Hybrid and Solid State Circuit Breakers

Dr. Marcel P.J. Gaudreau P.E., Dr. David Cope, Joe Harbour, Shannon Hunter, Dr. Susie Eustis,
Robert Phillips, Michael Kempkes, Rebecca Simpson
Diversified Technologies, Inc. (DTI) Bedford, MA (USA)

***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. This is motivating the adoption of Direct Current power distribution systems. The voltage range is from 1 kV to 12 kV or greater (LVDC to MVDC), and the steady state current range is up to 5 kA. DC circuit breakers operate faster than AC 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 and solid state circuit breaker development at DTI.**

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

I. Introduction

This century has seen tremendous advances in the capabilities of advanced switching devices and techniques. Diversified Technologies, Inc. (DTI) originally developed high voltage, solid state switching technologies for pulsed power applications, typically at high voltage but relatively low currents (100's of amps) and modest average powers (hundreds of kWs). 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 hundreds of MWs – the key requirements for a DC circuit breaker. This technology is based on hundreds of DTI-deployed solid state switches in high reliability applications and is inherently redundant. The devices are calculated to last for greater than 1 million cycles.

The benefits of solid state circuit breakers (SSCBs) are well-known: extremely high speed switching (microsecond speeds), no mechanical moving parts, no arcs, very low maintenance, low acoustic and magnetic signatures, etc. And being fully electronic, the circuit breakers are networkable for coordinated switchgear operation. Fig. 1 shows an air-cooled 20 MW/m^3, 12 kV, 750 A circuit breaker DTI has developed. The primary challenge facing a high-power, solid state DC circuit breaker is the heat dissipated by the semiconductors when carrying high steady state currents. The actual efficiency is still quite high (>99.9% is not uncommon), but the great capability of the circuit breaker means the controlled power might be 48 MW (12 kV, constant 4 kA), thus up to 48 kW of heat might be generated steady state. These losses arise from the voltage drops of the individual devices, which are typically ~2-3 V per device, but can result in significant losses when several devices are stacked in series and paralleled for high currents.

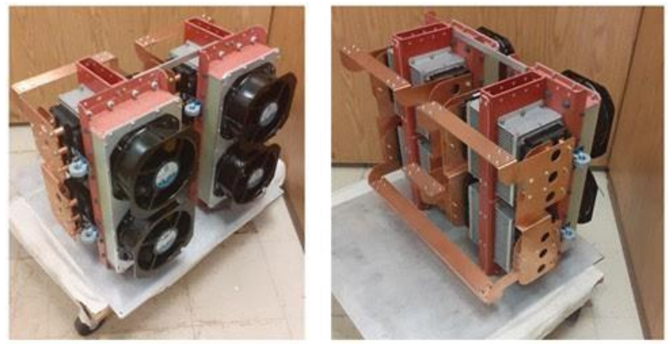

Fig. 1. MVDC solid-state circuit breaker rated at 12 kV, 750 A (9 MW).

Hybrid circuit breakers combine the low steady state losses of mechanical contacts with the arc-less and low maintenance aspects of semiconductor switches. DTI has recently demonstrated a medium-voltage direct current (MVDC) hybrid circuit breaker which operates in a three-step process:
(1) continuous high current through low-loss metal-metal conduction, (2) momentary current transfer to semiconductor switches and contact separation, (3) commanded switch interruption and energy transfer to dissipative devices. Note in this case, the solid state breaker conducts only during fault conditions.

II. Overview

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 the 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.

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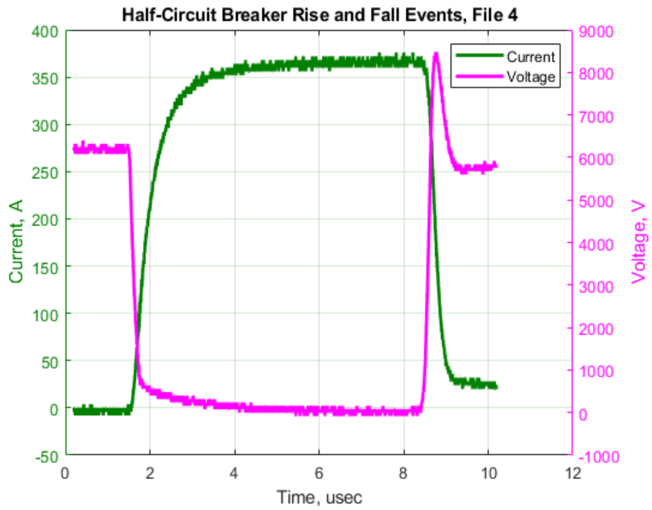

Fig. 2. 6 kV, 375 A MVDC SSCB module Close and Open sequence.

