Fault Protection and Ride-Through Scheme for MVDC Power Distribution Systems Utilizing a Supervisory Controller

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Abstract—The paper proposes a protection scheme for zonal MVDC systems that allows fault isolation and ride-through of unfaulted zones. A Supervisory Controller coordinates the actions of mechanical contactors and a switching power converter to achieve the protection and reconfiguration function necessary in MVDC systems. Experimental results demonstrate the feasibility and performance of the approach.

I. INTRODUCTION

Resurgence in the use of DC distribution systems is underway due to advances in switching power converters, particularly regarding reductions in cost and size and increases in performance and efficiency. Medium Voltage level DC (MVDC) distribution systems based on this technology are of great interest for shipboard use and have been proposed as a superior alternative to currently used Medium Voltage level AC (MVAC) distribution systems. In spite of many advantages, DC distribution systems are partially hindered by lack of appropriate circuit protection strategies and equipment. In fact, protection of DC distribution systems against short circuit and ground faults, especially at the Medium Voltage level, is widely perceived to be a significant challenge. The unavailability of DC circuit breakers with appropriate voltage and current ratings is considered a major risk factor in the adoption of MVDC for ship power distribution. In traditional MVAC systems, fault protection methods rely on a mechanical switch and arc extinction at a natural zero-current crossing of the ac waveform which occurs every semi-period. This approach cannot be applied in MVDC systems because they do not have periodic current zero crossings [1-4]. Thus, in MVDC systems the fault current has to be removed or at least greatly reduced to guarantee arc extinction.

Solutions to this problem are of different nature. The most traditional is to build a dc circuit breaker by modifying a conventional ac circuit breaker with the addition of bulky arc chutes that draw the arc in and fragment it in order to extinguish the fault current without relying on current zero crossing. Still at the present time dc circuit breaker with appropriate voltage and current ratings for MVDC applications are not available. Other solutions to solve the protection of DC system are the introduction of triggerable current oscillating circuits to cause an artificial current zero crossing and turn off thyristors of the upstream rectifier; the use of rectifier as a crowbar in order to open the circuit by means of the AC side circuit breaker; the employment of solid state based circuit breakers; and the use of switching power converters to limit and interrupt the current flow. This last approach is investigated in this paper.

Figure 1. Notional Zonal MVDC Distribution System

For military applications, where survivability and ride-through capability are absolutely necessary, it is generally agreed that protections are necessary not only at the point of electric power generation, but at each load zone, and preferably systematically along all transmission paths. Figure 1 represents a simplified system, comprising of a power electronics switching converter that regulates the system’s main DC bus. Each zone is connected to the main DC bus via a contactor that allows for isolation under fault conditions. For example, in the case shown in Figure 1 of a fault at zone “n,” contactor CT-n can be opened to disconnect the zone from the main bus and isolate the fault. It is assumed that each zone has a form of energy storage for fault ride-through capability. This
zonal energy storage should be decoupled from the DC bus so as not to be affected by a bus fault.

We propose a protection system in which a supervisory controller coordinates the action of the power electronics switching converter that provides power to the zones and of the mechanical contactors connecting the individual zones to the main bus in order to eliminate the faulted zone and reconfigure the network. The approach assumes that the power electronics converter has the capability to limit its output current under a short circuit condition on the main bus. This approach provides fast elimination of faults and ride-through capability for un-faulted lines. This work is a continuation of an investigation of MVDC system protections described in [2]. The proposed approach is discussed in Section II, the hardware platform used for experimental validation is introduced in Section III, experimental results are presented in Section IV and discussed in Section V.

II. APPROACH

A protection system in which a Supervisory Controller coordinates the actions of mechanical contactors and a switching power converter is implemented to achieve the protection and reconfigurion function necessary in MVDC systems. Referring to Figure 1, when a fault occurs in zone “n”, the bus voltage drops, the power electronics switching converter goes into output current limit mode, and all other zones decouple from the bus and are supplied by their local energy storage. The decoupling can be accomplished in several ways. A simple and robust way that does not require any active control action is to have a large energy storage capacitor at the input of each zone connected to the bus through a diode that allows power flow only from the DC bus into the zone, thereby providing ride-through capability with the above mentioned decoupling. These diodes can also be used to perform auctioneering functions in multi-feeder systems. By monitoring each load’s voltage and current, the Supervisory Controller can detect when a fault occurs and which load branch is faulted. When a fault is detected, the Supervisory Controller responds by using one of the two approaches that were investigated in this work:

A. Case 1

In this first approach, the controller executes the following steps during a fault:

1) Relying on the built in maximum output current limit of the switching power converter to limit the fault current, the Supervisory Controller opens the contactor supplying the faulted zone in order to isolate the fault from the rest of the system. The mechanical contactor typically has an opening time of the order of milliseconds.

