Advances in Science and Technology Research Journal

Advances in Science and Technology Research Journal, 2025, 19(4), 32–41
https://doi.org/10.12913/22998624/199736
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Received: 2024.11.01
Accepted: 2025.01.14
Published: 2025.02.19

A comparative study of power circuit topologies for two-wing armature electromagnetic launcher

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ABSTRACT

This study investigates the performance characteristics of a Two-Wing Armature Electromagnetic Launcher under various power circuit configurations. The TWAEL model able to enhances magnetic flux density, a maximum of 2.3383 T, significantly outperforming traditional quadrupole railguns. This increased magnetic flux density contributes to superior acceleration and velocity capabilities. The study reveals that the SCR-controlled inductive energy storage circuit offers over 100 times the force output compared to a switched RC circuit, highlighting its potential for optimizing projectile performance. The paper provides critical insights for different power circuit configuration for electromagnetic launchers. The findings emphasize the integration of power circuit designs to enhance the efficiency, acceleration, and overall effectiveness of electromagnetic propulsion systems. This work lays the groundwork for future advancements in electromagnetic launcher technology, aiming to improve military, aerospace, and industrial applications.

Keywords: electromagnetic launcher, power circuits, performance metrics, magnetic field strength, efficiency.

INTRODUCTION

Ongoing research and development are essential for advancing launch systems. Academic and industrial organizations are continously working to enhance the lethality, precision, and reliability of existing weapons. Concurrently, various entities explore innovative launch technologies that could potentially resolve diverse challenges. For certain applications and achieving previously unattainable objectives, electromagnetic propulsion offers a viable alternative to traditional chemical-based propulsion [1, 2]. Compared to traditional electromagnetic launchers such as railguns and coilguns, the reconnection electromagnetic launcher offers distinct advantages [3]. Railguns suffer from low launch efficiency due to armature contact rail ablation, while coilguns generate a high axial acceleration force that results in a small radial electromagnetic force, leading to significant ohmic losses and limiting their high-velocity launch capabilities [4]. The multi-wing reconnection electromagnetic launcher is a modified variation of the plate reconnection device, sharing analogous operating principles. This induction launcher showcases a contactless solid armature with either flat-plate or cylindrical geometry. Theoretical and experimental investigations have demonstrated that this launcher configuration can achieve high launch velocities with lower power requirements compared to conventional electromagnetic launchers [5]. The reconnection electromagnetic launcher overcomes many limitations of traditional railguns and coilguns, as it employs a contactless solid armature that undergoes low ohmic heating and experiences minimal erosion [6] during high-velocity launches [7, 8]. However, the performance of this launcher is highly dependent on the design and optimization of the power circuit configuration.

Experiments with three multistage reconnection electromagnetic launchers have demonstrated the acceleration of spin-stabilized projectiles to muzzle velocities reaching 1 km/s and 335 m/s. R. J. Kaye et al. presented test results showing a 5 kg projectile being accelerated from 12 m/s to 335 m/s, which convincingly proves the ability of the reconnection launcher to achieve high projectile velocities [9] with reasonably low power requirements [7]. Three-stage reconnection electromagnetic launcher [10] that utilized flat-plate projectiles. Their research explored the velocity and efficiency characteristics of various plate designs, including hollow, solid, and gridded configurations. The test results demonstrated that solid plate armatures achieved the highest launch velocity, reaching 1 km/s, with an energy efficiency of 15 to 20% in converting the capacitor's stored energy into the projectile's kinetic energy [11, 12]. Guangcheng et al. proposed a three-coil reconnection electromagnetic launcher design [13]. Their analysis and simulations demonstrated that this three-coil model had improved structural integrity and higher launch efficiency compared to the conventional reconnection electromagnetic launcher. A comparative evaluation of the two-stage three-coil and conventional REL models confirmed the conceptual viability of the three-coil design. According to the experimental results, the three-coil REL model outperformed the conventional REL model, achieving efficiencies of 15.818% and 8.248%, respectively, in the comparative assessment. Daldaban and Vekil elaborated on the underlying concept and highlighted the significant impact of the number of drive coil pairs per wing on the launch performance [14]. Their study revealed that utilizing a single coil pair per wing resulted in a projectile exit velocity of 474 m/s and an efficiency of 15.10%.

