Protective Devices for DC Power Networks

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SYNOPSIS

Current naval power architectures are based on AC, but this has not always been the case. The earliest power systems in warships were DC, but there is now a resurgence of interest in DC power distribution for warships. This may seem a backward step, until one considers that much of the power distributed in modern warships is either consumed as DC in electronic equipment, or passes through a DC stage as in power converters and motor drives. DC offers certain advantages over AC, which make it attractive for future naval platforms. Against this is the enduring difficulty in interrupting DC fault currents. This paper examines the challenges of interrupting DC fault current and reviews protective strategies and devices, including mechanical, solid-state and hybrid.

INTRODUCTION

With few (if any) exceptions, naval power architectures are based on 3-wire AC distribution. This has not always been the case. The earliest electric power systems in warships were predominantly DC, but by the 1930s the US Navy was beginning to standardise on 3-wire AC systems, and by the 1950s all new UK platforms were being constructed with AC power systems [1]. It is likely that this was driven by the ease with which one voltage level can be converted to another (using a transformer) and a desire to use commercial equipment. The 3-wire AC system has since become the de facto standard throughout the world. But there is now a resurgence of interest in DC power distribution for warships.

On the face of it, this may seem a backward step until one considers that a lot of the power distributed in modern warships is either consumed directly as DC (e.g. in computers and other electronic equipment), or passes through a DC stage, as in power converters and motor drives. But that is not the whole story: for a given mass of copper it can be shown that DC can transmit about 23% more power than the equivalent AC system (see Appendix). A well-designed DC system offers certain other advantages over AC, amongst which are:

- The absence of reactive power, leading to reduced losses;
- Opportunities to reduce acoustic signatures;
- Increased conversion efficiencies compared to AC through fewer conversion stages;
- Opportunities to use energy storage devices, which are inherently DC, for power failure ride-through duties and de-coupling of pulsed loads.

All this sounds very desirable, so what are the barriers that discourage further uptake of DC distribution? The answer lies in the difficulty of interrupting DC fault currents.

This can be understood if one considers that all mechanical circuit breakers dissipate the fault energy in an arc, which forms between the contacts as they separate. The fault energy is proportional to the square of the current times the time elapsed between detecting and clearing the fault, so it follows that early interruption of the fault...
current is desirable. Tripping times for mechanical circuit breakers are typically in the order of 50 – 70 ms, so the energy released can be considerable.

With AC there are natural current zeros as the current changes direction from positive to negative and vice-versa. These help to dissipate the fault energy when interrupting AC faults. As the contacts separate the distance between them increases and passes a point at which there is insufficient energy to re-strike the arc following a current reversal. This usually happens after about two to three cycles. In contrast, DC (being a unidirectional current) does not have the luxury of natural current reversals, so the fault energy continues to feed the arc as the contacts separate. Hence other means have to be provided to extinguish the arc, and in mechanical breakers this is usually achieved with bigger arc chutes. In practice, this either means that DC circuit breakers are substantially more massive than their AC equivalents, or else are considerably de-rated for a given package size.

Alternatives that are able to interrupt the fault current much earlier than mechanical contacts are therefore highly attractive, as the energy released during fault clearance will be considerably reduced. This can be expected to lead to more compact circuit protective devices. Solid-state switching devices, such as thyristors and insulated gate bipolar transistors (IGBTs), are capable of switching at very high speed and could form the core of a very fast-acting circuit protection system. On the other hand, solid-state switches exhibit losses in the on-state and during switching, and the isolation they provide in the off-state is dependent on the dielectric strength of a reverse-biased PN junction. These can be mitigated to some extent by hybrid devices, which use a mechanical contact to carry the load current (thereby minimising the on-state losses) and a solid-state switch to provide fast interruption of the fault current.

The aim of this paper, therefore, is to review the current state of DC switchgear and protection technologies. Both commercial and experimental devices will be considered. Along the way we will look at mechanical, solid state and hybrid circuit breakers and examine the different ways they dissipate the fault energy. We shall see that, while there is a wide choice of electro-mechanical circuit breakers for DC power networks, there is a strong trade-off between current handling capability, and size and weight. On the other hand, there are a number of development programmes focussing on fast solid-state or hybrid devices, and these are becoming more technically mature. Commercial pull-through, however, is lacking and this is retarding further development.

But before we review the protection technologies, we need to be clear about the challenges of interrupting DC faults and the main requirements of any circuit protection device. This is the subject of the next Section.

