DC Distribution Fault Analysis, Protection Solutions, and Example Implementations

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***Abstract*—A dc fault current can be approximated by its equivalent fault inductance. DC circuit breaker-based or converter-based protection solutions are different in protective devices and protection methods. Fast fault interruption is essential and critical to dc distribution protection. Specific speed requirements are derived and analyzed for different protection solutions. The effectiveness of different dc protection solutions is demonstrated on a dc distribution system. The issues in dc protection coordination are studied and discussed.**

***Index Terms*—Circuit breaker, converter, dc distribution, fast speed, protection.**

I. Introduction

With the advances in power electronics technologies, dc distribution becomes a competitive alternative to conventional ac distribution because of low losses and no synchronization. Marine dc shipboard power systems have been in operation [1]–[3] and their dc protection has been overviewed in [3]–[5]. The naval dc shipboard systems requiring high reliability and survivability are still in research and development stage [6], [7]. Other promising dc distribution applications are collection systems of renewable generation, offshore exploration platforms, industrial plants, data centers, buildings, and utility distribution systems.

Protection is one major challenge preventing the wide implementation of dc distribution applications. The rising rate of a dc fault current is in reverse to its inductance. With wide applications of power electronics devices in dc distribution, fast dc protection is required because rapidly increasing dc fault currents flow through semiconductor switches with low short-circuit withstands. A complete dc protection solution involves different hardware and software shown in Fig. 1 [8]. The dc distribution protection needs to be considered from initial system design stage in order to achieve overall low cost, high reliability, and high efficiency.

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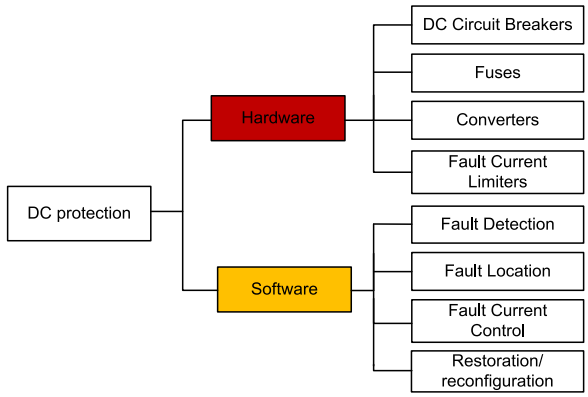

Fig. 1. Hardware and software required in dc protection [8].

According to key protective devices, different dc protection solutions can be classified into

1) dc circuit breaker (DCCB)-based protection;
2) fuse-based protection;
3) converter-based protection;
4) fault current limiter-based protection;
5) hybrid of different types of devices-based protection.

In this paper, DCCB-based, converter-based, and hybrid protection solutions will be discussed. Compared to the traditional fuse-based dc protection, DCCB-based protection is more reliable because of no repetitive usage of fuses and quickly developed DCCB technologies in recent years [9]–[22]. Considering the wide implementation of converters and extra passive elements in fault current limiters, converters are better than solid-state fault current limiters for dc protection [22]. Different dc protection methods were studied by researchers [16]–[30]. Depending on whether communication is critical or not, a dc fault identification and protection coordination method can be characterized as:

1) a local measurement-based method; or
2) a communication-based method.

The rest of this paper is organized as follows. The dc fault equivalent circuits and fast dc fault interruption are analyzed in Section II. Speed, as the most critical dc protection design requirement, will be derived for the DCCB and converter-based dc protection in Sections III and IV. Furthermore, overall dc protection design will be demonstrated by the two different solutions on a dc shipboard distribution system in Section V. The differences in dc and traditional ac distribution protection are compared in Section VI. A summary and some conclusions are presented in Section VII.

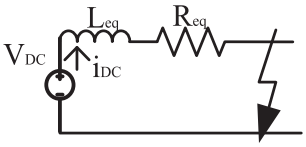

Fig. 2. DC fault equivalent circuit.

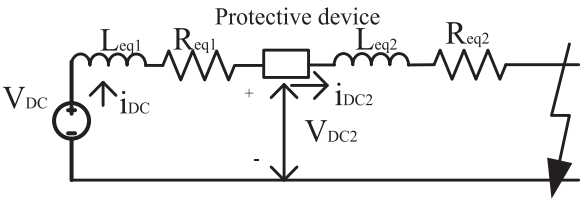

Fig. 3. Fault equivalent circuit with a dc protective device.

II. Fault Current Analysis and Interruption

Essentially, fast dc protection is required because of rapidly increasing dc fault currents from dc sources and low short-circuit withstands of power electronics.

