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Single-Stage Reluctance Type Coilgun

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Abstract: **This paper presents an introduction to design a single-stage reluctance coilgun. An equivalent circuit for coilgun is analyzed and equation for current through the coil is derived. Main components while designing the coilgun selection like capacitor, IGBTs, projectile for coil design are discussed in detail and their effect on performance of the coilgun is studied. The circuit is designed for measuring speed of the projectile using IR based sensors.**

Keywords: **Coilgun, electromagnet, muzzle speed, solenoid, suckback.**

I. INTRODUCTION

Coilgun is an electromagnetic projectile launching system. Electromagnetic launching (EML) system is advantageous over existing chemical launch system [1]; it's a fuel-free launching technology. EM launchers are eco-friendly and can have easily adjustable range by controlling the muzzle velocity through electrical current. It has higher repetition rate, it's smoke-free, silent and has low frictional losses. EMLs are mainly constructed as railguns or coilguns [2]. They both differ from conventional weapons; they use electromagnetism to propel the projectile rather than using an explosive charge.

A coilgun is a type of projectile accelerator having one or more coils which when energized behave as electromagnets in the configuration of a linear motor that accelerate a ferromagnetic or conducting projectile to high velocity.

Construction of coilgun is simple but it is conceptually complex to analyse. Coilgun is mainly divided into two categories:

1. Induction type coilgun.
2. Reluctance Type coilgun

In induction type coilgun, the projectile is repelled out of the coil through the action of eddy currents induced in the projectile. The projectile must be non-ferromagnetic in nature. The force experienced by the projectile depends on mutual inductance and magnetic diffusion processes.

While in reluctance coilgun a ferromagnetic projectile is placed near the coil and then coil is magnetized by carefully timing the coil current. Attractive forces pull the projectile towards it and hence projectile is accelerated. Both are similar in terms of their general construction.

Though the practical usage of coilgun is not given much consideration till now, but its potential future applications can be very attractive. The potential applications of this concept can range from firing a bullet to launching big space payloads. Hence it is gradually becoming more popular and various studies are being carried out in this field. In this paper the focus will remain on single-stage reluctance type coilgun.

II. COILGUN THEORY

The coilgun works on the simple principle of electromagnetism. In coilgun a quick current pulse is to be provided. In a reluctance type coilgun current pulse is passed through a solenoid which then magnetizes and creates a magnetic field. This field attracts magnetically active (material with positive susceptibility) projectiles with high velocity and thus they get accelerated along the axis of the solenoid (coil). The current through the coil should be quenched before the projectile reaches its center otherwise the coil tries to draw the projectile in opposite direction; this phenomenon is called suckback effect.

This suckback action exerts force to pull the projectile back into the coil and decreases the speed. But if the current pulse is too short it will affect the efficiency of the system. Therefore, timing the current pulse is critical for the performance of the coilgun. Single stage coilgun launching system is shown in Fig.1. In reluctance coilgun dc voltage supply is needed in order to charge the capacitor bank. This can easily be done using a dc voltage supply or a battery, but to obtain high voltage Switched Mode Power Supply (SMPS) is used.

