ABSTRACT

PENG, CHANG. Design, Optimization and Development of Ultra-fast Mechanical Switch for DC Circuit Breaker Applications. (Under the direction of Dr. Alex Huang and Dr. Iqbal Husain.)

Medium voltage to high voltage DC circuit breakers are considered the showstopper for wide adoption of DC systems for power transmission and distribution. The key challenge for high power DC circuit breaker is to achieve fast interruptions of direct current so as to protect the system against faults while keeping the conduction losses as low as possible during normal conduction. This thesis investigates the principles of various DC circuit breakers, the design of ultra-fast mechanical switches for DC circuit breakers and the operation control of such circuit breaker.

In this thesis, Chapter 1 reviews the challenges of DC system protections and summarized available high voltage DC interruption technologies. It has also briefly reviewed different DC interruption technologies in two categories based on the final current interruption mechanism and medium.

Chapter 2 evaluates and compares the four important groups of DC circuit breaker schemes. Such circuit breakers can be used as fast acting, current limiting AC circuit breakers as well. The fast acting mechanical switch has been identified as the key component for the development of DC circuit breakers.

Chapter 3 focuses on the operation transient analysis and multi-physics complexities in the design of a Thomson coil based ultra-fast mechanical switch for hybrid AC and DC circuit breakers. The electromagnetic, mechanical and thermal behavior of the switch has been analyzed through simulation using a multiphysics finite element software. The design variables have been classified into lumped circuit and geometric parameters; the sensitivity analysis by means of systematic and comprehensive simulations on these parameters helped establish the design guidelines.

Chapter 4 presents the impact different drive circuits have on the performance of the Thom-
son coil actuator. Three single pulse circuits and two multiple pulse circuits are evaluated by multiphysics modeling and simulation. The three single pulse circuits share very similar performances and are only slightly different from each other because of their different current loops; while multiple pulse circuit has the possibility of many different combinations and can potentially achieve a higher energy efficiency. The pulse forming network, though most complex, is able to generate multiple pulses of moderate magnitude to synthesize an optimized current waveform to boost the performance of the actuator.

Chapter 5 reports the design of Thomson coil based fast mechanical switch prototype for hybrid AC and DC circuit breakers rated at 30 kV voltage and 630 A current. The compact design with optimized circuit parameters and geometric dimensions of components targets 2 mm travel within 1 ms when driven by a 2 mF capacitor bank pre-charged up to 500 V. The use and design of a disc spring as the damping and holding mechanism is presented. The structural design of a complete 15kV/600A mechanical switch assembly rather than just the actuator is given. Experimental results show that the switch can travel 1.3 mm in the first 1 ms, and 3.1 mm in the first 2 ms when driven by a 360 V 2 mF capacitor bank. Such fast mechanical switches facilitate hybrid circuit breaker interruptions within 2 or 3 milliseconds for ultra fast protections with very low operation loss in 5 - 35 kV medium voltage DC as well as AC systems.

Chapter 6 investigates the active damping mechanism utilizing the closing coil to absorb excess kinetic energy of the moving mass at the later stage of its movement so that the disc spring can absorb the rest of the kinetic energy and hold it in the open position. In this way, the actuator is allowed to be accelerated faster and therefore the DC circuit breaker can interrupt a fault in a shorter time, which in turn stabilize the power system. The experimental results have verified the effectiveness of the active damping mechanism: more than 40% increase in displacement has been observed compared to the design without this active damping method.

Chapter 7 reports the experimental results of a DC circuit breaker consists of a 15 kV Silicon Carbide (SiC) Emitter Turn-off (ETO) thyristor device as the main breaker, the ultra-fast mechanical switch, and a commutating switch made of low voltage MOSFETs. The target
application is a 7.2 kV 200 A distribution system. The test method has been explained, and both low voltage and high voltage experimental results have been included.

Chapter 8 gives a design of an ultra-fast mechanical switch for the use in 100 kV, 1250 A DC circuit breakers. It can withstand 200 kV within 2 ms. The design includes the selection of a suitable vacuum interrupter, the design and parameters of the actuator based on the selected vacuum interrupter, the drive circuit and energy storage capacitors, and the preferred characteristics of the disc spring. Besides the design, a control strategy has been proposed for the hybrid DC circuit breakers to achieve shorter total interruption time based on the analysis of the system parameters and the hybrid DC circuit breaker characteristics.

Chapter 9 summarizes the work and proposed a few research topics for the future: a novel scalable design of the mechanical switch for heavier payloads and faster operation speed and an alternative DC circuit breaker that employs a series commutating switch and a parallel snubber capacitor for current interruption.
Design, Optimization and Development of Ultra-fast Mechanical Switch for DC Circuit Breaker Applications

by

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A dissertation submitted to the Graduate Faculty of North Carolina State University in partial fulfillment of the requirements for the Degree of Doctor of Philosophy

Electrical Engineering

Raleigh, North Carolina

2016

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BIOGRAPHY

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His research interests include solid state and mechanical circuit breakers, DC technologies, electromagnetic devices, and high power semiconductor devices and converters.
ACKNOWLEDGEMENTS

I would like to thank my advisor Dr. Alex Huang for his guidance, inspiration and support during my study and research. Discussions with Dr. Huang always intrigues new thoughts and guides me to innovative ideas. Without his support, I would not be able to start my work at FREEDM System Center and continue my research on DC circuit breakers. He has allowed me the time to grow and to learn power electronics, and the freedom to explore and investigate circuit breaker technologies.

I would like to thank my advisor Dr. Iqbal Husain who has been continuously encouraging me on the research of ultra-fast mechanical switches and DC circuit breakers. His trust in my judgment and his interest in my work has been a great motivation for me and will not be forgotten. This thesis would not be possible if not for his continuous support, help, and advises.

The help and consultation from Dr. Bruno Lequesne and Mr. Rogger Briggs are greatly appreciated. These two nice gentlemen have guided me though the design and test of the mechanical switch, my PhD study, and the starting of my career. They are always encouraging and supportive.

My thanks also go to Dr. John Strenkowski for teaching me the fundamentals of finite element analysis and serving in my exam committee, and to Dr. Wensong Yu for keeping his office open for me, serving in my exam committee, and many interesting discussions we have had.

I would like to extend special thanks to all faculty, staff and students at FREEDM System Center for their support and warmness.

I am deeply indebted to my family for their unwavering love and support through my years of study and research.
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Chapter 1

Introduction

As electric power transmission and distribution systems continue evolving, the structure and backbone of the system change, and the requirement of the performance and response of systems are more challenging. A few notable challenges include the endeavor to achieve higher energy efficiency, higher power quality and a more robust system. DC systems, no matter in low voltage micro-grid level, or medium voltage distribution level and high voltage transmission level, are considered the most promising to achieve these goals.

This thesis deals with the most challenging topic of DC systems: the DC circuit breakers. It investigates how various DC circuit breakers work; what is the requirement for such breakers; the design of the key component - the ultra-fast mechanical switch; the optimization and advanced control of the mechanical switch; and the optimization and control strategy of high voltage DC circuit breakers.

1.1 Benefits of DC grid systems

Interconnected DC grids would be a natural trend if the current HVDC transmission systems continue to expand. Fig. 1.1 shows how terminal to terminal HVDC transmission links can evolve into a DC grid; Fig. 1.2 shows an interconnected AC/DC system; Fig. 1.3 presents a conceptual diagram of a bipolar HVDC and MVDC network that is connected to AC networks.
The benefits brought by DC grids rather than AC grids include:

1. Only active power is transmitted through the DC network; thus transmission as well as distribution systems could be rated only for the active power.

2. Conductors are more cost-effective, because they are designed for average and constant values rather than peak values of AC systems. Besides, there is neither skin effect nor proximity effect in DC.

3. Without charging current, DC cables make DC grids more feasible. For AC overhead lines, it is difficult to get the permission for new line corridors than ever because of environmental, ecological, political, and safety considerations. For AC cables, which dominate the investment largely in transmission schemes, inherent capacitance effect makes them much less cost-effective. But DC cable systems have no such problems.

4. Black-start ability is another advantage with VSC technology in a DC grid. It can connect a passive or islanded AC network and also restore an AC network from down much easier,
such as the case of affected network by the Sandy storm in northeastern U.S., 2012.

5. DC grids can better integrate offshore energy parks through cable systems, such as wind park or wave energy park, and better in-feed cities through cable systems.

6. DC grids offer faster control response than AC grids. Since semiconductors can switch in microseconds and power electronics converters has less inertia, their controllability is better in both speed and preciseness.

7. AC/DC converters using self-commutated devices are able to control active and reactive power independently, so that a more flexible control over the connected AC systems can be achieved.

8. DC connections are the only way to connect AC systems operated at different frequencies or phase angles, which are often the cases when interconnections between regional grids or across the borders are needed.

9. Overall cost for HVDC transmission projects are less than HVAC when it comes to dis-
tance of more than 500 km, and capacity of several GW.

The benefits brought by DC grids rather than two-terminal HVDC connections include:

1. Multiple converter stations at one terminal are eliminated in DC grids, but multiple connections with other terminals to every DC node are still available. This greatly reduces the number and thus the cost of converters.

2. Frequency support requested by one or more interconnected AC systems could be handled by all the rest AC systems in a short time, and this burden is to be shared between them through the DC network.

3. When different regions are connected by a large DC grid, power support could also be distributed among each of nodes in the grid, and power deviation of the whole systems can be attenuated.

### 1.2 Challenges of Protections in DC Grid Systems

#### 1.2.1 Interruption of DC circuits

The first challenge is how to protect DC grid systems because of the difficulty to interrupt a high voltage high current DC circuit. Usually for transmission level DC grids, the voltage could be 150 - 320 kV, or even higher; and the current would be 1 to a few kA. Interrupting a continuous DC current of a few kA in a systems of hundreds of kV itself can be very demanding for the switching equipment. In Chapter 2, high voltage DC interruption techniques are discussed in details. Interrupting a DC current is more complicated than an AC circuit. For example, if mechanical circuit breakers are used, some auxiliary circuits are always required to interact with a burning arc in a mechanical circuit breaker so that the arc current is brought to zero and extinguished. Another difference from conventional AC circuit breakers is that, due to the large amount of magnetic energy stored in the circuit, which increases as fault current rises up, varistors are needed to absorb the energy.
1.2.2 Interruption Speed

For a voltage source converter based DC grid, once there is a short circuit, the DC bus voltage could drop very quickly and in the same time the short circuit current rises very fast if the faulted segment is not cleared and isolated quickly. If the DC voltage drops too low, all connected terminals may need to block out as preset by their own protection functions. The power transmission is interrupted for the whole DC grid which could consequentially cause instability in larger areas. If the short circuit current is too high, the value can go beyond the interruption capacity of installed DC circuit breaker and cause the equipment as well as the system to fail.

Therefore, the operation speed is crucial for the protection of DC grids. Ideally, the time should be as short as possible. Generally, researchers and manufacturers are targeting a few milliseconds as the total interruption time.

The speed requirement can be less stringent if current limiting inductors are installed in the lines or cables. However, such inductors store magnetic energy during normal operation and short circuit conditions that puts additional duty on the energy absorbers of the DC circuit breakers. On the other hand, considerations regarding the transients and system control should be given if such inductors are installed.

1.2.3 Interruption Capacity

In conventional AC circuit breakers, the interruption capacity is expressed in MVA which is the product of the rated voltage and the maximum current that can be interrupted at this voltage. This definition applies to DC circuit breakers as well. However, it is suggested that in the calculation the system voltage is replaced by the MOV clamp voltage value, which is also called transient interruption voltage (TIV).

The required interruption capacity of a DC circuit breaker is related to its operation speed and the system parameters such as the impedance of the transmission conductors, the nominal voltage and current, and the capacitance of the DC capacitors.

If the operation speed is slow, the circuit breaker will needs to interrupt a high current due
to the fast rise rate of fault current. If the nominal voltage and current are high, the circuit breaker needs to withstand higher voltage during and after current interruption.

1.3 High Voltage DC Interruption Technologies

High voltage DC interruption technologies can be divided into two main groups: mechanical based solutions and solid state based solutions. This section first provides a comparison of general mechanical and solid state switches.

1.3.1 Comparison of mechanical and solid state switches

What distinguish a mechanical circuit breaker and a solid state breaker are mainly in the following three aspects:

1. The voltage drop

A mechanical switch’s voltage drop when conducting a current is dependent on its contact resistance. The contact resistance is a function of the area of the effective contact surface, the condition and material of the contact surface, and the force applied to the contacts. If additional holding force is applied to the mechanical contacts, which are essentially made of certain metal with special coatings, the contact resistance is in the range of tens of micro-Ohms. Therefore the voltage drop when conducting hundreds of amperes of current is only in the range of tens of milli-Volts, and the power loss is only about a few watts, which does not require additional cooling auxiliaries.

The voltage drop of a solid state device at a certain current level depends on the physics of current transportation of the specific device used. Most commonly used power devices that can be used for power switching are metaloxidesemiconductor field-effect transistor (MOSFET), insulated gate bipolar transistor (IGBT), gate turn off thyristor (GTO) or GTO based devices, among which only MOSFET is so called unipolar device that only one type of carrier is conducting the current. The rest of them are bipolar devices in which
both types of carriers are contributing to current transportation. Therefore the voltage drop is much lower at higher current. However, they still exhibit a few volts of voltage drop during conductions which means hundreds or even thousands Watts of power loss. Additional cooling is required for such devices, which adds not only extra cost but also complexity, power loss and footage to the overall design.

2. The current turn-off mechanism and capability

The current in mechanical circuit breaker is cut off by the extinction of an arc which serves as an conduction path after contacts are open. Once the arc is extinguished and the open gap between contacts are sufficiently wide to withstand the forthcoming transient over voltage (TRV), the circuit is interrupted and the networks on both sides of the circuit breaker are isolated from each other.

The DC interruption capability of a mechanical circuit breaker depends on two factors. First, the DC current in the breaker chamber needs to be brought to zero by an external circuit. How much reverse current can be injected to the arc limits how much current the breaker can interrupt. Second, the breaker with a certain gap needs to withstand a
designed TRV level after arc extinction. Otherwise, a restrike happens between the gap because of high TRV or high rate of rise of recovery voltage (RRRV).

The turn off mechanism for solid state switches differ from one device to another. Take IGBTs for an example. Once the positive gate voltage is put on zero or a negative value, the gate voltage reduces linearly for a short period to Miller Plateau. Negative gate current draws current from the nonlinear capacitance $C_{GC}$ and increases $V_{CE}$. As $V_{CE}$ reaches source voltage, $V_{GE}$ continues decreasing and $I_C$ starts to drop. Due to the minority carriers stored in the n-base region, a current tail is observed. In the meanwhile the space charge is built-up to withstand the voltage. The turn-off capability of a semiconductor device is defined by its reverse blocking safe operation area (RBSOA). With snubber circuits, the $dv/dt$ is reduced and the device can potentially turn off much more current. In circuit breaker applications, the snubber circuits may take a few us to charge to the clamped voltage level, but this period is still very short compared to mechanical circuit breakers and therefore would be in favor for the circuit breaker to turn off a large current.

3. The operation speed

The time for a conventional mechanical circuit breaker to interrupt a current is in the range of tens of milliseconds, while for semiconductors it is in the order of microseconds, or even faster.

A mechanical circuit breaker has a lot of movable parts due to its mechanical structure. Though complicated, they are considered reliable and has been used in power systems for over a century. To drive a mechanical circuit breaker to open or close, significant kinetic energy is required to actuate the movable parts: more than enough energy is required to just actuate the electric contacts. Because during the interruption or even conduction of an AC circuit, the arcing can cause the contacts to weld together and therefore when opening some momentum is needed to break the welding interface. This momentum is necessary and established by accelerating a relative large moving mass before it engages
the actual payload which is the movable contact. The additional moving mass takes some
time to overcome the inertial and gain sufficient momentum, which adds to the total
interruption time. If SF6 is used as the dielectric, a single pressure or double pressure
structure is usually used. In such structures, pressurized SF6 gas is released when the
nozzle is opened and helps cool down the burning arc. Additional time is needed for this
pressurization period which also makes the total operation time longer.

There is no mechanical part in a solid state device, and the operation speed is defined
by the solid state physics. As discussed above, once the current conduction mechanism is
removed, the semiconductor device begins to turn off current by recombination of electrons
and holes. The time is dependent on how fast the conduction mechanism is removed and
how fast the carriers recombine in the solid materials. For voltage controlled devices, such
as MOSFET and IGBT, the gating signal can be removed rather quickly, usually less than
1 us; for current controlled device, the period may take some longer time. After that the
device tries to return to its blocking state while only leakage current flows. This process
could take a fraction of us for unipolar devices or a few us for bipolar devices. Sometimes,
snubber capacitors could be used in semiconductor devices to limit the dv/dt to enhance
the turn off capability of the device. In this case, the current of the circuit stops flowing
until the capacitors are charged to their peak value. Therefore, a few us more time should
be included. Overall, semiconductors are about three orders of magnitude faster than
mechanical devices.
1.3.2 DC interruption method classification

In this thesis, the high power dc interruption methods are grouped into two categories mainly based on how the DC current is interrupted: mechanical technologies and solid state technologies. It’s often easy to tell one from another, but for some hybrid techniques or techniques that include both high voltage semiconductors and high voltage mechanical switches, it can be a little confusing. Therefore the following definitions are used to classify DC interruption methods. If a mechanical breaker is used and arcing and arc extinguishing are evolved, it is classified as a mechanical interruption method; if the current is interrupted by turning off a semiconductor device without arcing, then it is called a solid state method. Mechanical DCCB includes passive and active oscillatory DCCBs, and solid state DCCB includes pure solid state and hybrid DCCBs.

1.3.3 Mechanical Technologies

There are a few typical mechanical DC interruption methods, in which the arc current is superimposed with an artificially created reverse current so the total arc current can be brought to zero at a certain instant.

One way to create a current zero in an arc is to form an oscillating circuit of which the oscillation magnitude increases with time. This method takes the advantage of the negative resistance characteristic of gaseous arcs. The parallel circuit is capacitive and under-damped. A high arc voltage is desired so that the oscillating current could be as high as to cancel out the line current in the arcing path. Oscillation frequency and the instability of the circuit also affects the time for the arc to be extinguished. The design of the circuit is very much dependent on the arc characteristics of the mechanical circuit breaker that is used. The time of circuit interruption is in the range of tens of milliseconds. If gaseous circuit breakers are used and higher arc voltage is preferred, pressurization is needed before arc is formed, and this potentially increases the total interruption time.

A second way to do this is to discharge a capacitor bank and inject the discharge current
into the mechanical circuit breaker during the arcing period. The injected reverse current is mostly determined by the capacitance, the pre-charged voltage and the loop parameters. This current is of high frequency and high magnitude. Once discharging is initiated, a current zero can be formed very quickly. As a high arc voltage is not necessary for this scheme, vacuum interrupters and simplified operating mechanisms could be used. Therefore these DCCBs can be potentially faster than those gaseous interrupters.

1.3.4 Solid State Technologies

There are different power devices that can interrupt a DC current, and the device selection could differ from one application to another. Modern power devices that are suitable for circuit interruption purposes and most seen in publications include power MOSFET, IGBT, Thyristor, GTO, IGCT and ETO, etc.

From gate control point of view, MOSFET and IGBT are voltage controlled devices whose drive circuits could be much simpler than current controlled devices such as Thyristor type devices (Thyristor, GTO, IGCT, ETO). From current conduction and switching capability point of view, only MOSFET is of unipolar type among the listed devices and therefore it switches very fast but has less current capability. Different from all other devices, thyristors rely on external commutation mechanisms to turn off current rather than via its gate.

This section aims to identify different interruption schemes rather than various device operation physics, so a DC interruption that employs IGBTs are considered same as another one that uses MOSFETs or IGCTs or ETOs, even though these power devices can be fundamentally different from each other in terms of their conduction, blocking and turn-off capabilities.

Solid state DC circuit breakers can be grouped into a subcategory of pure solid state solutions that only use semiconductors for both conduction and interruption, or a subcategory of hybrid solutions that mainly use mechanical switches for low-loss conduction and semiconductors for arcless interruption. Neither of them has any arc issues, and the turn-off capabilities rely only on the semiconductors.
1.4 Passive Oscillatory DC Circuit Breakers

Passive oscillatory DC circuit breakers are already used in conventional HVDC and UHVDC transmission systems but they are actually called DC transfer switches considering that their main function is to transfer DC current from one circuit to another. They are the earliest solutions for high voltage high power applications in the 1970s to 1990s motivated by the wide adoption of thyristor based HVDC transmission schemes worldwide. Researchers from industries as well as universities from Europe, Japan, United States and China have investigated this scheme both fundamentally and experimentally.

1.4.1 Operation Principle

The diagram of a passive oscillatory DCCB is shown in Fig. 1.6. The circuit is composed by a SF6 circuit breaker, a high voltage capacitor bank, an inductor (sometimes omitted), and metal-oxide varistors (MOVs).

![Figure 1.6: A passive oscillatory DC circuit breaker.](image)

This DC interruption method relies on the negative current-voltage (I-V) characteristic of the arc in SF6. When arc current is increased, the arc column has more carriers in the conduction path, and therefore the arc voltage drops. This negative resistive arc interacts with the secondary path consisting of a RLC circuit to oscillate (R is stray resistance of the loop).
Figure 1.7: Interruption of 5 kA DC current via a passive oscillatory DC circuit breaker, simulated results.

Figure 1.8: Interruption of 5 kA DC current via a passive oscillatory DC circuit breaker, tested results.

The magnitude of the oscillation increases over time when the LC circuit has proper parameters. It is desired that loop resistance is minimized so that the oscillation is not damped quickly. Both the arc characteristics and RLC circuit parameters play important roles in the process of DC current interruption.

The passive oscillatory DCCB can be simulated using EMTDC models to study the transients associated with the oscillations. The Cassie-Mayr model is used to represent the behavior of the SF6 arc, and those parameters used in such model are to be extracted from experimental tests of the circuit breaker used. Fig. 1.7 and Fig. 1.8, [3], show the simulation results using
PSCAD and test results from a prototype built for UHVDC transmission systems.

Using computational fluid dynamics (CFD) and finite element analysis (FEA) methods, the arc itself can also be modeled with physics rather than circuits. Such modeling work could take a lot of modeling and computation efforts.

1.4.2 Advantages and Limitations

Thanks to the simple circuit, only passive components are added to a conventional AC circuit breaker. No auxiliary power or control logic is needed. The trip or close signals sent to the ACCB can be considered the same to the whole DCCB. During normal operation, the conventional ACCB conducts current with minimum losses.