A. Fault Current Analysis

DC fault currents are from various types of ac and dc sources. AC and DC sources are connected to dc buses through cables with or without converters. It is straightforward to illustrate the fault equivalent circuit of a dc source as Fig. 2. $R_{\rm eq}$ and $L_{\rm eq}$ are the equivalent fault resistance and inductance between the source and fault location. In practical applications, a dc protective device can be installed at a location between a source and a fault location as shown in Fig. 3. $L_{\rm eq}$ is split into L_{eq1} and L_{eq2} at the installation location.

In real systems, the inductance of a medium-voltage/low-voltage dc (MV/LVDC) cable ranges from a few to one tenth microhenries per meter. DC fault currents from capacitors can have high dc fault current derivatives of a few hundreds of mega ampere per second and batteries of a few mega ampere per second. In dc distribution protection, due to the high current derivative at initial fault transients, the voltage drop on $L_{\rm eq}$ is much higher than $R_{\rm eq}$ and thus $L_{\rm eq}$ can be approximated by (1) and is critical to estimate the rising rate of the fault current and design an appropriate dc protection. In turn, once a dc protection design is selected, $L_{\rm eq}$ is defined by the protection speed, which limits the maximum allowable current increasing rate. In Fig. 3, L_{eq2} is the equivalent fault inductance seen by the local protective device and can be derived by (2) using the local voltage and current measurements V_{DC2} and i_{DC2}.

Several distributed ac generators can exist in a dc distribution system. The fault equivalent circuit in Fig. 2 is also applicable to ac sources but $L_{\rm eq}$ should be deduced from ac fault currents. The fault contributions from ac sources are the same in both ac and dc systems before reaching the first fault peaks. Therefore, the initial dc fault current and its derivative of an ac generator can be derived by (3) and (4). The dc fault current of a converter-interfaced ac generator rises to its first fault peak at approximately half-cycle. $L_{\rm eq}$ of an ac generator can be written into (5) with *K* as the ratio of E_{q0} and $V_{\rm DC}$. $L_{\rm eq}$ is a time-varying variable and its value at a time instant is its fault equivalent inductance at the specific time instant. This derivation of $L_{\rm eq}$ for dc fault analysis is also applicable to other ac sources. Normally, the fault current derivatives of ac sources are much lower than dc sources because of much higher machine impedances

$$L_{\rm eq} \approx \frac{V_{\rm DC}}{di_{\rm DC}/dt} \tag{1}$$

$$L_{\rm eq2} \approx \frac{V_{\rm DC2}}{di_{\rm DC2}/dt} \tag{2}$$

$$i_G = \frac{E_{q0}}{\omega_s L''_d}\left(-e^{-t/\tau''_d}\cos(\omega_s t) + e^{-t/\tau_a}\right) \tag{3}$$

$$\frac{di_G}{dt} = \frac{E_{q0}}{\omega_s L''_d}\left(\omega_s e^{-t/\tau''_d}\sin(\omega_s t) + \frac{e^{-t/\tau''_d}\cos(\omega_s t)}{\tau''_d} - \frac{e^{-t/\tau_a}}{\tau_a}\right) \tag{4}$$

$$L_{\rm eq}(t) = \frac{\omega_s L''_d}{K\left(\omega_s e^{-t/\tau''_d}\sin(\omega_s t) + \frac{e^{-t/\tau''_d}\cos(\omega_s t)}{\tau''_d} - \frac{e^{-t/\tau_a}}{\tau_a}\right)} \tag{5}$$

where $\tau''_d \approx \frac{L_f + \frac{1}{1/L_{ad}+1/L_{\delta s}+1/L_D}}{r_f}$, $\tau_a \approx \frac{\frac{1}{0.5(1/L''_d+1/L''_q)}}{r_s}$, and $\omega_s = 2\pi f_s$. E_{q0} is the generator internal voltage. L_{ad}, $L_{\delta s}$, and L_D are the generator inductances. L_d" and L_q" are the subtransient inductances. r_f and r_s are the rotor and stator resistances, respectively. f_s is the generator operating frequency. The ac line impedance can be combined into the generator impedance. Normally, the inductance of a short dc line is much lower than an ac generator and can be neglected. If long enough, the dc line resistance should be considered according to IEEE 61660 [31], [32].

B. Fast Fault Interruption

Conventionally, system stability and short-circuit withstands of equipment are used to determine required protection speed in order not to violate dynamic operation limits and overcurrent or thermal limits of the protected system. In dc distribution systems, most sources and loads are connected to dc buses through ac/dc and dc/dc converters. Compared to conventional power equipment, power electronics converters have much lower short-circuit withstands. Therefore, the dc fault currents should be interrupted currents faster to keep the maximum fault currents and accumulated fault energies below the short-circuit withstands of semiconductor switches.

