August 2023

Ultra Fast DC Switch

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ULTRA FAST MEDIUM VOLTAGE DC DISCONNECT SWITCH

by

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A Thesis Submitted in

Partial Fulfillment of the

Requirements for the Degree of

Master of Science

in Engineering

at

University of Wisconsin - Milwaukee

August 2023

This work was supported by the National Science Foundation under Grant No. 1939124
and by the Office of Naval Research under Award No. N00014-20-1-2667

ABSTRACT

ULTRA FAST MEDIUM VOLTAGE DC DISCONNECT SWITCH

by
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University of Wisconsin - Milwaukee, 2023
Under the Supervision of Professor Robert Cuzner

With advancements in power electronics, DC power systems are a strong contender for future power system and shipboard application studies. However, to ensure proper DC power systems, protection engineers must develop different DC protection schemes to maintain proper system protection levels. The critical issue behind developing DC protection devices is that the signal never crosses zero naturally, as in AC circuit breakers and AC disconnect switches. There is also a necessity for galvanic isolation in the DC protection system. A method developed is pairing a mechanical commercial-off-the-shelf vacuum interrupter, a Thomson coil actuator, and a current commutating drive circuit (CCDC). The Thomson coil offers fast repulsion capabilities to separate the interrupter. Next, the vacuum interrupter produces strong galvanic isolation and is rated for high current arcs. Finally, the CCDC extinguishes the arc by injecting a counter-current from a precharge capacitor and commuting the fault current into a separate semiconductor branch via coupled inductors. The Virtual Prototyping Process and Particle Swarm Optimization is implemented based on input parameters such as voltage and current and optimizes component-level values based on system-level requirements. After the optimization, the physical sizing of switch packaging can be optimized and sizes for the higer-level DC power system.

I dedicate this thesis work to my family. To my parents who drove me to be my most genuine self, and for my beloved Genevieve who loved me for my most genuine self.

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ACKNOWLEDGEMENTS

Throughout the research and writing of this thesis, there are many individuals who, without their help, this thesis could have never been done.

I want to thank Professor Cuzner, who took the mantle of a mentor when I was left without one, continued to point me in good directions for research, and continued working on me when I found it hard to keep going.

I want to thank the UWM Power Electronics group, who taught me the ins and outs of various software necessary for my research, helped me think through problems when I was stuck, and helped me edit so that my work was the best it could be.

I want to thank my family, who took the time to help me in countless ways outside the classroom, from transporting me when I did not have a car to dropping off food when I was low.

I want to thank my friends, who kept me in their prayers for the many years I was in school.

And finally, I want to thank my future wife, Genevieve, who continued encouraging me when I was at some low points and put in the extra effort when I was preoccupied.

Chapter 1

Introduction

Due to Wide Band Gap power semiconductors, Medium Voltage DC Power systems are possible. In order to fully develop Medium voltage DC power systems, protection systems must be engineered. The principles of MVDC protection systems are the same as MVAC, but the equipment is different. AC systems are based on relays, instrument transformers, and circuit breakers. DC systems are classified as Breakerless and breaker-based, which use power electronics for current limiting and current interruption. A Breakerless protection system is entirely based on full bridge power converters to limit the fault current and provide fault interruption. A Breaker Based system adds DC circuit Breaker to limit the fault current and provide fault interruption. Both DC protection approaches provide only some of the functions of an AC protection system, as galvanic isolation is neglected. DC protection systems can lead to fault conditions where leakage current can pass through PE, resulting in an uncleared fault. The current leakage will decrease system reliability and increase damage to equipment. The motivation for developing the Ultra-Fast Medium Voltage DC Disconnect Switch is to develop equipment that will interrupt leakage current and provide isolation.

Virtual Prototyping Process(VPP) is a system-level optimization of individual components for system-level objectives. VPP accounts for mechanical, thermal, and insulation coordination spacings. VPP uses allocations and physics-based models. VPP is used to virtually optimize dimensions, mass, reliability, and cost values. Saves time and effort by modeling component sizing instead of building physical prototypes. With projects where sizing is limited, VPP can optimize limited-sized components. This research takes the motivation of the developed design of the Medium Voltage DC Disconnect Switch and creates an optimization code that inputs parameters such as current or voltage and generates optimal passive electrical component values that will fit within the higher DC power system.

1.1 AC Power Systems

A power system is a collection of electrical devices that generate, transfer, and distribute power throughout a network. Typically, power systems consist of various equipment, including generators and motors for power generation and electrical conversion, transformers for distributing power within the system, array of transmission lines, and loads.

The electric grid serves as an excellent illustration of a power system. The grid's power provider employs machinery to generate electricity, transmission lines to transport and distribute power, and transformers to adjust the power to meet the required demand. The current electric grid power system standard is the AC power system. The main reason is that alternating current is more cost-effective and has fewer losses over long distances. Figure 1.1 is a picture of a simple AC protection scheme that is predominately protected by circuit breakers.

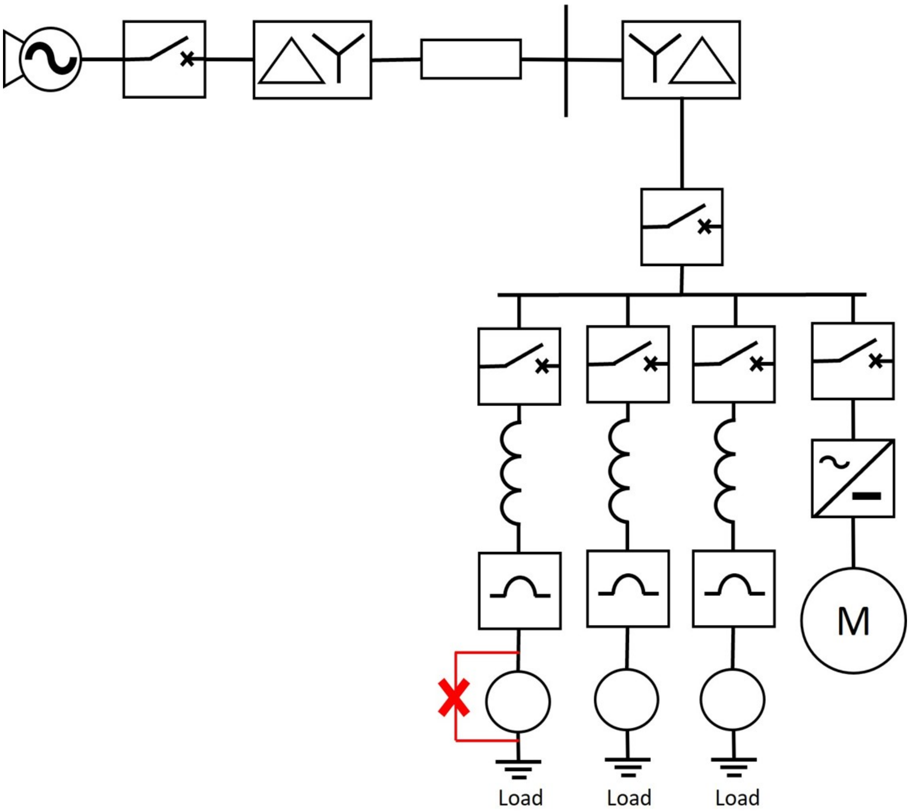


Figure 1.1: AC Power System Protection Scheme

1.1.1 Reliability

A vital area within the study of power systems is power system reliability. Power system reliability refers to the probability of the power system operating as intended in its design. High reliability in the power system ensures the delivery of electricity to consumers in the required manner. It is not solely about the power system's ability to never experience a fault, but rather its ability to quickly and efficiently isolate the fault and restart the system afterward.

A fault is any irregularity or anomaly that leads to equipment failure within the system. Given the potential impacts from both external and internal factors, faults are always a concern that power engineers need to address. To ensure the protection of the power system and achieve high reliability, protection engineers employ various equipment, including circuit breakers and switches. Faults can lead to over-current, which can cause various hazards such as fires. Therefore, the purpose of a circuit breaker device is to protect the power system from over-current.

When the circuit breaker opens and the arc begins, arc absorbs system voltage. Voltage build up across switch the switch will drive the current to zero. Once the Voltage in the breaker is increased to a threshold greater than the system voltage, the current will be driven to zero.

The primary protection scheme for the ac system include disconnection switches, but primarily the circuit breaker is the primary equipment for AC power system protection. The function of the circuit breaker is to isolate the fault current and precisely the fault current when a fault occurs in the power system.

The AC power system protection paradigm is built upon the innate reactance installed in an AC power system. The Average power system comprises components such as transformers and ac machines. Within these components are reactance due to the nature of the alternating current. Thanks to the reactance, the natural impedance in the systems adds redundancy to ensure further protection procedures to the system. A simple equivalent circuit can be constructed using the reactive impedance (42).

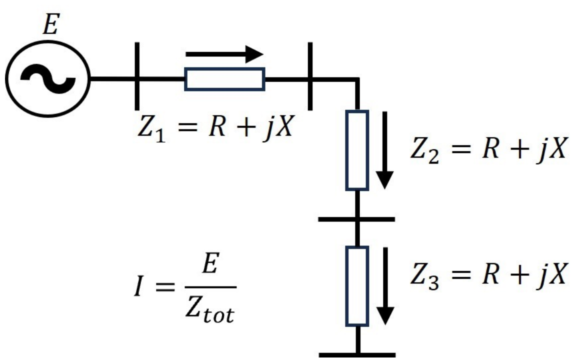


Figure 1.2: Protection System Equivalent

The transient reactance from the upstream component chains also provides natural current limiters, easing protection burdens off of other breakers. The added reactance also trip breakers the closest to the fault, accomplishing fault location more quickly.

When the circuit breaker opens, an arc will generate. When arc forms, the arc will begin to absorb voltage from the rest of the system. The voltage absorption causes the increase in arc voltage in the breaker and drives the current to zero.

AC power systems also have the ability to zero-crossing. This means that since the signal is sinusoidal, the output voltage will reach zero at some point. Zero crossing in an AC system is a natural form of arc extinguishing, which means that when the contacts of the breaker open and an arc is generated between the contacts, once the signal reaches zero, the arc will extinguish. Figure 1.3 displays the points at which the AC signal would cross zero.

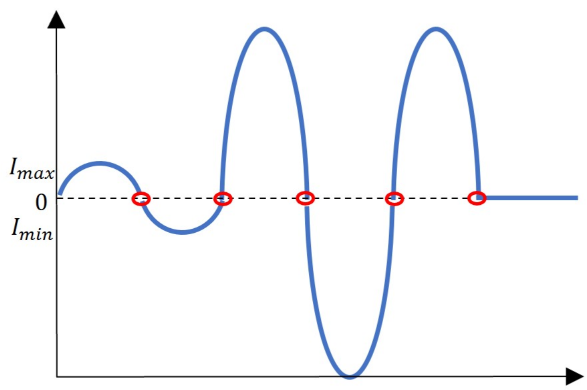


Figure 1.3: When the AC signal crosses zero

The final aspect of the current AC power system paradigm is proper isolation. To properly secure any power systems, create an arc across mechanical contacts. Once the arc is extinguished, creating air gap protection and securing galvanic isolation. Once galvanic isolation is accomplished, the fault has been cleared.

1.2 DC Power Systems

Between AC and DC power systems, power engineers favor AC power systems for the AC Power's ability to transport power long distances. Power Engineers also favor AC power systems for their low power loss in power transfer. One of the negative setbacks of AC power systems is that it requires large transformers to change the voltage to meet the demands of the grid. Another setback for DC power systems is the vast amount of power loss in DC systems. However, a recent paradigm shift in the power electronics field has begun. Figure 1.4 displays what a DC power system

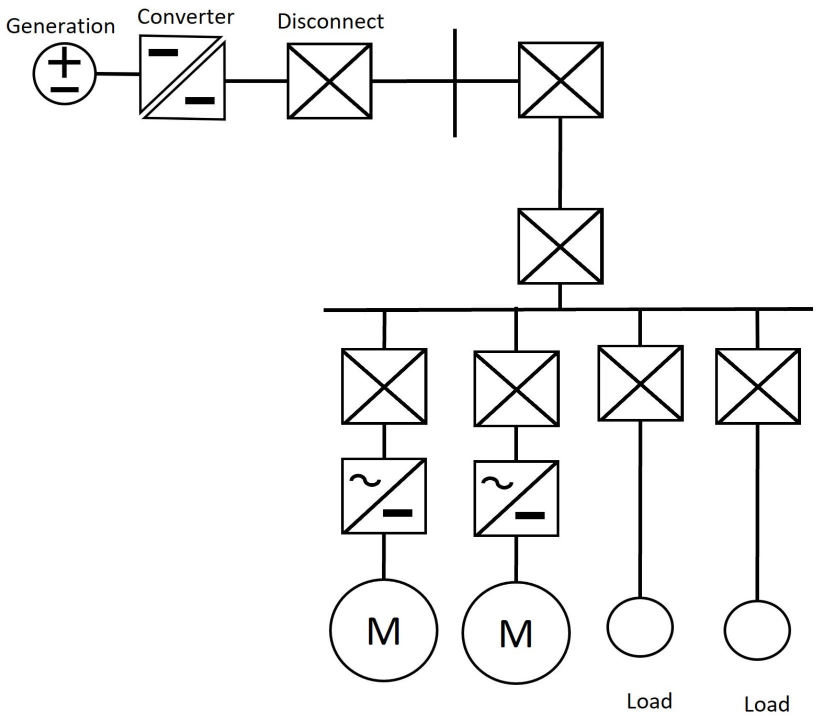


Figure 1.4: Protection System Equivalent

With further research into power electronics and semiconductors with wide band gaps, engineers have discovered have discovered the ability for less power loss due to high frequency switching. Materials and semiconductors like Silicon Carbide possess a wide band gap. Thanks to semiconductors with wide band gaps, power can be transferred at higher voltages, higher temperatures, and higher switching frequencies. Thanks to Silicon Carbide semiconductors, advancements in power electronics have made DC power systems possible in the modern age.

A ship are medium voltage DC power system. The ship contains this in order to operate a ship with full electrical capabilities without introducing too many current transition steps, as well as a reasonable size for the power system(45). Otherwise, the whole ship system would need to convert to a High voltage system in order to operate all required materials.

1.2.1 Reliability

The five aspects that drive the methodology of AC power system protection schemes are not natural in a DC power system protection scheme. There is no reactance in DC power system protection; therefore, there is no transient reactance and no current limiting factor. There is no current limiting factor due to no reactance as well. The signal in a DC power system will never cross zero. Contacts in a DC power system can separate. However, due to the DC signal, air gap protection and galvanic isolation are not secured naturally. Therefore, there is currently no single breaker equipment that meets the function of a circuit breaker for a DC system. Due to DC complications, protection engineers must resort to extra circuitry methods to develop DC Disconnect switches to clear faults at zero current.

However, some disadvantages come from power electronics that must be addressed for secured shipboard applications. One, in particular, is that proper isolation is necessary for leakage current in the semiconductors of the power electronic circuit (45). A benefit of a mechanical circuit interrupter is that it has physical isolation in the circuit. Since the primary breaking force for DC power systems are semiconductors and transistors, there is always a level of leakage voltage in the system. Thus power converters can only act as the current limiters in the DC power system and not circuit breakers.

Instead of AC protection systems' five natural protection aspects, DC protection has alternative implementations. In the place of natural chain reactance, In the place of achieving over current protection from either inductance slow down the rate of rise, breakers actively inhibit, or power electronics are used to limit the current. That is where AC systems' protection aspects end with the DC system. To attain voltage absorption, zero crossing, and galvanic Isolation, special breakers and an Ultra Fast DC switch must be installed.

DC power systems, and power electronic current limiters are now possible and have led to numerous more options in system protection. In AC systems, relays are utilized to detect faults. Either the relay is a differential relay and measures the changes in voltages across the system, or the relay is distance relay and calculates the impedance by calculating the current and voltage. With power electronics, the converter that limits the current in the DC system has the ability to detect the fault. Also, in the place of natural chain reactance, the DC protection system upstream inductance control the rate of rise of fault current This meets one of the aspects of AC power system protection.

The converters used in DC power systems can also detect the fault current. Modern power electronic converters use controller systems to control the response of the converters. The controllers also maintain the ability to detect and limit the fault current. This is another one of AC power systems protection that the power semiconductor based protection scheme can attain. This is also attained by current protection from either inductance's that slow down the rate of rise, breakers actively inhibit current rise, or power electronics are used to limit the current.

However, one chief complications for DC disconnect switches and circuit breakers is that there is no zero crossing in DC disconnect systems. An AC signal is a sinusoidal signal, meaning that every period, the signal crosses zero, yielding a repeating value of zero. This method is exceptional for circuit breakers and disconnects. The procedure for an AC circuit breaker is that once the contacts are open, the voltage returns to zero, and the breaker extinguishes the signal. An arc is not a concern since the voltage will return to zero and will not reignite if the contacts are not touching. The DC signal is constant, so there is no Zero crossing. This is one of the aspects of AC power system protection that DC power systems cannot perform.