In contrast, a two-coil-pair-per-wing configuration yielded a projectile exit velocity of 627 m/s with an efficiency of 21.83%, showcasing the substantial performance enhancement achieved by increasing the number of coil pairs per wing in the two-wing armature electromagnetic launcher [15]. Electromagnetic reconnection launchers leverage magnetic reconnection to accelerate projectiles, offering potential applications in military, aerospace, and transportation sectors. Research on reconnection electromagnetic launchers focuses on optimizing projectile acceleration and control, achieving high launch velocities, developing compact and portable systems, managing thermal effects, and improving overall design efficiency to minimize energy losses [16]. Key areas of optimization include novel coil configurations, advanced materials, and enhanced power supply and control systems. Precise magnetic field control and power supply timing are critical for projectile acceleration and control. High-velocity launch requires increasing projectile speed while maintaining precision and minimizing energy losses. Developing compact and easily deployable reconnection electromagnetic launchers is an active research focus. Thermal management strategies are essential to protect the launcher and projectile during launch [14]. While significant advancements in reconnection electromagnetic launcher technology have been made, numerous challenges remain. Transitioning this technology from laboratories to real-world engineering applications and potential civilian use is an ongoing research endeavor. Zhu et al. introduced octupole electromagnetic launching system, which is considered as the novel model in the launching systems [17]. The modelling results prove that the electromagnetic launcher with a magnetic multipole field possesses a strong acceleration force and a fast muzzle speed. A double-armature MFEL with one armature coaxial with the drive coil inside and the second armature with the drive coil outside was suggested [18].

The double-armature configuration achieved muzzle velocities comparable to the single-armature design. However, the double-armature system demonstrated higher energy conversion efficiency, as shown by simulation and experimental data. The proposed enhanced launch mode is the multistage twisted multipole electromagnetic launcher [18, 19]. They proposed a design with a three-stage twisty octupole field and analyzed the motion dynamics and electromagnetic force. The simulation results indicate that the magnetic torque of the rotational motion is impressively large, and the transverse displacement of the projectile is significantly reduced, demonstrating the advantages of the multistage twisty multipole electromagnetic launcher over conventional designs. The modeling results show the projectile's transverse displacement is small, and the magnetic torque of rotational motion is large. The torsional aspect does not greatly affect the axial acceleration force and exit velocity of the multistage pole coils. This suggests the armature accelerates by revolving around the axis [20]. The researchers also propose a promising launch mechanism for an evacuated tube vehicle.

The thorough investigation of eddy currents in the launcher, as presented in [21–23], adds weight to the idea that the Multipole field launching concept is intriguing and relevant. Furthermore, the research on various aspects of MFEL investigations, such as flux distribution, coil twisting, alternative armature shapes, and optimal design, using diverse methods, is valuable in providing greater insights into the potential of MFEL. Quadrupole fields are investigated in [24, 25]. A quadrupole magnetic field reluctance-based launcher with different coil switching patterns is analyzed. The design and simulation of quadrupole electromagnetic linear systems for precise positioning in aerospace applications are also studied [26]. Specific applications like aircraft catapult systems and hyperloop transportation are also included in the research [27]. A novel multi-stage outrunner electromagnetic launching configuration for aircraft catapults is proposed [28], and the design of a multi-stage dodecapole electrical propelling system for hyperloop systems is discussed. In, a quadrupole magnetic field reluctance-based launcher design is introduced, which can generate 1 kN force. The research on various aspects of MFEL investigations, such as flux distribution, coil twisting, alternative armature shapes, and optimal design, using diverse methods, is valuable in providing greater insights into the potential of MFEL.

The paper presents a comprehensive investigation into the performance characteristics of a two-wing armature electromagnetic launcher under the influence of various power circuit configurations. By systematically analysing the impact of different circuit topologies such as switched RC circuit with a diode clamping circuit and an SCR-controlled IEL power circuit. This study combines simulation results and theoretical insights to offer a comprehensive perspective on the power circuit effects and guide the development of high-performance electromagnetic launchers.

TWO-WING ARMATURE ELECTROMAGNETIC LAUNCHERS: DESIGN AND PERFORMANCE ANALYSIS INTRODUCTION

The two-wing armature electromagnetic launcher (TWAEL) has a stationary core with embedded coils and a movable armature. The armature's design resembles a quadrupole railgun, featuring a four-rail configuration that enables efficient electromagnetic acceleration. To minimize magnetic interference, the armature shape is modified into a two-wing structure, as shown in Figure 1. The powerful pulsed magnetic field from the core coils interacts with the current induced in the armature, generating substantial thrust to accelerate the projectile to high velocities.

