Pumped 2-Phase Cooling as an Enabler for a Modular, Medium-Voltage, Solid-State Circuit Breaker

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Abstract

The design approach and development of a 12kVDC, 2000A two-pole bidirectional circuit breaker capable of interrupting 80 kA available fault current in less than 0.5ms (time to current zero) is described. The extremely fast total interruption time of a DC current all but dictated a purely solid-state approach. Strict requirements for efficiency (≥ 99.8%) and power-density (≥ 25kW/L) were driven by intentions for future shipboard power systems. A pumped 2-phase cooling approach provided tight isothermality control and voltage isolation which enabled these advances in efficiency and power-density.

1 Introduction

DC distribution systems have been proposed for marine vessels, as they have several potential advantages over AC systems [1]. These zonal DC distribution systems require solid state circuit breakers (SSCB) for limiting fault currents and interrupting faults [2] [3]. The limited space available on shipboard systems drives need for very high volumetric power density of the SSCB, requiring careful insulation coordination between the semiconductors and other components in the system. For medium voltage DC distribution systems, the lack of semiconductors with sufficient voltage ratings requires that several semiconductors be connected in series [4] within the SSCB. This series topology further complicates the high power density design challenges, especially as it relates to cooling of the semiconductors.

This paper introduces a pumped 2-phase (P2P) cooling system as an enabler for a high power density SSCB for protection in a 12 kVDC distribution system. This cooling system provides isothermal operation of paralleled semiconductors for high current operation with good current sharing. Additionally, the use of a dielectric refrigerant in the cooling system allows for series-connected semiconductors with electrically isolated heat sinks, simplifying insulation coordination between series-connected devices.

2 Circuit Breaker Architecture

The target power system for this circuit breaker is a ± 6 kVDC supply with a high-impedance center reference to ground. While the nominal pole voltage is 6 kVDC, it is a requirement that the circuit breaker be able to operate continuously in the event of a single ground fault. If one rail is ground referenced, the other is forced to ± 12 kVDC. In this grounded-rail condition, a second ground-fault can cause a fault-current to bypass one pole of the breaker as illustrated in Fig. 1. This scenario drives the need for each pole to produce enough transient interrupt voltage (Vmov) to drive the current to zero within the required time and then hold-off the full 12 kVDC supply voltage. Also, in the grounded-rail condition, a pole-to-pole fault could occur (as shown in Fig. 2, causing one pole terminal to rise to twice the pole's transient interrupt voltage. Hence the circuit breaker insulation system had to be designed to withstand as high as 40 kV for as long as 500 µs.

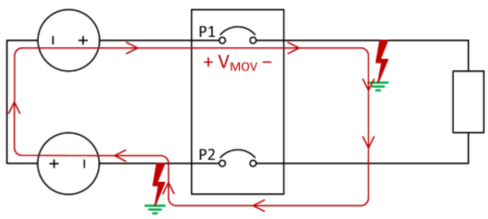

Fig. 1: Double-ground fault scenario

The design team decided on a modular approach to the bi-directional 12 kVDC, 2000 A solid-state circuit breaker built on a field-replaceable 4 kV, 1000 A bi-directional circuit breaker cell. To reach the 12 kVDC rating for each pole, three such cells are connected in series, together with a di/dt limiting inductor and an isolation contactor as shown in Figs. 3 and 4. This series connected group of components will be referred to as a string. To reach the 2000 A required rating, two of these strings are connected in parallel to form the pole.

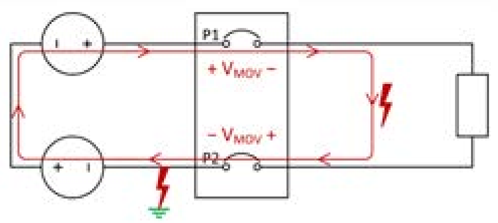

Fig. 2: Grounded pole-to-pole fault scenario

The 1000 A cells themselves utilize multiple, tightly-coupled (both thermally and electrically) semiconductor modules in parallel, with two sets of paralleled semiconductor emitters connected to allow for the interruption of current in both directions. Metal oxide varistors (MOVs) are connected collector-to-collector across the semiconductors to clamp the voltage during transients.

