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A Review on AC and DC Protection Equipment and Technologies: Towards Multivendor Solution

M. Wang[1]*, M. Abedrabbo[1], W. Leterme[1], D. Van Hertem[1],
C. Spallarossa[2], S. Oukaili[2], I. Grammatikos[2], K. Kuroda[2],

[1] Dept. Electrical Engineering, K.U. Leuven/EnergyVille, Leuven/Genk, Belgium

[2] Power System Group, Mitsubishi Electric Europe, London, UK

SUMMARY

At present, HVDC links are built as turnkey projects by a single vendor, who optimizes control and protection based on the project requirements. However, future DC grids require multi-vendor solutions to ensure a competition between vendors. Standards which aim at interoperability of protection equipment, and thus multi-vendor solutions, exist for AC systems whereas for DC systems such standards are currently lacking. This paper provides a review of AC and DC protection technologies, and assesses which aspects of AC protection can be applied to DC protection, especially from the view point of multi-vendor interoperability. In particular, this paper focuses on the review and comparison of recent developments of AC and DC protection equipment, such as measurement devices, relay, communication protocol and circuit breakers. As the result of this study, recommendations on standardization process of DC protection devices learned from AC protection are provided.

KEYWORDS

AC grid protection, DC grid protection, HVDC grids, Measurement devices, Communication protocol, Protective relay

1 Introduction

To integrate remotely located energy sources and to transport large amounts of energy over long distances, meshed HVDC grids can play a major role in the future transmission system. At present, HVDC technology is mainly used for point-to-point links, which are typically provided by a single vendor. Consequently, controls and protection components, such as measurement devices, relays and communication, are typically vendor-specific. This impedes the development of a meshed HVDC grid by multiple vendors since only limited standardization exists to ensure interoperability between vendor equipments.

Extensive standardization exists within AC systems, but due to differences in fault phenomena and methods of clearing a fault, it is unclear whether these standards can be applicable to HVDC grids. Conventional AC protection systems are designed based on a fully selective philosophy, which means only those protective devices closest to a fault will operate to remove the faulted component and power flow in the rest of the grid remains uninterrupted [1]. However, the protection speed of DC grid protection is expected to be one order of magnitude faster than that of AC systems due to the fast increasing fault current [2]. Furthermore, interrupting a DC fault current is much more challenging owing to the absence of zero-crossings. To tackle the challenges associated with DC grid protection, various DC protection philosophies and technologies have been proposed both by academia and industry in recent years. Different converter and DC circuit breaker technologies may be implemented in the application of various fault clearing strategies, ranging from fully selective fault clearing to non-selective fault clearing [3, 4]. In [2, 5] the authors outlined the limits of AC protection principles as they are not completely applicable to DC grid protection; however an evaluation on the transferability of AC protection devices and AC standardization procedures for DC grid protection is still missing.

*mian.wang@kuleuven.be

This paper provides a review of AC protection equipment and standards procedure to assess which aspects related to multi-vendor interoperability of AC protection can be applied to DC protection schemes. Furthermore it analyses DC protection components towards standardization/harmonization of requirements. In particular, this paper focuses on review and comparison of recent development of both AC and DC protection devices, such as measurement devices, relay, communication protocol and circuit breakers.

This paper is organized as follows. Section 2 gives an introduction on protection philosophies and schemes for AC and DC grids. Section 3 provides a review and comparison on measurement devices, relay, communication protocol and breaker technologies for AC and DC applications. Section 4 first reviews the current status on standardization of DC protection systems and proposes an initial procedure for such standardization based on lessons learned from relevant AC standards. Section 5 presents the conclusions of this paper.

2 Protection Philosophies and Principles

2.1 AC Grid Protection

In modern high voltage AC transmission systems, AC circuit breakers are installed at the end of each transmission line and protection zones are used to define the desired actions of these breakers for faults within or outside these zones. Protection zones associated with breakers are typically overlapping and coordination between protection zones is used to minimize the section of the power system to be disconnected in case of a fault.

Two types of protection zones exist, i.e., closed or open. The boundaries of a closed zone are precisely defined and all enclosed components are protected as a "unit". The highest selectivity is ensured in such protection scheme. An open protection zone is only precisely defined at one end whereas the other end depends on locally measured quantities. The zone is also said to be "non-unit" [6]. An overview of protection philosophies and algorithms of AC grid protection is shown in Fig. 1(a).