In contrast, the quadrupole railgun (QRL) utilizes a four-rail design, which generates a more uniform magnetic field distribution. The symmetrical current flow within the armature enables more efficient conversion of electromagnetic energy into propulsive force. Applying a 500V DC supply to the coils creates a strong pulsed magnetic field, inducing eddy currents in the conductive armature. The self-induced magnetic fields in the armature counteract the external magnetic field that initially generated the eddy currents, producing the desired Lorentz force to accelerate the projectile. The overall 3D model of the two-wing armature electromagnetic launcher, depicted in Figure 2. The Lorentz force equation is:

$$F = q(v \times B) \quad (1)$$

where: F is the force, q is the charge, B is the magnetic field, and v is the velocity.

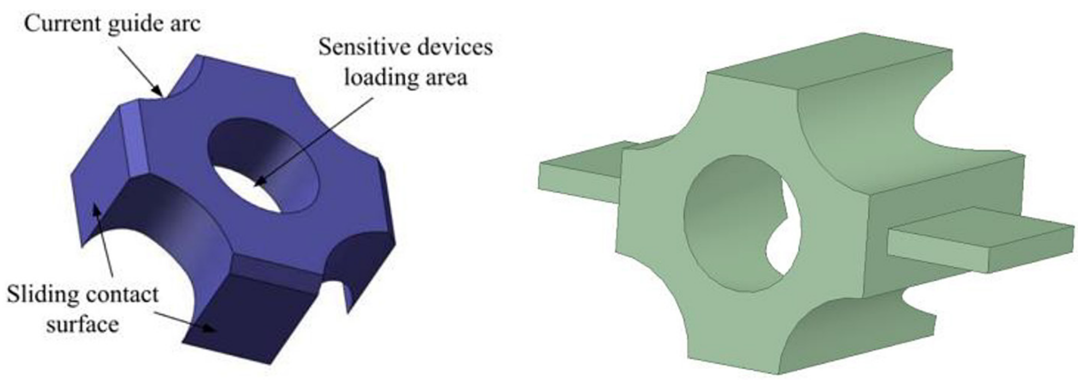

Figure 1. (a) Armature model mentioned in (Yang et al., 2017), (b) proposed armature model

This expression describes the relationship between the key factors governing electromagnetic acceleration in the two-wing armature electromagnetic launcher.

Analysing the magnetic flux density and intensity is crucial for enhancing the performance of the electromagnetic launcher. Elevating the flux density in specific regions of the device can generate greater thrust, which is essential for achieving higher projectile velocities. Conversely, reducing flux leakage can improve the overall energy efficiency of the system, minimizing power losses and enhancing the utilization of the available electromagnetic energy. Understanding these fundamental magnetic properties helps in selecting a suitable materials. In essence, a comprehensive analysis of the magnetic characteristics is a vital step in facilitating the design, optimization, and accurate prediction of the performance of electromagnetically-driven devices.

The two-wing armature electromagnetic launcher can generate a maximum magnetic flux density of 2.3383 T, as shown in Figure 3, which is over 23 times higher than the 0.10095 T achievable by the quadrupole railgun under the same current conditions. This substantial increase in magnetic flux density provides the TWAEL with a significant advantage in generating greater Lorentz forces to accelerate the armature and projectile.

The two-wing armature electromagnetic launcher has a lower maximum current density of

