DC Power Distribution: New Opportunities and Challenges

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***Abstract*—The benefits offered by the DC energy distribution in different applications raised the interests towards new power architectures and apparatus. The availability of the related LV and MV apparatus and protection schemes is in fact crucial to fully exploit the opportunities opened in the energy management for the smart grid. Experimental results of testing DC circuit breakers based upon current injection and solid-state technologies are presented and their effectiveness for DC distribution protection is discussed. The possibilities opened by local measurement and communication to support the operation of DC circuit breakers for DC protection as well as the design challenges and implementation issues are investigated.**

Keywords—DC, distribution, protection, circuit breakers

I. Introduction

With the growing of distributed energy resources and the availability of high power semiconductor devices, DC distribution has become a competitive alternative to conventional AC distribution. Existing and future applications of DC distribution include industrial systems, renewable energy collection systems, shipboard power systems, data centers, building systems, etc. Main benefits, such as higher efficiency, higher power rating, easy integration of DC renewables and energy storages, vary for different applications.

The design of LV and MV DC distribution architecture is based upon the combined usage of DC apparatus. Some DC components, such as AC/DC rectifiers, DC/AC inverters, and high ratio DC/DC converters, have already been used in AC distribution and can be revised and optimized for DC distribution. Other components, such as DC protective devices, are specifically required for DC distribution and they have to face challenges in the availability and/or development. Unlike in the AC currents, there is no natural zero crossing in DC currents both during nominal operations and at fault conditions; DC fault currents supplied by capacitors and DC sources increase promptly because of low inductances in DC lines and cables. Fast speed operations are the essential requirements for DC distribution system protection.

Several switching technologies have been introduced in literature in order to interrupt the DC fault currents and overcome the absence of natural zero crossing of the DC current waveforms. The paper addresses the opportunities and challenges opened by different technologies for the DC circuit breaker development; applicable DC protection methods are proposed. Examples of DC distribution systems along with their most relevant features are described in Section II. The design and development of a current injection DC circuit breaker and a solid state DC circuit breaker are presented in Section III and Section IV, respectively. The basic requirements for DC distribution protection and the applicable protection methods are presented in Section V . Finally, conclusions and some future work are given in Section VI.

II. DC Power Distribution Systems

DC distribution systems for marine and naval vessels, offshore wind collection, and industrial plants are described in this section.

A. Marine and naval shipboard power systems

DC distribution technologies have been applied to commercial marine electrical systems and are promising also to naval shipboard power systems [1]-[5]. Fig. 1 shows a commercial Low Voltage DC (LVDC) electrical distribution system [6][7]. Fig. 2 is a naval DC shipboard power system architecture described in IEEE Std 1709 [4]. In DC shipboard distribution, high system efficiency can be achieved with variable speed generation and propulsion; weight and volume can be greatly reduced by eliminating transformers. A high power shipboard DC distribution system, such as the naval system shown in Fig. 2, includes a Medium Voltage DC (MVDC) subsystem in ring bus configuration and several zonal LVDC subsystems due to high requirements on reliability and survivability. The main common features of commercial and naval DC shipboard distribution systems are:

- low inductances of the short connection lines between equipment;
- multiple capacitors connected to the DC link;
- prone to system instability since the generation capacity is comparable to the load demand.

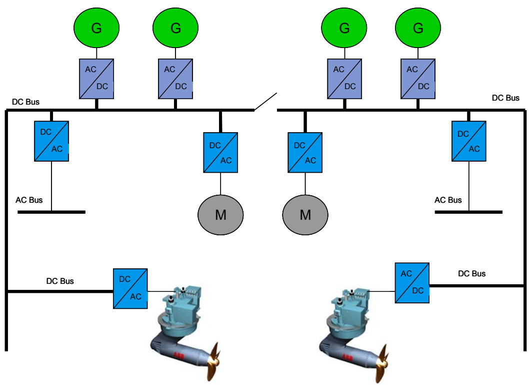

Fig. 1. A commercial LVDC electrical distribution system [6][7].