Since the entire system of a DC power system consist highly of power electronic semiconductors, and classic AC power system circuit breakers are not installed air gap protection is not present and galvanic isolation is not assured in a DC power system. Unless mechanical separation takes place somewhere in the DC protection system, galvanic isolation is another aspect the DC power system protection scheme does not meet naturally.

1.3 DC Protection Schemes

For shipboard applications and other DC power system, there are two predominating methods for circuit protection. One of the predominant methods is to implement breakerless, solid-state DC disconnect switches, or Hybrid DC breakers, which pair a mechanical circuit breaker and a power electronic circuit for power conversion to convert power to a DC signal.

In the DC power system, there are two philosophies behind System protection and disconnect switches. One is the breakerless form of system protection. In a breakerless protection system, the power electronics perform all the current limiting and isolation between converter-interfaced generators or energy storage systems and downstream DC-DC and AC-DC converter-interfaced loads. When a fault occurs in the system, upstream power converters work to de-energize the system and use communication systems to detect the fault. The breakerless system can accomplish much in the case of current limiting, fault detection, and voltage rise. In a breakerless system, it is possible to have galvanic isolation. However, it would require that large amounts of the protection system chain will be powered down until the fault is fixed. Also, there is still leakage current is still dangerous in the system, and there is no means of zero crossing or attaining air gap protection. At DC, a disconnect switch with physical isolation and zero crossing must be incorporated into the protection scheme.

For shipboard applications, another approach is the breaker-based protection method. The breaker-based circuit breaker method pairs solid-stated circuit breakers or solid-state current limiters upstream of a DC disconnect switch. This method attempts to form a DC protection scheme in the same way as a conventional AC system. The philosophy is to use mechanical breakers, hybrid breakers, or semi-conductor-based breakers like solid-state breakers and interrupt and isolate faults in the system. When a fault occurs, the power electronic converters in the electric chain of the DC system are still utilized to limit the current and detect the fault. The breakers are placed down stream of the current limiters and used as a redundancy to protect the DC system. However this method still struggles with leakage voltage, still requires galvanic isolation and still lacks zero crossing ability. Figure 1.6 is a pictures of what a breaker-less power system would look like compared to 1.5 which is a breaker-based power system.

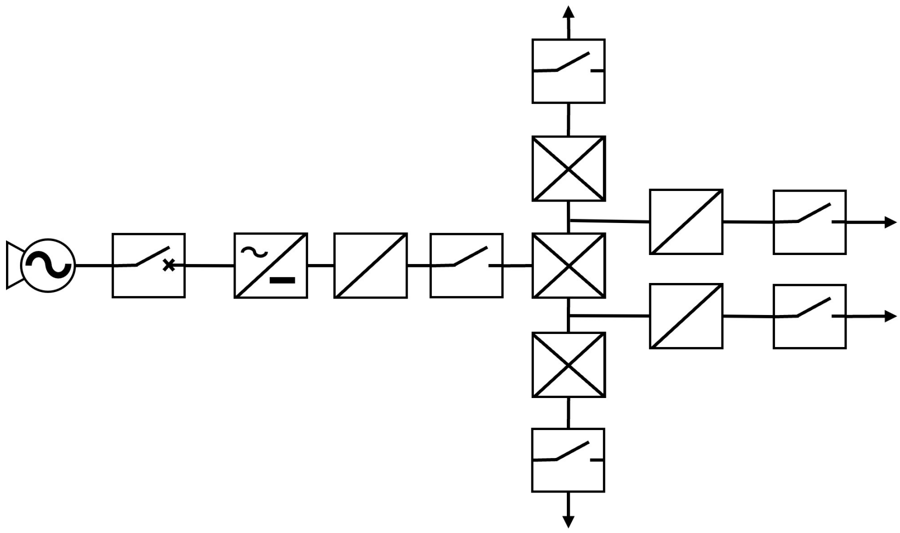


Figure 1.5: Example of a Breakerless DC Protection scheme

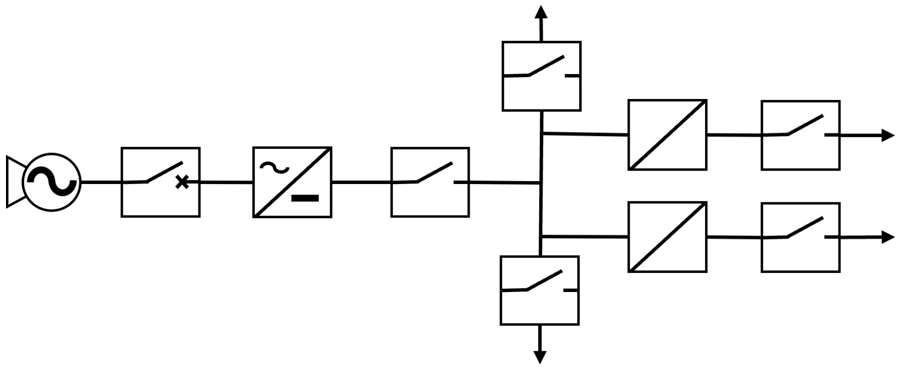
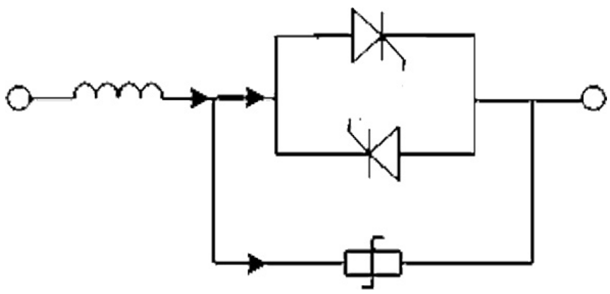


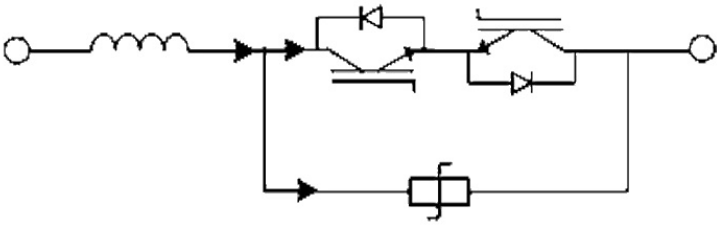
Figure 1.6: Example of a Breaker-based DC protection scheme

1.3.1 Solid State Circuit Breakers

In a breaker based system, the disconnect systems are made up of solid-state circuit breakers or hybrid solid-state circuit breakers. A solid-state circuit breaker is a breaker where electronics, not moving parts, work to break the signal. A solid-state circuit breaker utilizes semiconductors such as igbt based semi-conductor breakers or diode semi-conductors breakers. Leakage voltage still exists and isolation is not present once the breaker is used. Figure 1.7a is a thyristor based solid state breaker and 1.7b is a igbt based solid state circuit breaker.



(a) Thyristor Solid State Circuit semiconductors



(b) igbt Solid State Circuit semiconductors

Figure 1.7: Solid State Circuit Breaker Example

The Solid state breaker can work to limit the current, but unless there is a DC disconnect switch, is no Galvanic complete isolation. Also, since solid-state circuit breakers are semiconductors with breaking DC voltage, the current must be driven to zero to ensure life and equipment safety. In order to drive the current to zero in the breaker, the Solid State Circuit breaker must have zero crossing before the disconnect switch opens and a mechanical disconnector. This is accomplished with a CCDC and Vacuum interrupter. With the CCDC, the current in the breaker will be drawn to zero, the breaker will open, and there will not be danger.

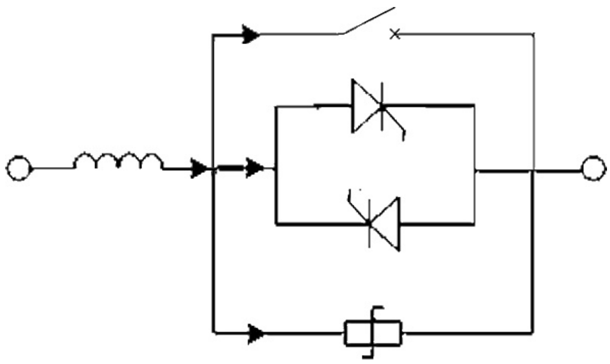
1.3.2 Hybrid Circuit Breakers

As stated, the practice of the breakers switch is to pair the solid-state, electronic-only circuit breaker with a mechanical disconnect downstream. This scheme is different from a Hybrid circuit breaker. A hybrid circuit breaker does include power electronic semiconductors as part of the disconnection but in parallel to it.

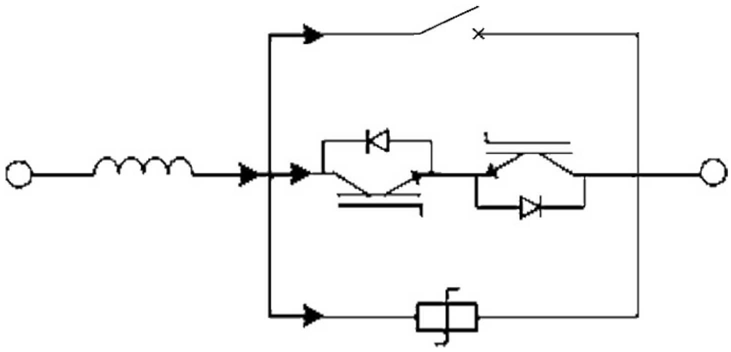
Hybrid Circuit utilizes both the mechanical domain and the electrical domain. The order of operations is this, mechanical breaker opens, separating the contacts, and concurrently, the power electronics bring down the current using semiconductors and capacitors. By implementing hybrid circuit breakers, the difference on implementation options is illustrated in.

However in both the breakerless system or a breaker-based system, leakage voltage still exists within the semiconductors. The mechanical breaker is in parallel with the electronics based circuit breaker, and in order for a human to access the isolated us it, the fault current needs to be cleared in both branches of the system. In order to properly clear the fault, protect human life, and not damage, galvanic must be present and air gap protection must be produced. Figure 1.8 displays a thyristor based and a igbt based hybrid circuit breaker.

For the DC protection system to mimic the AC power system by using a circuit breaker, a good method is to use the hybrid circuit breaker. However, there needs to be more circuitry in series with the physical breaker to ensure safety. Once a fault occurs in the DC protection system, the fault current increases in the breaker. It would be dangerous if it opened since the current is still present. Therefore, the current must be saturated and placed into the semiconductor branch. This can be done by introducing some resonance current into the breaker to induce zero crossing. A current injection circuit method can accomplish zero crossing in the breaker.



(a) Thyristor Hybrid Circuit semiconductors



(b) igbt Solid State Circuit semiconductors

Figure 1.8: Hybrid Circuit Breaker Example

1.4 Motivation

A benefit of a mechanical circuit interrupter is that it has physical isolation in the circuit. Since the primary breaking force for breaker-based solid-state circuit breakers and other power electronic breakerless systems are semiconductors and transistors, there is a possibility of leakage voltage in the system. Voltage leakage can be a problem, especially at high voltages.

For the optimal medium voltage DC disconnect switch, proper isolation must be in the circuit and extinguished an arc. There is one option to accomplish this optimally. Instead of a hybrid circuit breaker with a mechanical disconnect in parallel with a power electronic circuit, systems can use a different formation of the two.

There is a method for pairing a mechanical switch and a circuit, however, not in parallel to maintain isolation. The method combines the mechanical circuit breaker and a circuit that can inject a counter-current to extinguish the arc. There is isolation, and the counter-current draws the current to zero.

The system draws the counter to the current with an arrangement of a circuit called a current injection. This circuit method uses a precharged capacitor to lower the DC current to zero. When a fault occurs, some switches engage the precharge cap to distribute current in the counter direction of the current flow. The counter-current will lower the DC current to zero in order to force zero crossing in the system. The current cancellation will allow the arc to extinguish in the mechanical breaker and then have an isolation system.

A vacuum interrupter is a mechanical breaker rated for high and medium voltage. The commercial off-the-shelf (COTS) vacuum interrupter(VI) can open during a current fault condition. It is a pair of contacts sealed with a ceramic vacuum. Engineers developed the VI's for most high currents. That means the vacuum interrupter contacts can separate, generate an arc, and remain undamaged for a while. The vacuum interrupter is an excellent pairing option with a current injection circuit. Another influence on this design is the ability of a customer to purchase aspects of the breakers from vendors. Vacuum Interrupters are readily available for purchase from vendors. Figure 1.9 is a diagram of the Vacuum interrupter.

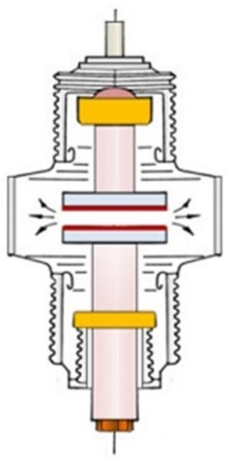


Figure 1.9: Mechanical Vacuum Interrupter

Another factor to take into weighing the mechanical breaker against the hybrid breaker, solid state breaker and against the breaker-less protection is the necessity for galvanic isolation. Galvanic isolation is when an electric device or component can prevent the current flow from traveling through the device into the rest of the circuit. Galvanic isolation is beneficial in a power system with many shared ground connects, for Galvanic Isolation prevents ground loops. The most outstanding example is the transformer, which provides isolation via current traveling via EMF instead of wire. The Vacuum interrupter also provides Galvanic isolation through its physical separation of contacts.

Now for the vacuum interrupter to work as a fast breaker, it will need a fast actuator. One such actuator is the Thomson coil. The Thomson coil is a form of actuator formed by a plate and a coil. When the power system induces Eddy currents, a coil generates a repulsion force that propels the metallic plate from the coil. It does so in an ultra-fast manner, which makes it a competitive actuator for the vacuum interrupter(41). Figure 1.10 is a picture of the Thomson coil actuator.

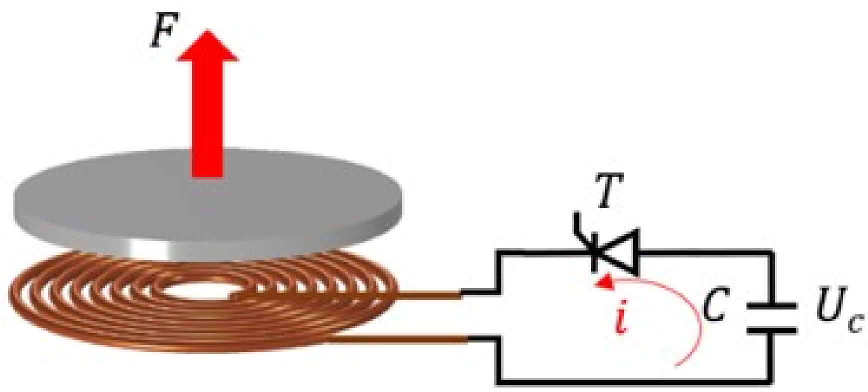


Figure 1.10: Physics of the Thomson Coil Actuator

With the advancements in DC power system technology and power electronic technology, protection engineers must develop medium voltage DC protection schemes in order to fully ensure the protection of functional grids, ships, and power systems in the future. If future engineers and researchers do not invest in DC protection schemes, the rest of our power systems will be compromised, rendering future studies moot. We aim to introduce a strong candidate to protect medium-voltage DC systems.

Protection engineers use various circuitry forms to inject a counter-current into the system. One proposed circuitry is the Current Commutation Drive Circuit (CCDC). The CCDC includes a thyristor, diode, precharged capacitor, and two coupled inductors. The two coupled inductors work as a current transformer. Once actuation occurs and the vacuum interrupter opens, the precharge capacitor discharges and drive the current to zero. The benefit of the CCDC is that the fault current circulates in the circuit while the vacuum interrupter is open. Figure 1.11 displays the circuitry of the CCDC.

Another options is use the disconnect switch like a No Load Switch with the CCDC in series with the vacuum interrupter. The No Load Switch scheme prevents voltage restrike once the system holds the current at zero. 1.11 displays the no load switch method for implementing the CCDC paired with a mechanical breaker. the entire DC disconnects system that when it is installed, will give galvanic isolation and induce zero crossing the the DC protection system.

In either case, the fundamental cornerstone of these protection schemes is the CCDC. The CCDC and the Thomson coil must be fast in both cases. When the fault current in the breaker begins to fall, the CCDC and the Thomson coil must respond when the current crosses zero, not before, not after; otherwise, there will be hazards. The way to key to a fast CCDC and Thomson coil is to size the electrical components. The optimization process and the Virtual Prototyping Process do component sizing. .