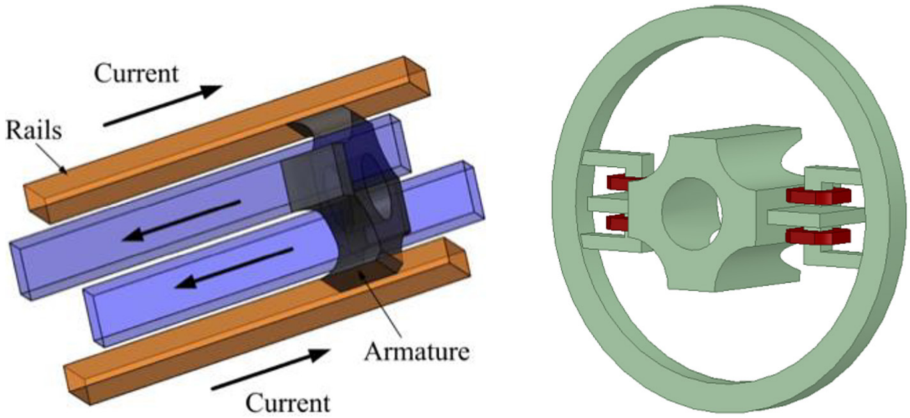

Figure 2. (a) Overall model of QRL (b) proposed TWAEL model

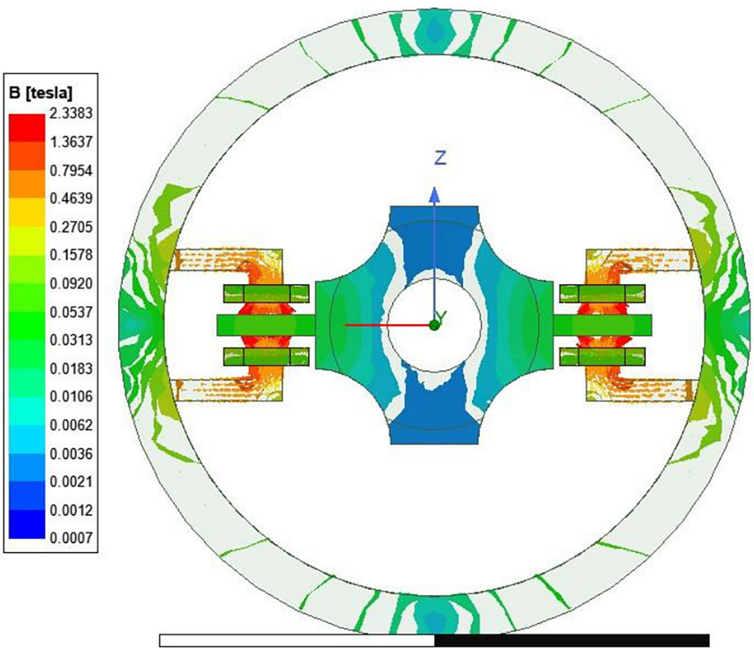

Figure 3. Magnitude of magnetic density in TWAEL

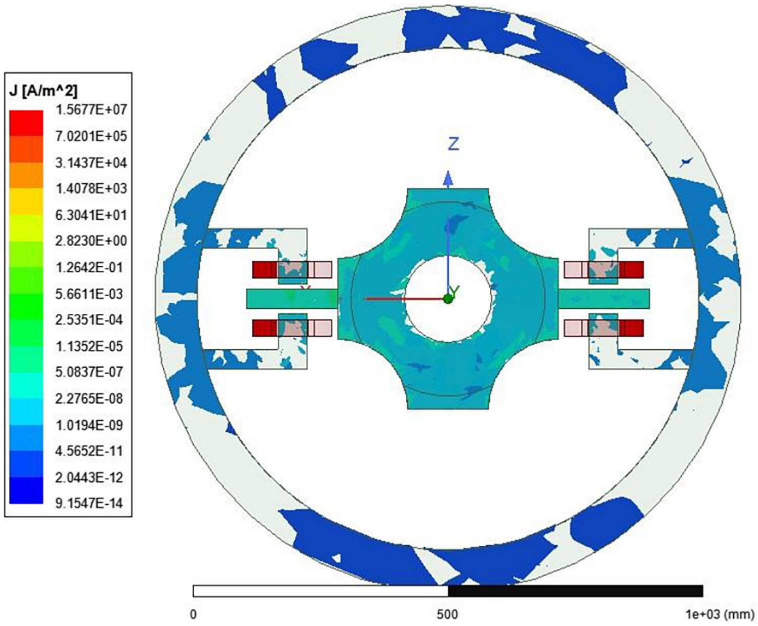

Figure 4. Current density in TWAEL

1.5677×10^7 A/m², as shown in Figure 4, compared to 9.9828×10^7 A/m² for the quadrupole railgun. This lower current density in the TWAEL allows for more efficient conversion of electrical energy into mechanical energy, leading to greater accelerative forces on the projectile.