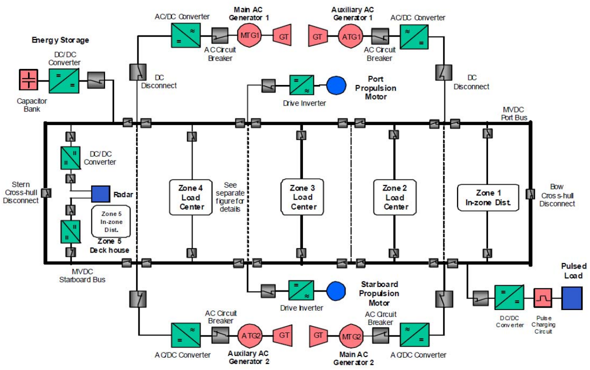

Fig. 2. A notional design of naval DC shipboard power systems [4].

B. *Offshore wind collection systems*

The configuration of a typical offshore wind farm collection system is a radial feeder system with the operating voltage of 33-36 kV. The size and distance of the wind farm from the grid connection point decides the selection of transmission technology, i.e., HVAC or HVDC. System architectures with MVDC collection grid have received increasing attention recently considering potential system benefits in comparison with AC collection grids. In order to implement a MVDC collection grid, it is required that the wind turbines should be able to produce sufficiently high DC voltage output. Three basic options of the DC wind turbine drivetrain using permanent magnet synchronous generators (PMSGs) are shown in Table 1 [8].

Fig. 3 shows two main variants of the DC collection grid architectures which are characterized by the points where the power outputs from individual feeders are aggregated at the collector substation. If an AC collection is used, feeders are connected to the AC bus of the collector substation through individual inverters. At faults, AC breakers can be used to isolate faulted feeders. If a DC collection is used, feeders are connected to the DC bus of the collector substation and then converted to AC power. At faults, DC switching devices are required to isolate faulted feeders.

One promising application is platformless MVDC integration schemes [9]. By eliminating offshore substation and connecting wind turbines direct to onshore inverter station, the potential economic benefits could reach up to 20-25% of CapEX reduction of electrical infrastructure in comparison with AC collection and HVAC transmission solutions. For integration schemes with HVDC transmission, high power DC/DC converters are needed at the offshore platform between the MVDC bus and HVDC cables.

Table 1 DC drivetrain arrangement options [8]

Simplified arrangements	Generator ratings	DC outputs
Two-stage	0.69…6.6 kV 10…120 Hz	±20 ~ ±60kV
Transformerless	13.2 kV 10…120 Hz	±10kV
Pre-transformer	0.69…6.6 kV 50…120 Hz	±20 ~ ±60kV

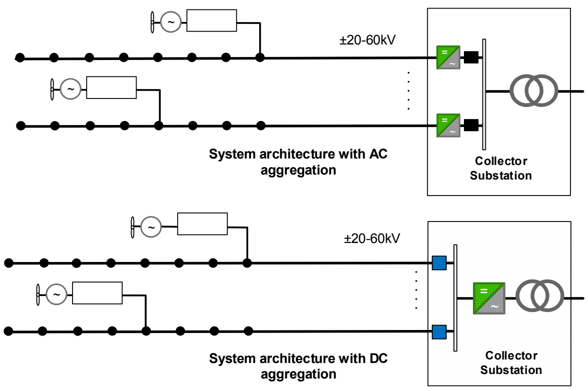

Fig. 3. DC collection grid architectures [8]

C. *Industrial distribution systems*

For certain industrial plants, such as water pumping station, mining, metals and other heavy process industry, a high percentage of total power consumption is used by large electric motors that are typically connected to the medium voltage switchyards. The pumps, fans and production process driven by electric motors typically run at variable load in most of operational time. Variable Frequency Drivers (VFD) have been widely used to improve plant energy efficiency and reliability. For further improved energy efficiency and cost reduction, MVDC electrification schemes become interesting topics recently. Fig. 4 shows a simplified MVDC electrification scheme with a common DC bus configuration as interconnection point of multiple drives.

As shown in Fig. 4 , power supply from utility distribution or transmission network is converted to DC and fed into the common DC bus. Medium voltage motors are connected to the common DC bus through respective inverters. Energy storage may be connected to the DC bus via bidirectional dc-dc converter. Local power supply, for example, waste heat recovery power system, may also be connected to the DC bus via ac-dc converter.

