Future cryogenic switchgear technologies for superconducting power systems

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Abstract. This paper introduces cryogenic switchgear that is needed for protection and control purposes in future multi-terminal superconducting power systems. Implementation of cryogenic switchgear is expected to improve system reliability and minimize overall volume and weight, but such switchgear is not available yet. Design of cryogenic switchgear begins by referring to conventional circuit breakers, a brief review of state-of-the-art switchgear technologies is presented. Then, promising cryogenic interruption media are identified and analysed with respect to physical and dielectric properties. Finally, we propose several cryogenic circuit breaker designs for potential aerospace, marine and terrestrial applications. Actuation mechanism for cryogenic switchgear is also investigated.

1. Introduction
Switching is an indispensable operation in any complex network infrastructure. For power distribution systems, switching ensures the system’s flexibility, reliability and efficiency in terms of fault management and optimal configuration. Equipping power systems with appropriate switchgear will not only ensure consistent power delivery, but also prevent spreading damages over the whole system. When it comes to superconducting power systems, only solid-state switchgear is applicable so far. However, solid-state devices have relatively high power loss in on-state conduction, and their isolation capability is very limited. Electromechanical switchgear (or switchgear) has negligible on-state loss and very high isolation capability, but current designs are not suitable for cryogenic switching due to frozen dielectric media, solidified lubricants, cracked polymers, and warped components as a consequence of mismatched coefficients of thermal expansion. Substantial heat load will be added to cryogenic system if ambient-temperature-rated switchgear is directly connected. To tackle these problems, we propose cryogenic electromechanical switchgear as a promising solution to cryogenic switching in this paper.

High temperature superconducting (HTS) power systems for future all-electric aircrafts and ships are also expected to be in need of switchgear: In turboelectric distributed propulsion (TeDP) systems, the lack of lightweight and efficient switchgear makes optimal network architecture unachievable [1, 2]. Solid-state circuit breaker (SSCB) at cryogenic temperature is a potential solution but will add substantial heat load to the cryogenic system due to on-state conduction losses, which will potentially increase total weight meanwhile decrease total efficiency in aircraft and naval applications.

Circuit breaker (CB) is the most advanced and complicated switchgear due to its fault current interruption capability. The cryogenic circuit breaker (CCB) is also the most fascinating device within cryogenic switchgear design. Low weight and high efficiency are expected to make CCBs more competitive in TeDP systems and other applications [3]. On the one hand, CCBs for TeDP systems and
all-electric ships can be designed with faster operation speed, because these systems are expected to be fault current limited by using power electronic devices. In terrestrial cryogenic power systems, the capability to interrupt substantial fault current becomes more important. In medium or high-voltage level, CCBs need to work with fault current up to several or tens of kiloamperes, same as the common fault current rating for conventional CBs. Similar to ambient-temperature CBs, CCBs can utilize various cryogenic dielectrics as interruption media, including gas, liquid and vacuum. While the switching chamber of CCBs will always be at cryogenic temperature, the actuator mechanism can either be at room temperature or at cryogenic temperature. We call the corresponding CCBs as “warm-actuated” and “cold-actuated” respectively, which will be further discussed in Section 4.

Section 2 reviews conventional ambient-temperature CBs with respect to interruption medium, chamber design and actuation mechanism, selection criteria for CCBs are generalized. These criteria are applied in potential cryogenic interruption medium identification, which is discussed in Section 3. Section 4 introduces several practical CCB designs, providing demonstrations of switchgear in cryogenic power systems for aerospace, marine and terrestrial applications.

2. Review of Conventional Circuit Breakers
Electromechanical circuit breaker (EMCB) and SSCBs are both conventional CBs working at ambient and elevated temperature. EMCBs have movable contacts and arcs for switching, while SSCBs utilize PN-junction for switching. Our focus is on developing the cryogenic counterpart of conventional EMCBs. According to types of interruption media used, EMCBs can be further divided into three subgroups. Figure 1 is an attempt to show conventional and cryogenic CBs side to side. It includes the interruption media and structure types of conventional CBs, and proposed media and types for cryogenic CBs (further discussed in Sections 3 and 4).