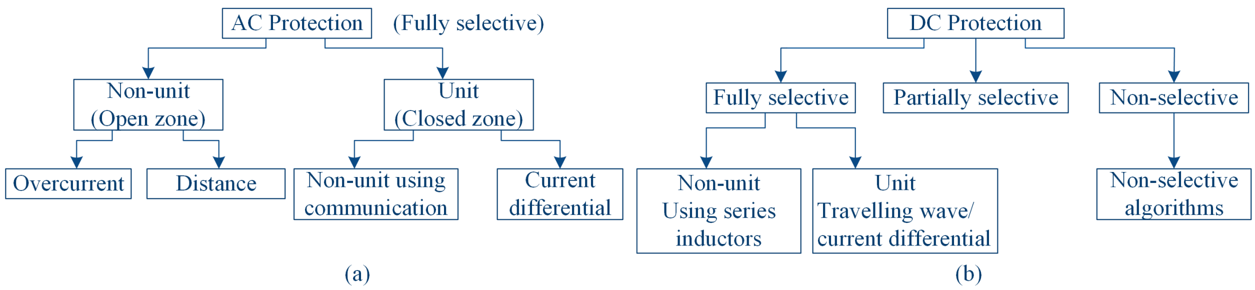

Figure 1: Protection philosophies and examples of algorithms for (a) AC grid protection (b) DC grid protection.

Typical examples of open zone (or non-unit) protection schemes are overcurrent or distance protection relays. Overcurrent relays are coordinated using current or time grading and can be improved by using the direction of the current. Distance protection relays define multiple zones covering different parts of the grid (e.g., zone 1 up to 80-90% of the protected line, zone 2 up to 50% of the shortest adjacent line, zone 3 up to 120% of the sum of the protected line and the longest adjacent line [7]). To coordinate these zones, time delays with intervals in the order of 200-500 ms are typically used [7].

Closed protection zones can be achieved by current differential or non-unit protection using telecommunication, such as directional comparison blocking/unblocking, permissive overreaching/under reaching transfer trip, direct under reaching transfer trip. Current differential protection requires communication channels with high bandwidth to exchange current samples and to synchronize these samples measured at both line terminals [8]. Non-unit protection schemes using telecommunication only need to transfer logic signals, e.g., tripping or blocking signals, via the communication channel, which greatly reduces required communication bandwidth. The non-unit protection schemes using telecommunication can be used to decrease the tripping delay of remote-end faults in distance protection schemes.

A typical fault clearing time in AC transmission systems is 4 cycles/80 ms for 50 Hz system (Fig. 2-(a)), including 2 cycles/40 ms relay tripping time and 2 cycles/40 ms circuit breaker operating time [9].

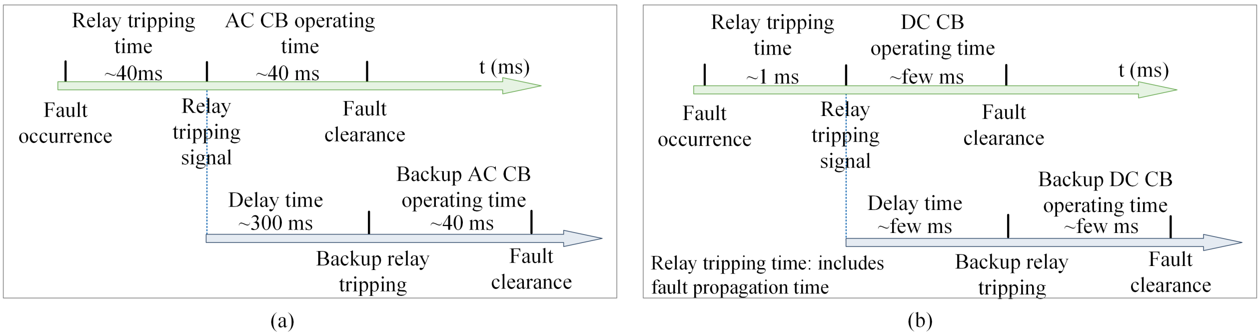

Figure 2: Fault clearing time of primary and backup protection: (a) AC grid protection (b) DC grid protection utilizing fully selective philosophy.

2.2 DC Grid Protection

Three main protection philosophies have been identified for DC grid protection, namely, non-selective, partially selective and fully selective fault clearing [4]. Similar to high voltage AC transmission systems, protection zones can be used within DC grids to define the section to be disconnected in case of faults. On the contrary, the section of the grid which is affected during fault clearing and the duration of the total fault clearing sequence depends on the technology used for fault current interruption.

The choice of the protection philosophy for a certain DC grid is likely to be determined by the constraints from the connected AC grids, the DC grid and its components and the expected performance of the DC protection [3]. A DC grid can be protected non-selectively as one protection zone by using converters with fault blocking capability or AC circuit breakers in the same manner as protecting a point-to-point link. A partially selective philosophy is a combination of non-selective and fully selective philosophies, where protection zones are used to define sub-grids. A fully selective philosophy resembles the ac grid protection philosophy, i.e., each line is individually protected using DC circuit breakers at each terminal.