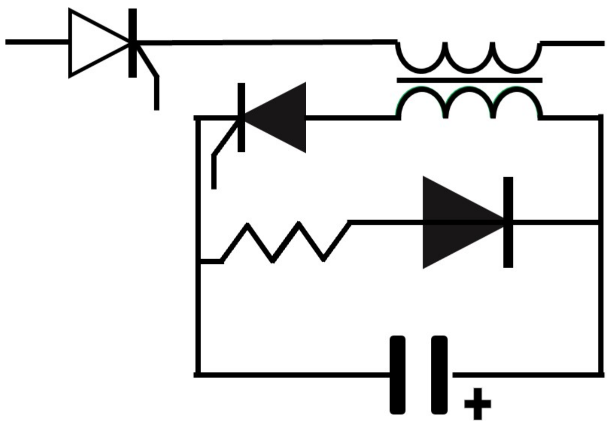


Figure 1.11: Circuit of the CCDC

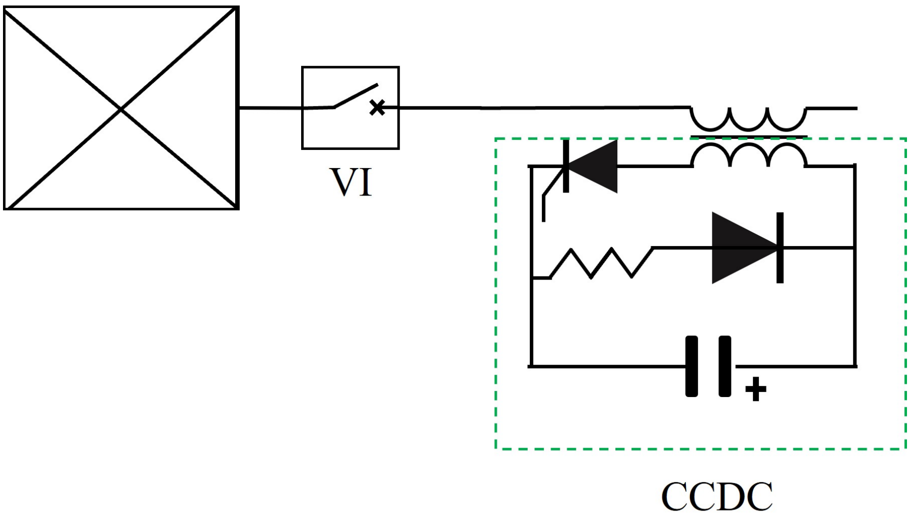


Figure 1.12: Circuit Diagram for the Proposed Disconnect Switch

1.5 Virtual Prototyping Process

The Virtual Prototyping Process (VPP) uses software or coding to size and test various electronic designs to avoid building physical prototypes. VPP utilizes an iterative coding process to derive values and parameters within the constraints of the design parameters and converge them into optimal design values. VPP is a benefit for it saves time and resources to develop and build physical prototypes. Engineers can also use the VPP to develop the cost of electronics. The use of VPP can be not only helpful with designing power systems but can also help develop the cost of materials and proposals. In the realm of power systems and power electronics, VPP can be used to calculate dimensions, component values, and performance.

1.5.1 System Level Optimization

In this research on medium voltage power systems, VPP is the scheme utilized to optimize cabinet space within the confines of a Navy ship. The optimization process considers various options for arranging power levels, inductors, frequency, and physical size. For ship designs, various components such as disconnect switches and transformers fit into drawers that enter into cabinet bays. The key to virtual prototyping and optimizing is developing the proper sizing for components with the drawers and cabinets that deliver the ship the most power per volume of space, known as power density.

1.5.2 Genetic Algorithm and Particle Swarm

One such iterative method of optimization is the method of Genetic algorithm. When using a genetic algorithm, the optimization program generates a population of solutions. The program takes The two best solutions, generating another population of solutions from those two best(37). The program generates populations numerous times until the program attains the optimized solution. Another iterative optimization method is the Particle Swarm Optimization (PSO) method. This method generates numerous solutions known as particles numerous times, from which the program studies each particle for the best. The program measures the distance of the personal bests of each particle swarm to the global best of all the swarms. The program yields the optimized solution once the program compares the personal best to the global best of each particle generation. PSO is the preferred method for this research due to its simplicity of coding and low computational cost(1). Figure 1.13 describes using particle swarm to optimize the number of turns in an inductor as well as the size of a capacitor. With a particle swarm, components for the CCDC and the Thomson coil can generate the values for the fastest response of current interruption.

1.6 Overview of Thesis

A literature review on the current state of the art of DC circuit breakers and DC disconnects design and testing, as well as current injection and zero crossing methods and actuator methods performed by academic scholars, will be discussed in Chapter 2. A proposed method of DC disconnect that combines a commercial off-the-shelf vacuum interrupter opened by a Thomson coil actuator and results in a zero current injection method of the CCDC will be discussed in Chapter 3. In Chapter 4, many calculations were derived to calculate the circuit breaker's reaction when interrupted by the current. The calculation equations and results are then used in the optimization code to optimize the best component values for the optimal DC circuit breaker. Finally, a synopsis of the work is described in Chapter 6, and the next step in future work will be explained.

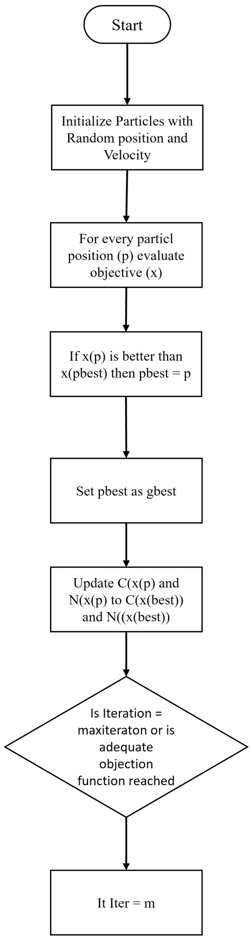


Figure 1.13: Example of a Breaker-Based DC Protection Scheme

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Chapter 2

State of the Arts

There are various methods for medium voltage DC circuit breakers in literature. The research aims to derive an optimal model to display the speed and the current breaking ability of a method that pairs a mechanical Vacuum with a fast Thomson coil actuator and the current injection method of a CCDC. In order to ensure proper optimization, parameters must be considered in order to start developing the optimization code. This is done by deriving equations and relating them to other aspects of the disconnecting system. Such aspects include opening speed, voltage and current ratings, capacitance, inductance, and physical size of the components.

In order to adequately research a method of DC disconnect, one can break down the circuit breaking system into three parts. The first part of the study is the mechanical breaking mechanism. Sometimes this is a physical breaking system such as the Vacuum interrupter (33)or an SF6 breaker (11), and other times, the breaking mechanism is that of semiconductors such as a Solid state breaker (52). The second is the actuator, which will speedily separate the physical contacts. Finally, the third part of the DC disconnect study is the part that prevents the arc during the physical separation or what extinguishes the arc once it forms. From these diverged parts, we can derive the parameters for optimization.

2.1 Current Limiters

2.1.1 Breaker-Based

Breaker-based DC protection systems attempt to reproduce an AC power protection system with DC power (15). It strongly relies on solid-state protection devices that limit the current and forces the current to zero. Since DC systems do not have the extra impedance that AC power systems contain, large current surges can result from short circuit faults. Therefore if a Breakerless system is to thwart the fault, it must act within microseconds. However, the leakage voltage is still present in the breaker-based system, and unless a disconnect is installed, there is still no air gap protection and no galvanic isolation.

2.1.2 Breakerless

Breakerless DC protection systems remove protection devices like solid-state or hybrid circuit breakers and utilize system protection in the power converters (15), (21). According to Deng, Qiu et al., the fault-clearing steps for a Breakerless system follow: First, the fault is detected and located by the power converter that works as a current limiter. Second, the system is de-energized. Third, actuated disconnect switches isolate the fault branch. Finally, the converter starts to re-energize the system. Breakerless can be an excellent form of protection, removing lots of weight and equipment from the protection system. However, there is still a need for DC disconnect switches to ensure galvanic isolation and air gap protection to clear fault currents to protect lives and equipment.

2.1.3 Breakers

Solid State circuit breakers are a means of limiting fault current. The solid state breaker. They are based in thyristors or igbt and implement a means of energy absorption and work to limit the current by phasing in the switching devices (24). Simulations show that the Solid State circuit breaker can operate with the AC circuit at the same time as the mechanical breaker. A commonly used semiconductor implemented in a solid state circuit breaker is a thyristor or igbt, but depends on the depended source for the semiconductor is voltage or current(24). However, novel topologies for solid state circuit protection have been designed to aid in efficiency of solid-state circuit breakers(56). Thanks to new emergence in semiconductor technologies and silicon carbide implementations, semiconductor based current limiters are being implode for protections systems at higher voltage levels.(2). However, when a fault occurs, the impedance in the solid state current limiter can increase rapidly (2). However one of thee complications of a steady state current limiter is the high current levels that are trapped in the semiconductor branch (34). The hybrid mechanical switch bypass installed in parallel with the parallel solid-state current limiter commuting branch (34) and (4). The Hybrid circuit breaker offers a means of commuting the high levels of current into a separate power electronic branch in order to mechanically open the circuit breaker, then the current is broken. Research shows that hybrid circuit breakers give galvanic isolation, and has shown to break the current at 2kA and 3kA and voltage ratings of 12kV (34),(4).

2.2 Switch Technology

MDVC switch technology varies in design from HVDC switch technology (62). HVDC circuit breakers and disconnect switches are developed for power transmission purposes. MVDC circuit breakers and disconnect switches, including for this design's purpose, MVDC circuit breakers are built for medium voltage systems on ships and various other mechanisms where limited space is required.

The essential operation of the switch is the opening operation. The driving factor of the opening operation is the amount of time it takes to open. One of the driving factors for an MVDC circuit breaker or switch is its speed in opening. The required speed is due to the low impedance in the DC system(29). In an AC power system, various reactive elements can add to the disconnect system's overall impedance. In a DC system, there are no such reactive elements. Therefore, MVDC switches must open and hold faster than their AC counterparts. With advancements in switch technology, MVDC switches can open and hold at 2ms (39), (41). These methods utilize solid-state circuit breakers and are fast. The procedure of a circuit breaker involves physically separating the circuit contacts and extinguishing the electron flow to prevent arcing. Two highly utilized methods for extinguishing current flow in a circuit breaker are breaking in a vacuum and breaking the circuit in SF6 insulation.

Permanent magnets can destabilize ions in the arc extinguish phase of the circuit-breaking or disconnecting action. While still utilizing a mechanical circuit breaker, permanent magnets are placed in the contacts. When the contacts are separate, a magnetic field tangential to the contacts destabilizes the ions, causing the plasma from the arc to bow away(28). Figure 2.1 is what the interrupter with the permanent magnet installed would look like. It is a daunting task to install permanent magnets in the vacuum interrupter since it would require a total redesign of the vacuum interrupter.

Sf6 circuit breakers are another circuit breaker design; however, breakers use sulfur hexafluoride as a medium for extinguishing current flow instead of a vacuum for the breaking medium. SF6 is one the heaviest gases (11) and has a dielectric strength three times greater than air. SF6 circuits are helpful for high-voltage circuit breaking and can help with transient voltage. However, vacuum circuit breakers are the popular means of circuit breaker for the modern day.

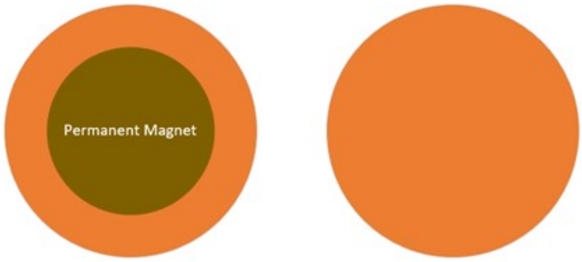

Figure 2.1: Example Permanent Magnet Implemented in Vacuum Interrupter

Vacuum circuit breakers are circuit breakers housed in a vacuum-sealed chamber. The vacuum chamber serves as the means for arc extinction. Vacuum circuit breakers have become the standard practice for medium-voltage circuit breaking. They are also quit cost effective, having many consumer off the shelf selections. Vacuum interrupters are by far more environmentally friendly than the alternative of Sf6 breakers due to no use of other gases.

This leads to the possible utilization of power semiconductors used in the circuit-breaking design space—the implementation of semiconductors for hybrid circuit breakers and disconnect switches. When paired with mechanical switches, using power semiconductors, such as power electronic thyristors, in hybrid circuit breakers provides a fast-acting arcless interruption(36), (4). However, there is still High power loss when using semiconductor solid-state circuit breakers[(4), even in parallel with mechanical circuit breakers, which is not ideal for the power requirements of this project.

Another aspect of circuit breaking is that of arc interruption medium. An arc generation is restricted in an NLSw.(39) A lack of arc generation is not advantageous because it disperses inductive energy into the system. However, breakers that allow for Arc generation must have a means of extinguishing the arc once generated. Thus, interruption mediums, such as Vacuums, SF6, CO2, or air circuit breakers and disconnects, are designed for such a task.

Air blast circuit breakers extinguish the arc in a high-pressure air-breaking environment. Air blast circuit breakers are different from vacuum interrupters, where the arc extinction occurs in a vacuum, and therefore no ionization can occur. However, Air blast circuit breakers are not recommended for Medium voltage systems. The difference is due to a large arc chute required in order to extinguish the arc (13).

When comparing vacuum interrupter capabilities with sulfur hexafluoride, vacuum interrupters make the best case for high voltage current interruption for the modern-day circuit protection scheme (49) (48). Through developments in vacuum interrupters, they can be built to withstand as high voltages at 140kV and 40kA (44) and make adequate interrupters for short-line fault currents (49). Vacuum interrupters can be rated for medium to high voltage. With the ability to place interrupters in series, research has shown their use in hybrid circuit breakers makes DC circuit breakers reasonable (33).

2.3 Actuator

Permanent Magnetic are used in repulsion mechanisms to separate the contacts on the mechanical disconnector, and a permanent magnet actuator repels and locks the actuators(57),(65). However, using permanent magnets as an actuation system is less effective than an actuator based on repulsion force driven by using eddy currents as a repulsion force like the Thomson coil actuator(32).

An actuator is a device that turns energy, in this case electrical, into mechanical force. As stated before, some methods exist for using electromagnetics as an actuator. One such electromagnetic actuator method uses monostable magnets in which magnets are both polarized and unpolarized (30). Yet another method of magnetic actuation uses Lorentz forces as a means of physical repulsion(51).

2.3.1 Thomson Coil

There are a few fast actuators outside the permanent magnet actuator. The double-sided and the Thomson coils are the two kinds of repulsive force actuators. The difference is that a double-sided coil includes a second movable coil connected in series instead of the metal plate. Between the two, the Thomson coil produces lower electric conversion efficiency (64). Yet, the Thomson coil actuator is the far most accessible coil to manufacture and has a longer lifetime than the double-sided disc (9). However, thanks to advancements in research, it is possible to increase efficiency when multi contacts are designed and inserted into mediums with high dielectric strengths (9). With the inserted medium, efficiencies can reach 91 percent. Figure 2.2 is portrays the difference between the Thomson Coil and Double-side coil.

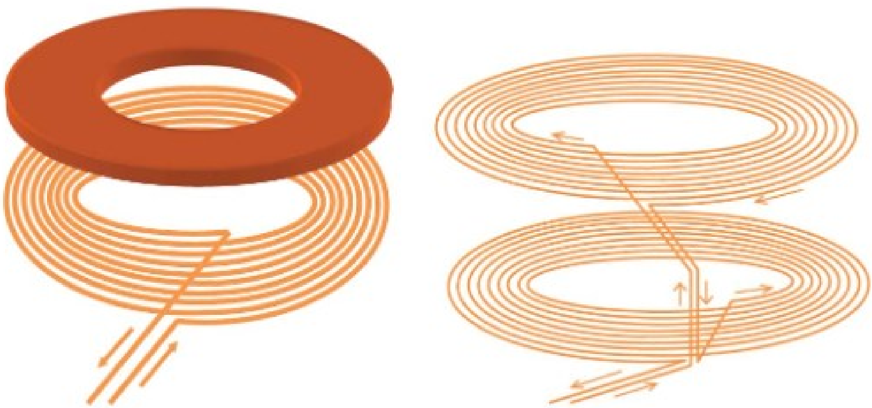

Figure 2.2: Thomson coil Actuator vs Double-Sided coil

To generate sufficient electromagnetic propulsion, both the metal disc and the coil repulsion mechanism use induced eddy currents (23). The repulsion force is calculated using energy conversion methods(23). Due to the skin effect in the Thomson coil, the eddy currents are not uniformly distributed (31). Therefore to calculate the Thomson coil electromagnetic effect, the plate is segmented, all inductance of the coils is calculated, and then the individual circuit equations are combined with motion equations to form electromechanically coupled equations (31). The following are the derived driving equations of the Thomson Coil to determine the eddy currents(31).

$$\frac{Q}{C} + I_s R_s + \frac{d\delta}{dt} = 0 \tag{2.1}$$

$$I_s R_s + d\lambda_l/dt = 0, i = 1, 2, \ldots N \tag{2.2}$$

$$\frac{d\lambda_s}{dt} = L_{ss}\frac{dI_s}{dt} + \sum_{j=1}^{N} L_s j\frac{dI_j}{dt} + \sum_{j=1}^{N} I_j \frac{\delta L_s j}{\delta z}\frac{dz}{dt} \tag{2.3}$$

$$\frac{d\lambda_i}{dt} = L_{si}\frac{dI_s}{dt} + \sum_{j=1}^{N} L_{sj}\frac{dI_j}{dt} + I_s\frac{\delta L_{si}}{\delta z}\frac{dz}{dt}, i = 1, 2, \ldots N \tag{2.4}$$

R_s is the resistance in the exciting circuit, λ_s is the flux linkage and I_s is the exciting current. Q and C are the charge and capacitance. R_i is the resistance in the i_{th} circuit, di is the flux linkage in the ith circuit, and I_i is the eddy current in the i_{th} circuit. $L_s i$ is the mutual inductance between the exciting circuit and the i_{th} circuit, and $L_i j$ is the mutual inductance between the i_{th} and the j_{th} circuit.