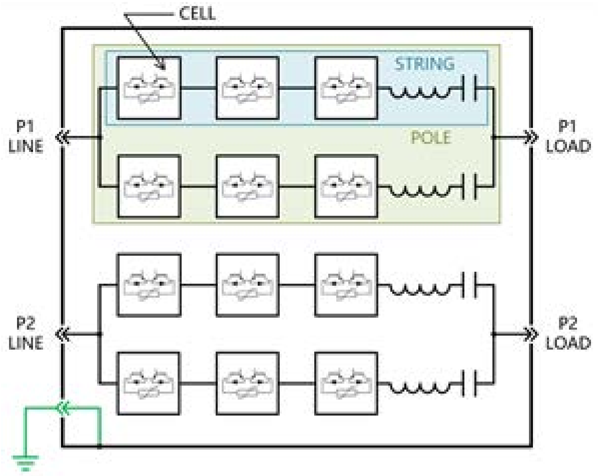

Fig. 3: Modular circuit breaker architecture schematic

3 Cooling System Design

3.1 Cooling Challenges

This circuit breaker topology introduces several significant cooling challenges. For hard-paralleled semiconductor modules to share current equally both statically and dynamically, a high degree of semiconductor junction isothermality is required across various mounting locations on a single evaporator plate. In addition, equal current sharing between the two paralleled strings of cells also requires the semiconductors in each string to operate at a similar temperature. Finally, the modular approach necessitates that the semiconductor modules operate far beyond their package baseplate isolation voltage.

Fig. 4: Modular units on the front of the prototype breaker

For these reasons, a P2P cooling system was selected to cool the semiconductors in the breaker. The selection of R134a, a dielectric coolant, when combined with electrically isolating coolant hoses between the cells, allows the cell's cold-plate to be referenced to the emitter of the semiconductor, greatly simplifying the dynamic voltage insulation coordination both within the cell and between cells, ultimately leading to superior power density for the overall system.

3.2 Overview of Pumped 2-phase cooling

P2P systems are ideal for the cooling of high-power semi-conductor devices where heat loads have increased to a level beyond what traditional air and water cooling systems can effectively manage while maintaining tight isothermality

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requirements. In P2P cooling systems, heat is transferred by the evaporation and condensation of a portion of the working fluid. Typically, a liquid near saturation is pumped into the evaporator, where it starts to evaporate, cooling the electronics and storing the energy in the latent heat of the fluid. The two-phase (liquid and vapor) fluid then flows to the condenser, where the heat is removed, condensing the vapor, so that a single phase (liquid) exits the condenser, and enters the pump, completing the cycle. A schematic of the P2P loop developed for this prototype is shown in Fig. 5.

During the evaporation, within the evaporators, a portion of the coolant undergoes a phase change from liquid to vapor, which captures a large quantity of heat via the fluid's latent heat capacity without raising the temperature of the coolant. As long as both liquid and vapor phases exist together, the temperature of the fluid is driven by the pressure according to the fluid's saturation curve. If the pressure is held constant, the temperature will likewise remain constant. This phenomenon provides an excellent means of maintaining isothermal junction temperatures both within and between the modular cells by controlling pressure.

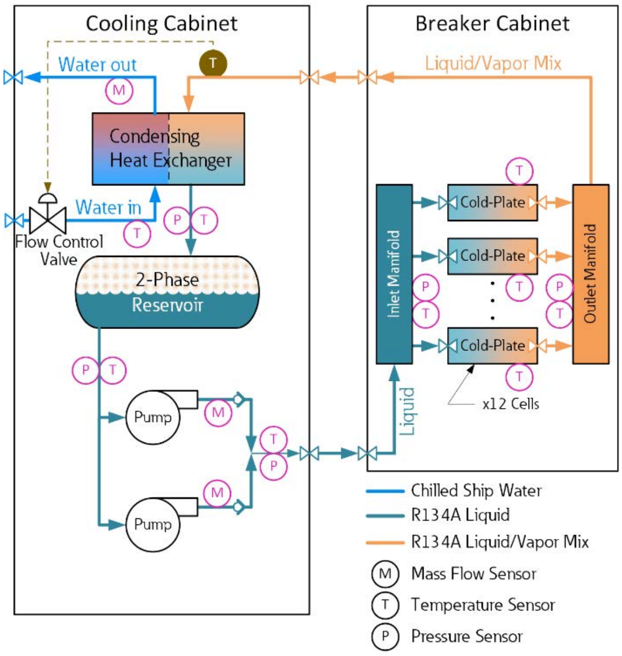

Fig. 5: Pumped 2-phase cooling system schematic

The pumping requirements of P2P systems are significantly less than those of a single-phase system which can only capture energy via sensible heating. Because single-phase liquid cooling has lower heat transfer coefficients than evaporative cooling and because the fluid will necessarily get hotter as it collects heat from the components, the flow rates required for liquid cooling must be quite high in high-heat-flux, high-isothermality applications.