Ultrafast protection is required by dc fault protection if high dc fault currents from dc sources, such as capacitors, flow through power electronics switches. In conventional voltage-source converters (VSCs), large terminal capacitors usually exist to maintain dc-bus voltages. The capacitor fault current paths of typical ac/dc and dc/dc VSCs at dc faults of load side are analyzed in [27] and [33] and shown in Fig. 4. At dc faults, the insulated-gate bipolar transistors (IGBTs) in the converters are turned OFF to avoid IGBT breakdowns. As shown in Fig. 4, uncontrollable capacitor currents first discharge as (1) and then commute

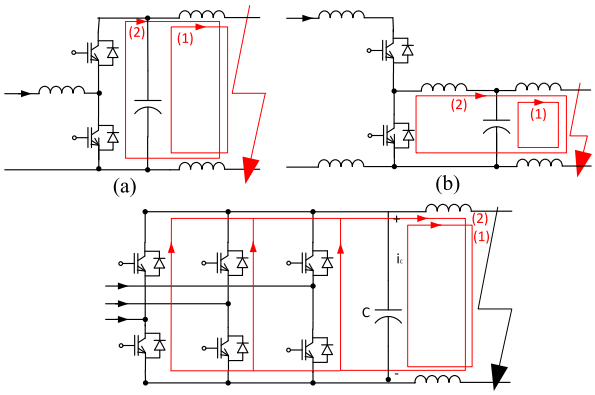

Fig. 4. Capacitor fault current paths of conventional converters.

to the freewheeling diodes as (2). The high rising rates of the capacitor discharging currents and the low short-circuit limits of the diodes require the ultrafast interruption within several microseconds.

The specific speed requirements of different protection solutions will be discussed and analyzed in Sections II and III, and the example implementations in Section IV.

III. DCCB-Based Protection Solutions

DCCB-based protection relies on DCCBs to interrupt fault currents. The breaker technologies and the protection coordination among different breakers are critical.

A. DCCBs

There are three types of DCCBs: electromechanical, solid state, and hybrid. Main technical challenges of different breaker technologies for dc distribution protection include:

1) the creation of artificial zero crossing;
2) fast turning-OFF speeds for fast fault interruption.

Different technologies to create artificial zero crossings, such as current injection, resonance *LC* circuits, and arcing voltage, were developed for different types of DCCBs [8]–[22]. If the same fault identification method is used, solid-state DCCBs have the fastest turning-OFF speeds of much less than 1 ms. Therefore, solid-state DCCBs are inherently suitable for fast dc distribution protection. Recently, different solid-state DCCB prototypes based on different semiconductor devices have been developed and demonstrated [9]–[18]. The hybrid DCCBs are capable of turning OFF within a few milliseconds while the mechanical DCCBs need a few to several milliseconds [19]–[21].

The selection of proper DCCBs can be decided by required fault interruption speed. If the capacitor discharging at dc fault needs to be handled, ultrafast fast solid-state DCCBs should be used. If the dc fault currents of a converter-interfaced generator should be interrupted, fast mechanical and hybrid breakers could be fast enough. In general, different DCCB technologies have different advantages and disadvantages in cost, efficiency, and turning-OFF speed. Often, fast breakers can reduce pressures on involved equipment and devices but are expensive. Cost of a DCCB is also determined by other factors, such as switching technology, maximum interrupted current level, and allowable fault energy. Cost-efficient DCCBs are more challenging for MVDC due to higher voltage than LVDC.

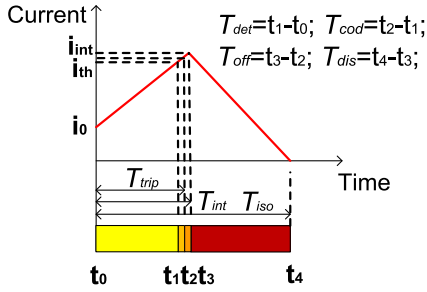

Fig. 5. Time decomposition of a fast DCCB-based protection solution.

B. Fault Identification and Location

Local measurement-based protection coordination methods, such as overcurrent [8], [16]–[18], [20], [23], [24], current derivative [8], [17], [18], [25], and distance [8], [24], [26]–[28], can be applied to dc distribution protection with little communication delays. In dc overcurrent protection, instantaneous fault currents are compared with current thresholds. Overcurrent protection is the fastest because of least requirements on signal processing and computation. Different fault currents and thresholds result in autonomous protection coordination among different DCCBs.

Current derivative protection is widely used by dc railway and traction protection. With rapidly increasing dc fault currents, high sampling rates and complex threshold definitions are required. In distance protection, the fault inductances estimated from transient fault conditions are used to estimate fault distances. In Fig. 3, the local voltage, current, and current derivative at the local DCCB can be used to estimate the equivalent inductance from the DCCB to the fault location [24], [28]. Compared to overcurrent and current derivative protection, distance protection requires more measurements and more complex computation.