**BACKGROUND**

On the occurrence of a fault in a DC system, the current rises exponentially with a time constant $\tau$, which depends largely on the inductances and resistances in the fault path. Left to itself the current will reach some final steady-state value, which is limited only by the impedance of the fault path. The energy released during the fault is proportional to the square of the current and its duration, that is $E \propto I^2 t$, and for any but the very lowest power systems this can be highly damaging. Clearly, then, fast interruption of the fault current is highly desirable. Having isolated the fault, we require the device to maintain the isolation until the fault is cleared and the circuit can be re-energised. This is the function of the protection system, the basic building-block of which is the circuit breaker.

**Generic Circuit Breaker Requirements**

From the foregoing it is possible to identify three main functions of a generic circuit breaker, whether AC or DC, *viz*:

1. To interrupt the fault current;
2. To dissipate the energy stored in the circuit inductances;
3. To provide a barrier to prevent further current flow.

The first requirement is met by a rapid increase in the fault path impedance, to the point where the current falls to zero. The second requirement is achieved by directing the fault energy into an energy-absorbing device or network. The third requirement is met by interposing a dielectric barrier between the fault and the driving voltage. The physical mechanisms by which these requirements are achieved depend on the specific implementation of a circuit breaker.

A Taxonomy of Protective Devices

Circuit breakers, whether for AC or DC, can be divided into three broad categories, viz:

1. Electro-mechanical;
2. Solid-state;
3. Hybrid.

In brief: electro-mechanical breakers are characterised by low on-state losses (desirable) but trip times can be high, in the order of 50 - 70 ms (undesirable); solid-state devices are capable of very high speed operation, in the order of a few µs (highly desirable), but on-state and switching losses can be significant (undesirable); hybrid devices are characterised by low losses (desirable) and high speed (also desirable). Each type is described in later sections of this paper.

Impact of Circuit Power Source

A further complication is that different DC sources have widely varying time-current characteristics. This leads to the need to adapt the protection time-current characteristics dynamically to suit the particular configuration of sources prevailing at the instant of the fault. Guidance is given in IEC 61660 Part 1 [2], which considers the following four main types of equipment:

1. Lead-acid battery;
2. Three-phase bridge rectifier;
3. Smoothing capacitor;
4. DC machines with independent excitation.

Each source has a different characteristic time evolution under a step change in loading. For example, a lead-acid battery source has a rapid rise time and sustained high fault current. By contrast, fault current due to a capacitor rises rapidly to a high value and falls to zero almost as rapidly. These are summarised in Fig 1.
The total fault current is taken to be the superposition of the contributions from all sources connected. This was straightforward when the only source was a lead-acid battery (say, in a submarine), but with the possibility of having several different sources connected depending on the system configuration a 'one size fits all' approach to DC circuit protection is no longer appropriate. This suggests that dynamic control of protective device characteristics and coordination is likely to be a requirement of a DC distribution system.

**REVIEW OF PROTECTIVE DEVICES**

**Electro-mechanical devices**

The most common form of circuit breaker is the mechanical air-break device, which consists of pairs of robust mechanical contacts operated by an electro-magnetic tripping mechanism. An arc chute, which consists of an enclosure containing a number of parallel plates presented end-on to the path of the arc, is situated close to the main contacts. Various means are used to expedite the transfer of the arc into the arc chute, including local shaping of the contacts, auxiliary arc transfer contacts, air puffers and blow-out coils, though not all of these will necessarily be found in all designs.

Fundamentally, all mechanical circuit breakers operate on the same principle: a rapid increase in fault current is detected (by means that need not concern us here) and when a pre-determined threshold is exceeded a trip signal is sent to the breaker contacts, which begin to separate. As the contacts separate, an arc forms between them and is guided into the arc chute (see Fig 2) where it is dissipated and extinguished. The arc voltage opposes the fault voltage and drives the fault current down to zero, while the energy stored in the circuit inductances is dissipated in the arc. When the contacts have separated fully, isolation is maintained by the air dielectric between the contact faces.
There are principally two types of arc chute: insulated plate and cold cathode (see Fig 3). In the insulated type the plates are (self evidently) made from insulating material. As the arc is driven into the chute it is stretched and cooled by being forced to follow a longer path. This type of arc chute has been largely superseded by the cold cathode type, in which the plates are conductive.

The cold cathode arc chute exploits that fact that most of the arc voltage drop takes place in the anode and cathode regions of the arc and is largely independent of the length of the arc. For most contact materials operating in air it is about 30V [3]. The cold cathode arc chute splits the arc into a number of discrete arcs, each of which with its own anode and cathode region volt drop. Thus if there are N plates then the mean arc voltage is about 30N volts [4].