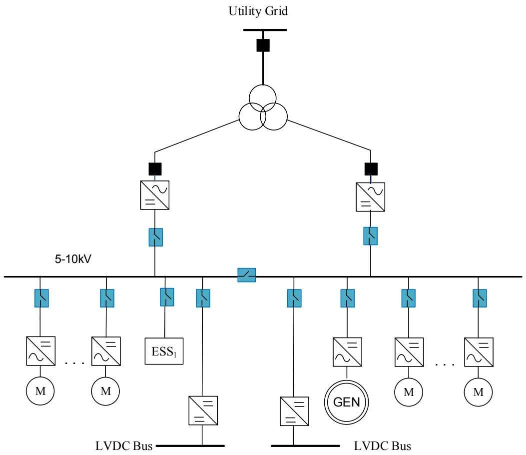

Fig. 4. DC electrification of industrial plants

The protection of the described DC distribution systems requires the use of DC circuit breakers. Different switching technologies have been introduced in literature in terms of complexity, performances, ratings and promptness of operations. In section III and IV, a current injection method and a solid state approach will be introduced.

III. Current Injection Circuit Breakers

One concept for DC switching apparatus is the current injection method shown in Fig. 5 [10][11]. DC interruption is accomplished by injecting a superimposed counter current that creates a local current zero within the breaker itself. This is made with a pre-charged capacitor C_{inject}, that is discharged by closing switch SW_2 and through the interrupting switch SW_1, producing a current zero crossing where SW_1 can interrupt the current. The fault or load current will however still continue to flow and start to charge the injection capacitor. To avoid excessive overvoltage across the capacitor and take care of the inductive energy in the system a surge arrester is placed across the capacitor. Once the voltage across the capacitor is above the protection level of the surge arrester it will start to conduct and the current will be commutated to the surge arrester instead. The protective level of the surge arrester should be chosen so that it is higher than the system voltage, typically 1.5-1.6 times, in order to create a counter voltage that effectively reduces the current to zero while absorbing the magnetic energy trapped in the system inductance.

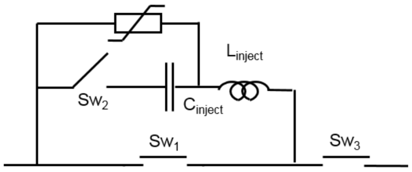

Fig. 5. DC circuit breaker with current injection [10].

Fig. 6. Vacuum DC circuit breaker with current injection.

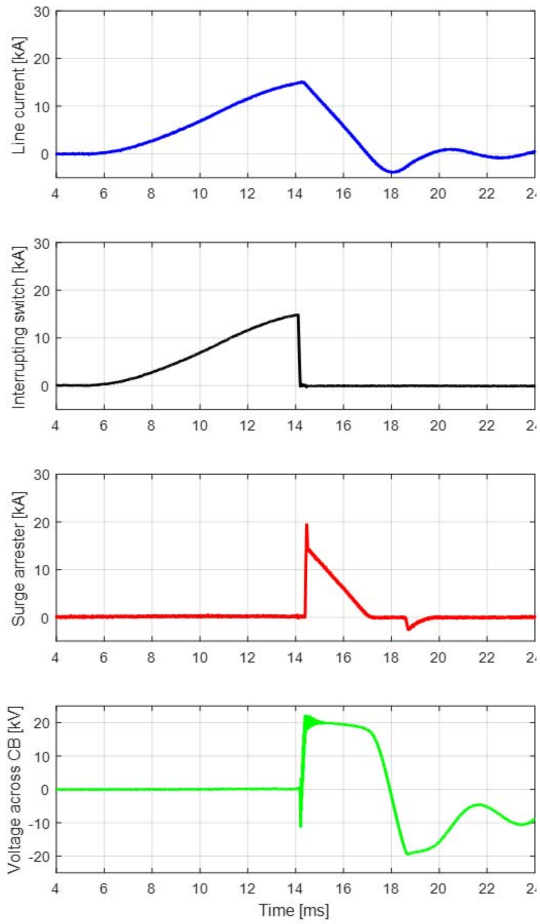

Fig. 7. Measured line current, current through switch Sw1, surge arrester current and voltage across the DC circuit breaker (from top to bottom) [10].