![Figure 1. Classification of cryogenic (left) and conventional (right) circuit breakers](image-url)

2.1. SF₆ Circuit Breakers
The history of gas-insulated CBs started with air-elongation and air-blast CBs. The increased voltage and fault current levels of power system made it necessary to employ strongly electronegative gases for interruption. Today’s high-voltage switchgear utilizes sulfur hexafluoride (SF₆) as insulation and interruption medium, because of its high thermal conductivity, high breakdown strength, and fast recovery rate [4].

Based on their arc quenching mechanisms, SF₆ circuit breakers can be divided into four sub-types (Figure 2): double-pressure, puffer, self-blast, and rotating-arc [4]. They all contain a main contact system for lowest contact resistance at closed state, an arcing contact system that provides conducting...
path for arcs during opening operation, and a nozzle to direct cold interruption medium onto the arc. The main contact system typically surrounds the arcing contact system in a concentric manner. For simplicity, only arcing contacts are shown in Figure 2.

**Figure 2.** Arcing contact system of SF$_6$ circuit breakers of (a) double-pressure type (b) puffer type (c) self-blast type and (d) rotating-arc type

Overall, SF$_6$ is the most common gaseous interruption medium applied in high voltage and ultra-high voltage circuit breakers. SF$_6$ circuit breaker utilizes various control methods for controlling gas flow in interruption chamber. Correspondingly, in cryogenic gas CBs, gas-control components like puffer and nozzle can also be adopted.

2.2. **Oil Circuit Breakers**

Mineral oil is a good interruption medium with high dielectric strength and excellent arc quenching properties, so it becomes the best choice for liquid-type CBs. There are two basic structures for oil CBs: bulk-oil and minimum-oil designs (Figure 3) [4]. CBs of bulk-oil design, or dead-tank design, have a grounded tank holding a large volume of oil to immerse conductors and contacts, while minimum-oil designs drive a small amount of oil through contacts solely for extinguishing the arc. Oil circuit breakers have very reliable designs for high voltage operations, and been in service for half of a century. After the 1980s, due to their large volume, large driving force and high flammability, oil breakers were supplanted by vacuum interrupters and SF$_6$ circuit breakers [4].

**Figure 3.** Oil circuit breaker of (a) bulk oil design and (b) minimum oil design
In the oil-type CB, when a fault occurs, movable contacts will draw back from fixed contacts, generating an arc between contacts and triggering nearby oil to evaporate, decompose and ionize. After the flow of cold oil has removed the heat of arcing plasma and the arc cannot be sustained by applied voltage, the hydrogen gas dissociated from mineral oil will quench the arc and re-establish the insulation between contacts. In this way, an opening process for interruption is accomplished.

The interruption process is somewhat similar in gas-type CBs and vacuum interrupters, the differences are the interruption media and the actuation mechanism for contact movement in various CBs. With respect to cryogenic liquid CBs, since cryogenic liquids don’t degrade or decompose during aging, bulk-oil design is more feasible due to its simpler actuation mechanism.

2.3. Vacuum Interrupters
Vacuum interrupters are best suited for medium voltage applications due to their high reliability, low driving force and small volume. Figure 4 shows the cross section of a typical vacuum interrupter. It consists of a pair of contacts attached to copper conductors that are each connected to a fixed and movable conductor. The movable conductor is connected to an end plate by metal bellows and movable terminal, the terminal is driven by the actuator. The contacts, conductors, and bellows are all enclosed in a ceramic chamber holding high vacuum, the ends of which are metallized and brazed to metal end caps.