The limitation lies in the operation speed or the interruption time. The total interruption time is defined as the instance from the trip signal to the moment the current of the circuit is brought to zero. For a passive oscillatory DCCB based on conventional SF6 circuit breakers, the interruption time can be roughly divided into three periods: the opening time, the arcing time, and the demagnetization time.

Due to the arc chamber structure and the necessity of compressing and releasing SF6 gas for arc extinguishing, more opening time is required for such circuit breakers, typically around 20 ms or longer. The need for higher arc voltage also justifies the puffer or self blast structure. The arcing time is the time from the start of arcing to the moment the oscillation reaches a zero current. As mentioned before, this time depends on the arc characteristics (arc voltage and negative resistance), the RLC circuit parameters and the magnitude of the current to be interrupted. This time is around 20 ms, which is sufficient for the DCCB to gain dielectric strength to withstand the TIV. For the DC system protection point of view, this response is too slow.

However, both these two periods can be shortened to make it more suitable for fast acting purpose. For example, the opening time can be reduced if one can change the geometry so that over-travel can be avoided: some external compression mechanism may be used.
1.5 Active Oscillatory DC Circuit Breakers

The active oscillatory DCCBs has a pre-charged capacitor bank instead of a passive and uncharged one. Therefore, a charging circuit with high voltage isolation is often required, which added to the complexity of the whole unit. They may or may not consists an inductor, but must have MOVs.

1.5.1 Operation Principle

Though active resonant DCCBs seems very similar to passive resonant DCCBs from circuit diagram point of view, they vary from each other fundamentally and can be very different in terms of performance. The most significant difference is that the operation speed of the active resonant DCCB can be really quick because of two reasons. First, simple and light-weighted vacuum circuit breaker rather than a SF6 circuit breaker can be used, and therefore its opening time can be minimized using an ultra-fast operating mechanism. Most vacuum circuit breakers have butt type contacts and requires no over-travel or pressurized gas flow. Furthermore, because the active resonant cause by current injection from a pre-charged capacitor bank, this current injection could be very fast and of high magnitude which easily creates an artificial current zero in sub-milliseconds. Figs. 1.9 to 1.11 shows the circuit diagram and operation transients [4].

Figure 1.9: A active oscillatory DC circuit breaker.
Figure 1.10: Interruption of 5 kA DC current via a active oscillatory DC circuit breaker, simulated results.

Figure 1.11: Interruption of 5 kA DC current via a active resonant DC circuit breaker, tested results.

1.5.2 Advantages and Limitations

Active oscillatory DCCBs can interrupt a lot of kA DC current as long as the reverse current can be injected.

Even though theoretically there is no limit of the current an active resonant DCCB can interrupt as long as the pre-charged capacitor can inject a sufficient high magnitude reverse current, the pre-charge circuit adds complexity to the unit. For example, though the charging power can be very low, the isolation between the power supply of the charger and the capacitor must be as high as the maximum line voltage could be. Innovations are pursed to simplify the
charging and current injection circuit.

On the other hand, since the injection is of high frequency, it poses challenges to the mechanical circuit breaker to withstand fast rising TRVs after the arc extinction. Also, the moment to initiate the injection needs to be optimally predefined and precisely controlled. Otherwise, the open gap may be too small to withstand forthcoming TRV after arc extinction. If the capacitor bank is pre-charged to a fixed voltage level, a current zero could be reached at different times if the fault current is at different levels.

1.6 Solid State DC Circuit Breakers

Solid state devices are able to turn off a current running through the device by changing their carrier flow conditions and behaviors in a few microseconds or even less. Besides their fast response, the other advantage of solid state devices is that they can repeatedly operation with virtually no wearing or erosion in contrast to mechanical circuit breakers. Depending on the devices that are used, there are a lot of variations of this technology. Commonly used power devices for power switching in circuit breakers are Insulated Gate Bipolar Transistors (IGBT), Metal-Oxide Semiconductor Field Effect Transistors (MOSFET), thyristors, gate turn-off (GTO) thyristors, emitter turn-off thyristors (ETO), and Integrated Gate Controlled thyristors (IGCT). Among them, IGBT and MOSFET are transistor type devices, while others are thyristor type. All listed devices except the thyristor can be turned off though gates. Therefore, to use thyristors in DC circuit breaker, one has to create a current zero similar to the case of mechanical circuit breakers.

One of the notable device is the ETO that has high voltage withstanding, high current conducting and easy-to-turn-off capabilities. The ETO has been proved to be an excellent choice for medium voltage to high voltage applications [5]. Its forward voltage drop is low, and the current conduction is high. The simplified gate control unit makes it easy to use.
1.6.1 Solid State Device Characteristics

The topology and the number of devices needed differ according to the device characteristics. Generally speaking, a circuit breaker should be able to block the voltages across it irrespective of the polarities and to conduct and interrupt current from both directions.

A device that can blocking both forward and reverse bias voltages are called a symmetric device. In power electronics applications, they are usually used in current source converters. Therefore, thyristors and GTOs are available with reverse blocking capabilities the same as the forward blocking ratings. However, this adds to the forward voltage drop because of a thick or long low doped region for the reverse blocking junction. IGBTs can be monolithically modified into symmetric versions as well [6]; or they can be packaged with discrete diodes into modules.

Devices such as MOSFETs can conduct bidirectional current themselves because of their parasitic diode. Other devices, such as IGBTs, thyristors would need a second device (swich or diode) in parallel or a monolithic integrated diode to conduct the reverse current [7, 8, 9].

Though both bidirectional voltage blocking and current conduction can be achieved monolithically, no single commercially available device can turn off current in both directions.

In Fig. 1.12, the IGBTs are asymmetric devices, so diodes are necessary to clamp the reverse bias voltage. To interrupt current from both directions, they would require two of them in anti-series connection so the SSCB can turn-off current from both directions.
1.6.2 Operation Principle

The turn on and turn off processes in different types of devices are different. Take the n-type ETO device for example, there are two stages in a current turn-off process. The first step is to commutate current from cathode to the gate so that the line current flow through the device’s p-n-p layers. Then the ETO acts like an open base p-n-p transistor so that the current is turned off.

If there is no capacitor across the semiconductor device, the voltage across it would surge to a high magnitude very quickly. This is especially the case if the line inductance is significant. MOVs are needed to prevent such overvoltages, protect the semiconductor devices, and bring the line current to zero.

1.6.3 Advantages and Limitations

Most power semiconductors have limited voltage and current ratings for direct use in power systems, and causes excessive power losses at operation. By series and parallel connection, their ratings can be scaled up. However, considerations in voltage balance and current sharing usually result in more complexity in the circuit and structure. Even if these issues can be addressed, the undesirable conduction losses make it a less viable option.

SiC devices up to more than 20 kV have been reported in the past five years. Theoretically, such devices could reach more than 50 kV which would cover the whole voltage levels of distribution systems. But quite a few volts of forward voltage drop is still a problem for efficiency.
and reliability.

1.7 Hybrid DC Circuit Breakers

Hybrid solutions have been proposed to combine the merits of both mechanical and solid state switching devices. A most intuitive scheme is the one shown in Fig. 1.14, composed by three parallel branches: the mechanical switch, the solid state switch, and the MOV circuit. The mechanical switch is the primary conducting path during normal operation; the solid state switch takes over the current after the mechanical switch opens and turns off the DC current without arcing in microseconds; the MOVs clamp the voltage, absorb the magnetic energy and bring down the current in the line.

![Figure 1.14: Hybrid circuit breaker using IGBTs.](image)

1.7.1 Operation Principle

For the hybrid DCCB shown in Fig. 1.14, the opening sequence is first to open the mechanical switch and then turn off the IGBTs as soon as there is no or sufficiently small current in the mechanical switch; to close the DCCB, the IGBTs are turned on first, and then the mechanical switch. The total operation time is dominated by the operation of the mechanical switch, which is in the order of milliseconds. Compared with the solid state DCCB, the fast speed has been compromised to reduce the conduction losses.
Compare the mechanical switch in this hybrid scheme with conventional AC circuit breakers, this mechanical switch still has to draw an arc during operation, and to withstand the arc burning. Therefore the contacts still needs to be treated specially, coated with special alloys. However, in the case of the hybrid DCCB, the arcing time and arc energy depend on the commutation process rather than the line currents: for a given loop inductance and current, the higher arc voltage, the shorter commutation time, and the less arc energy to be absorbed. In this sense, the low arc voltage of vacuum circuit breakers is not desirable as they are typically 20 to 30 Volts. For a 10 uH loop, 1000 A takes 300 to 500 us to commutate. Then a dielectric recovery period is required before the turn off of solid state switches so that the transient recovery voltage (TRV) does not cause a restrike across the mechanical switch.

An improved hybrid solution uses a low voltage solid state commutating switch [10, 11, 12] so that the current can be commutated in far less time, and the mechanical switch operation under zero voltage zero current conditions. Therefore the mechanical switches are free of arcing during operations, and could be easily manufactured.

1.7.2 Advantages and Limitations

The improved hybrid solution with a low voltage solid state commutating switch has been considered one of the most promising technologies so far. A 80 kV module for a 320 kV 9 kA DCCB has been developed and tested by ABB using IGBTs and fast mechanical switches. The total interruption is reported as approximately 5 ms.

As the solid state switch can withstand overvoltage in a few us, it is not to turn off until the moment that the opening gap of the mechanical switch can withstand designed voltage level. Such ultra-fast mechanical switches are far from available. ABB’s fast disconnect switch has a reported open operation time of 2 ms for the 80 kV module. Though acceptable, faster operation is always desirable and beneficial.

On the other hand, using a lot of IGBTs in series and in parallel makes the high voltage solid state switch rather expensive and complex. Voltage balancing and current sharing usually
pose challenges to the reliability and the footprint tends to be large.

1.8 Ultra-fast Mechanical Switches

Ultra-fast mechanical switches are the mechanical switches designed for active oscillatory DCCB or hybrid DC circuit breakers that can open to a certain gap in a few milliseconds or sub-milliseconds. It is the key component for low loss conduction and fast interruption in such DC circuit breakers. This mechanical operation speed has twofold meaning for the total interruption time. First, the opening time takes almost half of the total time. Second, if the speed is faster and therefore within the same time a larger separation is achieved so that higher TRV is allowed, the time to bring down line current is reduced. Therefore, this section gives an overview of possible fast actuation method that can be used in such mechanical switches. To summarize, the UFMS needs to meet the following requirements: 1) Low conduction losses. 2) Fast operation speed, especially the opening speed. 3) Reliably remained in open and closed positions during steady state.

1.8.1 Solenoid and permanent magnet actuator

A typical solenoid actuator with permanent magnet for bi-stable operation is shown in Fig. 1.15 with a cross section view. The figure shows the fixed laminated iron core, the permanent magnets (4), the moving plunger in steel (5) and coils for closing (3) and opening (6). Additionally, (1) is the lever shaft, (2) is the proximity sensor and (7) is the emergency manual opening handle.

The magnetic field lines drawn in figure 3 help to explain the function of the actuator. In the position shown, the plunger at the "top" (open position) together with the iron core forms a path of low magnetic resistance for the field of the permanent magnets. In contrast, the large gap at the bottom of the plunger represents a high magnetic resistance. The field lines therefore run almost exclusively through the end of the plunger being in contact with the core. The high concentration of field lines originating from the permanent magnets produces a large attracting force at this point. This attracting force is transmitted via the lever shaft (part 1 in Fig. 1.15)
directly onto the contacts of the vacuum interrupter.

The coils are required for switching. Figure 1.17 illustrates the closing operation: the additional magnetic energy of the lower coil compensates for the high magnetic resistance of the gap, directing the field lines more and more towards the lower path. The retaining force at the "top" declines, while the attraction at the "bottom" increases. When a certain level of current in the coil is exceeded, the plunger moves. Fig. 1.18 is an instantaneous representation of the field lines shortly before the plunger starts to move. When the final position is securely reached, as in figure 3c, the remaining current in the coil improves the latching process. The combination of permanent magnetic flux and electromagnetic flux leads to a very high force that damps out mechanical oscillations very effectively. Some milliseconds later, the coil current is switched off. The field line distribution is then similar to that in figure 3a, but this time with the plunger in the other limit position. Here, the closed position of the vacuum-interrupter contacts and the charged contact springs are latched with the static hold-force that is generated only by the permanent magnets. Current in the coils is not required as long as the circuit-breaker shall stay in this position.
1.8.2 Repulsion coil actuator (Thomson coil actuator)

A typical repulsion coil actuator (TCA) based mechanical switch is shown in Fig 1.19. It is considered as a very fast actuator, and is preferred choice when fast acting of circuit breakers are required. Even though there are quite a few different factors that may affect the actuation of a moving object, such as the mass and the driving force, TCA generally can have a very short delay of force delivery, typically less than a few hundreds of microseconds. Compared to the solenoid type actuator, TCA respond much faster, thanks to its inherently less turns of windings. On the other hand, however, the efficiency of the TCA could be less.

A similar concept to TCA is the double coil actuator (DCA), which uses two coils connected in series, discharged by the same capacitor bank. They are arranged in a way that repulsive magnetic fields and therefore force are generated between the two coils. If one of the coils are fixed, the other movable, then payload can be attached to the movable coil. It is reported that the energy conversion efficiency of the DCA can be higher than the TCA [13].
Figure 1.19: A fast mechanical switch based on TCA.
Chapter 2

Review of DC Circuit Breaker Technologies

This chapter mainly focuses on medium to high voltage high power DC circuit breakers because they are more challenging than low voltage DCCBs.

2.1 Introduction

2.1.1 Challenges of a high power high voltage DCCB

Interruption of high power DC circuits

The first challenge to protect DC grid systems is to interrupt a high voltage high current DC circuit. For transmission level DC grids, the voltage could be 150 - 320 kV or even higher and the current would be up to a few kA which is limited by the power devices that consist the voltage source converters (VSCs). Interrupting a continuous DC current of a few kA at hundreds of kV itself can be very demanding for the switching equipment. Interrupting a DC current is more complicated than an AC circuit: some auxiliary circuits are always required to interact with a burning arc in a mechanical circuit breaker and somehow to bring arc current to zero so that the arc is extinguished. Another difference from conventional AC circuit breakers is that, due
to the large amount of magnetic energy stored in the circuit, which increases as fault current rises up, varistors are always needed to absorb the energy.

**Interruption Speed**

For a voltage source converter based DC grid, once there is a short circuit, the DC bus voltage could drop very quickly and in the same time the short circuit current rises very fast if the faulted segment is not cleared and isolated. If the DC voltage drops to a value that is too low, all connected terminal may need to block out, and the power transmission is interrupted for the whole grid which could consequentially cause instability in larger areas. If the short circuit current is too high, the value can go beyond the interruption capacity of installed DC circuit breaker and cause the equipment as well as the system to fail.

Therefore, the operation speed is crucial for the protection of DC grids. Ideally, the time should be as short as possible. Generally, researchers and manufacturers are targeting a few milliseconds as the total interruption time.

The speed requirement can be less stringent if current limiting inductors are installed in the lines or cables. However, such inductors store magnetic energy during normal operation and short circuit conditions that they put additional duty on the energy absorbers of the DC circuit breakers. On the other hand, considerations regarding the transients and system control should be given if such inductors are to be installed.

**Interruption Capacity**

In conventional AC circuit breakers, the interruption capacity is expressed in MVA which is the product of maximum current that can be interrupted and the system voltage. This definition applies to DC circuit breakers as well with the system voltage is replaced by the MOV clamp voltage value.

The required interruption capacity of a DC circuit breaker is related to the system parameters such as the impedance of the transmission conductors, the nominal voltage and current,
the capacitance of the DC capacitors and its operation speed.

If the operation speed is slow, the circuit breaker will needs to interrupt a high current due to the fast rise rate of fault current. If the nominal voltage and current are high, the circuit breaker needs to withstand higher voltage during and after current interruption.

2.1.2 DCCBs and other switchgear

DCCBs and ACCBs

The absence of current zero in a DC circuit cause more profound differences in DCCBs from ACCBs.

First some external mechanism is required to bring the current to zero rather than waiting for a current zero. The various mechanisms vary and will be discussed in details in the following sections.

What is noteworthy in AC circuit interruptions is that the actual current at the moment the arc is extinguished is not ideally zero. This phenomenon is called current chopping which can cause very high TRV and RRRV across the gap of the ACCB because of the residual magnetic energy stored in the system inductance. To deal with this problem, the interrupters are optimized to reduce current chopping level, or capacitors and MOV are used to absorb the energy and lower the TRV.

For a DCCB, the magnetic energy is even more problematic because the rising fault current is injecting more energy into the inductance which eventually needs to be absorb. Therefore, MOVs are always required for DCCBs.

DCCBs and FCLs

Some fault current limiters (FCLs) can be very similar to a DCCB though their definitions of functionalities are totally different. FCLs are intended to limit fault currents so that the fault level is within the interruption capability of the circuit breakers. They were proposed originally because the short circuit levels had increased and exceeded the rated value of the installed
circuit breaker due to the expansion of existing transmission and distribution networks. So the main strategy of a FCL is to insert a high impedance to the circuit that reduced the fault current level.

On the other hand, circuit breakers are defined to interrupt a current and therefore the circuit. But sometimes a FCL is also able to interrupt a circuit, for example a pure solid state FCL that does not even include any high voltage inductors or capacitors.

**DCCBs and current limiting ACCBs**

DCCBs for the protections in VSC based DC systems needs to operate ultra fast compared to conventional ACCBs. The time scale for a DCCB is a few milliseconds or even less, which is about or preferably less than a quarter cycle in a 50 Hz or 60 Hz circuit. Therefore, if the DCCB is to interrupt an AC circuit, the ultra-fast interruption speed naturally limits the fault current level because typically it takes one to a few cycles to reach prospective fault current level in AC systems. However, due to the special circuits that are needed for some of the DCCBs, they are not guaranteed to function in AC circuits as well as in DC.

**2.1.3 Key parameters of a DCCB**

**Nominal voltage and maximum TIV level**

The nominal voltage is the DC voltage of the system during normal operations and sets the insulation requirement for the design and operation of the DC circuit breakers.

Maximum transient interruption voltage (TIV) level is the residual voltage clamped by the MOV during the current interruption, and this voltage serves as the back electromotive force (EMF) that drives the line current down to zero which is also the process the line is demagnetized and magnetic energy is dissipated. This back EMF value needs to be higher than the source voltage; otherwise the line current would not decrease. From this point of view, a higher TIV is better because of the shorter demagnetization time, and less energy absorption requirement [14].
The maximum TIV level is dependent on the voltage withstand capabilities of the DC circuit breaker components. In a hybrid DC circuit breaker topology that consists of a mechanical switch and a high voltage semiconductor switch in parallel, both two switches needs to withstand the TIV. Therefore, with a higher TIV level, more semiconductor devices are needed in series for the DCCBs, and a larger gap in the mechanical switch is needed as well. What is more important is that, the whole system needs to accommodate this relatively higher voltage for insulation purpose, which can cause a substantial increase in cost.

So the trade-off between the cost of the high voltage systems and the time to clear the fault is to be made when designing the hybrid DC circuit breakers. As reported in several recent prototypes from major manufacturers in high voltage DC equipment, the TIV is typically selected as 1.5 p.u. of the nominal system voltage, see Table. 2.1.

Nominal current and maximum interruption current

Nominal current sets the work condition for the primary current conducting path in the DC circuit breaker. A large current would require that the equivalent series resistance or voltage drop of the DC circuit breaker is sufficiently low.

For those having the mechanical switch as the primary conduction path, the contact resistance is a function of the contact area and material, the pressure applied to the contacts, and the surface condition of the contacts. Since fast opening is necessary for protection in HVDC grids, large contacts delay the acceleration for opening operation. Further more, the externally applied holding force for the sake of low contact resistance is another obstacle to overcome for the operation mechanism to open the contacts rapidly.

If the semiconductor switches conduct the continuous current, a large amount of power losses in the form of heat is expected and thermal management is crucial not only to ensure that semiconductor chip is not overheated during conduction, but also to alleviate thermal stress so that current interruption capability is not degraded.
Break time

The break time is defined by the Cigre Joint Working Group A3.B4.34 as the time interval from the instant the breaker receives the trip order and the instant when the current has been lowered to leakage current level (or below) [15], which is analogous to the AC breaker standard (IEC 62271-100, 3.7.135) [16].

For DC circuit breakers of different principles and topologies, the components of the total break time differ. For a comprehensive treatment of the break time analysis, please refer to Chapter 8.

MOV energy capacity

Similar to the time for the MOV to bring down the line current to zero, the energy it needs to absorb is also a function of the line current, line inductance, the residual voltage level and the system voltage. To obtain more accurate results, it is suggested that the system under study is modeled and simulated using electromagnetic transient programs. However, generally speaking, larger line current, larger line inductance and higher system voltage result in more energy required to be absorbed; higher residual voltage level reduces this amount of energy.

2.1.4 Prior work

There has been very few publications reviewing DCCB or related technologies that have emerged in the past decade. In [17], C. M. Franck has reviewed the DCCB technologies from system requirement by HVDC network systems, to general DCCB technologies and has identified that a lot of work can be done to optimize current technologies and emerging devices to meet the requirement set by HVDC network systems based on voltage source converter. However, the review covers a lot of relevant topics of DCCBs, such as the description of HVDC networks, fault current limiters and testing methods, rather than focusing on the technological details of various DCCBs. In stead, only general principles of most typical DCCBs are introduced.

Another useful paper [18], has focused on the hybrid circuit breakers which utilize power
electronics for power switchings. Though the paper has been striving to give as much information about each topology as possible, it does not provide sufficient insights into the differences between the abundant but similar topologies. For example, this paper has failed to point out that once power semiconductor devices are used to switch off current, there is insignificant difference between AC and DC switching because the fast turn-off speed of semiconductors, which is in the range of microseconds, together with the arcelss interruption capability eliminate the necessity of current zero crossings. Therefore, there is no need to differentiate AC and DC hybrid circuit breaker, especially if the DC circuit breaker is functional bidirectionally.

An interesting review paper [19] has published on fault current limiters by Alexander and Smedley in 2013. Though the paper focuses only on solid state type FCLs rather than DCCBs, it gives a good example of classification and comparison of a lot of similar yet different topologies, and can be very beneficial for the study of DCCBs.