An overview of protection philosophies and algorithms of DC grid protection is shown in Fig. 1(b). In recent years, a lot of work has focused on developing DC protection algorithms. In terms of primary protection, they can be categorized into protection algorithms for fully selective protection philosophies [10–15] and protection algorithms for non-selective protection philosophies [16–18]. Protection algorithms for fully selective protection philosophies can be further classified as non-unit protection [10–13] and unit protection [14, 15]. Non-unit protection algorithms typically use the series inductor at the cable terminal to define boundaries for the protection zones, and the operation speed of non-unit protection algorithms is less than 1 ms [10, 11]. On the other hand, unit protection algorithms, e.g. travelling wave differential [14] and current differential [15] do not require the use of series inductors. These algorithms however, rely on a fast communication channel between the remote relays.

A comparison of fault clearing time between AC protection and fully selective DC grid protection is given in Fig. 2. Fault clearing times of both primary and backup protection in DC grid are typically one order of magnitude shorter compared to those in AC grid. The fault clearing time of the primary protection is typically in the range of a few ms, including 1 ms relay tripping time and few ms DC circuit breaker operating time.

3 Protection Equipment and Technologies

3.1 Measurement Device

In AC power systems, the measurement devices primarily used for control, protection and metering are the so-called conventional instrument transformers. These devices use electromagnetic induction for measurement. The bandwidth of conventional transformers is usually limited to few kHz as beyond these frequencies, the ratio of these devices is non-linear due to resonances [19, 20]. For applications requiring a larger bandwidth for fast protection, digital interface with relays and HVDC applications, non-conventional instrument transformers must be used.

In DC systems, only non-conventional instrument transformers are applicable. These non-conventional instrument transformers can provide a high bandwidth ranging from tens of kHz to a few MHz. The sampling frequency used for DC protection algorithms is in the order of 100 kHz to capture fast transients during a DC

Table 1: Technologies and bandwidth of instrument transformers [19–21]

Type	Technology	Bandwidth	Application
CT	Electromagnetic (iron-core)	few kHz	AC
	Hybrid electro-optical (combined shunt and Rogowski coil)	few MHz	AC and DC
	Fibre optic current sensor (magneto-optic effect)	few MHz	AC and DC
	Zero-flux (Direct Current Current Transformer)	few hundred kHz	DC
	Zero-flux (Hall-effect current transformer)	few hundred kHz	DC
VT	Inductive voltage transformer	few kHz	AC
	Capacitor voltage transformer	few kHz	AC
	Compensated RC-divider	few MHz	AC and DC
	Fibre optic voltage sensor (magneto-optic effect)	few MHz	AC and DC

fault [11,22]. The bandwidth provided by non-conventional instrument transformers is considered adequate for DC grid protection. Table 1 summarizes main technologies and the bandwidth of instrument transformers. Among which, optical sensor, zero-flux sensor are the technologies primarily used for HVDC current measurement and compensated RC-divider is the main technology used for HVDC voltage measurements [23]. In IEC 61869-9 [24], the digital interface for instrument transformers for both AC and DC applications is specified. For general measuring and protective purposes, the sampling rates are 4,8 kHz and 96 kHz for AC and DC measurements, respectively.

3.2 Protective Relay

Protective relay technologies have evolved from early electromechanical to static, digital and numerical relays. Modern numerical relays use one or more digital signal processors (DSP) optimized for real time signal processing and capable of running a wide range of protection functions [7]. The performance of numerical relays greatly surpasses other technologies in terms of accuracy, range of parameter settings, built-in communications, and multiple functionalities including monitoring and self-diagnostics. As the capability of microprocessors continues to increase, numerical relays will continue being the favourable choices for both AC and DC applications.

The interface between relay and acting equipment, e.g., DC breakers or converters, is considered here to be the main difference between AC and DC relays (Fig. 3). The interface of a DC relay must allow the relay to communicate with DC breakers and converter, which are expected to provide more protection and control functions. Examples of such functions in a DC protection relay are shown in Fig. 3, adopting a similar structure for the DC relay as for an AC relay [25]. Relay coordination is expected to be not only between local/remote line protection relays, but also includes DC circuit breaker internal protection and converter protection. DC circuit breakers are likely to have more intelligent functions such as self-diagnostics [26], therefore it is necessary to communicate these breaker status to local relays for coordinated protection. Pick-up or start signals can also be used to initiate a proactive mode of a hybrid breaker to achieve fast fault current interruption [27]. In addition, coordination with converter protection and control might be advantageous in order to achieve safe and fast fault-ride-through/restoration. The mathematical functions and logics for a DC relay can be easily implemented and are not expected to differ fundamentally from AC relays.