Finally to ensure galvanic isolation and interrupt any residual leakage current from the surge arrester, a disconnecting switch, SW_3, is needed in series with the breaker. In total there is a need for three switches or breaker poles that can be operated independently; one closing switch (SW_2) for the capacitor discharge, one for the interruption of the current (SW_1) and one disconnecting switch (SW_3) for galvanic isolation. Since a normal AC breaker already has three poles it is suitable to use this standard product and modify the operating mechanism to have individual pole operation using single coil magnetic actuators [12]. Furthermore, vacuum technology is preferred for the excellent interruption performance of the high frequency injection current from the capacitor and the short stroke needed to ensure good voltage withstand in short time.

A demonstrator has been built and tested. Fig. 6 depicts the demonstrator with the three vacuum poles in the foreground, injection capacitors on top, grey surge arresters below the capacitors and a voltage transformer to the left for charging the capacitors, all mounted on a standard EU pallet.

The circuit breaker has been tested extensively and in Fig. 7 measured currents and voltage are shown from a high power test interrupting 15 kA and producing a counter voltage of 20 kV suitable for a 12 kV DC system. The results show that it is feasible to build a compact, low loss, high performance DC breaker with current injection using standard components. To achieve even higher performance and faster interruption speeds other types of actuators can be used for the vacuum poles such as Thomson coil actuators [11][13] instead of magnetic actuators. This breaker concept will be a key component and enabler for future DC power distribution systems.

IV. Solid State DC Circuit Breakers

The electrical system diagram of a typical SSCB is illustrated in Fig. 8. Bidirectional semiconductor devices and topologies permits bidirectional power flow. Low conduction loss requires semiconductor devices with low conduction resistances and high efficient cooling systems. The overvoltage after the device turning-offs is clamped by MOVs (Metal Oxyde Varistors). Due to the galvanic isolation required by safety, the MOV leakage currents should be interrupted by a mechanical disconnector. The auxiliary system has the functions of sensing and measurement, control, and communication. The protection control sends open/close command after fault identification and protection coordination.

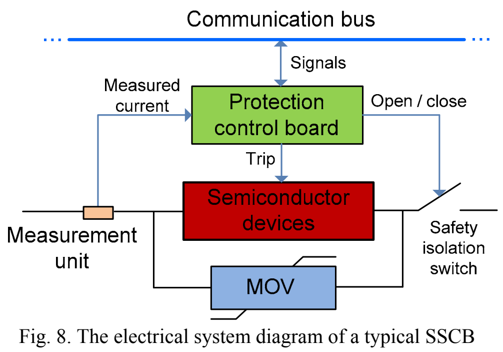

Fig. 8. The electrical system diagram of a typical SSCB

SSCBs having different semiconductor technologies were overviewed in [14][15]. SSCBs should be tested since high current derivatives during DC faults. DC fault protection by some lab prototypes and products were tested [16]-[27]. A detailed comparison of losses, nominal ratings, fault interruption currents, and protection speeds of different SSCBs used for DC protection can be found in [28]. In terms of speed, all SSCBs in comparison are capable of interrupting DC faults in less than one millisecond, which is much faster than conventional mechanical or hybrid circuit breakers.

Semiconductor technologies applicable to SSCBs include COTS (Commercially-Off-The-Shelf) IGBTs (Insulated-Gate Bipolar Transistors) and IGCTs (Integrated Gate-Commutated Thyristors) [14]-[22], as well as new normally-on SiC JFET/SIT (Junction gate Field-Effect Transistor/Static Induction Transistor) [23]-[27]. Reverse Blocking IGCT (RB-IGCT) was developed and implemented in a 1kV 1kA DC SSCB prototype [18]-[20]. The customized RB-IGCTs have much lower conduction losses compared to normal IGCTs. The slow interruption speed of 425µs at 1kA nominal current of the prototype demonstrated in Fig. 9 [20] is due to high inductance in its test setup. The SiC based SSCBs have low conducting losses and extreme fast protection speeds (10-20µs). However, today's SiC devices have low current ratings and therefore have difficulties in being used by SSCBs in high power DC distribution systems.