[20] has provided a good introduction of available mechanical, solid state and hybrid DC circuit breakers from various aspects, and good lists of references and the state-of-the-art products from industries. However, the report has missed out some important DCCB technologies, and is limited to DCCBs in the range of hundreds of Volts to a few kilovolts.

2.1.5 Necessity of the presented work

A classification method is crucial for the understanding of different DCCB topologies. Even though researchers have identified the most common DCCB types, various new topologies have been proposed in recent years, some of which might look similar to those common types but are essentially different in principle. A typical example is the so called hybrid circuit breakers, which are generally and intuitively understood as a circuit breaker including both a mechanical and a solid state elements. Without explicit classification criteria, inappropriately categorizing topologies as a hybrid DCCB can cause misleadingness.

A lot of new publications and proposed ideas have emerged in the past five to ten years. As mentioned earlier and also explained in Franck’s paper, the proposal of VSC HVDC networks
in the past decades has motivated the research of DCCBs in both industry and academia. In the last five years, more than twenty patents and publications have arised which are only included or discussed by very few papers. For example, at the same publication time of Franck’s review, ABB has announced their proactive HVDC circuit breaker on Cigre in 2011, which is not covered by [18].

On the other hand, it is always advisable to look back to what have been done a few decades ago. Back in 1970s and 1980s, the work was also motivated by the vision of an interconnected DC network, though in a different way that converters are of current source nature. Quite a few full scale prototypes have been developed and tested by major power apparatus manufacturers around the world. Their achievements are significant yet neglected in most of today’s publications.

Some work done on FCLs has been overlooked by researchers who are focusing on DCCBs, especially those proposed in the applied superconductivities community. Because of the ambiguity of the terminology of FCL, some of the FCLs can be used as DCCBs as well. This review will include such work so as to provide the readers a broader view and hopefully more inspirations.

2.2 Classification

A classification method is proposed to distinguish various different yet similar DCCB topologies and schemes, which will help researchers to better understand and identify the benefits, limits or bottlenecks for each type of DCCBs.

2.2.1 Classification criteria

A circuit breaker performs two basic functions: conducting a current, and interruption a current. So the criteria used to distinguish one DCCB from another is:

1. The main conduction mechanism.
2. The actual current interruption mechanism.

2.2.2 Mechanical DC circuit breakers

In mechanical DCCBs, the mechanical part conducts the current in normal operation, and extinguishes arc when switching DC current.

Low voltage mechanical circuit breakers can interrupt a circuit by forming an arc voltage higher than the source voltage. This technique finds its application in DC circuit breakers up to 3 kV [21]. However, this method is not practical for system voltages above a few kilovolts. In stead, additional passive components or active components are added to aid the direct current interruption, usually by superimposed current resonance, at higher voltage levels. Therefore, mechanical DCCBs can be further grouped into two sub-categories: passive oscillatory DCCBs, and active oscillatory DCCBs.

2.2.3 Solid-state DC circuit breakers

In contrary to mechanical DCCBs, the solid state DCCBs conducts nominal current and interrupt the current both via solid state switches.

As discussed in Section 2.5, based on the characteristics of the devices used, solid state DCCBs can be classified into Thyristor based DCCBs and active switch based DCCBs.

2.2.4 Hybrid DC circuit breakers

Hybrid DCCBs usually conduct current mainly by the mechanical parts, but the DC current interruption is achieved by solid state switches.

2.3 Passive Oscillatory DC Circuit Breaker

Passive oscillatory DCCBs are the widely used in HVDC transfer switches. They are simple and relatively low-cost. A typical circuit is shown in Fig. 2.1, with the simulation of the interruption
transients shown in Fig. 2.3. Fig. 2.3 redraws the current and voltage characteristics, which clearly shows the negative I-V characteristic.
Figure 2.1: A bidirectional mechanical DCCB based on passive resonance.

Figure 2.2: A bidirectional mechanical DCCB based on passive resonance.

Figure 2.3: I-V characteristic of a passive oscillatory DC circuit breaker during current interruption.
2.4 Active Oscillatory DC Circuit Breaker

A typical diagram of an active resonant DC circuit breaker is shown in Fig. 2.4. In the following, various sub-categories of active resonant DCCBs are discussed.

2.4.1 Pre-charged capacitor

A mechanical circuit breaker based active oscillatory DC circuit breaker is one of the oldest high power DC circuit breaker, as shown in Fig. 2.4. Usually, a high voltage isolated power supply charges C2. Greenwood had published the early work based on this topology using the vacuum interrupter [22, 23].

Marquardt’s DCCB, shown in Fig. 2.6, adapted from [24, 25, 26], falls in this category too, except that the charging and discharging circuits are different.

2.4.2 Transformer injected reverse-current DCCB

In stead of using a pre-charged capacitor via high voltage isolated transformer, one winding of the transformer itself can be placed in the active oscillatory circuit to inject the current and create artificial current zero, as shown in Fig. 2.5, adapted from [27], to extinguish arc in the mechanical circuit breaker.

Note that in [27], the circuit breaker is called hybrid because a series connection of a vacuum interrupter unit and a gas interrupter unit is used as the mechanical circuit breaker, meaning that BRK in Fig. 2.5 actually consists of two interrupter units. It is intended to utilize the high \(di/dt\) and \(dV/dt\) capability of the vacuum interrupter for the current interruption and initial voltage recovery, and take advantage of the high dielectric strength of pressured SF\(_6\) interrupter.

2.4.3 Transverse magnetic field commutated DCCB

Since late 1970s, there are a series of patents and papers published by Westinghouse researchers [28, 29, 30, 31, 32, 33] which investigated the utilization of a transverse magnetic field applied to the arc formed during interruption in a fast opening vacuum interrupter to cause stronger
Figure 2.4: A bidirectional mechanical DCCB based on active oscillation.

Figure 2.5: A unidirectional mechanical DCCB based on active oscillation (can be extended to bidirectional).

Figure 2.6: A bidirectional mechanical DCCB based on active oscillation.
arc instability for faster arc extinction. A diagram is shown in Fig. 2.7, adapted from [29]. The work was motivated by the need of fault current limiting in conventional AC systems, rather than direct current interruptions. However, the concept is directly applicable to DC circuit interruptions because such fault current limiting circuit breaker can interrupt a circuit in only a few milliseconds and does not need current zero crossings for arc extinction.

Later on in 1990s and 2000s, there are continued work to investigate the effect of transverse magnetic field on the vacuum arcs, in hope that DC interruption can be realized based by applying such magnetic fields [34, 35, 36, 37, 38, 39].

2.5 Solid State Devices

Semiconductor devices that have been studied for circuit breaker applications include: thyristors (SCR), gate turn-off thyristors (GTO), integrated gate commutated thyristors (IGCT), emitter turn-off thyristors (ETO), bipolar junction transistors (BJT), insulated gate bipolar transistor (IGBT), junction field-effect-transistors (JFET), metal-oxide semiconductor field-effect transistors (MOSFET), static induction transistors (SIT), etc.

From device structure and physics point of view, they vary from one another, but these
devices can be grouped into two categories based on whether the device can be turned off through external gate control: half-controllable devices, and fully controllable devices. This is very important considering that circuit breakers need to interrupt a current reliably whenever required. It also separate thyristors from other devices because thyristors themselves can not turn off the current by their own: commutation circuits are needed to turn off thyristors. Therefore, the topologies based on thyristors typically are more complex. On the other hand, since thyristors are simple in structure and very easy to fabricate, the cost is much lower than their counterparts at the same voltage and current ratings.

A second important feature is the conduction losses associated with solid state devices. Generally speaking, bipolar devices, such as thyristor devices and bipolar transistors, exhibit much lower forward voltage drop compared to unipolar devices, especially at high current levels, such as hundreds or thousands of amperes.

Lots of noteworthy research and development works on wide band gap semiconductors have been conducted published in the past two decades. There are two trends in such efforts: towards high performance power electronic systems compared to the conventional solutions based on Si devices, and towards high power applications where Si devices could not reach. Apparently devices used in circuit breakers fall into the second category.

In the following, various topologies rather than the detailed device characteristics are analyzed. From topology point of view, whether the device can be turned off is the most decisive factor. Therefore, the solid state DCCBs based on thyristors and that based on fully controllable devices are treated separately. It is noted that in the circuit diagrams a single semiconductor symbols may represent a stack of series connected devices to meet high voltage requirement or a parallel of devices for high current applications.

2.6 Thyristor-based Solid State DCCBs

A silicon controlled rectifier, also known as a Thyristor, does not have the capability to turn off its current internally and requires current commutation paths or any other external methods to
bring its current to zero so it is turned off. DCCB topologies based on Thyristors are important because they are the most powerful devices in terms of current and voltage ratings, and they are easy to fabricate because of their monolithic structure and therefore very cost-effective.

A general diagram of a thyristor based DC circuit breaker is shown in Fig. 2.8 which is adapted from Fig. 1 in [40]. Three functional blocks are present in Fig. 2.8: the main thyristors for current conduction, the commutating circuits to help turn off those thyristors, and a MOV branch which limits the overvoltage and absorbs the inductive energy stored in the system. However, in this diagram, no specific charging circuit for the pre-charged capacitors (C1 and C2) are represented. Since the topology is symmetric in both current directions, it can be used in AC circuits as well.

To charge the capacitors, two additional thyristors (T_{Chg1} and T_{Chg2}) are added as shown in Fig. 2.9. However, this circuit is not suitable for DC applications because if current flows as denoted by I_{P} in Fig. 2.9, only C2 can be charged but T_{Main1} serves as the primary current path which requires C1 to turn it off.

Even bidirectional current is possible in DC networks, the current does not change direction frequently. So a better solutions is the bridge type topology for the charging circuit presented in Fig. 2.10.

Figure 2.8: A thyristor based bidirectional DCCB, the isolated charger for the capacitors are not shown.
An early paper in 1976 published a solution based on this topology, which can be found in Fig. 2.11, adapted from Fig. 1 in [41]. There are three parallel branches: the primary current path T1, the commutating circuit consisting of TL, RL, DL, CK, LK and T2, and the snubber branch consisting of DF, RF and CF. There are two differences compared to Fig. 2.9 and 2.10. First, the charging circuit is based on a separate transformer (denoted as TL in Fig. 2.11) with the primary side connected to a low voltage source; second, the voltage clamping and energy absorbing unit is a resistor-diode clamp (RDC) circuit identical to the snubber circuit used in
power electronics. Otherwise, they are almost the same.

This is similar to the arc extinguishing in a mechanical circuit breaker. Therefore, it is inferred that a topology that utilizes a SCR is mostly likely to be modified to a version by replacing the SCR with an UFMS. In this way the conduction losses can be minimized, but at the expense of a relatively slower operation speed.

### 2.6.1 Power ratings

Thyristors are among the most powerful and rigid semiconductor devices available. ABB’s 5STP 37Y8500 device offers a maximum blocking voltage of 8.5 kV with 3600 A continuous current [42], which gives a power handling capability of 30.6 MW.

### 2.6.2 Operation losses

For the given ratings of 8.5 kV and 3600 A, if the device is operated at 60% of the voltage rating (approximately 5 kV) and full current rating (3.6 kA), the power is 18 MW. As the voltage drop at 3.6 kA is about 2.05 V, which gives an estimated power loss of 7.38 kW. This would require a cooling systems that is more bulky than the device it self.
2.6.3 Break time

The current turn-off in a thyristor is achieved by force current commutation to another current path by external circuits than the thyristor itself. Therefore, the interruption is expressed in Equation 7.3.

\[ t = t_{Aux} + t_{LC} + t_{MOV} \] (2.1)

The LC oscillation time can be very short compared with the demagnetization time.

2.6.4 Current commutation

Current commutation of the thyristor can be realized by a reverse current injection into the device, which generate a current zero condition in the thyristor. In Figs. 2.8 to 2.10, this is done by discharging a pre-charged capacitor bank. Compare Figs. 2.8 and 2.4, one can easily notice that the only difference is that the mechanical switch is now replaced by a pair of thyristor devices for bidirectional operation.

What is more substantial is that a DC interruption method based on thyristors or active resonant mechanical circuit breaker can always find a counterpart by replacing the thyristor devices with mechanical switches, or vice versa. The differences between these two types of DC circuit breakers are mainly on the following three aspects. First of all, the mechanical switch would take some time to open its contacts so it can withstand the TRV which causes certain mechanical delay time, and therefore the mechanical based DCCBs are inherently slower than the SCR based. Secondly, the thyristor devices cause a high conduction losses which is not only power loss from the system but also requires cooling system and a lot of auxiliary power. Thirdly, the thyristor can have a much longer lifetime in terms of total switching times.
2.6.5 Z-Source DCCB based on the thyristor

Z-Source DC circuit breaker (Z-DCCB) was introduced by Dr. Corzine since 2010 [43, 44, 45, 46, 47, 48, 49], which shares the name with the Z-source inverter which was invented by Dr. Peng [50] because it also has an impedance component, which facilitates the current commutation of the thyristor in the Z-source DCCB. The circuit is shown in Fig. 2.12, adapted from [47]. During a fault with low impedance, the current in the inductors of the Z-sources are assumed constant during short period transient, but the capacitors would discharge via the short with a current in reverse direction. This reverse current can have a large peak value that is sufficient to bring the thyristor current to zero and therefore turn it off.

Compared to the conventional thyristor DCCB, the commutation circuit is simplified because no isolated charger is required. In a recent publication [51], adapted from [51], the circuit has been improved from two aspects by the circuit shown in Fig. 2.13. Firstly, by reconfiguring the Z-source components, the transient discharge current from the capacitor would circulate within the Z-DCCB without feeding back into the source. Secondly, an artificial fault can be initiated by a dedicated switch to form a low impedance fault that always trip the Z-DCCB. This has greatly extended the detection and protection range.

2.6.6 Z-Source DCCB based on mechanical switch

Based on the observation made in 2.6.4, the authors have further improved the Z-source DCCB by replacing the thyristor by an ultra fast mechanical switch as shown in Fig. 2.14, which significantly reduces the conduction losses.

2.7 Active Switch-based Solid State DCCBs

The solid state DCCBs that employ fully controllable devices is very straightforward in topology and the operation principle. Referring to Fig. 2.15, only two parallel branches are needed: a solid state switch branch and paralleled MOVs. The operation can be really fast, depending on
the operation speed of the solid state devices used. For example, IGBTs usually take no more than a few us.

From the topology point of view, replacing IGBTs by GTOs, or IGCTs, ETOs, MOSFETs, JFETs does not matter. However, their behaviors during steady state and transients differ from
each other, and the practical implementation can be different too. Most notable differences are their forward voltage drops, the complexity of their drive circuits, and their reverse biased safe operation area (RBSOA). Nevertheless, in this paper, we represent active solid state switch by IGBTs unless otherwise noted for the simplicity regarding the understanding of different DCCB topologies.

2.8 Hybrid DC Circuit Breakers

Hybrid DCCBs are the result of a trade-off between operation losses and operation speed: with a reduction of more than 100 times, the speed is also lowered by more than 100 times.

Fig. 2.16 shows a typical topology of a hybrid solid state circuit breaker, which has three parallel branches: the mechanical circuit breaker branch, the solid state switch branch (IGBTs as shown), and the MOV branch.

Compared to the topology shown in Fig. 2.15, it can be considered as a combination of a solid state DCCB and a mechanical circuit breaker, which conducts normal current and transfers current into the solid state DCCB for interruption. Therefore, extra time is needed for the mechanical circuit breaker to open and to commutate current.

Besides the extended operation time, another challenge based on the topology shown in Fig. 2.16 is the arc voltage needed for current commutation, which actually relates to the

Figure 2.15: A solid state DCCB based on fully controllable switches, such as IGBTs.
commutation time. Generally speaking, a higher arc voltage is favorable for faster commutation and therefore less operation time.

![Figure 2.16: A general hybrid solid state DCCB.]

**2.8.1 Arc commutated hybrid DCCBs**

Conventional hybrid DCCBs rely on the arc voltage of the mechanical circuit breaker to commutate the current to the second path for current interruption, for example the 10 kA hybrid DCCB in [52]. The circuit diagram looks is very similar to the diagram in Fig. 2.16, except that three IGCTs are used in parallel to turn off the current. The presented hybrid DCCB is very powerful in current interruption, but slow in speed due to the speed of the mechanical switch: it takes 240 ms to separate contacts; and the current commutation takes tens of milliseconds because the arc voltage is only about 20 - 30 V. Similar arc voltage levels are observed in [53, 54, 55]. [56] has reported a hybrid circuit breaker using GTOs with an ultra-fast mechanical switch for low voltage application.

A low arc voltage as the commutating voltage can result in a long commutation time, and sometimes a failure of interruption at high current. In voltage source converter based DC networks, the break time requirement is in the range of a few milliseconds, which makes it unacceptable to use an arc voltage of 20 - 30 V for commutation, except that the stray inductance is in the range of 100 nH.
Table 2.1: Tested high voltage hybrid DCCB prototypes.

<table>
<thead>
<tr>
<th>Company</th>
<th>ABB</th>
<th>Alstom</th>
<th>SGCC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanism</td>
<td>Repulsion</td>
<td>Part turn motor</td>
<td>Repulsion</td>
</tr>
<tr>
<td>Rated voltage</td>
<td>80 kV</td>
<td>120 kV</td>
<td>50 kV</td>
</tr>
<tr>
<td>TIV</td>
<td>120 kV</td>
<td>180 kV</td>
<td>75 kV</td>
</tr>
<tr>
<td>Rated current</td>
<td>2.6 kA</td>
<td>1.5 kA</td>
<td>2 kA</td>
</tr>
<tr>
<td>Interrupted current</td>
<td>9 kA</td>
<td>5.3 kA</td>
<td>15 kA</td>
</tr>
<tr>
<td>Opening time</td>
<td>2 ms</td>
<td>2 ms</td>
<td>2 ms</td>
</tr>
</tbody>
</table>

[53] has managed to achieve a low inductance of less than 250 nH for the hybrid DCCB assembly, which takes less than 60 us for the commutation of 5 kA. In [57, 58], the prototype has a stray inductance of 135 nH thanks to a dedicated symmetric structure design, and therefore the commutation of 1200 A takes about 20 us. In the case of [59, 52], it takes 8 ms to commutate 10 kA by the arc voltage of 25 V.

It is possible to increase the arc voltage up to a few kVs, but at the expense of bulky and complicated mechanical structures such as cooling mechanisms, and increased operation time.

A hybrid DCCB can also employ thyristors in the semiconductor branch [60], as shown in 2.17. Similarly in [61], IGCTs are used in the secondary path in stead of thyristors as presented in Fig. 2.18, but the same tertiary path is still used to generate a counter current pulse to reduce the current the IGCTs have to turn off.

To solve the problem that current commutation is limited by low arc voltage in the primary path and high voltage drop in the secondary path due to series connected semiconductor devices for higher voltage levels, [62, 63] has proposed the usage of a combination of the semiconductor
switch and a so-called fast disconnect switch (FDS as shown in Fig. 2.19, adapted from [62, 63]) as the secondary path to reduce the number of semiconductor devices in the secondary path so that even for a medium to high voltage design, the commutation of a large current within a short period of time is possible. However, the introduction of FDS into the secondary path causes additional mechanical operation delay which adds to the total operation time.
With semiconductor switches open and current commutated to the third path, FDS opens and the positive temperature coefficient (PTC) resistor takes over and limits the current which is eventually cut off by the load switch (LS). The commutation from secondary path to third path is very similar to the case of from primary to secondary path in the topology shown in Figs. 2.23, 2.24 and 2.25. Figs. 2.20 to 2.22 are based on similar principles [64].

Figure 2.20: A hybrid solid state DCCB based on thyristors.

Figure 2.21: A hybrid DCCB based on thyristors, inspired by the topologies in Figs. 2.7 and 2.20.
2.8.2 Hybrid DCCB with commutating switch

Semiconductor device in the primary path as the commutating switch

Before ABB’s patent [65] and their publications [12, 66, 67], there were earlier patents by Société Technique for Atomic Energy that have included a commutating switch in series with the fast mechanical switch for arc-less and faster current commutation [10, 11, 68], as shown in Fig. 2.23. ABB has used IGBTs as the low voltage commutating switch as well as the high voltage switch, shown in Fig. 2.24, to build and test their hybrid DC circuit breaker prototype up to 80 kV.
Similarly, engineers at SGCC has proposed a hybrid DC circuit breaker [69, 70, 71] that uses IGBT H-bridges as the high voltage and low voltage solid state switches, as shown in Fig. 2.25.

In [72, 73], the proposed hybrid DCCB in Fig. 2.26 has the similar primary, secondary and tertiary circuit structure as in Fig. 2.24, but also incorporates the advantage of increased current turn off capability as the circuit in Fig. 2.18 does. Different from Fig. 2.18, additional controllable switches are introduced and the capacitors can be charged by the line voltage rather than from isolated power supplies, as shown in Fig. 2.27.

**Other devices in the primary path as the commutating switch**

Fig. 2.28 has shown a variation of the commutating switch in a hybrid DCCB, [74]. The liquid metal is used as a fault current limiter which becomes a high impedance during fault so the fault current is automatically transferred into T0, which will be turned off later by T1 generating a reverse current pulse. T0 and T1 circuit can be replaced by IGBT or other equivalent solid state switches. Similarly, the arc generator [75] and the transformer [76] can be the commutating switch as well.
Figure 2.25: SGCC topology: A hybrid solid state DCCB employing a solid state commutating switch.

Figure 2.26: KIT Topology: A hybrid solid state DCCB employing a solid state commutating switch.

Semiconductor device in the secondary path as the commutating switch

[77] has proposed an interesting topology that has a charge storage diode in the secondary path that can help accelerate current commutation from the primary path because of the
Figure 2.27: KIT - Topology: A hybrid solid state DCCB employing a solid state commutating switch.

charge storage effect [78]. Though originally designed for applications at 1250 V DC, it has the potential to scale up. And the topology has the simplicity as well as high efficiency.

2.8.3 Capacitor-aided hybrid DCCB with commutating switch

Alstom (now part of GE) had published their test results of the hybrid DCCB based on the topology shown in Fig. 2.33 [79, 80, 81]. The demonstrator is rated for 120 kV and 1500 A and is able to interrupt up to 7500 A.

2.9 Conclusions

This paper has reviewed the published DCCB technologies of different topologies.

Classification criteria can be summarized as:

It is also pointed out that the methods used to turn off thyristors can be very likely used to create current zeros in a mechanical circuit breaker. Therefore, they can form a duo using the same external circuit that create current zeros.