A typical commercial off-the-shelf (COTS) circuit breaker is the Schneider Masterpact NW series. A DC range is offered with a choice of three or four contacts [5, 6] and fixed or withdrawable chassis. As an example the NW 20 is rated for a load current of 2000 A with a rated short-time withstand current of up to 85 kA for 1 s in AC and DC forms. Both AC and DC devices weigh the same, about 120 kg for a 4-pole device in a withdrawable chassis, and overall dimensions are about 439 mm high x 441 mm wide x 395 mm deep.

The breaking capacity of the AC and DC devices are compared in Table 1, where it can be seen that, for short time constants ($\leq 5$ ms), the DC device has a very similar breaking capacity as the AC device. However, for longer system time constants the DC device has to be de-rated.
A few manufacturers offer devices aimed at the railway traction market. These single-pole devices have very high current interrupting capability, in the order of 125 kA at time constants of up to 150 ms, but the chassis size is large as the arc chute dominates. Since these are single-pole devices, space and cost allowances must be made to accommodate a second breaker if the design requires both poles to be isolated.

An example of a COTS circuit breaker in this range is the Secheron HPB45 [7], which is a single-pole device with electromagnetic blow-out intended for DC rail traction substation applications. Some relevant data is summarised in Table 2.

<table>
<thead>
<tr>
<th>System Voltage</th>
<th>AC Circuit Breaker, kA</th>
<th>DC Circuit Breaker, kA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>τ ≤= 5 ms</td>
<td>τ ≤= 15 ms</td>
</tr>
<tr>
<td>220 /415/440 VAC</td>
<td>100</td>
<td>-</td>
</tr>
<tr>
<td>525 VAC</td>
<td>85</td>
<td>-</td>
</tr>
<tr>
<td>690 VAC</td>
<td>85</td>
<td>-</td>
</tr>
<tr>
<td>500 VDC</td>
<td>-</td>
<td>100</td>
</tr>
<tr>
<td>750 VDC</td>
<td>-</td>
<td>85</td>
</tr>
<tr>
<td>900 VDC</td>
<td>-</td>
<td>85</td>
</tr>
</tbody>
</table>

Table 2 Summary of HPB45 air circuit breaker parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated Voltage, VDC</td>
<td>900</td>
</tr>
<tr>
<td></td>
<td>1800</td>
</tr>
<tr>
<td>Rated Load Current, A</td>
<td>4500</td>
</tr>
<tr>
<td>Rated Making and Breaking Capacity, kA</td>
<td>125</td>
</tr>
<tr>
<td>Time Constant, ms</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>31.5</td>
</tr>
<tr>
<td>Height, mm</td>
<td>810</td>
</tr>
<tr>
<td>Width, mm</td>
<td>240</td>
</tr>
<tr>
<td>Depth, mm</td>
<td>640</td>
</tr>
<tr>
<td>Weight, kg</td>
<td>108</td>
</tr>
<tr>
<td></td>
<td>119</td>
</tr>
</tbody>
</table>

Pros

Air-break circuit breakers for DC offer the following advantages:

- Commercial off-the-shelf products readily available from established manufacturers;
- Low loss in the on-state;
- Air-break breaker technology is well understood;
- Devices are resettable after trip operation.

Cons

The main drawback of mechanical circuit breakers for DC is low speed operation (in the order of 60 – 80 ms) so let-through energy is quite high. Longer time constants will require significantly larger arc chutes. Other drawbacks of air-break circuit breakers include:

- Arc chutes for DC-rated devices tend to be larger than those for AC;
• May require repair and recalibration after trip operation to restore to original specifications;
• Physical size can be large;
• Require regular maintenance, and can be unpredictable if not properly maintained.

Vacuum interrupters have been used with DC but require a separate arc snubbing network, so will not be considered further here.

**Solid-state Circuit Breakers**

Solid-state circuit breakers (SSCB) are attractive for their very high switching speed, which makes it possible to interrupt the fault while the current is still relatively low. Conceptually, a solid-state circuit breaker consists of a semiconductor switch such as a thyristor or IGBT and a snubbing device, as shown in Fig 4. The snubbing network is provided to dissipate the stored energy in the external circuit; this is the energy that, in a mechanical circuit breaker, would be dissipated in the arc chute.