2) After the fault is isolated, the DC bus switching converter comes out of current limit operation, the system bus is re-energized, and power transmission from the DC bus to the healthy branches is restored.

B. Case 2

In this second approach, the controller executes the following steps during a fault:

1) The Supervisory Controller commands the power converter to shut off, thereby removing power from the DC bus. Immediately afterwards, the Supervisory Controller sends a command to open the contactor supplying the faulted zone in order to isolate the fault from the rest of the system. The mechanical contactor exhibits the same response time.

2) When the Supervisory Controller detects that the fault is successfully isolated, it re-energizes the system bus by issuing a restart command to the converter. The system bus is re-energized, and power transmission from the DC bus to the healthy branches is restored.

Also investigated is a method, applicable to both Case 1 and Case 2, to further reduce the magnitude of fault current against which the contactor must open. By using the large amount of data gathered by the Supervisory Controller, we can program a smart delay into the isolation of a faulted zone. By waiting until the fault current is below a certain magnitude before opening the contactor, the maximum interruption requirements of the protection device can be reduced to a desired level, for example the zone nominal current.

III. HARDWARE PLATFORM

The approach was experimentally validated using the hardware setup shown in Figure 2. The schematic of the hardware setup is shown in Figure 3. It consists of a power supply feeding a DC-DC switching power converter (implemented using one leg of an American Superconductor (AMSC) PM1175 PEBB). The DC-DC converter supplies power to a DC bus, which feeds two zones. Each zone is equipped with a load, a hold-up capacitor that supplies power to the load during DC bus outages, a decoupling diode, and a contactor that allows the zone to be isolated from the DC bus. The ground fault is implemented by a contactor (CT-fault) that connects a fault resistance (R-fault). The details of the components are summarized in Table I.

<table>
<thead>
<tr>
<th>Component name</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC Source</td>
<td>DC Power Supply</td>
<td>400V, 16A</td>
</tr>
<tr>
<td>AMSC PM1175</td>
<td>PEBS DC-DC Converter</td>
<td>V_{in}=400V, V_{out}=100V, I_{out}=10A</td>
</tr>
<tr>
<td>L1</td>
<td>PEBB Output Filter Inductor</td>
<td>1mH</td>
</tr>
<tr>
<td>C_{out}</td>
<td>PEBB Output Filter Capacitor</td>
<td>0.9mF</td>
</tr>
<tr>
<td>C_{bus}</td>
<td>Bus Capacitor</td>
<td>1mF</td>
</tr>
<tr>
<td>C1, C2</td>
<td>Holdup Capacitor, Zone 1 and Zone 2</td>
<td>6.8 mF</td>
</tr>
<tr>
<td>R_{fault}</td>
<td>Fault Resistor</td>
<td>1 Ω</td>
</tr>
<tr>
<td>D1, D2</td>
<td>Decoupling Diodes</td>
<td>V_{max}=600V, I_{in}=100A</td>
</tr>
<tr>
<td>CT1, CT2, CT-fault</td>
<td>Contactors</td>
<td>LEV200</td>
</tr>
<tr>
<td>Load 1</td>
<td>Load Zone 1</td>
<td>60 Ω</td>
</tr>
<tr>
<td>Load 2</td>
<td>Load Zone 2</td>
<td>5 kΩ</td>
</tr>
<tr>
<td>CS1, CS2, H1</td>
<td>Current Sensors:</td>
<td>LEM LA 55P</td>
</tr>
<tr>
<td>VS1, VS2, VSBus</td>
<td>Voltage Sensors</td>
<td>LEM LV 20P</td>
</tr>
</tbody>
</table>

TABLE I. COMPONENT LIST AND VALUES
A. Local Controller of AMSC PM1175 PEBB DC-DC Converter

The AMSC PM1175 PEBB has been modified with a custom control board to enable the execution of custom code. The control strategy consists of an inner deadbeat current control loop fed by an outer voltage regulation loop. This ensures fast response to load changes, as well as a cycle-by-cycle enforcement of the current limit. The current reference to the inner deadbeat current control loop has a maximum limit of 10A. As a result, during fault conditions, the current through inductor L1 is limited to 10A. Notice that the converter output current $I_{PEBB}$ includes also the current from the converter output capacitor $C_{Out}$. If, during a fault condition, the bus voltage is decreasing rapidly, the output capacitor discharge current can be significantly larger than the current limit value. For this reason, it is desirable to move as much as possible of the DC bus capacitance into the zones (after the decoupling diodes). In the setup the total zone capacitance is 13.6mF and the DC bus capacitance is 1.9mF, which is approximately 10% of the total zone capacitance.

