Hybrid Circuit Breakers

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***Abstract*—U.S. Navy ships need more electric power for increased capability, automation, mobility, lethality, and they need increased operating efficiency for reduced fuel costs. The hybrid circuit breaker developed a Low Voltage Direct Current (LVDC) breaker operating at 1 kV with a steady state current of 5 kA, and, importantly, with up to 50 kA fault current interruption capability. DC circuit breakers can operate faster than AC and counter-pulse DC breakers, since they circumvent the current zero-crossing requirement of AC breakers. Protective DC switchgear is a key element in a DC power distribution system that provides electric power reliably and cost-effectively, utilizing more efficient, high-power sources, energy storage, and transmission. For over 25 years, Diversified Technologies, Inc. (DTI) has been designing and building high-voltage DC circuit breakers capable of multi-kA switching at voltages up to and greater than 100 kV. DTI has shipped and qualified for military applications hundreds of systems. These switches are well-suited for shipboard DC circuit breaker applications. This** *paper describes on-going hybrid circuit breaker development at DTI.*

Keywords—Low Voltage Direct Current (LVDC), hybrid circuit breaker, DC switchgear, Naval Power Systems, Integrated Power and Energy System (IPES)

I. Introduction

Advanced development of low voltage direct current circuit breakers is needed to better protect 1000 VDC, 5 kA circuits in DC power distribution systems. New technologies and techniques are critical to the implementation of a practical, qualification-ready unit. Diversified Technologies, Inc. (DTI) has designed and delivered high-voltage DC circuit breakers capable of multi-kA switching at voltages up to and greater than 100 kV and low current. DTI has shipped and qualified hundreds of systems for military applications. As the technology and underlying switching components have evolved, these switches are now capable of opening and closing in high power, continuous (DC) switching applications at many tens of MWs – the key requirements for a DC circuit breaker. Solid state hybrid circuit breakers, see Fig. 1, provide high performance with very low conduction losses and very large fault currents interruption capability. Note the two IGBTs represent many modules in parallel which share the fault current and allow scalability for increasing levels of fault current protection. DTI is developing a family of hybrid circuit breakers, see Fig. 2, for LVDC applications with high fault current capability up to 50 kA.

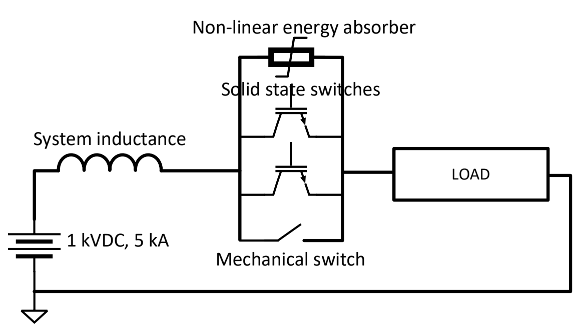

Fig. 1. Simplified electrical schematic of hybrid circuit breaker with parallel switches.

Fig. 2. Hybrid circuit breaker rated at 1 kV, 5 kA-continuous with mechanical contacts and modular solid state switch for 25 kA fault current. Module adiabatic thermal inertia allows network-coordinated interruption delays up to 50 ms; solid state switches interrupt in less than 1 ms. The breaker mechanically racks-out internal to the cabinet for galvanic isolation.

A. Hybrid SSCB

Hybrid circuit breakers combine the low steady state losses of mechanical contacts with the arc-less and low maintenance characteristics of solid state switches. For LVDC voltages, mechanical circuit breakers have been developed for commercial applications that can operate continuously up 5 kA to 8 kA. Modifying these breakers into a hybrid circuit breaker configuration yields specific performance advantages. The hybrid circuit breaker design utilizes a conventional mechanical contactor combined with solid state switches. The hybrid circuit breaker eliminates the arc chutes in the conventional mechanical breaker by substituting a solid state