Vacuum interrupters can operate over a wide temperature range since they need to be able to withstand the vacuum bake-out in the manufacturing process. The materials are expected to tolerate cryogenic temperatures and have matching coefficients of thermal expansion. With an appropriate actuation mechanism, vacuum interrupter will be a promising candidate for cryogenic switching. However, the prevalent problem in cryogenic switchgear, the changed material properties, would be more critical in cryogenic vacuum interrupters. The bellow is expected to become more brittle, which increases the potential of damage by fatigue, so certain parts of interrupter require a re-design to operator in superconducting power systems.

3. Potential dielectrics for cryogenic interruption
Former studies have thoroughly investigated the dielectric properties of cryogenic fluids, such as nitrogen (N₂), helium (He) and hydrogen (H₂) [5, 6]. The permittivity, conductivity, dielectric loss and breakdown strength under different conditions are known [7]. However, there has not been a research focuses specifically on the interruption performances of cryogenic fluids. Therefore, we discuss the “static” properties, that is, the physical and dielectric properties of cryogenic fluids now. Their “dynamic” performances like arc quenching and dielectric recovery require experimental statistics to be fully understood.

One of the most important requirements for an interruption medium is high dielectric strength, also known as breakdown strength. Dielectric strength is the capability of dielectrics to withstand high electric fields, which is crucial for switchgear at open-state. High dielectric strength leads to high survival rate under overvoltage, high reliability in open-state, and low likelihood of dangerous arc
restrikes and re-ignitions following interruption. Breakdown in gas is characterized by Paschen’s Law, which describes the dielectric strength of a gas as a function of the product of gas pressure $p$ and gap distance ($d$ for uniform field between parallel plate electrodes, or $R_1$ for non-uniform field between coaxial electrodes). When the gas pressure $p$ is replaced by the number of molecules per volume $N_v$ according to ideal gas law, the Paschen’s curves are independent from gas temperature [8]. Hence, cryogenic gases perform the same Paschen’s curves as ambient-temperature gases. The Paschen’s Law of cryogenic gases are shown in Figure 5. Breakdown in liquid cannot be characterized by a pure materials function [5]. Purity, presence of bubbles, time duration of applied voltage can all affect dielectric strength of liquid. Generally, liquids have higher dielectric strength than gases.

![Figure 5. Paschen’s curves of cryogenic gases measured at (a) uniform field of parallel-plate electrodes [5, 7] and (b) non-uniform field of coaxial electrodes [8, 9] at room temperature](image)

Besides the dielectric strength, an ideal cryogenic interruption medium should have low boiling temperature, low viscosity, high thermal conductivity and high heat capacity. For cryogenic liquids, the enthalpy of vaporization should be high enough to prevent excessive gas formation. Based on melting and boiling temperature shown in Figure 6, promising cryogenic liquids for interruption are liquid nitrogen (LN$_2$), liquid fluorine (LF$_2$), liquid oxygen (LO$_2$) and liquid methane (LCH$_4$). The rest of cryogens have a limited liquid temperature range. Furthermore, condensed noble gases (LHe, LNe, and LAr) have low dielectric strength as shown in Figure 5. LF$_2$ is an outstanding dielectric due to fluorine’s strongest electronegativity among all elements. However, the high toxicity, corrosivity, and oxidability exclude LF$_2$ from industrial application. Similarly, even though LO$_2$ has strong electronegativity that contributes to dielectric recovery after interruption process, high oxidability makes it hazardous. LCH$_4$ is considered as a promising candidate, since it can be used both as a cryogen and a fuel for space crafts, aircrafts and ships. Other hydrocarbons such as ethane, propane, ethylene as well as mixtures like liquid natural gas (LNG) are similarly promising. Flammability aspects will need to be considered in designs where evaporated cryogens are vented to the atmosphere.