Impacts of the high current derivatives at DC distribution faults should be considered in the SSCB design and testing. High sampling rate is required for the sensing, control, and communication auxiliary circuits. In order to improve overall protection speed, measurements of high sampling rates are required to pass through analog circuits during the stage of post signal processing. The operation of the SSCB is controlled by a microcontroller equipped tripping unit. Essentially, the protection control unit has different algorithms for overload and short circuit protection and all diagnostic routines. Different protection methods to be discussed in section V. can be implemented in this protection control unit.

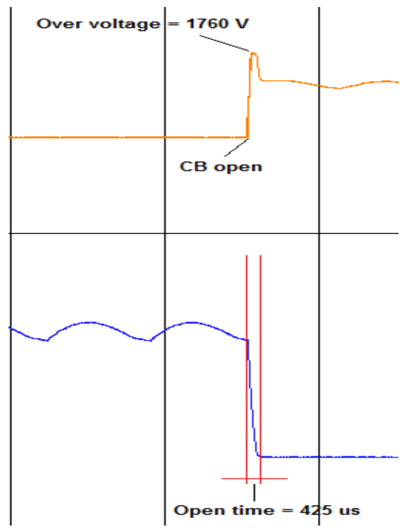

Fig. 9. Experimental waveforms to demonstrate the DC current interruption of RB-IGCT based SSCB [20]

Communication should also be considered in the SSCB design. Even for the protection methods using local measurements, communication links are needed between neighboring circuit breakers. At special fault conditions, an upstream SSCB should be prevented from tripping before a downstream SSCB. Therefore, one SSCB includes a link (shielded cable, fiber optics, etc.) to perform this function; priority in tripping order is hard-wired and given by the way the link is routed (typically in a daisy-chain fashion).

V. CIRCUIT BREAKER BASED DC PROTECTION

Fault identification and protection coordination methods for DC protection have been investigated in [28]-[34]. The discussion in this section focuses on circuit breaker based DC protection methods. Fast speed requirement in DC distribution protection is described first. Local measurement based overcurrent protection and communication based protection are then evaluated. Main benefits and issues of each protection method are studied.

A. Fast DC Protection

In DC distribution systems, the fault sources include capacitors, DC sources, AC synchronous machines, and AC induction motors. Detailed equations of the fault currents from different sources are given and discussed in [28]. Because of low inductances of DC circuits, the fault currents contributed by capacitors have the rising speeds from a few microseconds to hundreds of microseconds; and the fault currents contributed by DC sources have the rising speeds from several hundred microseconds to a few milliseconds. Therefore, one most distinguished feature of DC distribution protection is high derivatives of DC fault currents.

For each DC circuit breaker, the total protection time t_{prot} is a summation of the fault interruption time t_{int} and the extinction time t_{ext} as (1). As indicated by (2), the fault interruption time t_{int} consists of the fault detection time t_{det}, the protection coordination time t_{cod}, the communication time t_{com}, and the circuit breaker turning-off time t_{off}.

$$t_{prot} = t_{\text{int}} + t_{ext} \quad (1)$$

$$t_{\text{int}} = t_{\text{det}} + t_{cod} + t_{com} + t_{off} \quad (2)$$

Since a DC fault current can increase to a high fault magnitude rapidly, it becomes vital to interrupt DC fault currents fast enough to avoid any damage. In order for proper protection, the fault withstands of DC circuit breakers should be lower than those of downstream equipment and devices. The fault withstands are determined by the overcurrent and thermal limits of the DC circuit breakers. Once a DC circuit breaker is selected, the speed requirements on the fault detection, protection coordination, and communication can be obtained. Communication delays should be minimized in order to maximize the time for fault identification and location. The challenge of the current inject DC circuit breakers for the fast DC protection is fast turning-off speeds. With the ultrafast turning-off speeds and the low overcurrent limits, the bottleneck of SSCBs to achieve the fast DC protection becomes protection selectivity before reaching their low overcurrent and thermal limits.

B. Local Measurement based Overcurrent Protection

In overcurrent DC protection, an instantaneous current is compared with a current threshold for a given time period for the short circuit protection. With conventional circuit breakers, loss of selectivity may happen in the overcurrent protection since the upstream breakers may trip during the slow turning-off process of the downstream breakers [30]-[32]. With SSCBs, the ultrafast turning-off can reduce and even eliminate the false trippings.