Conventional communication-based protection methods, such as differential protection and current direction protection, may still be used for dc distribution protection [8], [17], [18], [24], [29]. A communication infrastructure is the basis and thus fast reliable communication is one major concern of these communication-based methods. A typical delay of 100 μs is required to transmit a trip event over industrial protocols such as CANopen [17]. With slow communication, dc fault currents may have already increased to a dangerously high level. Advanced fast communication techniques and stringent synchronization are required by rapidly increasing dc fault currents in order for accurate fault identification. A good example of a DCCB-based differential protection using fast field-programmable gate array and I/Os with high sampling rates was demonstrated in [29].

C. Protection Speed Requirements

A generalized protection process of a DCCB-based protection solution is illustrated by Fig. 5. i_0 is the initial fault current. i_{th} is the current threshold to detect a fault. i_{int} is the peak current where the fault current is interrupted by opening the DCCB. T_{det}

is the time to detect a fault. T_{cod} is the time to identify and locate a fault, which may include some communication delay T_{com}. T_{off} is the DCCB turning-OFF time. T_{dis} is the DCCB energy dissipation time. T_{det}, T_{cod}, and T_{com} are different for different fault identification and protection coordination methods. T_{off} and T_{dis} are different for different DCCBs. Fig. 5 demonstrates a solid-state DCCB with extremely short time T_{off} and thus the dc fault current can be approximated as a linearly increasing current before the fault interruption. T_{off} of a mechanical or hybrid DCCB would be much longer and thus the fault current may not be approximated as a linear current any more.

The total time T_{trip} for a DCCB to issue a trip command, T_{int} to interrupt a fault, and T_{iso} to isolate a fault can be calculated from (6), (7), and (8), respectively. The maximum allowable fault interruption time is determined by either the minimum short-circuit withstand i_{int} of all protected equipment as (9) or the critical clearance time T_{CCT1} as (10). T_{CCT1} is the maximum allowable time of the protected system under fault impacts and derived from transient fault analysis. The required speed of the breaker or protection algorithm can be further derived from (6) and (7) once other speeds known.

Selectivity imposes extra requirements on the turning-OFF speeds of DCCBs. To avoid the false tripping of the upstream breakers, the downstream breakers should be turned OFF earlier than the upstream breakers are tripped. This is indicated by (11). T_{cod} of all DCCBs are assumed to be equal. The required turning-OFF speeds of the downstream DCCBs can be derived as (12) from (6) and (7), and Fig. 5. According to (12), the false tripping can be prevented by adjusting the thresholds of the DCCBs and/or the current derivatives

$$T_{\text{trip}} = T_{\text{det}} + T_{\text{cod}} + T_{\text{com}} \tag{6}$$

$$T_{\text{int}} = T_{\text{trip}} + T_{\text{off}} \tag{7}$$

$$T_{\text{iso}} = T_{\text{int}} + T_{\text{dis}} \tag{8}$$

$$i_{\text{int}} \leq \min\left(I_{\text{sc1}}, I_{\text{sc2}}, \ldots, I_{\text{sc}N}\right) \tag{9}$$

$$T_{\text{int}} \leq T_{\text{CCT1}} \tag{10}$$

$$T_{\text{int down}} < T_{\text{tripup}} \tag{11}$$

$$T_{\text{offdown}} < \frac{I_{\text{thup}} - i_{0\text{up}}}{di_{\text{up}}/dt} - \frac{I_{\text{thdown}} - i_{0\text{down}}}{di_{\text{down}}/dt}. \tag{12}$$

IV. Converter-Based Protection Solutions

In converter-based dc protection, converters are responsible for fault current control, such as fault current limiting and fault current bypassing. The converter design and protection coordination among different converters are vital.

A. Converter Fault Limiting and Bypassing

The main function of converters is voltage conversion but not fault handling. The fault limiting capability of different types of converters for distribution systems can be found in [8], [22], [27], [30], and [33]–[36]. Because of economic and efficiency reasons, most commonly used commercial converters in dc distribution systems, such as the VSCs in Fig. 4 and the half-bridge multilevel modular converters (HBMMCs) in Fig. 6, do not have fault-limiting capability. As shown in Fig. 4, the fault currents from ac sources and capacitors can flow through the freewheeling diodes. In Fig. 6, although the capacitor discharging currents are blocked, the fault currents from ac sources and the circulating fault currents induced by the arm inductors still flow through the freewheeling diodes.