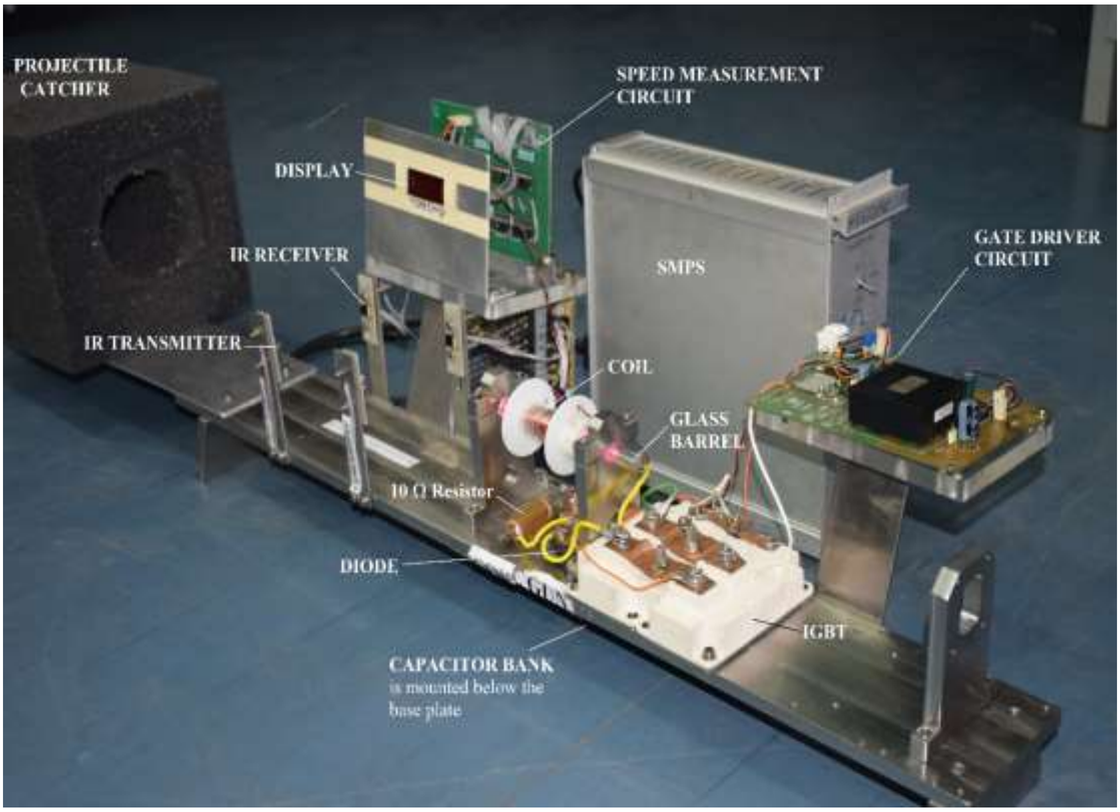

Figure 1: Single stage coilgun

After charging the capacitor it is then discharged across the coil using a fast response high rating power switch. When current flows through the coil it becomes an electromagnet and draws the projectile which is kept little off from the center of the coil along its axis. The current carrying coil pulls the projectile with a high speed such that it accelerates further into the coil due to initial inertia.

III. DESIGN PARAMETERS

1. Capacitor Bank:

A bank of electrolytic capacitor is needed in order to charge. Here batteries are not used because the internal resistance of a battery is much higher than a capacitor. It takes much longer time to get the same amount of energy from a battery, and the timing is very important. In fact, using a different combination of capacitors can give the exact control needed over this delicate issue. Capacitor should have low ESR and high voltage rating. Here a bank of ten capacitors of 470 µF are connected in parallel.

2. Coil:

Experimental results show that for getting satisfactory speed, the ratio of coil to projectile length should lie in the range 0.1 to 0.7 [4]. The coil should have low resistance so that higher current can be drawn therefore the coil is designed using 18 SWG Cu wire. The design of the coil used is shown in Fig.2.

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Resistance = 14 milleΩ /m
Total number of turns = 74Turns

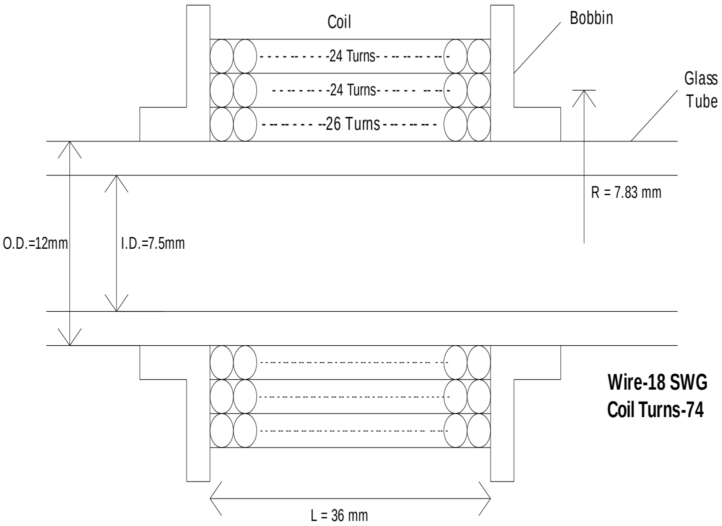

Figure 2: Coil layout

More the number of turns higher will be the magnetic field but the resistance also increases. Fig. 2 shows the design layout of the coil.