Another analogy is that, the hybrid circuit breakers with high voltage semiconductor switches can find their duos by replacing high voltage semiconductors with high voltage capacitors. The semiconductor switch can be seen as a highly nonlinear capacitor by the control of external gat-
Figure 2.28: Topology: A hybrid solid state DCCB employing a liquid metal fault current limiter as the commutating switch.

Figure 2.29: Topology: A hybrid solid state DCCB employing an arc generator as the commutating switch.

Figure 2.30: Topology: A hybrid solid state DCCB employing a transformer as the commutating switch.

ings that initiates rapid voltage step change while the passive capacitor is a linear component that allows a slowly rising voltage at a slope determined by the line current and the capacitance.
Solid state DCCBs have prohibitively high power losses and the passive oscillatory DCCBs have limited interruption capabilities and operation speed. Therefore, among the four categories of DCCBs for high voltage applications, hybrid DCCBs and the active oscillatory DCCBs have drawn the most research institute.
Figure 2.32: Siemens Topology: A hybrid capacitor-aided DCCB employing a solid state commutating switch.

Figure 2.33: Alstom Topology: A hybrid capacitor-aided DCCB employing a solid state commutating switch.

Figure 2.34: Surge-less Topology: A hybrid capacitor-aided DCCB employing a solid state commutating switch.
Chapter 3

FEA Modeling and Optimization of Ultra Fast Vacuum Switch

In Chapter 2 DC interruption techniques have been presented, and it is concluded that the ultra fast mechanical switch is an important component for the quick clearance of DC faults. In recent years, several hybrid DC circuit breakers that all include an ultra-fast mechanical switch have been reported in literature for power system applications [65, 12, 5, 82, 83, 24, 25]. Compared to relatively slow DC transfer switches [84, 3], ultra-fast operation in a few milliseconds is essential to provide the required protection in meshed DC systems [85, 86].

However, an ultra-fast mechanical switch with adequate response characteristics is still the missing link to build the hybrid AC and DC circuit breakers using mechanical switches and high power semiconductors. The fast opening mechanical switch is far from being readily available and is discussed in only a limited number of publications. The requirements for ultra-fast operating mechanism include conducting normal current with very low contact resistance, and achieving required separation in a few milliseconds.

In this chapter, a Thomson coil based ultra fast mechanical switch is presented, and modeled in COMSOL. A comprehensive multiphysics model is established to understand the operation transients of such a switch, and to optimize the design towards an ultra fast yet mechanically
robust switch. The model includes physics of electromagnetic, solid mechanics, thermal behavior and lumped circuit interactions. Optimization based on extensive simulations has identified the effect different design variables have on the performance of the switch during fast opening transients.

3.1 Introduction

In order to open the contacts in a mechanical switch to a gap of a few millimeter within a few milliseconds or a fraction of a millisecond, the operating mechanism has to be designed to generate sufficient driving force within a short period. Conventional mechanisms based on solenoids become obsolete because they tend to have a relatively large inductance, which takes relatively long time to energize and therefore impedes the fast action, and also low initial opening forces. Investigations in [87] have presented study to prove that with the same load condition and driving energy, the energization time of the Thomson coil actuators is one order of magnitude faster than solenoid type actuators, and the travel time is also approximately one order of magnitude shorter.

3.2 Operation Principle

The main parts and their operation principles of conventional circuit breakers in general and of fast acting Thomson coil based switch in particular are discussed in this section.

3.2.1 Main parts

There are four different parts in a mechanical switch: interrupter, driving mechanism, energy storage and control, and damping and holding as shown in Fig. 1.19. When the switch is able to interrupt short circuit, it is called a circuit breaker. This paper focuses on the driving mechanism, the energy storage and control.
Interrupter

According to the Paschen curve, the high vacuum allows a much shorter distance between contacts to withstand a certain high voltage level \([2]\). Vacuum interrupters (VIs) are sold as individual products or integrate circuit breakers. A standard VI for 15 kV class has a travel of 6 - 12 mm for the moving contact, which is able to withstand BIL of 95 kV. VIs are said to be a perfect match with operating mechanisms driven by electromagnetic force, because such mechanisms have the best acting performance in a short stroke.

In a hybrid circuit breaker whether it is AC or DC, the interrupter is used as a disconnect switch or a set of contacts because it’s not required to extinguish burning arc. In fact, there is no arcing in a hybrid circuit breaker. In this case, designing of the contacts is greatly simplified without considering issues such as arc extinguishing, current chopping, etc. Shields can also be eliminated.

In contrast to conventional circuit breakers, a hybrid circuit breaker is always equipped with MOV in parallel which limits the overvoltages that may be applied to it. Therefore, a hybrid circuit breaker is not required to withstand standard BILs. For example, a 15 kV hybrid AC or DC circuit breaker is only expected to withstand approximately 20 kV, which translates to 1 mm travel in vacuum.

Although the design and manufacturing of vacuum contacts can be optimized, it is not within the scope of this report. The VI has been treated as a black box with a moving mass, which acts as a payload to the operating mechanism. Note that since a higher current rating would need a larger contact area to keep the power loss low, the size of the contact and therefore its weight is increased. Also, with higher voltage rating, the moving mass of a VI would also increase. A typical 15 kV class 630 A vacuum interrupter has a moving mass of approximately 0.5 kg.
Operating mechanism

Four types of operating mechanisms are commonly used in commercial products: spring, pneumatic, hydraulic and magnetic mechanisms. In vacuum circuit breakers, the first and the fourth are commonly used.

Spring operated mechanisms have been widely used for many years and are still popular among SF$_6$ and vacuum circuit breakers because of their well known features. However, spring mechanism often exhibits mechanical delay because of associated moving parts, which is not acceptable if ultra fast operations are required.

Magnetic mechanisms comes often with vacuum interrupters because they are suitable for short stroke movement with fewer moving parts. Commercial products such as ABB AMAVC series medium voltage circuit breakers use permanent magnets because they can provide bistable latching as well as opening and closings operations.

Thomson coil based driving mechanism is preferred when ultra-fast operations are desired. A comparison based on experiments proved that under the same driving voltages, Thomson coil based mechanism operates much faster than the ones driven by PM [88]. Therefore Thomson coil based operating mechanism has been chosen in this research.

Energy storage and control

In spring mechanisms, springs are charged by low voltage motors or manually. Stored energy is release through using mechanical latches or electric relays.

Capacitors are needed in magnetic or electromagnetic mechanisms, including PM and Thomson coil actuators. The ratings of capacitors range from several hundreds to thousands of Volts; a dedicated charging circuit is used for the energy storage. The discharging circuit is made of power semiconductor switches that are controlled to discharge the capacitors. The preferred devices in Thomson coil actuators to achieve high operating performance are thyristors and IGCTs because of their high surge current capability.

The energy storage capacitor banks associated with fast acting operating mechanisms are
not trivial components. The energy storage units tend to be bulky since energy efficiency is often very low in the operating mechanism system. Besides, the capacitance value together with total inductance determines oscillating frequency of the discharging current, which has impacts on the operation transients. To tune the transients, the capacitance needs to be within a certain range and the pre-charge voltage need to be adjusted accordingly. This adjustments will also affect the requirements on the control circuits and their cost.

**Damping and holding mechanism**

As an extremely large force is needed to accelerate the moving part, it is challenging to stop them rapidly and hold them steadily in open or close positions.

During opening operation, it is required that the over-travel of moving parts is within the allowed range of the VIs. It is also important to protect the vacuum tube from damages caused by impact. A holding mechanism or a latch in close position is needed for low contact resistance and that will maintain contacts reliably closed even during large short circuit current; in the open position it is required to avoid undesirable re-closing of contacts.

### 3.2.2 Actuation by Thomson coil

When a coil is energized by a capacitor, the coil and the capacitor form a LC circuit that exhibits oscillatory behavior. The flux established by the ampere-turns of the coil penetrates the nearby copper disk and varies with time, which induces eddy currents in the copper disk. This induced current, in turn, causes a repulsive force between the coil and the disk. If the coil current be $i_c$, and the disk current is $i_d$, the force can be expressed as:

$$F_z = i_ci_d\frac{dM_{cd}}{dz}$$  \hspace{1cm} (3.1)

where $M_{cd}$ is the mutual inductance between the coil and disk.

However, it is very difficult to obtain $i_c$, $i_d$ and $M_{cd}$ from a closed form expression using an analytical approach. Therefore, this paper calculate the force using FEM.
3.3 Steady State Modeling of Thomson Coil Actuator

The steady state modeling of Thomson coil actuator starts with the simplest geometry to explore fundamental physics and phenomenon behind the actuator.

3.3.1 Methodology and setup

The geometry can be found in Fig. 3.1, in which a copper conductor is placed above a copper plate. Upon excitation the conductor is energized and current flows though it, if this current is time-variant, a time varying magnetic field penetrates the plate and the eddy current is induced in the plate in proximity. This eddy current creates another magnetic field which act against the field generated by the conductor and therefore a repulsive force would tend to pull the conductor and the plate away. If the coil is assumed stationary, then the plate will be repulsed away from the coil and actuate any payload attached to it.

Figure 3.1: 2D view of a coil above a plate.
3.3.2 Frequency sweep

We investigate the drive characteristics of a Thomson coil actuator by a frequency sweep of the energizing source. The source is an AC source with a frequency in the range of 1 Hz to 100 kHz with a constant magnitude. The conductor has a length of 10 meters and a cross section geometry shown in Fig. 3.1. The resistance, inductance, current and force of the coil under different excitation sources are calculated and presented in Fig. 3.2 to Fig. 3.5.

![Coil resistance vs. frequency](image)

Figure 3.2: Coil resistance vs. excitation frequency.

The results shown in Fig. 3.5 is most interesting because the pattern indicates that there is an optimum frequency for AC excitation to get the maximum force for actuation.

3.3.3 Frequency and gap sweep

To investigate whether the same patterns applies to different geometries or structural arrangements, another sweep is conducted on the distance or the gap between the coil and the plate.
This gap is varied from 1 mm to 4 mm; the simulation results are presented in Fig. 3.6 to 3.10.
Figure 3.4: Coil current vs. excitation frequency.

Figure 3.7: Coil inductance vs. excitation frequency with different gaps.
Figure 3.5: Coil force vs. excitation frequency.

Figure 3.8: Coil impedance vs. excitation frequency with different gaps.
From Figs. 3.6 to 3.9, those curves with different gaps seem to be very similar. However, Fig. 3.10 does show differences in two aspects: first, a structure with a smaller gap yields higher
force; second, the frequency at which peak force is generated slightly shift to the right with smaller gaps.

3.4 Transient Modeling of Thomson Coil Actuator

3.4.1 Methodology

This section describe the basic method used in FEA modeling. Equations that include electromagnetic, thermal, and structural characteristics are included in the FEA software to simulate the transients during operation. Those equations are applied to the copper coil, the copper disk, the air gap in between, the shaft, and external lumped circuit. The FE modeling based analysis is used for design optimization of the prototype [89].

In the FEA software, the $z$-component force is calculated for each element and integrated over the volume of the moving copper disk to get the total driving force. Then after adding the payload of the VI, the acceleration as well as displacement are calculated with time steps of 5$\mu$s. A moving mesh using arbitrary Lagrangian-Eulerian formulation method is defined on the moving copper disk so that the geometry especially the distance between coil and disk is updated at each time step. The same model can predict the force distribution on the copper disk, yielding useful information concerning local stresses and the mechanical integrity of the conducting disk.

3.4.2 Equations

Equations applied to the finite element model of the actuating system include electromagnetic, thermal, and structure equations. Those equations are applied to the copper coil, the copper disk, the air gap in between, the shaft and external lumped circuit, and solved by small time steps for each element in the model. The time domain calculations represent the multi-physics behavior of the operating mechanism in a comprehensive way that provides a lot of information.
which is otherwise difficult to observe in experiments. For example the current density distribution in the coil conductor, or the internal mechanical stress at certain points in the structure is available from the EM results. The set of equations used in FEA are given in Equation. 3.2 to 3.7 with all variables explained in Table 3.1.

\[
\sigma_e \frac{\partial A}{\partial t} + \nabla \times H - \sigma_e \mathbf{v} \times \mathbf{B} = J_e 
\]

\[
\mathbf{B} = \nabla \times \mathbf{A}
\]

\[
\rho c_p \frac{\partial T}{\partial t} + u_{\text{trans}} \cdot \nabla T = \nabla \cdot (k \nabla T) + Q
\]

\[
\sigma_e = \sigma_{e0}[1 + \alpha(T - T_0)]^{-1}
\]

\[
f_{em} = J \times \mathbf{B}
\]

\[
\rho \frac{\partial^2 \mathbf{u}}{\partial t^2} - \nabla \cdot \sigma_m = f_{em}
\]

In the above, Equations (3.3) and (3.4) describes the electromagnetic effects caused by ex-
<table>
<thead>
<tr>
<th>Variables</th>
<th>Descriptions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>A</strong></td>
<td>Magnetic vector potential</td>
</tr>
<tr>
<td><strong>H</strong></td>
<td>Magnetic field</td>
</tr>
<tr>
<td><strong>v</strong></td>
<td>Velocity</td>
</tr>
<tr>
<td><strong>B</strong></td>
<td>Magnetic flux density</td>
</tr>
<tr>
<td><strong>J_{\varepsilon}</strong></td>
<td>Electromagnetic</td>
</tr>
<tr>
<td><strong>\rho</strong></td>
<td>Density of material</td>
</tr>
<tr>
<td><strong>Q</strong></td>
<td>Ohmic heat source</td>
</tr>
<tr>
<td><strong>c_{p}</strong></td>
<td>Specific heat at constant pressure</td>
</tr>
<tr>
<td><strong>\sigma_{\varepsilon}</strong></td>
<td>Electric conductivity</td>
</tr>
<tr>
<td><strong>\sigma_{\varepsilon 0}</strong></td>
<td>Reference conductivity</td>
</tr>
<tr>
<td><strong>\alpha</strong></td>
<td>Temperature coefficient of resistance</td>
</tr>
<tr>
<td><strong>T</strong></td>
<td>Temperature</td>
</tr>
<tr>
<td><strong>T_0</strong></td>
<td>Reference temperature</td>
</tr>
<tr>
<td><strong>f_{\text{em}}</strong></td>
<td>Lorentz force</td>
</tr>
<tr>
<td><strong>\sigma_{\text{em}}</strong></td>
<td>Mechanical stress tensor</td>
</tr>
<tr>
<td><strong>u</strong></td>
<td>Displacement</td>
</tr>
</tbody>
</table>
ternal current; Equations (3.4) and (3.5) represents the temperature effects on heat transfer and electric conductivity; Equations (3.6) and (3.7) calculates the Lorentz force and acceleration.

In the FEA software, the $z$-component force is calculated for each element and integrated over the volume of the moving copper disk to get the total driving force. Then after adding the payload of the VI, the acceleration as well as displacement are calculated with time steps of $10\mu$s. A moving mesh using arbitrary Lagrangian-Eulerian formulation method is defined on the moving copper disk so that the geometry especially the distance between coil and disk is updated at each time step.

### 3.4.3 Baseline Case

A baseline case is first studied using parameters presented in Table. 3.2. Fig. ?? shows the results for the operation transients. Figs. 3.12 - 3.15 show the current density distribution and force distribution in z-axis and r-axis at 0.04 ms.

Four important parameters related to the operation performance are shown in Fig. ??: speed of the moving part $v$, total displacement $u$, total force exerted on the moving mass $f$ and current in the coil $i$. $i$ is the current in the lumped circuit and finite element modeled coil, $f$ is obtained by integration over the volume of moving part, $v$ and $u$ are calculated based on load. By discharging a 2 mF 500 V capacitor, the current surges to 15 kA and the corresponding peak force is 24 kN that accelerates the load to 3 m/s in 1 ms. The open distance reaches 3 mm at that time that translates to 60 kV in the vacuum.

### 3.5 Optimization of the circuit topology and parameters

Lumped circuit refers to the discharge circuit consisting of the pre-charged capacitor bank, inductive coil and some stray inductance and resistance in the loop.
Table 3.2: Base case parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper disc OD</td>
<td>80 [mm]</td>
</tr>
<tr>
<td>Copper disc thickness</td>
<td>4 [mm]</td>
</tr>
<tr>
<td>Coil ID</td>
<td>12 [mm]</td>
</tr>
<tr>
<td>Coil OD</td>
<td>77 [mm]</td>
</tr>
<tr>
<td>Wire gauge</td>
<td>10 [AWG]</td>
</tr>
<tr>
<td>No. of turns</td>
<td>11</td>
</tr>
<tr>
<td>Gap b/t coil and disc</td>
<td>3 [mm]</td>
</tr>
<tr>
<td>Moving mass</td>
<td>1 [kg]</td>
</tr>
<tr>
<td>Capacitance</td>
<td>2 [mF]</td>
</tr>
<tr>
<td>Pre-charged voltage</td>
<td>500[V]</td>
</tr>
</tbody>
</table>

3.5.1 Circuit topology

From electrical point of view, the lumped circuit is a simple series RLC circuit that is expected to exhibit damped oscillation after the discharging the pre-charged capacitor bank initiates. However, the semiconductor device could change its behavior based on two different circuit topologies which would change requirements on related components. The two circuits are shown in Fig. 3.16 and 3.17.

Bidirectional circuit

If bidirectional current flow is allowed, then it is again a simple RLC circuit, which in this case is under-damped. The induced current in the disk changes accordingly so that a repulsive force is always generated irrespective of the direction of current. The thyristor can be replaced by asymmetrical semiconductor devices such as IGBTs, as long as the IGBTs can handle the surge current, since an anti-parallel diode is connected with the thyristor.
Unidirectional circuit

If a clamping diode is used, current will flow in one direction. Once the capacitor is totally discharged, current in the coil reaches its maximum value and then gradually decrease to zero through the diode. Therefore, the diode clamps the voltage at the cathode of thyristor, which also makes it possible to replace the thyristor with IGBTs.

In terms of operation performance, the unidirectional circuit outperforms the bidirectional one, by approximately 10% more travel according to simulation results in Fig. 3.18. This is due to the reduced losses of ESR in the capacitor bank since current is cut off and not allowed to oscillate with the capacitor in the unidirectional circuit. On the other hand, surge current magnitudes are the same in both cases, and the thyristor switches can both be substituted by asymmetrical devices such as IGBTs.
3.5.2 Pre-charge voltage of the capacitor bank

Increasing the pre-charge voltage magnitude of the capacitor bank will result in larger current and force, as illustrated in Fig. 3.19. This is simply because a larger amount of energy is dumped into the electromagnetic device. From the implementation point of view, large current and high \( \frac{di}{dt} \) put the control switch under high stress. Fig. 3.19 shows that, if the capacitor is pre-charged to 1400 V, the discharge current peaks to 40 kA, which approaches the limit of the most capable devices in terms of surge current capability. Even if the semiconductor switch can handle that surge current, the 175 kN peak force is also very likely to over-stress weak components or parts within the structure which will reduce the long term reliability and life time of the device.

Figure 3.13: Transients during opening operation.
Figure 3.14: Lorentz force in z-axis.

Figure 3.15: Lorentz force in r-axis.
Figure 3.16: Bidirectional circuit

Figure 3.17: Unidirectional circuit

Figure 3.18: Comparison of unidirectional and bidirectional circuit
3.5.3 Capacitance and frequency

Simulations have been carried out with the same geometry and stored energy but varying the capacitance C and voltage U. Results shown in Fig. 3.20 indicate that larger voltage and smaller capacitance result in a higher current peak and speed, which are better in terms of force and speed. However, this requires both higher voltage rating and current rating for the semiconductor switch.
Figure 3.19: Actuator performance at different voltages.

Figure 3.20: Actuator performance at different capacitances and frequencies.
Figure 3.21: Actuator performance at different gaps.

Figure 3.22: Actuator performance at different disk thicknesses.
Figure 3.23: Actuator performance at different wire diameters.

Figure 3.24: Actuator performance at different disk outer diameters.
3.6 Optimization of geometrical parameters

3.6.1 Thickness of disk

When current is induced in the copper disk, the current density is higher closer to the surface, and most of it concentrates within the depth of 2 to 3 times of skin depth $\delta$ which is well approximated as:

$$\delta = \sqrt{\frac{2\rho}{\omega \mu_0 \mu_r}}$$  \hspace{1cm} (3.8)

In the equation, $\mu_0 = 4\pi \times 10^{-7}$ Vs/Am is the permeability of free space, $\mu_r$ is the relative magnetic permeability of the conductor, $\omega$ is the angular frequency of the current, and $\rho$ is the resistivity of the conductor. If current frequency is 10 kHz, then the skin depth $\delta$ in copper is approximately 0.65 mm. This means that when the disk thickness is three times of $\delta$, i.e. 2 mm, 95% of the current concentrates in this 2 mm thick layer. Therefore a thicker disk does not help boost the induced current, as verified by the results in Fig.3.22. On the contrary, it adds more weight to the payload.

Also, note that material conductivity is in the expression of $\delta$, which indicates that material with higher conductivity is preferred to potentially reduce the disk thickness. However, additional considerations are needed from mechanical stress point of view, since thinner disks tend to break easily.

3.6.2 Coil wire diameter

Coil wire diameter variations will change the resistance as well as inductance of the coil, and therefore, affect the transients while being discharged. However, as seen from Fig. 3.23, when the wire diameter is large enough, there is insignificant impact because of two reasons: First, skin effect will limit the active conducting area in a larger wire; second, the inductance does not change much. The inductance of a flat spiral coil is calculated according to Wheeler’s equation [90] as:

$$L = 31.33\mu_0 N^2 \frac{R^2}{8R + 11w},$$  \hspace{1cm} (3.9)
where \( N \) is the number of turns, \( R \) is the outer radius of the coil, and \( w \) is the width of the windings. From this equation, the wire diameter variation compared to the coil radius is pretty small and having a negligible impact on inductance.

### 3.6.3 Gap between disk and coil

The gap between the disk and coil is a sensitive variable, because it directly affects how strong those two parts are coupled. On one hand, a strong coupling reduces the equivalent inductance, and therefore, increases frequency which results in an earlier peak force. On the other hand, efficiency of energy transfer from disk to coil is boosted. Placing the two in close proximity enhances the acceleration of moving mass along its travel.

One of the limitations of reducing this gap is that, there has to be an insulating layer between the copper disk to provide insulation between them as well as to avoid structural damages caused by impacts. A minimum of 2 mm is required to have enough mechanical strength.