During fault clearance, the switching device turns off and the voltage across it starts to rise. The varistor starts to conduct and clamps the voltage across the switching element, dissipating the circuit stored energy. The level of isolation achievable depends on the dielectric strength of the PN junction. There is thus a risk that the switching element may fail to short circuit, so to minimise this risk a mechanical contact can be included in series with the main current path to provide galvanic isolation.

An example of a SSCB development is described by Kempkes, et al. [8], who describe a 'pure' SSCB based on six IGBTs mounted on a water-cooled cold plate and operating as a single switch. The device is rated for 8MW at 10kV DC that measures approximately 585mm x 228mm x 280mm, and weight is about 27kg. The authors claim that it has carried out 10,000 operations at 1kA, after which the IGBTs were individually checked and found to be fully functioning. It would appear that the device has not been progressed as a commercial product.

**Pros**

- Capable of very fast switching speeds (on microsecond scales);
- Fault current is prevented from reaching its peak value;
- Capable of silent operation.

**Cons**

- SSCBs do not provide galvanic isolation of the fault;
- SSCBs rely entirely on the dielectric strength of the semiconductor PN junction, which can fail to a short circuit;
- Separate off-load isolator using a mechanical contact may be required;
- Snubbing network required to dissipate the circuit stored inductive energy;
- Losses are incurred in the on-state and during switching.
There appears to be no SSCBs available as COTS items, all SSCBs noted being either concept designs or lab-based developmental devices. Although the technology appears to be quite mature, the lack of market pull-through appears to be hampering further development. Nevertheless, it is unlikely that SSCBs would be practical for shipboard DC protection purposes.

Hybrid Devices

Hybrid circuit breakers attempt to combine the best attributes of solid-state breakers (high speed operation) and mechanical circuit breakers (low on-state losses). The basic concept is shown in Fig 5, where it can be seen that the hybrid circuit breaker is similar to the SSCB but with the addition of a parallel mechanical contact and a series contact.

![Fig 5 Simple hybrid circuit breaker concept.](image)

There are detail variations on the theme, but all operate in essentially the same way [9]. In normal operation, the circuit load current flows with very low loss through the mechanical contacts (which are closed), and the solid-state switch remains in the off-state. When a fault is detected the solid-state switch turns on allowing the main contact to open under low load as the current can commutate away from the main contact. The solid-state switch then drives the fault current down in a controlled manner, while the snubbing network dissipates the fault energy. When the fault current is zero the auxiliary contact opens to maintain galvanic isolation. Operation times in the order of 5 ms have been reported.

**Pros**

- Load current is carried by the mechanical switch contacts;
- Conduction losses are not incurred in normal operation;
- Fault current is driven down using semiconductor switch;
- The mechanical contact opens off load.

**Cons**

- More complex than the equivalent electro-mechanical or solid-state circuit breaker.
- Does not provide galvanic isolation of the fault;
- Relies on the dielectric strength of the semiconductor PN junction. If required, a separate off-load isolator using a mechanical contact may be provided in series with the device.
- A snubbing network is required to dissipate the circuit stored energy.

In common with the SSCB, no commercial devices have been identified, although the technology would appear to be sufficiently mature.
Embedded Protection

Embedded protection attempts to take hybrid protection a step further by using the rectifier switching devices as the protective elements. The concept, shown in Fig 6, links sensors and off-load isolators through a system-wide protection logic. When a fault is detected the protection logic sends a signal to the controlled rectifier, which then limits the current into the network to a safe level while the protection logic locates the fault and opens the appropriate off-load isolator. The rectifier can then restore the full load current to the remainder of the network. Any essential loads would be supported during this period by local energy storage or alternate supplies.

![Fig 6 Embedded protection concept.](image)

There appears to be a number of embedded protection concepts under development, although the terminology describing them is far from consistent. For example Deng, et al [10] describe a concept that they call Centralized Fault Management (CFM), which relies on coordinated control of power converters via communication links with fault isolation being effected by off-load isolators. A local backup protection covers for failure of the primary method. They report promising results from modelling carried out in Matlab/ Simulink and have partially implemented it in a hardware-in-the-loop environment.

A similar concept was described by Rampen et al [11], which they describe as a smart DC grid concept that uses power electronics and data communications. In their concept the protection function is achieved with a ‘current router’, which consists of a semiconductor switch and an inductor. A laboratory-based test rig has demonstrated very fast circuit interruption with a wire link dropped across a pair of live contacts.

The choice of converter strategy is crucial for any embedded protection scheme. DC networks fed from fully controlled IGBT based rectifiers and AC loads fed from voltage source inverters (see Fig 7) cannot be used in embedded protection owing to the presence of the freewheeling diodes, which would become forward biased in the event of a short circuit on the DC side. In effect, the freewheeling diodes would act like a passive bridge rectifier, passing the fault current back into the supply.