After the Eddy currents are determined, the energy and the forces are derived with the following equations(31).

$$W = \frac{1}{2}\sum_{i=s,1}^{N}\sum_{j=s,1}^{N} L_{ij} I_s I_j \tag{2.5}$$

$$F_{em} = \frac{\delta W}{\delta z} = -\sum_{i=1}^{N} I_s I_i \frac{\delta L_s i}{\delta z} \tag{2.6}$$

The studies of Thomson coils have yielded it to be fit for fast opening of mechanical switches and in DC HCB. The electromagnetic actuation system of the Thomson Coil allows for sub-millisecond opening levels (3). Within recent years, the focus on Thomson coils has been around optimization and the increase in voltage ratings the components of the Thomson coil can endure(39), (40). The highest rated voltage rating of the Thomson coil is 500kV (65), and the highest reported with vacuum insulation was 40.5kV (58)

Thomson coils require a control circuit to activate the actuator. The circuitry entails a primary precharge capacitor and a thyristor switch (10),(3). Once the fault current activates the thyristor switch, the capacitor dissipates into the coil, inducing the eddy currents, causing the repulsion force to activate. Essentially, the control circuit of the Thomson coil actuator is a single pulse circuit. A multipulse circuits have been introduced (28). However, research into multipulse control circuits can show promise; now, they only add complexity and no other benefit yet (38). Today, the most convenient method of control circuit the single pulse control circuit

The steps towards designing the optimal Thomson coil include the following steps: designing a mover, designing a closing coil, and designing a shaft (35). These three design steps can be divided into the type of material, the inner and outer radius of the plate, and the space between the coil and base. The basic design parameters for the design steps are derived from parameters like voltage rating and short circuit breaking current. After determining the parameters and values, the design must pass a dynamic and static analysis (35), (32).

A circuit breaker that is a vacuum interrupter paired with a Thomson coil actuator, the results are promising. Test results of a designed Thomson actuator circuit breakers show an opening time of 2ms-3ms at a fault current of 8kA (7).

2.4 Methodology for Induced Zero Crossing

DC breakers add a level of complication to breaking that AC circuit breakers do not. As stated before, there is no zero crossing in DC circuit breakers, which requires more involvement in extinguishing the arc than just disconnecting the circuit. The breaker must be ultra-fast, and as mentioned before, the mechanical separation will cause an arc if the voltage is not at zero.

Various methods to deal with no zero crossing in DC circuit breaking have been researched and developed. One mentioned earlier is that of solid-state circuit breakers. However, due to high power loss in the semiconductors (33), solid-state circuit breakers are not ideal for HVDC or MVDC system without isolated disconnect switches. A second possible option for forcing zero current is using the circuit breaker's arc voltage (33). Advancements in permanent magnets have aided in the advances of DCCB and DC disconnect switches. A mechanical breaker where contacts are physically separate, instead of a solid-state semiconductor, is the best approach to ensure galvanic isolation. Besides utilizing current injection, another means of extinguishing the arc in a mechanical breaker is to increase the arc voltage(33) into arc chutes, thereby driving the arc current through a resistor and reducing the current to zero. One means of increasing the voltage is by using arc runners. The arc voltage is driven into an arc chute of metal splitter plates. The splitter plates generate several anodes and cathodes, increasing the voltage by creating many voltage sources in series(33). The use of permanent magnets is used to increase the self-excited magnetic field. The permanent magnets add additional current loops and ferromagnetic flux baffles. The extra magnets create an external magnetic field which leads to adequate arc motion(46)

The final method is current injection interruption (33),(60). Current injection interruption is an advantageous technology in DC protection and circuit breaking. The act involves introducing an oscillating current into the circuit breaker or disconnect switch higher than the short circuit current. This method induces a local zero crossing in the circuit-breaking system that, once held long enough; the circuit is isolated and secured.

The process of current injection involves using a precharge capacitor.(27). When the fault in the DC system occurs, the power electronic circuit connects the current flow, and the precharged capacitor injections a counter-current into the circuit breaker or disconnect switch. When there is no fault, and the circuit breaker is closed, the capacitor is charged and ready for another fault. Current injection is the prime method for interrupting the current in a DC system, especially when paired with a commutating circuit(60),(61)

A commutating circuit is a method of transferring current into another branch of the circuit by inductors. During a fault, the inductors commute the current into a parallel branch of semiconductors. The principle operations of a conventional circuit breaker paired with a commutation circuit are articulated in (63) and described as follows: The current passes through the load inductor. A resistor dissipates the magnetic energy of the load inductor. The CB opens at t_1. When contacts are separated at t_2, the semiconductor switch in the commutation branch is closed. The current in the arc is reduced to zero. Finally, the plasma extinguished in the arc

The current commutating process offers various means of implementing a local zero crossing in the circuit. Some methods utilize the commutating circuit in order to place the fault current in another circuit, charge the capacitor, and utilize a freewheeling diode to secure the current from the circuit breaker (60) (63). Another method includes using commutating to bypass the precharge capacitor. Another option is a novel method of the Current commutating Drive Circuit CCDC (5),.

The developed CCDC is a circuit utilizing coupled inductors, with a thyristor in parallel with a diode in parallel with the precharge capacitor. When the fault occurs and the fault current peaks, the thyristor is activated, and the inductors commute the current to the CCDC. The capacitor is discharged into the circuit, inducing zero current. Finally, once the system voltage increase, the polarity of the capacitor shifts and is charged (8). The method encourages a fast means of driving current to zero for the mechanical breaker. (63). 2.3 and 2.4 depict the stages of current in the CCDC.

2.5 Virtual Prototyping Process and Optimization

The virtual prototyping process of shipboard systems is a process for optimizing ship space and components. By using VPP, various aspects of the power and equipment meta models can be scaled (16). The scaling of the equipment is beneficial for producing values such as size, weight, efficiency, and other dimensions from calculations and inputs of voltage and power ratings. VPP can also be utilized to develop component ratings for converter topologies (17)(47). Using a genetic algorithm, such things as inductance and power loss can be derived and optimized using VPP. Other research has yielded a process of scaling inductor and capacitor size and volume to optimize power density[Waffler] (54). VPP shows a promising method for sizing naval equipment, for once developed adequately, VPP can be used to scale sizing and optimize power density by purely inputting voltage and current values(16).

2.6 Optimization

PSO optimization offer a simplistic approach to optimization compared to a genetic algorithm. Genetic algorithm is develop along the species ability to survive. The code generates sets referred to as candidates and selects individuals as parent values to develop the next iteration(37). Developed off of the movement of a bird flock, PSO optimization generate several solutions known as particles, and compares them. From in the group of particles, local best is assigned as the personal best, and best personal best is set as the global best. The optimization continues until the max iteration ends, or the optimal values are found(37). Compared to the Genetic Algorithm, the PSO Optimization offers the simpler method for finding the fast response components(26).

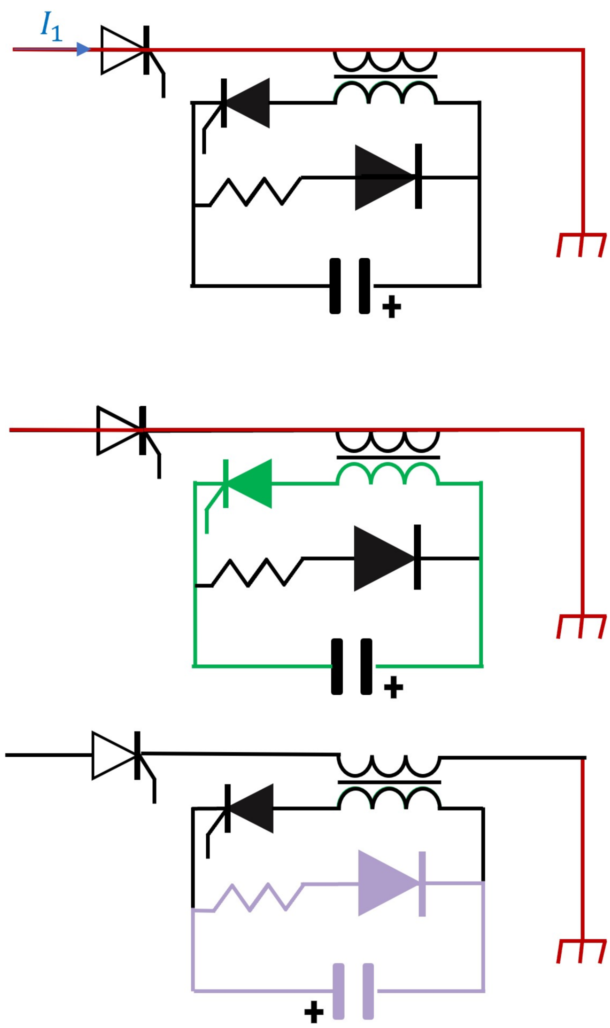

Figure 2.3: The Circuit Stages of Current Through the CCDC

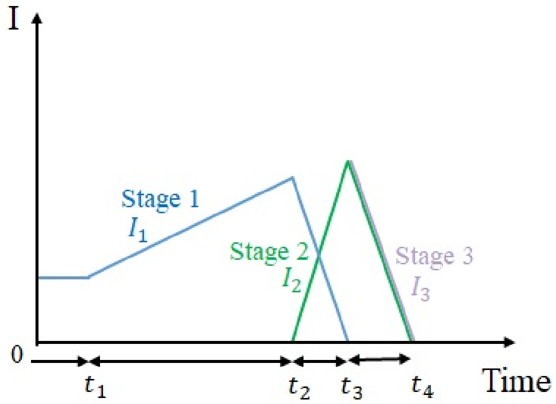

Figure 2.4: The Current Values at the Various Stages of the Current

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Chapter 3

Proposed Method and Analytical Approach

Whether DC protection system is a breakerless system or a Breaker-based system, A DC disconnect switch that is fast, and a CCDC for current commutating and current injecting is the proposed plan to establish galvanic isolation and zero crossing into the protection system. The figure 3.1 is the proposed method.

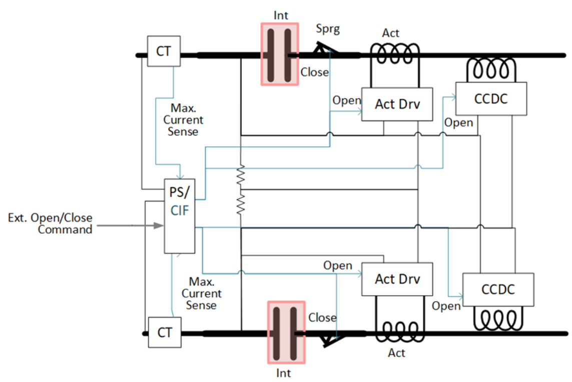

Figure 3.1: Design of the complete Fast DC Disconnect Switch

3.1 Consumer off the Self Vacuum Interrupter

The values for which the MVDC Disconnect switch had to be rated were 500A, 1000A, and 2000A. The disconnect switch must also be fast enough to open in under 10 ms and close in under 10 ms. The last necessity for the design was, at the very least, the switch would secure galvanic isolation. With these values and motivations in hand, the driving force component for the unique development of the design of the Ultra Fast DC Disconnect Switch was the Commercial-off-the-self (COTS) vacuum interrupter (VI). One of the reasons behind using the COTS VI was the various rated VI readily available for purchase. Due to this availability of VIs with different ratings, one can generate a family of switches with differing values around the Ultra Fast DC Disconnect Switch design. All one would have to do is take one of the rated VI and incorporate it into the optimization program to generate the appropriately sized values around the VI. Also, a majority of VI's are placed for arc within them. This rating means that COTS VI can open during a fault, and if a medium voltage arc is generated, it cannot damage the VI or the rest of the system. The rating of the VI aids the commutation circuit in drawing zero crossing. Other interruption mediums, such as SF6 gas or oil-based circuit breaking systems, could be used when developing the Ultra Fast Disconnect Switch. However, this design did not consider these methods, for they were phased out of modern circuit-breaking methods and are no longer viability.

For proper Vacuum interruption placement, the required calculation is the Vacuum insulator. The first value of importance for analysis is the rated voltage of the insulator and the corresponding insulation. For the insulation on the outside of the interrupter, requirements are formalized by IEC61800. In contrast, if the insulation is on the inside of the interrupter, the conditions are formalized by Paschen's law.

$$V_b = 2440(\frac{293pd}{T}) + 61\sqrt{\frac{293pd}{T}} \tag{3.1}$$

3.2 Thomson Coil and Dampening

3.2.1 Physics and Calculations

In order for the opening speed of the VI to be under 10ms, a Thomson coil actuator was used as an actuator. Purely, a Thomson coil is a coil inductor paired with a metal plate. When a time-varying voltage signal is introduced into the coil, a current is induced, and the coil repels the plate from the inductor coil. The repulsion force can be so large that a fast actuation time is not uncommon and makes 10ms opening time within range.

There are two main elements to the Thomson coil. The first element is the inductor coil and the plate. In the design phase, the size of the coils and plates and the inductance values of the inductor are evaluated. The Second element of the Thomson coil is the power supply. The power supply is designed around a precharge capacitor and a thyristor switch. Once a fault occurs, the thyristor activates, and the capacitor dissipates, introducing the activation voltage into the coil. Below is a mirrored power supply circuit developed to energize the indcutor plate of the Thomson Coil Actuator

The first fundamental design equation for the Thomson coil is the force. The geometry of the Thomson coil determines force, the current induced in the coil, and the change of the inductance depending on the plate's position. The following is the equation for the force with the current I, inductance L, and distance traveled by the plate z define the force.

3.2.2 Calculation

Due to the alternating excitation current of the primary coil of the Thomson coil and the secondary magnetic plate had the induced eddy current. The equation 3.2 articulates the time averaging force(6).

$$F = \frac{1}{2} I^2 \frac{\delta L_e}{\delta z} \tag{3.2}$$

The inductance of the coil can be derived by the self-inductance of the coil, the mutual inductance between the coil, and the plate self-inductance.

$$L_e = Lc - [M]^t [Lp]^{-1} [M] \tag{3.3}$$

The eddy current of the secondary plate is derived from the Grover method of inductance calculation. The Grover method divides the plate body into filaments with a larger diameter than the primary coil. Js represent the plate's current density, and each filament's current at any radial distance will be p.

$$i_e = \frac{J_s \delta d_\rho}{sqrt2} \tag{3.4}$$

δ is the skin depth, and d_ρ is the height of each section.

To force in totality can be calculated by summing forces resulting from each section's magnetic interaction between coil and eddy currents of each section. The equations are defined below.

$$dF = 2\pi \rho i_e B_\rho^* \tag{3.5}$$

$$F = \sqrt{2}\pi\delta \int_0^\infty \rho J_s B_\rho^* d\rho \tag{3.6}$$

Where B_ρ^* is the conjugate of the B field.

The average of the Averaging can be determined by the equation 3.7

$$F_a v = \pi \mu_0 N^2 I_m^2 a^2 F_a(z) \tag{3.7}$$

Where is the force factor and represents a polynomial of z and can be derived with the equation3.8 (6)

$$\begin{aligned} F_a(z) = 33.9846 - 32.8076 + 27.6963z^2 - 15.9007z^3 \\ +5.79463z^4 - 1.33543z^5 + 0.193527z^6 - 0.017065z^7 + 0.835410^{-3}z^8 \\ -0.17398410^(-4z^9 \end{aligned} \tag{3.8}$$

Within the design and optimization of the Thomson Coil is the weight of the coil and the plate, the two moving contacts of the Thomson coil. The other aspect of the electrical design for the Thomson coil was the inductance values. The design philosophy is that the current size would contribute to the coil inductance value. Ideally, the inductance value would contribute to the speed at which the coil opened.