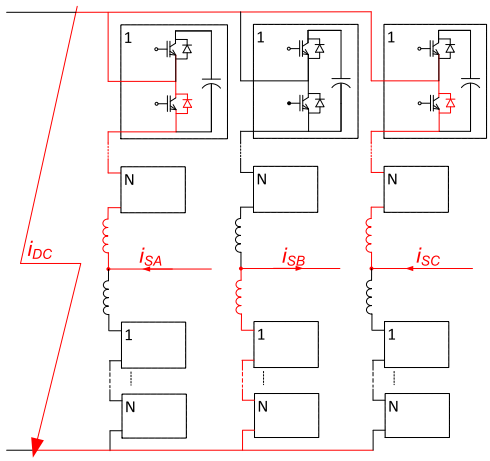

Fig. 6. DC short-circuit paths of a HBMMC in dc distribution [8].

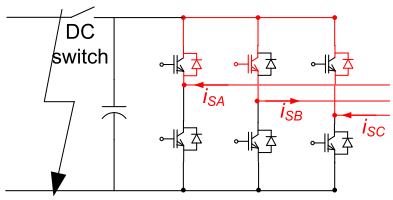

Fig. 7. DC short-circuit bypassing circuit of a two-level VSC [8], [37].

In order for converters to have the fault current limiting function, controllable switches should exist on dc fault paths to limit fault currents [8], [22]. Converter devices, topologies, and even control should be revised and specially designed for the converter fault limiting. Since event switching normally has different design specifications on semiconductor switches from converter switching, higher design tolerances, more switches, and more complex topologies are required for the fault current limiting converters, which results in higher cost, lower efficiency, and lower reliability.

An alternative way of converter fault current control is to create artificial ac short circuits to bypass dc fault currents by manipulating controllable switches [8], [22], [37]. As shown in Fig. 7, a dc pole-to-pole fault is artificially bypassed by a three-phase ac short circuit fault at the converter terminal. Instead of the special converters to limit fault currents, the conventional converters, such as the two-level VSC and HBMMC, can bypass dc faults. However, high-rating switches are required since high ac fault currents need to flow through the bypassing switches.

B. Fault Identification and Protection Coordination

The local measurement and communication-based protection methods described in Section III-B are also applicable to

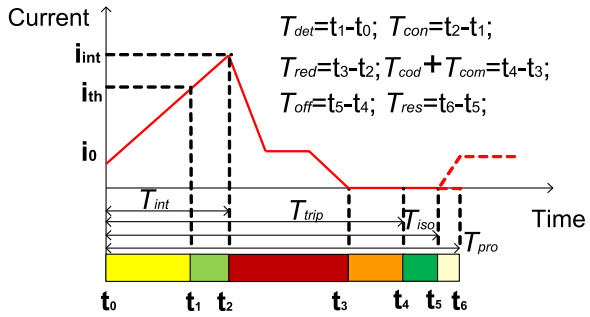

Fig. 8. Time decomposition of a converter-based protection solution of two-stage fault current limiting.

the converter-based protection. In the local measurement-based methods, each fault current limiting converter can be used as a DCCB [30]. Besides the special converter designs, ultrafast data processing and fault identification should be implemented in the converter control because of the required fast dc fault interruption. Additionally, extra load switches or no-load disconnectors should be installed with each converter to ensure galvanic isolation and safety.

The extra costs due to ultrafast data processing and fault identification on converter control make it favorable to use the communication-based methods in the converter-based protection. At a dc fault, all impacted converters first sense high fault currents and then quickly respond to limit or bypass dc fault currents to zero. No-load dc disconnectors then can safely isolate the dc faults and ensure galvanic isolation. At last, the converters should be restarted and back to normal operation after fault removal or in hot standby after fault isolation. Limited changes are required to the existing converter control. Since the dc fault currents are quickly reduced to zero, it is allowed to use low speed communication-based methods for accurate dc fault location and isolation.

C. Protection Speed Requirements

The complete protection process of a converter-based protection solution using the communication-based fault location and protection coordination is illustrated by Fig. 8. A two-stage current reduction is shown in the figure and convenient for fault location. $T_{\rm con}$ is the converter control delay. $T_{\rm red}$ is the time of the fault current going to zero after being controlled or interrupted. Different from the DCCB-based protection solution, the fault location and protection coordination are executed after the fault interruption. Once the fault is located, the no-load disconnector associated with the converter takes $T_{\rm off}$ to open. The converter takes $T_{\rm res}$ to restore to normal or standby.