### 3.6.4 Disk OD to coil OD ratio

The disk and coils are assumed to be circular on the outer edges as well as concentric. They are positioned closely such that one is above the other, namely the opening coil is above the disk, which is again above the closing coil. The ratio of disk outer diameter (DOD) to coil outer diameter (COD) is an indicator of how much they overlap horizontally, while the gap discussed reflects their coupling vertically.

Given the number of turns with a certain conductor and a coil inner diameter, the outer diameter is determined. Based on the coil dimensions given in baseline case, the ratio DOC/COD is swept from 68/77 -88/77 in a set of FEM simulations. Fig. 3.24 shows that the operation speed increase when disk OD reaches 76 mm for 77 mm diameter of coil. For even larger disk OD, the speed does not increase anymore. Therefore, a disk OD to coil OD ratio should always be optimized to 1 which means the two are almost completely overlapping each other.
Chapter 4

Drive Circuits for the UFMS

4.1 Introduction

The past two decades have witnessed a resurgence of research in high voltage DC circuit breakers [17]. In a manner that departs from high voltage DC (HVDC) transfer switches that are used in classical HVDC systems [14, 3], voltage source converter (VSC) based HVDC systems require much faster protections in order to provide high reliability and availability of power transfer in HVDC networks [12, 85]. Among the proposed schemes, the so-called “hybrid configuration” which combines mechanical and electronic switches is the most promising [12, 82, 24, 5]. Although driven by the needs in DC applications, such concepts could also be of advantage for AC systems. One of the most desirable features of the fast mechanical switches (FMS) for hybrid circuit breakers is a fast opening speed, which led to selecting the Thomson coil actuator design over other electro-mechanical actuator configurations.

4.1.1 Operation principle of the Thomson coil actuator

The FMS employing a Thomson coil actuator has four main parts, as shown in Fig. 4.1: the interrupter, the operating mechanism, the energy storage and control circuit, and the damping and holding mechanism. Referring to the control circuit in Fig. 4.1, when the FMS is to open,
the control switch (the SCR in Fig. 4.1) turns on and allows the capacitor bank to discharge through the opening coil (the upper one in the figure). The fast rising discharge current in the coil induces current in the conductive (typically copper) disk which results in a strong repulsive force between the coil and copper disk. The force drives the copper disk downwards and opens the FMS. The role of the diode in this particular circuit is to limit the rate of the current decay after it has peaked. This opening movement is stopped by a disc spring. The closing operation is accomplished in a similar way by turning on a second switch, not shown in this figure, that controls the discharge through the closing coil (the lower one), then the copper disk moves upward to close the contacts.

4.1.2 Problem description

One of the key challenges of the FMS is to actuate the moving mass as fast as possible. Figs. 4.2 - 4.6 show a number of drive circuits described in the literature for the repulsion coil application (Fig. 4.1 and the above description used the simplest of these drive circuits, Circuit 1, shown in Fig. 4.2). Both simulations and experiments indicate that a capacitor bank charged to a higher voltage drives the moving mass to a higher speed [91, 92, 93, 94, 95, 96, 97, 98, 89]. However, this is only a reflection of systems starting with more stored energy. What still needs to be elucidated is the effectiveness of the energy transfer from storage to motion. For instance, the peak force may be as important a parameter as force rise, and duration of that peak, in terms of inducing fast motion. Furthermore, a fair design comparison must be based on similar ratings of both the mechanical and electrical components, some of which are rated based on peak values. This is the case with the peak force which generally corresponds to the peak stress level in the moving parts.

It is also critical to use the stored energy wisely, to minimize the overall size of the energy storage, the rating of the control components and the dimensions of the actuator structure. The focus here is on design efficacy, that is, how to get the fastest motion from a given design and set of parameter and ratings. It is not a question of efficiency, understood as energy used per
motion, which is not of much concern since breakers operate very infrequently. Therefore this paper aims to investigate different drive circuits regarding the aforementioned considerations.

Most implementations of Thomson coil based FMS [91, 92, 93, 99, 94, 95, 63, 53, 96, 97, 98], employ a single pulse circuit, perhaps because of simplicity. Its variations include Circuits 1, 2 and 3 as shown in Figs. 4.2 to 4.4. But reference [100] has proposed a pulse forming network as shown in Fig. 4.5 (Circuit 4), to generate multiple pulses into the coil. Reference [30] has developed a fast acting circuit breaker using Circuit 5 shown in Fig. 4.6, which is called “two-stage fast actuator power supply” using only one control switch but two capacitors pre-charged to different voltage levels. Circuit 4 and 5 have more components and thus require more detailed optimization. Because of the problem complexity, this paper investigates the problems by finite element analysis (FEA); and the FEA model has been validated with experimental measurement.
4.2 FEA Modeling

The finite element modeling of the actuator consists of a coil as the stationary part, and a shaft and copper disk as the moving part. The actuator is then co-simulated with an external...
drive circuit with lumped parameters and sequence control. The drive circuit can be controlled by switches to discharge the coil in desired patterns. Electromagnetic, thermal, and structural physics are coupled into the model, and the multi-physics equations are solved simultaneously in time domain. The software used is COMSOL Multiphysics. For additional details regarding the method of the FEA modeling, the readers are referred to [89].

The system baseline consists of a copper disk with an outer diameter of 80 mm and a thickness of 4 mm. The coil has an inner diameter of 12 mm with 11 turns of 2.31 mm by 4.62 mm wires. The gap between the disk and coil is 3 mm. The payload of the actuator is 0.7 kg; and the total moving mass is about 1.2 kg. The geometry is built in axis-symmetrical two-dimensions because of the symmetry of the actuator structure. This reduces the required simulation time for this complex multi-physics problem. To obtain accurate results, the mesh
is refined and more than 40,000 elements are created; the time domain step size is 2 us. Fig. 4.7 shows a typical three-dimensional plot of current density for the actuator at a given position and moment. Fig. 4.8 corresponds to a stress distribution in the moving structure.
4.3 Single Capacitor Drive Circuits

Circuits that deliver a single pulse into the coil, shown in Figs. 4.2 - 4.4 are most common in the prior art. There are some subtle differences between Circuits 1 and 2; Circuit 3 is quite different as the current oscillates bidirectionally. Nevertheless, these differences have not been discussed by earlier publications and will be investigated in this section.

4.3.1 Simulation

Circuits 1, 2 and 3 were all modeled with the same components. C1, 2 mF and pre-charged to 300 V, represents the capacitor bank, charged with the same amount of energy in all 3 cases; R1, 0.002 Ω, represents the equivalent series resistance (ESR) of the capacitor; T1 and D1 are the thyristor switch and diode, respectively. Both T1 and D1 are modeled as a voltage drop in series with a certain resistance. By FEA simulation, the operation transients for all three single pulse drive circuits are compared in Fig. 4.9 and 4.10.

4.3.2 Circuits 1 and 2 - unidirectional circuits

Based on Figs. 4.9 and 4.10, it is apparent that the performance of the actuator driven by Circuit 1 is slightly better than Circuit 2. In both Circuits 1 and 2, the current and force rises and peaks are the same. After the current peak, its decay is limited by the voltage drop in the diode for Circuit 1 and in a similar manner in the diode and thyristor in series for Circuit 2. Therefore the current decays slightly faster in Circuit 2, and the control switch in Circuit 2 needs to withstand more current surge than in Circuit 1. This is because, after the current peaks in Circuit 1, the voltage across the coil is equal to the diode voltage drop, thus forcing the current to zero in the capacitor/thyristor branch of the circuit and making the coil current flow exclusively through the diode. While a similar voltage limitation across the coil is in operation in Circuit 2, it does not lead to an interruption of the current in the thyristor switch.

Considering the high current levels in such applications, it is therefore desirable that the current stress in the control switch should be minimized as is achieved in Circuit 1.
4.3.3 Circuit 3 - a bidirectional circuit

In contrast to Circuits 1 and 2, Circuit 3 generates a damped sinusoidal current in the coil, see solid green curve in Fig. 4.9. It should be noted that the polarity of the current in the solid disk follows that of the coil current (with some delay), so there is a repulsion force most or all
of the time, regardless of coil current polarity. Accordingly, as the current goes from positive to negative and back, multiple force pulses, with decreasing magnitudes, are observed, see broken green line in Fig. 4.9. The force in this case is therefore periodically higher and periodically lower than those observed with Circuits 1 and 2. However, overall, the effect of the multiple force pulses on the acceleration is weaker than with Circuits 1 and 2, as seen in Fig. 4.10. The forces are the same until the peak in all 3 cases, but with Circuit 3, the peak is followed by a temporary, but sharp decrease in the force during which the disk loses momentum, a loss it never recovers from completely despite the higher forces later on. Concerning the circuit design, the bidirectional current requires that the capacitor be unpolarized, an added cost for Circuit 3. Further, the force pattern may induce vibrations in the disk that are largely avoided with Circuits 1 and 2.

4.4 Pulse Forming Network (PFN) Drive Circuit

The pulse forming network (PFN) shown in Fig. 4.5 generates multiple pulses into the coil. In essence, this circuit decouples the peak and frequency of the current waveform, whereas these two parameters are linked in Circuits 1 to 3. In general, there can be as many pulses as possible in a PFN to drive the actuator. However, a two-pulse circuit is sufficient to show their differences to other circuits, and therefore is evaluated in this section.

4.4.1 Simulation

A set of simulations was conducted to find out how the delay between two discharge pulses in a PFN with two capacitors (C1 and C2) affects the transients behavior of the actuation. Both C1 and C2 are 1 mF and pre-charged to 300 V, therefore the total stored energy is the same as in Circuits 1 to 3. Instead of dumping the energy into the coil at the same time, C1 and C2 are separately controlled by two thyristor switches, T1 and T2 as shown in Fig. 4.5. The delay between firings of T1 and T2 are swept from 0 to 250 us.
4.4.2 Discussion

Fig. 4.13 plots motion versus time for various values of delay in the firing of Thyristor T2, with a delay of 0 making Circuit 4 equivalent in principle to Circuit 1. One can see in the figure that, from the displacement point of view, the delay does not help; on the contrary, the delay slows down the displacement compared with the circuit with no delay. At the same time, the forces profiles shown in Fig. 4.12 and the currents profiles shown in Fig. 4.11 also indicate that peak force and peak current are higher with no delay, which is consistent with the faster acceleration.

While faster accelerations are obviously desirable, they can come at a price if the higher force is much larger, in proportion, than the motion is faster. In other words, this raises the question of the effectiveness of the system to provide a given acceleration and a given motion pattern for a set level of peak rating, both on the electrical and mechanical components. In this example, when driven with no delay, the peak force is 9.4 kN and the device travels to 4 mm in 2 ms; with a 150 us delay, the peak force is 7.5 kN and the device travels to 3.7 mm in 2 ms.

Comparing these two cases, if driven with no delay, the peak force is more than 25% higher, but the displacement is less than 10% faster. Accordingly, from the mechanical point of view the maximum stress levels also increase significantly, Fig. 4.14, approximately in proportion of the peak force. From a system design point of view, a fair comparison must be made with comparable rating levels, including similar mechanical stress levels. Consequently, a design with a single pulse may require a reinforced, thus heavier, moving disk as compared to a system with a PFN circuit, which leads to a larger moving mass. This will result in a slower acceleration, especially if the mass of the moving disk is important compared to that of the payload. Similarly the electrical component rating must be increased thus leading to higher cost.

In conclusion, circuits with multiple control switches and discharging pulses would not necessarily result in faster actuation than a single discharge circuit when the total energy stored in the capacitors is the same. Allowing the energy to be delivered into the actuator in a few steps helps reduce the maximum stress and therefore improve the mechanical reliability of the switch unit. In the same manner, even if the mechanical design is strong enough, releasing
higher energy in a single shot would generate tens of kA current that could exceed the rating of the most powerful thyristor switches available and therefore require more complicated designs.

Figure 4.11: Currents when driven by PFN with different delays.

Figure 4.12: Forces when driven by PFN with different delays.
Figure 4.13: Displacements when driven by PFN with different delays.

Figure 4.14: Mechanical stresses when driven by PFN with different delays.

4.5 Two-stage Drive Circuit

Kimblin [30] has proposed a fast acting circuit breaker using Circuit 5, which is called “two-stage fast actuator power supply”, shown in Fig. 4.6. In that paper, C1 is 110 µF pre-charged
to 5 kV while C2 is 2 mF pre-charged to 2 kV. This two stage drive circuit can be considered as a special form of the PFN: the delay of the second discharge is dictated by the discharge time of the first capacitor. The second capacitor C2 is blocked by Diode D2 until the voltage of the first capacitor C1 falls below the voltage across C2. Since Circuit 5 uses 1 thyristor and 2 diodes, as opposed to 2 thyristors and 1 diode in Circuit 4, Circuit 5 is smaller and cheaper than Circuit 4.

4.5.1 Simulation

In this paper, FEA simulations were conducted to explore how these two capacitors should be selected to optimize the operation of the actuator and how the performance differs with different combinations of those two capacitors. In the simulation, Capacitor C2 of the two stage drive circuit is assumed 1 mF and pre-charged to 300 V, while Capacitor C1 has a variable capacitance but pre-charged with a voltage such that the stored energy in C1 is twice as much as that in C2. C1 varies from 2 mF to 0.125 mF, and the voltage U1 across C1 from 300 V to 1200 V. When C1 is 2 mF and U1 is 300 V (green curves in Fig. 4.15 and 4.16), this is equivalent to Circuit 1 with a 3 mF capacitor pre-charged to 300 V.

4.5.2 Discussion

The simulation results shown in Figs. 4.15 and 4.16 indicate that for the setup above, the currents and forces profiles shift to the right (later times) with lower peak values when C1 increases and U1 decreases. It is also observed that a higher U1 results in slightly higher current, but significantly larger force. However, after reaching the peaks, both the current and force drop sooner in the case with a lower C1 and a higher U1 than in the case with a larger C1 and a lower U1. This results in different accelerations in the periods before and after their peak values in each of the cases with different C1 and U1 combinations. In other words, the combinations that lead to higher current and force peaks also lead to earlier, and narrower, peaks.
In order to determine the impact of these force patterns on motion, two plots are presented: Fig. 4.17 with the entire displacement for all the cases studied, and Fig. 4.18 with a zoom-in view for two of these cases: Case 1, C1=0.125 mF, U1=1200 V; Case 2, C1=2 mF, U1=300 V (Case 2 is also equivalent to Circuit 1). Referring first to Fig. 4.17, motion is affected but not
very much across these various cases. Since one of them (Case 2, green curves) also corresponds to Circuit 1, a first conclusion is that the complexity of Circuit 5 will result in only minor improvement in performance, if improved at all.

Comparing the various cases studied for Circuit 5, a first impression could be that higher
capacitance and lower voltage values lead to both lower stresses (Figs. 4.15 and 4.16) and faster motion (at 2 ms on Fig. 4.17). However, the motion pattern is more complex, as revealed by Fig. 4.18 which shows that these motion curves actually cross one another. For Cases 1 and 2, the cross over occurs at round time 0.9 ms. This indicates that combinations with a higher $U_1$ and lower $C_1$ do give a faster initial acceleration, but later on the acceleration becomes slower.

For a given actuator mechanical design, the values of $C_1$, $U_1$, $C_2$ and $U_2$ will give different displacement curves. Some values will produce faster initial movement with slower ending speeds, while other values will result in slow initial displacement followed by faster acceleration later. This can be seen in Fig. 18 where the plots of two sets of values cross. Since each design will have a time target, the values for capacitances and voltages should be selected based on which gives the greater displacement at that time target while still staying within the stress limits of all the components.

Accordingly, Circuit 5 is more likely to be favorable when the time target is really short. It will give slightly faster acceleration within that time target at the cost of an additional diode and increased stress levels. In Cases 1 and 2, for example, if the time target is 0.6 ms, Case 1 with Circuit 5 gives a faster acceleration; if the time target is 1.2 ms, however, Case 2 with Circuit 1 shows better performance.

### 4.6 Experimental Verification

A prototype was fabricated to validate the accuracy of the model and simulation. It is shown in Fig. 4.19. Details regarding the electrical and structural design can be found in [101]. The prototype has the same dimensions and materials used in the FEA model.

This model in the finite element domain has been verified by measurements. Fig. 5.16 shows the comparison of the test results of the prototype driven by a 2 mF capacitor bank pre-charged to 300 V, and the simulation results obtained from FEA simulation of the modeled prototype driven based on Circuit 1. Both the discharging current in the coil and the displacement of the movable parts match well with each other in the simulation and experiment. The current peaks
at 4.5 kA at about 160 us and then drops slowly down to 1.5 kA at 1 ms, and 0.5 kA at 2 ms. The movable parts start moving at around 200 us; they reach 0.9 mm at 1 ms and 2.2 mm at 2 ms. The experimental data has verified the FEA model presented in the previous sections and therefore the study of drive circuit analysis based on such model is supported.

4.7 Conclusions

This paper has presented an investigation of different electric drive circuits used in Thomson coil actuators. Five different drive circuits are evaluated. Comprehensive FEA simulation, confirmed by experimental studies, have revealed that:

1) The circuits come in two broad categories, single and multiple pulse circuits. With two or more pulses, the PFN decouples the peak value and the frequency of the current pulse, providing an additional degree of freedom for the designer. With lower peaks, the PFN circuits result in slightly lower actuation speed compared to single pulse circuits, with the same amount of stored energy. However, they significantly reduce the mechanical stress on the structure, as well

Figure 4.19: FMS prototype assembly.
as the peak current the electrical components are exposed to. Whether single of multiple pulses is better depends therefore on rating margins. For instance if the load being moved is large compared to the moving disk, the disk can be made heavier to sustain higher forces, resulting in single-pulse circuits being better, and vice versa.

2) The single switch circuits such as Circuits 1 and 2 with a single pulse can drive the actuator to a comparable speed; however, the control switch in Circuit 1 is exposed to less current surge stress.

3) Circuit 3 generates a bidirectional current. It does not drive the actuator any faster than Circuits 1 and 2. The current oscillation can cause vibration of the moving structure and the circuit requires an unpolarized capacitor.

4) The PFN drive circuit is an attractive solution when the discharge current expected from a single pulse exceeds the current rating of the available semiconductor switches. The reduction in peak force can also be advantageous in reducing the moving disk mass, for a given stress level.

5) The two-stage drive circuit is more complex than the single-pulse circuit options. It will provide slightly better performance only in specific situations where travel is particularly short and the moving disk can be reinforced to accommodate higher stress levels, without impacting acceleration in a significant way.

6) The FEA simulation has been verified by a prototype. The measured movement and current transients match very well with the simulated results based on the same FEA model used in the drive circuit study.
Chapter 5

Design and Test of the 15 kV Class UFMS Prototype

5.1 Electrical Design Considerations

This preliminary examination report features a vertical design of the prototype. Though it is also possible to operate the device in any position, it is the best to put the heavy base plate on a horizontal platform so that high impacts during opening and closing operation does not shake the frame of the mechanical switch.

5.2 Vacuum Interrupters

The vacuum interrupters are a delicate device that can be used in different switchgear for protection purposes. According to their applications, vacuum interrupters can be divided into those for circuit breakers, contactors, reclosers, load break switches. The differences are mainly their contacts design and requirements on their operating mechanisms.

5.2.1 Structure of a vacuum interrupter

A typical vacuum interrupter is shown in Fig. 5.1.
5.2.2 Requirement of the VI in hybrid circuit breakers

For the application of ultra-fast mechanical switches designed for hybrid circuit breakers, the requirement on the vacuum interrupter differs from a conventional vacuum AC circuit breaker in the following ways.

First, the vacuum interrupter does not have to withstand short circuit current, or to extinguish short circuit arcs. This is because the hybrid circuit breaker would not see the prospective short circuit current thanks to the sub-quarter cycle operation speed. What is really needed is the dielectric strength of the vacuum during cold operation, rather than its capability to quench arc as in conventional AC circuit breakers and fast dielectric recovery after arcing. Therefore, the applied closing force by external mechanism is reduced.

Second, the vacuum interrupter needs to open very fast but does not have to be that fast
Table 5.1: Vacuum interrupter parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contact stroke</td>
<td>6</td>
<td>mm</td>
</tr>
<tr>
<td>Basic Impulse Level (BIL)</td>
<td>75</td>
<td>kV</td>
</tr>
<tr>
<td>Rated current</td>
<td>630</td>
<td>A</td>
</tr>
<tr>
<td>Contact resistance</td>
<td>55</td>
<td>μΩ</td>
</tr>
<tr>
<td>Contact force from atmosphere pressure</td>
<td>70</td>
<td>N</td>
</tr>
<tr>
<td>Holding force required when open</td>
<td>110</td>
<td>N</td>
</tr>
<tr>
<td>Holding force required when closed</td>
<td>110</td>
<td>N</td>
</tr>
<tr>
<td>Moving mass</td>
<td>0.5</td>
<td>kg</td>
</tr>
</tbody>
</table>

during closing. Both the response time or delay and the travel time must be minimized when designing the operating mechanism.

Third, the contacts of the interrupter can have not arcing when opening a DC current in a hybrid circuit breaker, or the arc period is very as short as the commutation time.

### 5.2.3 The selected VIs

A vacuum interrupter with light weighted moving mass and a moderate open gap is selected with the main parameters listed in Table. 5.1.

### 5.3 Thomson Coil Actuator

The actuator consists of a disk made of copper, a transmission shaft coupled with all other movable components and a multi-turn coil made of thick wire.
Table 5.2: Capacitor ratings (each).

<table>
<thead>
<tr>
<th>Capacitance</th>
<th>0.5</th>
<th>[mF]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacitor voltage</td>
<td>1100</td>
<td>[V]</td>
</tr>
<tr>
<td>Peak current</td>
<td>6000</td>
<td>[A]</td>
</tr>
<tr>
<td>dV/dt</td>
<td>12</td>
<td>[V/us]</td>
</tr>
<tr>
<td>ESR</td>
<td>1.1</td>
<td>[mΩ]</td>
</tr>
<tr>
<td>ESL</td>
<td>80</td>
<td>[nH]</td>
</tr>
</tbody>
</table>

5.4 Capacitor Bank

Film capacitors and electrolytic capacitors differ in a lot of ways. Most notably are their polarities, capacitance range, voltage range, ESR and ESL, and their prices.

For a medium voltage circuit breaker, voltage rating of a few hundreds for these energy storage capacitors is desired. Heavier loads needs higher voltages. The capacitance ranges from a few hundreds of uF to a few mF, which are covered by both film and electrolytic capacitors.

