Solid-State Circuit Breakers For Medium Voltage DC Power

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***Abstract* - How can the large power needs of future electric ships for propulsion, radar, and weapons systems be met given the prohibitive size and weight of the required number of standard 60 Hz AC generators and transformers? A solution may lie in a rugged, efficient, and compact solid-state, 10-20 kV Medium Voltage DC (MVDC) circuit breaker (Figure 1). In this paper, Diversified Technologies, Inc. will describe the architecture of a Medium Voltage DC (MVDC) circuit breaker. The solid-state, 10 - 20 kV class breaker is a breakthrough that establishes the viability of MVDC power distribution. It delivers extremely fast fault interruption, low peak currents, flexible and programmable coordination, and mechanical isolation; the keys to reliable and safe operation.**

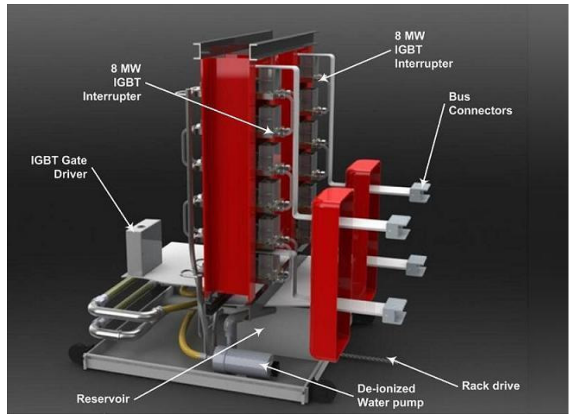

Figure 1. Conceptual drawing of a solid-state circuit breaker comprised of two 10 kV, 8 MW interrupters. Chassis barrier (not shown) measures 32” by 32” by 42” high. The entire breaker is on a horizontal drawout chassis which is disconnected or reconnected to the buswork by the isolated high-current bus connectors.

I. Introduction

The distribution of power via MVDC links is under serious consideration by power system designers for several reasons. First, Naval vessels must power propulsion, radar, and weapons systems, all of which require a DC input. However, the cumulative size and weight of the necessary number of standard 60 Hz AC generators and transformers is undesirable. Second, future electrical power requirements are expected to support power converters capable of integrating a range of alternative sources and storage systems, including wind power, solar power, battery storage, and flywheels, with a range of voltages, frequencies, and power levels. DC links are ideal for this integration, but cannot be safely deployed without effective DC circuit breakers. Ultimately, the flexibility of DC power distribution systems can enhance the capabilities of both commercial and Naval power systems.

In MVDC distribution, a central MVDC bus transmitting 10 – 15 kV DC supplies power from one or more sources to the various system loads. Within each zone, power converters (DC-AC and DC-DC) locally condition the power. The wide variety of loads in an all-electric ship require advanced circuit breakers / switchgear and power converter modules that are capable of meeting the emerging standards for MVDC power.

Solid-state circuit breakers are a key enabling technology for MVDC power distribution since they can interrupt current under full load, on microsecond timescales, resulting in fault currents only a few times the nominal load current. Unfortunately, the deployment of MVDC power has been hindered by the lack of suitable DC circuit breakers and high-voltage switches. These requirements can now be met using fast, solid-state, high voltage opening switches.

The same class of switches also enables high frequency, high-voltage switching power converters that are rugged, efficient, and compact.

II. Solid-State High Voltage Switching

DTI’s high-voltage, solid-state switches are series arrays of semiconductor devices operating as a single switch. Although the concept is simple, its execution requires careful synchronization of gate controls and snubbing of stray energy in order to ensure reliable operation and long life of the switch. These arrays can be constructed from several types of semiconductor devices. The Insulated Gate Bipolar Transistor (IGBT) is often the best choice, because of its wide commercial availability, ruggedness, speed, and low power requirement to run the gate drive. However, for very high power applications (> 10 MW), the Integrated Gate Commutated Thyristor (IGCT) is desirable because of its low conduction loss. In the future, this same high voltage technology can be used with SiC or GaN devices as they become available (and affordable), providing even lower conduction losses, and wider ranges of operating temperature, eliminating the need for active cooling.

A. Fast Fault Interruption

Solid-state, high-voltage switching enables dramatic advances in circuit breaker performance, yielding improved system reliability and safety. Because a solid-state switch can interrupt the full current in microsecond timescales, local fault protection can be provided completely through the control system of the switch itself, without the need for external fault detection.

