SYSTEM DESIGN CONSIDERATIONS AND THE FEASIBILITY OF
PASSIVELY COMPENSATED, PERMANENT MAGNET, IRON-CORE
COMPULSATORS TO POWER SMALL RAILGUN PLATFORMS

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Abstract

System Design Considerations and the Feasibility of Passively Compensated,
Permanent Magnet, Iron-Core Compulsators to Power Small Railgun Platforms

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This thesis provides insight into the different aspects of compulsator design for use with railgun systems. Specifically, the design space is explored for passively compensated, permanent magnet iron-core compulsators. Seven design parameters are varied within a compulsator model developed for the Cal Poly Compulsator (CPCPA). The Matlab code for this model is included within the appendix. Efforts were made to compare and validate this compulsator model to published data from existing systems. The compulsator model was found to match closely with discharge pulse length, but resulted in lower values for peak current and projectile velocity by 50% and 30% respectively when compared to published data.

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0.1 Nomenclature

B = field strength density (T)

D_r = diameter of rotor (m)

D_w = diameter of winding wires (m)

dI = change in output current over time (A/s)

dt = finite time step (s)

dx = particle velocity in railgun (m/s)

d^2x = particle acceleration in railgun (m/s²)

du = state space derivative placeholder

$d\omega$ = angular acceleration of rotor (rad/s²)

E_r = mechanical energy stored in rotor (J)

I = compulsator discharge current (A)

J_r = rotor inertia (kg-m²/rad²)

L = inductance (H)

L' = inductance gradient of railgun rails (H/m)

L_{min} = minimum inductance of compulsator (H)

L_{max} = maximum inductance of compulsator (H)

L_o = inductance of connecting busbar (H)

l_{cmtr} = length from rotor edge to commutator (m)

l_{turn} = length of windings based on number of turns (m)

l_{phase} = total length of a winding for one phase with two slots (m)

l_r = length of rotor (m)

m = mass of projectile (kg)

N_{cp} = number of conductors per pole on rotor

N_p = number of poles in rotor

N_{pairs} = number of pole pairs

N_t = number of turns for a winding
 P_{max} = peak discharge power (W)
 R' = resistance gradient of railgun (Ω/m)
 R_{rg} = resistance of railgun (Ω)
 R_c = compulsator internal resistance (Ω)
 R_o = resistance of connecting busbar (Ω)
 RPM = rotations per minute
 R_{ac} = AC Resistance for Skin Effect (Ω)
 t = time (s)
 u = state space placeholder
 V = instantaneous voltage of system (V)
 V_o = rotational electromagnetic voltage (V)
 v_p = projectile velocity (m/s)
 v_{tip} = rotor tip speed (m/s)
 X_{rg} = railgun barrel length (m)
 x = projectile position along railgun (m)
 δ = AC skin depth (m)
 δ_e = electrical phase angle (rad)
 δ_s = skin depth (m)
 Φ = Flux linkage (V-s)
 ρ = resistivity (Ω/m)
 ρ_c = compulsator inductance modulus
 ω = angular velocity (m/s)
 ω_m = mechanical angular velocity (rad/s)
 ω_e = electrical frequency (1/s)

1. Introduction and Background

1.1 Project Background and Purpose

The previous work leading to this paper [3, 14, 22, 10] involved the design and attempted assembly of the Cal Poly Compensated Pulsed Alternator (CPCPA). The final assembly of the CPCPA has been canceled for the immediate future due to a variety of factors that will be discussed later. The purpose of this paper is to expand the information related to the design of small iron-core passive-compensation compensated pulsed alternators.

1.1.1 Orbital Debris

Orbital debris, or space junk, and the hazards it imposes on spacecraft is a major concern within the Aerospace Industry. Sources of orbital debris include: the expended upper stages of launch vehicles, decommissioned satellites, occasional collisions between spacecraft, and micrometeorite impacts [23]. Impacts from space junk or micrometeorites that are smaller than 1cm in diameter are mitigated by employing protective shielding to the spacecraft. Various methods exist for tracking pieces of space junk greater than 10cm in diameter through optical and radio measurements [23]. These objects are tracked on the ground, and are generally avoided by maneuvering active spacecraft out of the way. However, the accuracy of these methods falls off greatly for objects smaller than 10cm, which cannot be safely stopped with current

shielding methods.

In order to provide sufficient shielding for spacecraft, significant research is necessary for the development of lightweight, impact-resistant shields. NASA and other space agencies have invested a lot of research in the study and design of micrometeoroid debris shields. A costly bottleneck in this process is the testing and validation of these shields. Traditional hypervelocity impact testing is handled at facilities that have a Light Gas Gun (LGG). LGGs hyper-compress a working gas to propel a particle to orbital speeds (approximately 1-10 km/s). These facilities require extensive infrastructure to maintain, creating a significant cost barrier for debris shield testing. Additionally, a lot of testing components are consumed during each firing which adds to the cost of LGG testing.

1.1.2 Electromagnetic Railguns

Electromagnetic railguns (EMRG) are a promising alternative to the LGG approach for hypervelocity impact testing. Typical EMRG research has focused primarily on applications involving military platforms; orbital debris testing is a relatively new application for this field. An EMRG requires a fraction of the total cost and occupied space of an LGG, making an economical option for hypervelocity impact testing. The feasibility of this concept was introduced last with the successful demonstration of the Cal Poly EMRG Mk.1, which was powered by a pulsed power supply comprising of a 16 kJ capacitor bank [29]. A one gram particle was successfully accelerated to 450 meters per second during Spring Quarter 2011. The team was able to achieve these results within a budget of \$5,000.

EMRGs require a large amount of energy to be pulsed over a very short time span, their power sources are referred to as pulsed power supplies. Pulsed power is a small, but growing, field within Electrical Engineering. Pulsed power involves the

accumulation of massive amounts of energy (kJ-GJ range) and releasing it over an extremely short period of time. Pulsed power technology is commonly used in radar, particle accelerators, fusion research, high-power pulsed lasers, ultra-strong magnetic fields, and electromagnetic pulses [6]. There are four methods of energy storage in pulsed power: capacitive, inductive, mechanical, and chemical. In the field of pulsed power, the two most common forms of energy storage are capacitive and mechanical.

Capacitive systems are relatively inexpensive, require only fundamental knowledge of electrical components and circuitry, but have a relatively low energy density. Most capacitive systems consist of a capacitor bank, a switching system or pulse formation network, and the load. Their simplicity and low cost are the trade-offs for their relatively low energy density.

1.2 Compensated Pulsed Alternators

1.2.1 Principle of Operation

A compensated pulsed alternator, or compulsator, is a specialized form of alternator whose primary design goal is to maximize power generation. It achieves this by having a high current carrying capability and minimizing the internal impedance of the device [8]. A compulsator works by storing its energy using inertial energy storage, converting this to electromechanical energy. A triggering switch then delivers the high power output to an external load over a short (ms to s) timespan [27]. Similar to a traditional alternator, voltage is produced by the relative motion of a multi-pole armature and electromagnetic field. Higher voltage can be obtained by increasing the relative speed between the two components, increasing the length of the armature, or using multi-turn windings. However, the top speed of the machine is typically limited by material strength of the rotating element. Magnetic field strength is dependent on the saturation level of ferromagnetic materials, or by current density of the excitation

winding conductors. Also, multi-turn windings can increase the internal impedance of the machine which limits any gains in current output that might be achieved [8].

The compulsator can also be thought of as a synchronous generator that is intentionally designed to maximize short circuit current output by minimizing internal impedance through the action of flux compression [6]. As the inertial energy storage component of a compulsator rotates, the mutual inductance between the stationary and rotating portions cause the inductance of the machine to vary over time. This cyclic variation of inductance compresses the magnetic flux generated by the load current and alters the shape of the output current pulse [9]. Flux compression occurs through the use of special internal compensating windings that fall into one of three categories: passive, selective-passive, or active compensation [6].

1.2.2 Historical Background

In the late 1970s there was significant interest in developing new technologies in pulsed power for energy storage and power delivery. Lawrence Livermore National Laboratory (LLNL) was developing a laser fusion facility that had a need for high power, short duration electrical pulses. Capacitor banks were found to be unable to provide repetitive, high-current pulses that were required for their research. This led to the concept of a compulsator and its subsequent patenting in 1978 [27]. An engineering prototype was developed at the University of Texas at Austin Center for Electromechanics for LLNL [20, 8].

During the 1980s significant research into electromagnetic launch (EML) began with railguns. After the successes seen with the LLNL fusion experiment, it became very clear that compulsators would prove to be an effective power supply for EML. The US Army who was looking into railgun technology as a possible next-generation weapons platform on tanks. As with the fusion experiment, capacitors proved to be

too unwieldy of a power supply for a mobile platform. Significant research was undertaken at the Center for Electromechanics, University of Texas at Austin into the feasibility of railgun platforms for future weapon systems. The Electromagnetic Gun Weapons System program was created to demonstrate the advantages of electromagnetic weapons for armor penetration. Several systems were developed to examine the feasibility of EML for weapon platforms [8, 19]. Present-day compulsator research is very active in China where research involves placing compulsators on amphibious assault vehicles to power next-generation EML weapon platforms [21].

1.2.3 Compulsator Topologies

There are many design architecture decisions that must be made when examining the implementation of a compulsator system for a pulsed power application. Since their inception in 1978, compulsator systems have gone through five generations of different technological advances at UT Austin CEM alone [6]. There are several major components in the topology of a compulsator that can be varied depending on the requirements of the system [8]:

- Excitation windings or another method of magnetic field generation
 - This generates the magnetic field in the system
- Compensation scheme, and subsequent compensation windings or shield
 - This dictates the output current waveform shape
- The type of rotating element
 - Source of inertial energy storage and typically houses the armature windings

The decisions made on the above compulsator topologies will affect the entire system as a whole. A compulsator can be broken down into the following major

elements:

1. Excitation windings
2. Armature windings, which interact with the excitation windings to generate voltage
3. Compensation winding or shield
4. Rotor
5. Stator
6. Bearings
7. Brush mechanisms, which deliver power from the compulsator into the switching circuitry and the external load
8. Support structure

Additionally, there are several discrete decisions that must be made when designing a compulsator system to meet the requirements and parameters for a pulsed power mission. These decisions are directly related to the different compulsator topology elements already mentioned. Further discussion on these different options will be handled in the following section, a diagram [6] depicting the different design options available for current compulsators is included below:

1.2.3.1 Core Topology Options

There are two options for core topology in a compulsator: iron-core and air-core magnetic circuits [24]. Iron-core machines have a higher magnetic permeability, and tend to be considerably more magnetically efficient than air-core machines. Because of the low specific strength and high density of ferromagnetic materials severely limits the maximum rotor tip speed, placing upper limits on the energy storage density of iron-core machines [24]. The excitation flux densities of iron-based alloys typically

Figure 1.1: Compulsator architecture decision tree [6] showing the different design options to consider for a complete compulsator system.

ranges close to 1.8 T, and serve as a material property cap for iron-core compulsators, except in the case of expensive, high saturation iron materials where flux densities can be increased to just above 2 Tesla [24]. Iron-core machines are typically more robust than air-core machines, but their delivered energy density is lower because they are a less energy-dense system [6]. Complex field winding schemes are difficult to implement in iron-core machines because of machining limitations as field windings in an iron-core machine are typically placed in slots.

As energy density and power delivery requirements rise, optimizing compulsators for maximum energy storage and power density favors air-core machines for two primary reasons [24]. The use of high strength, low density composite materials allows for operation at rotor tip speeds two to three times higher than what is possible in

iron-core machines [6, 24]. Unlike the magnetic saturation limit on iron-core machines, air-core compulsators can be optimized to operate at significantly higher flux densities. This allows for required voltages to be reached with fewer armature turns, which lowers the overall resistance of the machine [24]. Additionally, the lack of ferromagnetic materials in the core further reduces the internal inductance of the machine, leading to lower overall impedance in the system. Most air-core machines typically have self-excited magnetic fields, see section 1.2.3.6., and have an overall efficiency penalty in establishing the excitation field [24]. Air-core machines allow for parameters like rotor tip speed, excitation flux density, and efficiency to be optimized to provide a minimum weight and volume compulsator for a given duty cycle [24].

1.2.3.2 Output Phase Options

Early compulsators were all configured as single-phase machines, where the required current pulse came from a single voltage cycle. This design approach simplifies the output switch requirements; however it does require the desired output pulse duration to be close to the voltage period provided by the fundamental machine electrical frequency [24]. To minimize the physical size of a single-phase machine with a given stored energy requirement, the number of poles must be minimized to increase rotational speed. Reducing the size of a compulsator is important since less material is required and affects the overall system cost. There is a practical limit at two-pole configurations, where a variety of electromagnetic and mechanical problems such as arcing can arise [24]. The single-phase machine has a natural current zero and passive energy recovery from the railgun [6]. Electromagnetic field compensation schemes allow for further manipulation of the output pulse waveform, see Section 1.2.3.4.

Multi-phase machines offer more flexibility in current waveform shaping [3]. These compulsators utilize a higher electrical frequency than single-phase machines. Since

there are multiple phase outputs in a multi-phase machine, the entire output is rectified to provide the required pulse width and shape. Output waveform shaping removes the pulse duration and electrical frequency limitations experienced by single-phase machines [24]. This allows for the number of poles and the rotational speed of the rotor to be separately optimized to reach desirable parameters: high numbers of poles and high angular velocity, thus increasing the energy density of the system. Careful analysis and trades must still be made between machine size, switching hardware size, system mass, and cost [24].

Another major consideration in the multi-phase system architecture is the type of rectifier. A full wave, phase-controlled rectifier allows for the greatest pulse shaping capability. However, this requires approximately twice the number of switching devices as a half-wave, phase controlled rectifier because current flows in each bridge leg at all times [24].

1.2.3.3 Single Machine vs. Multi-Machine Systems

EML system can have very high delivered energy requirements in the Mega-ampere range, with Gigawatts of output power [15]. As performance requirements increase, compulsator design becomes more technically challenging to meet. Benefits can be seen in a system where the overall delivered energy is distributed across multiple, identical compulsators instead of a single specifically designed machine. The outputs of multiple compulsators would be combined in parallel to the load to meet performance requirements. Most EML systems are designed for use on mobile platforms; in this case, two smaller pulsed alternators could be configured to rotate in opposite directions to counteract induced effects of angular momentum that might negatively impact the operation of a mobile platform. Distributing energy delivery requirements across multiple compulsators is particularly useful for applications in-

volving armored combat vehicles, or for space-based railgun applications. Introducing a mass-producible compulsator system that could be modularly configured in parallel could be an intriguing commercial concept for future pulsed power applications.

1.2.3.4 Compensation Schemes

The main difference between compulsators and conventional alternators is through the use of compensation. Compensation reduces armature inductance through compensating currents which limit the volume occupied by the armature-produced fields [8]. To maximize the effect of inductance reduction, currents of equal magnitude and opposite sense flow in a conductor that is located physically close to the armature [8]. The total magnetic flux produced by the armature is reduced, and the fields are then contained between the armature and compensating conductors [8]. A common example is the coaxial cable, where the inductance is a function of the ratio of the radii of the two conductors. In the case of compulsators, opposing currents flow on the outer surface of the rotor and the inner surface of the stator bore [8]. To lower inductance, the magnetic air gap between the opposing currents and the thickness of conductors are minimized. Because a compulsator is a multi-pole machine, the degree of compensation depends on the relative alignment of the armature and compensating poles [8]. This can lead to an inductance that varies with rotor position, manipulating the inductance variation is the primary method of achieving a desired pulse shape and increasing output power through flux compression [8, 9]. Compensation is also useful for limiting the armature reaction in ferromagnetic machines, and protecting the excitation windings from armature-discharge-induced transients [8]. Shown in Figure 1.2 are the five different approaches to compensation for electromechanical power supplies. High voltage machines without compensation typically cover niche aspects in compulsator output performance. Compulsators have three possible compensation schemes available to them: passive, selective passive and active compensation.

Figure 1.2: The different compensation schemes in compulsators [8].

1.2.3.4.1 Passive Compensation

Passive compensation occurs when the compensating currents are induced in response to the transient armature fields produced during discharge [8]. The simplest form of this machine involves the use of a continuous conductive shield. During discharge, equal and opposite currents are induced in the shield. Because the shield is continuous, compensation is provided equally in all rotor positions resulting in a constant low inductance. A passively compensated machine will generate pulses that are effectively sinusoidal in shape [8]. This type of compensation is typically used in

compulsators with iron-core magnetic circuits because they are typically insensitive to the time constant of the excitation field circuit [24]. Air-core machines require rapid self-excitation to achieve reasonable efficiencies; a uniform compensation shield is not a practical option for air-core machines due to the length of time required for the excitation flux to penetrate it [24].

1.2.3.4.2 Selectively Passive Compensation

Selectively passive compensation is where currents are induced but compensation is not provided equally in all rotor positions, which results in a square output pulse shape [8]. Selective passive compensation can be employed in several ways, including non-uniform shielding or the use of shorted compensating windings. Both methods result in an inductance that depends on rotor position [8]. However, the compensating current is never in phase with the armature current and the flux compression ratio is significantly lower than in active compensation. At the start of discharge, if the compensation windings are aligned correctly, then current induced in the compensation winding compresses the armature flux to provide a lower inductance value [24]. The compensating winding axis is positioned so that maximum generated voltage coincides with minimum machine inductance, allowing for rapid rise in the output current pulse [24]. As the rotor rotates, the windings become out of phase and the armature flux is no longer confined. The lack of confinement increases the internal inductance, limiting the peak current achieved in the output pulse, and creates a flat pulse shape that is optimal for a railgun load [24]. As the rotor continues to rotate, similar interaction occurs that rapidly brings the current to zero [24].

The frequency of the induction variation is twice that of the machine electrical frequency [8]. This compensation scheme is extremely difficult to analyze since there are many variables related to the type of compensating winding, the orientation of the winding with respect to the excitation field, and the phase angle with respect to

the open circuit voltage where the pulse is initiated [8].