The total time for a converter to limit or bypass a dc fault current is $T_{\rm int}$ as (13). The time $T_{\rm trip}$ for the associated no-load disconnector to receive the open command and $T_{\rm iso}$ to isolate a fault can be calculated by (14) and (15). The required speeds of the converter fault current control and protection algorithms are determined by the designs limits as indicated by (16)–(18). Same as the DCCB-based protection, $i_{\rm int}$ is the minimum short-circuit withstand of all protected equipment and T_{CCT1} is the maximum allowable time of the protected system under fault impacts. T_{CCT2} is the maximum allowable surviving time of the isolated system with limited or no converter supply. In the converter fault current bypassing, T_{CCT2} is also decided by the fault withstands of the converter and its upstream ac system. In Fig. 8, the stages during the protection process take place in sequence. More efficiently, once a fault is detected, the dc fault current control can be executed simultaneously with the fault location and protection coordination as (19). The required speeds of the converter fault control and protection algorithms are then constrained by (16), (17), and (20)

$$T_{\rm int} = T_{\rm det} + T_{\rm con} \tag{13}$$

$$T_{\rm trip} = T_{\rm int} + T_{\rm red} + T_{\rm cod} + T_{\rm com} \tag{14}$$

$$T_{\rm iso} = T_{\rm trip} + T_{\rm off} \tag{15}$$

$$i_{\rm int} \le \min\left(I_{\rm sc1}, I_{\rm sc2}, \ldots, I_{{\rm sc}N}\right) \tag{16}$$

$$T_{\rm int} \le T_{\rm CCT1} \tag{17}$$

$$T_{\rm red} + T_{\rm cod} + T_{\rm com} + T_{\rm off} + T_{\rm res} \le T_{\rm CCT2} \tag{18}$$

$$T_{\rm trip} = T_{\rm det} + \max\{T_{\rm con} + T_{\rm red}, T_{\rm cod} + T_{\rm com}\} \tag{19}$$

$$\max\{T_{\rm con} + T_{\rm red}, T_{\rm cod} + T_{\rm com}\} - T_{\rm con} + T_{\rm off} + T_{\rm res} \le T_{\rm CCT2} \tag{20}$$

From the above equations, the longer a converter takes to interrupt a dc fault current, the higher fault withstands are required by the protected equipment and system. After the fault current reduced to zero and before system restoration, a part of or even the whole dc system could be isolated and under no power supply. High reliability requires fast fault location and restoration in order to prevent the loads from losing power for long and the isolated system from becoming unstable. Fast fault location and isolation are especially required by the converter fault bypassing since high fault currents continue to flow through the converter and its upstream ac systems before system restoration.

V. Example Implementations

Different dc protection solutions can be applied for different systems. In this section, an overall protection design and its implementation are demonstrated on a shipboard power system. Fig. 9 illustrates a naval dc shipboard distribution system architecture defined by IEEE Std 1709 [6]. High requirements on reliability and survivability drive the MVDC ring configuration and zonal LVDC distribution of naval ships. The short distance between components means high current derivatives at dc faults. Converters are installed system wide for ac and dc voltage conversions.

A. DCCB-Based Protection

At a dc fault, all source converters in the naval shipboard system can see high dc fault currents and then react to shut down. This loss of system-wide power supply is not acceptable by the high reliability and survivability required by naval ships. The DCCB-based protection is thus selected for its selectivity and placement flexibility. Fig. 10 indicates the equivalent fault circuit of the port side of the naval system in Fig. 9. The capacitors

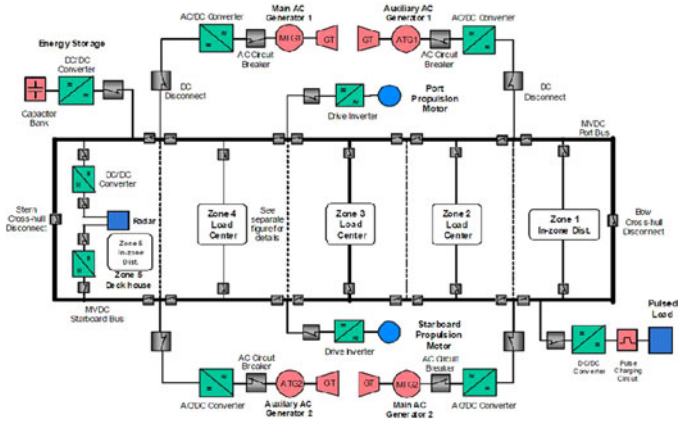

Fig. 9. Notional design of high-performance MVDC ship system [6].

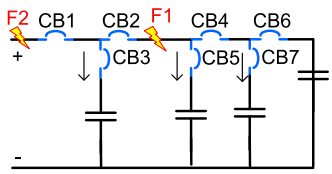

Fig. 10. Fault equivalent circuit of the port dc bus.

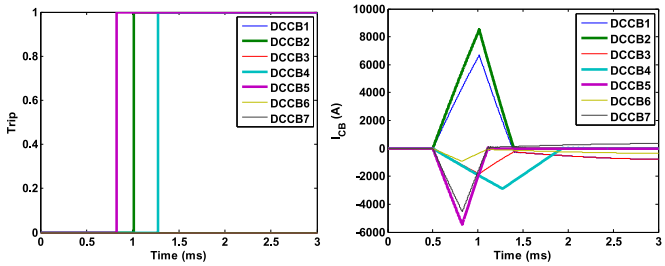

Fig. 11. Simulated trip signals and currents of DCCB1-7 at F1.

are the equivalent converter capacitors in zones. The placements of seven DCCBs, CB1-7, are indicated in Fig. 10. Because of the symmetric structure of the system, this partial dc system is representative and its protection design can be extended into the rest of the system.