To observe the flux lines in the IEL, a 2D model is developed using FEMM freeware [26]. Figure 5 presents the FEMM software's evaluation report, which provides detailed insights into the magnetic flux behaviour within the two-wing armature electromagnetic launcher. The report reveals ten distinct flux tubes flowing from the coils

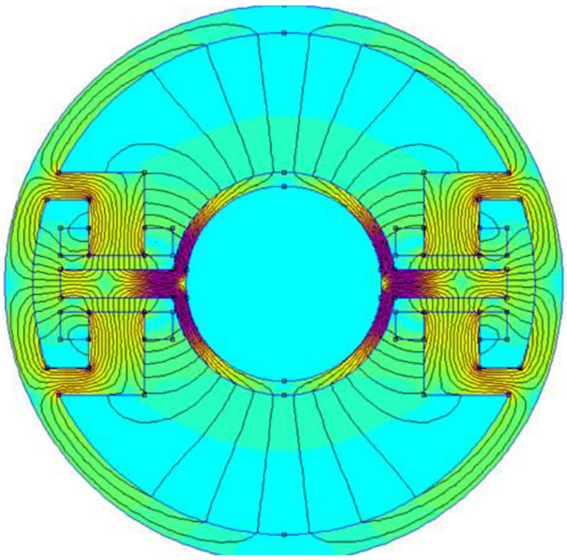

Figure 5. Flux line distribution

to the coils, traversing through the air gap, armature, and yoke components of the device. Using flux tube dimensions, the reluctance of the flux path 1 is derived and presented in Equation 2 to Equation 7.

$$\mathcal{R}_{coil} = \frac{5l_{coil}}{\mu_0\mu_r(h_{coil}-t_{coil})w_{coil}} \tag{2}$$

$$\mathcal{R}_{airgap1} = \frac{5l_{airgap}}{\mu_0\mu_r(h_{airgap}-t_{airgap})w_{airgap}} \tag{3}$$

$$\mathcal{R}_{armature} = \\ = \frac{\frac{\pi}{2}\sqrt{\frac{\left(\frac{l_a-t_{coil}}{10}+\frac{l_a}{2}-\frac{l_a-t_{coil}}{5}\right)^2+\left(\frac{h_p}{2}\right)^2}{2}}}{\mu_0\mu_r\frac{l_a h_p w_p}{2\sqrt{\frac{\left(\frac{l_a}{2}\right)^2+\left(\frac{h_p}{2}\right)^2}{2}}}-\frac{\left(\frac{4}{5}h_p\frac{l_a}{2}-\left(\frac{l_a}{2}-\frac{l_a-t_{coil}}{5}\right)\right)w_a}{\sqrt{\frac{\left(\frac{2h_p}{5}\right)^2+\left(\frac{l_a}{2}-\frac{l_a-t_{coil}}{5}\right)^2}{2}}}} \tag{4}$$

$$\mathcal{R}_{airgap2} = \frac{3}{\mu_0\mu_r l_p w_a} \tag{5}$$

$$\mathcal{R}_{yoke} = \frac{l_{coil}+l_g+\frac{l_a}{2}}{\mu_0\mu_r\frac{h_{yoke}}{5}w_{yoke}} \tag{6}$$

$$\mathcal{R}_{yoke_{shoe}} = \\ = \frac{\frac{\pi}{2}\sqrt{\frac{\left(l_{coil}+l_g+\frac{l_a}{2}\right)^2+\left(\frac{l_a}{2}\right)^2}{2}}}{\mu_0\mu_r\frac{l_a h_p w_p}{2\sqrt{\frac{\left(\frac{l_a}{2}\right)^2+\left(\frac{h_p}{2}\right)^2}{2}}}-\frac{\left(\frac{4}{5}h_p\frac{l_a}{2}-\left(\frac{l_a}{2}-\frac{l_a-t_{coil}}{5}\right)\right)w_a}{\sqrt{\frac{\left(\frac{2h_p}{5}\right)^2+\left(\frac{l_a}{2}-\frac{l_a-t_{coil}}{5}\right)^2}{2}}}} \tag{7}$$

Table 1. Circuit parameters of switched RC circuit

Parameter	Model in [31]	Model in [32]	QMFRL (proposed model)
Maximum flux density	0.1663 Tesla	0.00072 Tesla	2.331 Tesla
Current density	9.98*10^7 A/m^2	3.64*10^9 A/m^2	1.56*10^7 A/m^2

SIMULATION MODELS

Using ANSYS Simplorer, the a comprehensive mathematical model of the two-wing armature electromagnetic launcher is developed. In this paper, two different power circuits are used. One is switched RC circuit with diode clamping and other one is SCR controlled IEL power circuit.