1.2.3.4.3 Active Compensation

Active compensation occurs by connecting a second winding in series with the armature. In active compensation, the compensating current is forced to flow in a defined sense [8]. When the armature and compensating poles are aligned and the currents are 180 degrees out of phase, a low inductance (roughly equivalent to the passive case) occurs. Meanwhile, when the rotor moves into a position where the two currents are in phase, a high inductance results. This variation of inductance is sinusoidal in nature, and high compression ratios of the maximum inductance to the minimum inductance occur [24, 8]. The active machine generates a narrow pulse of very high peak power.

1.2.3.5 Armature and Excitation Field Rotation Schemes

The relative velocity between the excitation field and the armature windings directly affects the voltage output of an electromechanical machine. Higher rotational velocities result in higher voltages as and also result in more inertial energy stored within the machine. However, there are practical velocity limits on systems with rotating elements that are typically defined by material property constraints.

Either a rotating armature or a rotating excitation field is chosen as the means of providing angular velocity between the excitation field and armature windings. Deciding between these two options is largely driven by structural requirements which are based on the energy delivery requirements of a system. A rotating armature is a system where the windings that are meant to interact with the magnetic field rotate during the operation of the compulsator, and the brushes that transfer the power are held stationary. A rotating field means that the windings or permanent magnets

that generate the magnetic field are rotated while the armature windings remain stationary. In a rotating field configuration, the brushes rotate during the operation of the compulsator. There are different benefits and drawbacks to each option that must be considered [8, 24, 6].

1.2.3.6 Compulsator Excitation Schemes

For any electromechanical machine, a magnetic field must exist to interact with armature windings in order to generate voltage within the machine. Excitation generates the magnetic field within the compulsator, and can be accomplished through several different methods: permanent magnets, external excitation, and self-excitation.

1.2.3.6.1 External Excitation

External excitation is where powerful windings are run through the compulsator structure and a specified amount of current is carried through them similar to electromagnet operation. This excitation current generates a set magnetic field strength density within the compulsator for the armature windings to interact with. External excitation is a popular and relatively simple scheme used on a wide range of compulsator systems. External excitation was used on the first compulsator systems [8, 4]. There are significant design issues that must be accounted for when utilizing external excitation. Ohmic heating, where the flow of current through a resistor releases heat, also known as resistive heating must be taken into consideration as thermal constraints can limit the maximum current that can be run through the external windings, or some form of cooling must be integrated into the system. External excitation windings require a large power supply to maintain constant current during operation. Structural integrity must be accounted for in the windings to ensure that they are not damaged from magnetic torquing during both operation and discharge. External excitation is typically a popular option with iron-core machines, which have

a higher magnetic permeability and do not require high excitation energies [6].

1.2.3.6.2 Self-Excitation

Self-excitation can be pursued on both iron-core and air-core machines. However, due to the lower permeability and relative efficiency of air-core compulsators, drastically higher excitation energies are required [6]. These higher energies pose a difficult problem in providing a constant excitation current within the excitation windings of a compulsator, which would further compound thermal and structural issues already faced with external excitation.

Instead of a constantly provided excitation current, self-excitation operates in a more transient manner. In this mode of operation, the prime mover drives the pulsed alternator to a designated rotational speed. Once the desired speed is reached, a field initiation capacitor system discharges into the excitation field windings. Meanwhile the armature winding is connected to the excitation windings through a rectifier. The armature windings are rated to carry a high discharge current, the induced voltage across the armature windings interacts with the excitation windings to excite the field. This is a positive feedback process. The current of the exciting field rises rapidly. Once the current rises to the desired value, the rectifier stops and then the compulsator discharges into the load [16]. Self-excitation is the most technically complex excitation scheme to implement, but results in the highest magnetic field strength densities.

1.2.3.6.3 Permanent Magnet Excitation

Of the three different options, permanent magnet excitation is the most basic to understand and implement. Permanent magnets of a specified magnetic field strength density are placed inside the compulsator as a replacement to excitation windings [17]. Due to the inherent magnetic field that exists, an excitation scheme can be imple-

mented into a compulsator system in a straightforward manner. Care must be taken to ensure that the magnets are kept within their thermal limits so demagnetization does not occur. However, because there are physical limits to the magnetic field density strength of permanent magnet materials, this excitation scheme is typically utilized in iron-core compulsators.

1.2.3.7 Energy Reclamation

After discharge, significant amounts of magnetic energy can remain within a rail-gun barrel. Compulsators can be configured to reclaim this leftover magnetic energy through another route of switching circuitry back into the compulsator, this capability is not technically feasible in capacitive systems. Inductive energy reclamation is a complex process, but can drastically improve the efficiency of a compulsator. Typically, air-core compulsators will implement energy reclamation as a means to improve the overall system efficiency [16] because the lower magnetic permeability in an air-core machine results in a lower efficiency than iron-core.

1.2.4 Switching and Power Delivery

The switching circuitry is responsible for transferring all of the output power over a tiny (ms to μ s) timespan, and must be rated to handle a high peak load during that time. Therefore, careful consideration must be taken into account for the design of the switching circuitry in any pulsed power application. Switching circuitry provides additional control and safety to the system as a whole by controlling its output discharge.

For this project, two electrical engineering undergraduate students and an aerospace engineering graduate student focused specifically on the design of the switching circuitry. Several compulsator design parameters can affect the design: the electrical

frequency, the phase voltage, the number of phases, and the total electrical action per discharge [24]. For self-excited machines, the switching circuitry also provides the energy required to start the self-excitation process.

Early compulsators [20] relied on ignitrons, effectively a mercury-filled spark gap, as switches. Ignitrons are very effective high current rectifiers that provide a very quick rise time. Ignitrons must be triggered with an initial high voltage pulse to turn the mercury inside the chamber to arc and thus allow for current to flow from the pulsed power supply to the load. However, ignitrons have fallen out of favor as both performance requirements and technology advances have led to almost all pulsed power systems relying on solid state converters like large diameter SCRs [24].

High power switching circuitry is very costly and has extensive lead times (20+ weeks) if a requested switch is not in stock. Additionally, damage can occur to these switching elements during operation and that must be taken into consideration when scoping out a switching system for a pulsed power application.

1.2.4.1 Ignitron Switching Circuit

Budget and safety were the primary driving factors in the selection of a switching circuitry system for this project. The new switching system will be used for both capacitive and mechanical pulsed power systems, in an effort to stretch budgets as far as possible and allow for leftover resources to be used on different systems. The National Electronics NL7218H-100 ignitrons were donated to this project. Due to budgetary constraints and long lead times to acquire different switches, these ignitrons were selected as the switching circuitry for this project. These ignitrons allow for switching up to 15 kV and have peak currents of up to 100 kA, which will be able to handle all of the switching needs for EMRG Mk 1.1.

Significant effort was undertaken by several members of the team to develop the

ignitron switching circuit and its associated triggering circuitry [10]. For proper operation, a $5\ \mu\text{s}$ pulse with a minimum voltage rating of 1500V is required of the system. More detailed information regarding the triggering of the ignitron switching circuitry was covered by an electrical engineering student on the team [10]. Shown in Figure 1.3 in is a picture of the ignitron switching circuit system:

Figure 1.3: Ignitron switching circuit system with associated support equipment.

2. Modeling Compulsator Discharge

2.1 System Equations and Modeling

This section of the paper will cover the equations used in the modeling of the compulsator-railgun system. These equations were pulled from a variety of published sources, and have been compiled and organized for the benefit of anyone working within the pulsed power field. Significant effort was spent navigating between various published materials that led to the combined model of differential equations that will model the discharge of an iron-core compulsator.

Other useful papers were found that contained different analysis routes and governing equations for a variety of compulsator architectures. Due to differences in the physical architecture of the Cal Poly Compulsator, the analysis outlined in these papers was not used in section 3.1.1. However, references have been included to these papers since relevant information related to compulsator operation and design considerations are contained within these papers [25, 20, 28, 13, 7]. Refer to the nomenclature at the beginning of the document.

2.1.1 Railgun Governing Equations

Electromagnetic railguns impart acceleration upon their projectiles through the Lorentz Force and this force can be simplified to the following [15] :

$$F = j \times B = \frac{(L'I)}{2} \quad (2.1)$$

F is the force on the railgun projectile, j is the current density (A/m^3), B is the magnetic field strength (T), L is the inductance gradient of the rails (H/m), and I is the discharge current inside the railgun (A). Relating the force in Equation 2.1 to Newtons second law, the acceleration of a particle inside a railgun can be found, seen in 2.2:

$$\frac{d^2x}{dt^2} = \frac{L'I^2}{2m} \quad (2.2)$$

The notation has been modified in terms of dx/dt where x is projectile position in the rails (m), dx is projectile velocity in the rails (m/s), and d^2x is projectile acceleration in the rails (m/s^2). Additionally, m is the projectile mass (kg). This change in notation is important because the modeling of the compulsator-railgun system is converted into state-space form to combine the governing equations of these two systems. The velocity of the projectile within the railgun is found through numeric integration of Equation 2.2. For the analysis covered in this paper, that numeric integration was handled using the ode45 function in Matlab.

2.1.2 Supporting Compulsator Electromechanical Equations

The following equations are used to calculate a variety of parameters that must be known in order to model the interaction between the railgun and compulsator during

discharge. The voltage within the compulsator will have a sinusoidal oscillation, which can be calculated using the instantaneous voltage equation for a rotating machine [18]:

$$V(t) = V_o \sin(\omega_e t) \quad (2.3)$$

$V(t)$ is the instantaneous voltage at any given moment in time, V_o is the rotational emf voltage of the compulsator, ω_e is the electrical frequency of the compulsator (Hz), and t is time (s). The equation used to calculate V_o is the following [4]:

$$V_o = N_p N_{cp} l_r B v_{tip} \quad (2.4)$$

N_p is the number of poles in the rotor, N_{cp} is the number of surface conductors per pole on the rotor, l_r is the length of the rotor (m), B is the strength of the magnetic field (T), and v_{tip} is the tip speed of the rotor (m/s). The other parameter from Equation 2.3 is the electrical frequency, which is calculated using the following equation [24]:

$$\omega_e = \frac{\omega_m N_{pairs}}{2\pi} \quad (2.5)$$

N_{pairs} is the number of pole pairs in the compulsator, and ω_m is the mechanical angular velocity (rad/s). From Equation 2.4, rotor tip speed is found using the following expression:

$$V_{tip} = \frac{RPM \pi D_r}{60} \quad (2.6)$$

RPM is the rotations per minute of the rotor; D_r is the diameter of the rotor (m). Another important parameter that needs to be known within the machine is the resistance within the rotor windings, which is approximated using the following equation

[5]:

$$R_{ac} = \frac{l_{phase}\rho}{D\pi\delta} \quad (2.7)$$

R_{ac} is the AC resistance (Ω) that accounts for the skin effect on the rotor windings, since the operation of the compulsator is AC. l_{phase} is the length of the windings for one phase (m), ρ is the resistivity (Ω/m), and δ is the skin depth (m). The skin depth is found with the following equation [5]:

$$\delta = 503 \sqrt{\frac{\rho}{\omega_e \cdot 1}} \quad (2.8)$$

The physical length of each phase winding in the rotor was approximated with the following calculation:

$$l_{phase} = N_t \cdot l_{turn} + l_{cmttr} \quad (2.9)$$

N_t is the number of turns per phase, l_{turn} (m) is the length of the windings per turn, l_{cmttr} (m) is the length taken from the commutator to the windings.

2.1.3 Compulsator Governing Equations

The discharge current of a compulsator is found by examining the ratio of magnetic flux linkage over the inductance of the compulsator over time [1]:

$$i(t) = \frac{\Phi(t)}{L(t)} \quad (2.10)$$

$i(t)$ is the discharge current (A), $\Phi(t)$ is the magnetic flux linkage (V·s), and $L(t)$ is the instantaneous inductance (H). Inductance plays a critical role in the performance

of a compulsator, the instantaneous value for inductance during operation is found with the following equation [9, 18]:

$$L(t) = L_{min}\rho_c \sin(\omega_e t - \delta_e) \quad (2.11)$$

L_{min} is the minimum inductance of the compulsator, ρ_c is the compulsator inductance modulus, δ_e is the electrical phase angle (rad), and t is time. The compulsator inductance modulus is calculated with the following relationship [9]:

$$\rho_c = \frac{1}{2} \left(\frac{L_{max}}{L_{min}} - 1 \right) \quad (2.12)$$

L_{max} is the maximum inductance of the compulsator. The maximum and minimum inductance values were approximated by another student working on the project [3]. Calculating the magnetic flux linkage is a very difficult calculation to tackle directly. Instead, calculating the rate of change of current and the current can be found through numeric integration. Through the use of the following equation, the discharge current rate can be found with the following equation [9]:

$$\frac{dI}{dt} = \frac{V - I(R_c + R_o + R'x) + I(\omega_e L_{min} \rho_c \sin(\omega_e + \delta) - L'v_p)}{L_{min}(1 + \rho_c) + L + L'x + L_o} \quad (2.13)$$

dI/dt is the discharge current rate of change (A/s), V is the compulsator voltage (V), I is the instantaneous current (A), R_c is the compulsators internal resistance (Ω), R_o is the resistance of the connections from the compulsator to the railgun (Ω), R' is the resistance of the railgun (Ω), x is the particle position inside the railgun (m), L' is the inductance gradient of the railgun (H/m), v_p is the velocity of the projectile inside the railgun (m/s), and L_o is the inductance of the connections from the compulsator to the railgun (H). R_o and L_o should be kept close to R_c and L_{min} respectively to reduce losses within the system. The mechanical energy stored within the compulsator is

simply calculated by the kinetic energy equation for a rotating object:

$$E = \frac{1}{2} J_r \omega_m^2 \quad (2.14)$$

E is the mechanical energy stored (J), J_r is the polar moment of inertia of the rotor (kg-m²/rad²). From this equation a relationship was found to approximate the change in rotational velocity during discharge. This can be found in the following equation, a step-by-step of the equation manipulation and substitutions can be found in Appendix B: Energy Discharge Equation Derivation:

$$\frac{d\omega}{dt} = \frac{-\sqrt{\frac{2VI}{J_r}} dt}{dt} \quad (2.15)$$

2.1.4 State-Space Modeling of the Railgun-Compulsator System

From the equations outlined in the above sections, a state space model was developed that would rely on numerical integration to model the discharge of the compulsator.

$$\begin{bmatrix} u_1 = \omega \\ u_2 = x \\ u_3 = \frac{dx}{dt} \\ u_4 = I \end{bmatrix} \xrightarrow{\text{Derivative}} \begin{bmatrix} du_1 = \frac{d\omega}{dt} \\ du_2 = \frac{dx}{dt} \\ du_3 = \frac{d^2x}{dt} \\ du_4 = \frac{dI}{dt} \end{bmatrix}$$

All of the equations from the above analyses were implemented into Matlab as a function that handled the calculations for modeling the discharge. The relevant Matlab files that handled this analysis are included in the Appendix.

3. Cal Poly Compulsator System Overview

A more in-depth discussion of the CPCPA's design process can be found in the prior work before this paper [14]. Sections from that paper have been included where relevant to provide context about the CPCPA for the benefit of the reader.

3.1 Architecture Selection

The two main factors behind the design decisions for this projects compulsator architecture were cost and complexity. All other compulsator system developed typically have had large budgets, extensive fabrication and testing facilities, and knowledgeable personnel that are well versed in pulsed power. The overall budget for this project was approximately \$10,000, and almost everyone involved in the project started off with no prior knowledge of pulsed power systems or compulsators.

During the initial planning for this project, scoping of the system performance led to trying to match the performance of the existing capacitive pulse forming network (PFN) at Cal Poly. The existing PFN Mk 1 stored 16 kJ of electrical energy and could accelerate a 1 g projectile to 450 m/s. A design target of 45 kJ stored mechanical energy at 5,000 RPM was chosen after extensive discussion between the author, the mechanical engineering students working on the project, and the designer of EMRG Mk 1.0. These values were selected to provide large factors of safety on rotating components and to account for low efficiency values. Figure 3.1 contains a graphic

that illustrates the final system architecture for the CPCPA.

Figure 3.1: Cal Poly Compulsator Topology Selection Tree, the green highlighted sections represent the final architecture of the system [14].

3.1.1 Rotor Winding Scheme

Minimizing resistance is imperative to provide the highest discharge current possible, however the cost of materials and simplifying the winding scheme for future integration must be taken into account. Most compulsators use Litz wire for windings, which is a special type of magnet wire that is tightly bundled in a manner that minimizes the inductance of the windings. A variety of factors, mostly driven by cost and complexity led to Litz Wire not being incorporated into the system design.

Since Litz wire was too expensive of a design option, insulated 10 AWG copper magnet wire was selected by the team for its relatively low resistance properties and bending capability for winding construction. The decision to use 10 AWG copper magnet wire coupled with the geometric size of the permanent magnet poles limited the total number of surface conductor that can contribute to voltage generation.

Because of this limitation, the original desired voltage of 450 V could not be met. The number of surface conductors is limited by the cross sectional length of the magnetic pole they are going to interact with as they rotate in the machine. A diagram depicting this issue is shown in Figure 3.2.

Figure 3.2: Rotor phase winding interaction with permanent magnets [14].

The number of surface conductors was then constrained to four since 10 AWG magnet was chosen for the armature windings. Smaller gauge wire would have higher resistance and negatively impact performance. Each phase winding is comprised of a single lap winding of wire with four turns, where each phase is separated by one rotor slot pair. Further detailed discussion on this winding is discussed in the following section. A diagram of these windings is shown in Figure 3.3.

Figure 3.3: Rotor phase winding interaction with permanent magnets [14].