The IEC 60255 standard specifies the typical operating time of relay as the median value of the statistical distribution of operating times assessed over a long series of standardized tests. This standard also clarifies that the operating time is system parameter dependent. For instance, the typical operating time of a distance protection relay depends on several factors, such as fault current level, distance to fault, source impedance ratio (SIR), magnitude and time constant of DC component and type of fault. Similar to a distance relay, it is necessary to define the main factors to be considered when specifying the typical operating time of a DC line protection relay. For instance, the relay operating time may vary depending on the series line inductor size, fault type and DC system configuration.

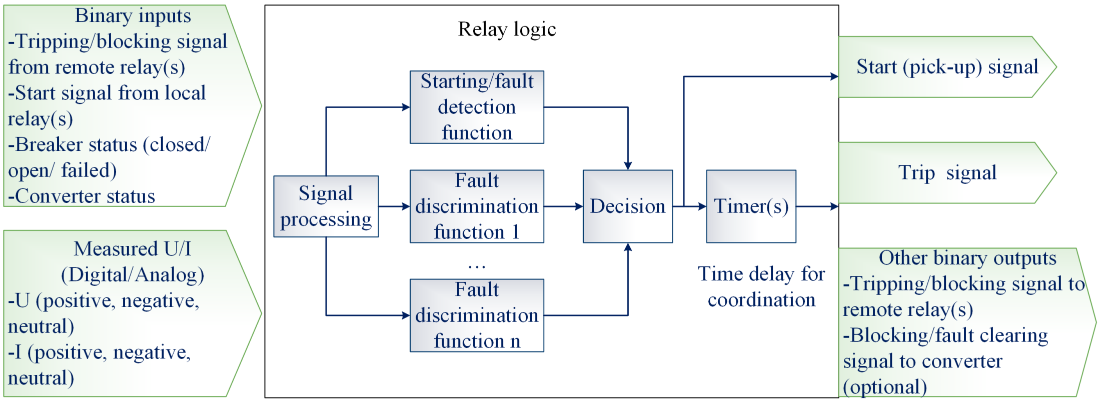

Figure 3: Simplified protection function block diagram for a DC grid protection relay.

3.3 Communication Protocol

3.3.1 Communication within a AC substation

The IEC standard 61850 defines the structure for substation automation and communications inside the substation for data acquisition, protection and data exchange between Intelligent Electronic Devices (IEDs). In IEC 61850, two types of messages are relevant to protection applications: firstly sampled values for exchanging measured voltage and current data between the merging units and IEDs, and secondly GOOSE messages (Generic Object Oriented Substation Event) for delivering tripping or reclosing signals to circuit breakers. GOOSE messages contain a simple binary code to represent a command or component status and are designed for fast transmission. Fig. 4 shows communication arrangements used within a substation and to remote substations.

Merging units provide the interface between measurement equipment and control and protection functions. For AC protection functions, the merging units send 80 samples/cycle in 80 messages/cycle via peer-to-peer communication (IEC 61850-9-1) or multicast to multiple subscribers (IEC 61850-9-2).

The performance of the communication speed is specified in IEC 61850-5 [28] into six classes, three for control and protection and three for metering and power quality. For transmission bay level, the total transmission time for both GOOSE message and sampled values should be below 3 ms.