Fig. 11 illustrates how the DCCB-based overcurrent protection can be achieved by the simulated trip signals and currents of DCCBs at F1. At the fault F1, CB2, CB4, and CB5 are the closest breaker to open. As expected, the trip signals of CB2, CB4, and CB5 jump from 0 (close) to 1 (open) in Fig. 11. These trip signals were send to the corresponding breakers to command them to open. After the openings of CB2, CB4, and CB5, their currents become zero while there are still currents in other DCCBs as in Fig. 11.

Special attention is paid to the overcurrent coordination among different DCCBs at different fault scenarios. Fig. 12(a) and (b) illustrates different coordination schemes among CB1, 2, and 3 at F1 and F2 in Fig. 10. The fault currents i_{CB1}, i_{CB2}, and i_{CB3}, and thresholds I_{th1}, I_{th2}, and I_{th3} of CB1, CB2, and CB3 are shown in Fig. 12. The downstream and upstream positions of a DCCB are relative to fault locations and could be reversal at different fault locations. For example, at F1, CB1

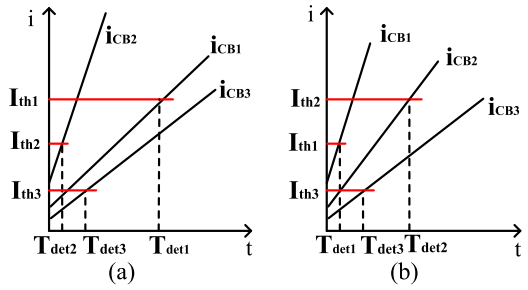

Fig. 12. Overcurrent protection coordination of CB1,2,3 at fault F1,2.

is upstream of CB2, while, at F2, CB1 is downstream of CB2. Since selectivity only permits the closest breakers open but not any other breakers, the current thresholds can be designed to be adaptive to fault locations in order to ensure selectivity. In Fig. 12, at F1, I_{th1} is higher than I_{th2} while I_{CB2} is higher than I_{CB1}. The lower threshold and higher dc fault current of CB2 guarantees the faster fault interruption of CB2 than CB1 at F1. I_{th1} and I_{th2} are then adjusted at F2. CB1 is opened before CB2 at F2 since I_{th2} is higher than I_{th1} while I_{CB1} is higher than I_{CB2}. This adaptive threshold setting can be realized by sensing and identifying reversal fault current directions flowing through the same DCCB.

B. Hybrid DC Protection

If the shipboard distribution system in Fig. 9 does not require high reliability and survivability, then a hybrid dc protection solution may be applied using DCCBs and converters. A hybrid protection using thyristor rectifiers, dc disconnectors, and fuses have been applied in a commercial LVDC shipboard power system [4], [5]. Another hybrid protection using an ultrafast solid-state DCCB as a tie breaker to separate a system into faulted and healthy parts and generators to limit fault currents was implemented on a naval LVDC shipboard power system [3]. In the proposed hybrid solution for a MVDC shipboard power system, LV DCCBs and MV converters are employed as protective devices considering the matureness and affordability of LV DCCBs and the high technical and economic challenges of cost-effective MV DCCBs. MV converters having fault current handling functions [22], [34]–[37] should be selected and implemented from the initial design stage.

As found from Sections III and IV, the DCCB-based protection and converter-based protection have different protection speeds and allow different discriminative principles based on different measurements and variables. These differences are main challenges of the protection coordination of a hybrid protection solution. For example, mechanical LV DCCBs have much lower speed than converters. At a LVDC fault, the MV converter control may react to limit before the opening of the closest LV DCCBs [17], [30]. Solid-state LV DCCBs are adopted to avoid the speed conflicts between slow downstream DCCBs and fast upstream converter control. The fault interruption in the communication-based coordination occurs before the coordination while it is reverse in the overcurrent protection. If different protection principles, such as the overcurrent coordination by LV DCCBs and the communication-based co-

ordination by MV converters, coexist at a LVDC fault, the fault currents can be quickly limited to zero by the upstream converters and the dc fault characteristics disappear. The protection discrimination is thus lost at the downstream DCCBs.