For the design of the Thomson coil actuator, a drive and pre-charge circuit is needed to activate the precharge capacitor to induce the current into the coil. This drive circuit it displayed below and is made up of the precharge capacitor, the thyrsitor used as a switch to activate the circuit, and two diodes to keep the current from traveling back towards the capacitor. Figure 3.2 displays the drive circuit with the precharge capacitor

For the prototyping portion of the drive circuit, the inductor and capacitor were optimized based on physical dimensions of the components.

A locking mechanism is designed into the system to ensure that the Thomson coil holds safely. Once the Thomson coil actuator opens a certain length, the mechanism

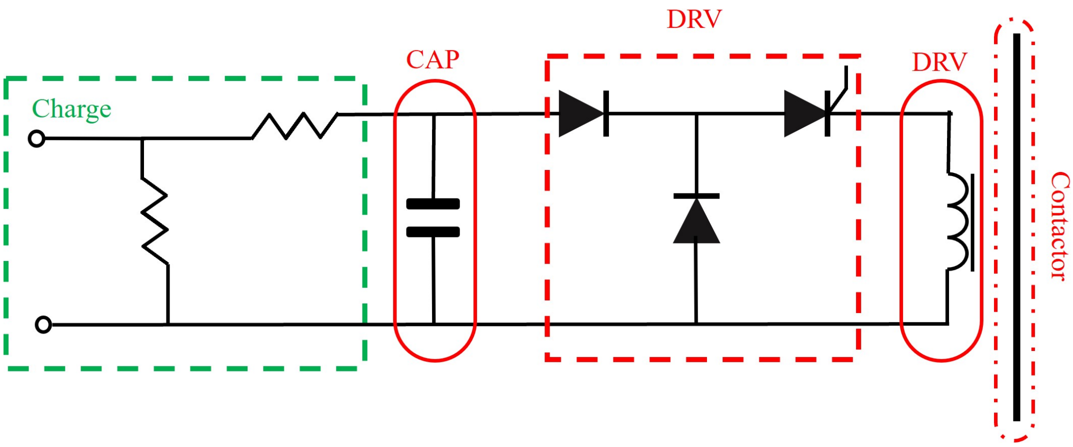

Figure 3.2: Drive and pre-charge circuit of the Thomson coil actuator

activates and holds the aluminum plate underneath. The locking ensures the Thomson coil does not reclose unless the mechanism is released. Figure 3.3 is the locking mechanism of the Thomson coil actuator.

A spring is incorporated into the Thomson coil actuator's design and used to dampen the actuator's kinetic energy. The spring, by the same kinetic energy, can then reclose the actuator after the locking mechanism is released. Using the spring to dampen the actuator eliminates the necessity of a second Thomson coil actuator to reclose the VI. One final benefit of the spring is ensuring the breaker stays closed due to mechanical vibrations.

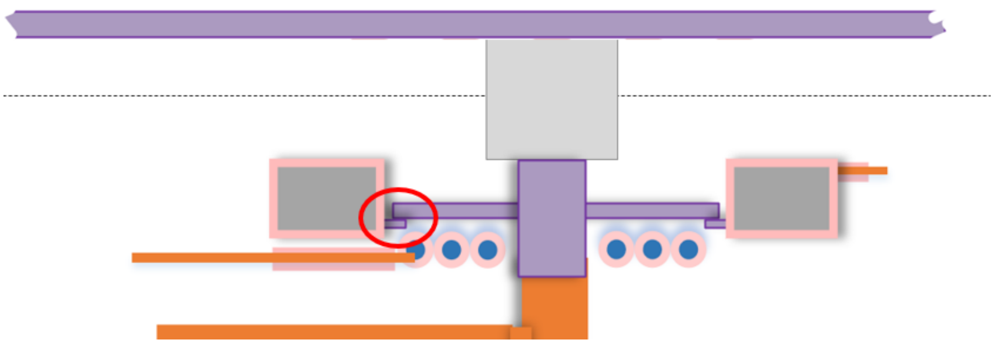

Figure 3.3: Thomson Coil Actuator Locking Mechanism

3.2.3 Spring Dampener

The force balance equation for the spring and damper system connected with the Thomson coil opening can be calculated with the equation 3.9.

$$\Sigma F = ma = F_{TC} - kx - b\dot{x} \tag{3.9}$$

Where F is the total force, m is the mass, a is the acceleration of the mass, F_TC is the force of the Thomson Coil, k is the spring constant, x is the position of the contactor, and b is the damping constant. The equation can be arranged in the standard form like the equation 3.10.

$$\ddot{x} + \frac{b}{m}\dot{x} + \frac{k}{m}x - \frac{\pi\mu_0 N^2 I_m(t)^2 a^2}{m}F_n(x) = 0 \tag{3.10}$$

The motion equation for the closing operation is defined by the equation 3.11.

$$\ddot{x} + \frac{b}{m}\dot{x} - \frac{k}{m}x = 0 \tag{3.11}$$

3.3 Current Commutating Drive Circuit

The central component of the design for the CCDC is the two inductors. The inductances of the CCDC drive the fault current's commutation into the semiconductor branch and commute the precharge counter current into the VI portion of the disconnect switch. Depending on the amount of the interrupting current is what determines the sizing and optimization of the mutual inductance.

After the commutation phase, the CCDC consists of three branches, a thyristor in parallel with the precharge capacitor in parallel with the free-wheeling diode. The thyristor works as the activator for the rest of the circuit. Once the fault current exceeds the activation current of the thyristor, the thyristor conducts, activating the rest of the circuit. The precharge capacitor actions include charging after the arc current is extinguished and discharging once activated to induce a zero crossing. The sizing of the capacitance for the precharge capacitor is based on the sizing of the commutating mutual inductance.

3.3.1 Inductance

The primary calculation necessary for the optimization process is the mutual inductance of the two commutating inductors—the driving calculation for optimizing the mutual inductance of the two coils. The mutual inductance is the ratio of emf between two inductors. From the inductor size, the size of the capacitor is calculated, and the rest of the circuit is physically sized.

The method for CCDC arrangement was similar to a Rogowski coil Current transformer. In other words, the primary coil, also labeled as L_2 is a helical coil with N numbers of turn with another N number of turns within the turns as well. This is to induce the current in the direction of the primary coil which is a cylindrical inductor. One of the inductors is cylindrical, and the other is a spiral inductor that is also curled around. The following equation defines the value of the inductance L1.

The primary driving factor for the sizing of both commutating inductors is the maximum current the inductors must be rated for and the duration of the maximum current in the inductor. The maximum current is one of the values derived from the PSO optimization; however, for this calculation, it is 4kA. With the maximum current determined, the diameter of the wire is calculated using the equation 3.12.

$$d_{wire} = 2\sqrt{\frac{7I_{Max}\sqrt{t}}{\pi}10^{-3}} \tag{3.12}$$

In the equation, t is the maximum current duration derived from the optimization code.

The next step is to determine the inductance of both inductors, the length, and the turns of the helical coil inductance. The following equation determines the length of the helical coil inductor:

$$l_2 = 2\pi(d_{coil} + d_{wire} + s) \tag{3.13}$$

d_{coil} is the diameter of the helical coil, and s is the insulation thickness coefficient with a value of 0.002.

The diameter of the helical coil is determined with the equation 3.14.

$$d_{coil} = 5d_{wire} \tag{3.14}$$

The determining values of the turns within the coil inductor are the diameter of the wire and the diameter of the inductor bus. The following equation determines the number of turns within the coil.

$$N_{Coil} = 2\pi\frac{d_{bus} + \frac{d_{wire}}{2} + s}{d_{wire} + s} \tag{3.15}$$

The diameter of the bus Inductor was an input value of 114mm.

The length of the inductor bus is determined by the values of the Turns in the helical coil, the coil's diameter, and the wire's diameter. The following equation was used to derive the length of the bus inductor.

$$l_{bus} = N_{Turns}(d_{coil} + 2d_{wire} + 4s) \tag{3.16}$$

N_Turns is the value of helical turns by the coil inductor.

Now with the dimensions determined, the inductances of both inductors are calculated. The inductance of the helical inductor is determined by the diameter of the coil, the length of the coil, the number of helical turns, and the turns within the helical turn. The equation used to derive the inductance from equation 3.17.

$$L_2 = \frac{\mu 0 N^2 \pi d_{coil}^2}{(l_2)} \tag{3.17}$$

$u0$ is a permeability of free space equal to $4\pi 10^{-7}$. N is the value of every turn in the helical inductor. The equation 3.18 determines the coils.

$$N = N_{Coil} N_{Turns} \tag{3.18}$$

The driving factors for determining the inductance of the bus inductor are the length of the inductor and the diameter of the wire. The equation is used to calculate the inductance of the bus inductor.

$$L1 = \frac{\mu_0}{2} l_{bus} \log \frac{2 l_{bus}}{d_{wire} - 1} \tag{3.19}$$

With the inductance values of the helical coil inductor and the cylindrical bus inductor calculated, the mutual inductance can be derived using equation 3.20.

$$M = \sqrt{L_1 * L_2} \tag{3.20}$$

3.3.2 Capacitance

The component of optimization is the precharge capacitor. This was a sizing dimension dependent on the size of the inductors. The precharge voltage was sent to a constant of 4000V in the capacitance. This value would never change in the optimization code. Although the capacitance sizing was dependent on the sizing of the 2 inductors, the according to Liljestrand et al. the equation 3.21 to derive voltage from current

$$I_{inject} = U_{charge}\sqrt{\frac{C_{inject}}{L_{inject}}} \tag{3.21}$$

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Chapter 4

Optimization and VPP Results

The benefit of this research is the plug-and-play ability of the simulations and optimizations. Once calculations are derived using experimental data and some simulated data, the optimization method can be utilized to find the outcome based on the demand of the designer. If developed appropriately, the optimization code could output the most optimal design based on cost, spacing, weight, or reliability, with only an input depending on voltage, current, or power.

4.1 Vacuum Interrupter Optimization

The key elements for optimization of the Vacuum Interrupter are dimensions and possibly the mass. In this research, consumers of the self-vacuum interrupters are used, not custom-designed ones. The benefit of the Vacuum interrupter is how power dense the interrupter is. However, to achieve optimal power density, one of the system's inputs is the dimensions of the vacuum interrupter. That is the only aspect of the vacuum interrupter needed for optimization.

4.2 Thomson Coil Optimization Method

The PSO optimization algorithm was utilized when using the previously defined equations for the Thomson Coil. Using the actuator equations defined and the table 4.1 was generated, yielding the capacitance and inductance values. 3.10 is the key Force equation to optimizing the Thomson coil actuator. In order to optimize the inductor of the precharge and drive circuit is the Inductance. The capacitor is dependent on sizing of the Inductance and the turns are dependent on the inductance of the turns. The inductance value is determined with equation 4.1, where A is derived from equation 4.2, and D_i is the internal coil diameter and the outer diameter is calculation with equation and D_o

$$L = \frac{n}{25.4}[\frac{N^2 A}{30A - 11D_i}] \tag{4.1}$$

$$L = \frac{D_i + N(w+s)}{2} \tag{4.2}$$

$$D_o = 2[D_i + (N-1)(w+s)] \tag{4.3}$$

The following figures are the simulated time results of the optimized Thomson coil. Figures 4.1, 4.2, and 4.3 shows the current in the coil for three current ratings, Figures 4.4, 4.5, and 4.6 shows the displacement of the actuator at the three current levels, and Figures 4.7, 4.8, and 4.9 show the velocity at which the actuator opens at the three current ratings, and figures 4.10, 4.11, and 4.12 show the force at which the Thomson coil repulses the metal plate. Some key notes are that for displacement, after 6mm of opening, the Thomson coil is designed to be locked by the locking mechanism and is closed after and, when closing, will stop moving after 6mm.