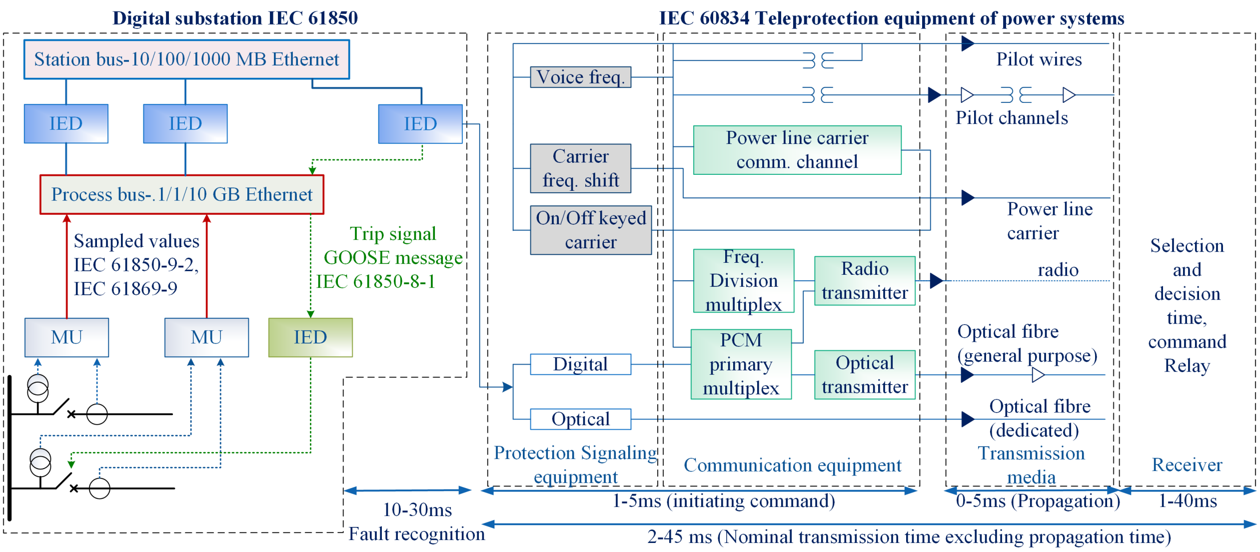

Figure 4: IEC 61850 substation and communication arrangements for teleprotection [7, 28, 29].

3.3.2 Communication between AC substations

Various communication media are available for protection schemes using communication. Historically, pilot wires and channels have been the most widely used due to their availability, followed by Power Line Carrier Communications (PLCC) techniques and radio. Recently, optic-fibres have become the usual choice for new installations, primarily due to their complete immunity from electrical interference [7]. Performance guidance given by IEC 60834-1 [29] specifies that the nominal transmission time delay excluding the propagation time is 2 ms - 45 ms, and maximum actual transmission time of digital teleprotection under noisy conditions for non-unit protection using communication is 10 ms.

Historically, line current differential schemes have been implemented using optic-fibre cable directly connected to the relays or synchronous communications channels using time division multiplexing (TDM) [30]. Most current differential relays today operate at 64 kbps over multiplexed systems such as SONET (Synchronous Optical NETwork) in North America or SDH (Synchronous Digital Hierarchy) in Europe [31]. Fig. 5 shows the data framing and a typical delay calculation over SONET communication. Each timeslot is called a Digital Signal Zero (DS0) which contains 64 kb (8k samples/s $\times$ 8 bits/sample) of data. Time Division Multiplexing (TDM) is used to combine 24 DS0s into one T1/DS1 frame. [32] estimates the total time delay excluding propagation using SONET of 575 μs, comprising of data in/out T1 channel (375 μs), synchronization/de-synchronization delay (100 μs each). 50 μs delay will be added for passing through each drop-and-insert location.

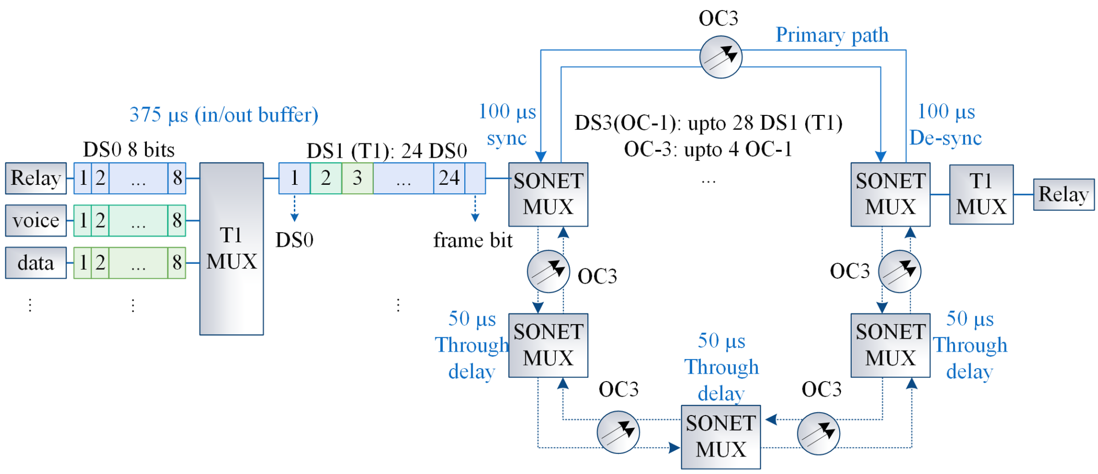

Figure 5: SONET data frame and communication delay [32].

3.3.3 Communication requirements for DC protection

Ideally, similar standards as IEC 61850 together with IEC 61869 and IEC 60834 could also be adapted for DC protection applications. However, the requirement on the communication speed and bandwidth for DC protection might be higher than those of AC protection, and could have different classes for fully selective, partially selective and non-selective protection. Fully selective DC grid protection is likely to have the highest requirement on communication speed.