Table 1. DC Circuit Breaker Specification

Nominal Voltage	1,000 VDC
Steady State Current	5,000 A
Modular Hybrid Fault Current	50,000 A via multiple modules; system is scalable and maximum fault current can be more or less
Reset Time	>few minutes 1st to 2nd close
	>5 minutes 2nd to 3rd close

circuit breaker for arc-less interruption and no arc debris. Greatly reduced breaker maintenance is achieved by eliminating this high current arc between the separating contacts, preventing arc debris and contact erosion. Power density is also improved by removing the arc chutes in favor of compact solid state devices. In addition, operator safety is increased because there is no danger of arc-flash. Quicker current interruption occurs since the contacts must separate only a much shorter distance to re-establish LVDC standoff voltage before the semiconductor switch interrupts the current. A hybrid circuit breaker offers scalability, eliminates hazardous, disordered, and chaotic arcs associated with separating-contact mechanical breakers, reduces fault currents and their damaging mechanical forces, and increases contact-life. Table 1 gives a typical LVDC hybrid circuit breaker specification.

II. METHODS—POWER DISTRIBUTION HEIRARCHY

A power distribution system typically has several levels of circuit breakers to provide redundancy in case of a failure. When a load experiences a fault, the circuit-breaker nearest that load should open first – this allows other loads to continue operation. The higher-level circuit-breaker opens only if the lower-level load breaker does not open (or if there is a fault in the line between the higher and lower-level breakers). In this way, power can be maintained to the maximum extent across the power system.

Ordinary mechanical circuit breakers can be built for very high currents but cannot physically open in times less than a few milliseconds and they often require several 10's of milliseconds to interrupt a fault. In the time before the switch opens, fault current can build up to very large values. As an example, in twenty milliseconds fault current for a mechanical breaker can rise to 20 kA for a 1 kV system with a total system inductance of 1 mH. This would generate a significant arc flash, arc debris, and maintenance action for the contacts after a certain number of such interruptions.

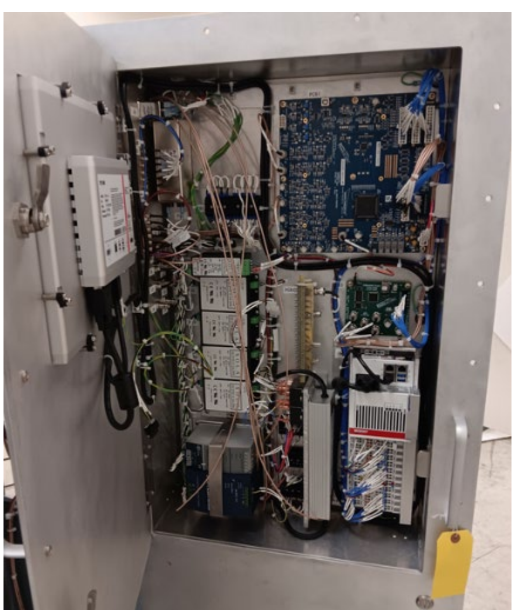

Fig. 4. Close-up of DTI Control Panel installed on the hybrid circuit breaker door. The control module includes PLC-based interface, touchscreen controls, remote operation capability, and fully programable interface.

Hybrid circuit breakers operate differently. If a delay in fault interruption is desired to allow downstream breakers to operate to minimize power system disruption, the mechanical contacts are immediately separated diverting the current into the solid state switches. As discussed earlier, there are many switch modules electrically in parallel to share the current. The modules have sufficient thermal inertia to ride out full fault current for up to 50 ms. Anytime after the contacts have separated and regained voltage standoff, the solid state switches can be electronically interrupted without arc flash, arc debris and no degradation of contacts occurs requiring maintenance. Upon electronic command, the fault current is quickly quenched, typically in less than 1 ms. Hence, the hybrid breaker offers advanced networking coordination capability along with arc elimination, and fast interruption.

III. CONTROLS AND SHIPBOARD INTEGRATION

The circuit breaker control module is physically separated from the high power breaker region, see Fig. 4. Circuit breaker control may be established locally or remotely via optional network connections. The network connections allow system-coordinated device operation and remote status indication and communications. If local controls are employed, a graphical user interface (GUI) is provided to enter operational parameters (instantaneous trip current, short- and long-trip parameters, etc.). The GUI also shows fault status when applicable. Fig. 3 shows sample results of programming the I^2t interruption curves.