Figure 2 shows waveforms from a 100 kV opening switch which responds quickly enough to limit the fault current (350 A) to less than twice the nominal maximum load current (200 A). The fault protection

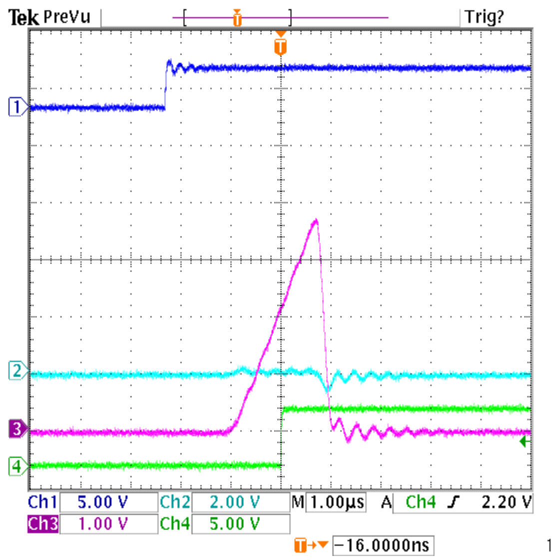

Figure 2. Typical DTI switch response to a fault. Ch1 Pulse Command; Ch2 Load voltage (short-circuit); Ch3 Load current (100 A/div); Ch4 Fault (trips at 200 A); Time 1 μs/div.

capability of the switch is dramatically demonstrated by shorting a #40 AWG wire directly across the load without destroying the test wire. It is this ultra-fast and ultra-safe opening capability that provides the basis for the MVDC solid-state circuit breaker.

B. Solid-State vs. Mechanical Switches

Fast solid-state opening switches are an enabling technology for DC power distribution, since these devices interrupt current without forming an arc and therefore, do not require voltage reversal. The differences between a solid-state switch and a mechanical switch can be seen by comparing their respective time-current plots.

The horizontal asymptotes of the inverse-time curves in Figure 3 indicate that mechanical switches *cannot* open in less than a few milliseconds. This means that the current into a short-circuit fault will rise to very for a mechanical switch would rise to 10 kA for a 10 kV

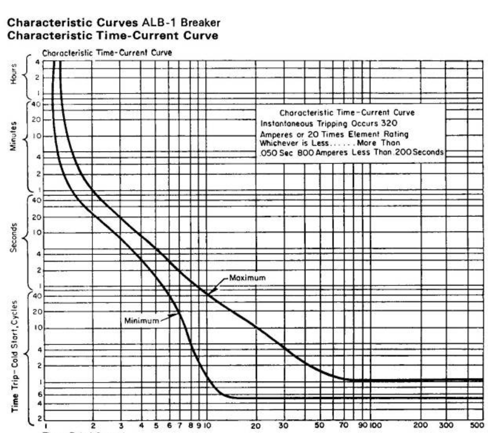

Figure 3. Typical characteristic time-current curve for a small, low-voltage Navy ALB-1 AC circuit breaker. Reliably tripping the breaker in one cycle (17 ms) requires many times the rated current.

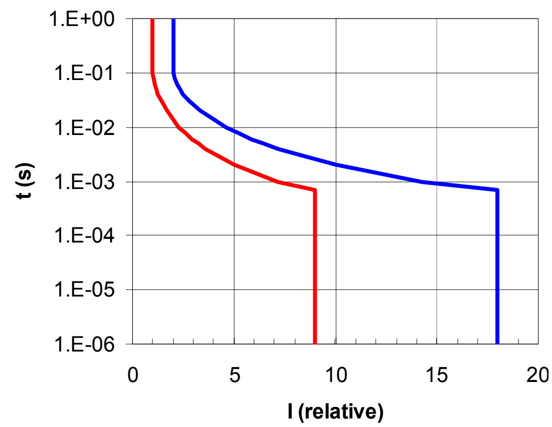

Figure 4. Conceptual time-current limits for two solid-state circuit breakers. The blue curve has twice the current capability as the red curve. Note that a solid-state breaker can open in 1 μs. The breakers can be programmed to open with a time-current profile less than or equal to the maximum interrupter current.

system with a total system inductance of 1 mH.

Figure 4, in contrast, shows curves for the maximum current that two coordinated solid-state switches are programmed to carry. The current rise for a solid-state switch into this same load would only be 10 A, with an opening time of 1 μs. The small fault current and fast opening time for a solid-state switch means that, unlike the system with a mechanical switch, there is minimal impact to the load from a fault – the fault will not be allowed to reach damaging energy levels. Solid-state switches can also be programmed to open at arbitrary currents, up to their maximum rating. If these two switches (circuit breakers) are in series, the switch corresponding to the red curve will always open sooner than the one represented by the blue curve.