The speed requirement on both sampled values and GOOSE messages within a DC substation is likely to be much shorter compared with 3 ms in AC substations. As stated in section 2.2, the total time delay including sampled values acquisition, relay time and sending a trip signal is likely to be restricted in the order of 1 ms for non-unit protection. In partially selective DC grid protection strategies, fast and reliable fault detection is necessary to separate the faulty sub-grid from the rest of the DC grid, which implies the speed requirement is of the same order of magnitude as in fully selective protection. Fault identification within the faulty sub-grid might have lower requirements on communication speed if non-selective protection strategy is employed in the faulty sub-grid. Various non-unit protection using communication and differential protection could be viable solutions using direct fibre optical links in non-selective DC grid protection.

The bandwidth for sampled values in DC protection should be adequate to transfer 96 k samples/s [24]. In [33], the data type for sampled values is defined as 32 bits integer or floating numbers. If 4 bytes are used to represent each sampled data [33, 34], the bit rate is 3,072 Mbps (4 bytes/sample × 8 bits/byte × 96 k samples/s) for one sampled DC value as compared to 0,128 Mpbs (4 bytes/sample × 8 bits/byte × 80 × 50 samples/s) for AC protection.

3.4 Circuit Breaker

High-voltage AC breakers are broadly classified according to the medium used for arc extinguishing between the contacts of the interrupter. The classification includes bulk oil, minimum oil, air blast, vacuum, SF_6, CO_2 breakers. Nowadays due to environmental and cost concerns over insulating oil spills, the preferred option is gas circuit breakers that apply SF_6 to quench the arc. However, vacuum breakers are becoming more attractive solutions especially for medium voltage applications since SF_6 has been found out to be one of the most potent greenhouse gases [35].

In DC grids due to the absence of natural zero crossing of current, the circuit breaker needs to be modified and additional branches are needed to interrupt DC fault currents. Based on the technology used in the additional branch, high-voltage DC breakers can be classified as passive resonance, active resonance, hybrid and pure power electronic breakers [36]. Fig. 6 shows exemplary topologies of these technologies, which can be generalized to a normal current branch, an energy absorption branch and a commutation branch (Fig. 6 (e)).

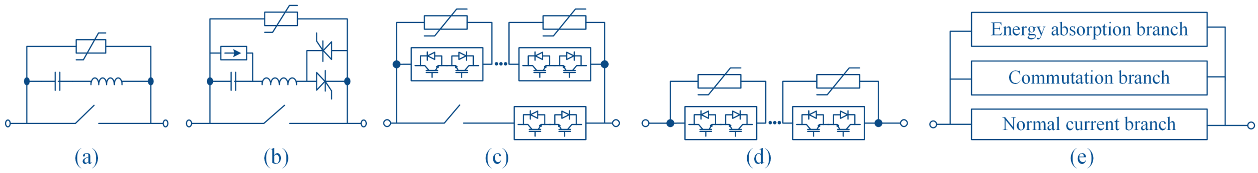

Figure 6: DC circuit breaker exemplary topologies of (a) passive resonance (b) active resonance (c) hybrid (d) pure power electronic (e) generic (commutation branch is not present for (d)).

Fig. 7 illustrates the fault interrupting process and the corresponding simplified circuits of AC and DC circuit breakers. The fault interrupting process of both AC and DC circuit breakers can be divided into three stages: (1) contacts start to open (2) arcing or energy dissipating stage (arcing and energy dissipating stage for passive and active resonance types) (3) fault interrupted. However, unlike AC current interruption process, a DC breaker has to endure both high voltage and high current during the fault current suppression time (t_{sup}). Therefore, an energy absorption branch is necessary to create a counter voltage which drives the DC current to zero and dissipates the energy stored in the circuit during interruption process. The required energy capability can range from few MJ to tens of MJ depending on the operation speed of the DC circuit breaker, the inductance in the circuit and the clamping voltage of the surge arrester [18].

According to IEEE C37.06 [38], AC circuit breakers can also be classified based on rated voltage (e.g. 362/500/800 kV) and rated short-circuit current (40/50/63 kA). Rated break time (t_{brk}) is 33 ms or 50 ms (2 or 3 cycles for 60 Hz) for voltage up to 362 kV and 33 ms for voltage above 500 kV. DC circuit breakers, on the contrary, are developed to fulfil project dependent requirements, and standardized ratings do not exist yet. The need of DC circuit breakers with high speed and high breaking current capability in meshed DC grids has driven the recent development of various DC breaker technologies (Fig. 8). DC circuit breakers can be classified into two large groups: low performance (low speed and low breaking current capability, passive resonant type) and high performance (high speed and high breaking current capability, such as active resonant and hybrid types). Passive resonance circuit breakers rated upto 5.3 kA with interruption time within 20 ms have already been used as transfer switches in point-to-point HVDC links [39–42]. Recent development on active resonance breakers demonstrates commutation can be achieved within 5~8 ms with breaking capability of 10.5~16 kA [43, 44]. The breaker opening time of hybrid breakers is in the range of 1.2~3 ms [27, 45, 46]. A hybrid breaker with a current interruption capability of 9 kA (rated at 80 kV) has been prototyped and tested [27, 47] and a hybrid breaker rated for 200 KV has been installed in the Zhoushan 5-terminal DC grid [46, 48]. 500 kV hybrid circuit breakers are planned to be installed in the Zhangbei 4-terminal DC grid by 2018 [49].