Cryogenic gases like gaseous hydrogen (GH$_2$), gaseous helium (GHe), gaseous neon (GNe), gaseous argon (GAr) and gaseous nitrogen (GN$_2$) are candidates for cryogenic gas CBs. GH$_2$ is a very appealing gas for arc quenching purposes due to its low viscosity, high thermal conductivity, and relatively high dielectric strength. It is also the functioning component of ambient-temperature transformer oil for arc quenching. GHe shares the high thermal conductivity with GH$_2$, but suffers from low dielectric strength like all noble gases. For the very low temperature range below 50 K, GHe is the only choice if a non-flammable solution is needed. However, it has been discovered that by adding small amounts of GH$_2$ to GHe, the dielectric strength of mixture can be substantially improved while maintaining the non-
flammable characteristics [10]. There are several more “exotic” cryogenic liquids that would be worth considering: Oxygen difluoride (LOF₂), carbon monoxide (LCO), nitric oxide (LNO). They are not discussed here for toxicity and reactivity reasons.

| Temperature [K] | He [11] | H₂ [11] | Ne [11,12] | N₂ [11] | Ar [11] | O₂ [11,12] | CH₄ [11] |
|----------------|---------|---------|------------|---------|---------|-----------|---------|
| Enthalpy of Vaporization [kJ g⁻¹] |
| 446.1 | 199.2 | 213.1 | 20.91 | 105.161 | 510.8 |
| Thermal Conductivity [mW m⁻¹ K⁻¹] |
| LN₂ | LHe | GHe | LNe | GNe | LAr | GAr |
| Density [g cm⁻³] |
| 1.06 | 1.08 | 1.61 | 1.68 | 1.68 | 1.65 |
| Viscosity [μPa s] |
| 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 |
| Heat Capacity [kJ g⁻¹ K⁻¹] |
| 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |

**Figure 6.** Physical properties of cryogenic fluids at normal boiling point (p = 0.1 MPa) [11, 12]. (a) melting and boiling temperature (b) enthalpy of vaporization (c) thermal conductivity (d) density (e) viscosity and (f) heat capacity at constant pressure. “L” stands for “Liquid”, “G” stands for “Gas”.

Nitrogen is the most widely-used cryogen in cryogenic engineering, it also exhibits excellent dielectric and interruption performances in superconducting power systems. Researchers have identified GN₂ as potential substitute for SF₆ in gas-insulated switchgear at ambient temperature [13], because N₂ is a strong electron slowing-down gas and can self-heal after breakdown[14]. GN₂ has the highest dielectric strength among cryogenic gases below 80 K, more than 10 times the strength of GH₂ at high pressure (N₂d = 10²⁴ m⁻²). Several studies have tested the interruption performances of LN₂. Morishita et al. [15, 16] invented a puffer-type LN₂ CB which directly blew LN₂ on arcs, showing a higher current interruption capacity and shorter arcing time than CB designs that directly immersed contacts in LN₂. In their experiment, at a gap distance of 10 mm and an applied voltage is 100 V, the maximum interruptible current is 300 A and interruption time is 7 ms. Golde et al. studied applicability [17], contact resistance [18] and short-circuit interruption [19] of commercial vacuum interrupter in LN₂ environment, providing preliminary references for cryogenic vacuum interrupter design.

**4. CCB case studies**

The voltage rating and interruption capability of cryogenic switchgear are dependent on interruption medium, actuation mechanism, arc control method, thermal management and so on. Conventional CB structures can be modified in CCBs when they have the same type of interruption medium. Cryogenic liquid CBs can be based on designs similar to conventional oil-type CBs, because the dielectric strength of cryogenic liquids is similar to mineral oil. However, cryogenic gas CBs need numerous modifications from conventional gas CBs. One reason is the large difference in interruption properties between SF₆ and cryogenic gases. The other reason is the pursuit of smaller, lighter and faster switchgear, traditional
actuation mechanism of SF₆ breakers would be too heavy for aerospace or naval applications. When it comes to vacuum interrupters, the cryogenic temperature would not influence the dielectric properties of vacuum itself, it may even further drop the vacuum pressure in the interruption chamber. For cryogenic vacuum interrupters, problem concentrates on thermal contraction coordination between different parts in the interrupter, which must be based on the very short list of materials compatible with ultra-high vacuum conditions.