The proposed winding scheme above was found to have a resistance of approximately $.0015 \Omega$, which had a predicted projectile performance of only 127 m/s. This loss in performance would not result in a system that would be comparable with the original 16 kJ capacitor bank that the team was looking to compare projectile performance to. Fortunately, this issue was found before any machining had occurred on the steel rotor section so a variety of solutions were available. In order to lower the resistance, the following options were considered:

- Increasing the gauge of the wire
- Shortening the length of the windings
- Parallel paths inside the rotor slots

Option three, parallel paths, resulted in a solution that led to a lower resistance that also kept the number of parallel conductors still at four. The rotor slots were designed to go deeper than originally planned, by having four parallel windings of four

turns stacked horizontally inside each rotor slot. Stacking the windings horizontally allowed for four separate surface conductors to interact with the permanent magnets. Additionally, having each of the windings in parallel and then brazed at the commutator lowers the resistance by a factor of four from the previous winding scheme. Instead of a resistance of $.0015\ \Omega$, a resistance of $.000375\ \Omega$ was calculated, resulting in a calculated projectile performance velocity slightly greater than 400 m/s. A circuit diagram comparing the old winding scheme to the parallel path winding scheme is shown in Figure 3.4.

Figure 3.4: Circuit diagram examination of the previous winding scheme and the finalized design winding scheme with parallel paths [14].

The equivalent circuit diagram of four parallel paths, results in a complex but feasible winding scheme. This duplex lap winding scheme can be visualized within the detailed view on the right side of Figure 3.5. Each of the sixteen commutator pads would have four brazed connections to connect the parallel paths to the commutator. Each connection is one segment from each parallel path, while the turns for each path wrap to connect between their two corresponding slots. This is shown in the Figure 3.5 on the right side.

Figure 3.5: Lap winding scheme for two phases, with each phase having four parallel paths with four turns per path. Each unique parallel path is color coded for clarity [14].

Commutation is critical for both delivering the energy from the compulsator into the switching circuitry as well as rectifying the output to prevent the voltage from dropping below zero during operation. Ignitrons stop switching current if the voltage drops close to zero. By having two phases in the rotor with commutated outputs, the operational voltage never approaches cutoff. Based off of information gleaned from other papers covering this topic, a four phase system would have been the preferred choice. However, the winding scheme would have been even more complicated to implement on the rotor section and then braze to the commutator. Since a two-phase system met the discharge voltage requirements of the ignitrons, this became the final architecture decision for compulsator topology. A schematic detailing the voltage variation in each of the two phases during the rotation of the rotor is shown below in Figure 3.6.

- Phase 1** Max Voltage (+/-) when windings pass underneath permanent magnet.
Phase 2 Zero Voltage when windings are halfway between permanent magnets.

Figure 3.6: Output voltage relationship for each of the phases within the rotor, as well as the commutated output of both phases [14].

3.2 Theoretical Analysis and Results

This section utilizes the model from Chapter 2 applied to the design variables of the CPCPA[14]. For reference, an illustration of the system has been provided in Figure 3.7 below.

Figure 3.7: External Mechanical System Overview of the Cal Poly Compulsator [14].

3.2.1 Cal Poly Compulsator System Parameters

The input parameters for this system are listed in Tables 3.2-3.3. For the benefit of the reader, an additional column is included to provide some context to how each variable's value was determined. Several terms have been used to describe the method for how each of the following parameters was determined in the system.

- **Known:** This is a discrete system parameter, which did not require any analysis to determine and is not an assumed value.
- **Measured:** This is a system parameter that was measured using the appropriate tool to determine the associated variable's value.
- **Calculated:** An equation was used to find this system parameter. Ideally, every calculated parameter would eventually be measured to better reflect real-world

information.

- **Approximated:** A finite element modeling program was used to determine a system variable. This was done for variables that did not have an equation for determining the exact value or could not be measured yet.
- **Assumed:** This was done for system variables that were not yet able to be measured, calculated, or approximated but required a value for design and analysis.

Table 3.1 contains the parameters that were used in the discharge simulation for the compulsator system.

Table 3.1: Compulsator Input Parameters

Variable	Value (units)	Method Determined
N_p	8	Known
N_{pairs}	4	Known
N_{cp}	4	Known
B	.45 (T)	Measured
D_r	.2 (m)	Measured
L_r	.25 (m)	Measured
J_r	.334 (kg-m ² rad ⁻²)	Calculated
L_{min}	1e-5 (H)	Approximated [3]
L_{max}	1e-5 (H)	Approximated [3]
R_c	3.75e-4 (Ω)	Calculated
R_o	1e-6 (Ω)	Assumed
L_o	1e-6 (H)	Assumed
$\delta_{e(phase1)}$	0 (rad)	Known
$\delta_{e(phase2)}$	π (rad)	Known

Table 3.2 covers the physical parameters taken from the EMRG Mk. 1 railgun that the compulsator will use as its load.

Table 3.2: EMRG Mk. 1 Railgun Parameters

Variable	Value (units)	Method Determined
X_{rg}	.762 (m)	Measured
R'	2.45e-04 (Ω/m)	Calculated
R_{rg}	3.21e-04 (Ω)	Measured [29]
L'	3.271e07 (H/m)	Calculated [29]

Table 3.3 lists the initial conditions of the compulsator just before the discharge event.

Table 3.3: Compulsator Initial Conditions

Variable	Value (units)	Method Determined
RPM_0	5,000 (rpm)	Assumed
ω_0	524 (rad/s)	Calculated
V_0	194 (V)	Calculated
x_0	0 (m)	Assumed
V_{p0}	0 (m/s)	Assumed
I_0	0 (A) %	Assumed

3.2.2 Discharge Performance Results from Theoretical State-Space Model

The following pages include figures showing the calculated output performance of the compulsator during discharge. For reference, the following output performance parameters were calculated with the Matlab simulation using the analysis from Chapter 2:

Table 3.4: Compulsator Discharge Performance Values

Variable	Value (units)	Method Determined
$V_{p,final}$	410 (m/s)	Calculated
I_{peak}	33 (kA)	Calculated
I_{avg}	22 (kA)	Calculated
$t_{discharge}$	4.3 (ms)	Calculated
P_{max}	3.3 (MW)	Calculated
Compulsator Efficiency	15 %	Calculated
Railgun Efficiency	1.8 %	Calculated
System Efficiency	0.18 %	Calculated

The calculated output velocity of the system is predicted to match the current performance of the 16 kJ capacitor bank, which is able to accelerate projectiles to approximately 430 m/s. The following figures outline the discharge performance characteristics of the compulsator over time. In Figure 3.8, the top plot shows the output current of the compulsator in kA during discharge. The output curve for current visibly seems to correlate in shape with other discharge curves for current seen in other papers. The middle plot shows the decay in voltage during discharge, which is directly related to the loss in mechanical energy as the rotors rotational velocity decays. The bottom plot shows the output power of the compulsator during discharge. Peak power is reached a third of the way through discharge, when the

voltage is still rather high and when current is approaching the average discharge current.

Figure 3.8: Discharge simulation results for output current, voltage, and power.

Figure 3.9 contains plots that show the kinematic performance of the railgun and compulsator during discharge. The top plot shows the change in the projectile's position and velocity as it accelerates down the railgun barrel. The red square denotes that the projectile has reached the end of the .762 m long barrel, and at this point the simulation ends. Superimposed on the same plot is the velocity of the projectile while it accelerates down the railgun barrel. An additional plot showing the acceleration

change during discharge will be shown and discussed later on.

The bottom plot in Figure 3.9 shows the change in kinetic energy stored in the rotor during discharge. The blue curve shows a decrease in RPM of the rotor speed. The green curve shows the change in stored mechanical energy remaining in the rotor, which decreases dramatically as the rotor speed decelerates from the electromechanical interaction in the system. It is important to note that the compulsator will still have a residual RPM of approximately 160 RPM after discharge; which is when the brake will be used to completely stop the rotors motion.

Figure 3.9: Discharge simulation results for projectile performance and energy loss in the compulsator.

The acceleration seen by the projectile during discharge is a kinematic parameter worth examining. High accelerations down the rails can induce extremely high stresses on a projectile, depending on the magnitude of the projectile's mass and acceleration

seen during discharge. In the case of this project, a 1 g solid aluminum projectile faces negligible stresses from its acceleration when compared to the frictional forces between the rails and arcing damage during discharge. Larger railgun systems looking into embedding payloads within the projectile might have to take stresses caused from acceleration into account when selecting materials for their projectiles. A variety of applications for compulsators exist in a variety of fields [2, 11, 6]. A plot of the acceleration seen by the projectile is included in Figure 23 below. The values for acceleration were calculated by using the kinematic equations at each time step from the data generated by the discharge simulation model.

Figure 3.10: Discharge acceleration performance of the 1g Aluminum projectile within the railgun barrel.

As mentioned above in Table 3.4, the calculated performance of the entire compulsator-railgun system will have a supposed total system efficiency of 0.18 %. A plot that visualizes the conservation of energy and how the energy flows through the system is

included below in Figure 3.11. The efficiency of the compulsator was calculated by dividing the peak value of the railgun energy (blue curve in Figure 3.11) by the difference in initial rotor energy (green curve in Figure 3.11) to the rotor energy at same point in time as the peak railgun energy. Railgun efficiency used the peak current of the projectile (red curve in Figure 3.11) divided by the difference between peak railgun energy and railgun energy at the end of discharge. Total system efficiency was calculated using the final projectile velocity divided by the difference between initial rotor energy and final rotor energy.

Figure 3.11: Conservation of energy visualized with the changes in energy during discharge between the rotor, railgun, and projectile.

The green line represents the total kinetic energy that is stored in the spinning rotor during discharge; this curve is identical to the green curve in the bottom plot of Figure 3.11. The blue line represents the electrical energy delivered to the railgun from the compulsator during discharge. The red line is the kinetic energy of the

projectile as it increases in velocity down the barrel. Lastly, the dashed black line is the summation of all three curves, and is included for clarity to show that throughout the entire discharge, energy is being conserved across the system. Because of energy losses during discharge, the rotor (green) should have the highest peak magnitude for energy, followed by the railgun (blue), and the projectile (red) should have the lowest peak magnitude for energy throughout discharge. The total system efficiency is calculated by comparing the final point on the red curve to the initial point on the green curve.

4. Validating the State Space Model

This section examines other iron, passive-compensation compulsator systems that have been published with the goal to try and validate the model outlined in Chapter 2. Papers that discussed air-core systems, did not use passive compensation, or lacked sufficient system information were not considered. After examining the available literature, two viable candidate systems were found for comparison analysis.

4.1 Culham Compulsator

The following paper [9] "Design Considerations for Compulsator Driven Railguns" discusses the different aspects of compulsator design for use with railguns. The amount of information provided in this paper was very helpful in the creation of the model outlined in Chapter 2. Enough data was provided within the paper that outlined a compulsator/railgun system. A table has been included below that outlines both the information provided by the paper and the values modeled for variables that were not included.

Table 4.1: Modeled system parameters compared with published data.

	CPA Model Value	Paper Published Value
Projectile Mass (kg)	1	1
Rotor Diameter (m)	0.7	N/A
Rotor Length (m)	0.8	N/A
Rotor Inertia (kg-m ²)	146	N/A
Number of Poles	4	4
Magnetic Field Strength (T)	.178	N/A
Number of Surface Conductors	4	N/A
Rotor RPM	12,000	12,000
L_{min} (H)	.1e-6	.1e-6
R_{cp} (Ω)	10e-6	10e-6
R_{busbar} (Ω)	10e-6	10e-6
$\& L_{busbar}$ (H)	.1e-6	.1e-6
Inductance Modulus ρ	15	15
Railgun Inductance Gradient ($\mu\text{H}/\text{m}$)	0.6	0.6
Railgun Resistance Gradient ($\mu\Omega/\text{m}$)	100	100
Railgun Length (m)	1	1

The data from Table 4.1 was run through the model. A graph of the results can be found in Figure 4.1 and Table 4.2 includes additional information. The black plot is data that was digitized directly from graphs within the paper. The red plot is the compulsator model nominal output, where the deceleration of the rotor is accounted for using Equation 2.15. Since the CPCPA was separated from its prime mover during discharge, deceleration was included in the analysis. In this paper, the rotor was not assumed to decelerate but was kept at a constant speed during discharge. The blue plot is the same model being run except $\frac{d\omega}{dt}$ was equal to zero instead of using Equation 2.15.

Figure 4.1: Compulsator discharge model comparison to the Culham Experimental Compulsator system.

Enough information was available to compare the current discharge profile from the paper to the compulsator model as seen in Figure 4.1. The red plot, which includes rotor deceleration, matches the pulse width found in the paper but only reaches about 40% of the peak current value. As seen in Table 4.2, the red plot's

velocity is also the lowest of the three at 504 m/s. The blue plot, which neglects to account for deceleration, has the same pulse width as well, a higher average current, and its velocity is 798 m/s.

The discharge current profile from the paper is much higher in amplitude, reaching a peak current of 2.3 MA and a final projectile velocity of 1,500 m/s at a displacement of 1 meter. The paper discussed a final velocity close to 1.8 km/s at a displacement of 5 m, and mentioned that they had expanded the length of the railgun barrel from 1 meter to 5 meters. It is not clear if the variables from Table 4.1 changed as well when the railgun length was modified.

Table 4.2: Additional comparison between the model and the results.

	Model with $-\frac{d\omega}{dt}$	Model with $\frac{d\omega}{dt} = 0$	Data from Paper[26]
Voltage (V)	1000	1000	1000
Velocity (m/s)	504	798	1500 at displacement of 1m
Peak Current (kA)	1034	1092	2315
Time to Exit (ms)	3.9	3.9	5

It is not clear as to why neither run of the compulsator model reached such a low peak currents and velocities in comparison to the published data. Drastically increasing the voltage from 1000 V to 6000 V in the system did raise to closer performance values, but this change did not seem to result in a comparable system.

4.2 UT Austin 1984 Compulsator Prototype

The following paper [26] "A Compulsator Driven Rapid-Fire EM Gun" documents the first attempt to drive a railgun using a compulsator. A picture of the system has been included for reference in Figure 4.2.

Figure 4.2: Cut-away view of the UT Austin CEM engineering prototype compulsator pulsed alternator [26].

This paper outlines several useful equations for modeling a compulsator system as well. The variables for the compulsator-railgun system published in this paper have been provided in Table 4.3.

Table 4.3: Modeled system parameters compared with published data.

	CPA Model Value	Paper Published Value
Projectile Mass (kg)	0.08	0.08
Injected Velocity (m/s)	200.0	200.0
Rotor Diameter (m)	0.813	0.813
Rotor Length (m)	1.83	1.83
Rotor Inertia (kg-m ²)	713.9	713.9
Number of Poles	8	8
Magnetic Field Strength (T)	.165	N/A
Number of Surface Conductors	8	Litz Wire 8 Parallel Lap Windings
Rotor RPM	3525.0	3525.0
L_{con} (H)	1.23e-6	1.23e-6
R_{cp} (Ω)	368e-6	368e-6
R_{busbar} (Ω) & L_{busbar} (H)	1e-6	N/A
Inductance Modulus ρ	0	N/A
Railgun Inductance Gradient ($\mu\text{H}/\text{m}$)	0.42	0.42
Railgun Resistance Gradient ($\mu\Omega/\text{m}$)	267.2	267.2
Railgun Length (m)	3	3

Like before, data that was not provided from the paper was assumed and is listed in the table above. The model was run both with deceleration accounted for and without deceleration. This time, plots for both current discharge and velocity over time can be compared in Figure 4.3.

Figure 4.3: Compulsator discharge model comparison to the UT Austin 1984 system.

The red plot, which accounts for deceleration with Equation 2.15, has an increased pulse width of almost double. However, a majority of the useful portion of the pulse does occur within 2 ms. The peak current approaches about 55% of the paper’s peak value, while only reaches a velocity of 863 m/s compared to the paper’s published velocity of 2,360 m/s.

The blue plot, which excluded the effects of deceleration, almost matched the peak current from the paper. Also, the pulse widths (also known as time to exit) very closely matched that of the paper, however the pulse does not fall off as rapidly and because of this the final velocity is 3,120 m/s compared to the paper’s published

velocity of 2,360 m/s. A table of this information has been included below.

Table 4.4: Additional comparison between the model and the results.

	Model with $-\frac{d\omega}{dt}$	Model with $\frac{d\omega}{dt} = 0$	Data from Paper[26]
Voltage (V)	2900	2900	2900
Velocity (m/s)	863	3120	2360
Peak Current (kA)	510	844	899
Time to Exit (ms)	4.3	2.3	2.2

4.3 Summary and Impacts of Using this Compulsator Model for Design Purposes

Two candidate compulsator systems [9, 26] were analyzed and compared to the results that the model from Chapter 2 generated. This model does not accurately match the performance levels in the papers analyzed, but can still be useful for initial engineering design efforts for these systems. If the CPCPA had been completed, experimental results would have been compared to the model for validation.

Pulse width correlated closely between the published data and the results from the model. As mentioned, pulse length is critical for railgun design with the goal of having the pulse end right as the projectile leaves the barrel. For someone interested in designing a compulsator-railgun system, this model could be a good starting point for analysis.

Although the performance values from the model were significantly lower by about $\frac{1}{3}$ for projectile velocity and up to $\frac{1}{2}$ lower for peak current. The model from Chapter 2 could be used as a conservative estimate for compulsator-railgun systems, however the discrepancies between this paper's model and the published data should be accounted

for in the design process. Knowing the amount of current flowing through the system is critical to safe structural design for these systems. Even with factors of safety, being aware that this model could already be off by 50%.

With the above analysis in mind, the model outlined in this paper can be useful starting point for iron-core, passive compensation compulsator design. The equations used in the model have drawn from different papers. Seen from Equation 2.10, current is affected by the magnetic flux linkage over the instantaneous inductance in the system. There are multiple equations for the rate of current discharge ($\frac{di}{dt}$) depending on compulsator topology. Experimental testing on a completed compulsator system would allow for real world laboratory data to be compared to the model. If real-world data came in below expected results than the system would be analyzed for unaccounted resistive losses in the system and would be modified to reduce resistance if possible. If real-world data came in above expected results, than there is an un-modeled source of magnetic flux linkage that would need to be identified and incorporated into the current discharge equation.