Mechanical circuit breakers can be built relatively inexpensively 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 the fault current can build up to very large values. As an example, in ten milliseconds the fault current for a mechanical breaker can rise to 100 kA for a 10 kV system with a total system inductance of 1 mH.

In contrast, the current rise for a solid-state switch into this same load is only 10 A, with an opening time of 1 μs. The small fault current and fast opening time for a solid-state switch mean that, unlike the system with a mechanical switch, there is minimal impact to the load from a fault – it never sees high currents, never experience high forces, and never endures damaging energy levels. Fig. 2 shows fast closing and opening times of a solid state breaker.

SSCBs can readily be programmed to open instantaneously at arbitrary currents, up to their maximum rating. In addition, short-time and long-time trip parameters can be programmed. Furthermore, if desired, a "battle-short" condition preventing interruption may be enforced for critical loads, even if a fault is detected. (Note the specifications for a mechanical switch should not be directly applied to a solid-state switch.)

In a power system with a combination of solid state and mechanical breakers, coordinating the vastly different time-scales of mechanical and solid-state breakers represents a critical controls challenge, but one that can present substantial opportunities for fault isolation and recovery. Ideally, since they open so quickly, SSCBs would be used at the point-of- load for individual loads. The speed of a SSCB will prevent damage to critical systems, while mechanical breakers can serve as the final stage of protection for entire power subsystems.

III. Solid-State Circuit Breakers

DTI has designed a family of 12 kV solid state circuit breakers with rated current from 750 A to 4000 A. In addition, DTI has fabricated and tested the MVDC circuit breaker in Fig. 1.

The 12 kV, 750 A device is composed of modules. Fig. 2 shows circuit breaker operation of a 6 kV, 375 A module. For the rated breaker, there are a total of four modules: two modules in series (total rated voltage of 12 kV) and two modules in parallel (total rated current of 750 A).

Fig. 3 shows measured data from module full-current tests. As expected, the air-cooled unit reaches thermal equilibrium in approximately 30 minutes.

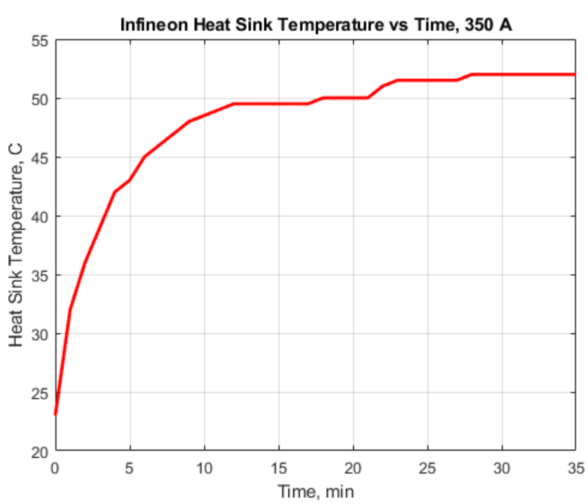

Fig. 3. Steady State SSCB Thermal Test. Measured heat sink temperature as a function of time. The time constant of the increase in temperature is about 8 minutes and equilibrium is reached in approximately 4 time constants or about 30 minutes.

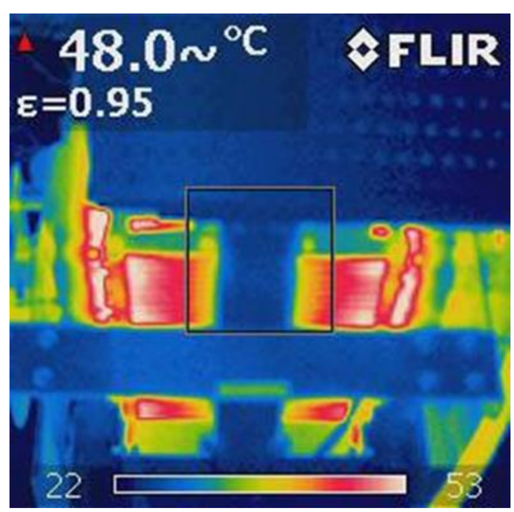

Fig. 4. Infrared camera view showing peak temperature of ~53 C during steady state rated current testing of Prototype breaker.

Fig. 4 shows an infrared camera view of the breaker heat sink. Peak measured temperature is 53 C.

DTI has performed detailed design studies, including simulations and critical component testing, to confirm a SSCB can be built which is designed for 1 kVDC 10 kA continuous current with maximum fault current of 105 kA for 0.5 seconds and 280 kA for 10 ms. This capability (rated_current : fault current :: 10 kA : 280 kA) is revolutionary in SSCB performance.