3.3 Evaporator design

The evaporators are aluminum plates with parallel internal fluid channels under the heat producing components. Four semiconductor modules are mounted on the front and four on the back. Each module contains two types of chips with different power dissipations, and which are not all active at the same time. Figure 6 shows outlines of the modules and chips in magenta overlaid on the basic fluid channel areas. The two larger channels are in-fact divided into numerous smaller channels all in parallel. The walls of the smaller channels form a fin structure, increasing the surface area for heat transfer. The small channels also serve as a flow control, to ensure coolant uniformly covers the entire heat transfer area.

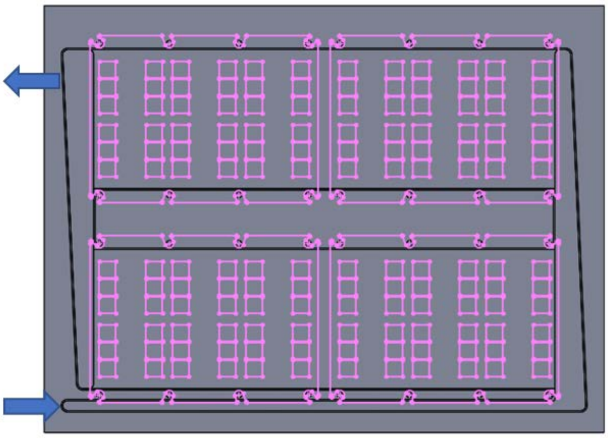

Fig. 6: Evaporator flow layout underneath chip layout

Since heat loads are applied to both sides of the evaporator plate, the channels must be equally close to the surface on both sides. The height of the channels was therefore set by the thickness of the aluminum plate, which was previously specified by non-thermal related requirements. The width of the channels was calculated to ensure that the forces of fluid's momentum dominate the gravitational forces, which enables the evaporator to operate independent of gravitational orientation.

The coolant flow is distributed into these channels through proprietary geometry in the manifold region, which ensures equal flow under the whole module. Because not all the chips are producing heat simultaneously, evaporation will primarily be occurring in the channels close to where the heat

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is being produced. Without proper flow distribution, the vapor being formed in those channels would create a flow restriction that would cause more fluid to go to the portions of the plate where no heat load is being applied and the channels beneath the heat loads would dry out, causing temperatures of the devices there to sharply increase. With the proper flow distribution, however, enough liquid coolant is provided to all the channels to handle the highest possible heat load on that channel, while maintaining a particular mass quality of liquid at the exit of the channel.

The outlet quality should be maximized in order to reduce the flow rate requirements, but this must be balanced with the isothermality requirements of the system. If the outlet quality is too high, insufficient liquid remains in the channel to maintain the high evaporative heat transfer coefficient. To maintain the proper outlet quality in the channels with the highest heat loads, channels with less heat load end up having excess flow. When the flow recombines as it exits the evaporator, the total vapor quality is relatively low for a typical P2P system.

With the evaporator designed and the flow rate requirement determined, the remaining components of the P2P system can be designed. The rest of the P2P is referred to as the “balance of plant.”

3.4 Balance of plant design

The first major component to be specified after defining the evaporator performance is the pump. The 12 modular cells are plumbed in parallel, so that each receives subcooled liquid at the inlet and operates within the same quality regions. This plumbing configuration reduces the pressure head requirements of the pump, but increases the flow rate requirement. To achieve the proper level of flow rate with a single pump and an extremely low viscosity fluid, a pump specifically designed for refrigerants was required. Additionally, in this system, a second identical pump is included to achieve n+1 redundancy.

The next component is the condensing heat exchanger. The refrigerant ultimately rejects the heat of the electronics to the shipboard cooling water by passing through a flat brazed-plate heat exchanger. This technology is fairly common and generally accepted as the most space-efficient and economical liquid-to-liquid heat-exchangers. A heat exchanger was sized to reject the total heat load of 48 kW with the given flow rates. This heat exchanger does not incur a large pressure drop or flow demand from the shipboard cooling water system.

