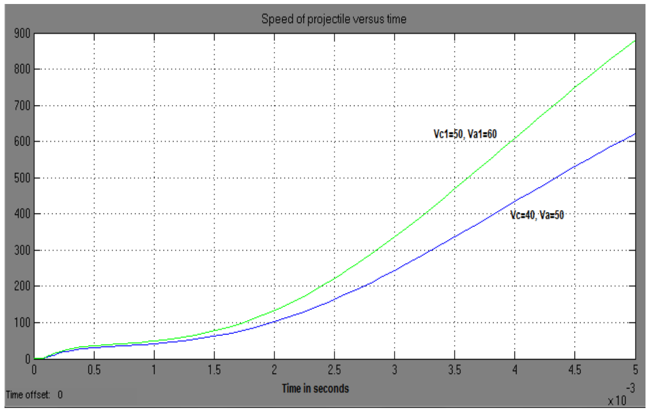

Fig.17. Speed of projectile versus time with improved system voltages.

The magnetic flux density and current density plots in the energized octapole coil when the projectile in the center of the accelerating coils are shown in figures 18 &19.

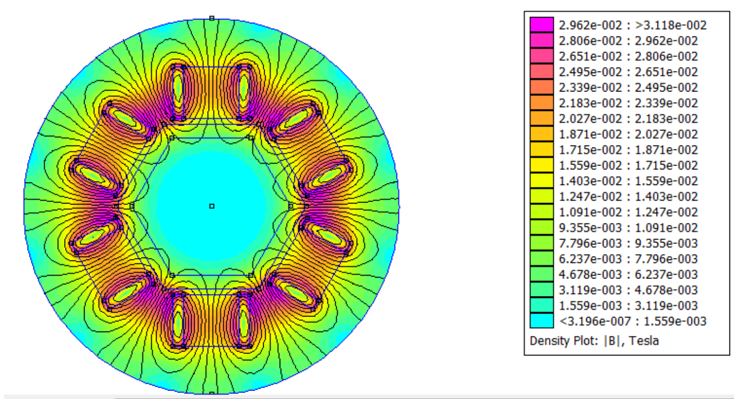

Fig.18. Magnetic Flux Density of Octapole configuration

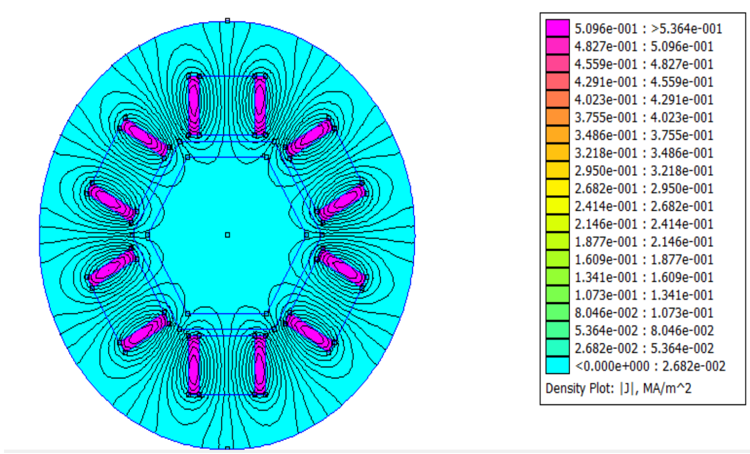

Fig.19. Current Density of Octapole configuration

V. CONCLUSION

This article presents a comprehensive analysis of an Octapole Electromagnetic Launcher. The detailed electrical equivalent circuit representation of the coils, their circuit parameters and dynamic equations of the launch system are derived. In this article, the acceleration coil circuit and catapult circuits are analyzed separately. The expressions for mutual inductance and inductance of the octapole coil with respect to the position of the projectile are developed. Analysis of electromagnetic accelerating force and velocity are carried out for different configuration parameters.

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