The inductance of the air-cored coil can be calculated theoretically using the formula mentioned below.

$$L = \frac{31.6\, r_1{}^2 N^2}{6r_1 + 9\, l + 10\, (r_2 - r_1)}$$

3. *Projectile:*

Material should be ferromagnetic and electrically non-conductive in nature. Mild Steel is selected having relative permeability, μ_r = 200-5000. The diameter of projectile is decided according to barrel's inner diameter such that air gap between projectile and barrel is minimum i.e. it should be a snug fit.

4. *Switch:*

The switch should be selected such that it is capable of withstanding high values of peak currents also switching should be faster. IGBT switch meets both the criteria. This device offers the ease of control of the MOSFET with the higher current capacity of the bipolar transistor. The IGBT does require a slightly higher gate voltage to ensure that it is fully turned on. Here BSM400GA120DLC IGBT is used having Voltage rating of 1200 V and peak current rating of 400 A.

IV. CIRCUIT ANALYSIS

The coilgun can be represented by a simple RLC circuit. First an electrolytic capacitor is charged with a dc supply when switch S1 is closed. As the capacitor is fully charged the switch 1 is turned off and switch S2 is closed and capacitor discharges through the coil. The selection of capacitor and coil is of utmost importance. As the current pulse has to be discharged quickly, the time constant becomes a crucial factor therefore the parameter values are chosen with great care. The equivalent circuit of coilgun is shown in Fig.3.

Where, R_c = External Resistance (Ω)
V_{dc} = DC supply voltage
C = Charging capacitance (F)
L = Coil Inductance (H)
R_{coil}= Coil Resistance (Ω)

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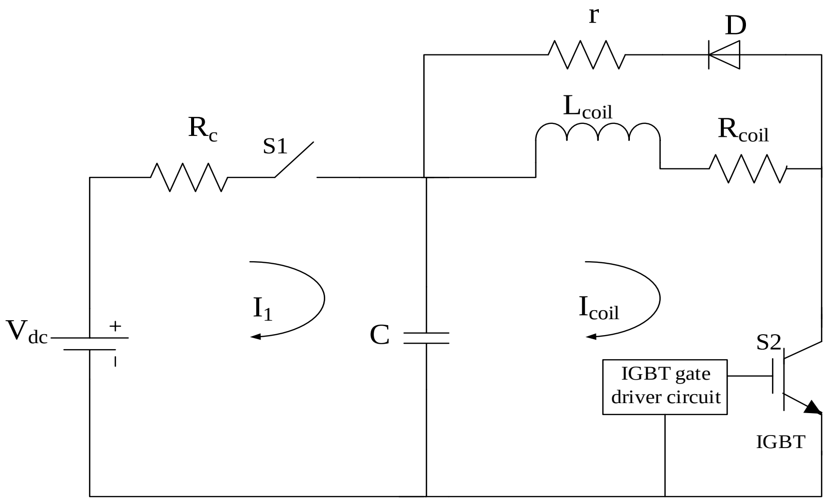

Figure 2: Equivalent coilgun circuit

1. Charging of capacitor (S1 is closed)

$$I_1(S) = \frac{V_{dc}}{S(1+\frac{1}{CS})}$$

Therefore, $$i_1(t) = \frac{V_{dc}}{R} e^{\frac{-T}{R_c C}}$$

Voltage across capacitor will be given by

$$V_c = \frac{1}{C}\int_0^t i_1(t)dt$$

$$= \frac{1}{C}\int_0^t \frac{V_{dc}}{R} e^{\frac{-t}{R_c C}} dt$$

$$V_c = V_{dc}\left[1 - e^{\frac{-t}{R_c C}}\right]$$

2. Discharging of capacitor (S2 is closed)

$$I_{coil}(S) = \frac{V_{dc}/S}{\frac{1}{CS} + R_{loop} + LS}$$

$$I_{coil}(S) = \frac{V_{dc}}{L\,(S^2 + \frac{R_{loop}}{L}S + \frac{1}{LC})}$$

Comparing above equation with the standard second-order equation

$$Y(s) = \frac{k}{S^2 + 2\xi\omega_o S + {\omega_o}^2}$$

We get, natural frequency = $\omega_o = \frac{1}{\sqrt{LC}}$

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Damping ratio = $\xi = \frac{R_{coil}}{2}\sqrt{\frac{C}{L}}$