5. Exploration of the Compulsator Design Space

One of the recurring challenges during the course of this project was the lack of information regarding the design of compulsators. Relevant equations are scattered among multiple conference papers and technical reports, and a majority of detailed information is not publicly accessible. Understanding design implications and system trade-offs requires extensive reading and rereading of published conference papers. One of the goals of this thesis is to provide foundational knowledge into the design of iron-core compulsators, and assist the engineering efforts for anyone interested in this topic.

This section explores the impact to the performance of a compulsator-railgun system as different design variables are changed. It is difficult to design a system when the physical limits, budgetary constraints, or manufacturing complexity of each design variable are unknown. At the start of this project in May 2011 the team started from zero knowledge and a lot of valuable time was expended learning about the system without accessible, well-documented information available about compulsators. The format for each of the following sections will roughly follow this outline:

- 1. Description of the Design Variable**

- What is it? How does it affect the system?

- 2. Boundary of Analysis for that Variable**

- Why were these upper/lower bounds chosen?

- 3. Graphical Results of the Impact on Performance**

— What is happening to the system as the variable changes?

4. Design Implications of the Results

— How does reaching different values impact the system's design/cost?

5. Design Feasibility of the Results

— What are the Engineering Limits for "improving" that Variable?

5.1 Exploring the Compulsator System Variables

This section will examine the impacts to discharge performance by varying the different compulsator design variables that were modeled in the previous sections.

5.1.1 Number of Poles in the Rotor [N_p]

N_p represents the number of magnetic poles in the rotor. This is a very important parameter in a compulsator as it affects both the voltage and the electrical frequency of the system. Both voltage and electrical frequency affect the rate of current discharge (Equation 2.13). Varying the number of slots in the rotor will change the number of poles in the system.

To see the impacts upon system performance, the compulsator model was run multiple times while varying number of poles in the system. The number of poles varied between a minimum of two poles to a maximum of forty poles in the system. Ten total test cases were run between these limits, and the CPCPAs pole count of eight was included as a data point for comparison. There must be an even number of poles in the system. Two poles was chosen as it is the lowest possible physical limit. Forty poles was chosen as the upper limit of analysis because the author felt that enough of a trend could be found by that point and there are geometrical and cost constraints imposed by continuously increasing the number of poles. A plot of the current discharge performance from varying the number of poles in the compulsator

can be seen below in Figure 5.1.

Figure 5.1: Compulsator discharge performance for varying the number of poles in the rotor.

As can be seen in Figure 5.1 the peak current increases directly with the number of poles, which is expected. The pulse width decreases inversely to the number of poles. Peak current is a very important parameter for both compulsators and railguns, where maximizing peak current is a priority for electromagnetic launch applications. In Figure 5.2 there are four additional plots that provide additional insight into how changing the number of poles affects system performance.

Figure 5.2: Continued compulsator discharge performance for varying the number of poles in the rotor.

The most important of these four graphs is the red plot in the top left which shows how projectile velocity is affected by the number of poles. There appear to be two different regions of interest in this plot: before ten poles and after ten poles. There is a high-slope region of improvement to projectile velocity until the ten pole point, after this the slope decreases. The green plot in the bottom left shows how pulse width is affected by the number of poles. The goal for pulse width is to try to have the pulse width end as the projectile leaves the barrel of the railgun. If this is not possible, then the secondary goal is to ensure that the pulse width ends before the projectile leaves the barrel of the railgun so all of the energy is discharged. Nonlinear trends like these are important to be aware of in the compulsator design space. Efficiency and voltage have fairly linear trends with respect to the number of poles and these were expected results.

To maintain a two-phase system, the ratio between the number of poles in the rotor and rotor slots is 2:1 the ratio of rotor slots to permanent magnet rails is 2:1, and the ratio of permanent magnet rails to interpole rails is 1:1. With these ratios in mind, the following design implications for varying the number of poles can be considered. In terms of cost-consequences, machining out rotor slots to high precision on a steel cylinder was very expensive. For reference, the machining of the CPCAs rotor had to be contracted out to a machinist off-campus and cost approximately \$1,800, which includes cost of materials. If a high number of poles is desired, the rotors fabrication cost must be considered and budgeted appropriately.

As the number of poles increases, the stators complexity increases as more permanent magnet poles are required to make the compulsator system stay two-phase. Approximately \$600 was spent on permanent magnets for just eight permanent magnet poles to go inside the stator. Assembling and storing the permanent magnet rails was both time-extensive and carried a slight risk of injury. The magnet rails also took a non-trivial amount of machining to fabricate as well. Additionally, the number of interpole rails will increase with permanent magnet rails to prevent arcing and neutral plane shift [3]. If a high number of poles is desired, the stators fabrication cost must be considered and budgeted appropriately.

Increasing the number of poles will also require more copper magnet wire for both the rotor poles and the interpole windings. The addition of more magnet wire will also result in more winding work that has to be done during fabrication and assembly. Winding is time-intensive and requires high-precision for the rotor slots, as the windings are epoxied into the rotor slots. The impacts of increased winding time must be considered into the scheduling of compulsator assembly and budgeted for.

Remembering the two different regions of projectile velocity performance discussed above, the author would recommend against systems with more than 10 rotor poles.

The overall cost for increasing the number of rotor poles past ten begins to spiral due to machining, materials, and time are too high for compulsators at this scale and performance level. However, increasing the number of rotor poles is a very straightforward route to increase compulsator performance and is a very valid design choice as long as the budgetary impacts are accounted for.

5.1.1.1 The Interaction between Electrical Frequency $[\Omega_e]$ and the Number of Poles $[N_p]$

The section above did not account for the fact that electrical frequency is affected by the number of pole pairs in an electric machine (Equation 2.5). As the number of poles increases, electrical frequency will rise. This will cause the skin depth to decrease (Equation 2.8), which will result in AC Resistance to rise in the rotor phase windings (Equation 2.7). Because of this, rising electrical frequency will have a negative impact system performance. The plots for projectile velocity and efficiency from Figure 5.2 have been included below, and additional plots have been superimposed that account for varied electrical frequency.

Figure 5.3: Compulsator discharge performance where varied electrical frequency is accounted for when the number of poles changes in the system.

For lower numbers of poles and lower electrical frequency, improved performance can be seen. This is because the AC resistance of the rotor windings is an extremely important design parameter, and is key to ensuring adequate system performance. Internal resistance is discussed in a later section. The CPCPA's resistance calculation included the affect of electrical frequency, as is shown where both lines intersect at the CPCPA's data point.

As it turns out, not accounting for the change to electrical frequency as the number of poles increases is significant. This divergence becomes more important after 12 poles. As discussed above, increasing the number of poles in the compulsator can be very costly and complex. The drawback of raising resistance from adding poles to the compulsator makes this design route even less favorable. Other parameters should be explored for improving performance before adding more poles to the system.

5.1.2 Number of Surface Conductors Per Phase [N_{cp}]

N_{cp} represents the number of surface conductors per phase that run along the rotor slots in the rotor. This is a critical design parameter for a compulsator as it affects the voltage of the system and the resistance of the machine. Both voltage and internal resistance affect the rate of current discharge (Equation 2.13). Varying the number of copper magnet wires that will exist within the rotor poles will change the number of surface conductors, assuming that there is a parallel lap winding for every surface conductor. The slot width and the magnet wire diameter might have to change to accommodate a desired number of surface conductors.

To see the impacts upon system performance, the compulsator model was run multiple times while varying the number of surface conductors in the system. The number of surface conductors varied between a minimum of one conductor to a maximum of eighty conductors in a pole. Ten total test cases were run between these limits, and the CPCPAs conductor count of four was included as a data point for reference. A minimum of one conductor is required to create the poles in the rotor. Eighty conductors was chosen as the upper limit of analysis because the author felt that enough of a trend could be found by that point and there are geometrical and assembly complexity constraints caused by continuously increasing the number of conductors. For all of these different analysis cases, the number of turns that

comprised the slot depth was four. Additionally, the effects of increased resistance to reach these conductor values was not included. A plot of the current discharge performance from varying the number of conductors in the compulsator can be seen below in Figure 5.4.

Figure 5.4: Compulsator discharge performance for varying the number of conductors per phase.

Similar to the results of increasing the number of poles in the system, it is shown that the peak current increases directly with the number of conductors, which was expected. The pulse width decreases inversely to the number of conductors. In Figure 5.5 there are four additional plots that provide additional insight into how changing the number of poles affects system performance.

Figure 5.5: Continued compulsator discharge performance for varying the number of conductors per phase.

The red plot in the top left shows how projectile velocity is affected by the number of conductors. Like before, there is a region of large gains in improvement for small increases in conductors until somewhere between 10-15 conductors. After this point, the logarithmic growth begins to fall off as the number of conductors increases. The green plot in the bottom left shows how pulse width is affected by the number of poles. The system efficiency does not grow linearly with conductors and appears to share an overlapping high-growth region with the velocity plot. This is an interesting trend to take note of that did not exist when the number of poles was increased shown in Figure 5.2. Meanwhile, voltage still has a linear trend with respect to the number of conductors and is an expected result because of the linear relationship in Equation 2.4.

From a cost standpoint, changing the width of the rotor slots will marginally

affect the cost of machining. Wider slots might have a lower cost to machine, while narrower slots might cost more to machine due to manufacturing tolerances. The number of poles will affect machining cost on the rotor more as that determines the number of slots that must be cut. If wider slots are needed for the rotor, the stator will have to grow accordingly to accommodate a larger rotor. The most expensive element will be acquiring permanent magnets that will have a width equal to the slot width. For the CPCPA, .5-inch permanent magnets were the largest commercial off the shelf (COTS) magnets that could be acquired without having to order custom magnets. Preliminary research into custom permanent magnets at the .5 Tesla range and higher were very expensive and ranged between \$2,000-\$10,000 depending on if they would be cubes or custom-length bars as well that matched the length of the rotor. Additionally, the amount of copper magnet wire required for the rotor windings might change and this must be accounted for as well.

There are several factors to take into consideration when determining the maximum number of surface conductors that will comprise the rotor poles. Winding complexity will go up as the number of conductors increases, because a parallel winding path will be needed for each surface conductor. If rotor slot width is held constant, then the diameter of wire will have to shrink. If the diameter of wire is held constant, then the slot width must increase which would correspond with the rotor diameter most likely increasing as well. Changing the diameter of the magnet wire will affect the resistance of the rotor phase. Increasing the number of parallel paths will change the total length of the winding which will also affect the resistance of the rotor phase. This is a very complex and coupled optimization problem and is discussed further in section 5.1.8.

5.1.3 Magnetic Field Strength Density [B]

B represents the magnetic field strength density of the permanent magnets that are placed inside the magnet rails inside the stator. The magnetic field strength has a direct linear relationship with the voltage of the system (Equation 2.4), and as a result will affect the rate of current discharge (Equation 2.13). Varying the magnetic field strength density involves either changing the type of permanent magnet or the changing quality of a given permanent magnets composition.

To see the impacts upon system performance, the compulsator model was run multiple times while varying the magnetic field strength density. The field strength varied between a minimum of .1 Tesla to a maximum of 1.8 Tesla. Permanent magnets hit a material property limit at around 1.4 Tesla, while high-end steel compositions cap out at magnetic saturation limits between 1.2-1.8 Tesla. Ten total test cases were run between these limits, and the CPCPAs field strength of .45 Tesla was included as a data point for reference. A plot of the current discharge performance from varying the magnetic field strength in the stator can be seen below in Figure 5.6, data points for a field strength above 1.4 Tesla would only be possible through external excitation.

Figure 5.6: Compulsator discharge performance with varied magnetic field strength density.

Similar to the results of increasing the number of poles and conductors in the rotor, it is shown that the peak current increases directly with magnetic field strength, which was expected. The pulse width decreases inversely to the magnetic field strength. In Figure 5.7 there are four additional plots that provide additional insight into what is going on within the system.

Figure 5.7: Continued compulsator discharge performance for varying the magnetic field strength density.

The red plot in the top left shows how projectile velocity is affected by magnetic field strength. It appears that the CPCPA happened to be right at the inflection point between the two regions of projectile velocity improvement that have been discussed in Figures 5.2 & 5.5. The green plot in the bottom left shows how pulse width is affected by the magnetic field strength. The system efficiency does not grow linearly with magnetic field strength and its trend line mirrors that of the projectile velocity plot. This is important to note like in Figure 5.5 where the number of conductors also had nonlinear growth in system efficiency. Lastly, voltage still has a linear trend with respect to magnetic field strength and is an expected result because of the linear relationship in Equation 2.4.

One important thing to note is that assembling the permanent magnet rails was very tedious and came with a slight risk of minor injury to fingers when working

with the magnets. Storing and transporting completed magnet rails carried a slight of major damage to any body parts that might come between a magnet rail and any ferrous object or surface. The author and those who worked with the magnet rails were actually relieved that the magnets that arrived had a strength of only .45 Tesla, handling anything stronger would have required specialized tools and would have been very dangerous.

Increasing the magnetic field strength of the stators magnet rails would be a straightforward route to improve compulsator performance, as long as the following are considered. Custom permanent magnets would need to be ordered above .45 Tesla, and it would be recommended to get custom-length rectangular magnets instead of combining cubes. This would simplify a lot of fabrication issues with the permanent magnet rails, however the acquisition cost of these magnets must be considered. As mentioned, .5-inch permanent magnets were the largest COTS magnets that could be acquired without having to order custom magnets. Custom-length magnets would be very expensive (\$4,000+). Two important properties would be the surface strength of the magnet and the maximum temperature of the magnets, too high of a temperature within the compulsator could result in demagnetization of the permanent magnets. Additionally, the safety impacts of storing and transporting stronger magnets would need to be considered. If the acquisition costs are budgeted accordingly, improving magnetic field strength density could be one of the best variables to target for improving system performance with minimal impact to system complexity.

5.1.4 Compulsator System Inductance

This section examines the overall inductance of the compulsator. Where it is assumed that $L_{min} = L_{max}$, which was the case with the CPCPA which had an approximated

inductance of 1e-5 H [?]. Inductance is a very important characteristic of a compulsator since it determines the rate of current discharge in the system (Equations 2.10 & 2.13). Inductance can be approximated using electromagnetic FEA tools [17] or calculated [12]. A variety of factors affect system inductance, the following equations can be used to calculate the inductance for a passive compulsator.

To computer the total internal inductance of a compulsator, the following equation is used [12].

$$L_T = L_i + L_E + L_\delta \quad (5.1)$$

L_T is the total internal inductance, L_i is the inductance of the conductor wire, L_E is the leakage inductance calculation for the end winding of the compulsator, and L_δ is the inductance of the effective part of one armature winding. A breakdown of the equations for the different inductance components is included in the following equations [12].

$$L_E = \frac{l_E}{l} L_\delta \quad (5.2)$$

where l_E is the end length of the armature winding and l is the effective length of the armature winding.

$$L_i = \frac{\mu_0 N(l + l_E)}{4\pi} \quad (5.3)$$

where N is the number of turns of the armature winding, and μ_0 is the magnetic permeability constant.

$$L_\delta = \mu_0 N^2 l \left[\frac{1}{2} - \frac{b}{\alpha r} + \left(\frac{b}{\alpha r} \right)^2 \ln 1 + \frac{\alpha r}{b} + \ln \frac{b + \frac{\pi r}{p}}{b + \alpha r} \right] \quad (5.4)$$

where p is the total poles of the compulsator, 2α is the filled radian of one armature winding on one pole. b is the length of the magnetic path of armature winding in radial direction, δ is the air gap between the outer surface of the conductive shield and the inner surface of the armature winding in the radial direction. h_a is the pure height of the armature windings in the radial direction and Δ is the insulation thickness between the outer surface of the armature winding and the inner surface of the laminated stator iron in radial direction. The equation for b is as follows [12].

$$b = \frac{\delta}{2} + h_a + \Delta \quad (5.5)$$

Using these equations, the inductance for the CPCPA was calculated and the results have been included in the table below.

Table 5.1: Internal inductance calculation of the Cal Poly Compulsator.

Inductance Term	Inductance (H)
L_i	1.422e-7
L_δ	7.992e-6
L_E	3.197e-6
L_{calc}	1.133e-5
L_{approx} [3, 14]	1.000e-5

Using the equations [12] above, it was found that the CPCPA's approximated value was only 13% off of from the calculated value. The approximated value was used for all analysis within this paper.

To see the impacts upon system performance, the compulsator model was run multiple times while varying the systems inductance, which ranged between 1e-7 H

and $2\text{e-}4$ H. The lower value was chosen from looking at system inductance values from other compulsators in the literature, while the higher value was chosen to see what a high inductance would do to system performance. Ten total test cases were run between these limits, and the CPCPA's inductance of $1\text{e-}5$ H was included as a data point for reference. A plot of the current discharge performance from varying the system inductance can be seen below in Figure 5.8.

Figure 5.8: Compulsator discharge performance for varying the overall inductance of the system.

The previous three cases examined changes to system voltage, and shared similar effects upon discharge performance. This time, drastically different behavior can be seen when inductance is varied within the system. Peak current increases for lower inductance values, which was an expected result. Interestingly, higher inductance values cause the pulse to lengthen and maintain an almost constant discharge current. In Figure 5.9 there are four additional plots that provide additional insight into what is going on within the system.

Figure 5.9: Continued compulsator discharge performance for varying the overall inductance of the system.

The red plot in the top left shows how projectile velocity is affected by system inductance. Velocity was extremely sensitive to changes in inductance, however lowering system inductance below $1\text{e-}6$ H surprisingly caused velocity to drop. A closer view of the top left plot has been included below.

Figure 5.10: Closer view of impact of low system inductance on projectile velocity.

It is unclear what exactly could be causing the negative diminishing returns for continuously reducing the inductance in the system shown in Figure 5.10. Inductance from the railguns characteristics could cause an lower limit for the minimum possible inductance in a compulsator. Further studies into this phenomena are not covered in this paper, but could warrant further investigation. Returning to the other plots in Figure 5.9, efficiency and peak discharge current are extremely sensitive to inductance variations within the system. The most interesting result of varying system inductance is how pulse width greatly increases for high inductance. This behavior might be useful for other high power applications beyond electromagnetic launch, and could warrant further investigation.