Switched RC circuit with diode clamping

The switched RC circuit with diode clamping depicted in Figure 6 is connected to the mathematical model of the electromagnetic launcher. To analyze the variation in output force, a simulation is conducted for a voltage range from 100 V to 500 V. The following circuit parameters are considered for the simulation: controlled switch 1 is driven by a gate pulse generator with a duty cycle of 0.1, a time period of 50 ms, and a delay time of 1 ms. Controlled switch 2 is driven by a gate pulse generator with a duty cycle of 0.1, a time period of 50 ms, and a delay time of 3 ms. To investigate the force-velocity behavior of the model, the force terminals are connected to a linear translational force source. This force source is externally excited, meaning it receives an external stimulus that generates a force. The force source is coupled to a translational mass of 0.5 kg and a translational damping of 100 millimeter-Newton-seconds per meter. This setup allows in understanding the relationship between the force generated by the electromagnetic launcher and the resulting velocity of the system. The resulting force and velocity characteristics are depicted in Figure 7 and 8. The simulation results demonstrate a force of 156 N and a velocity of 2 m/s for the 500 V input voltage. The force magnitude is adequate to accelerate the projectile to a speed of 2 m/s. The ability to generate significant force while maintaining a relatively low current density highlights power delivery of TWAEL compared to traditional railgun configurations.

SCR controlled IEL power circuit

The switched RC circuit with diode clamping faces practical challenges. Diodes have a forward voltage drop that can affect capacitor voltages. Diodes also have a reverse recovery time, causing current spikes and oscillations. Capacitors have leakage current that can discharge the capacitor over time, leading to voltage issues. Resistor tolerances can impact the RC time constants, and power dissipation in resistors can cause heating and potential failure.

Table 2. Circuit parameters of switched RC circuit

Parameter name	Parameter	Values
Resistor	R_1	0.1 ohms
	R_2	100 ohms
	R_3	5 kohms
Capacitor	C_1	0.0004 μF
	C_2	0.1 μF