4.1. Cryogenic Liquid Circuit Breakers

Proposed cryogenic liquid CB design is shown in Figure 7. The operation principle is similar to bulk-oil CB as described in section 2.2. The conductors and contacts are immersed in cryogenic liquid to stay at cryogenic temperature, but the actuators can be either at ambient temperature or at cryogenic temperature. The former choice can provide very large driving force and long stroke, while the latter choice has the potential to reduce the overall size. Transition from cryogenic to ambient zone will be isolated by vacuum layer and evaporated gas. This gas cushion contains the vapor generated during arcing process, thus modulates the internal pressure of chamber.

![Figure 7. Cryogenic liquid circuit breaker structure: (a) Venting type and (b) condensing type.](image)

However, the evaporated gas is the major threat for cryogenic liquid CB operation. To estimate amount of liquid evaporated during each interruption process, we assume the arcing is restricted in the channel between contacts, so only a small volume of liquid is heated and evaporated, and the evaporation process is isothermal. When the energy generated by arcing is completely absorbed by evaporating the interruption medium, the mass of vapor formed and chamber pressure change can be calculated as

\[ m_{\text{evap}} = \frac{V_{\text{arc}} I_{\text{fault}} t_{\text{interruption}}}{\Delta H_{\text{vap}}} \]  

(1)

\[ \Delta p = \frac{m_{\text{evap}} RT}{MV} \]  

(2)

Where \( V_{\text{arc}} \) is the applied voltage to sustain the arc, \( I_{\text{fault}} \) is the fault current flowing though the arc, \( t_{\text{interruption}} \) is the time used to extinguish the arc, and \( \Delta H_{\text{vap}} \) is the latent heat of vaporization given in Figure 6, \( M \) is the molar mass, \( R \) is the ideal gas constant, and \( V \) is the volume of gas. Table 1 lists the vapor mass for LN₂, LCH₄, LH₂, and LF₂ at arbitrary conditions of 100 V of arcing voltage, 2 kA of fault current, and 20 ms of interruption time. The pressure increase is calculated by the ideal gas law as in equation (2). It can be seen that the pressure increase is fairly moderate for most candidates, between 31.2 kPa for
LCH₄ and 45.9 kPa for LN₂, but a bit more substantial for LH₂ with 285 kPa. While LN₂, LH₂, and LF₂ will recombine after interruption, LCH₄ may dissociate and form some hydrogen gas and carbon soot along with a few other hydrocarbons. Filtration is needed for long-term use of CH₄ as interruption medium.

For the purpose of withstanding the pressure increase inside the interruption chamber, two different designs are considered. Open loop (venting) and closed loop (condensing) cryogenic liquid CBs are proposed and shown in Figure 7. The venting type CB includes a valve at the top of the tank which releases excess vapor formed during an arc quenching process. The condensing type CB replaces the valve by a cryocooler, which condenses the vapors and directs liquid back into the tank. The size of cryocooler depends on the volume of vapor formed each arcing cycle. This condensing design helps maintain a desired level of fluid in the tank.

4.2. Cryogenic Vacuum Interrupters
Vacuum interrupters can be used at cryogenic temperature by enclosing the interrupting chamber in a bath of cryogenic liquid, such as LN₂. This can potentially affect several characteristics of vacuum interrupters such as internal and external dielectric strength, current chopping and contact resistance. Also, materials of different thermal expansion rates at cryogenic temperature can cause mechanical stress in the interrupter. While it has been shown that the mechanical stresses due to thermal shock does not affect the vacuum pressure in the interrupter [17], the effect of thermal shock on short-circuit interruption is still unknown.

The breakdown voltage in vacuum largely depends on field emission at small gaps and particle effects at large gaps, along with contact material, geometry and surface quality. The breakdown voltage of LN₂ cooled copper electrodes are shown to be 15-20% higher than ambient temperature at 2 mm gap distance. Golde et al. have demonstrated that the breakdown voltage of a commercially available vacuum interrupter in an LN₂ bath with 11 mm contact separation to have a maximum of 10% higher breakdown voltage than at ambient temperature. It has also been shown that the current chopping of the vacuum interrupter is unchanged by enclosing it in an LN₂ bath, but the arc instability preceding current chopping occurs 10-20% earlier than at ambient temperature due to higher velocity of cathode spots [17].