As mentioned earlier, the most challenging issue of using SSCBs in the overcurrent protection is fast and accurate fault identification and protection coordination before their low overcurrent and thermal limits are reached. The fault currents can be assumed linearly increasing with time between fault occurrence and interruption. Fig. 10 illustrates how the selectivity of the SSCB based overcurrent protection can be achieved. Once a fault is detected by reaching a current threshold, a tripping command is sent. Proper protection coordination between upstream CB1 and downstream CB2 is achieved by different current thresholds, i.e. i_{th1} and i_{th2}, and different fault currents, i.e. i_{CB1} and i_{CB2}.

From Fig. 10, the tripping time difference between CB1 and CB2 is t_{trip1}-t_{trip2}, where t_{trip1} and t_{trip2} are the tripping time instants of CB1 and CB2, respectively. After reaching i_{th2}, CB2 takes some time to send its tripping signal and then takes t_{off2} to actually open. If CB1 receives its tripping signal before CB2 actually opens, CB1 also trips and will be turned off. Therefore, t_{trip1}-t_{trip2} should be larger than t_{off2} for selectivity. The false tripping can be avoided by increasing t_{trip1}-t_{trip2} by changing the thresholds. It should also be noted that t_{trip1}-t_{trip2} is reduced if the same current flows through CB1 and CB2 and the current derivative is higher. Selectivity can also be improved by sending the tripping signal of downstream CB2 as an interlocking signal to upstream CB1.

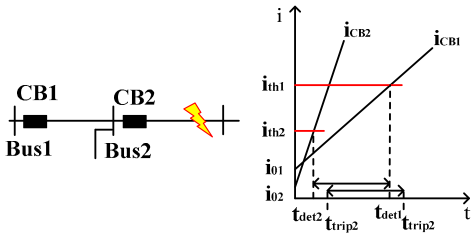

Fig. 10. Protection coordination of SSCB based overcurrent protection

C. Communication Based Protection Coordination

Conventional communication based protection methods, such as differential protection and current direction protection, can be used for DC protection. Due to rapidly increasing DC fault currents, faster algorithms are required by DC protection than AC [32]-[34]. Therefore, most design and implementation issues in the AC protection algorithms become more severe in DC. For example, more stringent signal synchronization is required in order to prevent false tripping caused by data mismatches. More detailed discussions on these issues can be found in [28][33][34].

Communication reliability and speed are major concerns for the communication based protection methods. A widely used industrial protocol CANopen has a typical delay of 100μs to transmit a trip. In AC systems, because of relatively long time to reach high fault current, timely fault location can still be achieved by the communication based protection methods. However, in DC distribution systems, the desirable fast DC protection cannot be achieved since DC fault currents may rise to high magnitudes and cause damages to equipment after communication delays. The communication based protection methods are preferred to be used with DC fault current limiting devices, which limit fault currents to low magnitudes to tolerant the required communication delays.

VI. Conclusions and Future Work

Protection Systems are among the main challenges in the design and operation of DC distribution system. Fast speed fault protection, including protection coordination and interruption, is the essential requirement for robust DC protection architectures as well as the availability of reliable and efficient LV and MV apparatus.

Several DC protection solutions are discussed in the literatures and shared in the international community. In this paper, the Solid State CB-based DC protection has been introduced as a possible proposal for LVDC applications: it offers ultrafast protection speed and reduces requirements on equipment fault withstand. Current injection CB-based DC protection is proposed as a very promising candidate for MVDC applications. Experimental results of testing campaigns have shown the main characteristics and benefits of both the proposals. The switching solutions are different in terms of complexity, performances, ratings and promptness of operations. Because of the differences, a unique co-design approach is recommended by combining and optimizing the design of the power distribution architecture together with the switching apparatus technology and protection schemes.

The International Standard Committees have been progressively involved in the preparation of guidance and recommendations for the validation of the new concept of LV/MV apparatus and of the DC distribution architectures both for microgrids in isolated applications (rural installation, naval, etc.) as for integration of DC areas in AC power distribution systems. The release of international recommendations and design guidelines as well as the availability of national or international sponsorships will be a significative leverage for new applications and large pilot installations.

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