The controller also monitors two of the analog to digital converter (ADC) channels for a turn on/shut down command and a voltage reference given by the Supervisory Controller.

B. Supervisory Controller

The distribution system is controlled by a LabView-based Supervisory Controller which is implemented on a commercial off the shelf (COTS) computer with LabView’s proprietary Real Time OS and a data acquisition card (DAQ).

The Supervisory Controller continuously monitors system information, such as converter output current, bus voltage, and zonal current and voltages. Using the sensed data, the Supervisory Controller determines which zone is faulted and sends the appropriate signal to the zone contactor to isolate the fault. The Supervisory Controller also has the ability to send operating point references and start/stop commands to the power electronics converter.

IV. RESULTS

During normal operation, the PEBB DC-DC converter controls the bus voltage at 100V, providing power to the two zonal loads. The fault is activated by switching in a 1Ω resistor with a mechanical contactor at the input of Zone 2, resulting in bouncing that can be seen in the irregular rise of the fault current in all experimental results (see for example Figure 9). The fault current decays with the system’s time constant, until interrupted by the zone’s contactor. There is an approximately 3ms delay from the command to open the contactor to its actual opening due to the mechanical speed of the contactors used.

The majority of current feeding the fault comes from the system’s energy storage (capacitors $C_{Out}$ and $C_{Bus}$). In experiments, the peak fault current ($I_{Fault}$) is measured to be approximately 80A, however, the output current limit of the converter ($I_{PEBB Max}$) is only set at 10A.

A. Case 1

Simply allowing the converter to go into current limit is generally the simplest strategy to implement since no
coordination is necessary; however, after the initial discharge of the output capacitor, the converter actively feeds the fault (Figure 4).

Figure 4. Simplified Equivalent Circuit during fault in Case 1

Figure 5. Case 1 Fault Current, Bus Voltage, Zone 2 Voltage, and Contactor Signal (5ms/div 20A/div)

Figure 6. Case 1 Zoom of Figure 5 (2ms/div 20A/div)

Figure 7. Simplified Equivalent Circuit during fault in Case 2

Compared to Case 1, the amount of current the contactor must interrupt is reduced (Figure 8), but the bus voltage takes
slightly longer to recover because the Supervisory Controller waits for the fault to fully extinguish before sending the signal to turn on the DC-DC converter (1.2ms delay). This is a limitation of the Supervisory Controller's bandwidth, and can be greatly improved with a faster Real Time PC.

By powering down the bus converter, the amount of current the contactor must interrupt is reduced by approximately the output current limit of the converter. Although not necessarily a huge change in this particular testbed, in systems with converters that must supply large loads, the difference could be on the order of hundreds or thousands of amps.

Figure 8. Case 2 Fault Current, Bus Voltage, Zone 2 Voltage, and Contactor Signal (2ms/div 20A/div)

C. Further Reduction of Interrupted Current

Another method to utilize the Supervisory control scheme's situational awareness is to purposefully delay the command to open the contactor on the faulted zone. Introducing this time delay allows the bus voltage to decay to a lower value, reducing the amount of current the zone contactors must interrupt. The delay allows the bulk of the energy stored in the bus capacitors to dissipate, thereby reducing the fault current at the time of interrupt. Since the amplitude and time constant of the fault current supplied by energy storage is determined by not only the bus capacitance, but also the equivalent impedance of the fault, it can be difficult to coordinate protections with classical methods. However, since the Supervisory Controller monitors system currents, it is easy to implement logic to interrupt the faulted zone once the fault current falls below a level that the protections can safely interrupt. In Figure 9 and Figure 10 the top trace is the Supervisory control loop iteration (600µs), the second waveform is the signal that a fault is detected by the Supervisory Controller, the third waveform is the command signal sent to the faulted contactor to isolate, and the fourth waveform is the fault current. We can see that in Figure 9 the contactor control signal is sent immediately after the fault is detected.

In Figure 10, the contactor control signal is delayed approximately 1ms and the magnitude of current the contactor must interrupt is reduced. This delay can be programmed to even further reduce magnitude of current to be interrupted.

Figure 9. Case 2 with Contactor Immediately Sent Interrupt Signal Timing (500us/div 20A/div)

Figure 10. Case 2 with Delayed Fault Interrupt (500us/div 20A/div)

Figure 11 and Figure 12 compare the effect of delayed timing on fault current and bus voltage for Case 1 and Case 2. Figure 11 illustrates this delay for Case 1. Just a 1ms delay can reduce the interrupted current by approximately 25% (~24A to ~18A) (compare with Figure 6).