The standard operating sequence of an AC circuit breaker is O-t-CO-t'-CO, where O = Open; CO = Close-Open; t' = 3 min; t = 0.3 s for circuit breakers rated for rapid reclosing duty [37]. Rapid reclosing of a DC circuit breaker might be required in the event of 1) DC breaker located at the healthy lines in the

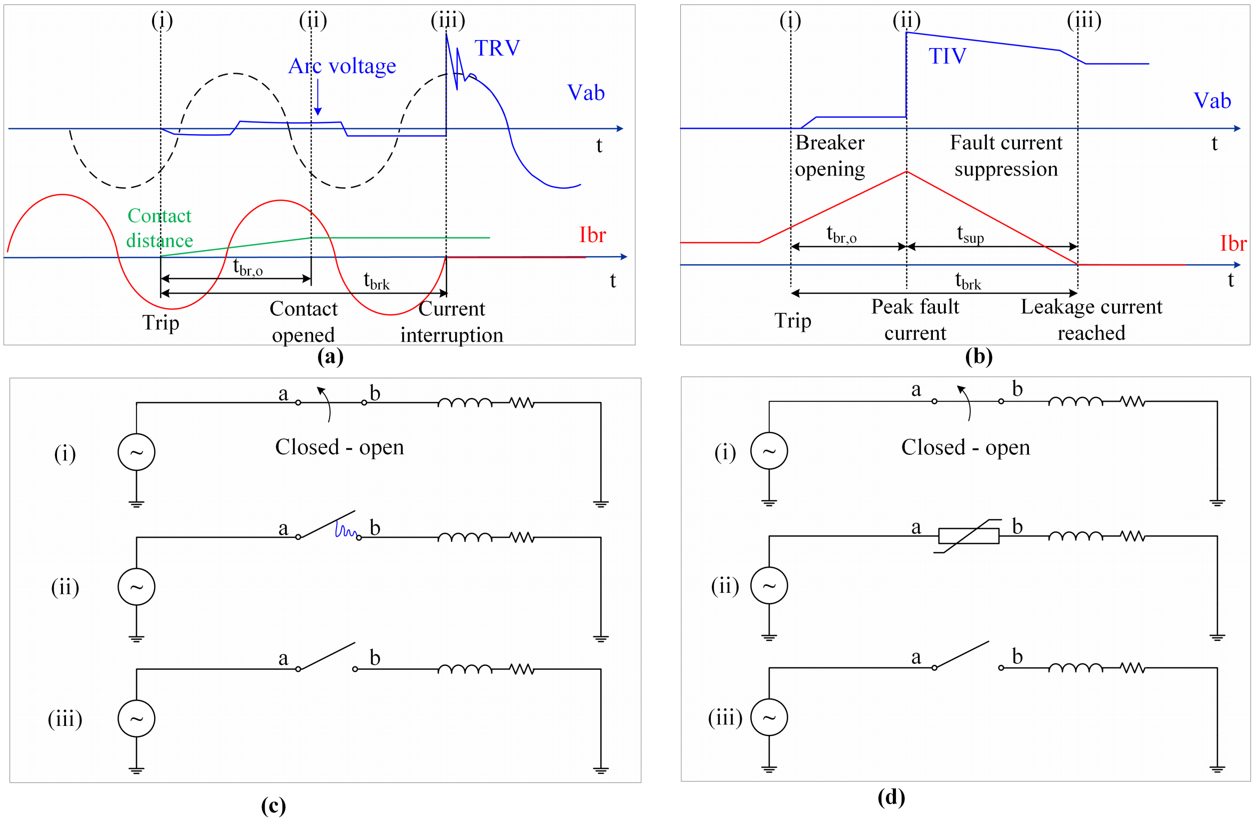

Figure 7: Fault current interruption process and timings (a) AC circuit breaker (ACCB) (b) DC circuit breaker (DCCB) (c) simplified circuit during breaking process for ACCB (d) simplified circuit during breaking process for DCCB. Timing markers: (i) contacts start to open (ii) contacts opened, arcing (ACCBs, passive and active resonance DCCBs using AC interrupter) /energy dissipating (all DCCBs, including hybrid) (iii) fault current interrupted. TRV: transient recovery voltage, TIV: transient interruption voltage.