Film capacitors are much more suitable for such applications because of two reasons. First, their ESRs are as small as a few mΩ while electrolytic capacitors have a few hundreds. Second, surge current capability of film capacitors reach a few kA while in electrolytic capacitors, their ESRs themselves would limit the current to a few hundreds of amperes.

Even though electrolytic capacitors are far cheaper than film made equivalent, they would not suffice in applications to drive Thompson coil actuators without paralleling quite a few to achieve lower ESRs and higher surge current capabilities.

5.5 Thyristor Switch

As the discharging current is in the range of kAs, thyristor is the most powerful semiconductor device in terms of current conducting capabilities. The key parameters are listed in Table. 5.3; and a photo of the SCR assembly is shown in Fig. 5.2.
Table 5.3: Thyristor ratings.

<table>
<thead>
<tr>
<th>Component</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thyristor</td>
<td>$V_{DRM}$</td>
<td>1600</td>
<td>[V]</td>
</tr>
<tr>
<td>Thyristor</td>
<td>$I_{T(\text{AV})M}$</td>
<td>2600</td>
<td>[A]</td>
</tr>
<tr>
<td>Thyristor</td>
<td>$I_{TSM}$</td>
<td>30</td>
<td>[kA]</td>
</tr>
<tr>
<td>Diode</td>
<td>$V_{RRM}$</td>
<td>2000</td>
<td>[V]</td>
</tr>
<tr>
<td>Diode</td>
<td>$I_{F(\text{AV})M}$</td>
<td>3270</td>
<td>[A]</td>
</tr>
<tr>
<td>Diode</td>
<td>$I_{FSM}$</td>
<td>28</td>
<td>[kA]</td>
</tr>
</tbody>
</table>

Figure 5.2: Thyristor control switch.

5.6 Disc Spring

In the design, a special disc spring is used and it is an essential mechanical part used for holing and compressing the movable contact against the stationary contact in closed position, and to hold the movable contact in open position when opened. The external force applied to the movable contact which will ensure reliable closed status can be adjusted by selecting the proper load-deflection curve of such a spring. The disc springs are sometimes also called coned-disk springs, or Belleville washers which take their name from their inventor, Julian F. Belleville. A drawing of a typical disc spring is found in Fig. 5.3, and their load-deflection curves are found in Fig. 5.4 [102, 103]. Table 5.4 gives the definitions of the dimensions and important parameters.
that determine the characteristics [103].

Figure 5.3: A disc spring

The functions of this disc spring are threefold, namely for static closed operation, static open operation and dynamic opening operation of the switch. Four positions are marked in Fig. 5.5.

In closed position, it applies a force on the movable contact towards to the stationary contact, as marked ‘C’ in Fig. 5.5. Therefore, the closing force upon the contacts during closed position is the sum of the disc spring and the atmosphere pressure. The former can be adjusted by positioning the rim of the disc spring so that a certain deflection is formed, which corresponds to a certain force according to its load-deflection characteristics. The latter is fixed for a specific vacuum interrupter assuming that the vacuum condition is maintained at high vacuum level. For the vacuum interrupter used, this force is $70 \pm 30 N$. If the force applied by the disc spring is approximately $120 N$, then the total closing force for the closed contacts is at least $160 N$, which will help achieve an extremely low contact resistance of the vacuum interrupter in closed operation.

Generally speaking, the larger this total closing force is, the lower the contact resistance.
However, this is also the force the actuator will overcome during ultra-fast opening operation. From this point of view, a larger force is undesirable, and some trade-off has to be made for this purpose.

For a conventional AC circuit breaker, a large closing force is required for the circuit breaker to remain its contacts closed under short circuit conditions because such high currents create a strong popping force tending to force the contacts apart, as well as to achieve larger actual contact area so as to reduce the magnitude of such a force. However, for ultra-fast hybrid circuit breaker with current limiting capability, the contacts does not see high magnitude of short circuit currents because of two reasons. First, the fast rising current will be commutated into a paralleled branch for switching off. Second, the circuit will be interrupted in as fast as less than a quarter cycle so that the prospective short circuit current is prevented in the circuit. These reasons benefit the design of the ultra-fast mechanical switch towards fast opening operations.

In open position, as marked 'O' in Fig. 5.5, it counteracts against the closing force on the
Table 5.4: Disc spring nomenclature

<table>
<thead>
<tr>
<th>Term</th>
<th>Symbol per DIN 2093</th>
<th>Symbol per Fig. 5.3</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer diameter</td>
<td>$D_e$</td>
<td>O.D.</td>
<td>[mm]</td>
</tr>
<tr>
<td>Inner diameter</td>
<td>$D_i$</td>
<td>I.D.</td>
<td>[mm]</td>
</tr>
<tr>
<td>Thickness</td>
<td>$t$</td>
<td>$t$</td>
<td>[mm]</td>
</tr>
<tr>
<td>Initial cone height without ground ends</td>
<td>$h_0$</td>
<td>$h$</td>
<td>[mm]</td>
</tr>
<tr>
<td>Free overall height in the initial position</td>
<td>$l_0$</td>
<td>$H$</td>
<td>[mm]</td>
</tr>
<tr>
<td>Spring load</td>
<td>$F$</td>
<td></td>
<td>[N]</td>
</tr>
<tr>
<td>Deflection</td>
<td>$s$</td>
<td></td>
<td>[mm]</td>
</tr>
</tbody>
</table>

movable contact due to the atmosphere pressure as mentioned above and stabilizes the movable contact in open position reliably when unexpected vibrations, such as seismic conditions.

Similar to the closed position, more reliable open operation is achieved with a larger opening force, which on the other hand will impede the movement to close the contacts. However, considering the closing operation sequence of a hybrid circuit breaker, ultra-fast closing of the mechanical switch is not as critical as the ultra-fast opening. Therefore, a larger opening force can be applied. Again, this force can be selected by adjusting the position of the disc spring.

During ultra-fast opening operation, the spring has to withstand the associated dynamic stress, and more importantly it has to achieve a stable open position by absorbing or damping out the kinetic energy in the overall moving mass.

At the first stage of the opening period, a repulsive force of several kN is generated by the actuator overcomes the load force of the disc spring, and very rapidly push the center part of the disc spring upside down while the disc edge is held by an external holder. This operation condition is not specified in standard DIN 3092 and is less explored. However, this is very important for the reliable ultra-fast operation of the mechanical switch.
At the second stage of the opening period, the movement has to be slowed and stopped by the disc spring as soon as possible. Once the disc spring reach position "C" and continues to deflect towards "P5" due to the inertia of the moving mass, the spring load tries to pull back the moving parts back to "C". If the moving mass has obtained excessive kinetic energy during acceleration for ultra-fast travel, this energy may be dissipated or absorbed in the form of resonance around the steady state position "C". For a moderate amount of kinetic energy, the moving mass may reach "C" smoothly without any over-travel. If on the other hand the moving mass has obtained too much energy, there is risk of re-closing.

5.7 Structural Design

The structural design in this paper focuses on the vacuum interrupter, the operating mechanism and the disc spring, and excludes the energy storage and control unit, which are all stationary parts that do not involve any mechanical movement. Future studies can take into account the size and weight of capacitor bank and control switch so the overall design is more compact.
5.7.1 The operating mechanism

Two coils are placed one above the other, and a copper disk sits in between with a steel made center shaft that goes through center holes on the coil holders. Each of the coil holder is shaped like a flat tank with a cover, and the coil is put into the tank. Between the coil and copper disk is the bottom layer of the tank. This layer has a certain thickness for two purposes: one is to provide insulation between the coil and the disk; the other is to withstand potential impact from the copper disk during closing operations.

5.7.2 The complete switch

As shown in the CAD rendering in Fig. 5.7, the structure of the fast mechanical switch is arranged in a way that the translation movement is vertical. In fact, each of the movable components allows movement that is in any direction as the gravity is insignificant compared to the driving force. On the other hand, although a single axis is employed here to reduce the moving mass and make the structure simpler and more robust, double axes with a lever shaft could also be used.

In the prototype, two coils sitting in coil holders are placed one above the other, with a copper disk in between. It is supported by a steel shaft that goes through the center holes on
the coil holders, and connects with the disc spring at one end, and the vacuum interrupter at the other end. All three parts are fixed to a rigid frame through several supporting rods. The vacuum interrupter is supported by two insulating plates, and the movable terminal is coupled to the steel shaft through an insulating rod.

The finished, generally cylindrical prototype is presented in Fig. 5.8. The diameter is 200 mm and the height is approximately 300 mm.

5.8 Experimental Evaluation - Mechanical Operations

The prototype has undergone approximately two hundreds switching operations. These tests provide reliability data and initial indication of durability. Consistent with the hybrid circuit breaker concepts, the interrupter was not energized. Since in such designs, the mechanical switch is not exposed to high voltage or arcing during operation, such tests are valid to study the mechanical operation transients.


5.8.1 Test setup

The test setup for the study of the mechanical switch features a reconfigurable capacitor bank, a set of powerful thyristors and diodes, and high resolution linear potential meter.

The capacitor bank, connected to a DC power supply as the charger, is composed of 0.5 mF, 1.1 kV film capacitors. With eight of such units, the bank can be configured from 0.0625 mF/ 8.8 kV to 4 mF/1.1 kV capacitor bank, which is versatile enough for our tests.

The control switches are made of disk type thyristors.

5.8.2 Opening operation

One of the most important function of the switch is to achieve a very rapid opening operation; Fig. 5.9 shows such an operation. With a 2 mF capacitor bank pre-charged to 300 V, a 4.5 kA current pulse is injected into the driving coil which accelerates the moving parts in the first few hundreds of microseconds. The initial parting of the contacts happens at approximately 300 us after the trip signal is commanded. The moving mass then travels at an approximately constant speed of 1.3 m/s. The gap is 1 mm at 1 ms and 2.2 mm at 2 ms.

If the vacuum interrupter is able to withstand 20 kV with a 1 mm gap, then the hybrid circuit breaker can potentially limit and switch off fault current in a 15 kV class distribution system within 2 ms.

The target was opening of 2 mm within 1 ms. The tests conducted so far indicate that this should be possible by precharging the capacitors to 500V, instead of 300V. This belief is based on comparing modeling results at 300V and 500V, and the good correlation of tests and model at 300V shown in Section VII.

5.8.3 Closing operation

Even though closing speed is of less concern in terms of the overall protection speed, it does have some effect on the thermal transient in the high voltage semiconductor switch, since the semiconductors need to conduct current first before the mechanical contacts are fully closed.
The closing coil is different from the opening coil in the conductor size and the number of turns for this prototype; and the pre-charged voltage is different as well.

In Fig. 5.10, it takes 10 ms for the movable contact to reach the closed position and some more ms for bouncing. The bouncing is because of inefficient damping of the closing movement in this initial prototype.

5.8.4 Operation reliability and repeatability

The reliability of circuit breakers is of special importance since the circuit breakers secure the power systems against faults. The prototype has therefore been tested under repetitive operations as a means to validate its operation reliability. Ten repetitive opening operations as well as closing operations are shown in Figs. 5.11 and 5.12, respectively with the displacement versus time curves. The switch openings and closings were scheduled for approximately every ten minutes.

The test results show that the switch features almost identical opening travel curves when repeatedly driven by the capacitor bank pre-charged to the same voltage (360 V), and the switch
can open to a gap of 1.3 mm in the first 1 ms and a gap of 3.1 mm in the first 2 ms. Slightly more variability is observed during closing strokes, attributed to varying initial conditions, such as exact disc spring pre-load.

5.9 Validation and Modification of the FEA Model

In the experimental set-up, certain deviation from measurements occurred since the multi-physics FEA simulation only considers the dimensions of the coil and the plate, and all other parameters are lumped. With the measurements, the authors were able to identify missing details that affect the real performance, and then integrate them into the model for further analysis as well as for second generation design.

In the multi-physics model, there are two parts involved to calculate the electromagnetic transients. The first part is the lumped circuit domain consisting of the components such as capacitors and their equivalent series resistance, control switches, and stray parameters. The second part is the coil and moving mass in the finite element domain. The original model
shown in Fig. 5.13 included the stray resistance, but not the stray inductance. To match the test results, the lumped circuit are modified based on the information from the discharging current while the FEA domain component remains the same. As shown in Fig. 5.14, additional inductances are inserted, with values derived from the frequency and damping ratio of the rising and falling of the discharging current. With such modifications, the simulated transients match very well with the measured transients (Fig. 5.16). This also points to the need for a careful layout design, in the case of Thomson coil, as the lead cable inductance cannot be neglected compared to the inductance of the coil.

5.10 Experimental Evaluation - Electrical Operations

Besides the fast mechanical operations, the electrical performances during both steady states and transients are important. In this section, the measurement of contact of resistance is given. A low contact resistance is obtained even with moderate holding force from the mechanism.
5.10.1 Contact resistance

In a fast acting mechanical operating mechanism, if an external holding mechanism is employed, it has to be released in order to open the switch which will potentially slow down the opening operation. In our case, the disc spring itself is used as the holding mechanism, and the force provided to hold the contacts can be derived from Fig. 5.5 and the exact deflection of the disc spring in close position. The maximum holding force is obtained at P1.

5.10.2 Voltage withstand capability

The dynamic voltage withstand capability is tested in Chapter 7 on the hybrid circuit breaker testing. In the test, a voltage is applied to the vacuum interrupter after about 1 ms since the triggering of SCR switch. And the mechanical switch is to withstand the transient overvoltage from the system so that the interruption by the hybrid circuit breaker can be successful.
Figure 5.12: Repeatability of closing operations.

Figure 5.13: The model before modification.

Figure 5.14: The modified model.
Figure 5.15: Opening speeds at different driving voltages.

Figure 5.16: Modified simulation and measured results.
Figure 5.17: Modified simulation and measured results.

Figure 5.18: Modified simulation and measured results.
Active damping is a method to stop the acceleration and movement of the moving part so that the over travel is limited or eliminated. In this way, excessive kinetic energy of the moving contact is damped away and it is easier to be secured at the steady state positions.

6.1 Reclosing issue with passive damping mechanism

The general issue addressed in this paper is the design of effective, reliable damping mechanisms to absorb the kinetic energy due to fast opening. Mechanical means are effective, but need to be tuned to the energy imparted to the system during opening. Not enough damping can lead to damage, and too much generates bounce and long effective travel time. If the bounce is large enough, the system recloses (opening failure). Therefore, a fixed damping can actually limit the opening energy and lengthen the travel time, by forcing the designer to use a level of energy below that which will lead to bounce. This was observed during initial tests of a prototype switch (shown in Fig. 5.8). In order to illustrate this, Fig. 6.1 shows a successful opening with a capacitor bank that is pre-charged to 400 V: the displacement curve is linear, overshoots, and finally settles at a steady state open position. When driven by 420 V, however, see Fig. 6.2, the travel is initially faster, but at the end of the travel and following the overshoot the switch does not stay at a steady state position; instead, it bounces back towards the closed position and the
opening operation fails. The specific mechanism used in the experiments used non-linear disc springs (see [4] for a more detailed description of the design). Other mechanisms are possible [104, 105, 53, 106], but all are expected to suffer from the same limitation due to their being set at the design stage, with no feedback control possible. With damping disc springs, a few factors can affect the damping process, such as:

1. The kinetic energy of the moving mass. Most of the energy is to be absorbed by the disc spring.

2. The non-linear load-versus-deflection characteristic of the disc spring (see [4]) and how much energy the disc spring can absorb. The disc spring provides holding forces both at the open and closed positions which correspond to different operation points on the load-versus-deflection curve.

3. The allowable over-travel during opening. Two components limit this over-travel range: the vacuum interrupter, and the disc spring. A longer over-travel results in larger sizes for both components, and therefore the overall size of the switch assembly.

Figure 6.1: Successful opening driven by 400 V.
6.2 Proposed active damping for Thomson coil actuated switches

This paper proposes an active damping method that utilizes the Thomson coils of such an actuator and does not require extra mechanical complexities in structure and design.

When the mechanical switch is to open, a large amount of energy is dumped into the opening coil, part of which is transferred to the movable mass as kinetic energy for acceleration. In the proposed method, as the fast opening is completed and the required gap is obtained, the closing coil is energized and used as a damping coil to generate a reverse, braking force which slows down the movement. Then the disk spring can easily handle the remaining kinetic energy and secure the moving parts in the open position.

Work on a similar concept was recently published [107] indicating that others working on the issue of DC current breaking are facing the same difficulties. The present paper adds to the literature a comprehensive parametric study as well as additional experimental investigations confirming the validity of the concept, including its potential for further shortening travel times.

The approach is developed here in the context of repulsion coils. It can be extended, at least in principle, to any actuator with two (or more) coils acting in opposite direction. Some work in that area was done, for instance, on actuators with permanent magnets [108, 109, 110].

The research was carried out first by comprehensive transient finite element method (FEM) simulation, complemented by experimental evaluation.

The FEM modeling includes different physics (electromagnetic, mechanical, and thermal),
see Fig. 6.3. The mechanical actuator is designed for a 630 A prototype at medium voltage range (15-50 kV). The geometry is shown in Fig. 6.4. Two typical snapshots of the simulated transients are presented in Figs. 6.5 and 6.6 to illustrate the eddy currents induced in the conductive copper plate upon the energization of the opening coil and the damping coil, respectively.

6.3 Design of the active damping control

The general principle of active damping was presented in Section III. This section addresses how to design the damping control, or in other words when and by how much the damping coil should be energized. For a given pulse of the opening coil, there are a few variables in the
damping pulse that can be changed to achieve the best performance for a given design of a FMS. They correspond to the timing, magnitude, and shape of the damping pulse, the magnitude and shape being controlled by the capacitance and voltage of the capacitor bank exciting the damping coil. If the same capacitor bank is used for both opening and closing operation, as is preferable for simplicity and to minimize cost, it is also the same for the damping operation. Therefore timing is the most convenient parameter to affect the damping performance. Voltage and capacitance may be used as additional degrees of freedom, if their impact on performance justifies the extra complexity.

Figs. 6.7 and 6.8 illustrate the active damping effects, as calculated by transient FEM modeling when the braking coil is energized at different times, with the same voltage and capacitance. Referring to Fig. 6.7, a negative force accelerates the moving mass, starting at time 0. Then, a positive force later dampens the movement, starting at time 2 ms or later (several model runs are superimposed on the same graph, all starting with the same opening pulse). Fig. 6.8 shows the corresponding displacement (solid traces) and velocity (dashed curves).

With a capacitor bank of 2 mF pre-charged to 400 V, the actuator is accelerated to 2.6 m/s (Fig. 6.8). At 2 ms, the gap in the switch reaches 4.5 mm which can withstand 60 kV. A sweep of delay times from 2.0 ms to 3.0 ms is presented in Figs. 6.7 and 6.8, and the following
observations can be made:

1. Energizing the braking coil has an immediate effect to dampen the opening movement. Braking therefore should not be initiated before the specified gap and opening time are reached, 4.5mm/2 ms in this case.

2. The later the damping coil is energized, the closer the disk becomes to the damping coil and therefore the damping force increases. Conversely, with shorter delays, the disk may be too far for the damping coil to have any substantial effect, the disk being out of range, so to speak. The largest peak damping force was obtained with a 3 ms delay. It is 160 percent that with a 2 ms delay. There is therefore an opportunity for optimization, with later pulses being more powerful, but intervening farther in the travel. Fig. 6.8 shows when the damping force starts to operate, and also shows the position at which the disk comes to a stop.

3. An earlier damping pulse results in a weaker force and takes a longer time to reduce the kinetic energy of the moving mass. But the travel is limited to a smaller range (the disk stops at position 6 mm at time 4 ms).
4. A later damping results in a stronger force, takes a shorter time to reduce the kinetic energy of the moving mass. However, the movable contact tends to travel further (7.7 mm at 4 ms).

![Active damping with different delays](image)

Figure 6.7: Driving force (from 0 to 2 ms) and damping forces (from 2 to 4 ms), simulation results.

## 6.4 Experimental test of active damping

Experimental tests were performed on a Thomson coil actuated fast mechanical switch to verify the approach and the FEM model. These results provide additional validation of both the calculated parameters of active damping, and the interactions that occur between the repulsion coils and the conductive disc.

### 6.4.1 Test Setup

A prototype of a Thomson coil actuated fast mechanical switch and associated driving mechanism was modified to test active damping in a laboratory setting. More details regarding the mechanical switch can be found in [111]. The closing coil was used as the damping coil; two ca-
Figure 6.8: Speed and displacement curves corresponding to Fig. 6.7 forces, simulated results.

Capacitor banks of the same capacitance were independently controlled by two thyristor switches to energize the opening coil and the damping coil. The physical setup is shown in Fig. 6.9.

Figure 6.9: Test setup of the active damping for a Thomson coil actuated fast mechanical switch (safety enclosure removed for picture).

The test setup allows incremental variations of the opening coil voltage, damping coil voltage, and trigger delay between the opening and damping current pulses. Testing has been conducted using the parameters listed in Tab. 6.1. Fig. 6.10 is a graph presentation of which
combination of parameters led to a successful opening, and which led to reclosure (opening failure).

Table 6.1: Opening voltage, damping voltage, and damping delay tested.

<table>
<thead>
<tr>
<th>Opening voltage (V)</th>
<th>Damping voltage (V)</th>
<th>Damping delay (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>355</td>
<td>322</td>
<td>3.0</td>
</tr>
<tr>
<td>370</td>
<td>345</td>
<td>2.8</td>
</tr>
<tr>
<td>385</td>
<td></td>
<td>2.6</td>
</tr>
<tr>
<td>400</td>
<td></td>
<td>2.4</td>
</tr>
<tr>
<td>415</td>
<td></td>
<td>2.2</td>
</tr>
<tr>
<td>430</td>
<td></td>
<td>2.0</td>
</tr>
</tbody>
</table>

6.4.2 Contribution of opening voltage

The impact of opening voltage for a fixed damping delay (either 2 ms or 3 ms) is shown as displacement curves in Figs. 6.11 to 6.14. Also shown in the figures, for reference, is a trace corresponding to the current pulses in the opening and damping coils. The force exerted on the movable mass for opening and therefore the acceleration of the opening contacts are controlled through the opening voltage applied to the opening coil. Increasing this opening voltage and therefore the magnitude of the current to flow through the opening coil, results in higher speeds being achieved during opening operation. However this also results in greater kinetic energy that
must be damped out of the system.

The variable voltage operations show that 3.0 ms damping is adequate to prevent reclosing of all test voltages as shown in Figs. 6.13 and 6.14. Given that the opening voltage was varied from 355 V to 430 V, this indicates a very favorable robustness for the system. That is, the system is able to guarantee a successful opening over a wide range of parameters, an important consideration for a device that is expected to perform reliably over a long period of time in varying environmental and other conditions.