As discussed above, a lot of different system parameters affect the inductance of a compulsator. Engineering design efforts would be best spent ensuring that a compulsator system will be low enough (somewhere between $1e-5$ and $1e-7$ H) so high discharge currents can be reached. Modifying other elements of the rotor/stator to tweak inductance beyond this point will probably cause adverse effects to other important system variables like resistance or voltage.

5.1.5 Compulsator Minimum Inductance [L_{min}]

L_{min} represents the minimum inductance within the compulsator. Inductance will vary with rotor position, this can be caused by compensation [8], rotor design, and stator design. The CPCPA was designed with the intent of having a constant inductance to simplify the understanding of the system and design. Inductance is a very important characteristic of a compulsator since it determines the rate of current discharge in the system 2.11. Inductance can be approximated using electromagnetic FEA tools [17] or calculated [12].

To see the impacts upon system performance, the compulsator model was run multiple times while varying the compulsators minimum inductance, which ranged between $6\text{e-}7$ H and $1\text{e-}5$ H. Diminishing returns were found below $1\text{e-}6$ H and the minimum inductance could not go higher than $1\text{e-}5$ H. Ten total test cases were run between these limits, and the CPCPAs inductance of $1\text{e-}5$ H was included as a data point for reference. A plot of the current discharge performance from varying the system inductance can be seen below in Figure 5.11.

Figure 5.11: Compulsator discharge performance for varying the minimum inductance of the system.

Peak current increases incrementally as minimum inductance decreases, which was an expected result. Unlike the previous variables that have been examined, only marginal decreases to pulse width occur as L_{min} decreases. In Figure 5.12 there are four additional plots that provide additional insight into what is going on within the system.

Figure 5.12: Continued compulsator discharge performance for varying the minimum inductance of the system.

Each of the four plots has the x-axis on a log scale for minimum inductance. As minimum inductance is varied, better system performance is observed for larger flux compression ($\frac{L_{max}}{L_{min}}$) ratios. The improvements in performance are fairly linear up until $1e-6$ H, where the diminishing returns observed in Figure 5.9 come into play.

As discussed previously, it is difficult to tailor the inductance of a compulsator without increasing system complexity. While there do appear to be tangible gains in system performance through lowering the minimum inductance, engineering design efforts would probably be best spent trying to improve performance by focusing on other compulsator parameters. The key is to ensure that the overall inductance is low enough prevent the elongated pulses seen in Figure 5.8.

5.1.6 Compulsator Maximum Inductance [L_{max}]

L_{max} represents the maximum inductance within the compulsator. Inductance will vary with rotor position, this can be caused by compensation [8], rotor design, and stator design. The CPCPA was designed with the intent of having a constant inductance to simplify the understanding of the system and design. Inductance is a very important characteristic of a compulsator since it determines the rate of current discharge in the system 2.11. Inductance can be approximated using electromagnetic FEA tools [17] or calculated [12].

To see the impacts upon system performance, the compulsator model was run multiple times while varying the compulsators maximum inductance, which ranged between 1e-5 H and 3e-3 H. Ten total test cases were run between these limits, and the CPCPAs inductance of 1e-5 H was included as a data point for reference. A plot of the current discharge performance from varying the system inductance can be seen below in Figure 5.13.

Figure 5.13: Compulsator discharge performance for varying the maximum inductance of the system.

Unlike the incremental performance gains seen by decreasing L_{max} , peak current decreases rapidly as L_{max} increases. This is an expected result after the previous examination into overall inductance. Pulse width quickly increases with maximum inductance, causing the constant-current discharge pulses that were also seen in Figure 5.8. In 5.14 there are four additional plots that provide additional insight into what is going on within the system.

Figure 5.14: Continued compulsator discharge performance for varying the maximum inductance of the system.

Each of the four plots has the x-axis on a log scale for maximum inductance. As maximum inductance increases, system performance falls off dramatically. For electromagnetic launch applications, a high peak current is desired. Varying the maximum inductance in the system is not recommended. Again, the key is to ensure that the overall inductance is low enough prevent the elongated pulses seen in Figures 5.8 & 5.13.

5.1.7 Resistance of Compulsator Rotor Winding Phase [R_c]

R_c represents the internal resistance of the compulsator, which primarily comes from the resistance within the copper windings inside the rotor. The internal resistance affects the current discharge rate (Equation 2.13) of the compulsator. Varying the

internal resistance of the compulsator requires changes to the design of the rotor winding scheme and the geometry of the rotor.

To see the impacts upon system performance, the compulsator model was run multiple times while varying the internal resistance. Resistance was varied between a minimum of $1\mu\ \Omega$ to a maximum of $1m\ \Omega$. During initial design investigations of the CPCPA, significant drop offs in system performance were seen above $1m\ \Omega$, which is the reason for that upper limit. The minimum limit of $1\mu\ \Omega$ was used to mirror resistance values for other compulsators found in the literature. Also, only marginal improvements to performance were seen as this limit was approached in the following analysis. Ten total test cases were run between these limits, and the CPCPAs resistance of $375\mu\ \Omega$ was included as a point for reference. A plot of the current discharge performance from varying the internal resistance in the rotor can be seen below in Figure 5.15.

Figure 5.15: Compulsator discharge performance for varying the system resistance.

Changing internal resistance affects the pulse shape differently than seen before where voltage or inductance were varied. In this case peak current rises when resistance is lowered, which is expected. The pulse width shrinks marginally, which can be beneficial when trying to match pulse length to the point the projectile leaves the barrel of the railgun. In Figure 5.16 there are four additional plots that provide further insight into what is going on within the system.

Figure 5.16: Continued compulsator discharge performance for varying the system resistance.

All of the plots in Figure 5.16 have a log scale for resistance on the x-axis. It is interesting to note that improvements to system performance are fairly linear for resistances below $500\mu\Omega$. This resistance regime also falls within the desirable resistance values for compulsators. However, there are diminishing gains in performance as $1\mu\Omega$ is approached. Voltage is not affected by changing the resistance within the system.

Although winding schemes with parallel turns can be difficult to assemble, designing the rotor and its windings to minimize resistance within the system should be a top design priority. It is fairly straightforward to calculate the resistance in the windings, and it is easy to understand how the rotor might have to be designed to reach a desired resistance value. Similar to when the number of poles was examined, the key things to consider will be machining costs and the size of the rotor and stator. Of all the compulsator parameters explored, internal resistance is probably the most important variable to focus design efforts on lowering. Further discussion on resistance and rotor geometry are explored in the next section.

5.1.8 Rotor Diameter and Length

As has been seen in the previous sections, a majority of design parameters are affected by rotor geometry. One particular example is the length of the rotor, which can affect the voltage of the system (Equation 2.4). A longer rotor would have a higher voltage and could lead to better performance. Meanwhile, the diameter of the rotor will affect both how many rotor slots could be placed for phase windings and how wide these slots can be. The width of the rotor slots is very important as that determines both the possible number of surface conductors (slot width) and how many parallel path windings (slot depth) can fit within a slot.

The interactions between all of these different variables was intriguing, and an investigation into how a redesign of the rotor's geometry would impact performance. Matlab's `fmincon` function was used to examine the optimal rotor geometry using the CPCPA as a starting reference point.

Fmincon finds the minimum value of a constrained, nonlinear multi-variable function. The compulsator model is the multi-variable function of interest, and the goal is to find the maximum projectile velocity possible within a variety of constraints. To

find a maximum value, output velocity is multiplied by $[-1]$ so fmincon can find a minimum.

To reduce computation time, the compulsator state space model was modified to output only the final projectile velocity. To ensure that the output rotor geometry that fmincon finds is comparable to the CPCPA, a nonlinear constraint was imposed on the rotational energy. Fmincon must calculate rotor geometries that will have a rotational energy of 45 kJ to match the CPCPA rotor. The initial rotor geometry of the CPCPA was used as a starting point, and the following boundaries were placed upon L_r , D_r , and Rotor RPM can be seen in the table below. The number of conductors was not included in this initial study, but is discussed later in this section.

Table 5.2: Boundary ranges for variables optimized with Fmincon.

	Initial Rotor	Lower Bound Limits	Upper Bound Limits
Rotor Length (in)	10	2	24
Rotor Diameter (in)	8	5	24
Rotor RPM	5000	500	5000

RPM was not allowed to surpass 5,000 so that more interaction could be seen in the geometry of the rotor. Increasing RPM would also raise the electrical frequency of the system, which would also increase internal resistance and make it more difficult to gain insight into rotor design. Rotor length had a practical lower limit set of 2 inches, and rotor diameter's lower limit of 5 inches is to ensure that there is still enough room to still fit 16 rotor slots into the rotor. Both of the upper limits for length and diameter were set to 24 inches because dimensions this large would be difficult to scale the rest of the compulsator system to match and result in a much

more expensive system.

The expected result of the optimization study would be that the rotor's length would extend to some maximum value. The rotor's diameter would shrink to keep stored rotational energy constant in the system. This change in length would raise the voltage within the system. Remembering the relationships seen from the previous sections, significant improvements to system performance would be seen with higher voltage. Graphical results of the current discharge between the CPCPA and the optimized rotor has been included in the figure below.

Figure 5.17: Compulsator discharge performance for varying rotor length and diameter.

From the relationships seen in Figures 5.1, 5.4, and 5.6 it can already be inferred that system voltage has increased based on the direction that the curve has shifted. Peak current has risen by approximately 15 kA, and significant improvements to system performance should be seen. A table of the results from the optimization of the rotor has been included in Table 5.3. Rotor length increased by 240% to the maximum upper limit imposed by the boundaries of the optimization, voltage increased by the exact same percentage. This direct relation should be expected due to Equation 2.4. Rotor diameter shrank to 6.4 inches, and projectile velocity improved

by almost 100 m/s from 409 m/s to 503 m/s. This could potentially represent another design path to improve system performance.

Table 5.3: Fmincon Results for Optimizing Rotor Dimensions

	Original Rotor Value	Optimized Rotor Value
Rotor Length (in)	10	24
Rotor Diameter (in)	8	6.4
Rotor RPM	5000	5000
Voltage (V)	156	375
Projectile Velocity (m/s)	409	503

However, there are a few problems with both the results and the limited depth of analysis from this optimization study. As the rotor geometry changes, the winding length required for the phase windings will change. Longer winding lengths will result in larger internal resistances, because internal resistance is one of the most important variables for compulsator performance this relationship must be included. Additionally, the cost of incorporating a rotor where the length is drastically larger than its diameter would be very high. As mentioned, the cost of materials for both the stator and the rotor were substantial for the CPCPA. Ordering a stock of steel that was 24 inches long would be both very expensive and very costly to machine to high tolerance. Additionally, the cost for more magnets and additional metal for the stator would be prohibitive.

Because of these factors, an additional optimization study was conducted to account for changes in resistance within the rotor. The following relationships were

used as part of the constraints within fmincon:

$$L_{slot} = \pi D_r \frac{.318}{16} \quad (5.6)$$

Where L_{slot} is the width of the rotor slots, .318 is the percentage of rotor circumference allowed for the total number of rotor slots, and is divided by 16 for the individual rotor width. This allows for rotor width to increase with rotor diameter, rotor slots were constrained to the geometry of a square. Although there could be benefits to increasing the number of parallel path windings with deeper rotor slots, this was option was not modeled to simplify the analysis. Resistance was calculated using Equations 2.7, 2.8, and 2.9. To account for parallel winding paths, the final AC resistance was divided by the total number of surface conductors. Finally, the diameter of the copper magnet wire was incorporated into the model where it could be compared with the slot width so that the number of surface conductors could increase or decrease as needed.

Table 5.4 shows the initial starting reference point using the CPCPA's parameters. The upper and lower limits for the new parameters modeled are shown as well. Wire diameter was not allowed to vary. A separate study, that was not included in this paper was conducted that kept the number of conductors constant and allowed the wire diameter to vary, but the results were not as effective as varying the number of conductors so that study was left out of this paper. The upper limit of 12 conductors was used since that was at the inflection point in performance gains seen in Figure 5.5.

Table 5.4: Boundary ranges for variables optimized with Fmincon that accounts for rotor resistance.

	Initial Rotor	Lower Bound Limits	Upper Bound Limits
Rotor Length (in)	10	4	24
Rotor Diameter (in)	8	6	24
Rotor RPM	5000	5000	5000
# of Conductors Per Phase	4	2	12
Wire Diameter (in)	.102	.102	.102

With resistance now incorporated into the model, `fmincon` should produce a rotor that is trying to minimize resistance to provide the maximum projectile velocity possible. The rotor length should decrease to lower the phase winding path length resistance. Rotor diameter should increase to allow for wider rotor slots so additional parallel paths can be incorporated to reduce resistance. Voltage will drop with a decreased rotor length, but it has already been shown that drops in resistance will outweigh gains in voltage. Graphical results of the current discharge between the CPCPA and the optimized rotor that accounts for resistive effects has been included in the Figure 5.18.

Figure 5.18: Compulsator discharge performance for varying rotor length and diameter while also accounting for winding resistance.

The shift in pulse width would suggest that a rotor with a lower resistance was found using `fmincon`, similar to what was seen in the plot of varied resistance in Figure 5.15. Peak current only appears to have risen by 2 kA, but there should

be concrete gains in system performance due to lowered resistance. A table of the resulting optimized rotor has been included below.

Table 5.5: Fmincon results for optimizing rotor dimensions while accounting for rotor resistance.

	Original Rotor Value	Optimized Rotor Value
Rotor Length (in)	10	4.55
Rotor Diameter (in)	8	9.74
Rotor RPM	5000	5000
Voltage (V)	237	108
Resistance (Ω)	3.69e-4	1.54e-4
# of Conductors	4	6
Wire Diameter (in)	.101	.101
Slot Width (in)	.500	.608
Single Path Winding Length (in)	100.5	88.5
Projectile Velocity (m/s)	409	468

Rotor length decreased significantly, while rotor diameter increased which was expected. It is important to note that the rotor's moment of inertia increases with larger diameters: $J_r = \frac{M_r}{2}(\frac{D_r}{2})^2$. This allows the rotor's diameter and the slot width to grow. The number of surface conductors increased from 4 to 6 (as did the number of parallel paths), and the single winding path length decreased by 12 inches from 100.5 inches to 88.5 inches. These two combining effects resulted in resistance dropping from $369\mu\Omega$ down to $213\mu\Omega$, which is significant. Dropping the rotor length does

result in a large drop in voltage within the system, however the benefits of lowered resistance still result in improved performance.

All of these different factors result in a large improvement in performance from 409 m/s to 468 m/s. These results are very important in identifying where to focus engineering design efforts to maximize the performance of a compulsator. One of the issues that plagued the CPCPA project was that the rotor size had been determined very early on in the design phase, and too much material and analysis had already been committed to that design route for redesigns to be implemented. Had this information been available earlier into the project very different results would have been seen.

This rotor geometry would have represented very large cost savings for the CPCPA project. The amount of materials (permanent magnets, stator structural elements, interpole copper windings, support structure) would have been reduced by slightly more than 50% which is significant. The cost of the rotor would have dropped as well. The original CPCPA rotor weighed approximately 140 lbs (64 kg), whereas the new optimized rotor's mass is 95 lbs (43 kg) the drop in material cost is noticeable.

Determining the rotor geometry for a compulsator system is the most important aspect of the system and will affect the final cost and complexity of the system. The coupled effects of resistance, voltage, and energy density of rotor design should be taken into consideration right away when designing a compulsator. The following section provides a more graphical overview to synthesize the separate analyses of the various compulsator parameters.

5.1.9 Combined Analysis of the Compulsator Design Space

The previous sections have discussed the individual portions of the compulsator design space. The information from the previous plots has been synthesized into Figures 5.19

and 5.20 for a more comprehensive discussion. Examining the changes to current discharge profile (Figures 5.1, 5.4, 5.6, 5.8, 5.11, 5.13, & 5.15) for each of the design parameters provides useful insight into about system performance. The data from prior analysis has been combined into a single plot which can be seen below in Figure 5.19 that shows the peak current and the time of peak current for each of the seven data sets analyzed.

Figure 5.19: Comparison of current discharge performance between the different compulsator design parameters.

As discussed, there was related behavior in how the current pulse would shift when N_p , N_{cp} , and B were varied. Very high peak current values are possible with large values for these terms, and the pulse length will decrease with higher currents. Meanwhile, dropping the system voltage will elongate the pulse width and result in a lower peak current.

Also, similar affects to the current pulse were noted between L_{con} , L_{min} , and L_{max} which affected system inductance. Lowering overall inductance resulted in similar results to raising voltage in the system: higher peak currents and smaller pulse lengths. If inductance was too high within the system, then peak current would drop dramatically and the pulse length increased as well.

The outlying variable in this plot is the affect that system resistance has on current discharge. Lowering resistance increases peak current and slightly changes the time of peak current. However, as seen in Figure 5.15 the total pulse length partially decreases with lower resistance.

The final plot of interest is in Figure 5.20 below, which takes all of the performance data from Figures 5.2, 5.5, 5.7, 5.9, 5.12, 5.14, & 5.16 and compiles it into one plot where all the different dimensions of compulsator design space can be seen in one place. The columns contain the performance data for each design variable analyzed, and the black diamond represents the CPCPA's spot in the space.

Figure 5.20: Compulsator design space with the CPCPA as a reference point.

Each of the columns within this figure are independent from each other, except for the anchor data point of the CPCPA. Each column represents the same performance changes seen from the seven prior studies of the different compulsator design parameters. The relative magnitude in performance gains or losses can be quickly

compared with this figure. The three voltage parameters (N_p , N_{cp} , and B) can be continuously increased for improved performance; however, the trade-off for increasing these variables will result in higher system cost and complexity. The system inductance (L_{con} , L_{min} , and L_{max}) should be minimized to allow for desired compul-sator discharge performance. While lowering the minimum and overall inductance of the system can improve performance, changing the inductance can complicate system design and increase cost for minimal benefit. Internal Resistance (R_{cp}) can drastically affect the performance of the system and should be minimized to reach desired perfor-mance values. Although system resistance can be continuously lowered for improved performance, the trade-offs of physical dimensional constraints and assembly com-plexity will need to be considered. After performing the variable-by-variable study and the rotor optimization study, the most important aspect of design in this system is the rotor. In retrospect, a shorter and wider rotor should have been pursued for the CPCPA. This would have dropped material costs and simplified the fabrication required for the machine.