In Figure 10, the contactor control signal is delayed approximately 1ms and the magnitude of current the contactor must interrupt is reduced. This delay can be programmed to even further reduce magnitude of current to be interrupted.
The same delay is applied to Case 2 in Figure 12. In this case, the interrupted current is actually reduced by approximately 50% (~16A to ~8A).

The delayed interrupt has a greater impact for Case 2 because the fault current is purely a function of bus capacitance and fault impedance; the Supervisory Controller is simply using the natural decay of the energy storage to reduce the fault current. Since Case 1 actively feeds the fault, at the tail end of the RC decay, the majority of fault current is comprised of the converter’s output current. In this case, the introduced delay provides a less significant benefit. In a practical MVDC system, impedance levels would be different as compared to this hardware setup: fault resistances would probably be in the range of milliohms rather than 1Ω, even if higher fault resistances cannot be ruled out; and bus capacitances would be significantly larger. As a result a wide range of fault time constants are to be expected. This approach improves fault protection reliability by preventing the contactors from interrupting too large currents, which could damage them.

The results for each case are gathered in Table II. We can see that the bus voltage is below the nominal 100V for the shortest time in Case 1, however the interrupted current is the largest. Simply by turning off the PEBB during a fault (Case 2), the interrupted current is reduced by 1/3, while only taking approximately 2ms longer for the bus voltage to return to nominal. Delaying the signal to interrupt also shows a great reduction of interrupted current with little effect on the time the bus voltage is below nominal. Case 2 in conjunction with a

Table II. Quantities of Interest for Test Cases

<table>
<thead>
<tr>
<th>Case</th>
<th>Fault Time</th>
<th>Interrupted Current</th>
<th>Delay to Restart</th>
<th>Vbus-Nominal Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>3.6ms</td>
<td>24A</td>
<td>0ms</td>
<td>23ms</td>
</tr>
<tr>
<td>Case 2</td>
<td>3.2ms</td>
<td>16A</td>
<td>1.2ms</td>
<td>25ms</td>
</tr>
<tr>
<td>Case 1 Delayed</td>
<td>4.4ms</td>
<td>18A</td>
<td>0ms</td>
<td>26ms</td>
</tr>
<tr>
<td>Case 2 Delayed</td>
<td>4.4ms</td>
<td>8A</td>
<td>1.2ms</td>
<td>28ms</td>
</tr>
</tbody>
</table>

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delayed interrupt reduces the interrupted current by 2/3, but only increases the time $V_{bus}$ is below nominal by 5ms. Clearly due to the exponential decay in fault current and linear charge up of the bus voltage after a fault is cleared, small delays in the interrupt of current make significant impacts on the interrupted magnitude while only slightly effecting time the bus is below nominal.

From the results, it is apparent that the majority of the fault current actually comes from the energy stored on the bus capacitors. Using the supervisory controller to turn off the bus converter and delaying the signal to isolate the faulted zone can reduce the requirements of system protections, but as a result these methods increase the time the main bus is off-line. However, since the majority of energy storage is zonal ($C_{out}$ is 0.9mF, $C_{bus}$ is 1mF while $C_{1,2}$ are 6.8mF) and isolation diodes are used, the non-faulted zones are able to ride through this fault.

The results indicate that steps to minimize the bus capacitance should be taken. If minimized, the RC time constant of the fault current can be reduced, and thereby reduce the fault time. Moving the energy storage to the zonal/load level and using isolation diodes provides the necessary voltage stabilization capabilities in normal operation, while at the same time reducing the energy storage on the main bus that could feed faults.

Reducing the bus capacitance is extremely important for faster protection schemes. If semiconductor based circuit breaker devices are used, the 3ms contactor time delay shown will be reduced to a $\mu$s scale. Since initially huge levels of current rush into the fault, devices that can interrupt these levels of current are needed. Such devices are difficult to find and cost prohibitive. However, a Supervisory Controller, using method outlined in Case 2 in conjunction with a delayed interrupt signal, can greatly reduce the interruption requirements of protections. In a larger distribution system significantly more current must be supplied by bus converter, therefore even under current limited operation during a fault, the interruption capability of the protections must be large. However, in Case 2, the bus converter is taken offline in fault conditions. In this instance, there should be no converter current actively feeding the fault and therefore the fault current can be reduced significantly.

VI. CONCLUSION

The experimental results presented demonstrate the feasibility and performance of the proposed protection scheme for MVDC systems. In future work, a more complex MVDC distribution architecture with multiple busses will be considered. Moreover, the advantages and disadvantages of a centralized protection control architecture versus a more localized architecture will be explored. One of the limitations of the explored architecture is that the zonal energy storage cannot be sent back to power the DC bus, due to the decoupling diodes. A more flexible (and more expensive) solution is to use power electronic converters to interface energy storage to the DC bus.

REFERENCES