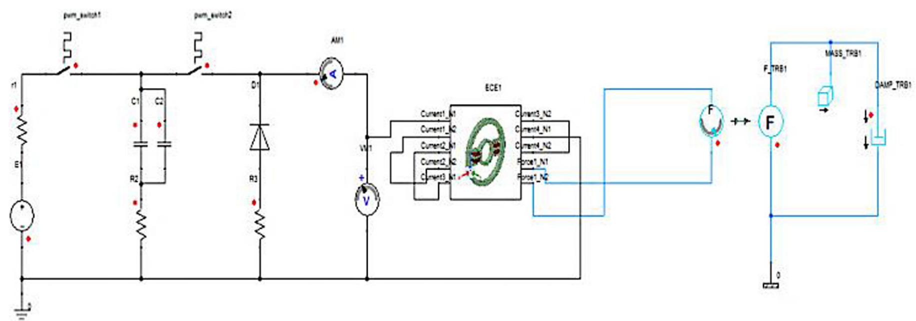

Figure 6. Switched RC circuit with diode clamping

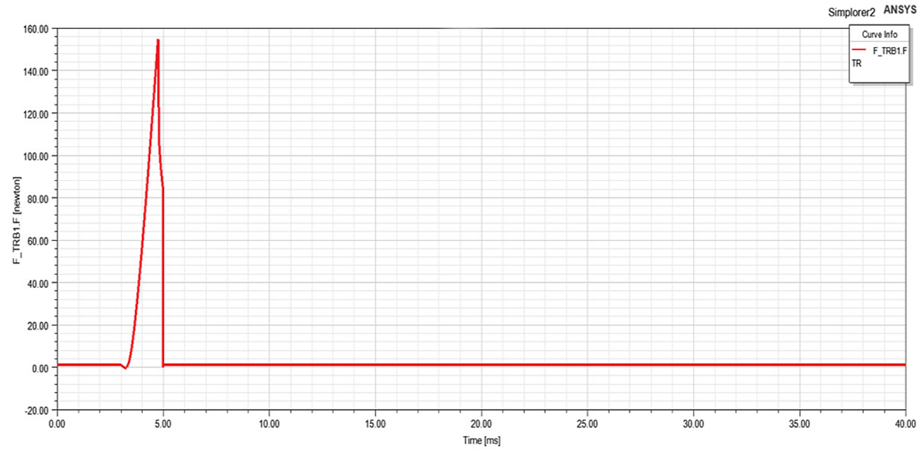

Figure 7. Force characteristics of switched RC circuit

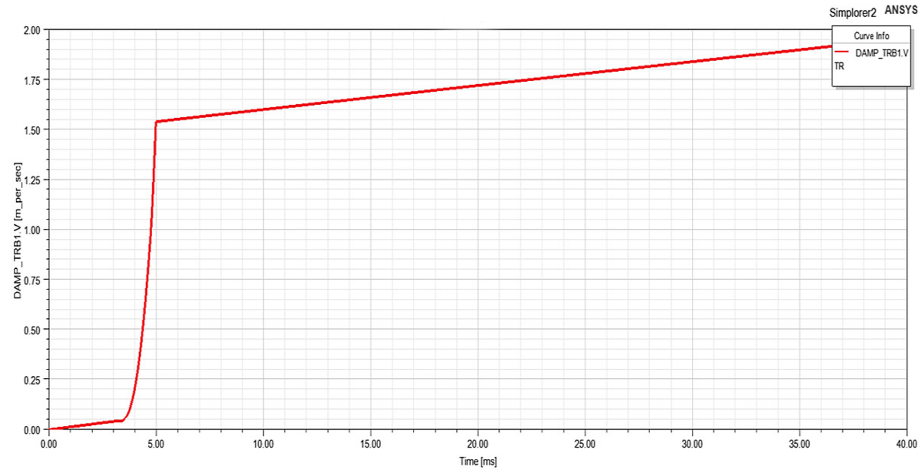

Figure 8. Velocity characteristics of switched RC circuit

To address these limitations, an alternative power circuit configuration, utilizing an SCR-controlled inductive energy storage and launch power circuit. A 230V voltage source is used for the simulation. The circuit parameters include a resistor R_1 with a resistance of 0.1 ohms and a capacitor C_1 with a large capacitance of 270 μF. Additionally, the simulation incorporates an SCR-controlled switch that is driven by a gate pulse generator with a duty cycle of 0.1, a time period of 50 milliseconds, and a delay time of 1 millisecond. This SCR-controlled switch allows for precise control and timing of the power delivery to the electromagnetic launcher. To analyze the force-velocity performance of the model, the force terminals of the electromagnetic