6. Feasibility of Low-Cost Compulsator Design

6.1 Lessons from the Cal Poly Compulsator Project

This project began in May of 2011 under the broad goal to design and build a compulsator to power a railgun system. The project began with no budget, and a multi-disciplinary team of students would be needed to for the project. There is minimal published information on compulsators which presented an extensive learning curve for someone wanting to design one of these systems for the first time. All of these factors should have been warning signals about the difficult engineering challenges that this project would face. The CPCPA project provided a great learning experience for the author in understanding the importance of systems engineering concepts and project management. The prior work on the CPCPA[14] already includes a list of lessons learned from the project.

Across multiple sources of funding, approximately \$11,000 was spent during the CPCPA project and the switching circuitry to the EMRG Mk 1.1. The author estimates that approximately \$5,000 in additional funds would be required to complete the CPCPA, assuming that there is a solid-state switch that could be used to transfer power into a dummy load and the existing data acquisition equipment at Cal Poly's labs could be used. More information about the remaining work required for the CPCPA is covered in the "Future Work" section of the paper.

The CPCPA project goals were too ambitious for the level of experience and

resources available two years ago. The efforts during the academic year of 2011-2012 should have been focused purely on developing a paper design for a compulsator system. However, it was within reason for pulsed power switching circuitry to be designed and developed during the academic year[10], which was done to some degree. The conflicting requirements for senior project objectives pushed the project into the riskier task of "design and build" all within one academic year.

The lack of information inhibited the ability for the team to design a system while understanding all the implications of architecture design decisions. This caused problems throughout the project as new insights into compulsator design would occur after materials had already either been ordered or machined. A great example would be the optimization study handled on the rotor where the results from Table 5.5 would have drastically altered the design of the system and reduced the amount of materials by almost half. Unfortunately, it took time to understand the governing equations of compulsator operation and develop a model for compulsator performance. If the efforts from the senior project in 2011-2012's was focused purely on system design and sourcing materials and components, then the Master's thesis in 2012-2013 would have been able to handle fabrication, assembly, and system testing. That was not the case, but the design space analysis and model developed to this point provide a comprehensive starting point for introductory compulsator design.

6.2 Low-Cost Compulsator Design

External excitation requires the use of high-performance power supplies for the field windings, which can be very expensive. As has been discussed, permanent magnet excitation could represent a viable design route for iron-core systems since the strength of permanent magnets hits its limit around the saturation limit for most iron compositions. Passive compensation is relatively simple to understand and implement

into the design of the rotor. Low-cost (around \$15k-\$25k for materials and contract machining) passive iron-core permanent magnet compulsators could be of use in applications requiring less than 100 kA of current. Separate costs would exist for switching circuitry, data acquisition, engineering overhead, and assembly overhead.

Since the CPCPA was not completed, no quantitative discussion can be had about the full life-cycle cost of the system regarding replacement parts or duty cycle. This would have been a very interesting aspect to explore and quantify, since the CPCPA was designed for extensive laboratory testing.

7. Conclusion and Future Work

7.1 Conclusion

Compulsator design is a complicated process that requires a multidisciplinary approach and a comprehensive understanding of the design space. Significant attention to detail must be considered early in the design process with respect to design for manufacturing in order to design a compulsator system with performance comparable to the CPCPA while staying within a budget level between \$10,000-\$20,000 for materials, components, and fabrication. The initial lack of detailed system knowledge in the Cal Poly Compulsator project during 2011-2012 hampered the efforts to keep the project on a one-year design and build schedule. This thesis was written with the goal of capturing the lessons learned from the CPCPA and synthesizing system information from multiple sources to assist individuals who are looking to design a compulsator but have limited prior experience with these systems.

This thesis provides a functional compulsator model with corresponding analysis of how system performance is affected by varying different design variables and discussing the associated design implications for each aspect of the system. The validation efforts performed in this thesis showed that the compulsator model used in this paper closely matches the pulse width from published data. Matching the pulse width is extremely important for railgun systems, because any current discharged after the projectile has left the barrel is wasted energy. However, the peak current value from

the model was 50% of the peak current from published data, and the final velocity from the model was 30% of the final velocity from the published data[26, 9]. Since the CPCPA was not completed, experimental validation of the compulsator model to real world results has not occurred. For safety reasons, if the model outlined in this thesis is used for compulsator design, all structural members should assume that at least two (2) times more current could discharge during operation.

The examination of the compulsator design space within this thesis provided the following design insights. As the primary element of the machine, the rotor should be the first place to begin sizing a compulsator system. The rotor's dimensions will drive the rest of the system's size and associated material costs. The rotor is also the main source of internal resistance within the system. Minimizing the resistance of the system can provide substantial improvements to system performance, with the only limiting factor being the physical constraints of the chosen winding geometry within the rotor. If resistance is too high ($1\text{ m}\Omega$ or larger), then performance falls off dramatically due to resistive heating losses in the system. Although a low system inductance is important to the operation of a compulsator (a minimum design target of $10\text{ }\mu\text{H}$ is recommended), it was found that continuously lowering inductance below $1\text{ }\mu\text{H}$ provided asymptotic improvements to performance. Determining the inductance of the rotor can be approximated with finite element tools or calculated[12] if the geometry of the rotor and stator is known. Engineering design efforts should focus on verifying that a given rotor and stator geometry will result in an inductance value that falls within the above range, but not on optimizing the design to minimize inductance. The third area of interest is system voltage, which can be increased through a variety of parameters (N_p , N_{cp} , B , L_r , RPM). Increasing any one of these variables will lead to improved performance but introduces either additional system complexity or requires the need for more expensive materials. A comprehensive approach to deciding on the final value for these variables within a system is recommended.

7.2 Future Work

7.2.1 Completing the CPCPA

The Cal Poly Compulsator is currently in a paused state of assembly, with all of the materials and components currently in storage with the Aerospace Engineering Department at Cal Poly. Right now, the plan for who will try to finish the assembly and testing of the CPCPA is not defined. One of the important remaining tasks is the assembly of the rotor, Appendix C: "Rotor Winding Task" outlines the necessary work required to complete the rotor. Contracting out this task to a third party was being investigated when the decision was made to halt construction of the CPCPA and the estimated cost of the project was between \$4,000-\$6,000.

The copper brushes need to be integrated with the brush holders and attached to the brush plate that rests outside the commutator. The ends of these brushes are to be connected to a copper plate which has a copper wire that runs through an end plate for attachment to the load of the compulsator.

A mechanism for holding the final assembly into place for testing will need to be constructed, as the original concrete base that was built has been disposed of. The surface must be level and either anchored into the floor or this mechanism must be very heavy to mitigate any vibrational effects from the spinning rotor.

Sensors for measuring the RPM of the rotor and controls for the prime mover need to be created. Solid-state switches are recommended to replace the ignitrons since the original switching circuit for the EMRG Mk 1.1 is no longer operational. The data acquisition equipment currently in use for the EMRG Mk 2 system will be sufficient for capturing the discharge data for the CPCPA.

7.2.2 Constructing a New Compulsator System Instead

Completing the CPCPA might be more expensive than the cost to build a new system that partially recycles some of the components of the CPCPA. From the insights gained from the rotor optimization study, starting from scratch might be preferred. A single-phase system would reduce the complexity of the rotor winding scheme, possibly allowing for it to be done on-campus. A smaller rotor would reduce overall material cost of the system. Most importantly, removing the requirement of discharging into a railgun and only using the graphite "dummy loads" donated by the Naval Postgraduate School would allow for a more modest system to be created as a proof of concept. The current commutator section, prime mover, brake, and clutch could all be reused as well. Lowering system requirements further, using the design insights from this paper, and drawing upon the lessons learned over the past two years would allow for a much higher chance of developing a working compulsator system at Cal Poly.

7.2.3 Additional Modeling Options

Further work could be done to expand upon the optimization code outlined in Appendix B that could allow FMINCON to vary other compulsator variables. However, penalty functions of some variety would be required for the terms that affect voltage. Otherwise the optimizer would just maximize these values to the upper limit without accounting for the additional complexities and costs imposed on the system. Making a useful optimizer around this model that accounted for both compulsator and railgun terms would require a non-trivial amount of effort and was left outside the scope of this thesis.

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A. CPCPA Model Nominal Analysis Code

The attached document contains the code that generates the data from Chapter 3. The following code files and a brief description of what their purpose is has been included.

- **System_Setup.m** - Script that runs the model.
- **CPA_EMRG.m** - Function of the compulsator discharge state space model.
- **Event_RailEnd.m** - Function that ends the simulation when the projectile leaves the railgun.

System_Setup.m

```
clear all
close all
clc
format compact

%% Setup of Variables
%Collin MacGregor
%ctmacgre@calpoly.edu
%California Polytechnic State University, San Luis Obispo, CA

%This code runs analytically solves for the discharge
performance of a
%compulsator/railgun system utilizing a state-space approach.

%% Variables
% global Xrg

Np = 8;           %Number of Poles in the System
Npp = Np/2;       %Number of Pole Pairs in Rotor
Ncp = 4;          %Number of conductors per pole on rotor
B = .45;          %Magnetic Field Strength Density (T)
Dr = 8*.0254;     %Diameter of Rotor (m)
Lr = 10*.0254;    %Length of Rotor (m)
Dst = 7750;       %Density of Steel (kg/m^3)
Mr = (pi*Dr^2/4)*Lr*Dst; %Mass of Rotor (kg)
Jr = Mr*(Dr/2)^2/2; %Inertia of Rotor (kg-m^2)
Lmin= 1e-5;       %Minimum Inductance of Compulsator (H)
Lmax= 1e-5;       %Maximum Inductance of Compulsator (H)
Rho = .5*(Lmax./Lmin - 1); %Compulsator Inductance Modulus
Rcp = .000375;    %Resistance of Compulsator Rotor Winding Phase
                (Ohms)
Ro = 1e-6;        %Resistance of connecting busbar/switching
                (Ohms)
Lo = 1e-6;        %Inductance of connecting busbar/switching
                (H)
Ph_1= 0;          %Electrical Phase Angle "1" (rad)
Ph_2= pi;         %Electrical Phase Angle "2" (rad)
Rrg = 3.2104e-004; %Resistance of the Railgun (Ohms)
Xrg = 2.5*0.3048; %Length of Railgun Rails (m)
RPrgr= Rrg*Xrg;   %Resistance Gradient of Rails (Ohms/m)
LPrgr= 3.2712e-007; %Inductance Gradient of Rails (H/m)
Mp = .001;        %Mass of Particle (kg)
dt = 1e-4;        % Time step size (s)
```

```

%Other Variables
RPM0= 5000;           %Initial RPM of the Rotor (rpm)
Wr0 = RPM0/60*2*pi; %Angular Velocity of Rotor (rad/s)
x0  = 0;              %Initial Particle Position (m)
Vp0 = 0;              %Initial Particle Velocity (m/s)
I_0 = 0;              %Initial Current of Compulsator (A)

%SETUP & RUN ODE45

t0  = 0;              %Initial Time (s)
tf  = 12e-3;          %Final Simulation Time (s)
tspan = t0:dt:tf;

IVP = [Wr0; x0; Vp0; I_0];

Vars = [Np; Npp; Ncp; B;...
        Dr; Lr; Jr; ...
        Lmin; Lmax; Rho; Rcp; Ro; Lo; Ph_1; Ph_2;...
        Rrg; Xrg; RPr; LPr; Mp; dt];

ODE_FUN = @CPA_EMRG;
options = odeset('AbsTol',1e-8,'RelTol',1e-
8,'Events',@Event_RailEnd);

[Tout, dIVP] = ode45(ODE_FUN,tspan,IVP,options,Vars);

Wout = dIVP(:,1);
Xout = dIVP(:,2);
Vout = dIVP(:,3);
Iout = dIVP(:,4);

%% Manipulate output Data
Vtip_out= Wout*Dr/2;
We_out = Wout*Npp/(2*pi);
Volt_out = Np*Ncp*Lr*B*Vtip_out;%.*sin(We_out.*Tout);
Wrpm_out = Wout*60/2/pi;
Er_out = .5*Jr*Wout.^2;
Pwr_out = Volt_out.*Iout;
Velocity = Vout(end);
RPM_dropP = (1-Wout(end)/Wout(1))*100;
Tend = Tout(end);

%Energy At end Calculation
Eo_s = .5*Jr*Wout(1)^2; %J
Ef_p = .5*Mp*Velocity^2; %J

```

```

P_accel = zeros(length(Xout),1);
for j = 2:length(Xout)
    P_accel(j) = (Vout(j)^2-Vout(j-1)^2)/(2*(Xout(j)-Xout(j-1)));
end

F_accel = Mp*P_accel; %kgs

CP_E_Out = Tout.*Pwr_out; %Energy Discharged by Compulsator (J)
P_E_Out = .5*Mp*Vout.^2; %Projectile Energy (J)

%% Plotting
subplot(3,1,1)
plot(Tout*1e3,Iout/1e3,'linewidth',2)
xlabel 'Time (ms)'
ylabel 'Current (kA)'
title 'Compulsator Output Current'

subplot(3,1,2)
plot(Tout*1e3,Volt_out,'m','linewidth',2)
xlabel 'Time (ms)'
ylabel 'Voltage (V)'
title 'Compulsator Voltage'

subplot(3,1,3)
plot(Tout*1e3,Pwr_out/1e6,'r','linewidth',2)
xlabel 'Time (ms)'
ylabel 'Power (MW)'
title 'Compulsator Power Output'

figure (2)
subplot(2,1,1)
plot(Tout(end)*1e3,Xrg,'rs','linewidth',2)
hold on
plotyy(Tout*1e3,Xout,Tout*1e3,Vout)
[AX,H1,H2] = plotyy(Tout*1e3,Xout,Tout*1e3,Vout,'plot');
set(get(AX(2),'Ylabel'),'String','Velocity (m/s)')
set(get(AX(1),'Ylabel'),'String','Position (m)')
set(H1,'linewidth',2);
set(H2,'linewidth',2)
xlabel('Time (ms)')
legend('End of Railgun','location','north')
title('Railgun Projectile Performance')

subplot(2,1,2)
plotyy(Tout*1e3,Wrpm_out,Tout*1e3,Er_out)

```

```

[AXo,H1o,H2o] =
plotyy(Tout*1e3,Wrpm_out,Tout*1e3,Er_out/1e3,'plot');
set(get(AXo(2),'Ylabel'),'String','Rotational Energy (kJ)')
set(get(AXo(1),'Ylabel'),'String','Rotor RPM (rpm)')
set(H1o,'linewidth',2);
set(H2o,'linewidth',2)
title 'Compulsator Energy Output'

figure(3)
semilogy(Tout*1e3,P_accel,'r','linewidth',2)
xlabel 'Time (ms)'
ylabel 'Particle Acceleration (m/s^2)'
title 'Projectile Accelleration within the Railgun Barrel'

%This is to prevent drastic 10^-15 on semilog plots
ind = min(find(P_E_Out > .1));
Tot_E = Er_out+CP_E_Out+P_E_Out;

figure(4)
semilogy(Tout*1e3,Er_out,'g','linewidth',2)
hold on
plot(Tout*1e3,CP_E_Out,'b','linewidth',2)
plot(Tout(ind:end)*1e3,P_E_Out(ind:end),'r','linewidth',2)
plot(Tout*1e3,Tot_E,'k--','linewidth',2)
hold off
xlabel 'Time (ms)'
ylabel 'Energy (J)'
legend('Rotor Energy','Railgun Energy','Projectile
Energy','Total Energy of Systems')
title('Energy Conservation Comparison From Rotor to Railgun to
Projectile')

disp(['Voltage @T=0 = ',num2str(Volt_out(1)),' (V)'])
% disp(['Final Voltage= '
disp(['End Velocity = ',num2str(Vout(end)),' (m/s)'])
disp(['Peak Current = ',num2str(max(Iout)/1e3),' (kA)'])
disp(['Avg Current = ',num2str(mean(Iout/1e3)),' (kA)'])
disp(['Peak Power = ',num2str(max(Pwr_out)/1e6),' (MW)'])
disp(['Pulse Time = ',num2str(Tout(end)*1e3),' (ms)'])
disp(['Efficiency = ',num2str((Ef_p/(Er_out(1)-
Er_out(end))))*100),' %'])