The control of the temperature of the condensing refrigerant is ultimately what drives the temperatures of the evaporators, and therefore, the electronics. This control is provided passively with a valve which adjusts the flow rate of cooling water based on a temperature measurement in the refrigerant. The temperature corresponds to a pressure which compresses a spring in the valve, opening it for more flow when the refrigerant gets too hot, or closing it as the refrigerant cools down. The setpoint is preset by adjusting the tension in the spring.

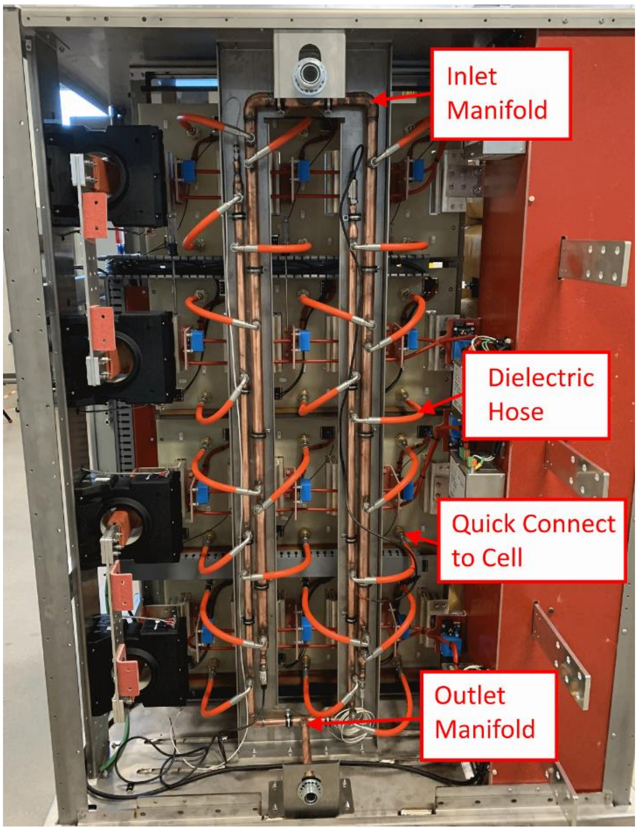

Fig. 7: Back of the circuit breaker showing the copper coolant manifolds and orange dielectric hoses connecting to each cell.

Between the condensing heat exchanger and the pump is an important component: the reservoir. This is simply a large tank that provides volume compensation for the large density change from liquid to vapor in the evaporator. When there is no heat load on the evaporator, liquid can be pumped through the system, filling the evaporator, condenser and all the plumbing in-between. The reservoir at this point is mostly filled with vapor, a small pool of liquid at the bottom feeds into the pump. When heat is applied to the evaporator the density change from liquid to vapor would cause the pressure in the system to spike, if it were not for the excess vapor in the reservoir, which is able to condense as excess liquid is pushed into reservoir. The vapor formed in the evaporator fills a large percentage of the volume of the evaporator, condenser and the plumbing in-between. Thus, while the system is operating under heat load, the reservoir is nearly full of liquid which is being fed to the pump.

The remaining aspects of the of the balance of plant design are primarily plumbing and packaging. Plumbing includes the manifolds for the evaporators. Similar to manifolds within the evaporators, the plumbing manifolds must distribute the flow uniformly and use some customized geometry in the fittings to provide equal flow distribution. The manifolds also include the non-conductive hose, which with the use of a dielectric coolant, provides the voltage isolation required by the system. The manifolds can be seen in Fig. 7. Additional plumbing components include filters, pressure relief valve, quick disconnects, and sensors.

For this prototype, the thermal balance of plant was placed in a separate thermal cabinet, due primarily to timeline limitations of the design phase that precluded the concurrent engineering that would have been required to integrate the P2P system fully into the electronics cabinet. Future iterations plan to integrate these systems into more compact packaging.

4 Prototype Fabrication

The proposed circuit breaker and cooling system was constructed as a prototype. The prototype circuit breaker is shown in Figs. 4 and 7. The thermal cabinet is shown in Fig. 8.

Much of the thermal system fabrication follows standard refrigerant plumbing practices, with the exception of two points of interest: the evaporators, and the quick disconnects.