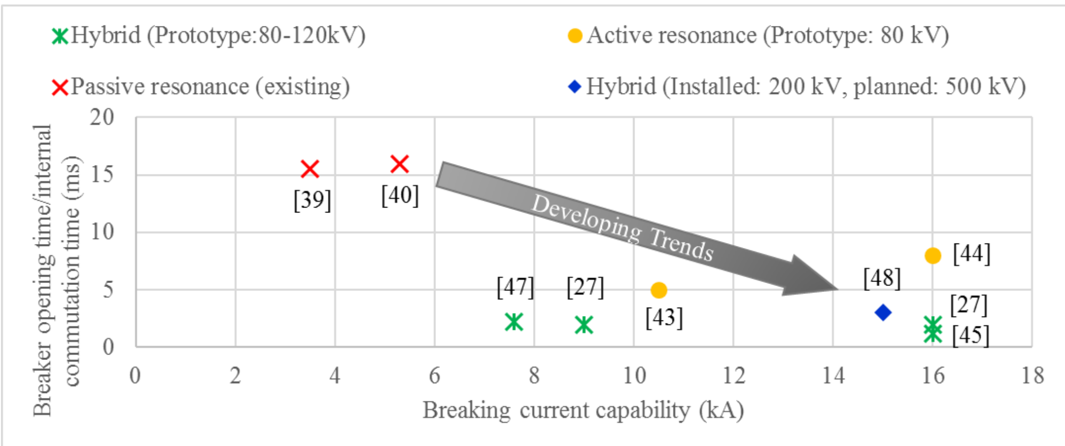

Figure 8: Development trends of DC circuit breakers towards the application in meshed DC grids.

open-grid protection strategy 2) backup operation 3) primary protection for self-clearing fault on overhead lines in fully selective protection. Particularly in the first two cases, the time interval (t) between opening and closing operation could be in the order of few ms in order to minimize the power interruption time.

4 Towards Multivendor Solution

Standardization of the HVDC systems is still in an initial stage because historically HVDC systems have been developed as turnkey projects by a single manufacturer. Recently, the necessity to implement a multi-vendor approach has driven several international standardization bodies to work on guidelines and standards for

HVDC systems. In particular, following working groups are related to HVDC grid protection:

- Cigré B4-56, Guidelines for the preparation of ”connection agreements” or ”Grid Codes” for multi-terminal schemes and DC Grids (2011-2016)
- Cigré B4/B5-59, Protection and Local Control of HVDC Grids (2011-2017)
- Cigré JWG A3-B4.34, Technical requirements and specifications of state-of-the-art DC switching equipment (2013 -2015)
- CENELEC TC8x WG6, European Study Group on Technical Guidelines for DC Grids (2010-2017)

The work done in Cigré B4/B5-59 and CENELEC TC8x WG6 are considered the first step towards standardization of DC grid protection. This first and utmost important step is to specify functional requirements of a DC grid protection system. These functional requirements could be based on the requirements/constraints from the AC/DC systems and user expectations. Once the functional requirements of DC protection are clarified at system level, the specifications on the protection equipment can be defined. In particular, requirements on communication, DC circuit breaker and protective relay are likely to fall into different classes to serve in different protection strategies, e.g., the fastest equipment grouped in a class to serve in a fully selective strategy and the slowest equipment for non-selective protection strategies.

It can be expected that, similar to AC protection technology, technology for DC applications becomes more mature and standardized after decades of continuous development. Although not perfect yet, the IEC 61850 standard is intended to provide interoperability between all equipment in AC substations. International standards for AC circuit breakers, instrument transformers and protective relays have been well established to achieve interoperability in AC system protection. Many of these standards (e.g. IEC 61869, IEC 60255, IEC 61850 and IEC 60834) and technologies used in AC protection can be adapted for DC protection to facilitate a multivendor-based DC grid protection solution.

5 Conclusion

AC and DC protection principles and technologies are reviewed and compared in this paper. As major differences in fault responses and requirements on the protection systems between AC and DC grids, AC protection technologies can not be fully transferred to DC grid protection. DC grid protection requires higher bandwidth and communication speed, more sophisticated relay coordination and breaker functionalities compared to AC grid protection. International standards for communication, AC circuit breakers, instrument transformers and protective relays have been well established to achieve interoperability in AC system protection. Many of these standards (e.g. IEC 61869, IEC 60255, IEC 61850 and IEC 60834) and technologies used in AC protection can be adapted for DC protection to facilitate a multivendor-based DC grid protection solution.

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