At a LVDC fault, the fault location of the LV DCCBs should be completed before the dc fault currents are limited by the MV converters as (21). To ensure selectivity, the opening of the downstream DCCBs should be finished before the opening commands are issued to the no-load disconnectors of converters as (22). Subscript *lv* and *mv* represent the LV DCCB and MV converter to be coordinated. After (21) is subtracted from (22), (23) and (24) are derived from (11) and (12) for the required turning-OFF speed of the LV DCCB. If necessary, certain time delay may be inserted into the converter fault control to satisfy (23) and (24). At a MVDC fault, the MV converters next to the fault should control the fault currents before the LV DCCBs are tripped as (25). Equation (25) ensures the disconnectors of the MV converters open before the LV DCCBs open

$$T_{\mathrm{triplv}} < T_{\mathrm{int\,mv}} \tag{21}$$

$$T_{\mathrm{intlv}} < T_{\mathrm{tripmv}} \tag{22}$$

$$T_{\mathrm{offlv}} < T_{\mathrm{redmv}} + T_{\mathrm{locmv}} + T_{\mathrm{commv}} \tag{23}$$

$$T_{\mathrm{offlv}} < \max\{T_{\mathrm{conmv}} + T_{\mathrm{redmv}}, T_{\mathrm{codmv}} + T_{\mathrm{commv}}\} - T_{\mathrm{conmv}} \tag{24}$$

$$T_{\mathrm{intmv}} < T_{\mathrm{triplv}}. \tag{25}$$

Equations (21) and (25) conflict each other because of reversal downstream and upstream positions of the converters and DCCBs at different fault locations. Adaptive delay settings at different current thresholds may be adopted by converter fault control to solve the conflict. Alternatively, at a dc fault, the dc/dc converters between the MVDC and LVDC buses can separate one interconnected system into independent MVDC and LVDC subsystems. In this way, the protection coordination is easier to achieve since the protection devices and discriminative principles are uniform in each MVDC or LVDC subsystem.

VI. DC Versus AC Distribution Protection

In traditional ac distribution, where no power electronics converter is involved, ac circuit breakers (ACCBs) rely on high fault currents for fault detection, location, and identification. AC sources are required by the traditional ac protection to contribute sustained high fault currents for protection discrimination. Conventional power equipment is thus designed to have high short-circuit withstands. Since long duration of ac faults are allowed in traditional ac distribution systems of high short-circuit tolerance, ac fault protection can be achieved timely even with communication delays and ACCBs are allowed to take several cycles, reaching steady state, to trip and open. Steady-state fault currents are discriminative enough in traditional ac distribution protection.

The most significant differences between traditional ac and dc distribution systems are the fault currents from dc sources through low inductances and the low short-circuit withstands of power electronics switches. These differences significantly reduce protection design limits in dc distribution systems. Specifically, the dc fault interruption should be much faster than ac. Essentially, dc distribution protection requires much faster fault interruption devices and protection methodologies than traditional ac. In addition, transient fault behavior should be studied to achieve fast discrimination in dc distribution protection.

High speed fault interruption devices, fault identification, and protection coordination are crucial in dc distribution protection. Instead of ACCBs in traditional ac distribution protection, either DCCBs or converters should be used as fault interruption devices for dc distribution protection. Unlike ac voltages and currents, dc voltages and currents do not have zero crossings and thus artificial zero crossings should be created to facilitate the openings of DCCBs. Fast or even ultrafast turning-OFF speed is also a necessity to DCCBs. In order to allow the converter fault current control, the semiconductor devices, topologies, and control of the converters may be revised to allow active turn -ONS/OFFS.

Traditional ac distribution protection methodologies, including overcurrent, distance, and differential protection, are also applicable to dc distribution protection with some revisions. Generally speaking, the protection methods capable of high speed fault identification and protection coordination, such as the overcurrent protection, is preferred by dc distribution protection. Higher sampling rate and faster data processing and computation should be adopted since dc fault currents can rise to much higher magnitudes within much shorter time frames than ac fault currents.

VII. Conclusion and Future Work

DC distribution protection is significantly different from its traditional ac counterpart. Fast or ultrafast fault interruption is required in order to prevent power electronics switches from damages caused by rapidly rising dc fault currents. Proper protective devices, protection coordination methodologies, and fault protection speed requirements are main focuses of various DCCB- and converter-based dc distribution protection solutions.

The DCCB-based protection is more feasible than the converter-based protection, majorly because of its fault-handling flexibility, selectivity, and reliability. Cost-effective high-speed DCCBs are needed for the fault interruption. The converter-based protection heavily depends on converter technologies. The converter fault current limiting requires special converter designs but allows more relaxed design requirements than the converter fault current bypassing. One major disadvantage of the converter-based protection is low reliability due to system-wide loss of power supply. Simulation results verify the effectiveness of a DCCB-based protection solution on a shipboard power system. Adaptive protection settings can be applied to ensure the protection coordination among different protective devices and discrimination principles. In practical applications, a feasible dc distribution protection solution should be developed from the initial design stage. It should satisfy not only protection design requirements on reliability, speed, selectivity, and sensitivity, but also system design requirements, such as cost.

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