![Fig 7 DC fault in controlled IGBT based rectifier and VS inverter network.](image)
Current-source rectifiers do not suffer from this phenomenon as there are no freewheeling diodes and the thyristor structures used would naturally block the current (see Fig 8). In the absence of a gate signal, the thyristors cease to conduct after extinction of any forward current. This opens the possibility of using current-source converters as part of the protection strategy and hence no separate circuit structures are necessary.

![Fig 8 DC fault in controlled rectifier and CS inverter network.](image)

**Pros**

- Avoids proliferation of protective devices by embedding the protection function within the converter.
- Faults are isolated off load.

**Cons**

- Extra complexity compared with AC network.
- May depend on converter architecture.
- Protection functions can become dependent of software systems.

No COTS offerings of embedded protection systems have been identified, although it is likely that any development at a scale of twelve inches to the foot would depend on the maturity of hybrid circuit breaker technologies. And, of course, there is a need for funding…

**SUMMARY AND CONCLUSIONS**

The number of DC loads in naval platforms is growing, supported by increased use of solid-state power converters. Notwithstanding the advantages offered by DC distribution, the challenge of interrupting DC fault current remains. This paper has attempted to draw together some of the technologies under consideration to address this, although in a paper of this length it is impossible to be exhaustive. Nevertheless the following conclusions can be drawn.

- Mechanical air-break circuit breakers are very mature, both commercially and technically, but a choice has to be made between large and heavy for high current (say, 2000 – 4000 A) and long time constants (up to 150 ms), or compact for lower fault current (800 – 2000 A) and short time constants (in the order of 5 to 15 ms).
- Most high-power mechanical DC circuit breakers are single-pole devices, so two will be required if both poles are to be interrupted (with an obvious impact on cost, weight and volume).
- The very high switching speeds of modern solid state switching devices such as IGBTs and thyristors make them attractive for fast fault interruption. However, in spite of their undoubted advantages in terms of speed of operation (and their consequent limitation of let-through energy), SSCBs suffer from on-state and switching losses, and the isolation after switching depends on the dielectric strength of a semiconductor PN junction.
To some extent, this can be overcome by incorporating an auxiliary mechanical contact in the architecture, giving the hybrid circuit breaker described above. This adds further complexity and slows the response time, but does obviate some of the drawbacks of the purely solid-state circuit breaker.

It is worth noting that the increased use of solid state converters will lead to an increase in harmonic current being drawn from the supply, although this can be managed with careful use of filters.

The mechanical air-break circuit breaker remains the only commercially viable means of protecting DC power networks. Despite the promise of high speed fault interruption offered by solid-state and hybrid circuit breakers, they are not yet commercially viable and are likely to remain so in the absence of sufficient market pull-through.

REFERENCES


APPENDIX

For a given power in a DC and an AC network, we have:

\[ P_{DC} = V_{RMS} \times I_{RMS} \]

\[ P_{AC} = \sqrt{3} \times V_{RMS} \times I_{RMS} \]

In DC networks the RMS and the peak quantities are identical, so \( P_{DC} = V_{peak} \times I_{peak} \).
In AC networks the individual conductors carry $\sqrt{3}$ times the line power, or line RMS voltage times the line RMS current.

For sinusoidal waveforms, the peak quantities are $\sqrt{2}$ times the RMS values, i.e $\sqrt{2} \times V_{RMS} = V_{Peak}$, so with $I_{RMS} = I$ and $V_{Peak} = V$ we get:

$$P_{DC} = V \times I$$

since $V_{RMS} = V_{Peak}$ and $I_{RMS} = I_{Peak}$.

And

$$P_{AC} = \left( \frac{\sqrt{3}}{\sqrt{2}} \right) \times V \times I$$

For the same transmitted power, substitute $P_{DC}$ for $V \times I$, which gives:

$$P_{AC} = \left( \frac{\sqrt{3}}{\sqrt{2}} \right) \times P_{DC} = 1.225 \times P_{DC}$$

This says that, from the bulk power perspective, AC can transmit 22.5% more power than DC.

But AC networks require 50% more copper than the DC network, so for the same mass of copper

$$P_{AC} = \frac{2}{3} \left( \frac{\sqrt{3}}{\sqrt{2}} \right) \times P_{DC} = 0.816 \times P_{DC}$$

That is, from a copper mass perspective DC can transmit 22.5% more power than AC.