```

CPA_EMRG.m

```
function [ dIVP ] = CPA_EMRG( T, IVP, Vars )
% global Xrg
Np = Vars(1); %
Npp = Vars(2);
Ncp = Vars(3); %
B = Vars(4); %
Dr = Vars(5); %
Lr= Vars(6); %
Jr = Vars(7);
Lmin = Vars(8); %
Lmax = Vars(9); %
Rho = Vars(10);
Rcp = Vars(11); %
Ro = Vars(12);
Lo = Vars(13);
Ph_1 = Vars(14);
Ph_2 = Vars(15);
Rrg = Vars(16);
Xrg = Vars(17);
RPrG = Vars(18);
LPrG = Vars(19);
Mp = Vars(20);
dt = Vars(21);

%This function analytically solves for the state space model of
the
%Compulsator/Railgun system.

Wr = IVP(1);           %Angular Velocity of Rotor (rad/s)
x  = IVP(2);           %Position of projectile (m)
Vp = IVP(3);           %Velocity of projectile (m/s)
I  = IVP(4);           %Current of Compulsator (A)

%% Calculate State 1: Change in Angular Velocity
Er = .5*Jr*Wr^2;       %Rotational Energy Stored in Rotor (J)
Vtip= Wr*Dr/2;         %Tip Speed of Rotor Edge (m/s)
Vo  = Np*Ncp*Lr*B*Vtip; %EMF Voltage of Rotor (V)
We  = Wr*Npp/(2*pi);   %Electrical Frequency of Machine (1/s)
V    = Vo*sin(We*T);   %Voltage of Machine over time (V)

% dWr = 0;
dWr = -sqrt(((2*V*I)/Jr)*dt)/dt;

%% Calculate State 3: Change in Particle Velocity
```



```

dVp = (LPrg*I^2) / (2*Mp); %Particle Accelleration (m/s^2)

%% Calculate State 2: Change in Particle Position

dx = Vp; %Particle Velocity (m/s)

%% Calculate State 4: Change in Compulsator Current
%Phase-1
L1 = Lmin*Rho*sin(We*T-Ph_1);
Top1 = V - I*(Rcp + Ro + RPrG*x) + I*(We*Lmin*Rho*sin(We+Ph_1) -
LPrg*Vp);
Bot1 = Lmin*(1+Rho) + L1 + LPrg*x + Lo;

L1b = Lmin*Rho*sin(We*T-Ph_1);
Top1b = V - I*(Rcp + Ro + RPrG*x) + I*(We*Lmin*Rho*sin(We+Ph_1)
- LPrg*Vp);
Bot1b = Lmin*(1+Rho) + L1b + LPrg*x + Lo;

L1c = Lmin*Rho*sin(We*T-Ph_1);
Top1c = V - I*(Rcp + Ro + RPrG*x) + I*(We*Lmin*Rho*sin(We+Ph_1)
- LPrg*Vp);
Bot1c = Lmin*(1+Rho) + L1c + LPrg*x + Lo;

L1d = Lmin*Rho*sin(We*T-Ph_1);
Top1d = V - I*(Rcp + Ro + RPrG*x) + I*(We*Lmin*Rho*sin(We+Ph_1)
- LPrg*Vp);
Bot1d = Lmin*(1+Rho) + L1d + LPrg*x + Lo;

%Phase-2
L2 = Lmin*Rho*sin(We*T-Ph_2);
Top2 = V - I*(Rcp + Ro + RPrG*x) + I*(We*Lmin*Rho*sin(We+Ph_2) -
LPrg*Vp);
Bot2 = Lmin*(1+Rho) + L2 + LPrg*x + Lo;

L2b = Lmin*Rho*sin(We*T-Ph_2);
Top2b = V - I*(Rcp + Ro + RPrG*x) + I*(We*Lmin*Rho*sin(We+Ph_2)
- LPrg*Vp);
Bot2b = Lmin*(1+Rho) + L2b + LPrg*x + Lo;

L2c = Lmin*Rho*sin(We*T-Ph_2);
Top2c = V - I*(Rcp + Ro + RPrG*x) + I*(We*Lmin*Rho*sin(We+Ph_2)
- LPrg*Vp);
Bot2c = Lmin*(1+Rho) + L2c + LPrg*x + Lo;

L2d = Lmin*Rho*sin(We*T-Ph_2);
Top2d = V - I*(Rcp + Ro + RPrG*x) + I*(We*Lmin*Rho*sin(We+Ph_2)
- LPrg*Vp);

```

```

Bot2d = Lmin*(1+Rho) + L2d + LPrq*x + Lo;

%Summation of Phase outputs
dI  = Top1/Bot1 + Top2/Bot2 + + Top1b/Bot1b + Top2b/Bot2b + ...
      Top1c/Bot1c + Top2c/Bot2c + Top1d/Bot1d + Top2d/Bot2d;

dIVP = [dWr; dx; dVp; dI];

end

```

Event_RailEnd.m

```
function [value,isterminal,direction] = Event_RailEnd( t, y,  
Vars )  
% global Xrg  
Xrg = Vars(17);  
%Stop integration when particle leaves the rails  
v1 = y(2) - Xrg;  
value      = v1;  
isterminal = 1;  
direction  = 0;  
  
end
```

B. Rotor/Resistance Optimization Code

The attached document contains the code that performed an optimization of the rotor while accounting for changes to system resistance. The following code files and a brief description of what their purpose is has been included.

- **O10_RotorResist.m** - Script that runs the optimization study.
- **CPA_EMRG.m** - Function of the compulsator discharge state space model.
[Same as in Appendix A]
- **O10_Objective.m** - Objective function that optimizes for peak velocity.
- **Exit_Velocity.m** - Streamlined compulsator model that provides peak velocity.
- **O10_NLCON.m** - Function that provides the constraints around the optimizer.
- **Rot_Energy.m** - Allows the rotor dimensions to change, but constrains the total stored kinetic energy of the system.
- **Wire_Dia.m** - Allows the wire diameter of conductors to change within the rotor slot.
- **Rcp_Calc.m** - Allows the number of conductors to change inside the rotor slot.
- **Event_RailEnd.m** - Function that ends the simulation when the projectile leaves the railgun. [Same as in Appendix A]

O10_RotorResist.m

```
clear all
close all
clc
format compact

%x = [Lr,      Dr,      RPM0, Ncp,      Dwire,      ]
X0 = [10*.0254, 8*.0254, 5000, 4,      .102*.0254];      %.1019
LB = [4*.0254, 6*.0254, 5000, 2,      .102*.0254];      %.01
UB = [24*.0254, 24*.0254, 5000, 12,      .102*.0254];      %.2294

% X0 = [10*.0254, 8*.0254, 5000, 4,      .1019*.0254];      %.1019
% LB = [6*.0254, 6*.0254, 5000, 4,      .01*.0254];      %.01
% UB = [24*.0254, 24*.0254, 5000, 4,      .2294*.0254];      %.2294

% LB = [2*.0254, 5*.0254, 500, 1e-6, 1,      .01*.0254];
% UB = [24*.0254, 24*.0254, 7000, 1e-3, 12,      .2294*.0254];

exit = [];

[X,fval,exit,output] =
fmincon(@O10_Objective,X0,[],[],[],[],LB,UB,@O10_NLCON);

%%
%Other Variables
RPM0= X(3);      %Initial RPM of the Rotor (rpm)
Wr0 = RPM0/60*2*pi; %Angular Velocity of Rotor (rad/s)
x0 = 0;      %Initial Particle Position (m)
Vp0 = 0;      %Initial Particle Velocity (m/s)
I_0 = 0;      %Initial Current of Compulsator (A)

Np = 8;      %Number of Poles in the System
Npp = Np/2;      %Number of Pole Pairs in Rotor
Ncp = X(4);      %Number of conductors per pole on rotor
B = .45;      %Magnetic Field Strength Density (T)
Dr = X(2);      %Diameter of Rotor (m)
Lr = X(1); %Length of Rotor (m)

Dst = 7750; %Density of Steel (kg/m^3)
Mr = (pi*Dr^2/4)*Lr*Dst; %Mass of Rotor (kg)

Jr = Mr*(Dr/2)^2/2; %Inertia of Rotor (kg-m^2)
Lmin= 1e-5;      %Minimum Inductance of Compulsator (H)
Lmax= 1e-5;      %Maximum Inductance of Compulsator (H)
```

```

Rho = .5*(Lmax/Lmin - 1); %Compulsator Inductance Modulus
Rcp = Rcp_Calc( Lr, Dr, RPM0, Ncp, X(5)); %Resistance of
Compulsator Rotor Winding Phase (Ohms)
Ro = 1e-6; %Resistance of connecting busbar/switching
(Ohms)
Lo = 1e-6; %Inductance of connecting busbar/switching
(H)
Ph_1= 0; %Electrical Phase Angle "1" (rad)
Ph_2= pi; %Electrical Phase Angle "2" (rad)
Rrg = 3.2104e-004; %Resistance of the Railgun (Ohms)
Xrg = 2.5*0.3048; %Length of Railgun Rails (m)
RPrG= Rrg*Xrg; %Resistance Gradient of Rails (Ohms/m)
LPrG= 3.2712e-007; %Inductance Gradient of Rails (H/m)
Mp = .001; %Mass of Particle (kg)
dt = 1e-4; % Time step size (s)

```

```

%SETUP & RUN ODE45

```

```

t0 = 0; %Initial Time (s)
tf = 10e-3; %Final Simulation Time (s)
tspan = t0:dt:tf;

```

```

%Optimized Compulsator Rotor

```

```

IVP = [Wr0; x0; Vp0; I_0];
Vars1 = [Np; Npp; Ncp; B;...
Dr; Lr; Jr; ...
Lmin; Lmax; Rho; Rcp; Ro; Lo; Ph_1; Ph_2;...
Rrg; Xrg; RPrG; LPrG; Mp; dt];

```

```

%Guess Compulsator Rotor

```

```

RPM2 = X0(3);
Mr2 = (pi*X0(2)^2/4)*X0(1)*Dst; %Mass of Rotor (kg)
Jr2 = Mr2*(X0(2)/2)^2/2; %Inertia of Rotor (kg-m^2)
Wr2 = RPM2/60*2*pi; %Angular Velocity of Rotor (rad/s)
Ncp = X0(4);
Rcp2 = Rcp_Calc( X0(1), X0(2), X0(3), X0(4), X0(5));

```

```

IVP2 = [Wr2; x0; Vp0; I_0];
Vars2 = [Np; Npp; X0(4); B;...
X0(2); X0(1); Jr2; ...
Lmin; Lmax; Rho; Rcp2; Ro; Lo; Ph_1; Ph_2;...
Rrg; Xrg; RPrG; LPrG; Mp; dt];

```

```

ODE_FUN = @CPA_EMRG;
% tspan = linspace(0,3e-3,1e3);

```

```

%'AbsTol',1e-8,'RelTol',1e-8,
options = odeset('Events',@Event_RailEnd);
[Tout1, dIVP1] = ode45(ODE_FUN,tspan,IVP,options,Vars1);
[Tout2, dIVP2] = ode45(ODE_FUN,tspan,IVP2,options,Vars2);

plot(Tout1*1e3,dIVP1(:,4)/1e3,'-k','linewidth',1.5)
grid on
hold on
plot(Tout2*1e3,dIVP2(:,4)/1e3,'-r','linewidth',1.5)
xlabel('Time (ms)')
ylabel('Current (kA)')
legend('Optimized Rotor','Original Rotor')

% print -dpng 'C:\Users\Collin MacGregor\Dropbox\College\5th
Year\Thesis\LaTeX Thesis\ThesisFigures\10_Rotor_01.png'

Vel_Out = max(dIVP1(:,3));
Vel_Out2 = max(dIVP2(:,3));

Vtip = Wr0*Dr/2;
Volt_Start = Np*Ncp*X(1)*B*Vtip;

Vtip2 = Wr2*Dr/2;
Volt_Start2 = Np*Ncp*X0(1)*B*Vtip2;

Ef_p = .5*Mp*Vel_Out.^2; %J
Er_in = .5*Jr*Wr0^2;
Er_out = .5*Jr*dIVP1(end,1).^2;

Ef_p2 = .5*Mp*Vel_Out2.^2; %J
Er_in2 = .5*Jr2*Wr2^2;
Er_out2 = .5*Jr2*dIVP2(end,1).^2;

Eff_CPA = (Ef_p./(Er_in-Er_out))*100;
T_pulse = Tout1(end);

Eff_CPA2 = (Ef_p2./(Er_in2-Er_out2))*100;
T_pulse2 = Tout2(end);

SlotWidth2 = pi*X0(2)/.0254*.318/16;
SlotWidth = pi*X(2)/.0254*.318/16;

%%
disp(['Original Rotor : Length = ',num2str(X0(1)/.0254,3), '(in)
| Diameter = ',num2str(X0(2)/.0254,3), '(in) | RPM =
',num2str(X0(3))])

```

```

disp(['Original Voltage = ',num2str(Volt_Start2), ' (V)'])
disp(['Original Velocity = ',num2str(Vel_Out2,3), ' (m/s)'])
disp(['Original Resistance = ',num2str(Rcp2,5), ' (Ohms)'])
disp(['Original # of Conductors = ',num2str(X0(4),2)])
disp(['Original Wire Diameter = ', num2str(X0(5)/.0254,4), '
(m)'])
disp(['Original Slot Width = ',num2str(SlotWidth2,3), ' (in)'])
disp('=====')
disp(['Optimized Rotor: Length = ',num2str(X(1)/.0254,3), '(in)
| Diameter = ',num2str(X(2)/.0254,3), '(in) | RPM =
',num2str(X(3),4)])
disp(['Optimized Voltage = ',num2str(Volt_Start), '(V)'])
disp(['Optimized Velocity = ',num2str(Vel_Out,3), ' (m/s)'])
disp(['Optimized Resistance = ',num2str(Rcp,5), ' (Ohms)'])
disp(['Optimized # of Conductors = ',num2str(X(4),2)])
disp(['Optimized Wire Diameter = ', num2str(X(5)/.0254,4), '
(m)'])
disp(['Optimized Slot Width = ',num2str(SlotWidth,3), ' (in)'])

```


O10_Objective.m

```
function [ Velocity ] = O10_Objective( X0 )

RPM0 = X0(3);    %Initial RPM of the Rotor (rpm)
x0   = 0;        %Initial Particle Position (m)
Vp0  = 0;        %Initial Particle Velocity (m/s)
I_0  = 0;        %Initial Current of Compulsator (A)

Np   = 8;        %Number of Poles in the System
Ncp  = X0(4);    %Number of conductors per pole on rotor
B    = .45;      %Magnetic Field Strength Density (T)
Dr   = X0(2);    %Diameter of Rotor (m)
Lr   = X0(1);    %Length of Rotor (m)

Dst  = 7750;     %Density of Steel (kg/m^3)

Lmin= 1e-5;      %Minimum Inductance of Compulsator (H)
Lmax= 1e-5;      %Maximum Inductance of Compulsator (H)
Rcp  = Rcp_Calc( Lr, Dr, RPM0, Ncp, X0(5)); %Resistance of
Compulsator Rotor Winding Phase (Ohms)
Ro   = 1e-6;     %Resistance of connecting busbar/switching
(Ohms)
Lo   = 1e-6;     %Inductance of connecting busbar/switching
(H)
Ph_1= 0;         %Electrical Phase Angle "1" (rad)
Ph_2= pi;        %Electrical Phase Angle "2" (rad)
Rrg  = 3.2104e-004; %Resistance of the Railgun (Ohms)
Xrg  = 2.5*0.3048; %Length of Railgun Rails (m)
LPrg= 3.2712e-007; %Inductance Gradient of Rails (H/m)
Mp   = .001;     %Mass of Particle (kg)

[ Velocity ] =
Exit_Velocity(Np,Ncp,B,Dr,Lr,Dst,Lmin,Lmax,Rcp,...

Ro,Lo,Ph_1,Ph_2,Rrg,Xrg,LPrg,Mp,...
                    RPM0,x0,Vp0,I_0);
Velocity = -Velocity;
end
```

Exit_Velocity.m

```
function [ V_proj ] =  
Exit_Velocity(Np,Ncp,B,Dr,Lr,Dst,Lmin,Lmax,Rcp,...  
  
Ro,Lo,Ph_1,Ph_2,Rrg,Xrg,LPrG,Mp,...  
  
RPM0,x0,Vp0,I_0)  
Npp = Np/2; %Number of Pole Pairs in Rotor  
Mr = (pi*Dr^2/4)*Lr*Dst; %Mass of Rotor (kg)  
Jr = Mr*(Dr/2)^2/2; %Inertia of Rotor (kg-m^2)  
Rho = .5*(Lmax/Lmin - 1); %Compulsator Inductance Modulus  
RPrG= Rrg*Xrg; %Resistance Gradient of Rails (Ohms/m)  
dt = 1e-4; % Time step size (s)  
Wr0 = RPM0/60*2*pi; %Angular Velocity of Rotor (rad/s)  
  
%% SETUP & RUN ODE45  
  
t0 = 0; %Initial Time (s)  
tf = 10e-3; %Final Simulation Time (s)  
  
IVP = [Wr0; x0; Vp0; I_0];  
Vars = [Np; Npp; Ncp; B;...  
Dr; Lr; Jr; ...  
Lmin; Lmax; Rho; Rcp; Ro; Lo; Ph_1; Ph_2;...  
Rrg; Xrg; RPrG; LPrG; Mp; dt];  
  
ODE_FUN = @CPA_EMRG;  
% tspan = linspace(0,3e-3,1e3);  
tspan = t0:dt:tf;  
options = odeset('AbsTol',1e-8,'RelTol',1e-  
8,'Events',@Event_RailEnd);  
  
[Tout, dIVP] = ode45(ODE_FUN,tspan,IVP,options,Vars);  
  
Wout = dIVP(:,1);  
Xout = dIVP(:,2);  
Vout = dIVP(:,3);  
Iout = dIVP(:,4);  
  
V_proj = max(Vout);  
end
```

O10_NLCON.m

```
function [ c, ceq ] = O10_NLCON( X0 )

Lr = X0(1);
Dr = X0(2);
RPM0 = X0(3);
Np = 8;
Ncp = X0(4);
Dwire = X0(5); %(m)
Nturns = 4;
Lslot = pi*Dr*.318/16; %Slot width as a % of Rotor Diameter
scaled from 8in Diameter & .5in slot
% Lslot = .5*.0254;
E_RotC = 45.15e3; %Target Compulsator Stored Energy (J)
RcpMax = 3.7e-4; %Max Compulsator Resistance (Ohm)

% Rcp      = X0(4);

E_Rot = Rot_Energy(Lr, Dr, RPM0);
% Ncp      = Slot_Width( Dwire, Lslot, Ncp );
Dwire = Wire_Dia( Ncp, Lslot, Dwire );
Rcp     = Rcp_Calc(Lr, Dr, RPM0, Ncp, Dwire);

ceq1 = E_Rot - E_RotC;
c1 = Rcp - RcpMax;
ceq2 = 1 - Lslot/(Dwire*Ncp) ;

c = [c1];
ceq = [ceq1,ceq2];

end
```

Rot_Energy.m

```
function [ E_Rot ] = Rot_Energy( Lr, Dr, RPM0 )
% Dr  = 8*.0254; %Diameter of Rotor (m)
% Lr  = 10*.0254; %Length of Rotor (m)
% RPM0= 5000;    %Initial RPM of the Rotor (rpm)

Dst = 7750; %Density of Steel (kg/m^3)

Mr = (pi*Dr^2/4)*Lr*Dst; %Mass of Rotor (kg)
Jr = Mr*(Dr/2)^2/2; %Inertia of Rotor (kg-m^2)
Wr0 = RPM0/60*2*pi; %Angular Velocity of Rotor (rad/s)

E_Rot = .5*Jr*Wr0^2; %Rotational Energy (J)

end
```

Wire_Dia.m

```
function [ Dwire ] = Wire_Dia( Ncp, Lslot, Dwire )

Length1 = Dwire*Ncp;
Length2 = Lslot;

Length3 = Length2 - Length1;

Dwire = (Length2+Length3)/Ncp;

end
```

Rcp_Calc.m

```
function [ Rcp ] = Rcp_Calc( Lr, Dr, RPM0, Ncp, Dwire)
% Lr = 10*.0254;
% Dr = 8*.0254;
% RPM0 = 5000;
Np = 8;

Rho = 1.68e-8; %Resistivity of Copper (Ohm-m)
Lwire = (Dr/2)*2 + Ncp*(((Dr/2)*2*pi)*(2/(Np*2)) + Lr*2);
SkinD = 503*sqrt(Rho/(1*((RPM0*Np)/120)));
Rac = (Lwire*Rho)/(pi*Dwire*SkinD);

Rcp = Rac/Ncp;

end
```

C. Rotor Winding Task

The attached document outlines the work required to complete the phase windings in the rotor of the CPCPA.