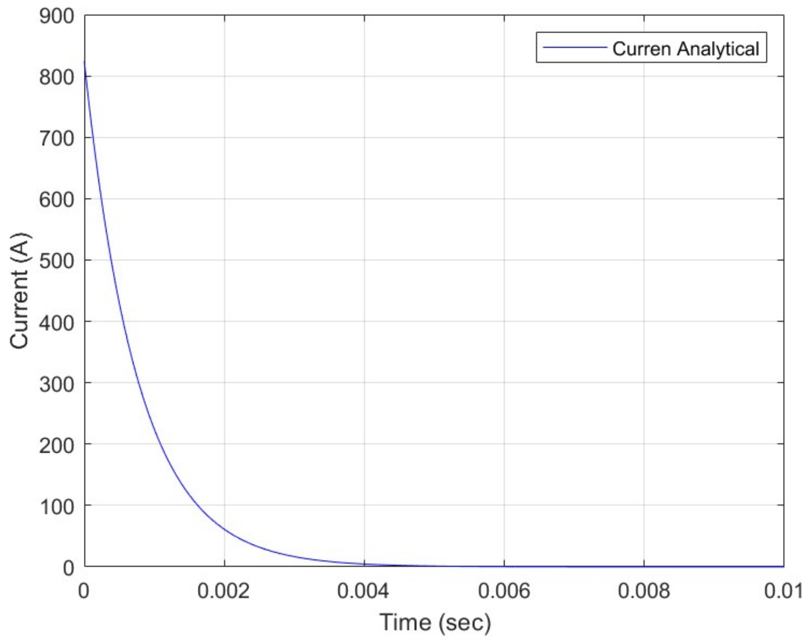

Figure 4.1: Actuator coil current vs. time at 500A

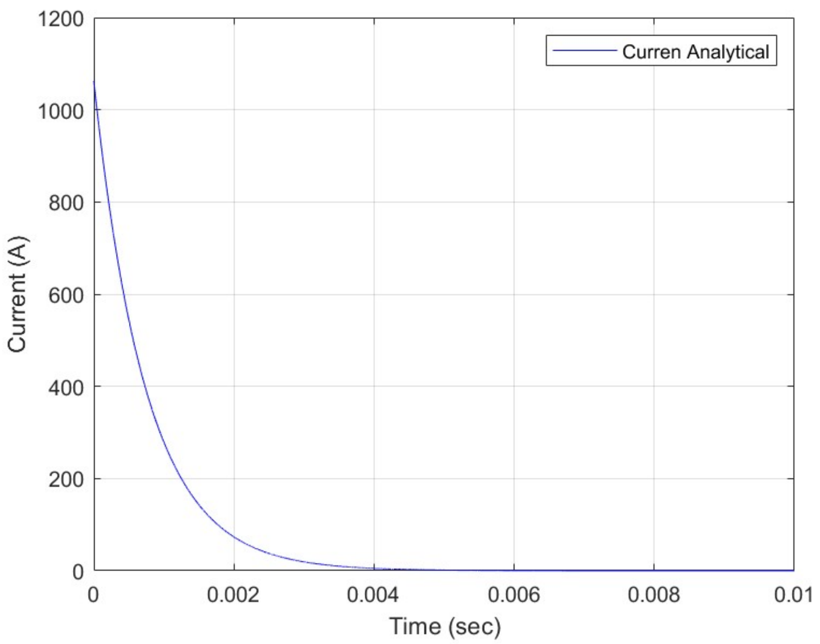

Figure 4.2: Actuator coil current vs. time at 1000A

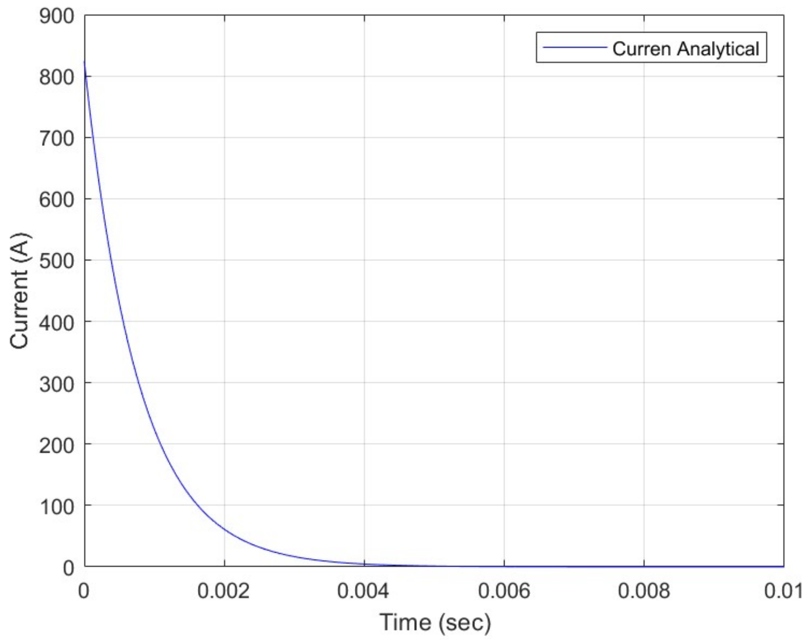

Figure 4.3: Actuator coil current vs. time at 2000A

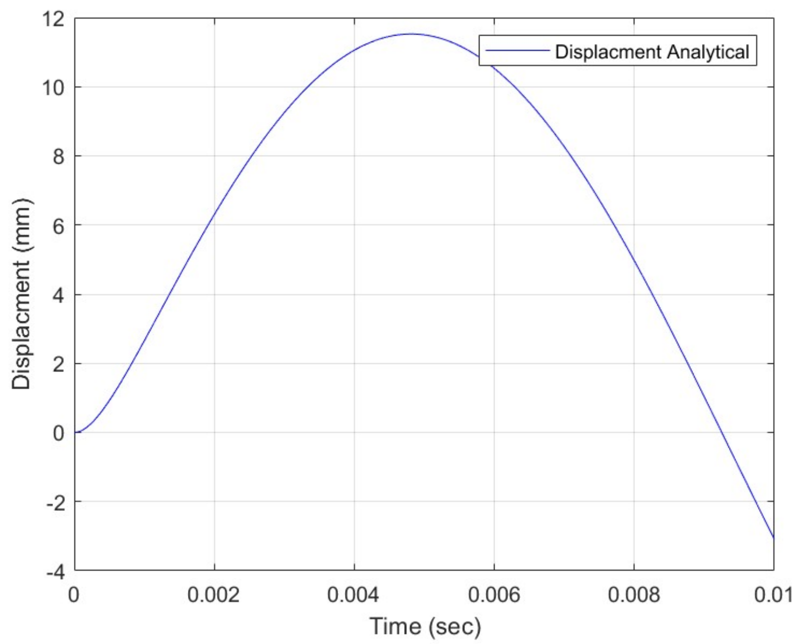

Figure 4.4: Displacement vs. time at 500A

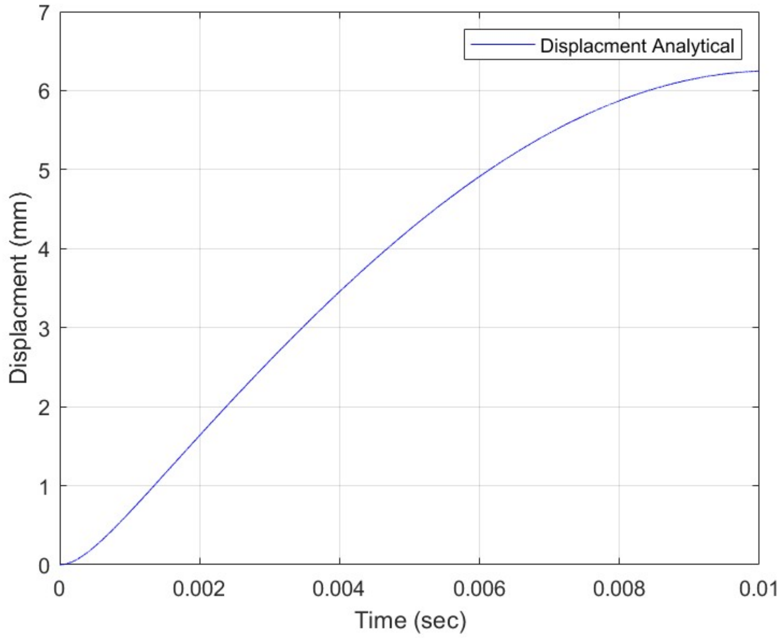

Figure 4.5: Displacement vs. time at 1000A

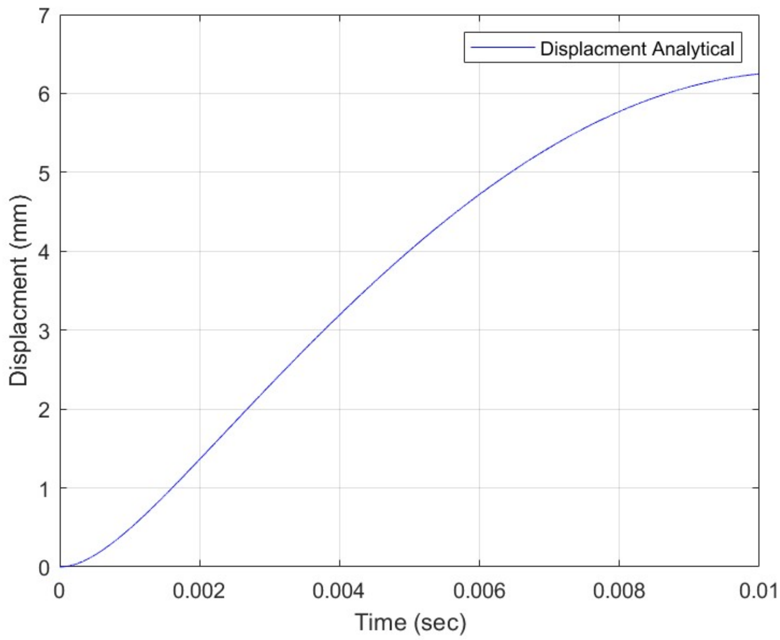

Figure 4.6: Displacement vs. time at 2000A

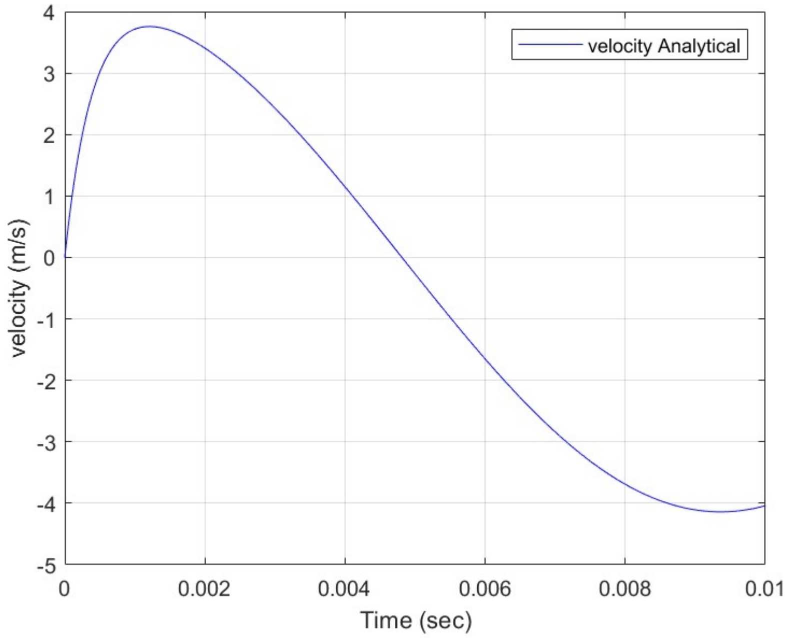

Figure 4.7: Velocity vs. time at 500A

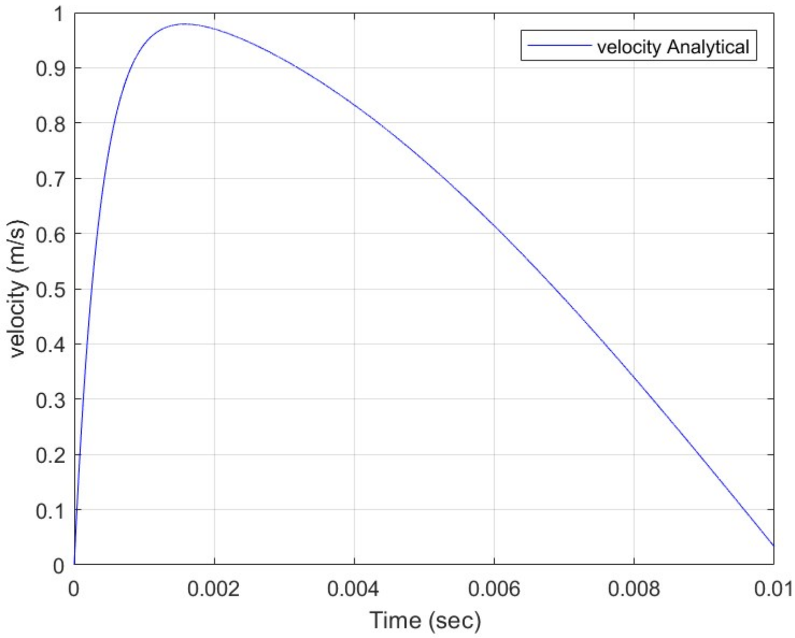

Figure 4.8: Velocity vs. time at 1000A

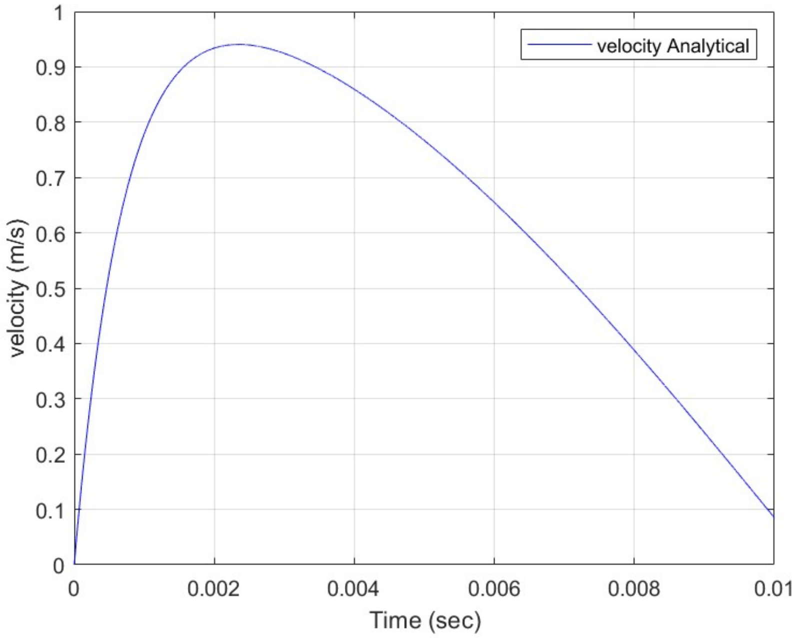

Figure 4.9: Velocity vs. time at 2000A

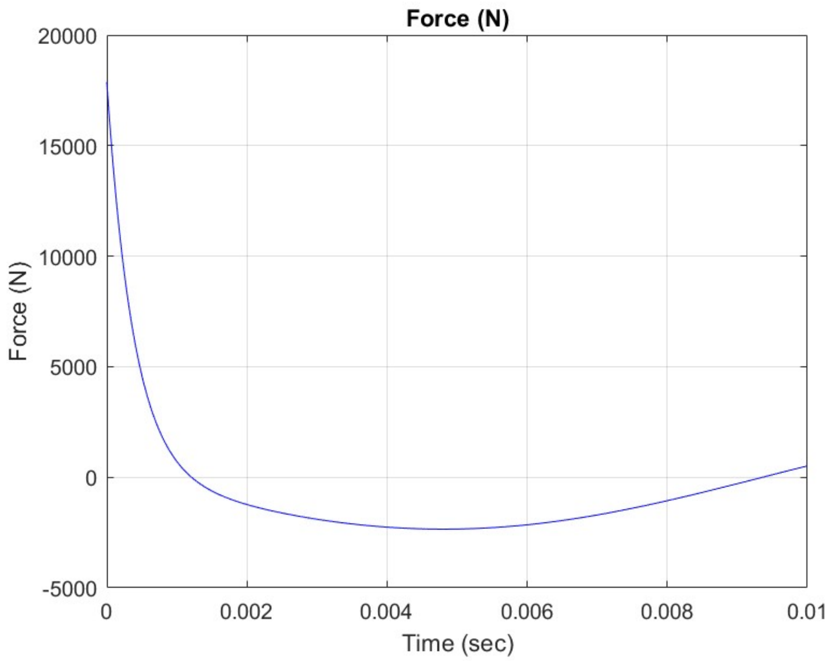

Figure 4.10: Force vs. time at 500A

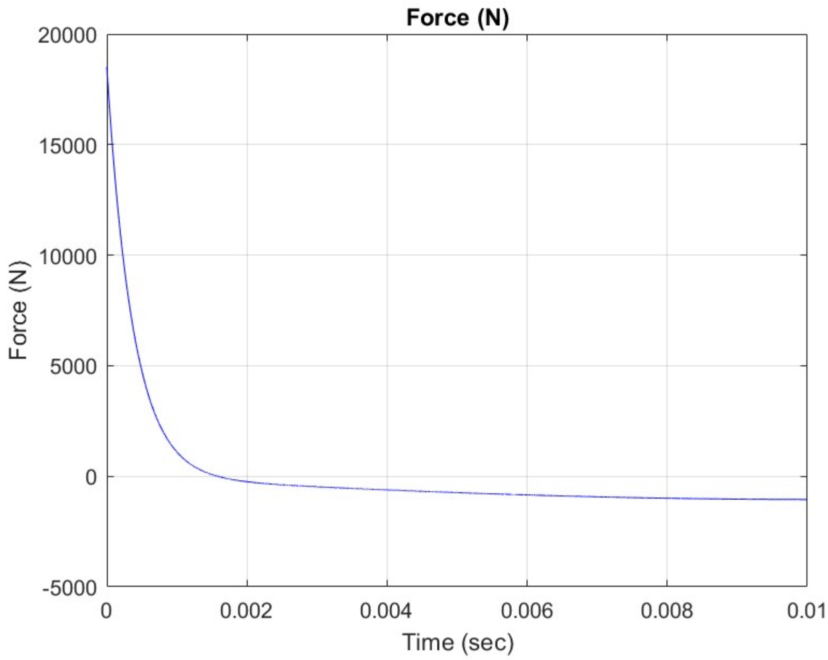

Figure 4.11: Force vs. time at 1000A

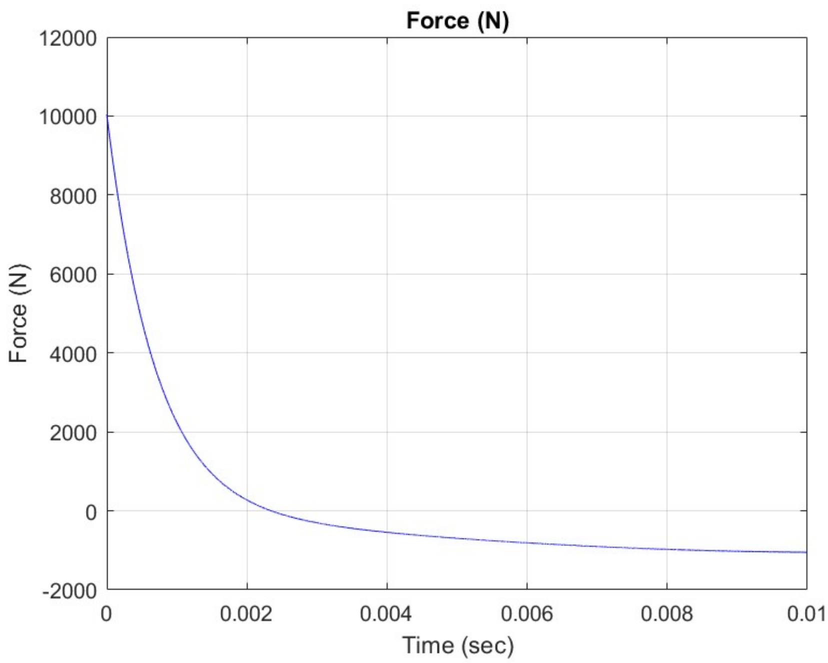

Figure 4.12: Force vs. time at 2000A

IDC (A)	Cap (μF)	Inductance (H)	Max Current of coil (A)
2000	4.63	6.94e-5	534
1000	4.48	5.34e-5	567
500	4.63	3.85e-5	491

Table 4.1: Thomson Coil Actuator Optimization Results

4.2.1 Plecs Verification

Now that the optimization code has generated the optimal values for Inductance and Capacitance, the values are placed in a Plecs simulation to validate the results. Figures 4.13,4.14,4.15 show the simulations results of Plecs at the three current ratings

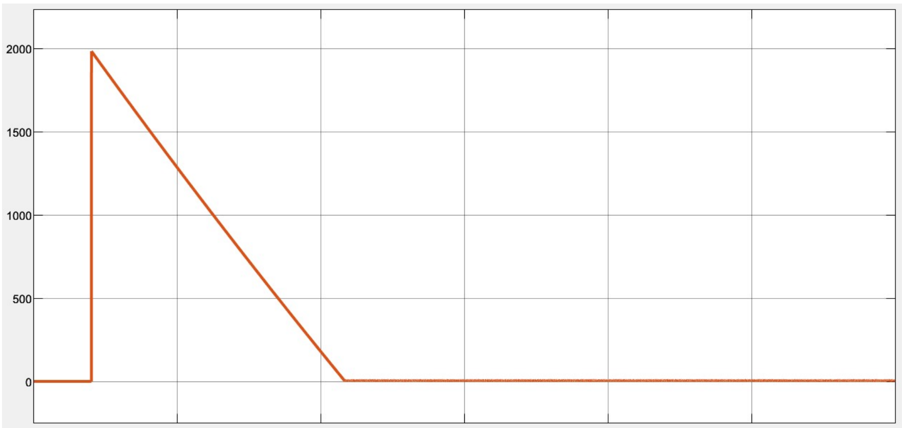

Figure 4.13: Thomson Coil Drive Circuit Current Output at 500A

The next verification of the optimization process is COMSOL multiphysics modeling.