The internal channels in the aluminum evaporators were formed by machining grooves in an aluminum plate and sealing the top off with another aluminum plate, secured via a vacuum brazing process. Afterwards the required mounting holes and surface finishes were machined. Several challenges in meeting the tight tolerances for mounting the electronics were encountered and overcome.

Fig. 8: Thermal cabinet with balance of plant components

The modular nature of the cells, meant that the evaporator plates needed to be easily removed and inserted into the circuit breaker chassis. Because the back of the chassis may not be accessible, the fluid connections had to be blind-mate connectors which seal when disconnected to prevent venting refrigerant from the system. For the specific requirements of this system a of low-loss, blind-mate, quick-disconnect fitting could not be found off-the-shelf, so custom fittings were designed and fabricated. Included in the design of these fittings is customized geometry to aid in coolant flow distribution between the evaporators, which is critical to providing isothermality from one evaporator to another.

5 Test Procedure

The isothermal operation of the cooling system at each evaporator was validated by testing the SSCB and cooling system in the lab. A 20 ton water chiller was connected to the cooling cabinet to emulate the shipboard water supply. The chiller regulated the cooling water temp between 10-15°C by using simple on/off thermostat control of its compressor.

Pressure and temperature sensors were included in the refrigerant flow at several points in the system: the pump inlet, pump discharge, manifold inlet, manifold outlet, and condenser outlet. These sensors allow the calculation of the operating point of the refrigerant on the saturation curve. These sensors were monitored during testing to ensure proper operation of the cooling system, such as making sure that the refrigerant had not completely evaporated at the manifold outlet.

The cooling system was tested by turning on one of the refrigerant pumps and setting it to run at 75 percent of its rated speed. For this system, this speed was determined to provide enough refrigerant flow to cool the SSCB under all load conditions without boiling off all the refrigerant in the evaporators. Closed loop control of the refrigerant pump to match the refrigerant flow rate with the instantaneous cooling demand of the semiconductors is possible but was not tested here.

When the breaker is conducting current, the evaporators heat up due to the semiconductor losses, with the system temperature regulated by the cooling water flow control valve. During initial testing, the flow control valve spring tension was adjusted while the system was running until the regulated temperature at the manifold outlet reached the desired operating point.

6 Experimental Results

With the system at ambient temperature, and the refrigerant pump running, the SSCB rated current was applied to the system. Figure 9 shows the measured temperatures of each of the 12 evaporators as measured by thermocouples during the test. The temperature of the evaporators quickly rises until the cooling water flow control valve opens to regulate the temperature by allowing cooling water into the condensing heat exchanger. After the cooling valve starts regulating, the coolant continues to heat up slightly for about 1 hour as other components in the system such as bus bars reach the final steady state operating point. After 1 hour, the temperature measured at each evaporator stays approximately constant. The small variations seen are due to the water chiller swinging between its upper and lower setpoints. The test results show that each evaporator is regulated to within < 4°C of the other evaporators for the duration of the test. The observed differences in the evaporator temperatures are most likely due to slight flow imbalances between the different coolant paths.