Now depending on the value of ratio, the response can be critical, under or over damped. Critical damping shows the fastest response. Though the peak is highest in case of under-damping, but resonance generates waves of opposite polarity. These waves could damage both triggering semiconductor and capacitors. Peaks of opposite voltage can be eliminated using anti-parallel diode in parallel to the coil, as shown in Fig. 3.

V. SPEED MEASUREMENT OF MOVING PROJECTILE

Determining the muzzle speed can be challenging. Speed measurement of the moving projectile can be done mainly by two methods.

1. Parabolic method (kinematic method)
2. Light gate method

The parabolic method and light gate method for velocity measurement is discussed in detail. Parabolic method is basic kinematics calculations but there can be errors of approximately 15% or more. The validity of this method diminishes as the target range increases. With light gate method using IR sensors and electronic circuit higher accuracy can be obtained.

The Fig.4 shows the block representation of speed measurement circuit using Light-gate method. In this assembly two pairs of optical transmitter and receiver are mounted on a frame such that they are aligned in parallel 10 cm apart. When bullet interrupts the first pair the timing pulse starts and ends when bullet passes through the second pair. The time to travel 10 cm for a projectile can be determined and thus speed can be calculated.

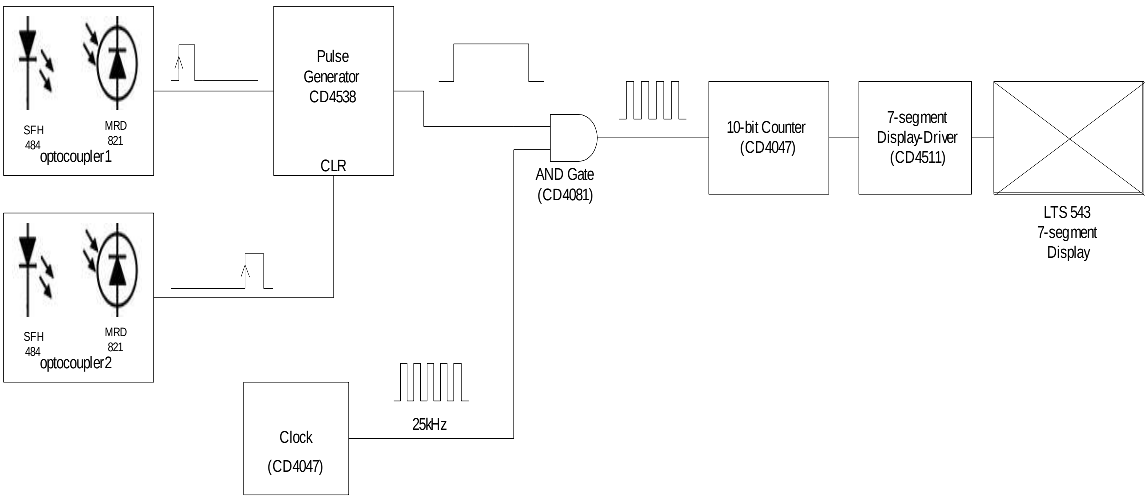

Figure 3: Block representation of speed measurement circuit

The display records the time (millisecond) taken for the projectile to travel between the pair of opto-couplers. The speed can therefore be easily calculated. This circuit estimates the speed lower than the actual muzzle speed.

VI. CONCLUSION

This paper shows design and development of single-stage reluctance type coilgun. The parameters and considerations while designing a reluctance coilgun are also discussed. Also, Light-gate method for obtaining the speed of the moving projectile is explained.

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