As mentioned above, it is desired to delay upstream circuit breaker action with downstream (slow) mechanical breakers to give them opportunity to operate. Hence, in this scenario, the

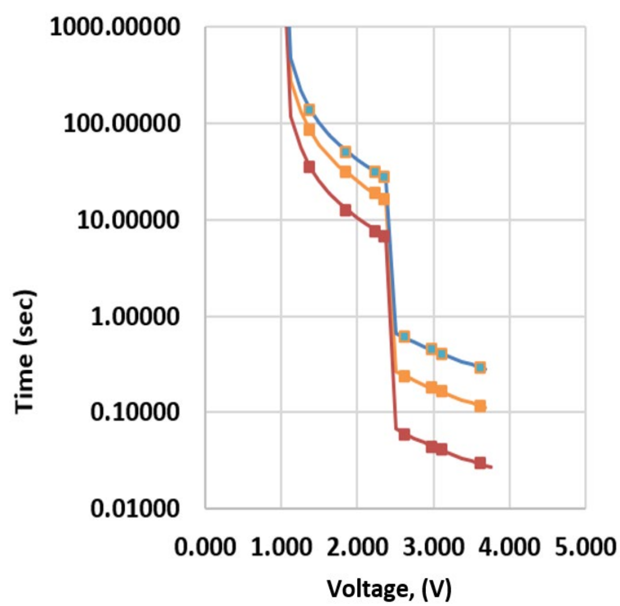

Fig. 3. DTI's hybrid circuit breaker permits remotely and dynamically programmed parameters defining the I^2t interruption curves. Three curves demonstrate various settings. The x-axis is the control voltage for the test.

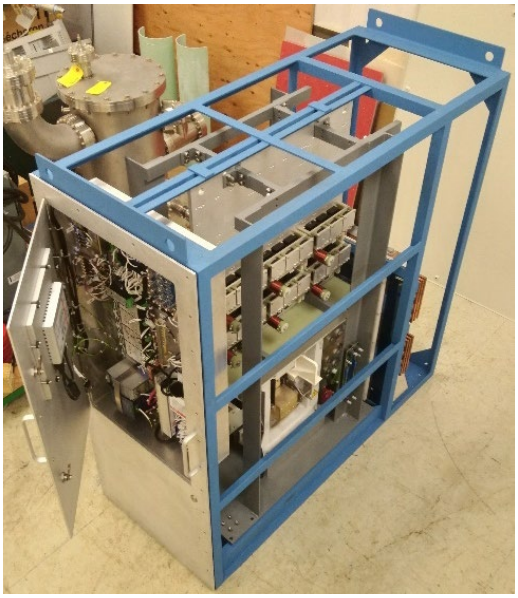

Fig. 5. Modified hybrid circuit breaker with open control panel and semiconductor switch modules. The number of modules installed determine the maximum fault current and can be up to 50 kA with this design.

upstream hybrid circuit breakers must have a peak current capability far in excess of its rated current.

DTI is developing a family of production circuit breakers to cover the range of current ratings the Navy needs for future ship electrical needs. See Fig. 5. The development of switchgear enclosures for the (eventually) fully military-qualified breakers is being planned. Shipboard integration is approached by merging commercial and Naval switchboard architecture. Each switchboard is self-contained and modular – adaptable configurations depending on specific distribution node. The high voltage bus bars are in the upper rear power distribution area, and the load distribution system in lower rear area. Physical separation between the two areas can be provided facilitating safe access if needed, e.g., while the breaker is racked out. The breaker section has shutter doors to secure access to upper and lower distribution areas while racked out for maintenance.