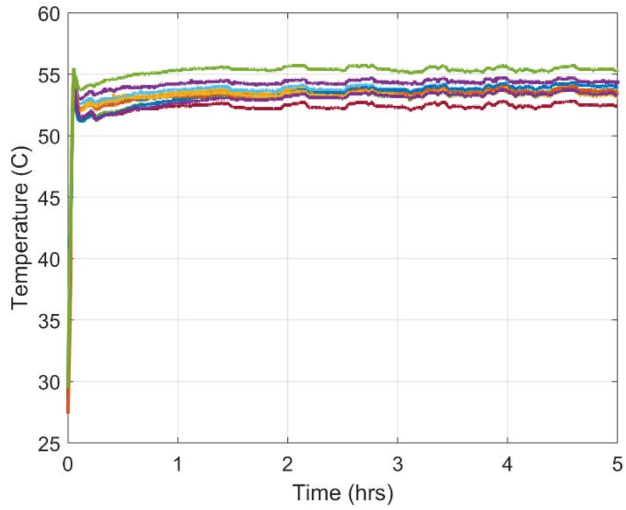

Fig. 9: Temperature of each of the 12 evaporators during a 5-hour thermal test

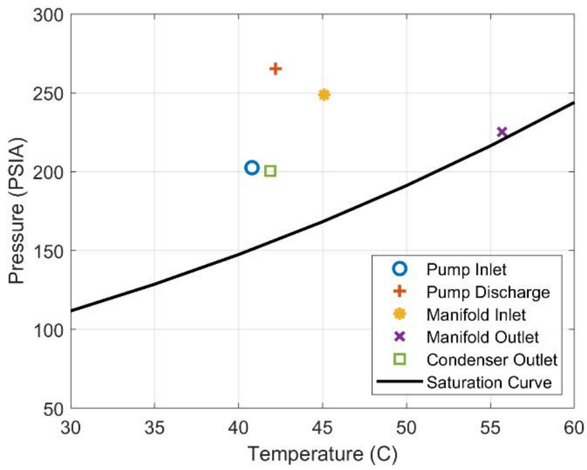

Fig. 10: Steady state operating point of the cooling system at full load

To understand that the cooling system is operating as designed, the pressures and temperatures at each point along the fluid path can be monitored. Figure 10 shows the steady-state operating point pressures and temperatures of the refrigerant in the cooling system at full load, which are plotted at various points along the refrigerant flow path. As expected, the refrigerant is sub-cooled at the condenser outlet, pump inlet, pump outlet, and manifold inlet. As the refrigerant absorbs heat along the evaporator, a fraction of the refrigerant boils off and the refrigerant at the manifold outlet is

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on the refrigerant saturation curve. Note that slight inaccuracies in the thermocouple temperature measurement of the refrigerant make the manifold outlet appear to be slightly off the saturation curve even though the refrigerant is partially evaporated at this location.

The control system of the breaker monitors the operation of the cooling system and calculates the state of the refrigerant in the system. If the refrigerant becomes super-heated at the manifold outlet or any other point in the system, the breaker is opened automatically to prevent overheating.

7 Analysis

Experimental results revealed that at steady-state operating conditions, the refrigerant inlet was subcooled by about 10°C which was far greater than the 2°C expected. A mathematical model of the cooling system was developed to understand the discrepancy. Based on measured temperatures and pressures, and estimated pressure drops of various system elements, refrigerant specific enthalpy was calculated with the aid of look-up tables of the R134a properties [5]. The resulting pressure – enthalpy diagram is shown in Fig. 11.

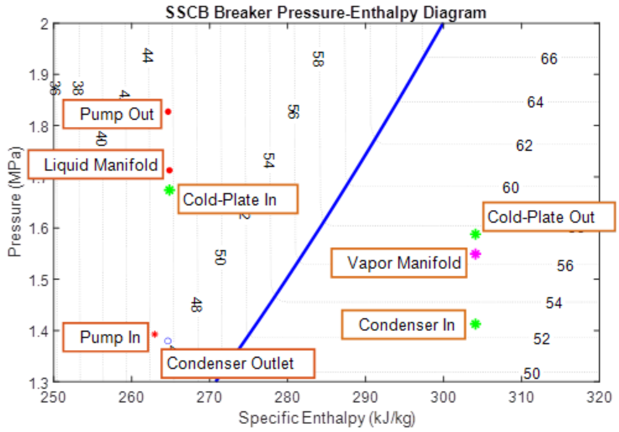

Fig. 11: Steady-state conditions around the cooling loop as modeled using measured data.

The green and magenta stars are calculated operating points of the evaporator, vapor manifold, and input of the condenser; points where sensors do not exist in the prototype system. The unexpectedly high pressure drop of 39 psi between the vapor manifold within the breaker cabinet and the condenser inlet at the cooling cabinet is because of a ten-foot hose connecting the cabinets. The pressure drop results in a temperature drop which ultimately results in greater subcooling of the refrigerant. As previously mentioned, future iterations of the system will co-locate the balance of plant refrigeration components with the SSCB components. This will significantly reduce system pressure drops and pump power, resulting in a more compact and efficient system.

8 Conclusions

Medium voltage SSCBs present several design challenges due to the need for paralleled and series-connected modules to meet the system current and voltage ratings. Combining P2P cooling with this medium-voltage SSCB design allows for significant advances in efficiency and power-density while maintaining the isothermal operation and voltage isolation requirements of the design.

P2P provides significant advantages over liquid cooling in the realms of isothermality and system efficiency, which enables the advancements demonstrated by this SSCB prototype. The dramatically lower flow rates required by P2P, as compared to liquid cooling, result in smaller pumps, plumbing, and electrical power draw.

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