III. BREAKER LAYOUT

A simplified block diagram of a solid-state circuit breaker is shown in Figure 5. The solid-state current interrupter is comprised of a series string of solid-state devices to safely handle the DC bus voltage. A fast coordinated inverse-time controller provides the gate drive signal for the switches in the interrupter which synchronously open and close. The fast inverse time controller receives commands from either a manual input, from other breakers in the network, or from fast sensors that detect local fault currents. The inverse-time controller provides inverse trip time control for overcurrent states, and a fast instantaneous trip if the overcurrent limit is reached, as shown in the coordination curve in Figure 4. These operational parameters can be adjusted for each breaker depending on its location in the network, providing orderly, sequenced response to fault conditions.

A. Solid-state Interrupter

The solid-state interrupter provides the primary functionality of a complete circuit breaker assembly: fast fault protection and isolation. The complete circuit breaker assembly must also provide a means of safely

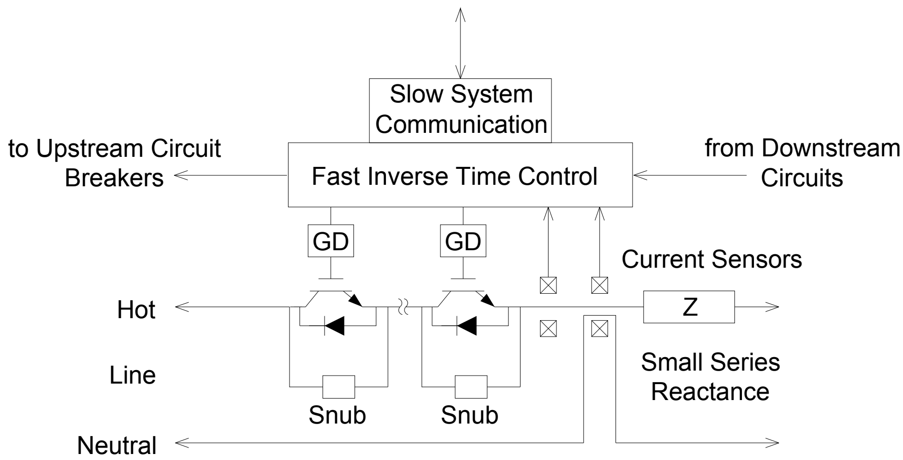

Figure 5. Simplified system diagram of a typical MVDC solid-state circuit breaker.

disconnecting the interrupter from the power network when maintenance or service is required.

The chosen design concept for the MVDC interrupter is an IGBT based load interrupter that carries up to 800 A at 10 kV, and relies on series combinations of power devices to handle the MVDC bus voltage. Parallel arrays of these assemblies are used to meet the overall current requirements for the load.

A preliminary layout for an 8 MW load-level circuit interrupter is shown in Figure 6. This interrupter consists of six 4,500 V IGBTs (CM900HB-66H) connected in series. The 8 MW interrupter is approximately 23” wide x 9” high × 11” deep and weighs approximately 60 lb. The IGBTs are mounted on water-cooled aluminum cold plates, which are, in turn, mounted on an electrically insulating mechanical frame. The non-metallic water lines are sufficiently resistive to limit the current leakage down the lines. This will require a small, closed-loop cooling system and a long lasting ion-exchange cartridge to maintain the resistivity of the cooling water.

B. Distribution Topology

As in conventional AC distribution, the DC circuit breaker could be used in the simple radial distribution system where the power generation is connected to a central switchgear lineup and is then distributed to the various loads. In DC distribution, each load can be isolated from the central bus by diodes (to prevent backflow) and the circuit breakers only require unidirectional current conduction and isolation. For example, the next generation of Navy ships, are envisioned to use a combination of radial and ring bus

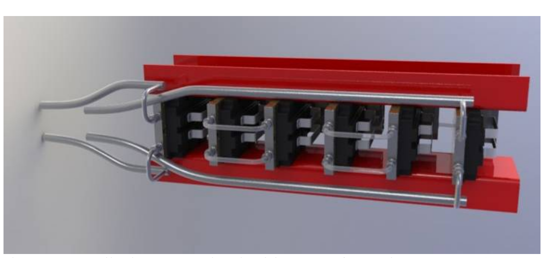

Figure 6. Preliminary mechanical layout of a 10 kV, 8 MW (800 A) IGBT interrupter. The IGBTs are mounted on water-cooled cold plates. Non-metallic cooling lines between adjacent cold plates are designed to stand off the full switch voltage when the switch is open.

distribution. The port and starboard buses will each contain a radial distribution, but will be tied together at the bow and stern with bus tie circuit breakers that must be able to conduct and isolate in both directions. The bus tie circuit breakers are essentially two of the interrupters described above in anti-series or anti-parallel connection.