With a shorter delay (damping pulse starting at 2 ms, Figs. 6.11 and 6.12), opening fails (large bounce leading to reclosure) if the damping pulse is too strong, see for instance traces 415 V and 430V in Fig. 6.11. This is primarily due to the distance from the damping coil at time of current flow. At 2.0 ms, the conductive disc is not within an effective range of the damping coil and cannot transfer enough kinetic energy to the damping coil. The excess kinetic energy then remaining in the moving mass is too large for the disc spring to absorb, resulting in under-damping and eventual rebound, or reclosing of the switch.

Figure 6.10: Test results performed with an active damping voltage of 322 V.
6.4.3 Contribution of damping voltage

The effect of the damping voltage is shown in Fig. 6.15. Within the range of 322 V to 370 V damping voltages, the system opened the contact successfully. Further, it can be observed that the damping voltage has a significant impact on the amount of overshoot.

In terms of design, the damping coil is the same used for closing the actuator after the fault has been cleared. It appears that it may be desirable to have two different voltage levels in the design: For normal closing operation, the voltage should be smaller, simply large enough to close the switch reliably and avoid slamming and damage. However, higher closing coil voltages may be preferable for damping operations.

Having two operating voltages for this coil, one for normal closing and one for damping the opening pulse can be implemented with no additional complexity to the physical switch or driving mechanisms.

6.4.4 Contribution of damping pulse timing

How the time delay affects the damping transients is shown in Figs. 6.16 and 6.17.
In both cases of 322 V and 355 V damping voltages, a shorter pulse delay (comparing 2 ms with 3 ms) would generate a slightly higher overshoot in the traveled distance and relatively larger oscillation magnitudes later on. This is because at 2 ms the moving disk had not yet arrived in the most effective region for the damping coil to absorb the kinetic energy. However, the length of damping period for an early damping pulse is longer than that of a late one, which is why the speed are both decelerated to approximately 1.6 m/s for the 2 ms and 3 ms delay with 430 V opening voltage and 322 V damping voltage as shown in Figs. 6.18 and 6.19.

It is interesting to note from Figs. 6.18 and 6.19 that with increased opening voltage, the effectiveness of the damping pulse with the same voltage and delay is increased. This is because a higher opening voltage drives the moving mass closer to the damping coil within the same period of time. Therefore, the design and optimization of the damping pulse would closely depend on driving conditions for opening and the spacing among the coils and the disk.
Figure 6.13: FMS motion for various opening voltages, with 3.0ms damping delay and 322 V damping voltage.

6.5 Conclusions

A novel active damping mechanism has been proposed to address the reclosing issues observed during high speed operations of Thomson coil actuated fast mechanical switches. The concept has been verified by a comprehensive transient FEM model based on coupled multiphysics involved in the operation, and with validation from experiments carried out on a DC breaker prototype.

An important contribution of this paper is that active damping not only helps absorb kinetic energy and minimizes the side effects of high actuator speed. It also makes it possible to select operating parameters that lead to faster, yet reliable, operation.

The evaluation of different damping delays for a particular design has been presented. It is found that earlier damping pulses result in weaker damping forces while later damping pulses generate stronger forces because the disc and the coils are closer to one another at the onset of the braking pulse. Optimized delay would depend on the design specifics, including the layout of the coils and the moving disk, as well as the disc spring characteristics.
Figure 6.14: FMS motion for various opening voltages, with 3.0ms damping delay and 345 V damping voltage.

Figure 6.15: FMS motion for various opening and damping voltages, with 3.0 ms delay.
Figure 6.16: FMS motion for various damping pulse timings with 430 V opening voltage and 322 V damping voltage.

Figure 6.17: FMS motion for various damping pulse timings with 430 V opening voltage and 345 V damping voltage.
Figure 6.18: FMS velocity pattern for various opening voltages, with 2.0 ms damping delay and 322V damping voltage.

Figure 6.19: FMS velocity pattern for various opening voltages, with 3.0 ms damping delay and 322V damping voltage.
Chapter 7

An Ultra-fast MV Hybrid Solid State DC Circuit Breaker

This chapter presents some test results of an integrated medium voltage hybrid DC circuit breaker. The hybrid circuit breaker consists of a high voltage semiconductor switch that actually turns off current as well as a low voltage semiconductor switch that commutates current from mechanical switch to the high voltage semiconductor.

The voltage rating of the hybrid circuit breaker depends on both the transient voltage withstand capability of the high voltage semiconductors and the mechanical switch. This voltage level is clamped by the MOV in parallel with them. Depending on the specific hybrid scheme used, the transient voltage build-up could be different. Usually the voltage rating of the semiconductor could be more likely the limiting one.

7.1 Introduction

The testing methods of an ultra-fast hybrid DC circuit breaker differ from the ones used for AC circuit breakers. One of the most distinguishing difference is that, the current interruption between the mechanical contacts a DC circuit breaker is not associated with a fast rising
forthcoming TIV, and even later on there is a TIV across these mechanical contacts, the instance moment and the value of the voltage can be changed by configuring the hybrid DC circuit breaker. Unlike the case of conventional AC circuit breakers, the waveform of TIV is mostly expressed by the parameters of the systems and the circuit configuration at the moment of arc extinction.

7.2 Operation Principle

The topology and operation principle of the hybrid DC circuit breaker which incorporates a low voltage auxiliary breaker as the commutating switch are explained first, as these are important to establish the design guidelines for the hybrid circuit breaker.

7.2.1 Topology

There are four primary components for current conducting, commutation, and interruption, which are shown in Fig. 7.1: an ultra fast mechanical switch (FMS), a low voltage MOSFET switch as the auxiliary breaker (AB), a SiC ETO as the main breaker (MB) and a stack of

Figure 7.1: Hybrid DCCB diagram.
MOVs. Secondary devices not shown include digital controller and current sensors for control and protection purposes. Compared to SiC device based solid state circuit breaker in [112], the hybrid schemes is a further improvement to reduce total power losses [5].

### 7.2.2 Conduction

In normal conducting, the mechanical switch and the MOSFET connected in series carry the current. So the total loss is the sum of both. For mechanical switches, the loss is mostly caused
by contact resistance in the interrupter, which is normally less than 100 uΩ for a medium voltage interrupter. The conduction loss of the MOSFET can be reduced to less than 1 mΩ by using advanced low voltage power MOSFET devices.

### 7.2.3 Opening

Once overcurrent is detected, the hybrid DC circuit breaker is commanded to trip. The current interruption process is shown in Figs. 7.4 to 7.6. First, the auxiliary breaker is turned off to drive current to the main breaker path, which takes around 10 us depending on AB selection and AB to MB loop design. In the next step, as soon as current commutation is finished, the fast mechanical switch opens in a zero current, almost zero voltage, arcless condition. This simplifies the mechanical switch design and elongate its lifetime. After a few µs and there is enough opening gap between contacts, the main breaker is allowed to turn off its current. Using SiC ETO devices, it takes less than 10 us to switch off 100 A. When it transits from conduction mode to blocking mode, its impedance increases rapidly to hundreds of MΩ.

### 7.2.4 Closing

The mechanical switch has asymmetrical operation speed requirement on the opening and closing operations. During opening, longer operation time means larger final current to interrupt, which requires higher interruption capability of the main breaker and energy absorption capability of the MOV. This increases not only the associated cost but also the system complexity. Therefore closing function is not a major concern and can be closed by closing the MB first and then FMS and AB. This way the closing of the FMS is also under zero voltage condition.

### 7.2.5 Commutation analysis

Commutation can be done by either a mechanical vacuum switch or a semiconductor switch. The following analysis will help explain how they perform differently in later experimental results.
Figure 7.4: AB and FMS conduct current in normally operation.

Figure 7.5: To trip, AB and FMS open, current is commutated to MB.

Figure 7.6: MB turns off, MOV brings line current to zero.
Suppose the commutation begins at t=0 and ends at t=T, the total current remains $I_0$ as shown in Fig. 7.7 and 7.8. During the process, a voltage is established by the commutating switch represented by a constant voltage source as $V_1$ in Fig. 7.8 to overcome $V_2$ which is the voltage drop of the main breaker. The currents in both branches satisfy the following equations.

\[ I_0 = i_1 + i_2 \]  
\[ V_1 + L_1 \frac{di_1}{dt} = V_2 + L_2 \frac{di_2}{dt} \]  
\[ i_1 \] is the current in the bypass conducting branch with $L_1$ as the associated stray inductance, while $i_2$ is the current in the main breaker branch with $L_2$ as the associated stray inductance. Solving the equations, the total commutation time $T$ and the energy to be absorbed $E$ by the commutating switch are as follows:

\[ T = \frac{L_1 + L_2}{V_1 - V_2} I_0 \]  
\[ E = \frac{(L_1 + L_2) I_0^2}{2} \]

From Equations (7.3) and (7.4), one can see that current transfer is driven by the voltage of the commutating switch minus the main breaker forward voltage, through a total inductance of the loop. And the energy is just the magnetic energy stored in the loop inductance. These two equations give quantitative guidelines for designing the commutating switch and also indicate that a compact mechanical design is preferred for less inductance.

Figure 7.7: Current commutation.
7.3 High Voltage Main Breaker

In this study, the SiC ETO device is used as the high voltage main breaker for the following reasons:

1. SiC material has a very wide band gap that makes it possible as well as practical to fabricate devices up to more than 15 kV. A 15 kV SiC ETO device is used in the prototype.

2. A thyristor device is favored here due to the high surge current capability and low conduction losses. Though the device is design for 50 A continuous current, the turn off capability is verified up to more than 200 A at 7 kV.

3. The advantageous turn off mechanism makes the drive circuit very simple, and the device is more like voltage controlled.

Aiming at the 12.47 kV distribution power systems, 10 kV voltage withstand capability for the hybrid SSCB is required. In our case one single 15 kV SiC ETO device is enough to withstand such a voltage. Relatively lower cost silicon high voltages diodes forms a diode bridge that reduces the number of SiC devices and therefore lower the cost. Using high voltage SiC devices obsoletes series connection of multiple device, and their complex and bulky balancing networks, therefore the structure is simplified and the reliability is improved [5].
7.3.1 Forward Characteristics

The forward voltage drop is less than 5 V conducting 50 A for a 1 cm\(^2\) device according to its I-V curve (see Fig. 7.9), and is approximately 6 V at 200 A. As a diode bridge is used here to reduce the number of SiC devices, additional 15 V drops across the diodes, which adds up to 21 V of total voltage drop. This voltage drop will be too high in a pure solid state breaker but does not directly associate with power losses in hybrid circuit breaker because during normal operation the current flows through the FMS and AB path.

Though this voltage drop does not directly cause excessive power losses in hybrid circuit breaker, it does affect the driving voltage requirement for the commutating switch, which will be further explained in the next section. Therefore lower forward voltages are still preferred and the SiC ETO has really low voltage drop in high current density applications compared to the case with series connected Si devices.

![Figure 7.9: IV curve of 15 kV SiC p-GTO.](image-url)
7.3.2 Turn-off capability without snubber

The ETO has been tested under standard pulse test circuit. It is already proved by earlier investigations based on silicon devices that ETOs have superior switching capability under
snubberless switching conditions [113, 114], and are very suitable for circuit breaker applications [115, 116, 117, 118]. In Fig. 7.10, 123 A current is turned off at 6 kV by a single 1 cm² SiC ETO without any snubber circuit. It takes 2 us to switch off the current in the ETO device. The peak di/dt is 500 A/us; the peak dv/dt is 16 kV/us. The peak power reached exceeds 1.2 MW/cm². The large turn off SOA demonstrated is important to achieve high interruption capability using a small number of ETOs, and is an ongoing research topic by the authors group [112, 119, 120].

7.3.3 Turn-off capability with a snubber capacitor

To enhance the turn off capability of the SiC ETO device, a snubber capacitor is added considering that slower turn off of current in the semiconductor switch does not affect the operation speed of the hybrid circuit breaker. This allows the same SiC chip to turn off much higher current, and potentially reduces the total cost of the hybrid circuit breaker.

The snubber capacitor can be placed across the ETO as well as the diode bridge to limit the turn off dv/dt. However, if directly paralleled with the ETO, this capacitor is basically a DC capacitor. Once ETO is turned on, the capacitor is short circuited and stored energy may cause the ETO to fail. Though a RCD snubber circuit can prevent this unlimited discharging, it increases the complexity of the circuit and the number of high voltage semiconductor devices. Therefore, the capacitor is placed between the AC terminals of the diode bridge. In this way, by monitoring the voltage across the diode bridge, zero voltage turn on can be realized to protect the ETO device. To monitor the voltage, a resistive divider shown in Fig. 7.12 is used.

In Fig. 7.11, 250 A current is turned off at 7 kV within 3 us. It can be seen from the graph that the current in the device is immediately commutated into the snubber capacitor up switching off, followed by a voltage linearly rising at a rate limited by the capacitance. Using a 30 nF snubber capacitor, the dv/dt at 250 A should not exceed 8 kV/us. With a larger capacitor, the dv/dt can be limited to a even lower rate so that the voltage stress of the device is much alleviated, allowing it to turn off a even larger current. The snubber circuit is especially appreciated in applications such as circuit breakers because to cut off current in microseconds

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Figure 7.12: Voltage divider for zero voltage turn on.

is not preferred.

7.4 Inductive Interruption Test Circuit

To test a medium voltage circuit breaker at a university lab is not a trivia task, because usually the required power rating for the test of circuit breaker is very high considering that the short circuit current ratings could be as high as several tens of kA. Therefore, this subsection presents a low cost test circuit that can be used to test the inductive circuit interruption of fast acting medium voltage hybrid circuit breakers.

The best way to test a hybrid DC circuit breaker is through an inductive circuit interruption test because this is the actual condition that the DC circuit breaker operates.

7.4.1 Requirement of DCCB test

To test the function of circuit interruption of a DC circuit breaker, two capabilities needs to be verified: the DC current interruption in the switching device, and demagnetization of the line by the overvoltage clamped by the MOVs.
7.4.2 A low cost test circuit

The test circuit developed at the laboratory is shown in Fig. 7.13 that includes a low voltage high current power supply, an inductor, the device under test and a few high voltage diodes.

![Inductive interruption test circuit of the hybrid DC circuit breaker.](image)

The power supply provides sufficient current to the inductive circuit which stores sufficient magnetic energy which will be released during circuit interruption. The high voltage diodes are used to block reverse current which might cause damage to the power supply.

7.5 Discussion on the Test results

Results shown in Fig. 7.16 were from an inductive circuit interruption test. The operation sequence is marked in the graph together with the voltage and current transients. A 3.5 kV transient recovery voltage was observed across the hybrid circuit breaker when interrupting 24 A inductive load current. The whole interruption process takes less than 1.5 ms. Though the prototype should be able to interrupt higher current at voltage voltages, the testing capability
is limited by the facilities in the laboratory.

Such tests has verified the fast acting capability of the developed hybrid circuit breaker, which is essential for control and protection in DC systems. This is also beneficial to AC systems because current limiting and synchronous switching are made possible thanks to milliseconds operations.
Figure 7.16: Inductive interruption test circuit of the hybrid DC circuit breaker: voltage clamping.
Chapter 8

Design and Optimization of UFMS for High Voltage High Current Applications

In previous chapters, this thesis has designed, developed and tested a medium voltage level mechanical switch and hybrid circuit breaker based on the fast acting mechanical switch. It is expected that the actuator can also achieve high voltage and high current DC interruptions at high speeds. This chapter aims to design such a mechanical switch by first outlining a set of specifications, and then selecting appropriate components based on FEM simulations. Because of the long travel and heavy moving mass associated with high voltage high current applications, this chapter also evaluate scaling techniques and several different design to achieve a fast and reliable design.
8.1 Total interruption time and mechanical operation speed

8.1.1 Displacement and dielectric strength functions of time

As observed in both FEM simulation and experimental measurement, it is found that the mechanical opening of the mechanical contacts has a certain delay which is in the range of a few hundred of microseconds, and after that the opening speed is almost constant because the acceleration happens in the first period.

If the mechanical delay is assume almost twice the time for the LC circuit current to reach peak current, then the delay time can be denoted as half the period of the LC oscillation:

\[ t_d = T_{LC} = 2\pi \times \sqrt{LC} \times 1/2 = \pi \sqrt{LC} \quad (8.1) \]

in which, \( L \) is the total loop inductance of the driver circuit, the Thomson coil, and the parasitic inductance in between, while \( C \) is the total capacitance of the capacitor bank in the drive circuit. In other words, the delay is a function of the Thomson coil actuator and its drive circuit parameters.

After the opening delay, the speed is assumed constant, denoted as \( v \). The speed and the time delay are somewhat independent of each other, because the speed is also a function of the pre-charged voltage of the capacitor bank. Therefore the displacement as a function of time, \( t \), is:

\[
\begin{align*}
  d &= 0 & 0 \leq t \leq \pi \sqrt{LC} \\
  d &= v(t_M - 2t_d) & t \geq \pi \sqrt{LC} 
\end{align*}
\quad (8.2)
\]

Assuming that the dielectric strength is vacuum is 20 kV / mm, the dielectric strength in terms of the voltage that the switch can withstand at \( t \) can be expressed as:

\[
\begin{align*}
  V_d &= 0 & 0 \leq t \leq 2\pi \\
  V_d &= 20v(t_M - 2t_d) & t \geq 2\pi 
\end{align*}
\quad (8.3)
\]
This value of $t_M$ is a variable for the design and operation of the hybrid solid state circuit breaker, because the main breaker can be turned off at any moment and $t_M$ can be in a certain range. With a large value of $t_M$, the current decrease begins later, but because of the higher allowable clamped voltage, the current decrease rate can be faster. Therefore, to achieve the shortest total interruption, the selection of $t_M$ can be optimized.

### 8.1.2 Break time

The break time is defined by the Cigre Joint Working Group A3.B4.34 as the time interval from the instant the breaker receives the trip order and the instant when the current has been lowered to leakage current level (or below) [15], which is analogous to the AC breaker standard (IEC 62271-100, 3.7.135) [16].

![Current and voltage profiles of a hybrid DC circuit breaker with a commutating switch during interruption.](image)

Figure 8.1: Current and voltage profiles of a hybrid DC circuit breaker with a commutating switch during interruption.

To calculate the break time $t$, let $t_{CS}$ be the commutation time for the CS, $t_{FMS}$ be the FMS operation time, $t_{MB}$ be the MB interruption time, and $t_{MOV}$ be the time the current is brought
to zero by the MOV clamp voltage, then

\[ t = t_{CS} + t_{FMS} + t_{MB} + t_{MOV} \]  \hspace{1cm} (8.4)

In the equation, \( t_{CS} = t_2 - t_1 \) and \( t_{CS} \) is less than 100 us and is dominated by the commutation time of CS as the turn off delay is usually less than 1 us; \( t_{FMS} = t_3 - t_2 \) and it depends on the designed clamp voltage of the MOV and how fast the MS can open to a gap to withstand this voltage; \( t_{MB} = t_4 - t_3 \) which is the turn off time of the MB semiconductor switch and should be in us; \( t_{MOV} = t_5 - t_4 \) and it depends on the clamped voltage, the current at that moment and the line inductance.

Since \( t_d \) is a well predicted value for a given mechanical switch design which is about a few hundreds of microseconds, a commutation time shorter than this value can be easily achieved, and therefore the current commutation and trip of mechanical switch can overlap. In this case,

\[ t = t_{FMS} + t_{MB} + t_{MOV} \]  \hspace{1cm} (8.5)

On the other hand, the main breaker turns off in only a few microseconds, and therefore can be neglected.

Therefore, \( t_{FMS} \) and \( t_{MOV} \) takes most of the interruption time.

\[ t \approx t_{FMS} + t_{MOV} \]  \hspace{1cm} (8.6)

As \( t_{MOV} \) is more related to the system parameters, such as the system inductance and current, and also the designed clamp voltage, \( t_M \) should be optimized and it is one of the key parameters for the design and operation of the ultra-fast mechanical switch. Let us introduce the system voltage as \( V_S \), the system inductance as \( L_S \), and the line current to be interrupted as \( I \), then the total time to bring line current to zero by the counter voltage clamped by MOV
Table 8.1: Baseline value for optimization of total interruption time.

<table>
<thead>
<tr>
<th>$V_S$</th>
<th>Nominal DC voltage</th>
<th>100 [kV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_S$</td>
<td>System inductance</td>
<td>100 [mH]</td>
</tr>
<tr>
<td>$i$</td>
<td>Interrupting current</td>
<td>2000 [A]</td>
</tr>
<tr>
<td>$t_d$</td>
<td>Opening delay</td>
<td>0.2 [ms]</td>
</tr>
<tr>
<td>$v$</td>
<td>Openg speed</td>
<td>4 [mm/ms]</td>
</tr>
</tbody>
</table>

can be estimated as:

$$t_{MOV} = \frac{i}{(V_d - V_S)/L} = \frac{L_S \times i}{V_d - V_S}$$  \hfill (8.7)

Here, the line current is assumed constant during the operation of the circuit breaker.

Substitute Equations 8.3, 8.7 into Equation 8.5, the total interruption time as a function of $t_{FMS}$ is:

$$t \approx t_{FMS} + \frac{L_S \times i}{20v(t_{FMS} - 2t_d) - V_S}$$ \hfill (8.8)

Given the values for the system and mechanical switch variables in Tab. 8.1, the following curve of total interruption time can be obtained.

With parameters shown in Table. 8.1, the optimal turn off time of the main breaker semiconductor switch can be found at 3 ms to achieve the shortest total interruption time, which is 4.6 ms in this case.

If the constant opening speed $v$ varies, a family of curves can be obtained as shown in Fig. 8.3, assuming all other variables the same. From Fig. 8.3, it is concluded that, the faster the mechanical switch operates, the shorter the mechanical operation time should be in order to minimize the total interruption time. For example, for a system voltage of 100 kV, line inductance of 100 mH and line current of 2000 A, the mechanical switch with a speed of 6 m/s should turn off high voltage solid state switches at 2.3 ms in order to achieve a minimum interruption time of 3.6 ms; with a speed of 3 m/s, the best timing is 3.6 and the total interruption time is
Figure 8.2: Diagram of the Thomson coil actuator based fast mechanical switch.

5.6 ms.

Figure 8.3: Total interruption time as a function of $t_{FMS}$ at different speeds.