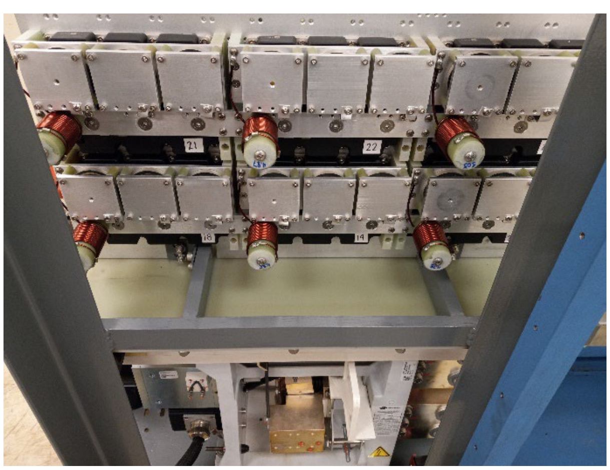

Fig. 7. Installed solid state switch modules. The system was designed for 50 kA; it was populated and tested with modules for 25 kA.

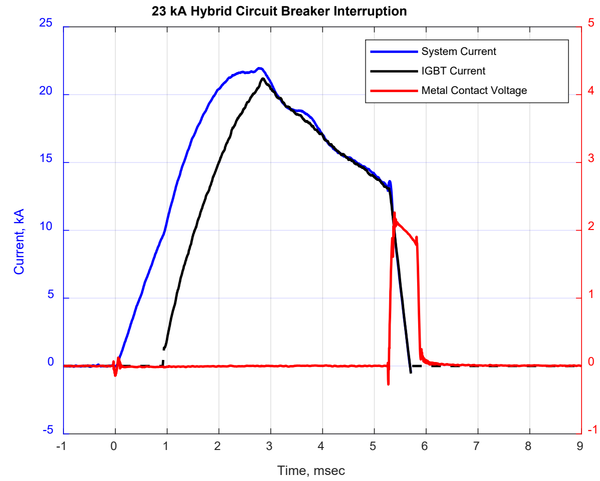

Fig. 6. Interruption of a peak current of 23 kA using hybrid circuit breaker.

IV. Reliability of Solid State Systems

Solid state circuit breakers can be extremely reliable, and DTI has fielded hundreds of systems over 25 years without failures. In fact, when operated within design limits, field failures are invariably attributed to one of two errors: operator error, or thermal system failure. DTI employs rigorous design margins, device de-rating, internal fault protection (overcurrent, overvoltage,) and thermal design. As an example, since March 2011 DTI has had circuit breakers on the seabed 2 miles below the surface, 600 miles off the Oregon coast.

The hybrid breaker was designed for a fault current of 50 kA; to conserve costs and demonstrate the capability, amply de-rated and protected modules sufficient for 25 kA were installed and tested, as shown in Fig. 7 and Fig. 6.

V. Results

A controlled high-current capacitor discharge was utilized to simulate a fault-current scenario and test the hybrid circuit breaker. (The test circuit is similar to Fig. 1 with the battery source replace by a capacitor and the discharge initiated by an SCR.) A current interruption test achieving 23 kA was performed as shown in Fig. 6. The mechanical contacts first carried the current, and then separated and transitioned the current to the IGBTs. At the selected time (5.3 ms in Fig. 2), the IGBTs open, and the current transitioned to the energy absorber. The voltage rises to 2 kV and the current interrupts in about 0.5 ms = $\Delta t = L*\Delta I/V$, where L=64 uH.

VI. Conclusions

Advanced development of low voltage direct current (LVDC) circuit breakers to protect 1000 VDC, 5 kA circuits was performed for DC power distribution systems. DTI has demonstrated a networkable LVDC hybrid circuit breaker rated at 1 kV, 5 kA-continuous, 25 kA fault-current (scalable to 50 kA). It operates in a three-step process: (1) continuous low-loss metal-metal conduction, (2) pulsed current transfer to semiconductor switches during metal contact separation period,

(3) commanded switch interruption and energy transfer to dissipative devices. The solid state switches can carry the fault current for up to 50 ms to allow coordinated network switching. The circuit breaker has been demonstrated up to 2 kV, 23 kA.

Hybrid circuit breakers offer scalability, eliminate interruption arcs and arc debris, reduce fault currents and associated forces, and increase contact-life and reduce maintenance.

A qualified family of hybrid circuit breakers sized for particular applications at greater or lesser capabilities is readily possible.

VII. Acknowledgments

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