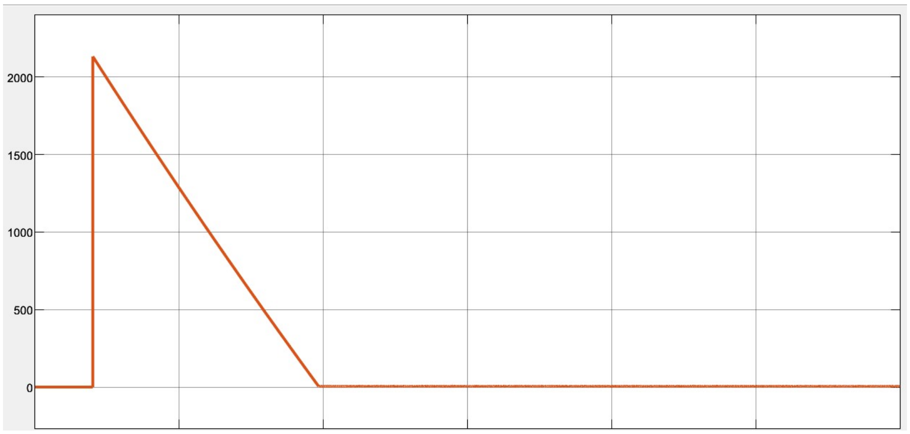

Figure 4.14: Thomson Coil Drive Circuit Current Output at 1000A

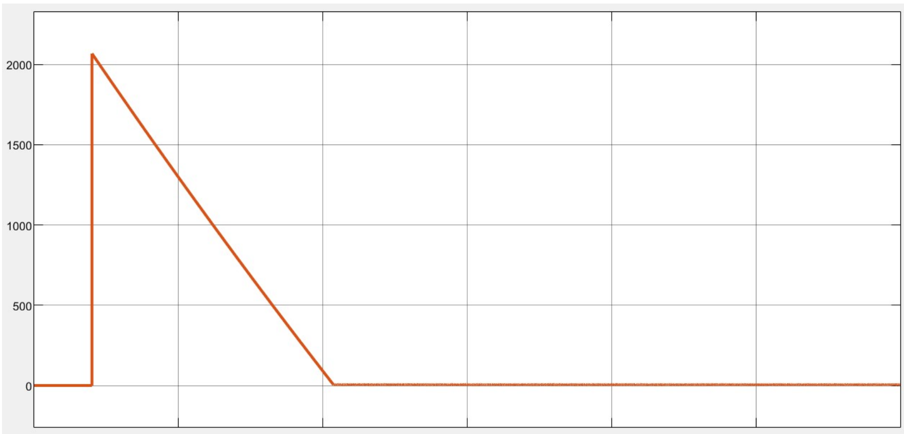

Figure 4.15: Thomson Coil Drive Circuit Current Output at 2000A

The multiphysics modeling was based off of the PSO Results of the 2000A rated components. This is why there is 24 coils in the model. the results are displayed in figure 4.16

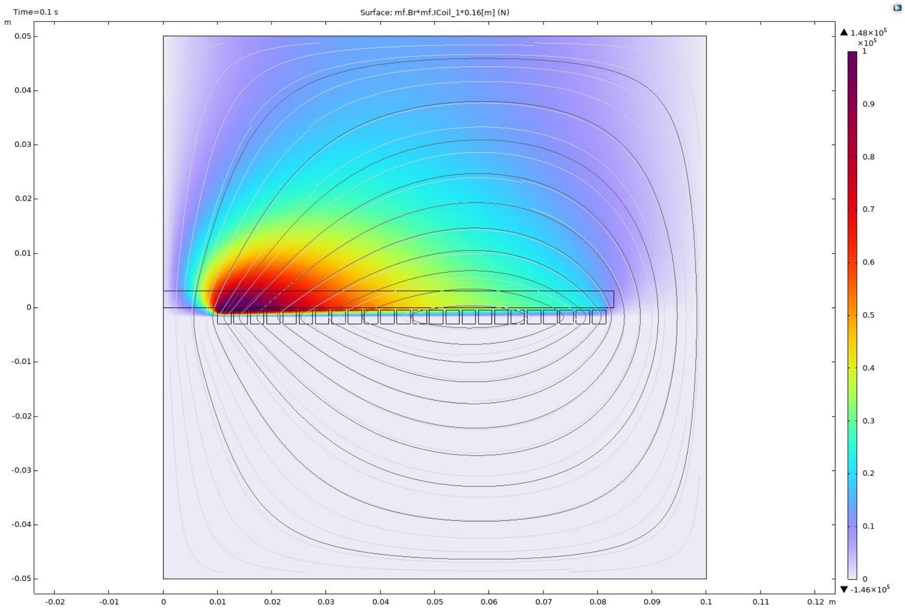

Figure 4.16: Thomson Coil Drive Circuit Current Output at 2000A

4.3 CCDC

This research was developed in order to plug and play the entire DC switch system. This development would include optimizing the CCDC as well. Just like the optimization of the Thomson Coil circuit, the CCDC optimization algorithm was also the PSO. A Simulink power electronics model with a variable Capacitor value, primary inductor value, secondary inductor value, and the mutual inductance of the two inductors.

4.3.1 CCDC Matlab Optimization

The CCDC values ran through the PSO optimization code in order to optimize primarily the Capacitor, Number of turns, and dimensions of the primary and secondary inductors. the length of the wire of the primary inductor drives the sizing of the optimization. The number of turns, inductance, and mutual inductance values are dependent on the wire length optimization which is driven by the interrupt current values of either 500A, 1000A, or 2000A. Table 4.2

Utilizing the same inductor equations used to derive the mutual inductance of the

IDC (A)	Cap (μF)	Inductance1 (μH)	Inductance2 (mH)	Mutual Inductance(μH)
2000	8.85	5.45116	3.4073	81.77124
1000	1.18	4.55	29.9	69.00
500	1.47	53.7	20.3	6.26

Table 4.2: CCDC Component Optmization Values

commutating inductors in the CCDC were implemented into the optimization code. From the code, the sizes and turns were generated, giving the capacitance, self-inductance, and mutual inductance of the CCDC. Plecs circuit model is then used to model the circuit response for the CCDC. Figures 4.17, 4.18, 4.19 show the response of the induced zero crossing of the current in the CCDC. Figures 4.20, 4.21, 4.22 display the commutating current path into the CCDC. Figures 4.23, 4.24, 4.25 display the injection current that the pre-charge capacitor injects into the circuit.