C. Design for Reliability

DTI’s modern solid-state switch arrays are overvoltage and overcurrent protected in such a way that it is not possible for transients to exceed the de-rated specifications of the individual components.

Single IGBTs that fail, always fail shorted, so that operation of the switch can continue. Typically, DTI’s switch arrays are built with at least a 20% redundancy margin, in addition to a 2:1 device voltage de-rating, so that a few shorted elements do not require de-rating of the voltage handling of the entire array. On-board diagnostics can detect component level faults, and flag them for replacement at the next maintenance period. For facilities where strict requirements of uptime and Mean Time Between Failures (MTBF) must be met (such as for systems with large accelerators or military radars), the system MTBF is greatly enhanced by such redundancy in the overall system design.

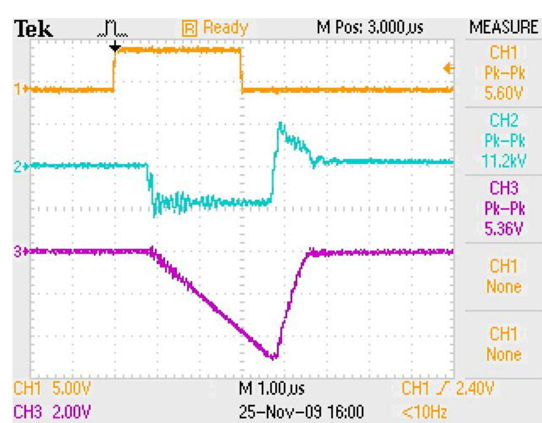

Figure 7. 10 kV, 1 kA waveforms demonstrating closing and opening into a near short circuit (23 µH) load at 1 µs/division. Traces shown; orange, command signal; blue, voltage (10 kV/div); purple, current (400 A/div). The delay between command and switch opening is 800 ns.

Device temperature plays a critical role in determining MTBF of the switch. Though silicon-based semi-conductors are typically rated for operation at up to 125°C, this design provides sufficient cooling so that the switch operates at 90°C or lower. Operation at this lower temperature improves reliability by a factor of fifteen.

IV. PERFORMANCE

DTI has demonstrated the key solid-state circuit breaker performance parameter: fast opening under full short-circuit fault current and DC loads.

Figure 7 shows waveforms demonstrating a 10 kV DC short-circuit current interruption of 1000 A in the breadboard test setup. The orange top trace is the 5 V logic pulse that controls the switch. The blue middle trace is the voltage across the inductor load measured with a North Star PVM-5 voltage probe. The sensitivity on the scope is 10 kV/division. The purple lower trace is the current, measured with a Pearson 101 current monitor. This monitor has a sensitivity of 200 A/V into a 50 Ω load; the scope was set to 2 V/division, giving a scope sensitivity of 400 A/division. The peak current is 2.5 divisions or 1 kA. The switch opens 800 ns after the command. This can be seen by the difference in time between the command signal turning off (at the middle of the top waveform) and the current reaching its peak.

Reliable operation of the switch was verified by opening the switch 10,000 times at 1 kA. The IGBTs were individually checked after this test and all were found to be fully functioning with no signs of damage.

A. Cooling

Waste heat is a significant issue that needs to be addressed in the development of a solid-state circuit breaker, especially for the high current branches.

Air cooling is perceived as being desirable because of the simplicity of the cooling system, however, the multi-kilowatt levels of heat that are anticipated for the high current applications will require relatively large air blowers with capacities of some six thousand cubic feet per minute (CFM). Water cooling systems of relatively compact size can provide sufficient cooling for the largest heat loads. Water can readily be used to cool high-voltage equipment provided the system design ensures that the water resistivity is maintained at sufficiently high levels. In the future, the availability of semiconductor devices with both high current capability and high temperature operation will simplify this tradeoff considerably.

V. CONCLUSIONS

The availability of high-voltage, solid-state switches enable the transition of shipboard power distribution to MVDC power systems and the significant benefits that they contribute. The ability of MVDC systems to interrupt full load currents in microsecond timescales delivers dramatic advances in circuit breaker performance, yielding improved system reliability and safety. The same technology also enables high frequency, high-voltage switching power converters that are rugged, efficient, and compact.