If the opening speed is held constant (4 m/s), the system voltage is varied from 60 kV to 120
kV on the other hand, then the optimal mechanical operation time and the total interruption time can be found in a family of curves shown in Fig. 8.4. It is observed that, with increased system voltage levels, the optimal mechanical operation time is extended.

![Total interruption time as a function of $t_M$](image)

Figure 8.4: Total interruption time as a function of $t_{FMS}$ at different system voltages.

### 8.2 Specifications of the high voltage and high current design

#### 8.2.1 Rated voltage

High voltage is generally considered a voltage level above 50 kV. 72.5 kV (rms value) is a typical voltage level in AC systems, which gives a peak value of 89 kV. In the thesis, 100 kV DC voltage is considered as high voltage DC though there is no definition of the lowest value for high voltage DC voltages. Therefore, 100 kV is assumed as the system source voltage, and considering a certain overvoltage factor of 2, the mechanical switch needs to withstand 200 kV at the moment of interruption. With vacuum interrupters used, this is equivalent to 10 mm. To ensure that the opening speed of the first 10 mm is maximum, the vacuum interrupter should
Figure 8.5: Total interruption time as a function of $t_{FMS}$ with different currents.

have at least 20 mm which would allow the later 10 mm travel for declaration.

8.2.2 Rated current

Rated current levels of high voltage circuit breaker are typically 630 A, 1250 A, 3150 A, etc, based on IEC standard [121]. In this chapter, the design target is a 1250 A circuit breaker, and therefore the design employs a vacuum interrupter rated for 1250 A. A larger current rating means a heavier moving mass, and also a higher holding force for steady state positions, especially the closed position. The reason is two fold: first of all, a lower contact resistance is needed so that high current does not cause excessive heat in the vacuum tube; secondly, a sufficient holding force is necessary to keep the contacts closed during high surge current, which can cause a large repelling force between the contacts, or during unexpected vibrations such as earthquakes.
Table 8.2: Specifications of the ultra fast mechanical switch.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value 1</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated voltage</td>
<td>100</td>
<td>[kV]</td>
</tr>
<tr>
<td>Transient recovery voltage (TRV)</td>
<td>200</td>
<td>[kV]</td>
</tr>
<tr>
<td>Rated current</td>
<td>1250</td>
<td>[A]</td>
</tr>
<tr>
<td>Gap to withstand TRV</td>
<td>10</td>
<td>[mm]</td>
</tr>
<tr>
<td>Time to open the gap</td>
<td>2</td>
<td>[ms]</td>
</tr>
</tbody>
</table>

8.2.3 Operation speed

Consider the increased displacement and payload requirement for the actuator, the design is very challenging. The time for the mechanical switch to open and travel a gap that can withstand the aforementioned TRV is set to 2 ms, which including the opening delay, the acceleration period and constant velocity travel time. Therefore, the mechanical requirement is to achieve 10 mm travel within 2 ms.

8.2.4 Break time

To calculate the total interruption time, inductances of the transmission lines and current limiting reactors is estimated as 100 mH, then 100 kV give 1 kA/ms current decreasing rate. Therefore, if 2000 A is to be interrupted the total interruption time is estimated as:

\[ T = T_{FMS} + T_{MOV} = 2ms + \frac{2000A}{1kA/ms} = 4ms \] (8.9)

Note that in Equation 8.9, the solid state switching times which are neglected.

8.3 Vacuum interrupter parameters

The selected vacuum interrupter is VTF52401, which has the parameters listed in Table. 8.3. The vacuum interrupter is design for 40.5 kV AC systems with 20 mm contact stroke (gap),
which can withstand approximately 400 kV. Therefore, its stroke makes it sufficient for a hybrid
circuit breaker rated at 100 kV.

Figure 8.6: A loglog plot of the breakdown voltage, $UB$, as a function of contact gap in vacuum [1].

Figure 8.7: A linear plot of the breakdown voltage, $UB$, as a function of contact gap in vacuum [1].
Table 8.3: Vacuum interrupter parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value 1</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contact stroke</td>
<td>20 ± 1</td>
<td>mm</td>
</tr>
<tr>
<td>Basic Impulse Level (BIL)</td>
<td>185</td>
<td>kV</td>
</tr>
<tr>
<td>Rated current</td>
<td>1250</td>
<td>A</td>
</tr>
<tr>
<td>Rated peak current</td>
<td>63</td>
<td>kA</td>
</tr>
<tr>
<td>Contact resistance (at rated contact holding force)</td>
<td>30</td>
<td>µΩ</td>
</tr>
<tr>
<td>Contact force from atmosphere pressure</td>
<td>150 ± 40</td>
<td>N</td>
</tr>
<tr>
<td>Holding force required when open</td>
<td>210 ± 50</td>
<td>N</td>
</tr>
<tr>
<td>Holding force required when closed</td>
<td>2000</td>
<td>N</td>
</tr>
<tr>
<td>Moving mass</td>
<td>1.3</td>
<td>kg</td>
</tr>
</tbody>
</table>

According to the function in Fig. 8.6:

\[ U_B = 58d^{0.58} \]  

(8.10)

Substitute \( d=10 \) mm, we get:

\[ U_B = 58 \times 10^{0.58} = 220kV \]  

(8.11)

A commercially available 20 mm vacuum interrupter has provided good information regarding the moving mass associated with the targeted high voltage high current applications, which is one of the most important parameters for the mechanical design.

It is noted that the increase of current and voltage ratings has resulted in a weight increase from 0.5 kg for 630 A, 10 mm VI to 1.3 kg for 1250 A, 20 mm VI. This is reasonable because large current carrying capability requires a large contact area, and a long stroke vacuum interrupter has a long shaft. Both factors adds to the total weight.
8.4 Thomson coil actuator

A Thomson coil actuator to meet the requirement as listed in Table 8.2 are achieved by a design shown in Figs. 8.8 and 8.9.

As the payload is much heavier, more energy is needed to be converted into the kinetic energy of the moving part. In this case, the pre-charge voltage of the capacitor bank is increased to 800 V rather than only 400 to 500 V. The capacitance is kept the same.

As the operation time target is 2 ms in stead of 1 ms, more acceleration time is allowed, meaning a larger coil with a larger inductance is allowable. In the meanwhile, the capacitor does not have to be reduced to a smaller capacitance with higher voltage. In the design, there are 19 turns of wires in the coil with a current and force rise time of about 170 us.

A summary of the key parameters of the actuator design is listed in Table 8.4, together with the displacement and the opening speed.

![Figure 8.8: A design that meets 1300 g payload, 2 ms operation time target.](image)

More opening operation transients are presented in Figs. 8.11 to 8.13. The average displacement of the moving parts and the velocity calculated based on the displacement are plotted in
Table 8.4: 1250 A, 100 kV, 2 ms design parameters of the Thomson coil actuator.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper disc OD</td>
<td>116 [mm]</td>
</tr>
<tr>
<td>Copper disc thickness</td>
<td>4 [mm]</td>
</tr>
<tr>
<td>Coil ID</td>
<td>12 [mm]</td>
</tr>
<tr>
<td>Coil OD</td>
<td>116 [mm]</td>
</tr>
<tr>
<td>Wire gauge</td>
<td>10 [AWG]</td>
</tr>
<tr>
<td>Number of turns</td>
<td>19</td>
</tr>
<tr>
<td>Gap between coil and disc</td>
<td>3 [mm]</td>
</tr>
<tr>
<td>Total moving mass</td>
<td>2.04 [kg]</td>
</tr>
<tr>
<td>Capacitance</td>
<td>2 [mF]</td>
</tr>
<tr>
<td>Pre-charged voltage</td>
<td>800[V]</td>
</tr>
<tr>
<td>Mechanical delay</td>
<td>170 [us]</td>
</tr>
<tr>
<td>Displacement at 1 ms</td>
<td>5.5 [mm]</td>
</tr>
<tr>
<td>Displacement at 2 ms</td>
<td>12.5 [mm]</td>
</tr>
<tr>
<td>Velocity</td>
<td>7 [m/s]</td>
</tr>
</tbody>
</table>
Figure 8.9: The 3D view of the design.

Figure 8.10: Operation transients of a design that meets 1300 g payload, 2 ms operation time target.

Fig. 8.11. The displacement and velocity have indicated that the approximation in Equations 8.2 and 8.3 is reasonable: the acceleration is finished mostly in the first few hundreds of mi-
croseconds, and the rest of the travel is at almost constant velocity. 7 m/s is achieved with this design; at 1 ms, the displacement is 5 mm and at 2 ms it is 12 mm.

From Fig. 8.12, the force peaks at about 170 us to a magnitude of 47 kN and dies down to 10 % at about 800 us. The accumulation of impulse also shows that after 800 us, the impulse does not increase significantly and reaches a steady state value of about 15 Ns. Based on the total moving mass given in Table 8.4, one can calculate the velocity as:

$$v = \frac{15 \text{ N}s}{2.04 \text{ kg}} \approx 7.5 \text{ m/s}$$ \hspace{1cm} (8.12)

which matches very well with the results shown in Fig. 8.11.

The other important consideration is the current stress during the discharge period that both the capacitor bank and the control switch has to handle. The instantaneous current value and the current squared integration have been plotted in Fig. 8.14. These are discussed in the following section to determine if the energy storage and control unit can meet the high transient
Figure 8.12: Force and impulse transients during operation.

Figure 8.13: von Mises stress transients during operation.

stress during discharges.
8.5 Energy storage and control

A capacitor bank with 2 mF that can withstand 800 V can be easily achieved. The capacitor units shown in Fig. 8.15 can withstand up to 1100 V.

The peak current is close to 9 kA with an equivalent duration of much less than 10 ms considering the decaying current profile. This value is within the 33 kA current surge capability of the thyristor used. On the other hand, the current squared integration over time is approximately $0.3 \times 10^6 \text{ A}^2\text{s}$, which is less than one tenth of its rated capability of $5.45 \times 10^6 \text{ A}^2\text{s}$ [122]. The stresses are also below the capabilities of a thyristor module (MCO600-22io1, 10 ms 12.8 kA, and $1.13 \times 10^6 \text{ A}^2\text{s}$) [123], which can be used for a more compact assembly design.

8.6 Disc spring

The disc spring design itself can be a separate topic that needs a through discussion as well, and can go beyond the scope of this work. However, this section will design the characteristics required for the ultra-fast mechanical switch to function well in both dynamic and static
operation conditions.

8.6.1 Popping force and holding force

The electromagnetic force generated between two contacts needs to be considered when designing the operating mechanism. This force is repulsive, sometimes called popping force, and therefore requires additional holding force to keep the contact in closed position. To illustrate the origin of this force, Fig. 8.17 shows the actual current distribution of a set of contacts.
If this force is sufficient to open the contacts and therefore an arc is formed, the arc can generate a large amount of energy because of the high current, which can cause damage or corrosion on the contact surface and significantly shorten the lifetime of the contacts.

![Current constriction at the actual point of contact](image)

Figure 8.17: Current constriction at the actual point of contact, [2] (Page 206).

A practical expression to estimate the popping force is given by Greenwood [124] (Page 137) as:

\[ F = 0.112 \times \left( \frac{I}{n} \right)^2 \text{ lb. per finger} \]  \hspace{1cm} (8.13)

\[ F = 0.445 \times 10^{-7} I^2 \text{ N} \]  \hspace{1cm} (8.14)

Equation 8.13 gives the force per finger; with a butt type contact design for vacuum interrupters, the number of fingers \( n \) equals 1. A curve is obtained based on this equation for a range of currents in Fig. 8.18.

Equation 8.14 is another way to estimate the popping force generated by a certain current, and the curve is plotted in Fig. 8.18 as well, which is very close the curve by Equation 8.13.

Holding force is provided by the operating mechanism to keep the contacts in closed position.
during operations when they are required to remain closed. Therefore the holding force should be larger than the popping force between contact at a certain range of currents. This current range is subject to the design of the circuit breaker.

In a conventional AC circuit breaker, the rms value of the short circuit current could be up to 63 kA, which can generate more than a thousand of newtons of force between contacts. This is why the VI has a required holding force of 2000 N as per Table. 8.3.

However, this is not the case for the fast acting, current limiting circuit breakers because they limit the prospective current to a much lower value. Neither it is the case for the DC circuit breakers meant for the protection in the voltage source converter based DC networks. For DC circuit breakers, it is anticipated that fault current would be limited within 10 kA [66, 80].

Fig. 8.18 has shown that, up to 10 kA, the popping force is less than 100 N. Therefore, this number would be compared to the force required to achieve a sufficiently low contact resistance. Whichever is larger would be used as the number to select and design the disc spring and its operation point.
8.6.2 Contact resistance and holding force

There is a natural force caused by the atmosphere applied to the contact of the VI, which is around 150 N as per Table. 8.3. This force alone would be enough to overcome the repulsion force between the contacts at a current up to 10 kA.

However, the VI’s datasheet also specifies that the contact resistance of $30\mu\Omega$ is obtained under an additional holding force of 2000 N.

8.6.3 Opening delay because of holding force

Before opening sequence, the contacts are pressed against each other by externally applied force from atmosphere and the operation mechanism, which is the disc spring in the presented design. Upon opening, the Thomson coil actuator is energized, and the repulsion force will overcome this holding force before acceleration of moving parts begins. Therefore, the larger the total holding force is, the later the acceleration begins.

Based on the operation transients of the actuator in Fig. 8.10, it takes less than 50 us for the opening force to overcome the 2150 N holding force. Therefore, 2000 N holding force does not significantly delay the response of the mechanical opening operation.

8.6.4 Holding force for open position

It is also important that the switch stays in open position even under harsh environment. Table 8.3 has specified a holding force of 210 N which is 60 N larger than the force from the atmosphere and can be used as a good design criteria.

Similarly, the holding force in opening position would delay the closing operation. It needs to be considered when choosing the operation points of the disc spring.

8.6.5 Desired characteristics of the disc spring

The load-deflection characteristics are given in Fig. 8.19, where a few important operation points are marked: C, C’, O, O’. Operation points C and C’ meet the holding force value of
2000 N in the closed steady state position; while O and O’ can provide about 210 N in the open steady state position. The arrows on the curve indicates the movement along the curve during the opening operation.

When the disc spring operates from the closed position, be it either C or C’, it first passes O’ but since the moving mass still has great momentum and the spring force at this point still helps accelerate the movement, the disc spring does not stay at this point; rather, it continues to travel past the point O, after which it will over-travel till a third regime where the spring force decelerate the movement by a very steep load-deflection curve.

The third regime dampens and stabilizes the spring back to the position O, at which the spring provides a small amount of force that is enough to balance the force from atmosphere, and therefore considered as the open steady state point.

From C to O, the distance is 13 mm, which is sufficient to withstand 200 kV voltage. As the VI allows a total gap of 20 mm, there is 7 mm available for over-travel and damping. With the
active damping mechanism integrated, the over-travel distance can be significantly shortened.

On the other hand, the point C’ can also be used as the operation point of the disc spring for the closed position. However, in that case, at the initial acceleration period, the actuator needs to do additional 8 J work more than starting the opening from point C. From Fig. 8.10, the estimated velocity achieved is 6 m/s and the moving mass is approximately 2 kg, which gives the total kinetic energy of 36 J. Therefore, additional 12 J work could undesirable slow down the acceleration substantially. Because of this, C is the preferred point rather than C’.

8.7 Conclusions

This chapter has investigated the possibility to identify an optimized opening timing for the switching components in a high voltage hybrid DC circuit breaker based on the topology in [66]. It is concluded that, for different system voltage, current to be interrupted, and the opening characteristics of the fast opening mechanical switch that is based on the Thomson coil actuator, there is an optimum turn off time for the high voltage semiconductor switch so that the total break time can be minimized.

A 100 kV, 1250 A, 2 ms ultra-fast mechanical switch has been proposed. A design based on Thomson coil actuator is given. The opening operation transients are simulated in COMSOL; important transients regarding the mechanical and electrical component and their stresses are presented and discussed. Dimensions of parts for the actuator, the selection of the vacuum interrupter, the energy storage and control unit are given. Consideration for the mechanical operations both during transients and at steady state positions are discussed. The characteristics desired from the disc spring are studied and a curve has been proposed.
Chapter 9

Summary and Future Work

9.1 Conclusions

In this thesis, a comprehensive FEA model has been established to analyze and design the Thomson coil actuator based ultra-fast mechanical switch. A medium voltage prototypes has been designed and developed. With test results, the FEA model has been validated to be accurate and helpful. In addition, the thesis has also made the following conclusions.

9.1.1 Design guidelines of the Thomson coil actuator based ultra-fast mechanical switch

The design guidelines for the Thomson coil actuator as the operating mechanism are derived from comprehensive multi-physics transient simulations and are summarized below:

1) The unidirectional circuit is better than a bidirectional circuit in terms of the operating speed of the mechanism. The components in both circuits used for evaluation have almost the same current and voltage ratings.

2) A device with higher voltage and lower capacitance but with the same stored energy generates higher and earlier peak current and peak force. This is preferred for high speed operation; but this also requires higher semiconductor device ratings.
3) To design a switch that is required to open within 1 ms, it is useful to design a Thomson coil and capacitor with a resonant frequency somewhat above 1 kHz (resonant frequency as defined by the capacitor bank and the coil inductance), such that the force peaks in the first quarter cycle, and then optimize the geometry accordingly.

4) Higher voltage or larger capacitance will drive the mechanism to a faster speed, but will add both mechanical and electrical stresses on the components.

5) Copper disks with thickness in the range of 2-5 mm result in almost the same operation speed; coils made with AWG 8-12 wires give almost the same operation speed. Therefore they are considered not sensitive in these ranges.

6) To achieve fast opening, the gap between disk and coil should be kept to a minimum. The disk and the coil outer diameters should be kept the same, which will give a better coupling between disk and coil.

9.1.2 Active damping method of the Thomson coil actuator based ultra-fast mechanical switch

A novel active damping mechanism has been proposed to address the reclosing issue observed during high speed opening operations of Thomson coil actuated fast mechanical switches. The concept has been verified by a comprehensive transient FEM model, and with validation from experiments carried out on a DC breaker prototype.

The evaluation of different damping delays for a particular design has been presented. It is found that earlier damping pulses result in weaker damping forces while later damping pulses generate stronger forces because the disc and the coils are closer to one another at the onset of the braking pulse. Optimized delay would depend on the design specifics, including the layout of the coils and the moving disk, as well as the disc spring characteristics.
9.1.3 Prototype and experimental results

A prototype has been designed and fabricated based on the above design guidelines and FEA simulations.

The prototype has been tested to verify its mechanical and electrical performances.

The mechanical switch is able to open to 1 ms gap within 1 ms; and it takes around 10 ms to close the switch. This asymmetrical operation speed fits the operation of the hybrid circuit breakers using high voltage semiconductors very well.

The measured contact resistance is below 172 µΩ. This value can be adjusted by tuning the positioning of the disc spring outer rim up and down, which changes the steady state operation point on the deflection-load curve accordingly.

The thesis also presents the design of a prototype for a 100 kV 1250 A DC circuit breaker.

9.2 Future Work

9.2.1 A novel Thomson coil actuator design

The research will pursue a novel scaling design of the Thomson coil actuator employing multiple disks. An exemplary design is given in Fig. 9.1.

Figure 9.1: A two-disk design for higher performance Thomson coil actuators.
The advantages of such design is summarized as follows.

1. The structural stress of the mechanical parts is reduced; the bending issue of the disks is alleviated.

2. As the mechanical limit of the actuator is expanded, higher transient acceleration force and higher speed is possible. Or on the other hand more payload can be actuated.

3. As less disks are involved in closing operation than opening operation, the operation speeds are asymmetric, which is perfectly suitable for operating the mechanical switch for hybrid circuit breakers. Because on one hand opening operation should be as fast as possible, however closing operation should avoid too high speed since too much impact on the fixed contact from the moving contact can cause damage to the contact surfaces.

4. Only one control switch can be used for both opening and closing operations with one capacitor bank.

9.2.2 An alternative hybrid DC circuit breaker

An alternative hybrid scheme that can be used in medium to high voltage DC interruptions has a similar circuit diagram like except that the high voltage semiconductor device is replaced
by a high voltage capacitor. The benefits are obvious: passive components are less expensive and less complicated; high voltage capability can be easily obtained without complex and bulky voltage balancing networks; no control or auxiliary power supplied are needed; potentially more current could be interrupted. The only disadvantage that might have been brought in is the voltage built up across the capacitor after each interruption, which can be easily addressed by using a parallel discharging resistor that has a much longer time constant compared to the interruption time.

Some similar methods were explored in 1970s by Kimblin and 2000s by Meyer.

In Kimblin’s research, a magnetic pulse is applied transversally to the vacuum arc in order to help commutate the current to a parallel capacitor branch. Kimblin’s scheme was initially proposed to achieve fast current interruption for the purpose of current limiting in AC systems; but the idea can be used to interrupt DC as well because a quarter cycle interruption of AC current is no different than the interruption of DC current. The electromagnetic force exerted on the vacuum arc acts like an additional voltage source that drive the current from the arc path to the capacitor path. A stronger magnetic force creates a larger commutating voltage. However, considering the effort to build a sufficiently large magnetic field, the authors had
investigated the current interruption limit’s dependency on the capacitance as well.

The alternative method discussed in this section uses the avalanche voltage of MOSFETs as the commutating voltage. Though this has introduced some extra conduction losses, the commutating voltage can be built up in a few microseconds with a simple gate circuit. This voltage level can be adjusted by selecting the devices of different voltage ratings. Generally speaking, a device rated for higher voltage tends to have more power losses. However, compared to the complex magnetic method that requires powerful and bulky circuits, this solution is more compact and more suitable for higher current interruption.

Meyer has investigated the DC circuit breaker topology with a mechanical breaker and a capacitor in parallel. His paper derived the equations to calculate the rate of the rise of the recovery voltage (RRRV) with consideration to the loop inductance. The study assumed that as long as the RRRV is not exceeded the DC breaker should work. This may not be true because the current interruption has to be dealt with first before the RRRV issue. Even though the snubbered mechanical DC circuit breaker can interrupt a DC current, its contact surfaces need to be treated like AC circuit breaker in order to achieve fast dielectric recovery.

Because the operation speed of the mechanical switch and the capacitance of the capacitor greatly affect the interruption performance of the circuit breaker, the circuit can be first modeled and simulated in PSCAD, and experimental study can be conducted to verify the simulation. Fig. 9.4 and 9.5 show some preliminary modeling work.
Figure 9.4: The model in PSCAD.

Figure 9.5: The simulation in PSCAD.
REFERENCES