Rotor Assembly Task and Statement of Work

The language throughout this document will consistently incorporate the terms listed below, a short description and relevant reference has been included.

1.0 List of Terms

- **Rotor** – machined steel cylinder (*Appendix B*)
- **Rotor Slot** – a 0.5"x0.5"x10.0" channel that runs from one face of the rotor to the other along placed at the outer radius of the rotor, there are sixteen rotor slots (*Appendix B*)
- **Armature Windings** –copper magnet wire field coils that will be wound and epoxied onto the rotor, the armature windings encompasses two sets of four phase winding pairs (*Appendix D*)
- **Phase Winding** – copper magnet wire field coil that runs inside of two rotor slots, a phase winding has four parallel path windings (*Appendix D*)
- **Parallel Path Winding** – copper magnet wire field coil that runs inside of two rotor slots, a parallel path winding has four winding turns of the copper magnet wire and each end of a parallel path winding is brazed to the commutator (*Appendix D*)
- **Winding Turn** – a single turn of copper magnet wire that forms a loop between two rotor slots, a phase winding is comprised of sixteen winding turns (*Appendix D*)
- **Commutator** – cylindrical copper assembly that the parallel path windings are brazed onto (*Appendix A*)
- **Compensation Shield** – 1/16-inch Aluminum sheet that is uniformly epoxied to the circumference of the rotor, the armature windings are located in between the rotor and compensation shield (*Appendix F*)
- **Commutator Shaft and Flange** – steel cylindrical shaft that is welded onto a steel cylindrical plate that is screwed into one of the rotor's faces (*Appendix C*)
- **Brake Shaft and Flange** – a steel shaft assembly similar to the Commutator Shaft and Flange that is screwed into the opposite face of the rotor
- **Rotor Assembly** – Finished assembly comprised of the rotor, armature windings, compensation shield, shafting, and the commutator

2.0 Background and Purpose:

A compensated pulsed alternator, or compulsator, is a specialized form of alternator whose primary design goal is to maximize power generation. It achieves this by having a high current carrying capability and minimizing the internal impedance of the device. A compulsator works by storing its energy using inertial energy storage, converting this to electromechanical energy. A triggering switch then delivers the high power output to an external load over a short (ms to μ s) timespan. Similar to a traditional alternator, voltage is produced by the relative motion of a multi-pole armature and electromagnetic field.

The compulsator can also be thought of as a synchronous generator that is intentionally designed to maximize short circuit current output by minimizing internal impedance through the action of flux compression. As the inertial energy storage component of a compulsator rotates, the mutual inductance between the stationary and rotating portions cause the inductance of the machine to vary over time. This cyclic variation of inductance compresses the magnetic flux generated by the load current and alters the shape of the output current pulse.

A compulsator can be broken down into the following major elements, the elements that pertain to the scope of this particular task have been highlighted in yellow:

1. Excitation windings
2. Armature windings, which interact with the excitation windings to generate voltage
3. Compensation winding or shield
4. Rotor Assembly
5. Stator
6. Bearings
7. Brush mechanisms, which deliver power from the compulsator into the switching circuitry and the external load
8. Support structure

The rotor assembly of the compulsator is responsible for the following two functions:

1. Inertial mechanical energy storage (~45 kJ stored energy at 5,000 rpm)
2. Electromagnetic field generation from relative velocity between the armature windings and the permanent magnets located in the stator

The rotor assembly incorporates the armature windings, compensation shield, commutator, and shafting. A view of what the completed rotor assembly should look like can be seen below.

Figure 1: Rotor completed assembly view [not to scale]

A more detailed internal view of the armature windings is included below

Figure 2: Rotor Winding diagram [not to scale]

A more detailed breakdown of the rough estimate of the copper winding task at hand is shown in the image below

Figure 3: Diagram of the estimated length of each section of the windings [not to scale]

The parallel path windings are brazed into the pads of the commutator in the following manner. Approximately .35-inches of the pad shall be left bare for the brushes to make their mechanical surface connection with.

Red Sections indicate approximate brazing locations of 10 AWG copper wire.
Clearance must be left for copper brush section.

Figure 4: Diagram of the approximate brazing locations for a single commutator bar [not to scale]

All of the armature windings shall be epoxied into the rotor slots, and the compensation shield shall be epoxied to the external circumference of the rotor. A diagram outlining the different areas that require epoxy is shown below.

Figure 5: Diagram of approximate locations that require epoxy work to be handled. [not to scale]

3.0 Scope of Work:

The following parts and materials will be provided for this task:

1. Rotor – x1 (*individual part*)
 - a. Rotor will arrive lubricated
 - b. Before any windings are placed in a rotor slot, the rotor slot shall be completely cleaned of all surface lubricants
2. Commutator – x1 (*individual part*)
 - a. This will be press-fit onto the commutator shaft. There is an aluminum spacer between the commutator and the base of the rotor flange that raises the commutator above the nearby bolt heads.
3. Commutator Steel Shaft – x1 (*assembly of: itself, commutator, and aluminum spacer*)

- a. This shaft can be delivered already press-fit and screwed into the rotor, or it can be delivered as its own unique assembly that will have to be press-fit and screwed into the rotor before the parallel path windings can be brazed onto it.
 - b. **Delivery Question: Is it preferred to have the commutator/shaft arrive already attached to the rotor, or left separate for it to be attached later on during the task?**
4. Brake Shaft – x1 (*individual part*)
 - a. Similar to above, this shaft can be delivered already press-fit and screwed into the rotor, or it can be delivered as its own unique part that will have to be press-fit and screwed onto the rotor
 - b. Attaching this shaft to the rotor can be done at any point during this project, but shall be attached to the rotor for the rotor assembly to be considered ‘complete’
 - c. **Delivery Question: Is it preferred to have the brake shaft arrive already attached to the rotor, or left separate for it to be attached later on during the task?**
5. Threaded Bolts – x8 (*individual parts*)
 - a. These bolts attach the two shaft flanges into the steel rotor
 - b. If any of the shaft/flanges are delivered already attached to the rotor, then the bolts will not be delivered as separate parts
6. Aluminum Compensation Shield – x1 (*individual part*)
 - a. This part has not been machined to its final dimension for length and will require machining before it can be epoxied to the rotor.
 - b. **Delivery Question: Is there equipment at your disposal for cutting an aluminum sheet from several feet down to ~25-inches at a tolerance in the +/- .01-inch range?**
7. 10 AWG Copper Magnet Wire – 347 feet (*material*)
8. Duralco Epoxy – (*material*)
 - a. A sufficient amount of epoxy shall be provided for this task to handle all required epoxy work
9. WD-40 Lubricant – x1 Can (*material*)
 - a. The steel shafts require a constant coat of WD-40 to prevent rusting on exposed steel surfaces

The scope of work for this task has been broken up into two categories: Assembly Work and Machining Work.

3.1. Machining Work:

The following work involves machining that shall be handled to complete this task.

3.1.1. Compensation Shield Length Dimension:

The aluminum compensation shield currently is the following dimensions:

- Length = 48 inches
- Width = 12 inches
- Thickness = 1/16 inches

The final dimensions of the compensation shield are the following:

- Length = 25.13 +/- .005 inches
- Width = 10.0 +/- .020 inches

- Thickness = 1/16 inches

The length of the shield must be shortened by approximately 23 inches.

The width of the shield must be shortened by approximately 2 inches.

Cutting this part down to length is required before the compensation shield can be epoxied onto the rotor.

3.2. Assembly Work

The following tasks incorporate the assembly work that is required to complete the rotor assembly.

3.2.1. Armature Winding Task

1. Two **rotor slots** shall be filled with **rotor windings** for each winding turn.
 - a. The spacing for the windings are offset by one slot.
2. **Parallel winding paths** shall be wound one at a time until all four have filled both rotor slots.
 - a. Four winding turns comprise a single **parallel winding path**.
3. The rotor winding for a **parallel path** shall start from the commutator section.
 - a. The rotor winding does not need to be brazed to the commutator to start the armature winding task
4. The winding shall then run up to the first **rotor slot**.
5. The winding then runs along the length of the first **rotor slot** to the end.
6. The winding then skips one **rotor slot**, until reaching the second **rotor slot**.
7. The winding then runs along the length of the second **rotor slot**.
8. The winding then connects back to the first **rotor slot**.
9. Steps 5-8 are repeated with the next **winding turn**, starting on top of the previous **winding turn**.
10. Step 9 is repeated until all four **winding turns** that comprise a **parallel path** have been wound through the two **rotor slots**.
11. The winding then runs down from the second **rotor slot** to the commutator.
 - a. The rotor winding does not need to be brazed to the commutator to start the armature winding task
12. Steps 3-11 are repeated three more times for the other **parallel winding paths**
 - a. The winding starts from the next available location on the commutator, moving outwards from the rotor side as shown in Figure 4
13. Steps 1-12 are repeated three more times to complete one entire **phase winding**
14. Steps 1-13 are repeated for the other eight **rotor slots** to complete **phase winding** number two

3.2.2. Shafting Press-Fit & Attachment to Rotor

1. The shafting shall be press-fit onto the rotor before any brazing occurs
2. Each shaft is aligned with the two dowel pins on the shaft flange
3. The four screws are threaded into the shaft flanges
4. Each of the four screws is evenly tightened around the shaft flange
5. The screws are tightened until the shaft has been press-fit onto the rotor

3.2.3. Brazing of Parallel Winding Paths to the Commutator

1. The armature windings must be completely wound into all of the rotor slots before brazing
2. The shafting shall be press-fit onto the rotor before brazing
3. The armature windings shall be epoxied into the rotor slots before brazing.

4. The ends of the parallel path windings shall be brazed onto their corresponding commutator bars, as outlined in Figure 4.
 - a. Ensure that no brazing accidentally shorts the connections between the commutator bars

3.2.4. Epoxying Armature Windings into their Corresponding Rotor Slots

1. The armature windings shall be wound into all of the rotor slots before epoxy work
2. The epoxy shall be mixed as described in Appendix E, and on the Duralco bottle, to prep for epoxy work.
3. The epoxy shall fill the rotor slots that have been filled in with the rotor windings.
4. Follow the drying instructions of the Duralco epoxy as outlined in Appendix E
 - a. The epoxy may need to be applied to small numbers of rotor slots at a time to prevent excess epoxy from dripping down
5. Brush/remove any excess epoxy on the exterior of the rotor circumference
 - a. A smooth external surface finish is required for the compensation shield to be epoxied to the rotor

3.2.5. Epoxying Compensation Shield to the Rotor

1. The rotor windings must be wound before the compensation shield can be added.
2. The rotor windings must be epoxied into the rotor before the compensation shield can be added.
3. The aluminum compensation shield shall be rolled into an arc that fits the circumference of the rotor
4. Fit check the aluminum compensation shield with the rotor to ensure that it will completely encircle the rotor
5. Epoxy the inside of the aluminum compensation shield onto the outside of the rotor's circumference
6. Clamp the compensation shield tightly to the rotor while the epoxy cures.

A dependency table of the tasks listed above has been included below to help clarify which tasks are either independent from each other or are linearly dependent and coupled. Each Task is referred to by the bulleted numbers listed above (ie. #.#.X.)

Task:	Pre-Requisite Task:				
	3.2.1.	3.2.2.	3.2.3.	3.2.4.	3.2.5.
3.2.1.		Independent	Dependent	Dependent	Dependent
3.2.2.	Independent		Dependent	Independent	Independent
3.2.3.	Dependent	Dependent		Dependent	Independent
3.2.4.	Dependent	Independent	Dependent		Dependent
3.2.5.	Dependent	Independent	Independent	Dependent	

This table highlights the dependency of each task with respect to all other tasks associated with the rotor winding task. The major takeaway from this table is that there are three possible orders that can be pursued to complete this task, this is highlighted in the table below.

Order	Route 1	Route 2	Route 3
1	3.2.2.	3.2.1.	3.2.1.
2	3.2.1.	3.2.4.	3.2.4.

3	3.2.4.	3.2.2.	3.2.5.
4	3.2.3.	3.2.3.	3.2.2.
5	3.2.5.	3.2.5.	3.2.3.

The order placement of when to press fit the shafting/commutator assembly can be placed in different orders to complete the rotor winding task.

Delivery Question: I do not know whether it is beneficial for you to have the shafting attached from the start of the task to use with any existing jigs/setups you might have. I do not know which route is the most feasible and least expensive option. However, I do know that all three of these options are valid and can be pursued.

Appendix A: Kirkwood Commutator Dimensions

Appendix B: Steel Rotor Dimensions

Appendix C: Steel Shaft for Commutator and the Welded on Rotor Flange

Appendix D: Magnet Wire Data Sheet

Wiring Information

**Magnet Wire, Neodymium Magnets, Wind Generator and Rotor Blades.
Applied Magnets (www.magnet4less.com), Top Quality, Lowest Price !!!**

Product Details

Magnet Wire Premium Quality 10 AWG Enameled Copper MW-35C High Temp. 200 Degree C

Magnet Wire Technical Specifications:

High temperature Class: 200°C (392°F)

Magnet Wire AWG size: 10 AWG, round

Insulation type: polyester-polyamide-imide, polyester basecoat, polyamide-imide topcoat.

Insulation build: heavy build, more durable than single/double builds

Shipping Weight: 9 lbs or more (shipping weight including package weight)

Nominal Diameter: 0.1019 inch

Nominal OHMS/LB. -20 Celsius: 0.0314

Feet/LB: 31.48

Appendix E: Epoxy Specifications

500°F - Duralco™ 4461

Ultra Thin Bond Lines

Seals Porous Materials

Impregnates Fine Structures

Forms Protective Coatings

Duralco Low Viscosity Adhesives are formulated with Cotronics' unique polymer system to provide the ultimate in high temperature chemical, electrical and moisture resistance. They are user friendly, 100% solid formulations.

No volatiles. No VOC's. No harsh odors.

Duralco 4461 is a free flowing, liquid adhesive that is ideal for forming ultra thin bond lines, impregnating, coating and encapsulating applications.

Has excellent adhesion to metals, plastics, ceramics, glass, etc.

Cures at room temperature to provide chemical, solvent and corrosion resistance in any high temp. application.

Can be used up to 500°F as a protective coating for coils, filament windings, electronics, etc.

It is an ideal choice for high temperature applications in electronics, optics, instrumentation, etc.

Users Report:

- Fiber Optic Cables consisting of 3,000 glass strands were encapsulated, and bonded, with 4461 in a 1/8" stainless steel tube. The low viscosity of 4461 enabled full penetration in and around the fiber stands.
- 4461 Bonds optical components and protects them from moisture absorption and transmission.
- 4461 Pots a transformer for high temperature service.

Availability:

Cat No.	Description	Temp.	Price
Duralco 4461-1	Pint Kit.	500 °F	89.95
Duralco 4461-2	Gallon Kit	500 °F	328.75
Duralco 4461IP-1.	Pint Kit.	500°F.	79.95
Duralco 4461IP-2.	Gallon Kit.	500°F.	304.95

4461SS, New, Slow Setting Version

Ideal for large volume potting and casting applications.

Duralco 4461SS-1	Pint Trial Kit	500 °F	84.95
Duralco 4461SS-2	Gallon Kit	500 °F	317.65

Pre-Measured Kits

Each Unit Contains: 1 jar of resin, 1 syringe of hardener and 1 mixing stick. (see page 19 for details)

EE 4461-10	10 Epox-Eez	10 gm units/box	75.95
EE 4461-25	10 Epox-Eez	25 gm units/box	85.95
EE 4461IP-10	10 Epox-Eez	10 gm units/box	69.50
EE 4461IP-25	10 Epox-Eez	25 gm units/box	79.50

**4461 Penetrates and Encapsulates
A Semi-Conductor Device**

4461 Bonds an Optical Component

**4461 Potting a Transformer
for High Temp. Use**

Duralco™ Maximum Temp	Units °F	4461 500
Components	Color	2-Amber
Viscosity	cps	600
Hardness	Shore 'D'	90
Tensile Strength	psi	9,500
Thermal Conductivity	Btu-in/ Hr. Ft² °F	4
Thermal Expansion	10⁻⁵/°C	5.4
Dielectric Strength	volts/mil.	450
Volume Resistivity	ohm-cm	10¹³
Heat Distortion	°C	210
Elongation	%	5
Thermal Stability	% 1000 hrs @ 200°C	0.20
Shrinkage	% max.	0.8
Moisture Absorption	% after 30 Days	0.15
Mix Ratio	R/H	100/17
Cure	Hr. @ R. T.	16
	Min. @ 250°F	5