IV. Hybrid SSCB

For voltages in the range of LVDC, mechanical circuit breakers have been developed for railway applications that can operate up 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. Greatly reduced breaker maintenance is achieved by eliminating the high current arc between the separating contacts. This eliminates the arc, arc debris, and contact erosion. 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. The hybrid circuit breaker eliminates the arc chutes and substitutes a solid-state circuit breaker for arc-less interruption and no arc debris. 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. Table1 gives the LVDC hybrid circuit breaker specification.

DTI is part-way thru a hardware upgrade of a commercial-off-the-shelf (COTS) LVDC mechanical breaker (Fig. 5) to pass military environmental qualification testing as a hybrid breaker. Since designed as a breaker for railway substations,

Fig. 5. DTI-modified hybrid circuit breaker with ruggedized, smaller enclosure. The cream-colored volume is the arc chutes. These will be removed and replaces with the hybrid semiconductor switch.

Fig. 6. Local SSCB controls. Unit may also be networked for coordinated switchgear operation.

various internal components such as the trigger mechanism and system interlocks require ruggedization, as well as changes to the enclosure frame to meet shock and vibration requirements. In addition, substantial customization is also necessary to achieve suitable controls programmability, rackability, and bus bar distribution panel connectivity.

V. Controls and Shipboard Integration

The SSCB Control box is shown in Fig. 6. Control may be provided locally or remotely via optional network connection. The network connection allows 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 SSCB fault status when applicable.

Fig. 7 shows exercise of the SSCB controls. The control parameters were changed to demonstrated various I^2t interruption characteristics.

As mentioned above, the fast switching capability of SSCBs allows the maximum device current be only slightly greater, say 10% greater, than rated current. This is because the device can assuredly interrupt fault current before it increases to unmanageable levels.

When combining fast SSCBs with downstream slow mechanical breakers, however, it is desired to delay SSCB interruption until the downstream breakers have had an opportunity to operate. Hence, in this scenario, the SSCB must have a peak current capability far in excess of its rated current.

A simplified zonal MVDC power distribution system is shown in Fig. 8. A networked switchgear protective system monitors load integrity between zones, and cable integrity within zones. The yellow boxes in the figure identify power system intelligent node checking. That is the current leaving node 52 and the current arriving at node 42 should be equal and opposite. Other integrity checks are also possible, as indicated.

DTI is characterizing the family of production circuit breakers to cover the range of current ratings the Navy needs for future ship electrical architectures. The development of

TABLE 1. DC CIRCUIT BREAKER SPECIFICATION

Nominal Voltage	1,000 VDC
Steady State Current	5,000 A
Modular Hybrid Fault Current	50,000 A; multiple modules can be used
Reset Time	2 min 1st to 2nd close
	5 minutes 2nd to 3rd close

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 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.

VI. RELIABILITY OF SOLID STATE SYSTEMS

Solid state circuit breaker reliability is determined by the design margins and device de-rating, internal fault protection (overcurrent, overvoltage,) and thermal design. DTI has fielded

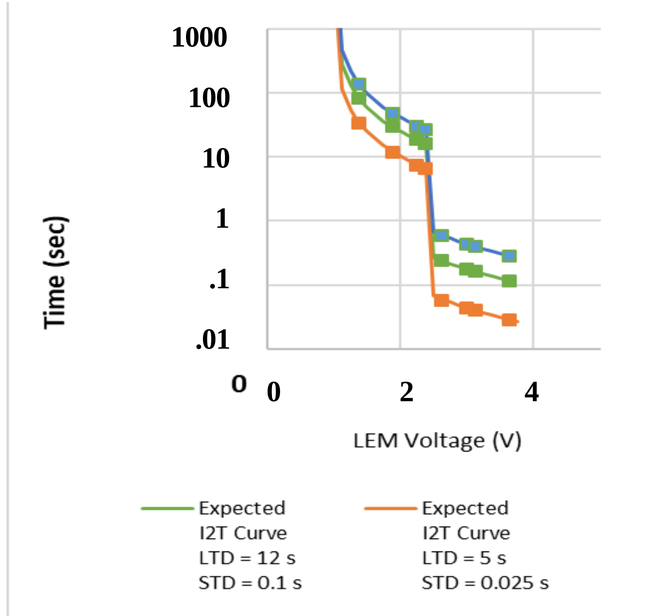

Fig. 7. Demonstration of variation of I^2t circuit interruption parameters.

hundreds of systems over 25 years without failures. Those systems which have experience failures in the field had one of three types of errors: operator error (e.g., disconnected overcurrent sensor), thermal failure (e.g., operating with fans or pumps), or simply operating well beyond device specifications.