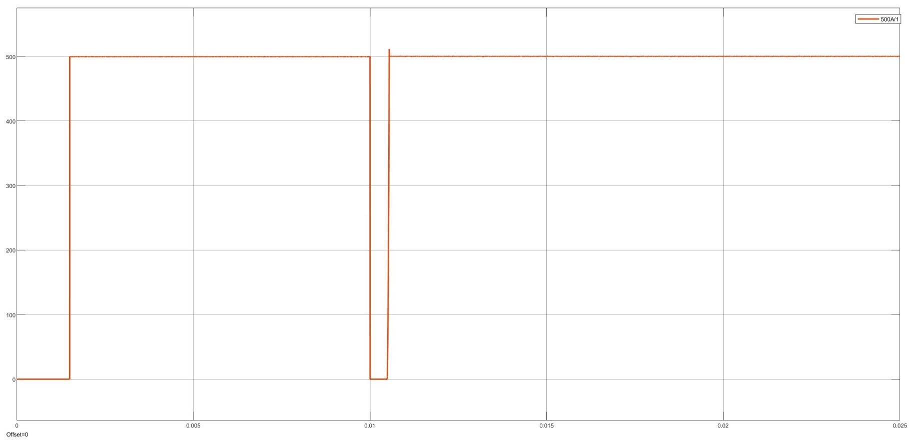

Figure 4.17: Induced zero Crossing form the CCDC at current rating of 500A

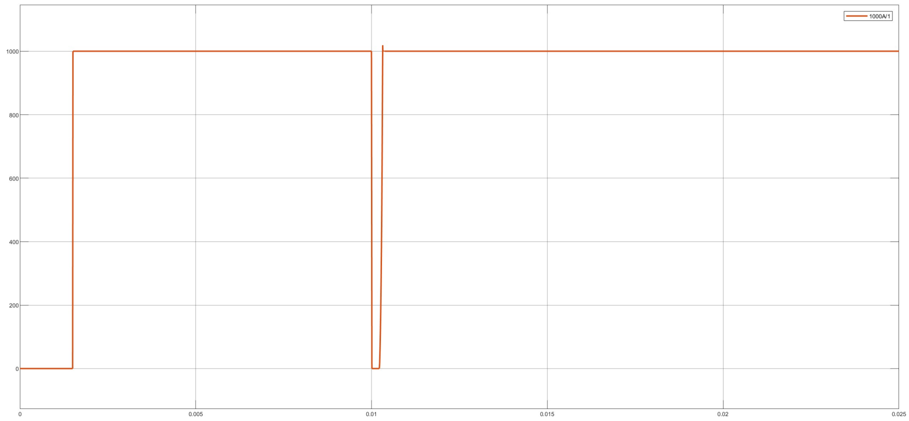

Figure 4.18: Induced zero Crossing form the CCDC at current rating of 500A

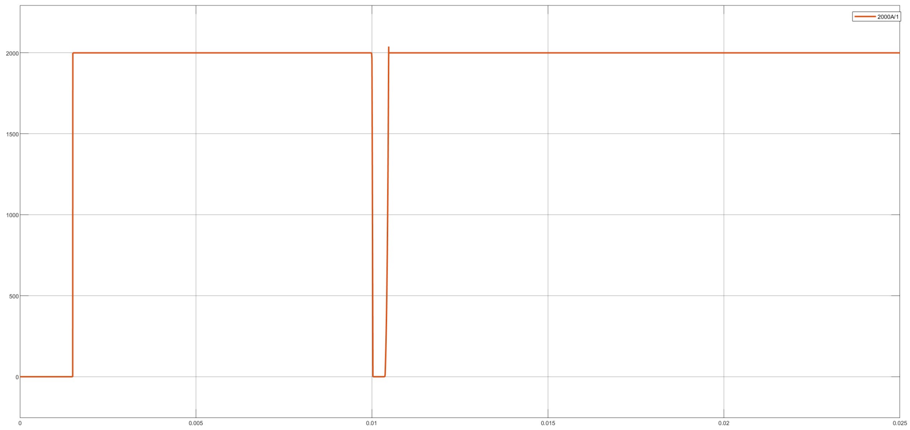

Figure 4.19: Induced zero Crossing form the CCDC at current rating of 500A

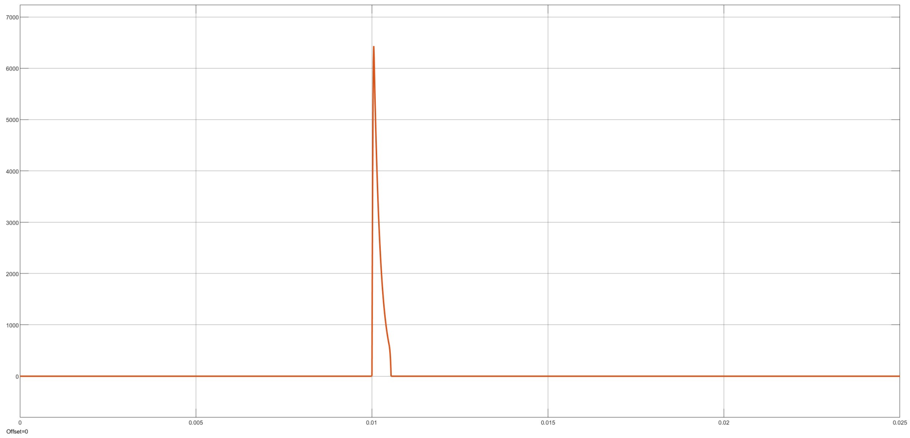

Figure 4.20: Commutation Current in the CCDC at 500A

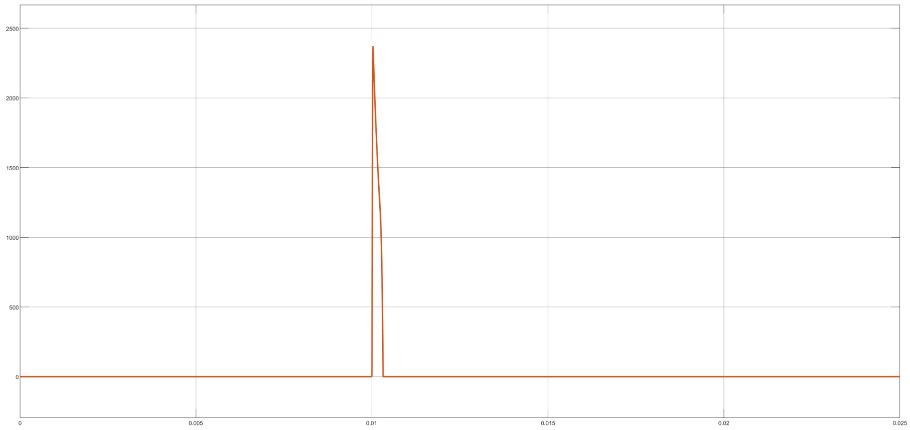

Figure 4.21: Commutation Current in the CCDC at 1000A

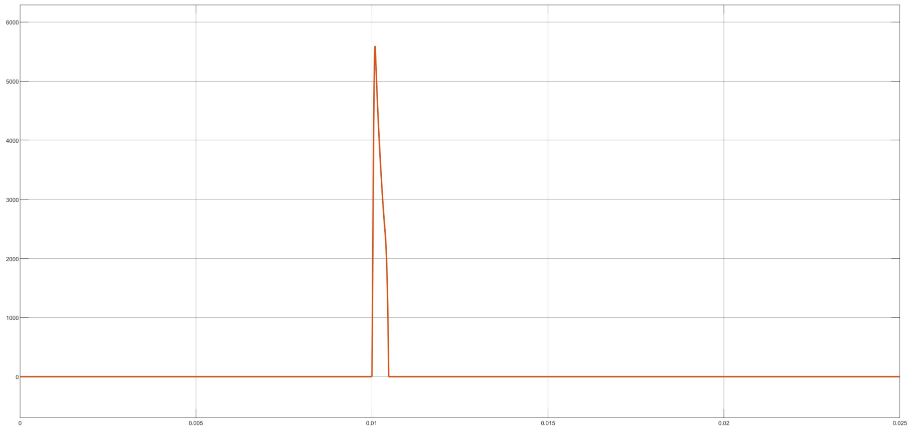

Figure 4.22: Commutation Current in the CCDC at 2000A

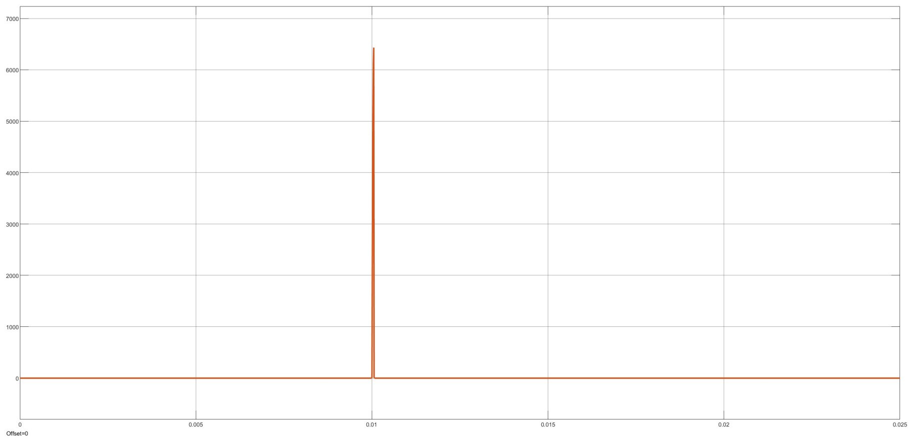

Figure 4.23: Inject Current in the CCDC at 500A

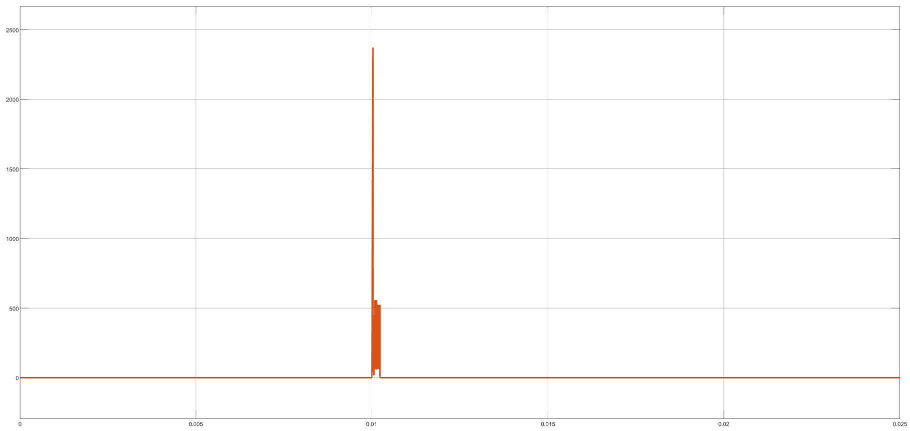

Figure 4.24: Inject Current in the CCDC at 1000A

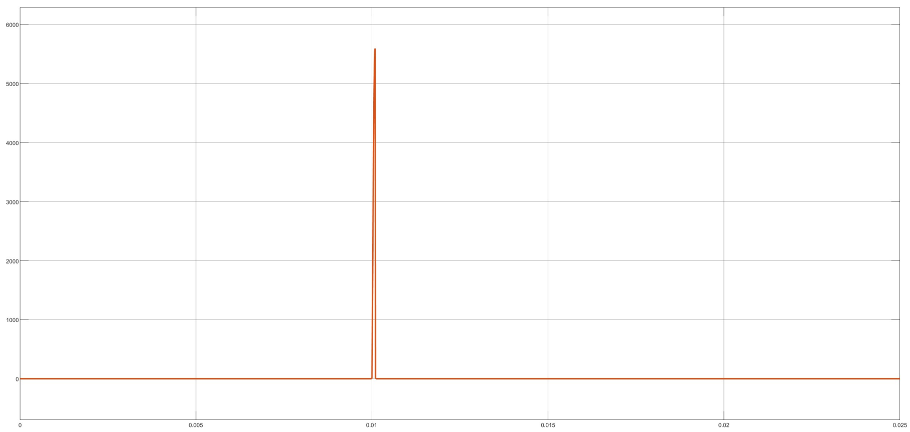

Figure 4.25: Inject Current in the CCDC at 2000A

Results, CCDC components was optimized to induce a zero crossing at rated current at 500A, 1000A, and 2000A. The CCDC components were also optimized to inject the current for the longest amount of time is was possible. According to the simulation results, with the parameters set such as dissipation voltage of 4000V, the CCDC can properly induce zero crossing into the DC current signal.

Figure is the COMSOL model represents the two inductors of the CCDC. The 3D structure resembles the Rogowski coil arrangement of the inductance. Within the spiral inductor, the homogenous multiturn in the coil models the turn within the turn of the size. The parameters of the COMSOL 3D model are based form the parameters of the 2000A PSO optimization code. The models needs lost of computational power, therefore for any future work requires more computational power.

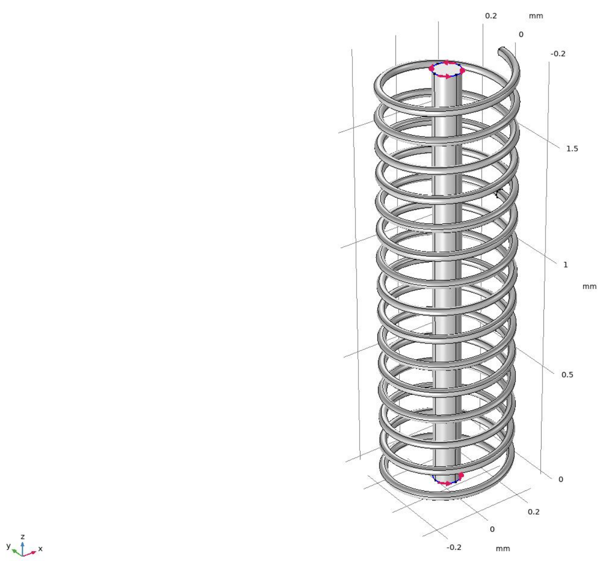

Figure 4.26: Top down of complete DC Disconnect Switch

4.4 Physical Layout

Figure 4.27 represents the complete DC physical layout of the completed DC disconnect switch with the locking mechanism connected.

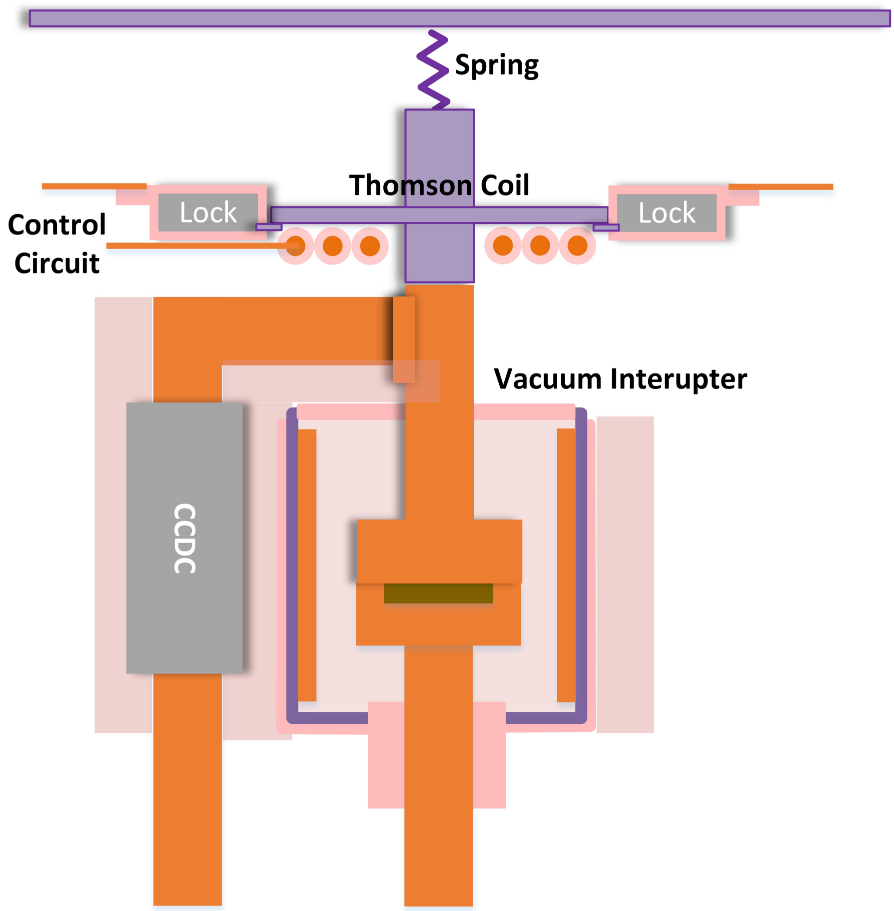

Figure 4.27: Top Down of Complete DC Disconnect Switch

Now that the optimization code sized the electrical values of the components as well as the physical dimensions of the components, the optimal switch layout is generated. The method begins with the COTS VI. The COTS VI dimensions are displayed in the following figure with the dimensions of w_{int}, h_{int} and l_{int}.

The orange depicts copper assemblies, the pink depicts insulation, and the grey represents assemblies such as the CCDC, the Thomson Coil actuator, and other control boards. Any blue coloring depicts cooling systems, and green is free space. The Following figure portrays the completed VI system with a connected switch system.

4.27 represents the entire Ultra Fast DC Disconnect Switch and 4.28 is the entire drawer allocations for the switch gear with a top view and figure 4.30 with a front view. The Purple areas depict the chassis of the cabinet. Below are the added power electronic assemblies. PE1 is the thyristor/ diode unit and the required heat sinks for the Thomson coil, and PE2 is allocated as the capacitor bank assembly. In addition, PE3 is the circuitry for the CCDC power electronic assembly, and PE4 and capacitor to the CCDC, respectfully. In addition, PC1, PC2, and the current sensor CT are components of voltage level control

The compilation of the drawer compilation switch assembly is shown in in a Bulkhead mounted system in figure 4.30 while figure 4.31 in a deck mounted. The drawer compilation includes positive and negative rail assemblies and power supply. Creepage between the two switches and the connection end to the drawer slides would be determined based on an 8kV with 5 percent tolerance included. Then cable allocations, connection, and stationary buses determine the rest of the switch buildup. This buildup ensures that when a drawer slides, it maintains space allocation. The following figure describes the entire 3-dimensional switch drawer compilation for Bulkhead Mounted switches in an AutoCAD model.

At the system level of VPP for ships is to optimize dimension based on spacing. The key values for this level of optimization is for the power density. Power density is the measurement of amount of power per volume of space.

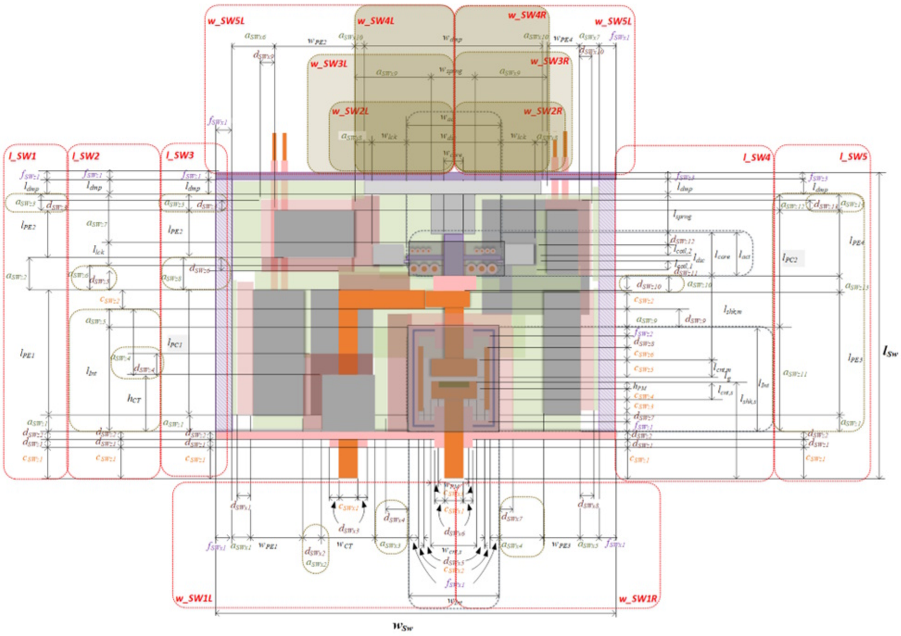

Figure 4.28: General compilation of a Single Pole Switch Assembly (top view)

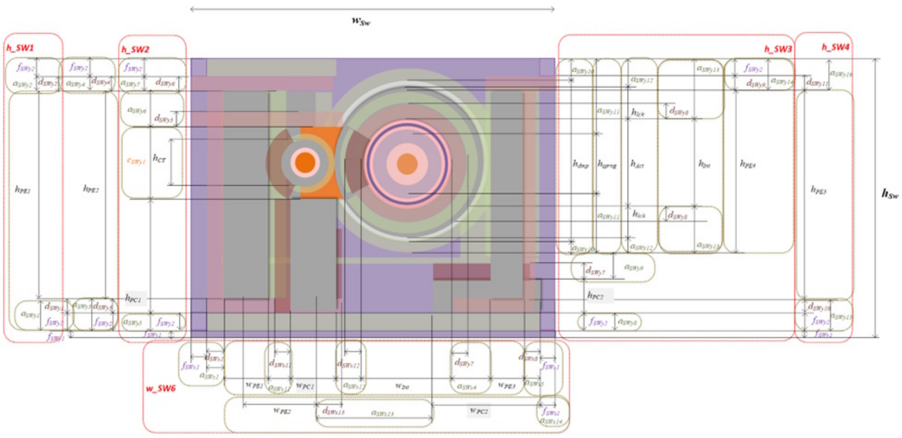

Figure 4.29: General compilation of a single pole switch assembly (view from the back)

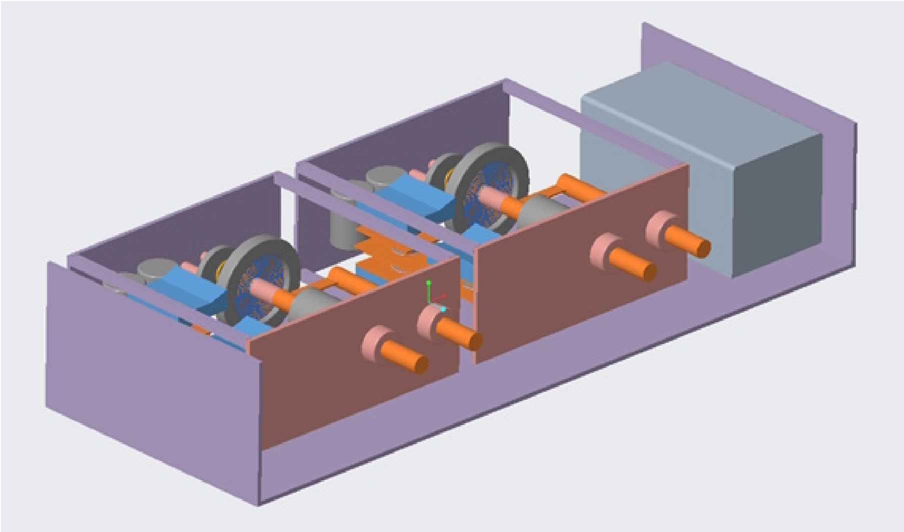

Figure 4.30: 3D Switch Gear Drawer Layout for Bulkhead Mounted switches

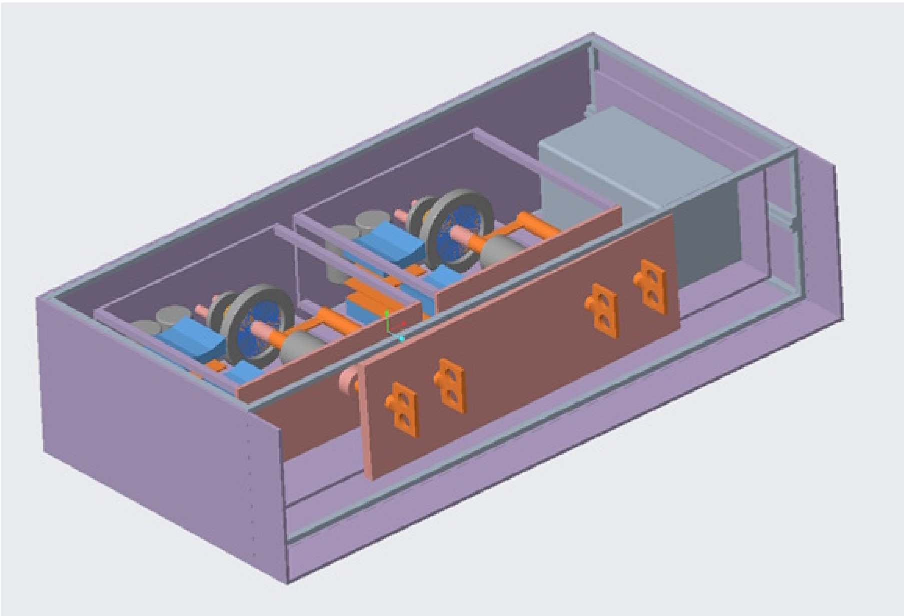

Figure 4.31: 3D Switch Gear Drawer Layout for Deck Mounted Switches

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Chapter 5

Conclusions

5.1 Summary

A circuit breaker is an electrical device designed to interrupt fault current and to isolate the current in the case of a fault in order to protect life and equipment. Within an AC system, this is possible with conventional Circuit breakers. There is also a natural current limiting from upstream chain transient reactance with components. AC system can trip close to the fault location due to reactance calculating changes in voltage and current, the circuit breaker opens, and the arc begins. The current will continue until the zero crossing is reached when the dielectric recovery begins. AC contains natural zero crossing, and Once the arc is extinguished, air gap protection is created, and galvanic isolation is secured. Within a DC protection system, none of these aspects occur naturally. Thanks to power electronics, and the designed DC disconnect switch, there is now an added induced zero crossing from the CDCC and galvanic isolation from the mechanical VI. With VPP and PSO optimization code, the method can properly generate dimensions and component values for a DC disconnect design for the fitted power density that can fit any protection system. Now that optimization algorithm is developed, the optimization method can be used for any range of input parameters for the code is general based on the input parameters.

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