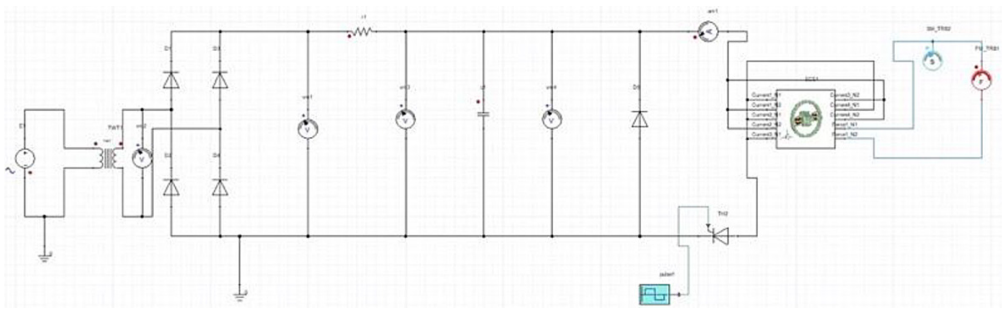

Figure 9. SCR controlled IEL power circuit

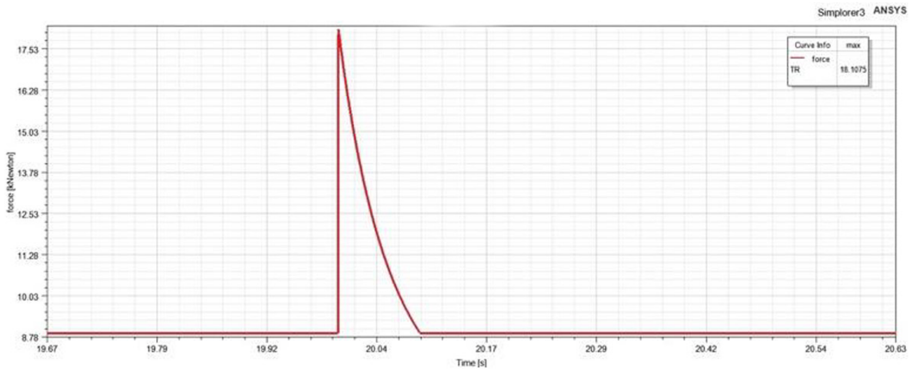

Figure 10. Force characteristics of SCR controlled IEL power circuit

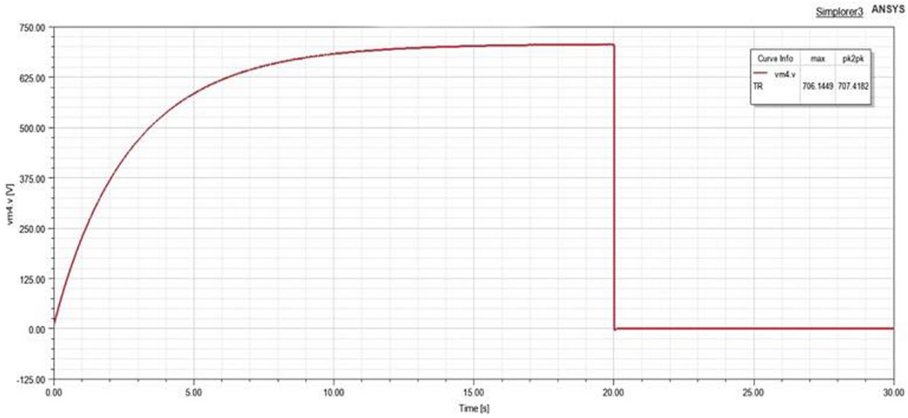

Figure 11. Voltage across the capacitor of SCR controlled IEL power circuit

launcher to a linearly-actuated force source. This externally-excited force source enabled the simulation to capture the dynamic relationship between the output force and the velocity of the launched projectile. The simulation results showed that the two-wing armature electromagnetic launcher could produce a maximum force of 18,107 N, corresponding to a capacitor voltage of 700 V. This force output underscores the enhanced efficiency and power delivery capabilities of the two-wing armature design. The force-related characteristics, are depicted in detail in Figures 10 and 11.

The SCR-controlled inductive energy storage circuit demonstrates higher force output, over 100 times greater than the switched RC circuit. The SCR-controlled circuit has ability to operate at higher input voltages, directly contributing to the increased force generation. The SCR-controlled inductive energy storage configuration is inherently capable of delivering the high-power pulses. The higher force output of the SCR-controlled circuit enables much greater potential for projectile acceleration and velocity.

CONCLUSIONS

This papers presents a comprehensive analysis of the performance characteristics of the two-wing armature electromagnetic launcher under various power circuit configurations. The findings emphasize the advantages of the TWAEL design compared to the traditional quadrupole railgun.

The TWAEL has achieved a maximum magnetic flux density of 2.3383 T, which is over 23 times greater than the quadrupole railgun. This enhances higher Lorentz forces, leading to improved projectile acceleration and velocity.

The analysis reveals that the SCR-controlled inductive energy storage circuit outperforms the switched RC circuit in delivering the high-power pulses for optimal electromagnetic launcher performance. The SCR-controlled circuit has generated a force of 18,107 N at 700 V, which offers over 100 times the force output of the RC configuration.

The TWAEL operates at a lower maximum current density compared to the quadrupole railgun. This lower current density facilitates more efficient conversion of electrical energy into mechanical energy, further contributing to the launcher's superior performance.

The study provides valuable insights into the influence of magnetic field dynamics and power circuit architecture on the overall efficiency and performance of electromagnetic launchers..

In conclusion, this investigation presents the advantages of the two-wing armature design and sets the stage for future advancements in electromagnetic launcher technology. By continuing to refine both the design of the launcher and its power delivery systems, researchers and engineers can pave the way for the next generation of high-performance electromagnetic launchers.

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