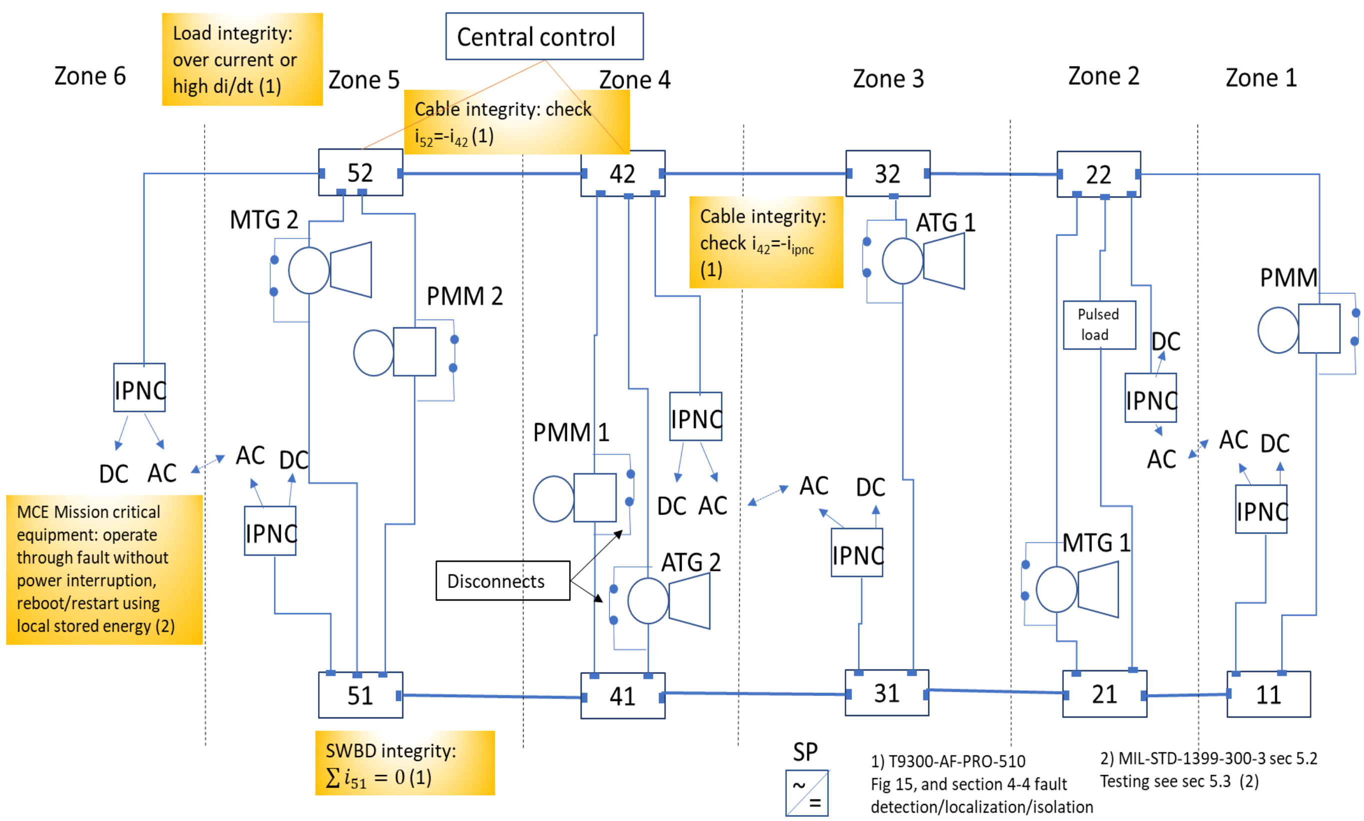

Fig. 8. Communications and control of an example MVDC system with zonal control and load integrity monitoring. The yellow boxes identify power system intelligent node checking. That is, the current leaving node 52 and the current arriving at node 42 should be equal and opposite

VII. Results & Conclusions

Solid state circuit breakers enable new operating principles for power distribution switchgear. The very fast opening capability allows more efficient power systems by eliminating the design for overload penalties. This means loads such as motors do not need to be designed for 100X rated forces because fault currents can be limited to 110% of rated current. Network coordination can occur quickly enough to still take advantage of fast interruption switchgear.

Hybrid circuit breakers offer scalability, eliminate arcs, reduce fault currents and forces, and increase contact-life. Naval shipboard integration will be accomplished through the merging of advanced solid-state designs and the legacy commercial and Naval breaker architectures.

Purely SSCBs represent a longer-term development effort. Increasing the efficiency of these devices, and configuring their capabilities to integrate with both mechanical and hybrid breakers in future Navy applications remain as challenges to be addressed. DTI is investigating both LVDC (1 kV) and MVDC (12 kV) solid-state circuit breaker designs under multiple research projects.

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