During arc interruption, the temperature of contacts will increase and generate metal vapor, which make the arc harder to extinguish. A cryogenic vacuum interrupter would result in lower contact erosion, since the contact resistance is lower at cryogenic temperature. The contact resistance of a LN₂ enclosed vacuum interrupter is shown to be about 15% of ambient value under DC current and 30% under AC current [18]. The lower resistance of contacts means lower energy loss caused by heat dissipation. The power loss for a 126 kV vacuum interrupter in a bath of LN₂ calculated to be 15% of the power loss of a 126 kV SF₆ gas insulated switchgear [20].

Vacuum interrupters have desirable characteristics to make it work as a cryogenic switchgear device. However, the effect of thermal shock on short-circuit interruption needs to be further explored, as well the breakdown voltage at cryogenic temperatures and the external dielectric strength of the device when the cooling fluid is at a higher temperature and has bubbles. Furthermore, the material properties will change at cryogenic temperature. This becomes especially important for parts that bend like the metal bellows or slide like conventional actuator. These elements could fail prematurely due to excessive wear and material fatigue in cryogenic environment, thus need extra attention.
4.3. Cold actuated switchgear
Concerning the weight and volume constraints of CCBs used in highly-integrated power systems, the actuation mechanism must be carefully designed to fulfill contact separation within a short period of interruption time. Conventional actuation mechanisms are pneumatic, hydraulic or spring operated. Most of them are assisted with electromagnetic devices, which results in bulky device and slow operation. On the other hand, cryogenic actuation utilizes actuators that can fully function below 100 K, like piezoelectric and magnetostrictive actuators. Cold actuator designs are expected to have weight and volume savings compared to warm actuator designs. However, the driving forces and stroke distance are often reduced at the same time.

Piezoelectric actuators and magnetostrictive actuators are well suitable for cold actuation in cryogenic CBs. Piezoelectric actuators have been historically studied and used in aerospace applications. NASA, for example, designed and tested PMN-PT single crystal piezoelectric stack actuators and flex-tensional actuators for cryogenic applications [21]. Other organizations like ESA [22] and ISRO [23] are also working with piezoelectric actuators in cryogenic atmosphere due to their low power consumption and lubricant-free design. Magnetostrictive actuators are also lubricant-free, which is necessary for cryogenic or vacuum applications. Compared with conventional actuator, piezoelectric and magnetostrictive actuators have limited driving force and short stroke length but light weight and fast response. Considering these features, a piezoelectric-actuator-based high-speed disconnect switch design is being studied for cryogenic applications. The ambient-temperature counterpart is covered by an ongoing research project funded by the National Science Foundation that focuses on fault isolation devices for the FREEDM Systems Center [24].

5. Conclusion
Apart from a short-term experiment with a vacuum interrupter under laboratory conditions, conventional switchgear does not function at cryogenic temperature. However, switchgear based on liquid and gaseous media as well as vacuum can lend themselves for adaptation to cryogenic operation, major technical issues of this transition are foreseen in this paper. With respect to the interruption medium, a wide variety of cryogenic fluids are expected to performing well as interruption media in cryogenic switchgear. The actuator of cryogenic switchgear can operate at either room or cryogenic temperature, the design with cryogenic actuator could further reduce the heat leakage from ambient into the cryogenic system, resulting in additional weight and space savings for cryogenic switchgear.

Further investigations concentrate on both material and structure perspectives. On the one hand, interruption performances of cryogenic dielectrics will be studied in detail, providing necessary information for chamber design and actuation selection. The optimal contact material and geometry for cryogenic interruption will also be specified. On the other hand, the overall structures for aerospace, marine and terrestrial application will be explored respectively, evaluating their estimated volume, weight and efficiency in real-time operations.

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